Climate Change Impacts in the United States

CHAPTER 22
ALASKA

Convening Lead Authors

F. Stuart Chapin III, University of Alaska Fairbanks

Sarah F. Trainor, University of Alaska Fairbanks

Lead Authors

Patricia Cochran, Alaska Native Science Commission

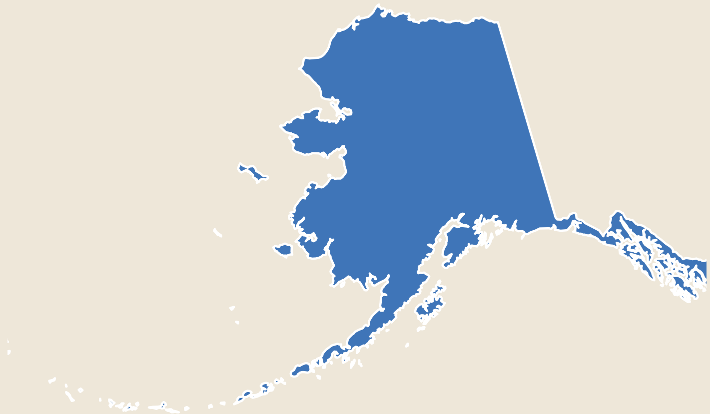
Henry Huntington, Huntington Consulting

Carl Markon, U.S. Geological Survey

Molly McCammon, Alaska Ocean Observing System

A. David McGuire, U.S. Geological Survey and University of Alaska Fairbanks

Mark Serreze, University of Colorado



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22 ALASKA

Key Messages

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

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

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

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

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

Observed Climate Change

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

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

Projected Climate Change

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

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

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

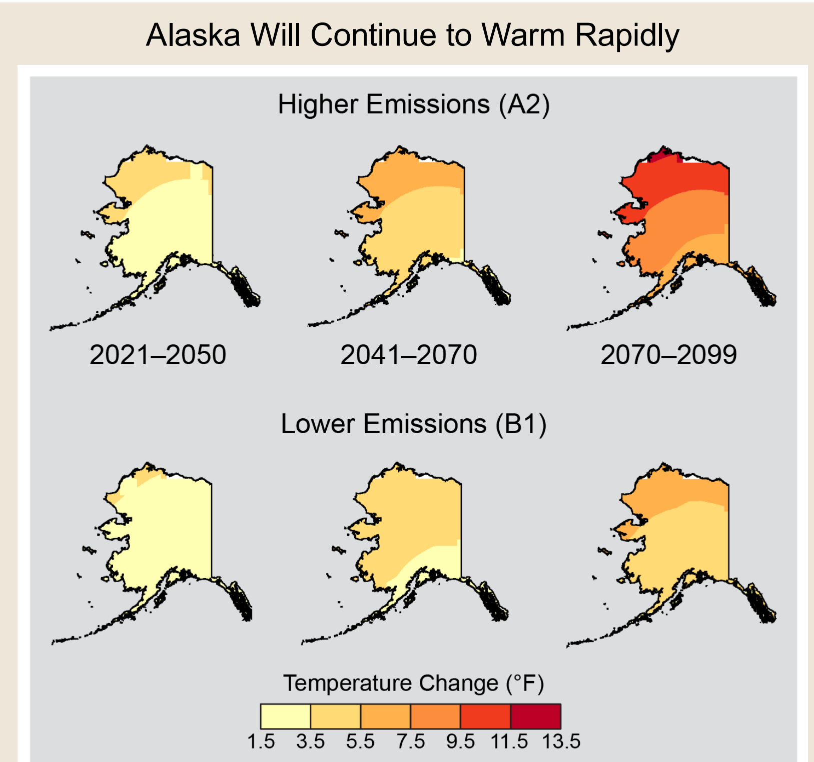


Figure 22.1. Northern latitudes are warming faster than more temperate regions, and Alaska has already warmed much faster than the rest of the country. Maps show changes in temperature, relative to 1971-1999, projected for Alaska in the early, middle, and late parts of this century, if heat-trapping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

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

Key Message 1: Disappearing Sea Ice

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

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

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

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

Declining Sea Ice Extent

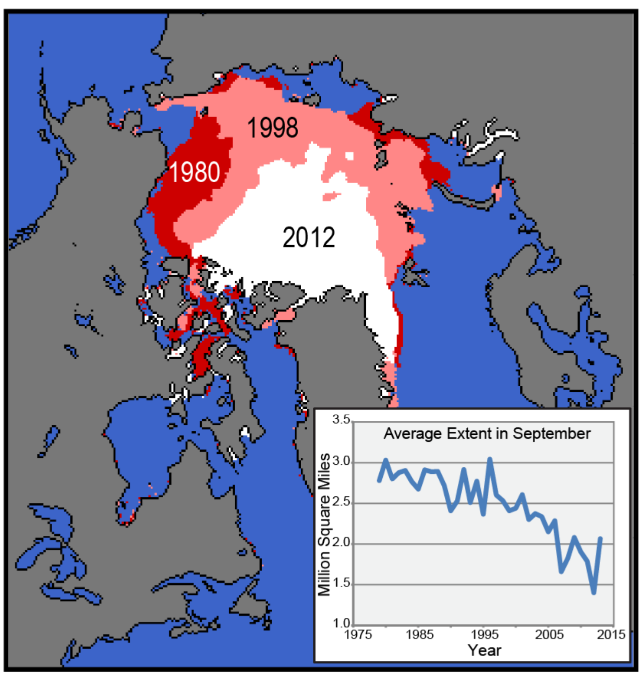


Figure 22.2. Average September extent of Arctic sea ice in 1980 (second year of satellite record and year of greatest September sea ice extent; outer red boundary), 1998 (about halfway through the time series; outer pink boundary) and 2012 (recent year of record and year of least September sea ice extent;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

Sea Ice Loss Brings Big Changes to Arctic Life

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

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

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

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

Living on the Front Lines of Climate Change

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

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

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

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

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

Newtok, Alaska

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

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

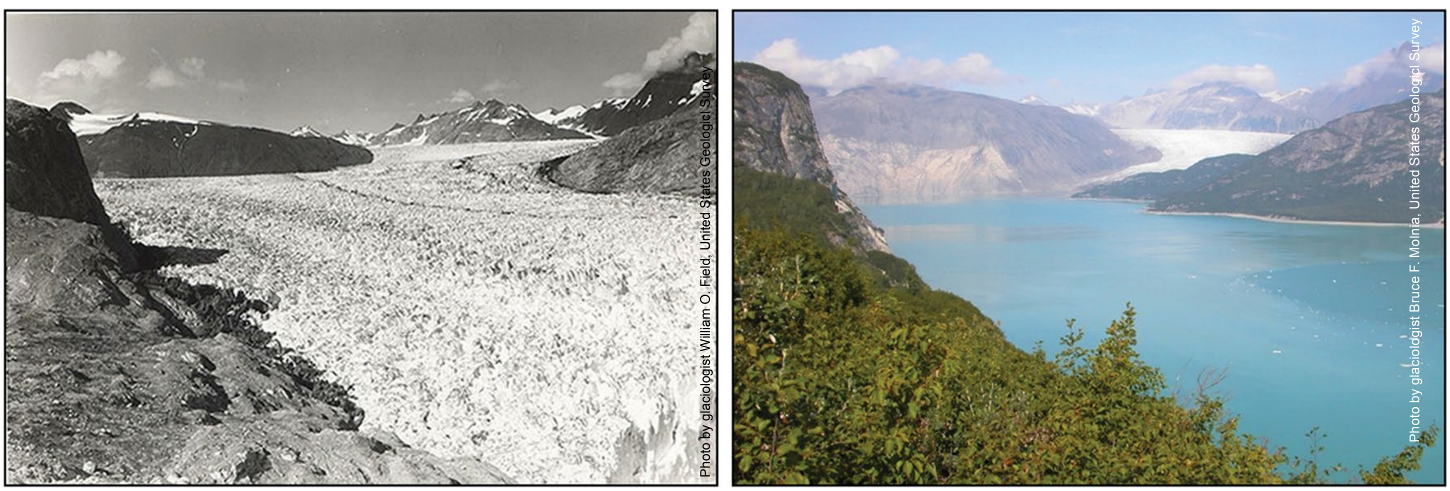
Key Message 2: Shrinking Glaciers

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

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

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

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



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

Key Message 3: Thawing Permafrost

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

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

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

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

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

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

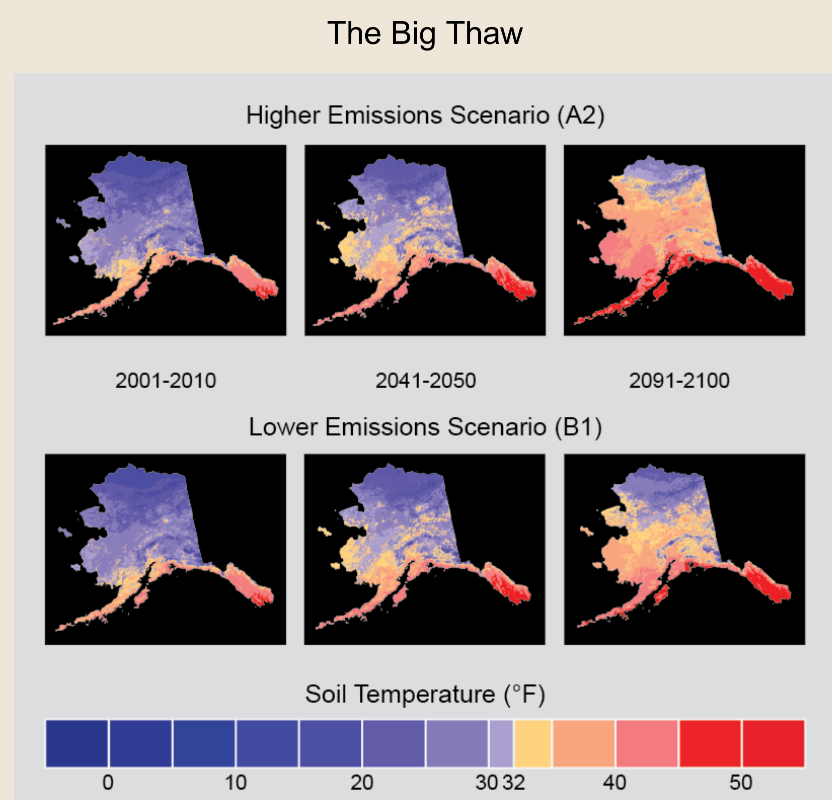


Figure 22.5. Projections for average annual ground temperature at a depth of 3.3 feet over time if emissions of heat-trapping gases continue to grow (higher emissions scenario, A2), and if they are substantially reduced (lower emissions scenario, B1). Blue shades represent areas below freezing at a depth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

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

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

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

Mounting Expenses from Permafrost Thawing

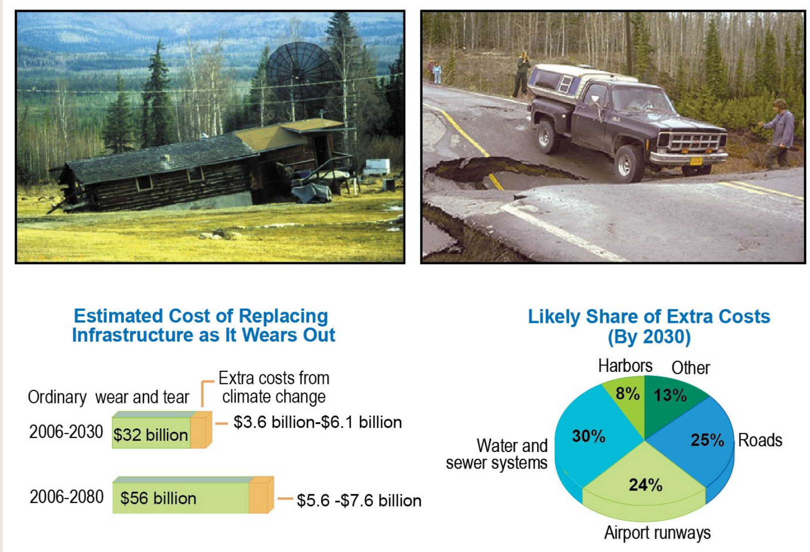


Figure 22.6. Effects of permafrost thaw on houses in interior Alaska (2001, top left), roads in eastern Alaska (1982, top right), and the estimated costs (with and without climate change) of replacing public infrastructure in Alaska, assuming a mid-range emissions scenario (A1B, with some decrease from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

Drying Lakes and Changing Habitat

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

Key Message 4: Changing Ocean Temperatures and Chemistry

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

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

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

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

Ocean acidification in Alaska

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

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

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

Key Message 5: Native Communities

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

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

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

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

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

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

Alaska Coastal Communities Damaged

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

References

1. NMFS, 2010: Fisheries Economics of the United States, 2009. U.S. Dept. Commerce, NOAA Tech. Memo. NOAA Fisheries-F/SPO-118, 179 pp., National Marine Fisheries Service, Silver Spring, MD. [Available online at http://www.st.nmfs.noaa.gov/st5/publication/econ/2009/FEUS%202009%20ALL.pdf]

2. Leask, K., M. Killorin, and S. Martin, 2001: Trends in Alaska's People and Economy, 16 pp., Institute of Social and Economic Research, University of Alaska, Anchorage, Alaska. [Available online at http://www.iser.uaa.alaska.edu/Publications/Alaska2020.pdf]

3. Cherry, J. E., S. Walker, N. Fresco, S. Trainor, and A. Tidwell, 2010: Impacts of Climate Change and Variability on Hydropower in Southeast Alaska: Planning for a Robust Energy Future, 28 pp. [Available online at http://alaskafisheries.noaa.gov/habitat/hydro/reports/ccv_hydro_se.pdf]

4. Yu, G., Z. Schwartz, J. E. Walsh, and W. L. Chapman, 2009: A weather-resolving index for assessing the impact of climate change on tourism related climate resources. *Climatic Change*, **95,** 551-573, doi:10.1007/s10584-009-9565-7.

5. Trainor, S. F., F. S. Chapin, III, A. D. McGuire, M. Calef, N. Fresco, M. Kwart, P. Duffy, A. L. Lovecraft, T. S. Rupp, L. O. DeWilde, O. Huntington, and D. C. Natcher, 2009: Vulnerability and adaptation to climate-related fire impacts in rural and urban interior Alaska. *Polar Research*, **28,** 100-118, doi:10.1111/j.1751-8369.2009.00101.x.

6. BIA, cited 2012: Alaska Region Overview. U.S. Department of the Interior, Bureau of Indian Affairs. [Available online at http://www.bia.gov/WhoWeAre/RegionalOffices/Alaska/]

7. Stewart, B. C., K. E. Kunkel, L. E. Stevens, L. Sun, and J. E. Walsh, 2013: Regional Climate Trends and Scenarios for the U.S. National Climate Assessment: Part 7. Climate of Alaska. NOAA Technical Report NESDIS 142-7. 60 pp. [Available online at http://www.nesdis.noaa.gov/technical_reports/NOAA_NESDIS_Tech_Report_142-7-Climate_of_Alaska.pdf]

8. Bieniek, P. A., J. E. Walsh, R. L. Thoman, and U. S. Bhatt, 2014: Using climate divisions to analyze variations and trends in Alaska temperature and precipitation. *Journal of Climate*, **in press**, doi:10.1175/JCLI-D-13-00342.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/JCLI-D-13-00342.1]

   Wendler, G., L. Chen, and B. Moore, 2012: The first decade of the new century: A cooling trend for most of Alaska. *The Open Atmospheric Science Journal*, **6,** 111-116, doi:10.2174/1874282301206010111. [Available online at http://benthamscience.com/open/toascj/articles/V006/111TOASCJ.pdf]

9. CCSP, 2008: *Weather and Climate Extremes in a Changing Climate - Regions of Focus - North America, Hawaii, Caribbean, and U.S. Pacific Islands. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research.* Vol. 3.3, T. R. Karl, G. A. Meehl, C. D. Miller, S. J. Hassol, A. M. Waple, and W. L. Murray, Eds. Department of Commerce, NOAA's National Climatic Data Center, 164 pp. [Available online at http://downloads.globalchange.gov/sap/sap3-3/sap3-3-final-all.pdf]

10. Markon, C. J., S. F. Trainor, and F. S. Chapin, III, Eds., 2012: *The United States National Climate Assessment – Alaska Technical Regional Report. U.S. Geological Survey Circular 1379.* 148 pp. [Available online at http://pubs.usgs.gov/circ/1379/pdf/circ1379.pdf]

11. Hinzman, L. D., N. D. Bettez, W. R. Bolton, F. S. Chapin, III, M. B. Dyurgerov, C. L. Fastie, B. Griffith, R. D. Hollister, A. Hope, H. P. Huntington, A. M. Jensen, G. J. Jia, T. Jorgenson, D. L. Kane, D. R. Klein, G. Kofinas, A. H. Lynch, A. H. Lloyd, A. D. McGuire, F. E. Nelson, W. C. Oechel, T. E. Osterkamp, C. H. Racine, V. E. Romanovsky, R. S. Stone, D. A. Stow, M. Sturm, C. E. Tweedie, G. L. Vourlitis, M. D. Walker, D. A. Walker, P. J. Webber, J. M. Welker, K. S. Winker, and K. Yoshikawa, 2005: Evidence and implications of recent climate change in Northern Alaska and other Arctic regions. *Climatic Change*, **72,** 251-298, doi:10.1007/s10584-005-5352-2. [Available online at http://www.springerlink.com/index/10.1007/s10584-005-5352-2]

12. Wendler, G., and M. Shulski, 2009: A century of climate change for Fairbanks, Alaska. *Arctic*, **62,** 295-300, doi:10.14430/arctic149. [Available online at http://www.jstor.org/stable/40513307]

13. UAF, cited 2013: Scenarios Network for Alaska & Arctic Planning. University of Alaska Fairbanks. [Available online at http://www.snap.uaf.edu/datamaps.php]

14. Kasischke, E. S., D. L. Verbyla, T. S. Rupp, A. D. McGuire, K. A. Murphy, R. Jandt, J. L. Barnes, E. E. Hoy, P. A. Duffy, M. Calef, and M. R. Turetsky, 2010: Alaska's changing fire regime — implications for the vulnerability of its boreal forests. *Canadian Journal of Forest Research*, **40,** 1313-1324, doi:10.1139/X10-098. [Available online at http://www.nrcresearchpress.com/doi/abs/10.1139/X10-098]

15. McGuire, A. D., R. W. Ruess, A. Lloyd, J. Yarie, J. S. Clein, and G. P. Juday, 2010: Vulnerability of white spruce tree growth in interior Alaska in response to climate variability: Dendrochronological, demographic, and experimental perspectives. *Canadian Journal of Forest Research*, **40,** 1197-1209, doi:10.1139/x09-206.

16. Hezel, P. J., X. Zhang, C. M. Bitz, B. P. Kelly, and F. Massonnet, 2012: Projected decline in spring snow depth on Arctic sea ice caused by progressively later autumn open ocean freeze-up this century. *Geophysical Research Letters*, **39,** L17505, doi:10.1029/2012GL052794.

17. Maslowski, W., J. Clement Kinney, M. Higgins, and A. Roberts, 2012: The future of Arctic sea ice. *Annual Review of Earth and Planetary Sciences*, **40,** 625-654, doi:10.1146/annurev-earth-042711-105345. [Available online at http://www.annualreviews.org/doi/pdf/10.1146/annurev-earth-042711-105345]

18. Stroeve, J. C., M. C. Serreze, M. M. Holland, J. E. Kay, J. Malanik, and A. P. Barrett, 2012: The Arctic's rapidly shrinking sea ice cover: A research synthesis. *Climatic Change*, **110,** 1005-1027, doi:10.1007/s10584-011-0101-1. [Available online at http://link.springer.com/content/pdf/10.1007%2Fs10584-011-0101-1.pdf]

19. Stroeve, J., M. M. Holland, W. Meier, T. Scambos, and M. Serreze, 2007: Arctic sea ice decline: Faster than forecast. *Geophysical Research Letters*, **34,** L09501, doi:10.1029/2007GL029703. [Available online at http://www.agu.org/pubs/crossref/2007/2007GL029703.shtml]

Wang, M., and J. E. Overland, 2009: A sea ice free summer Arctic within 30 years? *Geophysical Research Letters*, **36,** L07502, doi:10.1029/2009GL037820. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2009GL037820/pdf]

20. ——, 2012: A sea ice free summer Arctic within 30 years: An update from CMIP5 models. *Geophysical Research Letters*, **39,** L18501, doi:10.1029/2012GL052868. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2012GL052868/pdf]

21. Tietsche, S., D. Notz, J. H. Jungclaus, and J. Marotzke, 2011: Recovery mechanisms of Arctic summer sea ice. *Geophysical Research Letters*, **38,** L02707, doi:10.1029/2010GL045698. [Available online at http://www.agu.org/pubs/crossref/2011/2010GL045698.shtml]

22. Fetterer, F., K. Knowles, W. Meier, and M. Savoie, 2002: Sea Ice Index. [Monthly Sea Ice Extent and Area]. Updated 2013. National Snow and Ice Data Center, Boulder, CO. [Available online at http://nsidc.org/data/G02135]

23. Screen, J. A., and I. Simmonds, 2010: The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature*, **464,** 1334-1337, doi:10.1038/nature09051. [Available online at ftp://ftp.soest.hawaii.edu/coastal/Climate%20Articles/Arctic%20sea%20ice%202010.pdf]

Serreze, M. C., A. P. Barrett, J. C. Stroeve, D. N. Kindig, and M. M. Holland, 2008: The emergence of surface-based Arctic amplification. *The Cryosphere Discussions*, **2,** 601-622, doi:10.5194/tcd-2-601-2008. [Available online at http://the-cryosphere-discuss.net/2/601/2008/tcd-2-601-2008.pdf]

24. Porter, D. F., J. J. Cassano, and M. C. Serreze, 2012: Local and large-scale atmospheric responses to reduced Arctic sea ice and ocean warming in the WRF model. *Journal of Geophysical Research: Atmospheres*, **117,** D11115, doi:10.1029/2011JD016969.

25. Francis, J. A., and S. J. Vavrus, 2012: Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters*, **39,** L06801, doi:10.1029/2012GL051000. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2012GL051000/pdf]

26. Serreze, M. C., A. P. Barrett, and J. Stroeve, 2012: Recent changes in tropospheric water vapor over the Arctic as assessed from radiosondes and atmospheric reanalyses. *Journal of Geophysical Research*, **117,** 1-21, doi:10.1029/2011JD017421.]

27. Wu, D. L., and J. N. Lee, 2012: Arctic low cloud changes as observed by MISR and CALIOP: Implication for the enhanced autumnal warming and sea ice loss. *Journal of Geophysical Research*, **117**, doi:10.1029/2011JD017050.

28. Smith, L. C., and S. R. Stephenson, 2013: New Trans-Arctic shipping routes navigable by midcentury. *Proceedings of the National Academy of Sciences*, **110,** E1191–E1195, doi:10.1073/pnas.1214212110. [Available online at http://www.pnas.org/content/110/13/E1191.full.pdf+html]

29. Laidre, K. L., I. Stirling, L. F. Lowry, Ø. Wiig, M. P. Heide-Jørgensen, and S. H. Ferguson, 2008: Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecological Applications*, **18,** S97-S125, doi:10.1890/06-0546.1. [Available online at http://www.esajournals.org/doi/abs/10.1890/06-0546.1]

30. Rode, K. D., S. C. Amstrup, and E. V. Regehr, 2010: Reduced body size and cub recruitment in polar bears associated with sea ice decline. *Ecological Applications*, **20,** 768-782, doi:10.1890/08-1036.1.

Rode, K. D., E. Peacock, M. Taylor, I. Stirling, E. W. Born, K. L. Laidre, and Ø. Wiig, 2012: A tale of two polar bear populations: Ice habitat, harvest, and body condition. *Population Ecology*, **54,** 3-18, doi:10.1007/s10144-011-0299-9.

Cameron, M. F., J. L. Bengtson, P. L. Boveng, J. K. Jansen, B. P. Kelly, S. P. Dahle, E. A. Logerwell, J. E. Overland, C. L. Sabine, G. T. Waring, and J. M. Wilder, 2010: Status Review of the Bearded Seal (*Erignathus barbatus*). NOAA Technical Memorandum NMFS-AFSC-211, 246 pp., U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Alaska Fisheries Science Center. [Available online at http://www.afsc.noaa.gov/Publications/AFSC-TM/NOAA-TM-AFSC-211.pdf]

Kelly, B. P., J. L. Bengtson, P. L. Boveng, M. F. Cameron, S. P. Dahle, J. K. Jansen, E. Logerwell, J. E. Overland, C. L. Sabine, G. T. Waring, and J. M. Wilder, 2010: Status Review of the Ringed Seal (*Phoca hispida*). NOAA Technical Memorandum NMFS-AFSC-212, 250 pp., U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Alaska Fisheries Science Center. [Available online at http://www.afsc.noaa.gov/Publications/AFSC-TM/NOAA-TM-AFSC-212.pdf]

31. Schliebe, S., K. D. Rode, J. S. Gleason, J. Wilder, K. Proffitt, T. J. Evans, and S. Miller, 2008: Effects of sea ice extent and food availability on spatial and temporal distribution of polar bears during the fall open-water period in the Southern Beaufort Sea. *Polar Biology*, **31,** 999-1010, doi:10.1007/s00300-008-0439-7. [Available online at http://alaska.fws.gov/fisheries/mmm/polarbear/pdf/SchliebeEtAl.pdf]

32. Fischbach, A. S., S. C. Amstrup, and D. C. Douglas, 2007: Landward and eastward shift of Alaskan polar bear denning associated with recent sea ice changes. *Polar Biology*, **30,** 1395-1405, doi:10.1007/s00300-007-0300-4. [Available online at http://www.springerlink.com/index/10.1007/s00300-007-0300-4]

33. Stirling, I., M. J. Lunn, and J. Iacozza, 1999: Long-term trends in the population ecology of polar bears in Western Hudson Bay in relation to climate change. *Arctic*, **52,** 294-306, doi:10.14430/arctic935. [Available online at http://www.jstor.org/stable/40511782]

34. Regehr, E. V., N. J. Lunn, S. C. Amstrup, and I. Stirling, 2007: Effects of earlier sea ice breakup on survival and population size of polar bears in western Hudson Bay. *The Journal of Wildlife Management*, **71,** 2673-2683, doi:10.2193/2006-180. [Available online at http://www.bioone.org/doi/pdf/10.2193/2006-180]

35. Molnár, P. K., A. E. Derocher, T. Klanjscek, and M. A. Lewis, 2011: Predicting climate change impacts on polar bear litter size. *Nature Communications*, **2,** 1-8, doi:10.1038/ncomms1183. [Available online at http://www.nature.com/ncomms/journal/v2/n2/pdf/ncomms1183.pdf]

36. Hunter, C. M., H. Caswell, M. C. Runge, E. V. Regehr, S. C. Amstrup, and I. Stirling, 2010: Climate change threatens polar bear populations: A stochastic demographic analysis. *Ecology*, **91,** 2883-2897, doi:10.1890/09-1641.1. [Available online at http://www.esajournals.org/doi/pdf/10.1890/09-1641.1]

37. Fay, F. H., 1982: *Ecology and Biology of the Pacific Walrus, Odobenus rosmarus divergens Illiger.* U.S. Department of the Interior, Fish and Wildlife Service, 279 pp. [Available online at http://www.fwspubs.org/doi/pdf/10.3996/nafa.74.0001]

38. Douglas, D. C., 2010: Arctic Sea Ice Decline: Projected Changes in Timing and Extent of Sea Ice in the Bering and Chukchi Seas: U.S. Geological Survey Open-File Report 2010-1176, 32 pp., U.S. Department of the Interior, U.S. Geological Survey. [Available online at http://pubs.usgs.gov/of/2010/1176]

Kelly, B. P., 2001: Climate change and ice breeding pinnipeds. *"Fingerprints" of Climate Change*, G. R. Walther, C. A. Burga, and P. J. Edwards, Eds., Springer US, 43-55.

39. Fay, F. H., and B. P. Kelly, 1980: Mass natural mortality of walruses (*Odobenus rosmarus*) at St. Lawrence Island, Bering Sea, autumn 1978. *Arctic*, **33**, doi: 10.14430/arctic2558. [Available online at http://arctic.synergiesprairies.ca/arctic/index.php/arctic/article/view/2558]

Fischbach, A. S., D. H. Monson, and C. V. Jay, 2009: Enumeration of Pacific Walrus Carcasses on Beaches of the Chukchi Sea in Alaska Following a Mortality Event, September 2009. Open-File Report 2009-1291, 10 pp., U.S. Geological Survey. [Available online at http://pubs.usgs.gov/of/2009/1291/]

40. Overeem, I., R. S. Anderson, C. W. Wobus, G. D. Clow, F. E. Urban, and N. Matell, 2011: Sea ice loss enhances wave action at the Arctic coast. *Geophysical Research Letters*, **38,** L17503, doi:10.1029/2011GL048681. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2011GL048681/pdf]

41. State of Alaska, cited 2011: Adaptation Advisory Group of the Governor's Sub-Cabinet on Climate Change. State of Alaska. [Available online at http://www.climatechange.alaska.gov/aag/aag.htm]

42. Bronen, R., 2011: Climate-induced community relocations: Creating an adaptive governance framework based in human rights doctrine. *NYU Review Law & Social Change*, **35,** 357-408. [Available online at http://socialchangenyu.files.wordpress.com/2012/08/climate-induced-migration-bronen-35-2.pdf]

43. GAO, 2009: Alaska Native Villages: Limited Progress Has Been Made on Relocating Villages Threatened By Flooding and Erosion. Government Accountability Office Report GAO-09-551, 53 pp., U.S. Government Accountability Office. [Available online at http://www.gao.gov/new.items/d09551.pdf]

44. Alaska Department of Commerce and Community and Economic Development, 2012: Strategic Management Plan: Newtok to Mertarvik, 38 pp., Alaska Department of Commerce and Community and Economic Development, Anchorage, AK. [Available online at http://commerce.alaska.gov/dnn/Portals/4/pub/Mertarvik_Strategic_Management_Plan.pdf]

45. USACE, 2008: Revised Environmental Assessment: Finding of No Significant Impact: Newtok Evacuation Center: Mertarvik, Nelson Island, Alaska, 64 pp., U.S. Army Corps of Engineers, Alaska District, Anchorage, Alaska. [Available online at http://www.commerce.state.ak.us/dcra/planning/pub/Newtok_Evacuation_Center_EA_&_FONSI_July_08.pdf]

46. ——, 2008: Section 117 Project fact sheet. Alaska Baseline Erosion Assessment, Erosion Information Paper. U.S. Army Corps of Engineers, Alaska District, Koyukuk, AK. [Available online at http://www.poa.usace.army.mil/Portals/34/docs/civilworks/BEA/Koyukuk_Final%20Report.pdf]

47. Nicholls, R. J., P. P. Wong, V. R. Burkett, J. O. Codignotto, J. E. Hay, R. F. McLean, S. Ragoonaden, and C. D. Woodroffe, 2007: Ch. 6: Coastal systems and low-lying areas. *Climate Change 2007: Impacts, Adaptations and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. Van der Linden, and C. E. Hanson, Eds., Cambridge University Press, 316-356. [Available online at http://ro.uow.edu.au/cgi/viewcontent.cgi?article=1192&context=scipapers]

48. Berthier, E., E. Schiefer, G. K. C. Clarke, B. Menounos, and F. Rémy, 2010: Contribution of Alaskan glaciers to sea-level rise derived from satellite imagery. *Nature Geoscience*, **3,** 92-95, doi:10.1038/ngeo737. [Available online at http://www.nature.com/doifinder/10.1038/ngeo737]

49. Jacob, T., J. Wahr, W. T. Pfeffer, and S. Swenson, 2012: Recent contributions of glaciers and ice caps to sea level rise. *Nature*, **482,** 514-518, doi:10.1038/nature10847. [Available online at http://www.nature.com/doifinder/10.1038/nature10847]

50. Larsen, C. F., R. J. Motyka, A. A. Arendt, K. A. Echelmeyer, and P. E. Geissler, 2007: Glacier changes in southeast Alaska and northwest British Columbia and contribution to sea level rise. *Journal of Geophysical Research*, **112,** F01007, doi:10.1029/2006JF000586. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2006JF000586/pdf]

51. Arendt, A. A., K. A. Echelmeyer, W. D. Harrison, C. S. Lingle, and V. B. Valentine, 2002: Rapid wastage of Alaska glaciers and their contribution to rising sea level. *Science*, **297,** 382-386, doi:10.1126/science.1072497.

52. Arendt, A. A., S. B. Luthcke, and R. Hock, 2009: Glacier changes in Alaska: Can mass-balance models explain GRACE mascon trends? *Annals of Glaciology*, **50,** 148-154, doi:10.3189/172756409787769753.

53. Oerlemans, J., 2005: Extracting a climate signal from 169 glacier records. *Science*, **308,** 675-677, doi:10.1126/science.1107046. [Available online at http://www.geology.byu.edu/wp-content/uploads/file/Readings/Oerlemans%202005.pdf]

54. Kaser, G., J. G. Cogley, M. B. Dyurgerov, M. F. Meier, and A. Ohmura, 2006: Mass balance of glaciers and ice caps: Consensus estimates for 1961–2004. *Geophysical Research Letters*, **33,** L19501, doi:10.1029/2006GL027511. [Available online at http://www.agu.org/pubs/crossref/2006/2006GL027511.shtml]

55. Luthcke, S. B., A. A. Arendt, D. D. Rowlands, J. J. McCarthy, and C. F. Larsen, 2008: Recent glacier mass changes in the Gulf of Alaska region from GRACE mascon solutions. *Journal of Glaciology*, **54,** 767-777, doi:10.3189/002214308787779933.

Pritchard, H. D., S. B. Luthcke, and A. H. Fleming, 2010: Understanding ice-sheet mass balance: Progress in satellite altimetry and gravimetry. *Journal of Glaciology*, **56,** 1151-1161, doi:10.3189/002214311796406194. [Available online at http://openurl.ingenta.com/content/xref?genre=article&issn=0022-1430&volume=56&issue=200&spage=1151]

56. Pelto, M., 2011: Utility of late summer transient snowline migration rate on Taku Glacier, Alaska. *The Cryosphere Discussions*, **5,** 1365-1382, doi:10.5194/tcd-5-1365-2011. [Available online at http://www.the-cryosphere-discuss.net/5/1365/2011/tcd-5-1365-2011.pdf]

Van Beusekom, A. E., S. R. O'Neel, R. S. March, L. C. Sass, and L. H. Cox, 2010: Re-analysis of Alaskan benchmark glacier mass-balance data using the index method. U.S. Geological Survey Scientific Investigations Report 2010-5247, 16 pp., U.S. Geological Survey Washington, D.C. [Available online at http://pubs.usgs.gov/sir/2010/5247/pdf/sir20105247.pdf]

57. Dai, A., T. Qian, K. E. Trenberth, and J. D. Milliman, 2009: Changes in continental freshwater discharge from 1948 to 2004. *Journal of Climate*, **22,** 2773-2792, doi:10.1175/2008JCLI2592.1. [Available online at http://journals.ametsoc.org/doi/abs/10.1175/2008JCLI2592.1]

58. Maier, J. A. K., J. M. Ver Hoef, A. D. McGuire, R. T. Bowyer, L. Saperstein, and H. A. Maier, 2005: Distribution and density of moose in relation to landscape characteristics: Effects of scale. *Canadian Journal of Forest Research*, **35,** 2233-2243, doi:10.1139/x05-123. [Available online at http://www.nrcresearchpress.com/doi/abs/10.1139/x05-123]

59. Radić, V., and R. Hock, 2011: Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise. *Nature Geoscience*, **4,** 91-94, doi:10.1038/ngeo1052. [Available online at http://www.nature.com/ngeo/journal/v4/n2/full/ngeo1052.html]

60. Bhatia, M. P., S. B. Das, K. Longnecker, M. A. Charette, and E. B. Kujawinski, 2010: Molecular characterization of dissolved organic matter associated with the Greenland ice sheet. *Geochimica et Cosmochimica Acta*, **74,** 3768-3784, doi:10.1016/j.gca.2010.03.035.

61. Hood, E., J. Fellman, R. G. M. Spencer, P. J. Hernes, R. Edwards, D. D'Amore, and D. Scott, 2009: Glaciers as a source of ancient and labile organic matter to the marine environment. *Nature*, **462,** 1044-1047, doi:10.1038/nature08580. [Available online at http://www.nature.com/doifinder/10.1038/nature08580]

62. Hood, E., and D. Scott, 2008: Riverine organic matter and nutrients in southeast Alaska affected by glacial coverage. *Nature Geoscience*, **1,** 583-587, doi:10.1038/ngeo280. [Available online at http://www.nature.com/doifinder/10.1038/ngeo280]

63. Schroth, A. W., J. Crusius, F. Chever, B. C. Bostick, and O. J. Rouxel, 2011: Glacial influence on the geochemistry of riverine iron fluxes to the Gulf of Alaska and effects of deglaciation. *Geophysical Research Letters*, **38,** 1-6, doi:10.1029/2011GL048367. [Available online at http://hal-sde.archives-ouvertes.fr/docs/00/64/58/79/PDF/GRL-Rouxel_al-2011.pdf]

64. Fellman, J. B., R. G. M. Spencer, P. J. Hernes, R. T. Edwards, D. V. D'Amore, and E. Hood, 2010: The impact of glacier runoff on the biodegradability and biochemical composition of terrigenous dissolved organic matter in near-shore marine ecosystems. *Marine Chemistry*, **121,** 112-122, doi:10.1016/j.marchem.2010.03.009.

Hood, E., and L. Berner, 2009: Effects of changing glacial coverage on the physical and biogeochemical properties of coastal streams in southeastern Alaska. *Journal of Geophysical Research*, **114**, doi:10.1029/2009JG000971. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2009JG000971/pdf]

Royer, T. C., and C. E. Grosch, 2006: Ocean warming and freshening in the northern Gulf of Alaska. *Geophysical Research Letters*, **33,** L16605, doi:10.1029/2006GL026767.

65. Neal, E. G., E. Hood, and K. Smikrud, 2010: Contribution of glacier runoff to freshwater discharge into the Gulf of Alaska. *Geophysical Research Letters*, **37,** 1-5, doi:10.1029/2010GL042385. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2010GL042385/pdf]

66. Osterkamp, T. E., and V. E. Romanovsky, 1999: Evidence for warming and thawing of discontinuous permafrost in Alaska. *Permafrost and Periglacial Processes*, **10,** 17-37, doi:10.1002/(SICI)1099-1530(199901/03)10:1<17::AID-PPP303>3.0.CO;2-4. [Available online at http://onlinelibrary.wiley.com/doi/10.1002/(SICI)1099-1530(199901/03)10:1%3C17::AID-PPP303%3E3.0.CO;2-4/pdf]

67. Romanovsky, V. E., S. L. Smith, H. H. Christiansen, N. I. Shiklomanov, D. S. Drozdov, N. G. Oberman, A. L. Kholodov, and S. S. Marchenko, 2012: [The Arctic] Permafrost [in "State of the Climate in 2011"]. *Bulletin of the American Meteorological Society*, **93,** S137-S138, doi:10.1175/2012BAMSStateoftheClimate.1. [Available online at http://www1.ncdc.noaa.gov/pub/data/cmb/bams-sotc/climate-assessment-2011-lo-rez.pdf]

68. Romanovsky, V. E., S. S. Marchenko, R. Daanen, D. O. Sergeev, and D. A. Walker, 2008: Soil climate and frost heave along the Permafrost/Ecological North American Arctic Transect. *Proceedings of the Ninth International Conference on Permafrost*, Institute of Northern Engineering, University of Alaska Fairbanks, 1519-1524 pp.

69. Jorgenson, T., K. Yoshikawa, M. Kanevskiy, Y. Shur, V. Romanovsky, S. Marchenko, G. Grosse, J. Brown, and B. Jones, 2008: Permafrost characteristics of Alaska. *Extended Abstracts of the Ninth International Conference on Permafrost, June 29-July 3, 2008.* , D. L. Kane, and K. M. Hinkel, Eds., University of Alaska Fairbanks, 121-123. [Available online at http://permafrost.gi.alaska.edu/sites/default/files/AlaskaPermafrostMap_Front_Dec2008_Jorgenson_etal_2008.pdf]

70. French, H., 2011: Geomorphic change in northern Canada. *Changing Cold Environments: A Canadian Perspective*, H. French, and O. Slaymaker, Eds., John Wiley & Sons, Ltd, 200-221.

Romanovsky, V. E., S. L. Smith, and H. H. Christiansen, 2010: Permafrost thermal state in the polar Northern Hemisphere during the international polar year 2007-2009: A synthesis. *Permafrost and Periglacial Processes*, **21,** 106-116, doi:10.1002/ppp.689. [Available online at http://onlinelibrary.wiley.com/doi/10.1002/ppp.689/pdf]

71. Avis, C. A., A. J. Weaver, and K. J. Meissner, 2011: Reduction in areal extent of high-latitude wetlands in response to permafrost thaw. *Nature Geoscience*, **4,** 444-448, doi:10.1038/ngeo1160.

72. Euskirchen, E. S., A. D. McGuire, D. W. Kicklighter, Q. Zhuang, J. S. Clein, R. J. Dargaville, D. G. Dye, J. S. Kimball, K. C. McDonald, J. M. Melillo, V. E. Romanovsky, and N. V. Smith, 2006: Importance of recent shifts in soil thermal dynamics on growing season length, productivity, and carbon sequestration in terrestrial high-latitude ecosystems. *Global Change Biology*, **12,** 731-750, doi:10.1111/j.1365-2486.2006.01113.x. [Available online at http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2486.2006.01113.x/pdf]

Lawrence, D. M., and A. G. Slater, 2008: Incorporating organic soil into a global climate model. *Climate Dynamics*, **30,** 145-160, doi:10.1007/s00382-007-0278-1. [Available online at http://www.springerlink.com/index/10.1007/s00382-007-0278-1]

73. Jafarov, E. E., S. S. Marchenko, and V. E. Romanovsky, 2012: Numerical modeling of permafrost dynamics in Alaska using a high spatial resolution dataset. *The Cryosphere Discussions*, **6,** 89-124, doi:10.5194/tcd-6-89-2012.

74. Larsen, P. H., S. Goldsmith, O. Smith, M. L. Wilson, K. Strzepek, P. Chinowsky, and B. Saylor, 2008: Estimating future costs for Alaska public infrastructure at risk from climate change. *Global Environmental Change*, **18,** 442-457, doi:10.1016/j.gloenvcha.2008.03.005. [Available online at http://linkinghub.elsevier.com/retrieve/pii/S0959378008000216]

75. Alessa, L., A. Kliskey, R. Busey, L. Hinzman, and D. White, 2008: Freshwater vulnerabilities and resilience on the Seward Peninsula: Integrating multiple dimensions of landscape change. *Global Environmental Change*, **18,** 256-270, doi:10.1016/j.gloenvcha.2008.01.004.

76. Jones, B. M., C. D. Arp, K. M. Hinkel, R. A. Beck, J. A. Schmutz, and B. Winston, 2009: Arctic lake physical processes and regimes with implications for winter water availability and management in the National Petroleum Reserve Alaska. *Environmental Management*, **43,** 1071-1084, doi:10.1007/s00267-008-9241-0.

77. White, D. M., S. C. Gerlach, P. Loring, A. C. Tidwell, and M. C. Chambers, 2007: Food and water security in a changing arctic climate. *Environmental Research Letters*, **2,** 045018, doi:10.1088/1748-9326/2/4/045018. [Available online at http://iopscience.iop.org/1748-9326/2/4/045018/pdf/1748-9326_2_4_045018.pdf]

78. Brubaker, M., J. Berner, R. Chavan, and J. Warren, 2011: Climate change and health effects in Northwest Alaska. *Global Health Action*, **4,** 1-5, doi:10.3402/gha.v4i0.8445. [Available online at http://www.globalhealthaction.net/index.php/gha/article/view/8445/12705]

79. Larsen, P., and S. Goldsmith, 2007: How Much Might Climate Change Add to Future Costs for Public Infrastructure? Understanding Alaska Research Summary #8, 8 pp., Institute of Social and Economic Research, University of Alaska Anchorage, Anchorage, AK. [Available online at http://www.iser.uaa.alaska.edu/Publications/Juneclimatefinal.pdf]

80. Klein, E., E. E. Berg, and R. Dial, 2005: Wetland drying and succession across the Kenai Peninsula Lowlands, south-central Alaska. *Canadian Journal of Forest Research*, **35,** 1931-1941, doi:10.1139/x05-129. [Available online at http://www.nrcresearchpress.com/doi/abs/10.1139/x05-129]

Riordan, B., D. Verbyla, and A. D. McGuire, 2006: Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images. *Journal of Geophysical Research*, **111,** G04002, doi:10.1029/2005JG000150. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2005JG000150/pdf]

81. Roach, J., B. Griffith, D. Verbyla, and J. Jones, 2011: Mechanisms influencing changes in lake area in Alaskan boreal forest. *Global Change Biology*, **17,** 2567-2583, doi:10.1111/j.1365-2486.2011.02446.x. [Available online at http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2486.2011.02446.x/pdf]

82. Rover, J., L. Ji, B. K. Wylie, and L. L. Tieszen, 2012: Establishing water body areal extent trends in interior Alaska from multi-temporal Landsat data. *Remote Sensing Letters*, **3,** 595-604, doi:10.1080/01431161.2011.643507.

83. Griffith, B., and A. D. McGuire, 2008: A3.1 National wildlife refuges case study - Alaska and the Central Flyway. P*reliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources - A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*, S. H. Julius, and J. M. West, Eds., U.S. Environmental Protection Agency, A-25 - A-31. [Available online at http://downloads.globalchange.gov/sap/sap4-4/sap4-4-final-report-all.pdf]

84. Hu, F. S., P. E. Higuera, J. E. Walsh, W. L. Chapman, P. A. Duffy, L. B. Brubaker, and M. L. Chipman, 2010: Tundra burning in Alaska: Linkages to climatic change and sea ice retreat. *Journal of Geophysical Research*, **115,** G04002, doi:10.1029/2009jg001270. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2009JG001270/pdf]

85. Mack, M. C., M. S. Bret-Harte, T. N. Hollingsworth, R. R. Jandt, E. A. G. Schuur, G. R. Shaver, and D. L. Verbyla, 2011: Carbon loss from an unprecedented Arctic tundra wildfire. *Nature*, **475,** 489-492, doi:10.1038/nature10283. [Available online at http://www.nature.com/nature/journal/v475/n7357/pdf/nature10283.pdf]

86. Balshi, M. S., A. D. McGuire, P. Duffy, M. Flannigan, J. Walsh, and J. Melillo, 2008: Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. *Global Change Biology*, **15,** 578-600, doi:10.1111/j.1365-2486.2008.01679.x. [Available online at http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2486.2008.01679.x/pdf]

87. Barrett, K., A. D. McGuire, E. E. Hoy, and E. S. Kasischke, 2011: Potential shifts in dominant forest cover in interior Alaska driven by variations in fire severity. *Ecological Applications*, **21,** 2380-2396, doi:10.190/10-0896.1.

88. Johnstone, J. F., T. S. Rupp, M. Olson, and D. Verbyla, 2011: Modeling impacts of fire severity on successional trajectories and future fire behavior in Alaskan boreal forests. *Landscape Ecology*, **26,** 487-500, doi:10.1007/s10980-011-9574-6.

89. Nelson, J. L., E. S. Zavaleta, and F. S. Chapin, III, 2008: Boreal fire effects on subsistence resources in Alaska and adjacent Canada. *Ecosystems*, **11,** 156-171, doi:10.1007/s10021-007-9114-z.

90. Joly, K., F. S. Chapin, III, and D. R. Klein, 2010: Winter habitat selection by caribou in relation to lichen abundance, wildfires, grazing, and landscape characteristics in northwest Alaska. *Ecoscience*, **17,** 321-333, doi:10.2980/17-3-3337. [Available online at http://www.bioone.org/doi/pdf/10.2980/17-3-3337]

Rupp, T. S., M. Olson, L. G. Adams, B. W. Dale, K. Joly, J. Henkelman, W. B. Collins, and A. M. Starfield, 2006: Simulating the influences of various fire regimes on caribou winter habitat. *Ecological Applications*, **16,** 1730-1743, doi:10.1890/1051-0761(2006)016[1730:STIOVF]2.0.CO;2.

91. Kofinas, G. P., F. S. Chapin, III, S. BurnSilver, J. I. Schmidt, N. L. Fresco, K. Kielland, S. Martin, A. Springsteen, and T. S. Rupp, 2010: Resilience of Athabascan subsistence systems to interior Alaska's changing climate. *Canadian Journal of Forest Research*, **40,** 1347-1359, doi:10.1139/X10-108. [Available online at http://www.nrcresearchpress.com/doi/pdf/10.1139/X10-108]

92. Cortes-Burns, H., I. Lapina, S. Klein, M. Carlson, and L. Flagstad, 2008: Invasive Plant Species Monitoring and Control: Areas Impacted by 2004 and 2005 Fires in Interior Alaska: A survey of Alaska BLM lands along the Dalton, Steese, and Taylor Highways, 162 pp., Bureau of Land Management – Alaska State Office. Alaska Natural Heritage Program, University of Alaska, Anchorage, AK. [Available online at http://aknhp.uaa.alaska.edu/wp-content/uploads/2010/11/Cortes_etal_2008.pdf]

Lapina, I., and M. L. Carlson, 2004: Non-Native Plant Species of Susitna, Matanuska, and Copper River Basins: Summary of Survey Findings and Recommendations for Control Actions, 64 pp., University of Alaska Anchorage, Anchorage, AK. [Available online at http://www.uaa.alaska.edu/enri/publications/upload/Non-native_Plants_final-report.pdf]

93. Grove, C., 2011: Chokecherry trees are deadly for 3 Anchorage moose. *Anchorage Daily News*, February 16, 2011. [Available online at http://www.adn.com/2011/02/16/1706123/ornamental-vegetation-kills-three.html]

94. Schuur, E. A. G., and B. Abbott, 2011: Climate change: High risk of permafrost thaw. *Nature*, **480,** 32-33, doi:10.1038/480032a. [Available online at http://www.seas.harvard.edu/climate/eli/Courses/EPS134/Sources/19-Biosphere-feedbacks-amazon-rainforest-and-permafrost/permafrost/Schuur-Abbott-2011_High-risk-of-permafrost-thaw.pdf]

95. Walter, K. M., S. A. Zimov, J. P. Chanton, D. Verbyla, and F. S. Chapin, III, 2006: Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. *Nature*, **443,** 71-75, doi:10.1038/nature05040.

96. French, N. H. F., P. Goovaerts, and E. S. Kasischke, 2004: Uncertainty in estimating carbon emissions from boreal forest fires. *Journal of Geophysical Research: Atmospheres*, **109,** D14S08, doi:10.1029/2003JD003635. [Available online at http://www.agu.org/pubs/crossref/2004/2003JD003635.shtml]

Zhuang, Q., J. M. Melillo, A. D. McGuire, D. W. Kicklighter, R. G. Prinn, P. A. Steudler, B. S. Felzer, and S. Hu, 2007: Net emissions of CH_4 and CO_2 in Alaska - Implications for the region's greenhouse gas budget. *Ecological Applications*, **17,** 203-212, doi:10.1890/1051-0761(2007)017[0203:NEOCAC]2.0.CO;2.

97. Yuan, F. M., S.-H. Yi, A. D. McGuire, K. D. Johnson, J. Liang, J. W. Harden, E. S. Kasischke, and W. A. Kurz, 2012: Assessment of boreal forest historical C dynamics in the Yukon River Basin: Relative roles of warming and fire regime change. *Ecological Applications*, **22,** 2091-2109, doi:10.1890/11-1957.1.

98. Chapin, F. S., III, M. Strum, M. C. Serreze, J. P. McFadden, J. R. Key, A. H. Lloyd, A. D. McGuire, T. S. Rupp, A. H. Lynch, J. P. Schimel, J. Beringer, W. L. Chapman, H. E. Epstein, E. S. Euskirchen, L. D. Hinzman, G. Jia, C. L. Ping, K. D. Tape, C. D. C. Thompson, D. A. Walker, and J. M. Welker, 2005: Role of land-surface changes in Arctic summer warming. *Science*, **310,** 657-660, doi:10.11263/science.1117368.

99. Euskirchen, E. S., A. D. McGuire, F. S. Chapin, III, S. Yi, and C. C. Thompson, 2009: Changes in vegetation in northern Alaska under scenarios of climate change, 2003-2100: Implications for climate feedbacks. *Ecological Applications*, **19,** 1022-1043, doi:10.1890/08-0806.1.

100. MacDougall, A. H., C. A. Avis, and A. J. Weaver, 2012: Significant contribution to climate warming from the permafrost carbon feedback. *Nature Geoscience*, **5,** 719-721, doi:10.1038/ngeo1573.

McGuire, A. D., L. G. Anderson, T. R. Christensen, S. Dallimore, L. Guo, D. J. Hayes, M. Heimann, T. D. Lorenson, R. W. MacDonald, and N. Roulet, 2009: Sensitivity of the carbon cycle in the Arctic to climate change. *Ecological Monographs*, **79,** 523-555, doi:10.1890/08-2025.1. [Available online at http://www.esajournals.org/doi/pdf/10.1890/08-2025.1]

101. Allison, E. H., M.-C. Badjeck, and K. Meinhold, 2011: Ch. 17: The implications of global climate change for molluscan aquaculture. *Shellfish Aquaculture and the Environment*, S. E. Shumway, Ed., Wiley-Blackwell, 461-490.

Doney, S. C., V. J. Fabry, R. A. Feely, and J. A. Kleypas, 2009: Ocean acidification: The other CO_2 problem. *Annual Review of Marine Science*, **1,** 169-192, doi:10.1146/annurev.marine.010908.163834. [Available online at http://www.annualreviews.org/doi/abs/10.1146/annurev.marine.010908.163834]

Pauly, D., 2010: *Gasping Fish and Panting Squids: Oxygen, Temperature and the Growth of Water-Breathing Animals*. International Ecology Institute, 216 pp.

Pörtner, H. O., and R. Knust, 2007: Climate change affects marine fishes through the oxygen limitation of thermal tolerance. *Science*, **315,** 95-97, doi:10.1126/science.1135471. [Available online at http://www.sciencemag.org/cgi/doi/10.1126/science.1135471]

Sumaila, U. R., W. W. L. Cheung, V. W. Y. Lam, D. Pauly, and S. Herrick, 2011: Climate change impacts on the biophysics and economics of world fisheries. *Nature Climate Change*, **1,** 449-456, doi:10.1038/nclimate1301. [Available online at http://www.nature.com/doifinder/10.1038/nclimate1301]

102. Cooley, S. R., and S. C. Doney, 2009: Anticipating ocean acidification's economic consequences for commercial fisheries. *Environmental Research Letters*, **4,** 8, doi:10.1088/1748-9326/4/2/024007. [Available online at http://iopscience.iop.org/1748-9326/4/2/024007/pdf/1748-9326_4_2_024007.pdf]

103. Gaines, S. D., B. Gaylord, and J. L. Largier, 2003: Avoiding current oversights in marine reserve design. *Ecological Applications*, **13,** S32-S46, doi:10.1890/1051-0761(2003)013[0032:ACOIMR]2.0.CO;2. [Available online at http://www.esajournals.org/doi/pdf/10.1890/1051-0761%282003%29013%5B0032%3AACOIMR%5D2.0.CO%3B2]

104. NRC, 2011: *Frontiers in Understanding Climate Change and Polar Ecosystems Summary of a Workshop.* National Research Council, National Academies Press, 86 pp. [Available online at http://www.nap.edu/catalog.php?record_id=13132]

Moore, S. E., and H. P. Huntington, 2008: Arctic marine mammals and climate change: Impacts and resilience. *Ecological Applications*, **18,** S157-S165-S157-S165, doi:10.1890/06-0571.1. [Available online at http://www.esajournals.org/doi/abs/10.1890/06-0571.1]

Grebmeier, J. M., 2012: Shifting patterns of life in the Pacific Arctic and Sub-Arctic seas. *Annual Review of Marine Science*, **4,** 63-78, doi:10.1146/annurev-marine-120710-100926.

105. Ruiz, G. M., P. W. Fofonoff, J. T. Carlton, M. J. Wonham, and A. H. Hines, 2000: Invasion of coastal marine communities in North America: Apparent patterns, processes, and biases. *Annual Review of Ecology and Systematics*, **31,** 481-531, doi:10.1146/annurev.ecolsys.31.1.481.

106. Loeng, H., K. Brander, E. Carmack, S. Denisenko, K. Drinkwater, B. Hansen, K. Kovacs, P. Livingston, F. McLaughlin, and E. Sakshaug, 2005: Ch. 9: Marine systems. *Arctic Climate Impact Assessment*, C. Symon, L. Arris, and B. Heal, Eds., Cambridge University Press, 453-538. [Available online at http://www.acia.uaf.edu/PDFs/ACIA_Science_Chapters_Final/ACIA_Ch09_Final.pdf]

107. Sigler, M. F., M. Renner, S. L. Danielson, L. B. Eisner, R. R. Lauth, K. J. Kuletz, E. A. Longerwell, and G. L. Hunt, 2011: Fluxes, fins, and feathers: Relationships among the Bering, Chukchi, and Beaufort seas in a time of climate change. *Oceanography*, **24,** 250-265, doi:10.5670/oceanog.2011.77. [Available online at http://bsierp.nprb.org/results/documents/24-3_sigler_Oceanography.pdf]

Stabeno, P. J., E. V. Farley, Jr., N. B. Kachel, S. Moore, C. W. Mordy, J. M. Napp, J. E. Overland, A. I. Pinchuk, and M. F. Sigler, 2012: A comparison of the physics of the northern and southern shelves of the eastern Bering Sea and some implications for the ecosystem. *Deep Sea Research Part II: Topical Studies in Oceanography*, **65-70,** 14-30, doi:10.1016/j.dsr2.2012.02.019.

108. Mueter, F. J., N. A. Bond, J. N. Ianelli, and A. B. Hollowed, 2011: Expected declines in recruitment of walleye pollock (*Theragra chalcogramma*) in the eastern Bering Sea under future climate change. *ICES Journal of Marine Science*, **68,** 1284-1296, doi:10.1093/icesjms/fsr022. [Available online at http://icesjms.oxfordjournals.org/content/68/6/1284.full.pdf+html]

109. Farley, E. V., Jr, J. M. Murphy, B. W. Wing, J. H. Moss, and A. Middleton, 2005: Distribution, migration pathways, and size of Western Alaska juvenile salmon along the eastern Bering Sea shelf. *Alaska Fishery Research Bulletin*, **11,** 15-26. [Available online at http://www.adfg.alaska.gov/static/home/library/PDFs/afrb/farlv11n1.pdf]

110. Hunt, G. L., Jr., K. O. Coyle, L. B. Eisner, E. V. Farley, R. A. Heintz, F. Mueter, J. M. Napp, J. E. Overland, P. H. Ressler, S. Salo, and P. J. Stabeno, 2011: Climate impacts on eastern Bering Sea foodwebs: A synthesis of new data and an assessment of the Oscillating Control Hypothesis. *ICES Journal of Marine Science*, **68,** 1230-1243, doi:10.1093/icesjms/fsr036. [Available online at http://icesjms.oxfordjournals.org/cgi/doi/10.1093/icesjms/fsr036]

111. Mundy, P. R., and D. F. Evenson, 2011: Environmental controls of phenology of high-latitude Chinook salmon populations of the Yukon River, North America, with application to fishery management. *ICES Journal of Marine Science*, **68,** 1155-1164, doi:10.1093/icesjms/fsr080. [Available online at http://icesjms.oxfordjournals.org/content/68/6/1155.full.pdf+html]

112. NOAA, 2010: NOAA Ocean and Great Lakes Acidification Research Plan, NOAA Special Report, 143 pp., National Oceanic and Atmospheric Administration - Ocean Acidification Steering Committee. [Available online at http://www.nodc.noaa.gov/media/pdf/oceanacidification/NOAA_OA_Steering2010.pdf]

113. Orr, J. C., V. J. Fabry, O. Aumont, L. Bopp, S. C. Doney, R. A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, R. M. Key, K. Lindsay, E. Maier-Reimer, R. Matear, P. Monfray, A. Mouchet, R. G. Najjar, G.-K. Plattner, K. B. Rodgers, C. L. Sabine, J. L. Sarmiento, R. Schlitzer, R. D. Slater, I. J. Totterdell, M.-F. Weirig, Y. Yamanaka, and A. Yool, 2005: Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, **437,** 681-686, doi:10.1038/nature04095.

114. Steinacher, M., F. Joos, T. L. Frölicher, G.-K. Plattner, and S. C. Doney, 2009: Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model. *Biogeosciences*, **6,** 515-533, doi:10.5194/bg-6-515-2009. [Available online at http://www.biogeosciences.net/6/515/2009/]

115. Yamamoto-Kawai, M., F. A. McLaughlin, E. C. Carmack, S. Nishino, and K. Shimada, 2009: Aragonite undersaturation in the Arctic ocean: Effects of ocean acidification and sea ice melt. *Science*, **326,** 1098-1100, doi:10.1126/science.1174190.

116. Lombard, F., R. E. de Roacha, J. Bijma, and J.-P. Gattuso, 2010: Effect of carbonate ion concentration and irradiance on calcification in planktonic foraminifera. *Biogeosciences*, **7,** 247-255, doi:10.5194/bg-7-247-2010. [Available online at http://epic.awi.de/21680/1/Lom2010a.pdf]

Moy, A. D., W. R. Howard, S. G. Bray, and T. W. Trull, 2009: Reduced calcification in modern Southern Ocean planktonic foraminifera. *Nature Geoscience*, **2,** 276-280, doi:10.1038/ngeo460.

117. Sambrotto, R. N., C. Mordy, S. I. Zeeman, P. J. Stabeno, and S. A. Macklin, 2008: Physical forcing and nutrient conditions associated with patterns of Chl *a* and phytoplankton productivity in the southeastern Bering Sea during summer. *Deep Sea Research Part II: Topical Studies in Oceanography*, **55,** 1745-1760, doi:10.1016/j.dsr2.2008.03.003.

118. Fabry, V. J., J. B. McClintock, J. T. Mathis, and J. M. Grebmeier, 2009: Ocean acidification at high latitudes: The bellwether. *Oceanography*, **22,** 160-171, doi:10.5670/oceanog.2009.105. [Available online at http://www.tos.org/oceanography/archive/22-4_fabry.pdf]

119. Aydin, K. Y., G. A. McFarlane, J. R. King, B. A. Megrey, and K. W. Myers, 2005: Linking oceanic food webs to coastal production and growth rates of Pacific salmon (*Oncorhynchus* spp.), using models on three scales. *Deep Sea Research Part II: Topical Studies in Oceanography*, **52,** 757-780, doi:10.1016/j.dsr2.2004.12.017.

120. Armstrong, J. L., J. L. Boldt, A. D. Cross, J. H. Moss, N. D. Davis, K. W. Myers, R. V. Walker, D. A. Beauchamp, and L. J. Haldorson, 2005: Distribution, size, and interannual, seasonal and diel food habits of northern Gulf of Alaska juvenile pink salmon, *Oncorhynchus gorbuscha*. *Deep Sea Research Part II: Topical Studies in Oceanography*, **52,** 247-265, doi:10.1016/j.dsr2.2004.09.019. [Available online at http://linkinghub.elsevier.com/retrieve/pii/S0967064504002401]

121. Mathis, J. T., J. N. Cross, and N. R. Bates, 2011: The role of ocean acidification in systemic carbonate mineral suppression in the Bering Sea. *Geophysical Research Letters*, **38,** L19602, doi:10.1029/2011GL048884. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2011GL048884/pdf]

122. Donkersloot, R., 2012: Ocean Acidification and Alaska Fisheries - Views and Voices of Alaska's Fisherman, Marine Industries and Coastal Residents. Alaska Marine Conservation Council, Anchorage, AK. [Available online at http://www.akmarine.org/publications/ocean-acidification-alaskas-fisheries-final-full-report-spring-2012]

123. Goldsmith, S., 2008: Understanding Alaska's Remote Rural Economy, 12 pp., UA Research Summary. [Available online at http://www.iser.uaa.alaska.edu/Publications/researchsumm/UA_RS10.pdf]

124. Cochran, P., O. H. Huntington, C. Pungowiyi, S. Tom, F. S. Chapin, III, H. P. Huntington, N. G. Maynard, and S. F. Trainor, 2013: Indigenous frameworks for observing and responding to climate change in Alaska. *Climatic Change*, **120,** 557-567, doi:10.1007/s10584-013-0735-2.

125. Huntington, H. P., S. Fox, F. Berkes, and I. Krupnik, 2005: The Changing Arctic – Indigenous Perspectives. *Arctic Climate Impact Assessment*, Cambridge University Press, 61-98. [Available online at www.cambridge.org/9780521865098]

126. Kruse, J. A., 1991: Alaska Inupiat subsistence and wage employment patterns: Understanding individual choice. *Human Organization*, **50,** 317-326.

127. Berner, J., C. Furgal, P. Bjerregaard, M. Bradley, T. Curtis, E. D. Fabo, J. Hassi, W. Keatinge, S. Kvernmo, S. Nayha, H. Rintamaki, and J. Warren, 2005: Ch. 15: Human Health. *Arctic Climate Impact Assessment*, Cambridge University Press, 863-906. [Available online at http://www.acia.uaf.edu/PDFs/ACIA_Science_Chapters_Final/ACIA_Ch15_Final.pdf]

Loring, P. A., and C. Gerlach, 2010: Food security and conservation of Yukon River salmon: Are we asking too much of the Yukon River? *Sustainability*, **2,** 2965-2987, doi:10.3390/su2092965. [Available online at http://www.mdpi.com/2071-1050/2/9/2965/pdf]

McNeeley, S. M., and M. D. Shulski, 2011: Anatomy of a closing window: Vulnerability to changing seasonality in Interior Alaska. *Global Environmental Change*, **21,** 464-473, doi:10.1016/j.gloenvcha.2011.02.003.

Moerlein, K. J., and C. Carothers, 2012: Total environment of change: Impacts of climate change and social transitions on subsistence fisheries in northwest Alaska. *Ecology and Society*, **17**, doi:10.5751/ES-04543-170110. [Available online at http://www.ecologyandsociety.org/vol17/iss1/art10/]

128. Davis, M., 2012: Appendix C. Alaska Forum on the Environment: Climate Change: Our Voices, Sharing Ways Forward. *The United States National Climate Assessment – Alaska Technical Regional Report. U.S. Geological Survey Circular 1379*, C. J. Markon, S. F. Trainor, and F. S. Chapin, III, Eds., U. S. Geological Survey, 121-128. [Available online at http://pubs.usgs.gov/circ/1379/pdf/circ1379.pdf]

Downing, A., and A. Cuerrier, 2011: A synthesis of the impacts of climate change on the First Nations and Inuit of Canada. *Indian Journal of Traditional Knowledge*, **10,** 57-70. [Available online at http://nopr.niscair.res.in/bitstream/123456789/11066/1/IJTK%2010%281%29%2057-70.pdf]

Krupnik, I., and D. Jolly, Eds., 2002: *The Earth Is Faster Now: Indigenous Observations of Arctic Environmental Change. Frontiers in Polar Social Science*. Arctic Research Consortium of the United States, 383 pp.

129. McNeeley, S. M., 2012: Examining barriers and opportunities for sustainable adaptation to climate change in Interior Alaska. *Climate Change*, **111,** 835-857, doi:10.1007/s10584-011-0158-x. [Available online at http://link.springer.com/content/pdf/10.1007%2Fs10584-011-0158-x]

130. Lindsey, S., 2011: Spring breakup and ice-jam flooding in Alaska. *Alaska Climate Dispatch***,** 1-5. [Available online at http://accap.uaf.edu/sites/default/files/2011a_Spring_Dispatch.pdf]

131. Galloway McLean, K., A. Ramos-Costillo, T. Gross, S. Johnston, M. Vierros, and R. Noa, 2009: Report on the Indigenous Peoples' Global Summit on Climate Change. Darwin, Australia, United Nations University – Traditional Knowledge Initiative, 116 pp. [Available online at http://www.unutki.org/downloads/File/Publications/UNU_2009_Climate_Change_Summit_Report.pdf]

132. McLaughlin, J. A., A. DePaola, C. A. Bopp, K. A. Martinek, N. P. Napolilli, C. G. Allison, S. L. Murray, E. C. Thompson, M. M. Bird, and J. P. Middaugh, 2005: Outbreak of *Vibrio parahaemolyticus* gastroenteritis associated with Alaskan oysters. *New England Journal of Medicine*, **353,** 1463-1470, doi:10.1056/NEJMoa051594. [Available online at http://www.nejm.org/doi/pdf/10.1056/NEJMoa051594]

Macdonald, R. W., T. Harner, and J. Fyfe, 2005: Recent climate change in the Arctic and its impact on contaminant pathways and interpretation of temporal trend data. *Science of the Total Environment*, **342,** 5-86, doi:10.1016/j.scitotenv.2004.12.059.

133. Weller, G., 2005: Summary and Synthesis of the ACIA. *Arctic Climate Impact Assessment*, Cambridge University Press, 989-1020. [Available online at http://www.amap.no/documents/doc/arctic-arctic-climate-impact-assessment/796]

134. Baffrey, M., and H. P. Huntington, 2010: Social and economic effects of oil and gas activities in the Arctic. *Assessment 2007: Oil and Gas Activities in the Arctic – Effects and Potential Effects. Volume One*, Arctic Monitoring and Assessment Program, 3.1-3.71. [Available online at http://www.amap.no/documents/doc/assessment-2007-oil-and-gas-activities-in-the-arctic-effects-and-potential-effects.-volume-1/776]

135. Krupnik, I., and G. C. Ray, 2007: Pacific walruses, indigenous hunters, and climate change: Bridging scientific and indigenous knowledge. *Deep Sea Research Part II: Topical Studies in Oceanography*, **54,** 2946-2957, doi:10.1016/j.dsr2.2007.08.011.

Laidler, G. J., 2006: Inuit and scientific perspectives on the relationship between sea ice and climate change: The ideal complement? *Climatic Change*, **78,** 407-444, doi:10.1007/s10584-006-9064-z.

Riewe, R., and J. Oakes, Eds., 2006: *Climate Change: Linking Traditional and Scientific Knowledge*. Aboriginal Issues Press, University of Manitoba, 289 pp.

136. Karl, T. R., J. T. Melillo, and T. C. Peterson, Eds., 2009: *Global Climate Change Impacts in the United States*. Cambridge University Press, 189 pp. [Available online at http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf]

SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for developing key messages

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

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

Key message #1 Traceable Account

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

Description of evidence base

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

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

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

New information and remaining uncertainties

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

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

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

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

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

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

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

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

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

High confidence regarding offshore development opportunity.

Key message #2 Traceable Account

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

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

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

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

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

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

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

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

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

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

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

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

Assessment of confidence based on evidence

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

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

Key message #3 Traceable Account

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

Description of evidence base

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

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

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

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

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

New information and remaining uncertainties

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

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

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

Assessment of confidence based on evidence

Very high confidence that permafrost is warming.

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

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

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

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

Key message #4 Traceable Account

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

Description of evidence base

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

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

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

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

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

New information and remaining uncertainties

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

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

A key uncertainty is what the actual impacts of rising temperatures and changing ocean chemistry, including an increase in ocean acidification, will be on a broad range of marine biota and ecosystems. More monitoring is needed to document the extent and location of changes. Additional research is needed to assess how those changes will affect the productivity of key fishery resources and their food and prey base.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties:

High confidence of increased ocean temperatures and changes in chemistry.

Medium confidence that fisheries will be affected.

Key message #5 Traceable Account

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

Description of evidence base

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

Evidence exists in recorded local observational accounts as well as in the peer-reviewed scientific literature of the cumulative effects of climate-related environmental change on Native communities in Alaska; these effects combine with other socioeconomic stressors to strain rural Native communities (Ch. 12: Indigenous Peoples).[124,125,126,131] Increasing attention to impacts of climate change is revealing new aspects, such as impacts to health and hunter safety (for example, Baffrey and Huntington 2010; Brubaker et al. 2011[78,134]). There is also strong evidence for the cultural adaptive capacity of these communities and peoples over time.[91,130,135]

New information and remaining uncertainties

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

The precise mechanisms by which climate change affects Native communities are poorly understood, especially in the context of rapid social, economic, and cultural change. Present day responses to environmental change are poorly documented. More research is needed on the ways that Alaska Natives respond to current biophysical climate change and to the factors that enable or constrain contemporary adaptation.

Alaska Native communities are already being affected by climate-induced changes in the physical and biological environment, from coastal erosion threatening the existence of some communities, to alterations in hunting, fishing, and gathering practices that undermine the intergenerational transfer of culture, skill, and wisdom. At the same time, these communities have a long record of adaptation and flexibility. Whether such adaptability is sufficient to address the challenges of climate change depends both on the speed of climate-induced changes and on the degree to which Native communities are supported rather than constrained in the adaptive measures they need to make.[124]

Assessment of confidence based on evidence

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