U.S. Fish & Wildlife Service

Wildlife Response to Environmental Arctic Change

Predicting Future Habitats of Arctic Alaska

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Cover Image

Ice floating in a lagoon near Collinson Point in the Arctic National Wildlife Refuge. Photo by Philip Martin.

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Predicting Future Habitats of Arctic Alaska

Report from the
Wildlife Response to Environmental Arctic Change (WildREACH):
Predicting Future Habitats of Arctic Alaska Workshop
17–18 November 2008
Westmark Hotel
Fairbanks, Alaska

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Chapter 1
Executive Summary

Climate is changing worldwide, but the Arctic is warming at a rate almost twice the global average. Changes already observed in arctic terrestrial landscapes include rapidly eroding shorelines, melting ground ice, and increased shrub growth at high latitudes. Because the Arctic will likely experience early and disproportionately large impacts of climate change, the U.S. Fish and Wildlife Service (Service) has identified America's Arctic as a priority region for developing management strategies to conserve fish, wildlife, and their habitats.

The Service convened a Wildlife Response to Environmental Arctic Change (WildREACH) workshop on 17–18 November 2008 in Fairbanks, Alaska. Our goal was to identify the priority research, modeling, and synthesis activities necessary to advance our understanding of the effects of climate change on birds, fish, and mammals of arctic Alaska, focusing on terrestrial and freshwater systems. We used a conceptual modeling approach to identify the potential changes that would most strongly influence habitat suitability for a broad suite of arctic species. In doing so, we embarked on the first essential step toward incorporating climate considerations into biological planning and conservation design for the Arctic. The workshop was attended by over 100 participants representing federal and state agencies, academia, and commercial and nonprofit organizations. WildREACH provided a forum for communication among specialists from multiple disciplines, a vital first step toward establishing effective partnerships. Summaries of each workshop report chapter are provided below.

Climate, Permafrost, Hydrology

The average annual temperature of Alaska's North Slope is projected to rise approximately 7°C by 2100. The magnitude of change is imprecisely known, but Global Circulation Models identify northern Alaska as one of the fastest warming regions of the planet. Annual precipitation is also expected to increase, although there is less certainty surrounding this prediction.

In the Arctic, climate affects habitat uniquely through the interdependencies of permafrost, hydrology, and vegetation. The deep, cold, continuous permafrost of the North Slope represents a reservoir of resilience for this landscape. Nevertheless, enhanced seasonal melting of near-surface ice is already measurably altering habitats and hydrology. Understanding how variation in the type and quantity of ground ice influences a landscape's susceptibility to warming is fundamental to predicting the extent and magnitude of habitat change.

Hydrologic processes are a pivotal determinant of climate-influenced habitat change in arctic Alaska. Changes in overall water balance and in timing and magnitude of seasonal water and energy fluxes will strongly affect habitat availability and quality for arctic-adapted species of fish and wildlife. The seasonal allocation of precipitation is key to ecosystem response in an environment where water remains frozen most of the year. Despite the expectation of higher annual precipitation, models predict a generally drier summer environment. Refining models to more confidently predict water balance and the resultant water supply available to various habitat types is one of our most important challenges.

The presence of ice-rich permafrost soils makes arctic tundra uniquely vulnerable to the effects of warming. Photo from USFWS, Ikilyariak Creek, Arctic National Wildlife Refuge.

Habitat Change

Effects of climate change on North Slope habitats will vary depending on the permafrost-influenced geomorphic processes specific to particular ecosystems. It is useful to consider the coastline, Coastal Plain, Foothills, and floodplains separately.

- In the coastal zone, rapid shoreline erosion is occurring, associated with the retreat of summer sea ice. Rising ocean temperatures, sea level rise, permafrost degradation, increased storm surges, and changes to river discharge and sediment transport will continue to affect habitat availability and quality in the coastal zone.
- The vast shallow wetlands of the Coastal Plain landscape are sensitive to changes in water balance that could lead to drying. Lakes may enlarge through melting and erosion at their edges. Alternatively, lakes may drain if surrounding ice wedges degrade, resulting in the formation of new drainage networks.
- The hilly terrain of the Arctic Foothills is prone to thaw slumps and gully formation. In the lower Foothills, extremely ice-rich soils are susceptible to ice wedge degradation, melting of massive ice, and formation or drainage of thermokarst lakes.
- Floodplains are very dynamic landscapes and could respond to climate change in a variety of ways. Floodplain processes are influenced more strongly by extreme flood events than by average conditions, and models of future flood frequency and severity must be better developed in order to predict habitat change.

Historically, tundra fires have been rare on the North Slope, but fire frequency will likely increase as the climate warms. A positive feedback relationship exists whereby soils tend toward a warmer and drier condition after fire, which in turn promotes shrub growth and a more fire-prone landscape. Although widespread conversion of North Slope tundra to spruce forest is not expected within this century, increased shrub cover has been documented in the Brooks Range and Foothills, a trend that is expected to continue. Changes in plant phenology (e.g., earlier green-up and senescence) are certain to occur as spring melt comes earlier.

Climate change may increase availability and uptake of contaminants for fish, wildlife, and their habitats. Contaminants currently contained within glacial ice, multi-year sea ice, and permafrost, including persistent organic pollutants and mercury, will almost certainly be released to aquatic ecosystems as the temperature rises.

Climate Effects on Fish and Wildlife

WildREACH workshop participants formed working groups for birds, fish, and mammals. Each working group developed conceptual models to illustrate hypotheses of likely pathways by which fish and wildlife populations of arctic Alaska may be affected by climate change. Hydrologic process models for summer and winter provided linkages among climate variables, physical processes (hydrologic and permafrost), and habitat change. These processes were relevant to all species groups.

The bird working group developed conceptual models organized around four broad topics: abundance and distribution of surface water, vegetation community change, invertebrate community change, and coastal processes.

Spring melt is accompanied by a sharp peak in flow for rivers that arise in the Brooks Range—changes in precipitation and warming temperatures may change flow regimes and sediment transport in arctic rivers. Photo from USFWS, Sadlerochit Mountains, Arctic National Wildlife Refuge.

The fish working group developed a single conceptual model emphasizing pathways related to the effects of increased water temperature and hydrologic changes related to soil moisture, glacial input, drainage changes related to permafrost degradation, and changes in lake area.

The mammal working group developed separate models for the summer and winter seasons. Key factors in winter included changes in the timing, amount, and nature of precipitation (e.g., rain-on-snow events, deeper snow). In summer, changes in plant species composition, amount of forage, and seasonality were expected to have the greatest potential for affecting mammal populations.

Common Themes and Research Gaps

Despite the uncertainty in projecting climate change impacts on arctic species and habitats, workshop participants identified monitoring, research, and modeling priorities that will help improve our understanding of future conditions. Specific information gaps varied among species groups, but most fell into four cross-cutting themes: 1) changes in precipitation and hydrology; 2) changes in vegetation communities and phenology; 3) changes in abundance and timing of invertebrate emergence; and 4) coastal dynamics.

All working groups emphasized that predictions regarding climate effects on fish and wildlife populations must be tentative, given the uncertainty surrounding climate forecasts and unavailability of models that couple climate, geophysical, and ecological processes at appropriate spatial and temporal scales. All working groups agreed that in order to more accurately predict climate change effects on species and habitats, multidisciplinary work is needed to better understand the underlying biological and physical processes that drive terrestrial and aquatic ecosystem function and the response of those systems to climate change. Hydrologic processes, in particular, are pivotal determinants of climate-related habitat change, and enhanced data collection and modeling in this area will benefit multiple users.

All working groups emphasized that information available on life history, habitat requirements, distribution, abundance, and demography is inadequate for many arctic species. Basic biological studies, therefore, are also needed. Focal species should be chosen based on their predicted vulnerability to climate change and potential to serve as indicators of hypothesized habitat changes.

Conclusions and Recommendations

WildREACH workshop discussions revealed several specific information gaps within the four major thematic areas previously listed (see Table on page 7). These gaps represent the highest scientific priorities for scientific inquiry, which should be pursued in an organized, multidisciplinary fashion. Specific recommendations include:

1. Establishment of at least three long-term observatories on the North Slope to collect integrated hydrologic, climate, and geophysical data. The central mission of these observatories should be to develop an understanding of the response of permafrost (active layer dynamics), hydrologic, and ecological systems to changes in thermal regime. To ensure applicability to fish and wildlife biology, water budgets should be estimated for key ecotypes.
2. Intensive observations at the observatory sites should be supplemented by instrumentation (e.g., meteorology, radiation, stream discharge, soil moisture) at dispersed sites arrayed across important environmental gradients.
3. Modeling that dynamically couples soil thermal and hydrologic regimes, and biological systems at appropriate spatial and temporal scales.
4. Centralized data storage and interpretation for the mutual benefit of multiple end-users.

A flock of black brant migrate along the Beaufort Sea coast. Optimal timing for bird migration could change under an altered climate regime. Photo by Philip Martin from Canning River delta, Arctic National Wildlife Refuge.

We also recommend immediate attention to developing predictive models of habitat change, focusing initially on processes that are occurring now and that act on short (e.g., decadal) time scales. Priority topics include:

1. Coastal processes (e.g., erosion, storm surge, deposition, vegetation succession);
2. Seasonality (e.g., plant phenology, animal migration, life stages of aquatic invertebrates);
3. Shrub advance;
4. Fire regime (as a function of interactions among climate, permafrost, and vegetation); and
5. Thermokarst effects on surface water storage, drainage systems, and lakes.

The Service should engage the U.S. Geological Survey (USGS) and others in a structured decision-making process to refine the selection of indicator species/parameters as components of a long-term climate monitoring program. Upon reaching consensus, management agencies should seek stable funding for monitoring these species/attributes.

The Service recognizes that we must change the way we do business to succeed in managing fish, wildlife, and their habitats in a rapidly changing climate. We can no longer manage for the *status quo*—we must manage for an uncertain future. These challenges exceed the capacity of any one agency, and we must pool our collective resources. By strategically targeting financial resources, we can build Landscape Conservation Cooperatives that increase capacity, eliminate redundancy, and provide the technical expertise to implement conservation, research, and management at all scales.

An undercut bluff on the Beaufort Sea coast, the result of a severe storm in August 1980, illustrates the susceptibility of ice-rich coast to rapid erosion. Photo by Catherine Moitoret, Canning River delta, Arctic National Wildlife Refuge.

The Service will improve communication and collaboration with the arctic research community to initiate building of wide-ranging partnerships. On a local, regional, and national level the Service will:

1. Work with the National Science Foundation (NSF) to define climate research priorities relevant to resource management agencies;
2. Increase collaboration with academia and other researchers to develop grant proposals that address priority questions;
3. Participate in planning and implementation of the interagency Study of Environmental Arctic Change (SEARCH) Program to ensure inclusion of research relevant to resource management agencies;
4. Work with arctic science program managers in the research agencies (e.g., NSF, USGS, National Oceanic and Atmospheric Administration) to obtain funding for work that addresses priority questions; and
5. Promote a collaborative approach to acquire, process, archive, and disseminate essential satellite-based remote sensing data products (e.g., snow cover, green-up, and surface water) needed for regional-scale monitoring.

Climate change presents an unprecedented challenge to managers of arctic natural resources. By initiating a collaborative process among biologists, physical scientists, and managers, the WildREACH workshop successfully identified priority information gaps and activities needed to provide the basis for adaptive management of arctic fish and wildlife resources. Since the workshop, the Service has identified America's Arctic as Alaska's first Landscape Conservation Region, which will be supported by the technical capacity housed in the Northern Alaska Landscape Conservation Cooperative. Adopting the WildREACH recommendations is the next step in strengthening our capacity to anticipate climate-related habitat change and to identify the most promising strategies to conserve fish and wildlife populations in America's Arctic.

Scientific Priorities

Workshop participants identified important information gaps in our understanding of climate change effects on birds, mammals, and fish populations. The specific gaps varied among species groups, but most fell into four cross-cutting thematic areas and underlying research questions (see Chapter 6 for more details):

1. Precipitation, Water Balance, and Distribution of Surface Water

a. How reliable are the projections for increasing precipitation and evapotranspiration?
b. How will the annual precipitation input on the Coastal Plain and Foothills be allocated between winter (snow pack) and summer?
c. How will changes in precipitation, evapotranspiration, and active layer depth alter summer surface water availability in shallow-water and mesic/wet tundra habitats?
d. How will changing patterns of seasonal runoff affect stream flow?
e. What is the contribution of groundwater in various systems, and is it sufficient to maintain year-round flow?
f. Will drought conditions and changes in drainage patterns decrease water body connectivity?
g. Which Coastal Plain lakes are susceptible to tapping (rapid drainage) and on what time scale?
h. What are the expected changes in snowpack characteristics (depth, density, presence of ice layers) and how might these vary on a regional and local scale?
i. How much change will occur in the timing of snow melt and snow onset?
j. How will the frequency of rain-on-snow and severe winter storm events change?

2. Vegetation Community Composition and Phenology

a. How will changes in the length and timing of the growing season influence plant phenology, including seasonal changes in nutritional quality?
b. How will plant species composition shift in response to long-term climate change, and what are the implications for habitat structure and quality of the prevalent available forage (i.e., digestibility, nutrient content)?
c. What is the time scale of expected shrub increase, and how will this vary by species/growth form (low vs. tall shrub) and ecoregion?
d. What is the likelihood of widespread conversion from sedge and sedge-shrub meadow to bog meadow (paludification) and how would this affect herbivore and detritus-based trophic systems?
e. How will changes in the seasonality of stream discharge and occurrence of flood events influence development of riparian vegetation communities?

3. Abundance and Phenology of Invertebrates

a. How does earlier spring thaw affect timing of life cycle events and peak availability to predators?
b. How does temperature affect growth and development of aquatic insects?
c. What climate-related changes are likely in community composition of macroinvertebrates in stream, lake, and saturated soil environments?
d. How will changes in the distribution and quality of surface waters and shifts from pelagic to benthic productivity in deep lakes affect availability of macroinvertebrates to fish and wildlife?
e. How will warming and changing seasonality affect abundance and peak activity periods of biting insects and what are the bioenergetic consequences for caribou in particular?
f. How will warming and changing seasonality affect the prevalence of parasites and disease vectors (e.g., nematode parasites of muskoxen and Dall's sheep)?

4. Coastal Dynamics

a. Will higher water temperatures, sea level rise, and retreat of summer sea ice cause degradation of the barrier island systems of the Beaufort and Chukchi seas?
b. Will alluvial deltas continue to build or will rising sea levels outpace potential increases in sedimentation rates?
c. How quickly will shoreline retreat result in newly breached lake basins?
d. To what extent will coastal erosion, in combination with sea level rise, cause salinization of low-lying coastal areas?
e. Will coastal wet sedge meadows establish at a rate equal to loss of this habitat through erosion and inundation?
f. Will increased fogginess/cloudiness exert a negative or positive feedback effect on air temperature in the coastal zone? What is the expected spatial extent of this effect?

Chapter 2
Introduction

Climate warming is having profound effects on fish, wildlife, and their habitats, challenging resource agencies to manage ecosystems that are being fundamentally altered.

Climate is changing across the planet, but the Arctic is warming at a rate almost twice the global average, and precipitation is projected to increase significantly by the end of the century. Sea ice extent has decreased steadily over the past 40 years, and the Arctic may be ice-free in the summer within a decade. Arctic terrestrial landscapes are also being altered by warming with rapidly eroding shorelines, melting ground ice, and increased shrub growth at high latitudes. The presence of frozen ground creates an environment uniquely sensitive to warming, because permafrost holds water at the surface, creating vast wetlands and aquatic habitats in a region that would otherwise be classified as arid. If unabated, melting ground ice will ultimately result in the drying of northern Alaska with profound consequences for fish and wildlife.

The mission of the U.S. Fish and Wildlife Service is, in part, to conserve fish, wildlife, and their habitats for future generations. To date, the Service's management objectives have generally been defined in terms of maintaining the *status quo* or restoring past conditions. Climate change forces us to consider a future in which ecosystems and species assemblages will differ dramatically from the historical condition. Because the Arctic will likely experience early and disproportionately large impacts of climate change, the Service has identified America's Arctic as a priority region for developing management plans and adaptation strategies to conserve fish, wildlife, and their habitats.

The North Slope of Alaska encompasses America's terrestrial Arctic and is a large and relatively non-impacted landscape north of the Brooks Range. It is the only example of the arctic biome within the United States. Two well-known areas of high-value wildlife habitat are the portion of the Arctic Coastal Plain within the Arctic National Wildlife Refuge and the Teshekpuk Lake Special Area in the National Petroleum Reserve–Alaska. The Teshekpuk Lake region is a unique molting area for Pacific black brant and three other species of geese, and is used by many other water birds for feeding, nesting, and molting. The refuge's Coastal Plain is best known as the calving ground of the Porcupine Caribou herd. High-value wildlife habitat is by no means restricted to these discrete locations, however. Wetland and coastal habitats across the North Slope provide nesting and rearing habitat for millions of birds that migrate north from four continents to exploit this seasonally productive habitat. Four distinct caribou herds roam the North Slope, from the Chukchi Sea to the Canadian border. This rich landscape also provides habitat for three threatened species, a variety of resident and anadromous fish species, muskoxen, and furbearers.

Across this region, the Service manages significant trust resources including threatened species (Steller's eider, spectacled eider, and polar bear) and migratory bird species of concern (Pacific black brant, yellow-billed loons). Refuge-held lands within the Arctic are not only significant for their habitat values, as illustrated in part by their importance to caribou, fish, and migratory birds, but also contain the only designated Wilderness in the Arctic. In addition, the Service is responsible for providing opportunities to the residents of North Slope villages for continued subsistence harvest. In the Arctic, climate change is already impacting Native cultures and natural resources. It is vital that stakeholders work collaboratively to develop systematic approaches for monitoring impacts, predictive models, and strategies for management and conservation.

The Service convened a Wildlife Response to Environmental Arctic Change workshop (WildREACH) on

Caribou (Rangifer tarandus) *in the Arctic National Wildlife Refuge. Photo by Doug Canfield, USFWS.*

17–18 November 2008 in Fairbanks, Alaska, to identify the priority research, modeling, and synthesis activities necessary to advance our understanding of the effects of climate change on birds, fish, and mammals dependent on the terrestrial and freshwater systems of arctic Alaska (see Appendix 3 for the workshop agenda). Scientists from a variety of disciplines joined fish and wildlife managers to discuss the linkages between climate, hydrologic and geomorphic processes, and ecosystem change (see Appendix 4 for list of participants). A conceptual modeling approach was used to identify potential changes that would most strongly influence habitat suitability for a broad suite of arctic species. The conceptual models are considered the forerunners to a later generation of spatially explicit models that will be designed to forecast changes in habitat availability and quality. Landscape-change models are critical to the Service and others working toward identifying those species and habitats most vulnerable to adverse climate-related impacts. As models are refined and informed by new research and monitoring data, we will improve our ability to design and implement management strategies that are responsive to urgent conservation problems and are logistically and financially achievable.

The WildREACH workshop also was a first step in establishing a Landscape Conservation Cooperative (LCC). Because the scope and complexity of climate change problems surpass the abilities and budget of any one agency or organization, the Service envisions building shared capacity among scientists to design and implement conservation strategies via LCCs. By identifying areas of common interest among researchers and managers and promoting collaborative efforts, we, as a conservation community, will improve the quality of information available to support management decisions. WildREACH was the beginning of a collaborative process to develop conceptual models and to highlight areas of uncertainty and information gaps, including aspects of both geophysical and biological processes. Since the workshop, the Service has identified America's Arctic as Alaska's first Landscape Conservation Region, which will be supported by the technical capacity housed in the Northern Alaska LCC. In order to provide better information and decision-making tools for managers, our next steps will be to begin to address information gaps and development of habitat change models. The Service recognizes that our success in conserving fish, wildlife, and their habitats depends on building shared capacity and establishing effective collaborative partnerships with specialists from multiple disciplines.

This report synthesizes the information presented at the workshop. Background information on the region's current and projected climate, permafrost, and hydrology is presented in Chapter 3; processes of geomorphic and habitat change are outlined in Chapter 4; and conceptual models of fish and wildlife response to climate change are developed in Chapter 5. Priority research, monitoring, and modeling tasks are summarized in Chapter 6, and final recommended actions are in Chapter 7. The priorities and conclusions are those of the Fish and Wildlife Service, as informed by input from the diverse group of workshop attendees. We recognize this as a first of many steps toward coordinating efforts with other resource agencies, researchers, and non-governmental organizations. At present, the scale of our knowledge does not match the scale of our management responsibilities. We look forward to continuing to develop this coordinated partnership to assess, monitor, and predict the impacts of climate change on terrestrial and freshwater landscapes in America's Arctic so that we may conserve this landscape and the animals who live there for future generations.

Tussock tundra covers vast areas of the Arctic Foothills and Brooks Range. USFWS photo.

Ice remnants in Lake Ikpikpuk in July 2005. Photo by Leslie Pierce, TREC 2005, courtesy of ARCUS.

Chapter 3
Arctic Alaska in a Changing Climate

This background chapter provides a brief introduction to the ecoregions of the North Slope of Alaska, an overview of both observed and projected climate change in the region, and some general information about permafrost and hydrologic processes in the Arctic.

North Slope Ecoregions

Alaska's North Slope covers approximately 204,000 km^2 of arctic lands, extending from the shores of the Beaufort and Chukchi seas to the crest of the Brooks Range mountains. Human population within the region is about 7,000 residents (2004 census), with activity and infrastructure concentrated within eight small communities and the widespread industrial zone with a hub at Deadhorse/Prudhoe Bay. Land management and ownership is partitioned among seven major entities (Figure 3.1). The Bureau of Land Management (Department of the Interior [DOI]) is responsible for management of a large portion of the region—nearly 45% of the total area or roughly 91,000 km^2. The State of Alaska is the second largest landowner, responsible for 41,000 km^2 (20%). Fish and Wildlife Service (DOI) lands account for approximately 35,000 km^2 (17%), and Native lands encompass about 26,000 km^2 (13%). The remaining lands are held by the National Park Service (DOI), private owners, and the Department of Defense.

The North Slope is divided into three ecoregions: Arctic Coastal Plain, Arctic Foothills, and Brooks Range (Figure 3.2). Information for each ecoregion is derived from Gallant et al. (1995).

Arctic Coastal Plain

The 50,000 km^2 Arctic Coastal Plain is the northernmost ecoregion in Alaska. The Coastal Plain is bounded on the west and north by the Chukchi and Beaufort seas and extends east nearly to the U.S.-Canada border. The region is underlain by thick permafrost, up to 650 m deep at Deadhorse/Prudhoe Bay. Permafrost-related surface features are common, including pingos, ice wedge polygons, peat ridges, and frost boils. Most major streams originate from the other ecoregions to the south. Lakes of both thermokarst and non-thermokarst origin are ubiquitous, constituting over 14% of the landscape. Streams west of the Colville River are interconnected with lakes and tend to be sluggish and meandering, while those east of the Colville River are braided and build deltas into the Arctic Ocean. Most of the smaller streams freeze completely during winter.

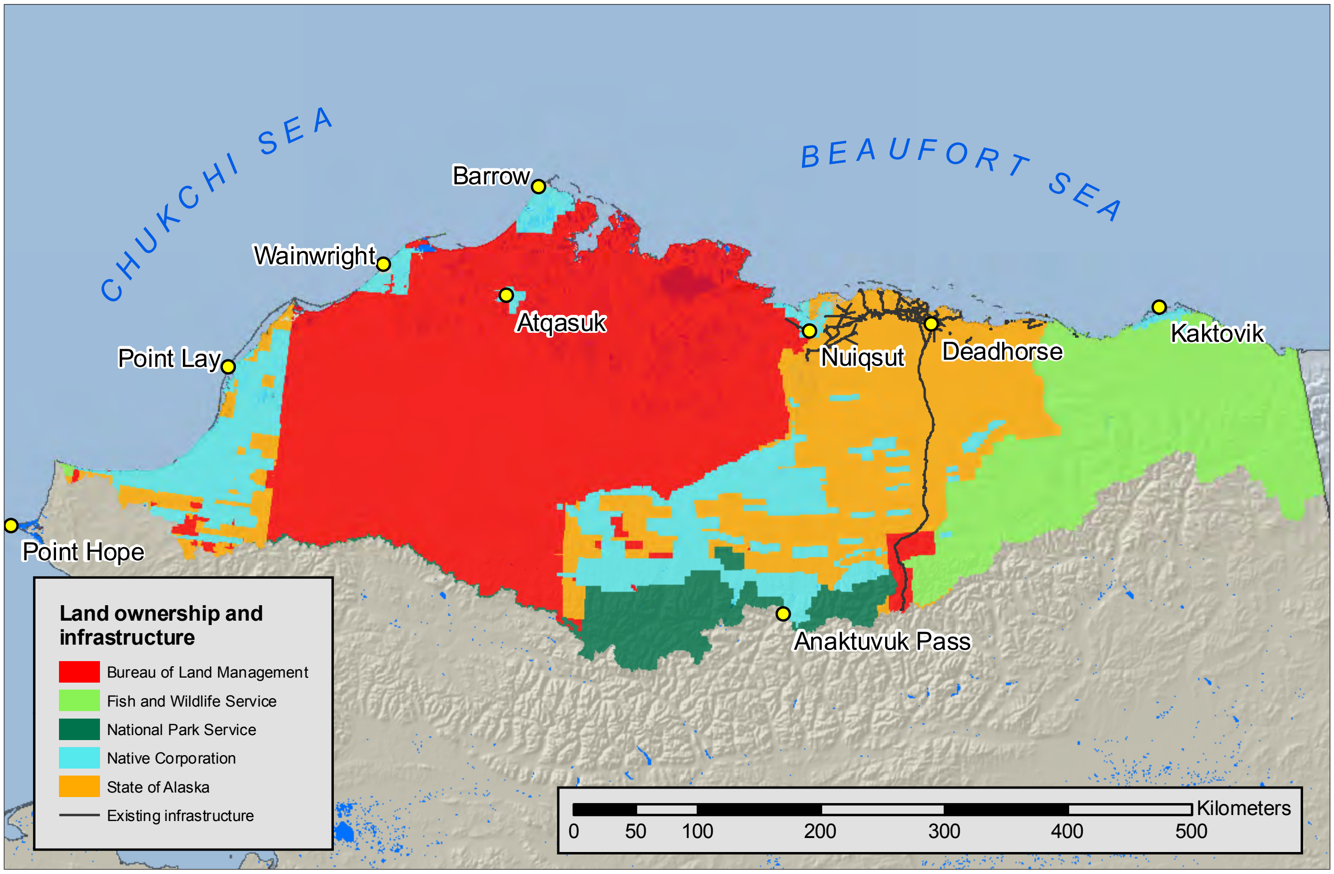


Figure 3.1. Land ownership and location of human infrastructure on Alaska's North Slope. Map by USFWS from Alaska Department of Natural Resources data.

Arctic Foothills

The Arctic Foothills, a 96,000 km^2 band of rolling hills and plateaus, grades from the Coastal Plain to the Brooks Range. The Foothills stretch from the Chukchi Sea in the west to the U.S-Canada border. The ecoregion is underlain by permafrost, and permafrost-related surface features are common on the landscape. The Foothills have better defined drainage networks than the Coastal Plain. Most streams tend to be swift, but portions may be braided and smaller streams dry or freeze during winter. Flooding and channel shifting is common during breakup of river ice. Lakes of glacial origin and oxbow lakes, located along major streams, are the predominant types in the region.

Brooks Range

The Brooks Range ecoregion is the Alaskan extension of the Rocky Mountains, of which 58,000 km^2 lies north of the continental divide. The ecoregion covers most of the east-west extent of northern Alaska—from the U.S.-Canada border to within 100 km of the Chukchi Sea. In contrast to the Arctic Coastal Plain and Arctic Foothills, this ecoregion was extensively glaciated during the Pleistocene epoch, but the few remaining glaciers are limited to the eastern sector. The terrain is dominated by rugged mountain complexes, and continuous permafrost underlies the region. The combination of harsh climate, shallow soils, and highly erodible slopes result in sparse vegetation cover that is generally limited to valleys and lower hill slopes. Streams in the Brooks Range often have braided drainage patterns, with larger streams draining north and their tributaries flowing east or west. Lakes constitute less than 1% of the landscape and tend to occur in rock basins at the mouths of large glaciated valleys, in areas of ground and terminal moraines, and on floodplains of major rivers.

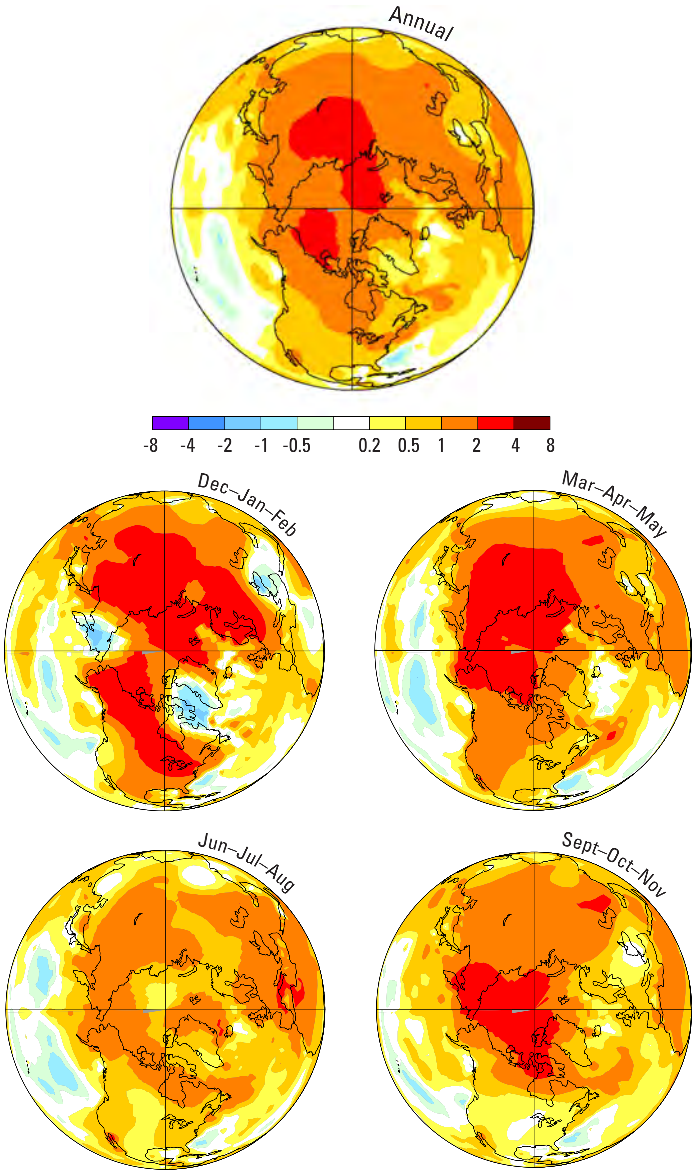


Figure 3.2 (top). Ecoregions on the North Slope of Alaska. Map by USFWS from USGS data (Gallant et al. 1995).

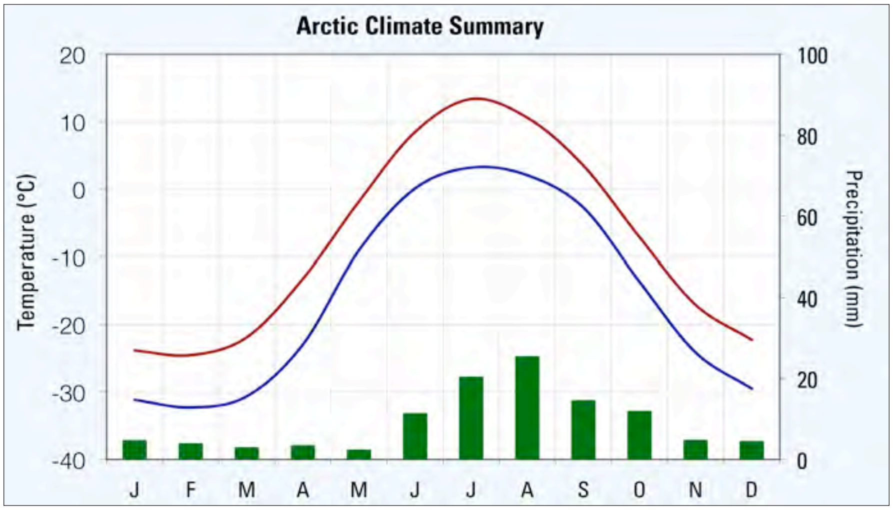
Figure 3.3 (bottom). Annual and seasonal temperature trends for the northern hemisphere, 1958–2008. The scale indicates temperature change (°C) over the period, based on local linear trend. Data from Goddard Institute for Space Studies (http://data.giss.nasa.gov/gistemp), downloaded January 15, 2009.

Climate Trends in the Arctic

The arctic climate has warmed rapidly over the past 50 years. Annual average temperature has increased nearly twice as fast as the rest of the world (ACIA 2004: 10). This polar amplification of warming is attributed to: 1) positive feedback effects of greater heat absorption associated with reduced snow and ice cover on land and sea, 2) larger fraction of energy going to warming rather than evaporation relative to the tropics, 3) shallower troposphere (lower atmosphere) and frequent surface-based temperature inversions, and 4) atmospheric and oceanic circulation (ACIA 2004: 20). Compared to the rest of the circumpolar Arctic, terrestrial areas in northern Alaska, western Canada, and central Russia have experienced the most rapid warming (Figure 3.3). In northern Alaska, the most pronounced warming has occurred during winter and spring.

Observed Climate Change in Arctic Alaska

Recent warming notwithstanding, the climate of arctic Alaska is cold and dry (Figure 3.4) with a mean annual air temperature (MAAT) of -12°C (10.4°F) and mean temperatures below 10°C (50°F) in every month of the year. Surface air temperature on land is strongly influenced by proximity to the coast, with inland areas experiencing warmer summers and colder winters in comparison to the coastal zone (Figures 3.6, 3.7, and 3.8 top panels). Annual precipitation ranges from 150 mm (6 in) near the coast at Barrow to 600 mm (24 in) or more in portions of the Brooks Range (Figure 3.9 top panel). There are only four stations in the region with multi-decadal weather records, and only one (Barrow) with a continuous record from the early 1900s until present (Shulski and Wendler 2007), resulting in a data-poor historical record. Despite considerable annual variation, however, the 50-year trend in mean annual temperature is positive (Figure 3.5), rising at a rate of 0.45°C (0.81°F) per decade. Based on the two best time series (Barrow 1949–1996 and Barter Island 1949–1988), precipitation on the Coastal Plain has declined in recent decades (Curtis et al. 1998).



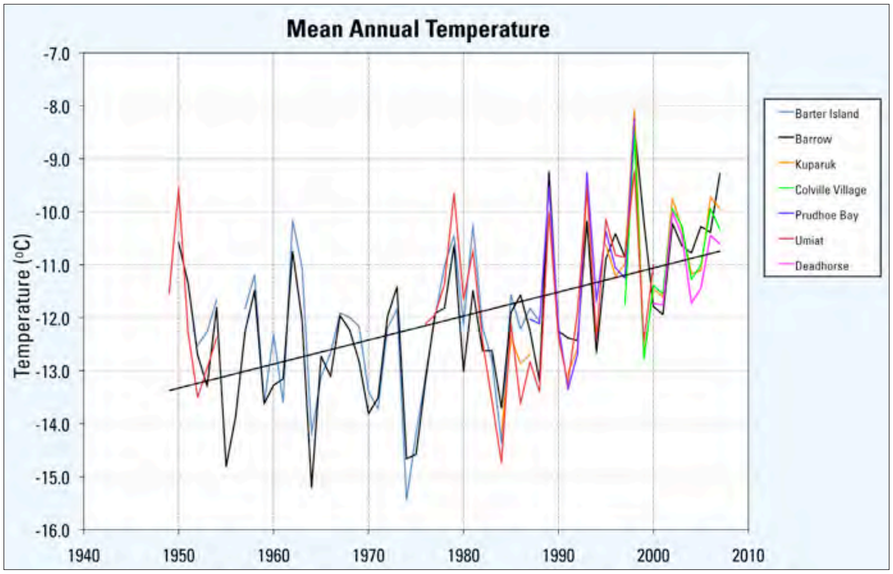


Figure 3.4 (top). Average monthly high (red line) and low (blue line) temperatures and precipitation (green bars) in the Arctic from 1971–2000. Data courtesy M. Shulski.
Figure 3.5 (bottom). 50-year trend in mean annual temperature at seven sites on the North Slope. Data courtesy M. Shulski.

Table 3.1. Projected magnitude of increase from historic[1] values for temperature and precipitation for mid-century (2051–2060) and end of century (2091–2100) time series. Seasonal[2] and annual data are summarized by ecoregion.

Mid-century			
	Temperature (increase °C)		
Ecoregion	Winter	Summer	Annual
Arctic Coastal Plain	5.7	1.6	4.4
Arctic Foothills	5.5	1.8	4.3
N. Brooks Range	5.2	2.0	4.1
	Precipitation (% increase)		
	Winter	Summer	Annual
Arctic Coastal Plain	48	12	28
Arctic Foothills	33	10	21
N. Brooks Range	13	12	13
End of century			
	Temperature (increase°C)		
Ecoregion	Winter	Summer	Annual
Arctic Coastal Plain	9.5	3.0	7.3
Arctic Foothills	9.1	3.3	7.2
N. Brooks Range	8.6	3.4	6.9
	Precipitation (% increase)		
	Winter	Summer	Annual
Arctic Coastal Plain	77	27	50
Arctic Foothills	53	23	38
N. Brooks Range	36	19	22

1. *Baseline temperature and precipitation values are based on the Parameter-Elevation Regression on Independent Slopes Model (PRISM) 1961–1990 dataset created by the PRISM Group.*
2. *Summer is calculated as the average of June–September. Winter is calculated as the average of October–May.*

Table 3.2. Projected magnitude of increase from historic[1] values for frost-free season length for mid-century (2051) and end of century (2100) time series. Regression equations for calculation of frost-free season length, advance of thaw, and delay in freeze provided by The Wilderness Society.

	Mid-century		
Ecoregion	increase in frost-free season length (days)	Advance of thaw	Delay in freeze
Arctic Coastal Plain	18	5	13
Arctic Foothills	16	6	10
N. Brooks Range	16	7	9
	End of century		
Arctic Coastal Plain	33	8	25
Arctic Foothills	28	10	17
N. Brooks Range	27	11	15

1. *Baseline temperature and precipitation values are based on the Parameter-Elevation Regression on Independent Slopes Model (PRISM) 1961–1990 dataset created by the PRISM Group.*

Projected Climate Change in Arctic Alaska

Climate projections here are based on the composite of outputs from 5 of the 15 General Circulation Models (GCMs) from the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC 2007), chosen for their superior performance at high latitudes and available through the Scenarios Network for Alaska Planning (SNAP, http://www.snap.uaf.edu; for details see Appendix 1). Based on these outputs, temperatures are projected to rise during the 21st century. Mean annual air temperature for the decade 2091–2100 is expected to increase 6.5–7.5°C (Table 3.1, Figure 3.6) compared to the baseline period 1961–1990, depending on location. Most of this warming will occur during winter (October–May) and is expected to affect coastal areas more than inland areas, most likely due to the influence of a longer marine ice-free period (Table 3.1, Figure 3.7). Projected summer temperature increases are of a lesser magnitude and more pronounced in inland areas (Table 3.1, Figure 3.8).

By the end of the century, annual precipitation is projected to increase by 20–60%, depending on location, compared to the baseline period 1961–1990 (Table 3.1, Figure 3.9). Most of this increase is expected to occur in winter, thereby contributing to a deeper snow pack. In both summer and winter, the relative precipitation increase in coastal areas is anticipated to be nearly twice that of the Brooks Range (Table 3.1, Figures 3.9 and 3.10). As noted above, the climate records from Barrow and Barter Island indicate a decrease in precipitation over the past half-century, unlike the increasing trend projected for the future by the GCMs.

Along with warming temperatures and increased precipitation, the length of the frost-free season is projected to increase across all three ecoregions (Table 3.2). By the end of the century, frost-free season length is projected to increase by 27–33 days over baseline values, depending on location. Projected change in season length is due primarily to delayed onset of freezing in the fall, but also to an advance in first-thaw date in spring (Table 3.2). Increases

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Average Annual Air Temperatures (°C)

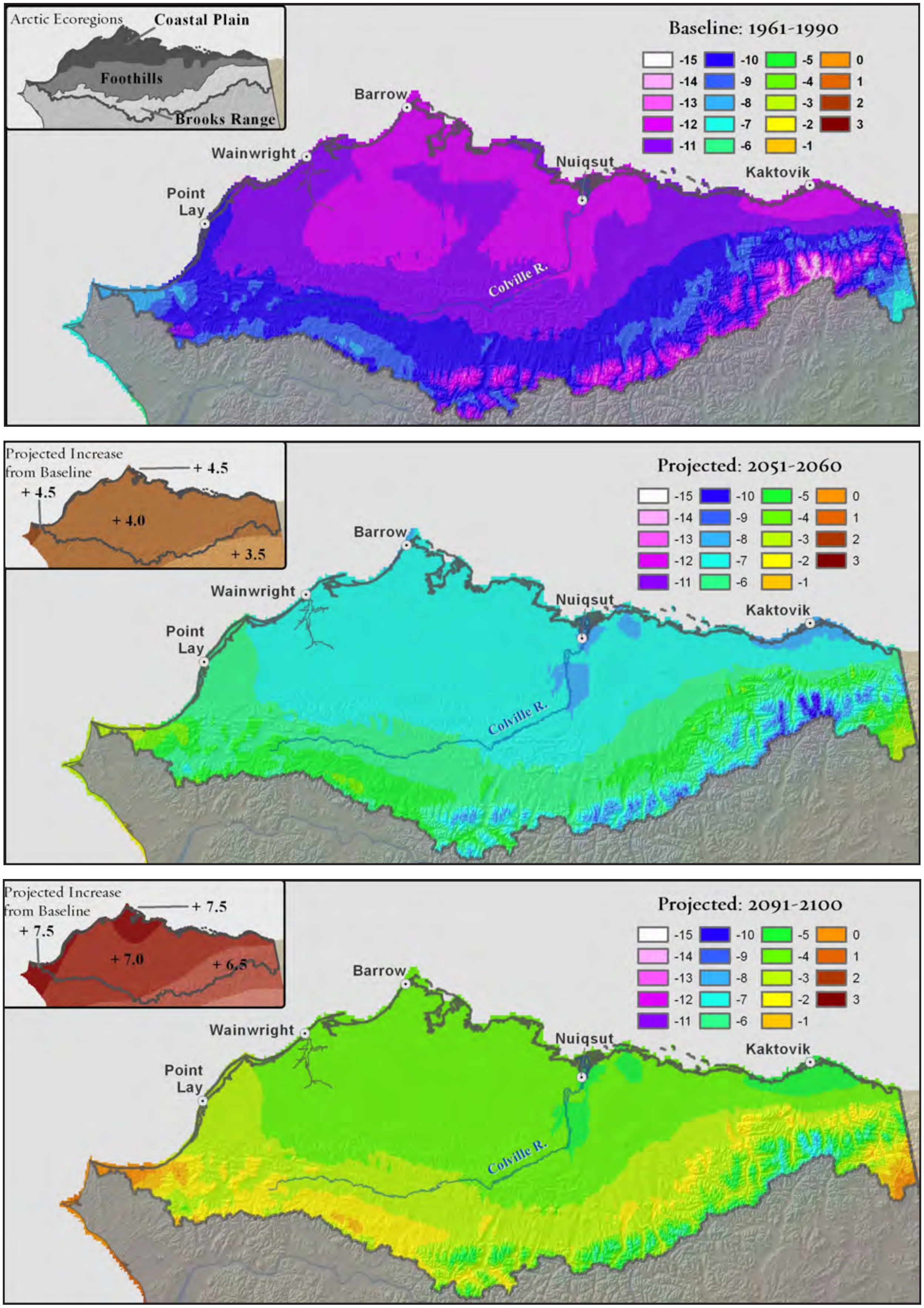


Figure 3.6. Average annual air temperatures (°C), baseline (top panel, 1961–1990) and projected (middle panel, 2051–2060, bottom panel, 2091–2100). Insets depict North Slope ecoregions (top panel) and projected change from baseline for periods 2051–2060 (middle panel) and 2091–2100 (bottom panel). Map created by The Nature Conservancy, Anchorage, Alaska.

Winter Air Temperatures (°C)

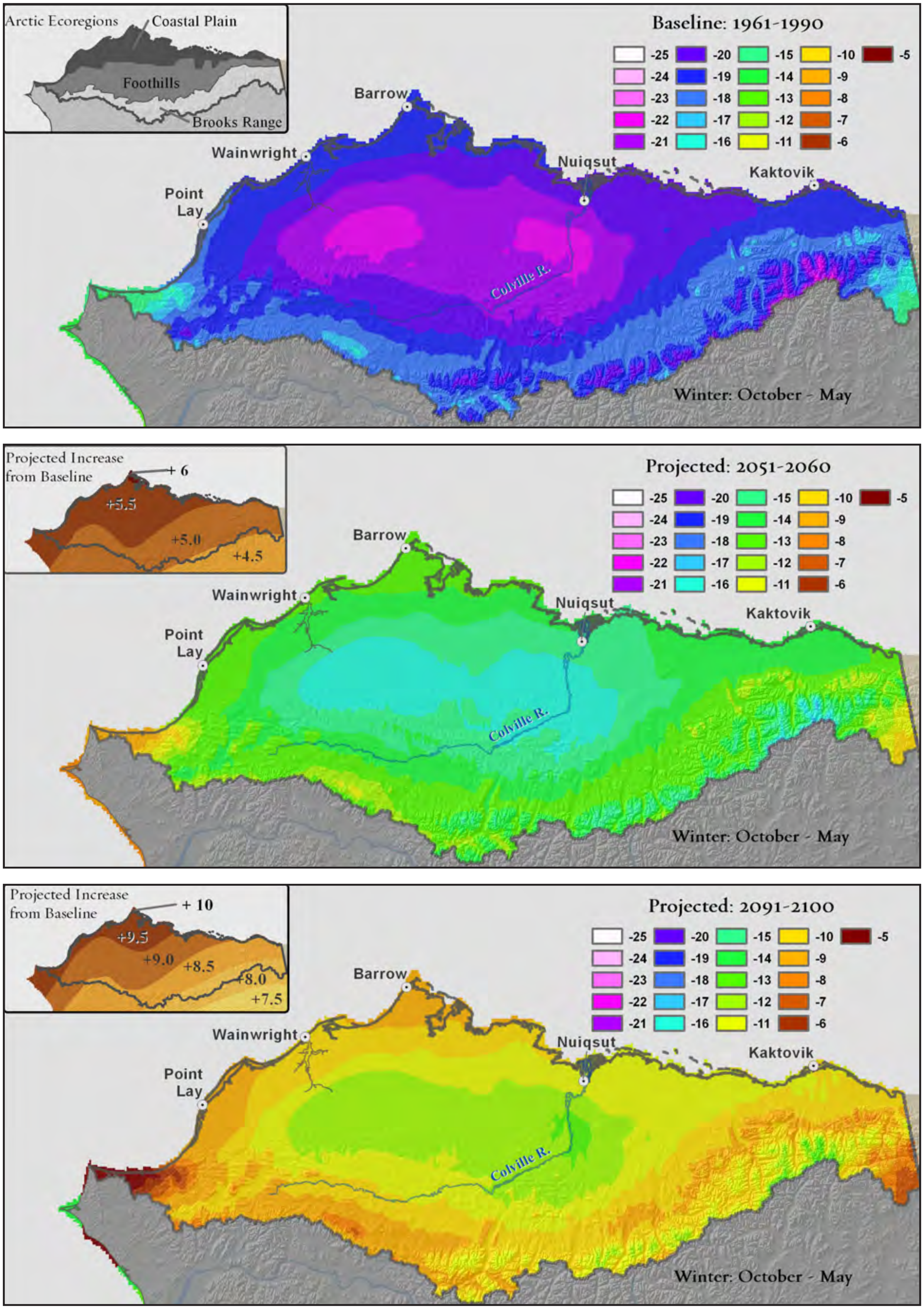


Figure 3.7. Winter air temperatures (°C), baseline (top panel, 1961–1990) and projected (middle panel, 2051–2060, bottom panel, 2091–2100). Insets depict North Slope ecoregions (top panel) and projected change from baseline for periods 2051–2060 (middle panel) and 2091–2100 (bottom panel). Map created by The Nature Conservancy, Anchorage, Alaska.

Summer Air Temperatures (°C)

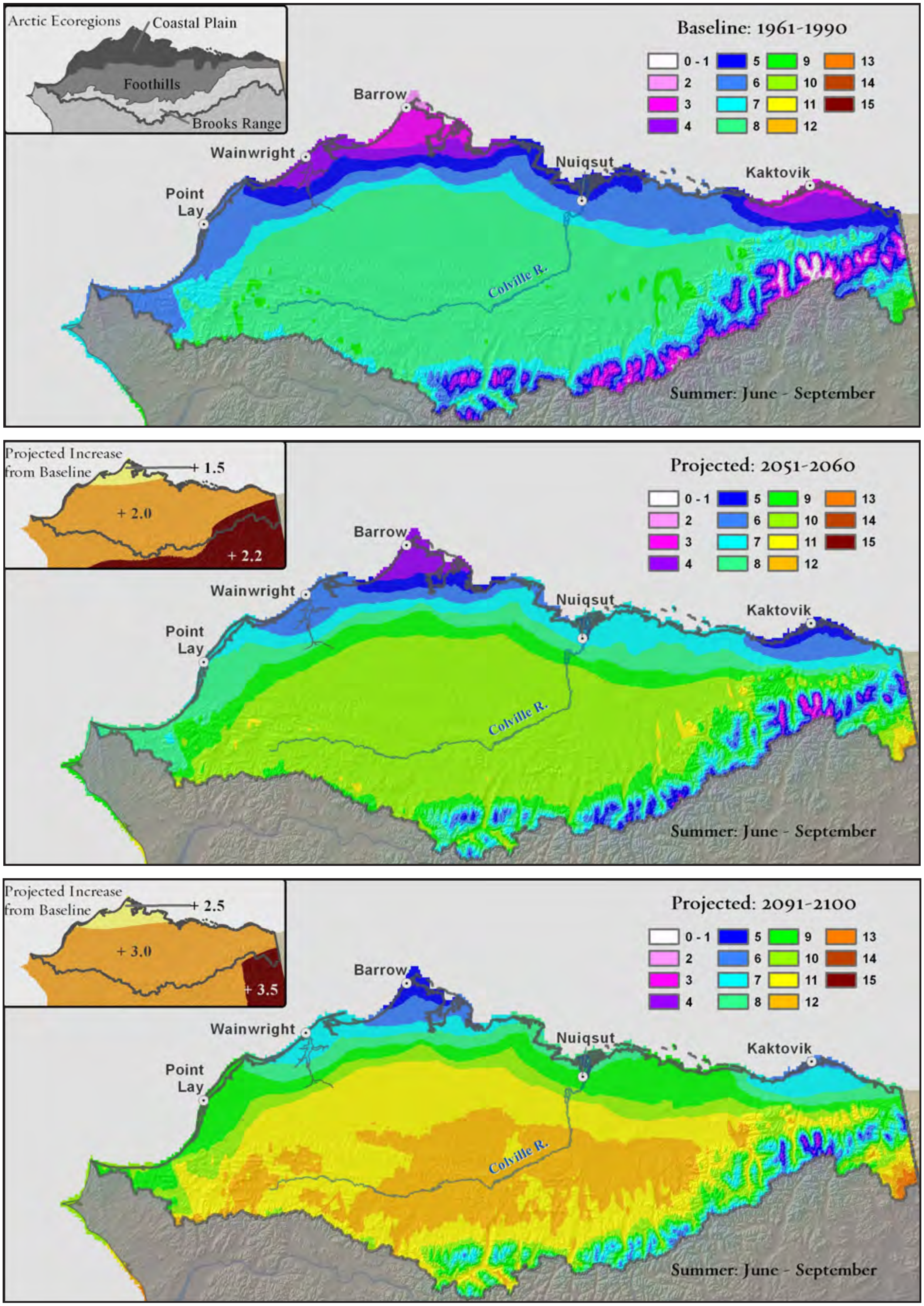


Figure 3.8. Summer air temperatures (°C), baseline (top panel, 1961–1990) and projected (middle panel, 2051–2060, bottom panel, 2091–2100). Insets depict North Slope ecoregions (top panel) and projected change from baseline for periods 2051–2060 (middle panel) and 2091–2100 (bottom panel). Map created by The Nature Conservancy, Anchorage, Alaska.

Average Annual Precipitation (mm)

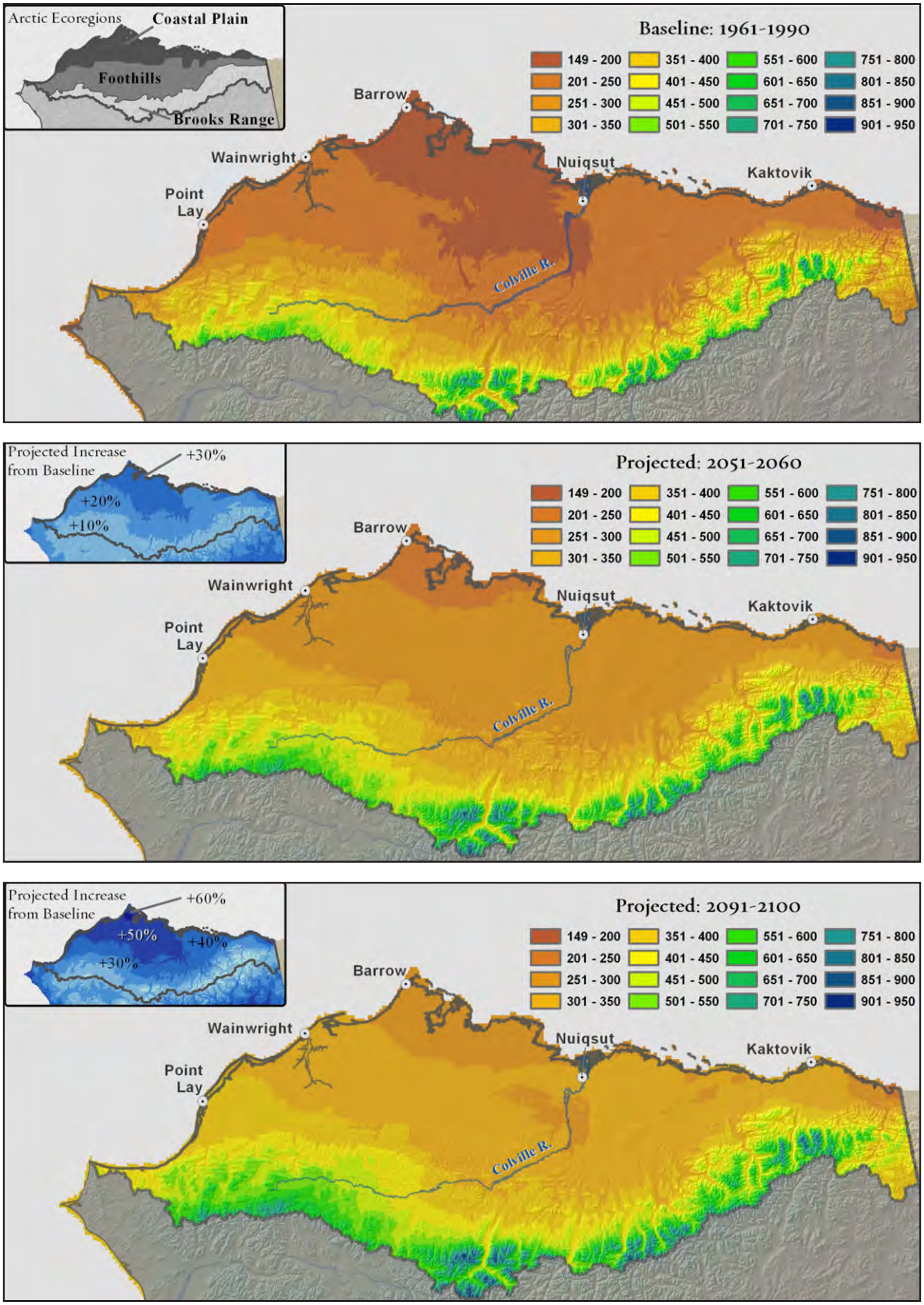


Figure 3.9. Average annual precipitation (mm), baseline (top panel, 1961–1990) and projected (middle panel, 2051–2060, bottom panel, 2091–2100). Insets depict North Slope ecoregions (top panel) and projected change from baseline for periods 2051–2060 (middle panel) and 2091–2100 (bottom panel). Map created by The Nature Conservancy, Anchorage, Alaska.

Continued from page 16

in summer temperature and duration of the frost-free period are expected to result in an increase in evapotranspiration, with drying projected across the three ecoregions (Figure 3.10). Near the middle of the century (2035–2044), the landscape may be 10–16% drier, and near the end of the century (2075–2084), the North Slope could be 23–37% drier (Figure 3.10).

Cloud cover, including fog, can substantially alter the amount of solar energy available at ground level by intercepting and reflecting solar energy away from the earth's surface and by emitting longwave radiation (i.e., heat) back towards the ground (e.g., Weller and Holmgren 1974). During summer, the balance between reflected and emitted energy tends to be negative, meaning that the net effect of cloud cover is a cooling of the surface (Chapin et al. 2005). Historical data from Barrow shows that peak cloudiness occurs in August and September, coinciding with the presence of open water along the coast (Maykut and Church 1973). Cloudiness in the Arctic is expected to increase as sea ice retreats, creating larger areas of relatively warm open water for a longer period (Walsh and Chapman 1998). While there is agreement that changes in cloud cover will affect the arctic landscape, there is substantial uncertainly regarding the magnitude of those effects (ACIA 2005, Walsh and Chapman 1998).

Model Confidence

The point estimates for change in temperature and precipitation should be considered in the context of model reliability. Figure 3.11 depicts the geographic pattern of among-model variance in temperature and precipitation for the mid-century. The differences in model output can be attributed largely to differences in the way each of the five models treats the seasonal retreat of sea ice, which substantially influences projections for fall and winter temperatures (John Walsh, International Arctic Research Center, personal communication). Sea ice distribution is difficult to model and was one of several deficiencies noted by Kattsov and Källén (2005) in GCMs. Other identified areas of deficiency included representation of clouds, atmospheric bound-

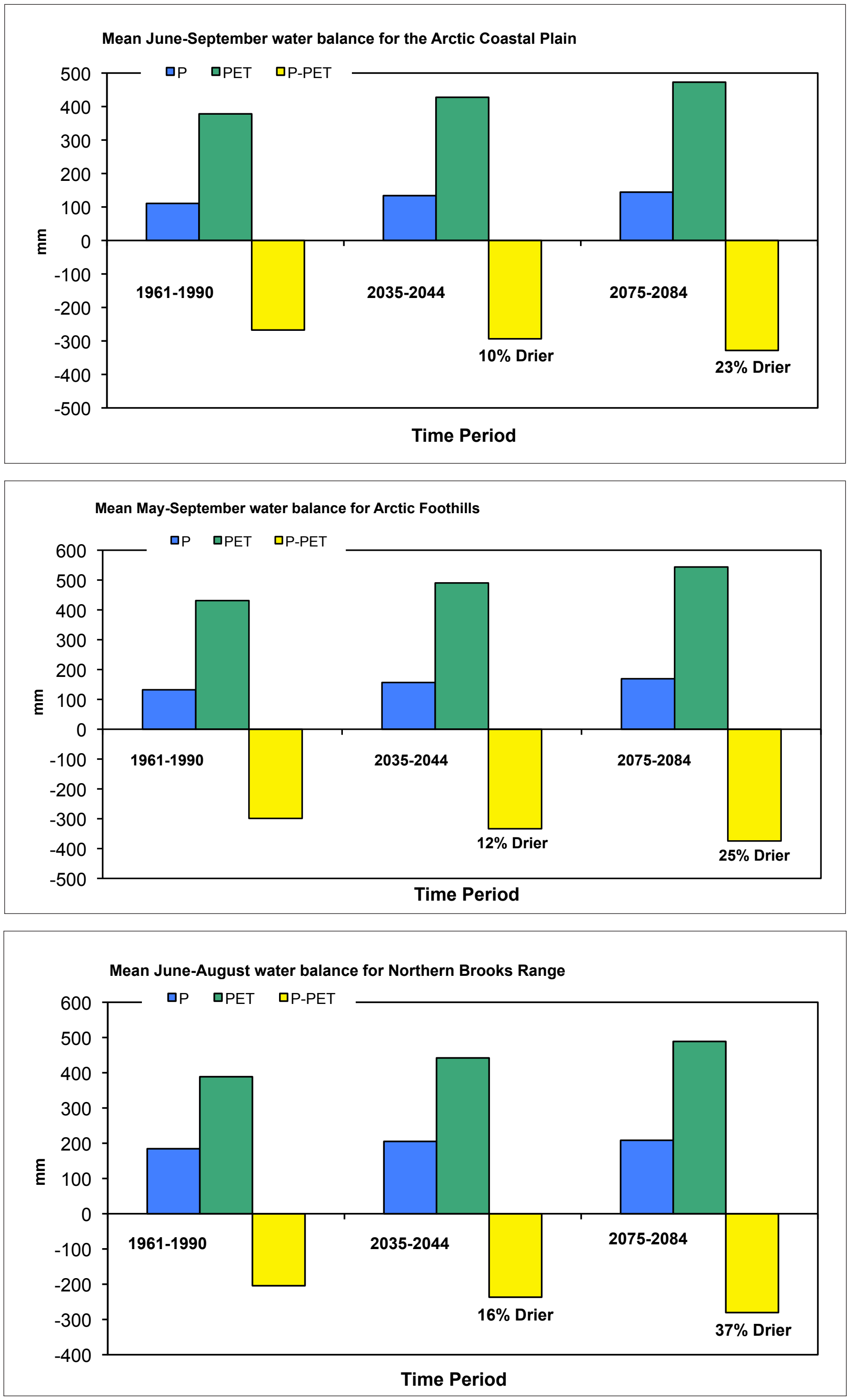


Figure 3.10. Growing season water balance, baseline (1961–1990) and projected (2036–2044 and 2075–2084) for the three North Slope ecoregions. Top panel: Arctic Coastal Plain, middle panel: Arctic Foothills, bottom panel: Northern Brooks Range. P=precipitation; PET=potential evapotranspiration. When the difference between these two quantities (P-PET) is negative, a drier condition is indicated. Figures courtesy Wendy Loya and Brendan O'Brien, The Wilderness Society, Anchorage, Alaska.

ary layers, freshwater discharge into marine waters, and vegetation feedbacks.

Differences among models are not the only potential source of uncertainty in climate projections. Another source of variation includes assumptions regarding atmospheric concentrations of greenhouse gases; the results presented here are based on just one of the many potential emissions scenarios assembled by the IPCC Special Report on Emissions Scenarios (Nakicenovic et al. 2000). We chose to base our discussions on a "middle-of-the-road" scenario (scenario A1B) but there is no assurance that this is the most probable scenario.

Potential within-model variation is also not incorporated into this discussion; rather, results are based on a single run of each model with initial conditions set to the average over the period 1961–1990 (see Appendix 1). An "initial condition ensemble" approach would employ multiple runs of a single model with variable initial conditions. This type of analysis would permit the inclusion of natural variability through the statistical distribution of climatic conditions and the probability of extreme events (Kattsov and Källén 2005).

A retrospective analysis of the performance of the five models (SNAP 2008) demonstrated that model output corresponded reasonably well to actual climate records from 1980–2000 at 32 stations across Alaska. That analysis, however, included only one arctic site (Barrow). Models performed better for temperature than precipitation due to the inherent variability of precipitation over time and space. At Barrow, model outputs accounted for 85–91% of the variation in monthly mean temperature, but only 21–51% of the variation in precipitation aggregated into four-month intervals. On the circumpolar scale, Walsh (2005) also reported a large range of uncertainty in projections of future precipitation regimes. Given the importance of water balance to habitat conditions, improvements in the reliability of projections of precipitation and evapotranspiration are urgently needed.

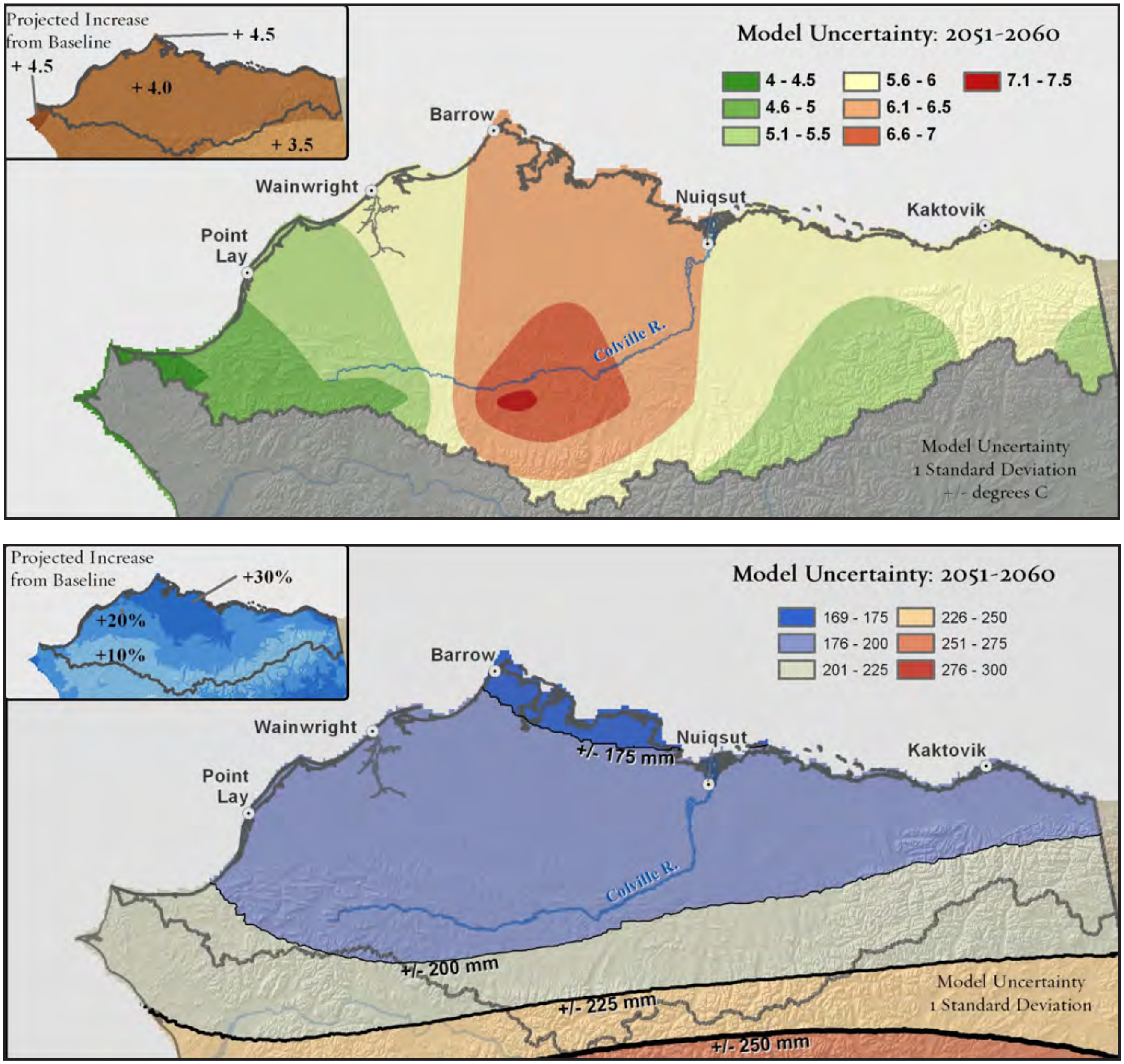
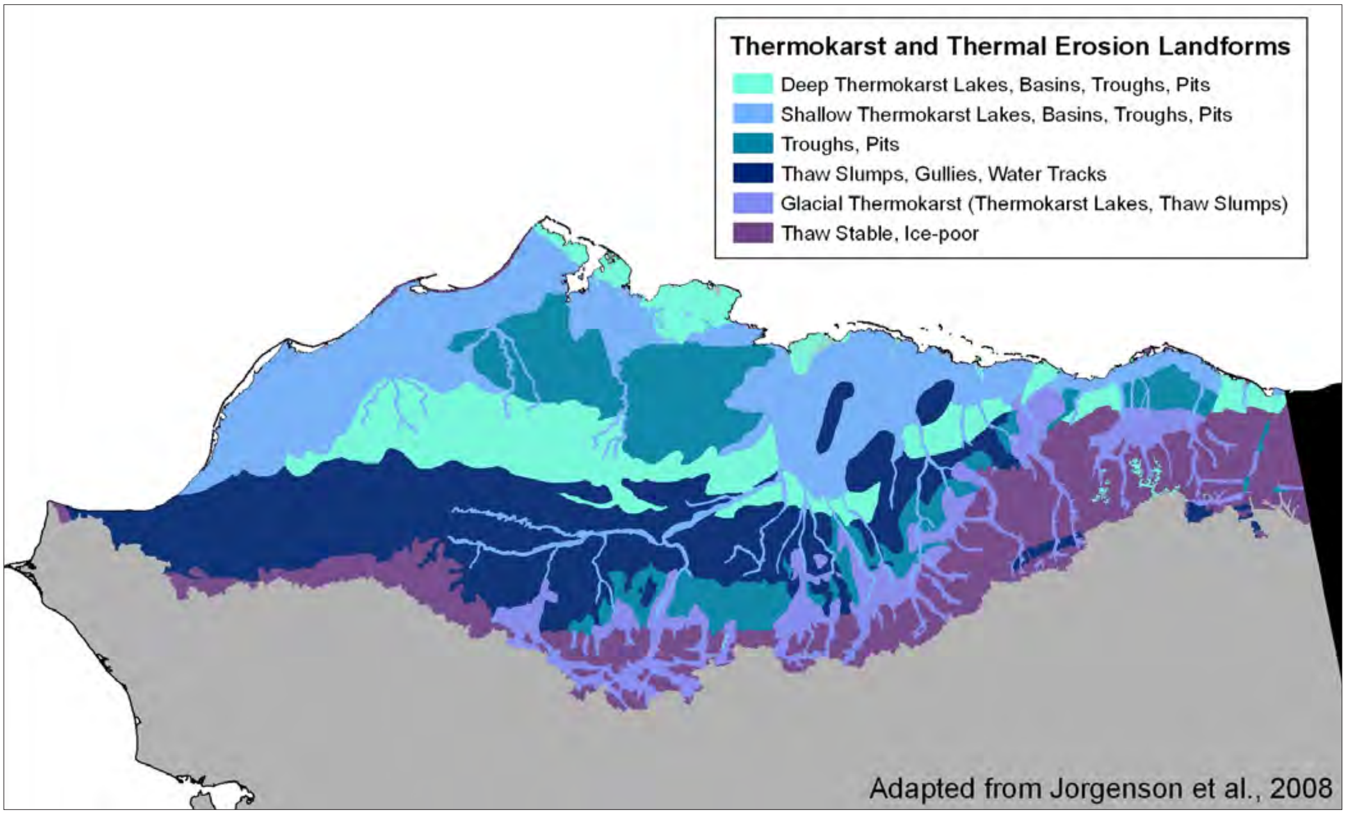


Figure 3.11. Model uncertainty for annual temperature (°C*; upper panel) and precipitation (mm; lower panel) projections for 2051–2060. Insets depict projected temperature change relative to baseline (upper panel) and projected precipitation increase relative to baseline (lower panel). Map created by The Nature Conservancy, Anchorage, Alaska.*

Permafrost

Permafrost is earth material (soil, rock, ice, and organic material) that remains at or below 0°C for at least two consecutive years (van Everdingen 1988). Permafrost is unique to those areas characterized by low mean annual air and ground temperatures (Smith and Riseborough 2002) and is believed to underlie approximately 13–18% of the exposed land in the northern hemisphere (Zhang et al. 2000). The areal distribution of permafrost is divided into four zones based on the relative proportions of the land underlain by permafrost (Brown et al. 1997): continuous (>90%), discontinuous (50–90%), sporadic (10–50%), and isolated (0–10%). These zones are loosely related to mean annual air temperature (MAAT), with continuous permafrost generally beneath areas with MAAT at or below -6° to -8°C (Smith and Riseborough 2002). The North Slope falls within the zone of continuous permafrost, and thermokarst and thermal erosion features are found across most of the region (Figure 3.12). Thawing of ice-rich permafrost causes the surface to subside, creating characteristic surface landforms termed thermokarst features. Processes associated with thermokarst include thaw, ponding, surface and subsurface drainage, surface subsidence, and erosion (Yoshikawa and Hinzman 2003). Along the Beaufort Sea coastline, permafrost thickness is generally in the range of 200–400 m (650–1,300 ft) although a thickness of 650 m (2,130 ft) has been measured at Prudhoe Bay (Gold and Lachenbruch 1973).

At the surface, above the permafrost, soil thaws during the summer and freezes again in winter—this zone is termed the “active layer.” Soil texture and moisture play a key role in determining active layer depth; gravelly soils tend to be well drained with deep active layers, whereas organic soils tend to be poorly drained with shallow active layers. Active layer depth also varies across the terrain: it can be as little as 35 cm (14 in) in upland tussock tundra, with organic-rich soils to as deep as 130 cm (51 in) in riverine tall willow shrub with sandy soils, and up to 4 m or more in coarse-grained sediments and in the Brooks Range (Jorgenson et al. 2003). In addition to influencing active layer depth, topography and texture of the predominant soil type determine the ground ice content of permafrost (Box 3.1). Within the permafrost layer, pockets of perennially unfrozen ground, or taliks, can form in locations where temperature is maintained above



Adapted from Jorgenson et al., 2008

Figure 3.12. Permafrost distribution and associated thermokarst and thermal erosion landforms on the North Slope of Alaska. Map by USFWS from Jorgenson et al. 2008.

0°C, such as under lakes, rivers, or in areas influenced by groundwater movement (van Everdingen 1988).

The thermal regime of permafrost is mediated by topography, surface water, soil moisture, groundwater movement, vegetation, and snow. Wet, near-surface soils increase heat transferred into the ground in summer, while drier soils reduce that heat transfer. Unfrozen water provides an important positive feedback by enhancing permafrost degradation when impounded on the surface, when moving through the active layer, or flowing through taliks. During the warm season, vegetation protects permafrost from thaw by shading the ground surface from incoming solar radiation and acting as insulation (Streletskiy et al. 2008). Similarly, interception of snow by shrubs can act to insulate soils against extremely cold air temperatures in winter. Because permafrost is strongly influenced by ecological components such as vegetation structure and composition, its properties evolve along with successional patterns of ecosystem development (Jorgenson et al. 1998). In turn, the patterns of ice accumulation and degradation influence the patterns of vegetation and soil development. This co-evolution of permafrost and ecological characteristics at the ground surface is most evident after disturbance, such as river channel migration, lake drainage, and fire (Shur and Jorgenson 2007).

Over the past 2–3 decades, permafrost temperatures have generally increased 1–2°C at sites throughout the northern hemisphere, although some are stable (for review see Brown and Romanovsky 2008). Permafrost warmed about 2–3°C near Prudhoe Bay from the mid-1980s to 1997 (Romanovsky and Osterkamp 1997). Long-term monitoring of deep wells along a north-south transect from Prudhoe Bay to the Brooks Range shows a general warming trend over the past 25 years, but with stable and cooling periods (Figure 3.13; Osterkamp 2005). The greatest change in temperature at the surface of the permafrost, a warming of 3–4°C, was detected on the Arctic Coastal Plain. In Alaska, the changes in permafrost temperature coincide with warming air temperatures in winter (Osterkamp 2005, 2007).

Sensitivity of the landscape to climate warming is greatly influenced by the quantity and nature of ground ice (Box 3.1). On a local scale, the stability of permafrost is affected by terrain, surface water, groundwater movement, soil properties, vegetation, and snow (Osterkamp 2007). If permafrost does degrade, the type of thermokarst and the ecological implications vary depending on climate, landscape position, soils, hydrology, and amounts and types of ice (Jorgenson and Osterkamp 2005).

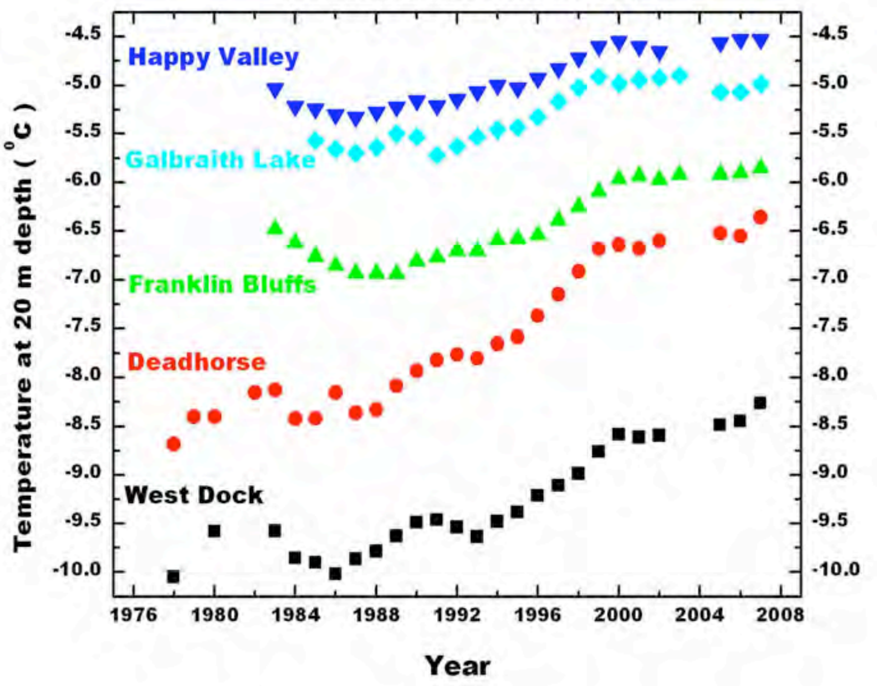


Figure 3.13. Temperature records from deep wells along a north-south transect from Prudhoe Bay to the Brooks Range. Figure from Romanovsky et al. 2007.

The dependence of permafrost stability on both air temperatures and ecological factors adds complexity to the task of forecasting the biological consequences of climate change. Landscape-level models have been developed to project the distribution of permafrost under scenarios of climate change. For example, the GIPL model (http://www.gi.alaska.edu/snowice/Permafrost-lab/methods/modelling.html) incorporates the effects of surface geology, lithology, ground temperatures, soil properties, snow cover, vegetation, air temperature, and precipitation into a numerical model of heat transfer through the atmosphere, snow, vegetation, and active layer. The model outputs predicted mean annual ground temperature at various depths, from which the persistence of permafrost may be inferred. When applied to long-term (decadal and longer time scale) averages, this approach shows an accuracy of +0.2–0.4°C for mean annual ground temperature (Sazonova and Romanovsky, 2003). Using climate projections based on the SNAP data set under the A1B emissions scenario, permafrost distribution in arctic Alaska is expected to remain stable through the end of the century, as evidenced by projected mean annual soil temperature below 0°C (Figure 3.14).

Despite the relative stability projected for permafrost in arctic Alaska, recent observations suggest that warming temperatures can accelerate thermokarst processes at mean annual ground temperatures well below 0°C, as evidenced by an increase in both area and density of degrading ice wedges in a study area on the Arctic Coastal Plain (Jorgenson et al. 2006). In the near term, thermokarst processes, such as the degradation of ice wedges, that affect local drainage and vegetation are the likely agents of habitat change, rather than widespread deepening of the active layer or a shift to discontinuous permafrost.

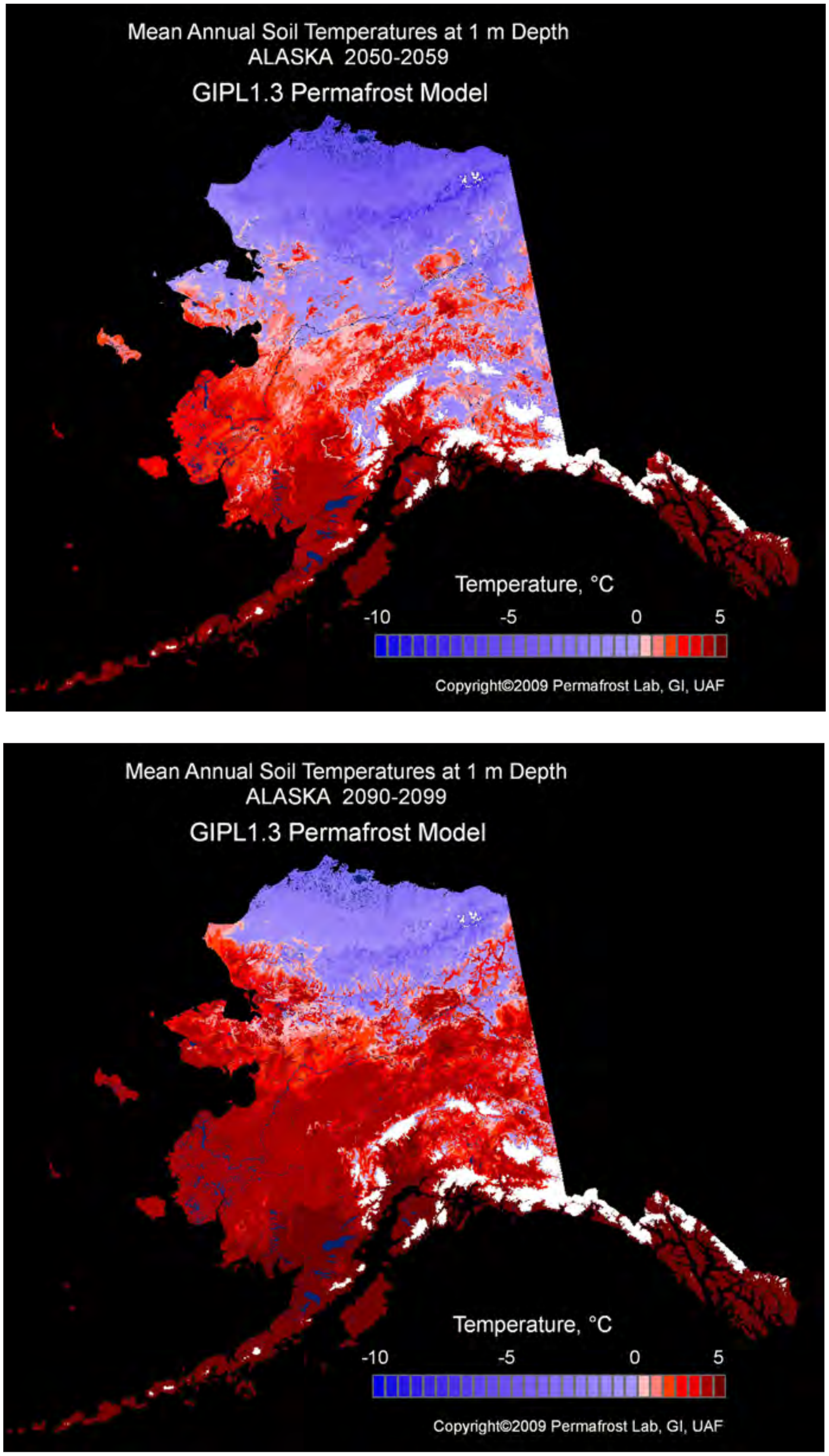


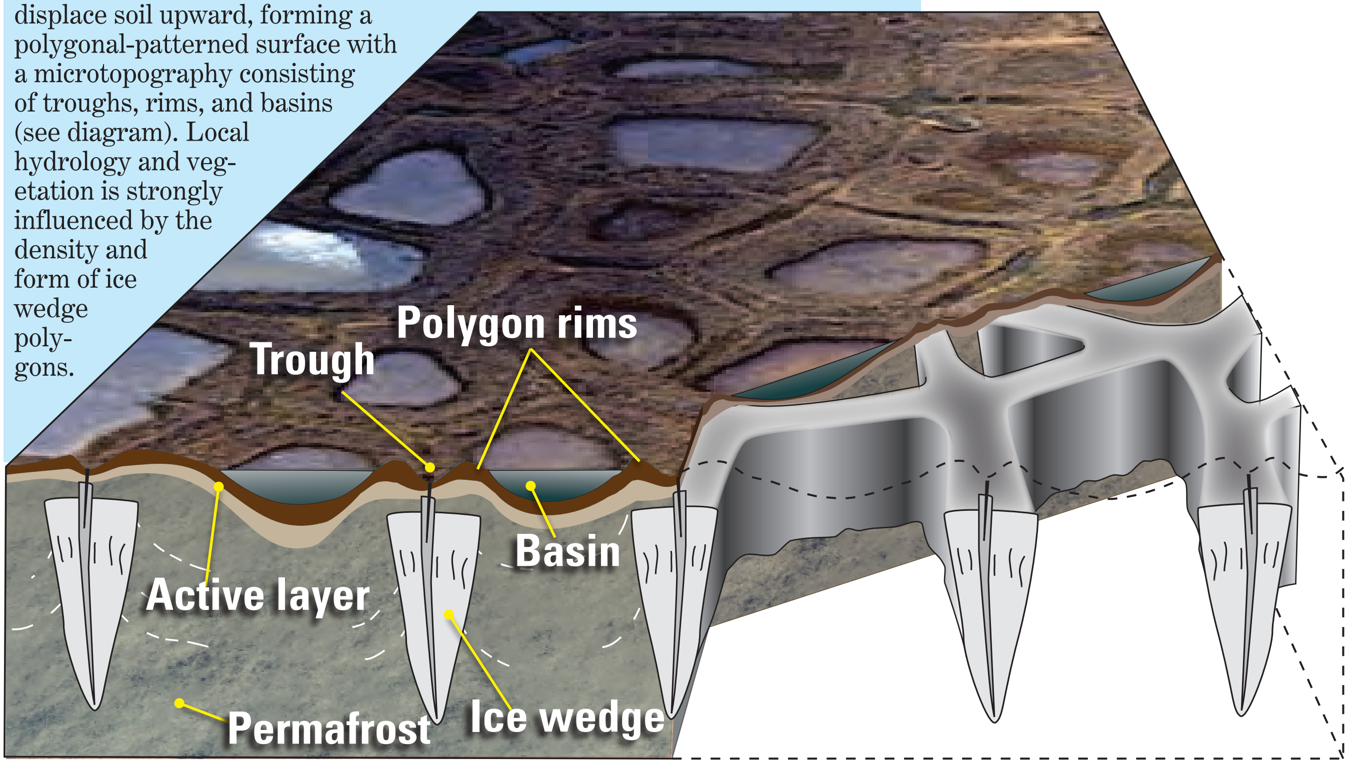
Figure 3.14. Projected mean annual soil temperatures for Alaska at 1 m depth, 2050–2059 (above) and 2090–2099 (below). Based on output from the GIPL 1.3 Permafrost Model using the SNAP climate data set. Figure courtesy of S. Marchenko and V. Romanovsky (Geophysical Institute Permafrost Laboratory, University of Alaska Fairbanks) and SNAP (University of Alaska Fairbanks).

Box 3.1 Ground Ice Formation

Permafrost—frozen ground—varies in the amount and type of ice contained. Ground ice can take the form of:

1. massive ice (e.g., ice wedges and pingo ice),
2. ice contained within microscopic soil pores, or
3. discrete lenses of segregated ice that are highly variable in size and shape (van Everdingen 1988).

On the Arctic Coastal Plain, ice wedge polygons are the most common form of massive ice. The process of ice wedge formation was described by Lachenbruch (1962). Ice wedges begin to form when frozen soil contracts and cracks in response to abrupt temperature drops during winter. In spring, water seeps down into the crack and freezes when it reaches the permafrost zone. The following winter, the growing ice wedge cracks in nearly the same location. In spring, the cracks are again filled with water that soon freezes after it enters the ice wedge. This iterative process of cracking and freezing forms a polygonally patterned network, which is, from above, similar in appearance to the cracks in drying mud, but with polygons measuring 5–40 m in diameter. Over a period of hundreds to thousands of years (Jorgenson et al. 1998), growing subterranean ice wedges displace soil upward, forming a polygonal-patterned surface with a microtopography consisting of troughs, rims, and basins (see diagram). Local hydrology and vegetation is strongly influenced by the density and form of ice wedge polygons.



Above: Schematic illustrating formation of ice wedges by R. Mitchell/Inkworks from cited sources.

Hydrology

This section provides an overview of the hydrology of the Alaskan Arctic and a number of potential future impacts of increasing air temperature and possible increasing precipitation. There is a considerable amount of uncertainty associated with our description of current conditions, as well as projections of how arctic hydrology may differ in the future. The uncertainty derives from many sources, including difficulty measuring hydrologic parameters in an extreme environment, limited observational data sets covering time periods of several decades or less from only a few locations, and climate modeling errors. The arctic hydrologic cycle exhibits high natural variability that can make it difficult to clearly detect changes. Furthermore, the system is highly complex and involves many feedbacks that may accelerate some changes while inhibiting and restoring stability in reaction to other changes.

Hydrologic processes are a pivotal determinant of climate-influenced habitat change. In arctic Alaska, continuous permafrost forms an impermeable layer below a shallow seasonally frozen surface soil layer. In the Arctic Foothills, limited soil storage capacity and topographic gradients result in high runoff ratios in spring and summer. On the Coastal Plain, the underlying permafrost and low topographic gradient results in a landscape dominated by wetlands, ponds, and lakes (see photo this page) in a region that would otherwise be classified as arid on the basis of annual precipitation. Deep, continuous permafrost is expected to persist for centuries in arctic Alaska, even under scenarios of continued arctic warming. Nevertheless, changes in overall water balance (Box 3.2) and timing and magnitude of seasonal water and energy fluxes could significantly affect the aquatic and semi-aquatic habitats upon which many species depend.

The vast Arctic Coastal Plain is covered with lakes and ponds. Photo by Steve Zack, Wildlife Conservation Society.

Box 3.2. Water Balance

The water budget of a basin can be described by the following equation:

$$(P_s + P_r) - (E_s + ET) - R = \Delta (S_{surface} + S_{soil}),$$

where input occurs as either snow (P_s) or rain (P_r) and output can take the form of either sublimation (E_s), evapotranspiration (ET), or surface runoff (R). When this quantity is positive, there is a net increase in basin storage, partitioned into surface water storage ($S_{surface}$) and soil moisture (S_{soil}). When this quantity is negative, as occurs in a dry summer, a soil water storage deficit ensues. The larger the deficit at the end of the summer season, the greater proportion of next spring's snow melt will be taken up to recharge ponds and lakes and absorbed into surface and near-surface soils.

In arctic Alaska, the best available water balance data are from the Kuparuk watershed, including Imnavait Creek in the Kuparuk headwaters, and the adjacent Putuligayuk River (Bowling et al. 2003, Kane et al. 2000, 2008, Kane and Yang 2004; see map in Box 3.3, page 33).

Imnavait Creek and the Upper Kuparuk River are representative of systems in the Arctic Foothills, whereas the Putuligayuk River lies wholly within the Arctic Coastal Plain. Water input to the systems is represented by Snow Water Equivalent (SWE) and rainfall; water loss is through ET and runoff (snow and summer). As indicated in the figure, the hydrologic regime on the Coastal Plain (Putuligayuk River) is dominated by snowfall and snowmelt-generated runoff. Although snowfall and snowmelt are also very significant in the Foothills, it can be seen that summer rainfall is typically greater than end-of-winter SWE, and rainfall yields considerable runoff.

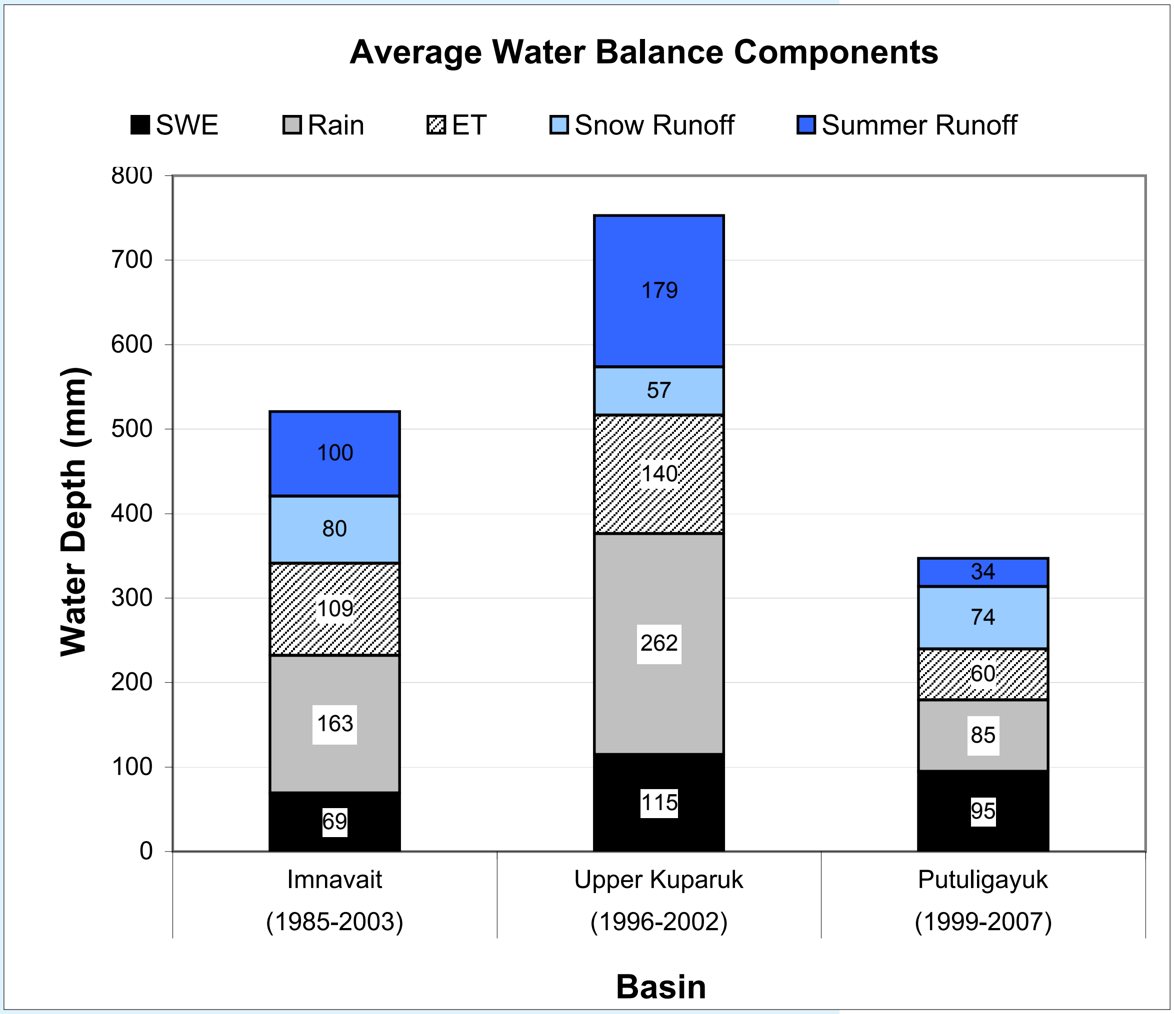


Figure by Amy Tidwell for WildREACH from cited sources.

Overview of Hydrologic Processes by Season

Figure 3.15 is a generalized representation of the current hydrologic processes in arctic Alaska.

Winter

Winter generally lasts from October until mid- to late May. During the cold season, precipitation falls as snow and is temporarily stored in the snow pack at the ground surface. Snow accumulation is reduced to some extent by sublimation (vaporization directly from the solid phase). Water stored in the snow pack at the end of winter is an important hydrologic quantity and is referred to as the end-of-winter snow water equivalent or SWE (Figure 3.15: A). On average, SWE represents approximately 40% of annual North Slope precipitation. However, this can vary greatly from year to year and by location. For example, in the upper Kuparuk River basin, SWE represents approximately one-third of total precipitation (minimum 14% in 1999; maximum 42% in 2000), while the lower Kuparuk region on the Coastal Plain receives an average one-half of its precipitation as snow (minimum 41% in 2002; maximum 85% in 2007; Kane et al. 2004, 2008).

Winter snow cover and winter temperatures strongly affect soil temperatures. Snow acts as an insulator between the relatively warm soil and cold air temperatures throughout the winter. Therefore, greater snow depth and warmer air temperatures act to reduce winter heat loss from the soil, while more shallow snow and lower air temperatures lead to colder soil temperatures.

Spring Melt

The spring season is very brief, with snow melt, spring flood, and leaf-out occurring within a period of 2–3 weeks beginning in mid- to late May. During the spring, the snow pack that developed during winter is lost through combined processes of melting and evaporation (ablation) in a short period of time, usually within 1–2 weeks (Figure 3.15: B). Once ablation is complete, surface soil temperatures begin to increase and soils begin to thaw. As surface soils thaw, they become much more permeable, and water can more readily

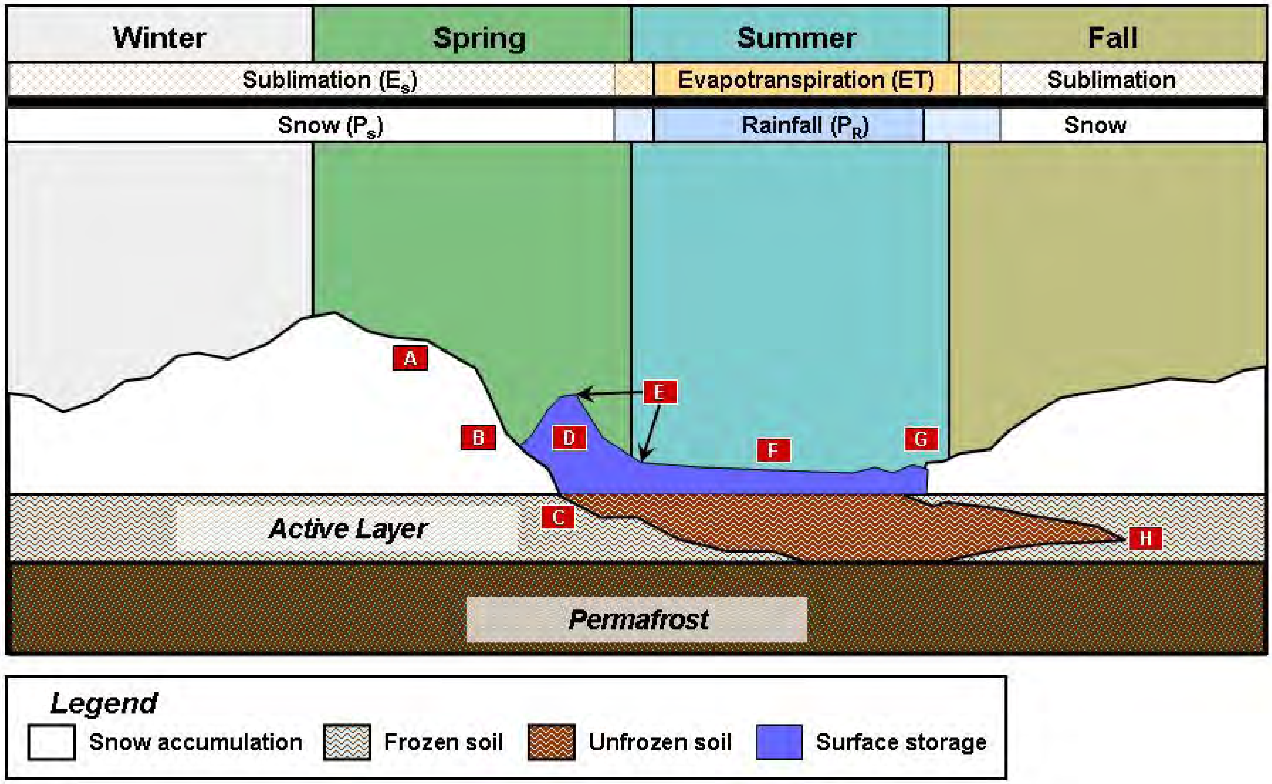


Figure 3.15. Generalized representation of hydrologic processes in arctic Alaska in seasonal sequence. Specific features of the illustration are discussed in the text. Processes above the thick black line represent the primary mechanism of water movement from the surface to the atmosphere for each season. Processes below the black line represent movement of water from atmosphere to surface. Figure by Amy Tidwell for WildREACH from data in Kane et al. 2003, 2004, 2008.

enter the soil column, provided that it is not saturated (Figure 3.15: C). Water released from the snow pack during spring melt recharges lakes, ponds, and emergent wetlands, and drains off the surface into streams (Figure 3.15: D).

Shortly following snow ablation, streamflow rises sharply. Although much of the snowmelt drains into the Arctic Ocean, a considerable portion remains on the surface in the form of lakes, ponds, wetlands, and soil moisture. Over the course of a few weeks, the inundated land surface area, and thus surface water storage, rapidly decreases as lakes and wetlands drain downslope until water surface elevations fall below their outlets (Figure 3.15: E). Surface water storage is further decreased as surface (lakes, ponds, etc.) and soil-stored water is lost to the atmosphere through evapotranspiration (the sum of evaporation and plant transpiration from the earth's surface to the atmosphere).

Summer
From early June through August and potentially into September, average daily temperatures remain above 0°C, and most precipitation occurs as rain and condensation. Early summer tends to have much lower precipitation than late summer. During this period, evapotranspiration often exceeds precipitation (Bowling et al. 2003), and the landscape undergoes progressive drying (Figure 3.15: F). Rainfall typically increases throughout the season, while evapotranspiration declines due to reduced evaporation from the ground surface and plant transpiration. Consequently, late summer and early fall precipitation may reduce much of the surface drying that occurs in early summer (Figure 3.15: G).

Currently, the Coastal Plain exhibits little stream response to summer rainfall events. This is due to the high surface storage capacity, low topographic gradient, and progressive surface drying during summer. As rainfall arrives at the surface, it replenishes soil moisture and surface storage and typically does not result in significantly increased streamflow (Bowling et al. 2003). In contrast, significant rainfall events do result in streamflow response in the Foothills (Box 3.3), where there is considerably less surface storage and steeper topographic gradients (Kane et al. 2003, 2008).

Fall Freeze
Freezing temperatures may occur throughout the summer, but a hard freeze is likely any time between late August and mid-September. The onset of persistent snow cover usually occurs in September. In early fall, surface soils begin to cool and eventually reach the freezing point. Between mid- and late fall, the active layer undergoes freeze-back, primarily at the surface but also at the interface with the permafrost table (Figure 3.15: H).

The Kuparuk River in winter. Photo by J. Benstead, University of Alabama.

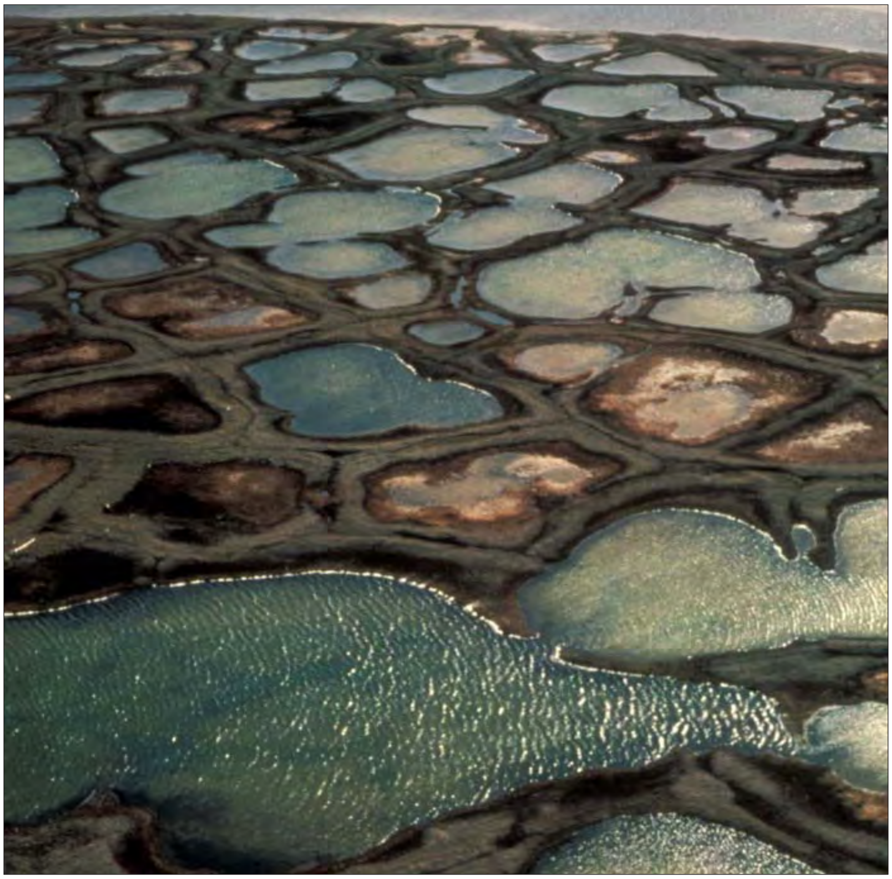
Implications of Climate Change to Hydrologic Processes

A climate shift toward higher temperatures and/or increased precipitation will likely alter the seasonal pattern described previously. Potential changes as compared to current conditions are presented in the following descriptions.

Winter

Increasing winter temperatures may not directly impact the water balance on the North Slope but will alter depth and qualities of the snow pack, such as density. These factors will affect several mammal species by altering access to forage for grazers, quality of subnivean habitats for small mammals, and soil temperatures for hibernators. Warmer winter temperatures may be accompanied by an increased frequency of rain-on-snow events, midwinter snow melt, and ice formation within the snowpack (Kane 1997). As discussed previously, increasing winter temperatures may also lead to warmer soil temperatures, with important implications for nutrient cycling and vegetation (Sturm et al. 2005).

Many climate model projections suggest that winter snowfall may also increase in the coming decades. Potential changes to winter precipitation can directly impact the water balance, spring floods, soil temperatures, and wildlife foraging. Increasing winter precipitation would yield greater end-of-winter SWE and more effectively insulate soils from winter air temperatures.



Polygonal ground and ponds on the Arctic Coastal Plain. USFWS photo.

Spring Melt

Given a scenario of increased temperature and snowfall, effects on the timing of spring melt may be offsetting to some extent—increasing air temperatures facilitate earlier snowmelt, while increasing snow depth retards it. Alternatively, if the winter snow accumulation does not increase due to a shorter winter season and/or if winter precipitation does not increase, then the average timing of spring melt would be earlier in spring. If earlier snowmelt does develop, it would result in earlier surface storage recharge, peak streamflow, and onset of active layer thaw. Furthermore, because rainfall tends to be at a minimum early in the warm season, an earlier melt may result in a longer period of surface drying prior to increasing rainfall later in the summer season.

Surface soils remain frozen during snow ablation and the active layer plays little role in the spring streamflow peak. In the Arctic Foothills, where lakes and ponds are less prominent, spring peak flows will be determined largely by the end-of-winter SWE. On the Coastal Plain as well as Foothills areas with little topographic relief and significant surface storage (lakes and ponds), spring hydrologic response will depend on end-of-winter SWE as well as on the water content of the organic mat and soils. If the surface and near-surface water storage deficit is high due to dry conditions in the previous summer, then a larger volume of snowmelt the following spring will go directly to recharge surface water bodies and soils (see Box 3.2). Alternatively, if fall surface storage is high and vegetation and soil are wet, spring peak flow may be larger relative to available SWE. It is important to note that fall surface storage depends on many factors, such as the timing of precipitation, summer air temperatures, and vegetation changes.

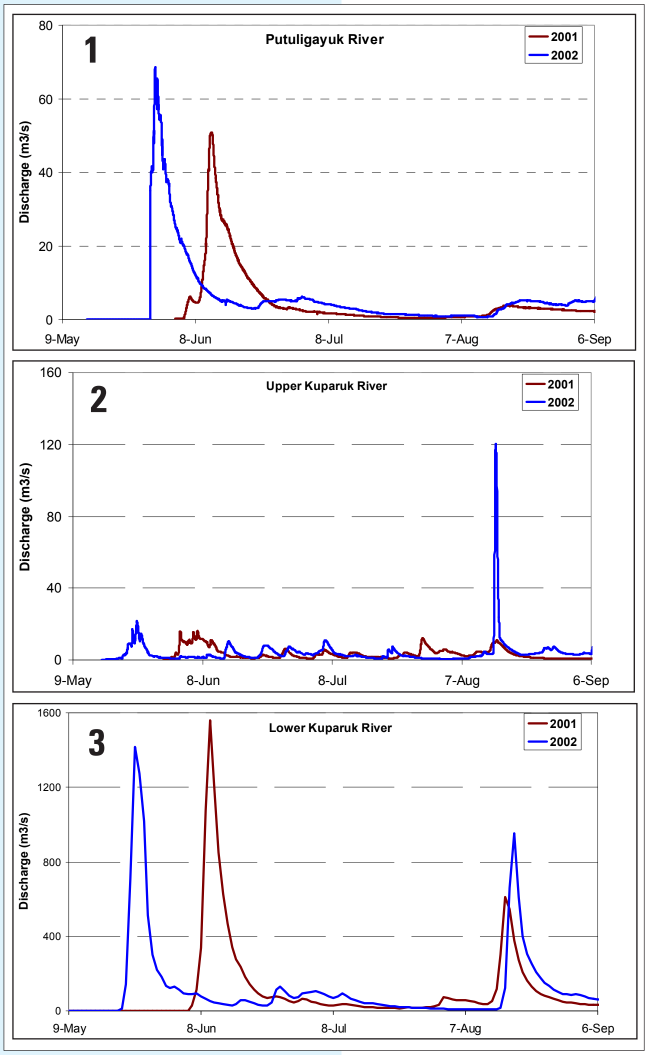
Summer

Soil moisture is an important determinant of summer hydrologic response. Runoff response to a

Box 3.3 Inputs into Stream Ecosystems

The source and timing of freshwater inputs into stream systems of arctic Alaska varies by ecoregion. The Putuligayuk River is representative of a Coastal Plain watershed, with input dominated by snowmelt. As illustrated by the hydrograph in Panel 1, this system is characterized by a single large peak coinciding with the spring freshet, resulting from the rapid melting of the snowpack. After the initial peak, discharge declines sharply and remains low throughout the mid-summer, with a slight rise at the end of summer corresponding to the period of increased precipitation. The Upper Kuparuk River (Panel 2) in the Foothills exemplifies a rainfall-dominated headwater stream. The spring snowmelt peak is still seen as a significant hydrologic event, yet this regime is also characterized by multiple peaks associated with rainfall throughout the summer. Relative to the Putuligayuk, the Upper Kuparuk is susceptible to flash floods, such as the one in mid-August 2002. The Kuparuk River flows through all three ecoregions, and the Lower Kuparuk (Panel 3) has a hydrologic regime with a mix of characteristics typical of both Coastal Plain watersheds and rainfall-dominated headwater systems. In the Lower Kuparuk, the spring freshet produces a readily detectable peak in stream flow that quickly declines. Large precipitation events do produce additional increases in stream flow; these spikes in streamflow, however, are less pronounced than those seen in the upper reaches of the river.

Groundwater can also be a significant input into the annual water budget of arctic stream systems. There are three general types of groundwater in the Arctic: suprapermafrost (within the active layer in summer), intra-permafrost (in taliks), and sub-permafrost (beneath the permafrost table). Although the thick, continuous permafrost of arctic Alaska restricts the input of sub-permafrost groundwater to surface waters, spring-fed stream systems are distributed widely in the eastern Brooks Range, most commonly in limestone areas at an elevation of about 600 m (Yoshikawa et al. 2007). Groundwater enters streams, becoming baseflow, by migrating through the organic mat or unfrozen soil until it enters a drainage network or by flowing directly into the system (i.e., spring flow).



Glacial discharge can also be a significant water source for systems originating in the Brooks Range between the Sagavanirktok and Kongakut rivers. Glacier-fed systems are less sensitive to summer precipitation events, exhibit more diurnal variation, and less among-year variability in runoff (Hock et al. 2005). In the initial stages of warming, as melt rate increases, summer runoff will increase. Ultimately, however, loss of glacial mass will reduce overall runoff and render these systems more susceptible to reduced flows in summer.

Map (left) shows location of Kuparuk and Putuligayuk rivers. Numbers indicate the location of gauging stations used to generate the hydrographs (above). Map by USFW. Hydrographs by Amy Tidwell for WildREACH from cited sources.

Data sources:

Upper Kuparuk and Putuligayuk Rivers:
Kane DL and Hinzman LD. 2008. Climate data from the North Slope Hydrology Research project. University of Alaska Fairbanks, Water and Environmental Research Center. URL: http://www.uaf.edu/water/projects/NorthSlope/. Fairbanks, Alaska, variously paged. November 2008.

Lower Kuparuk:
U.S. Geological Survey. 2009. Surface Water data for Alaska: USGS Surface-Water Daily Statistics. URL: http://waterdata.usgs.gov/ak/nwis/dvstat? Accessed March 31, 2009.

given storm can be vastly different depending on soil conditions, such as moisture content and active layer depth. For example, when the soil water deficit is high, there is greater capacity for soil to store water temporarily for gradual release over a longer period, with the effect of reducing peak flow and prolonging flow recession.

The magnitude and direction of change in soil moisture under changing climate scenarios is not well understood. The state of soil moisture depends on total soil storage capacity, recharge from rainfall, evapotranspiration, the ability of plants to access and exploit available soil water, and topographic gradients. Although increasing temperatures will provide additional energy to drive evaporation and transpiration, actual evapotranspiration can be water- or energy-limited. If early summer rainfall does not change considerably, then summer evapotranspiration can be expected to become water-limited earlier in the season than is currently observed. Fall evapotranspiration tends to be limited by available energy, as well as the onset of plant senescence. Therefore, changes in late summer and early fall rainfall can potentially have significant impacts on the state of surface water storage at the onset of winter.

Warmer soil temperatures and earlier onset of active layer thaw will enhance the potential depth of seasonal thaw and, thus, soil water storage capacity. Actual active layer thickness is complicated by soil moisture-energy balance-vegetation feedbacks. Soil water content affects the absorbtion of solar energy at the surface—a wet surface is darker and hence absorbs more heat than a dry surface. Dry near-surface (upper 10 cm) organic soils act as an efficient insulator, reducing heat transferred into soil in summer (suppressing active layer depth) and heat flux out of the soils in winter. In contrast, wet soils in late summer retard the freezing of the soil in fall due to the large amounts of latent heat associated with the phase change from water to ice. Similarly, ice-rich soils require more energy to thaw than ice-poor soils.

If active layer thickness increases, the distribution of stored water may shift downward. This redistribution of water in storage may produce a drier surface in both wetlands and uplands even if the absolute volume of stored water is higher. It is important to note, however, that this effect may be offset by ground settlement and vegetation changes. In the Foothills, a longer warm season may prolong the time available for soil moisture to move down gradient and into drainage networks. This may lead to late summer and early fall soil drying, while baseflows, the portion of streamflow derived from subsurface sources, may increase due to additional shallow groundwater flow.

Increasing soil storage capacity and more rapid moisture export through evapotranspiration may lead to decreased hydrologic response to summer storms. As the active layer depth increases and surface storage decreases, the Foothills will have muted hydrologic response to storms but greater base flow due to suprapermafrost groundwater flow from soil moisture. On the Coastal Plain, reduced surface storage (e.g., lower lake levels) and drier soils will require greater rainfall recharge before significant surface runoff to streams can occur, absent changes to drainage systems (see *Coastal Plain*, Chapter 4). Changes in evapotranspiration and soil storage capacity can also lead to drier surface conditions, which then require a larger amount of the following year's spring snowmelt for recharge. This redistribution of water in spring may reduce peak streamflow to some extent.

Fall Freeze

Warmer soil temperatures and a prolonged fall season will lead to later and more gradual soil freezing. In extreme scenarios, warmer fall soil temperatures and increased winter snowfall may lead to talik formation if the active layer does not fully refreeze. Although this may occur in some cases, it is not likely to occur on a large scale for a very long time—on the order of centuries. In the Foothills, prolonged thaw and formation of taliks could mean continued soil drainage throughout the winter and drier spring soil moisture. This winter drainage may lead to greater under-ice streamflow. Fall and winter drainage may be less important on the Coastal Plain where soil moisture distribution is largely determined by microtopography.

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A male American tree sparrow (Spizella arborea) *sings after arriving on his breeding grounds. Shrub-dependent songbird species will likely benefit from increased shrub cover on the North Slope. Photo by Ted Swem, USFWS.*

Alder shrubs (Alnus crispa) *colonizing the rims of polygons on the Colville River Delta. The colonizing seeds were dispersed by water movement along the floodplain corridor. This novel habitat may increase across the North Slope. Photo by M.T. Jorgenson.*

Chapter 4
Habitat Change

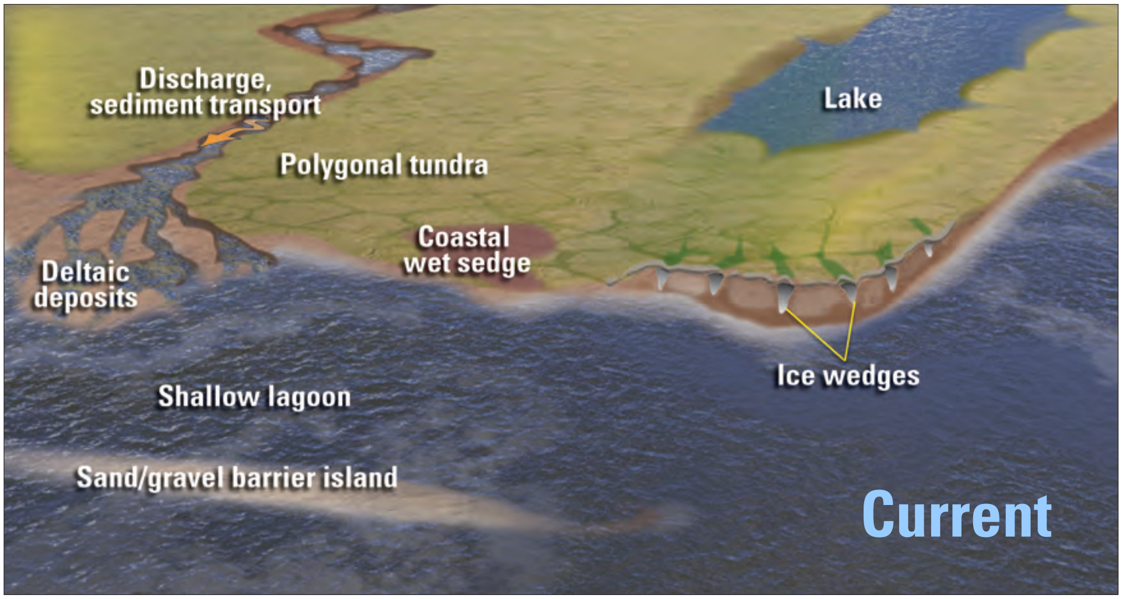
This chapter describes four North Slope landscapes influenced by the presence of permafrost—the coastline, coastal plain, foothills, and floodplains—and what we can project about how they may change under a warming climate. This chapter also outlines how processes such as fire, vegetation community change, and contaminant mobilization may affect future habitats in the region.

Permafrost-influenced Geomorphic Processes

Coastline

The Beaufort and Chukchi sea coasts are characterized by lagoons with sandy barrier islands, exposed coast with high peat bluffs, deltas, and low-lying drained lake basins that are occasionally flooded by storm surges (Figure 4.1). These dynamic environments are greatly affected by sea ice, wind-driven waves and storm surges, surface water temperatures, coastal erosion and accretion, sedimentation by rivers and eroding coastal bluffs, and long-shore currents.

The Beaufort and Chukchi sea coasts are ice-free for 3–4 months per year, with the open-water period occurring from July–September. By early September, the sea ice retreats to a distance of 300–500 km off Barrow, and 100–300 km off Kaktovik (Jorgenson and Brown 2005). In the past few decades, the length of the ice-free period in the Chukchi and western Beaufort seas has increased dramatically. From the late 1970s to 2006, the ice-free period increased by an average of 50–95 days, depending on the region, with



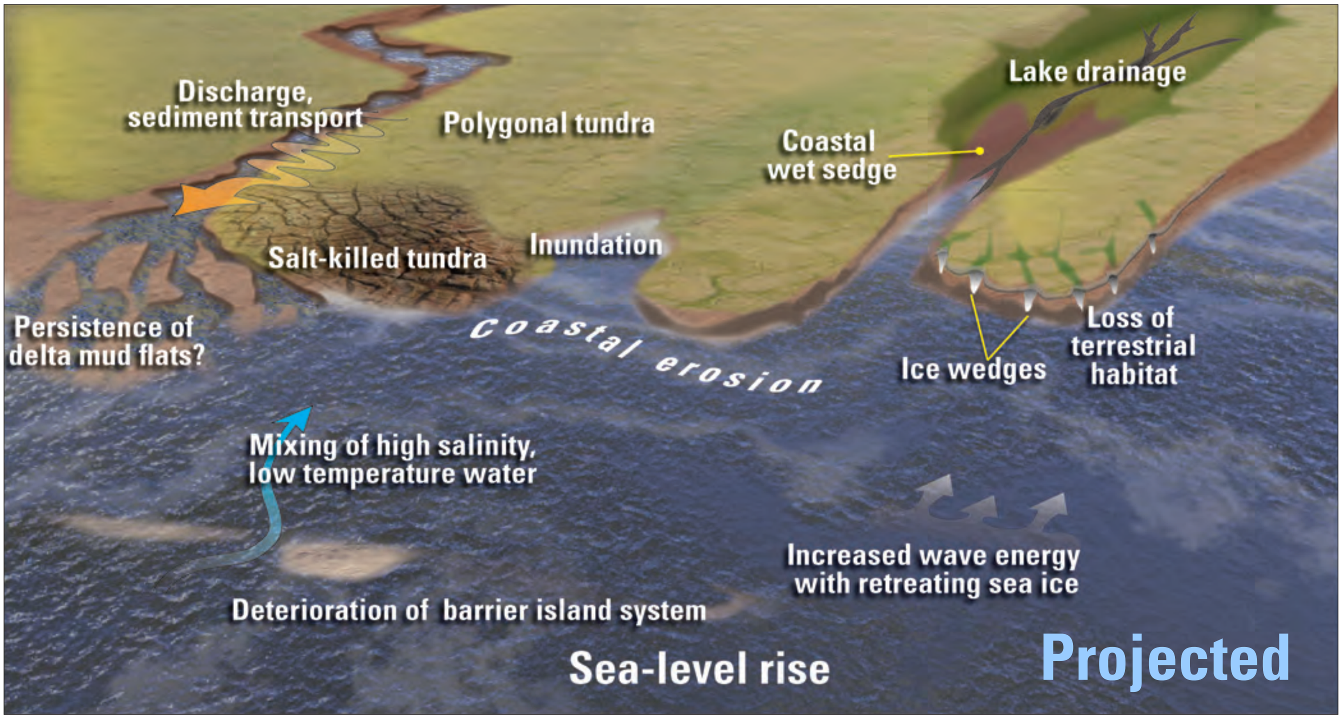


Figure 4.1. Schematic of arctic coastline landscape, current (above) and projected (below). The projected landscape illustrates elements likely to change as a result of climate warming. Figure by R. Mitchell/Inkworks for WildREACH from cited sources.

the greatest increase between Point Lay and Barrow where the ice-free season grew from approximately 30 to 125 days (Rodrigues 2008, unpublished). Arctic sea ice extent reaches its annual minimum at summer's end and has declined at a rate of 11% per decade since 1972 (Richter-Menge et al. 2008). Open-water conditions increase the probability that strong wind conditions will result in a storm surge, because the presence of ice would otherwise inhibit wave formation (Reimnitz and Maurer 1979).

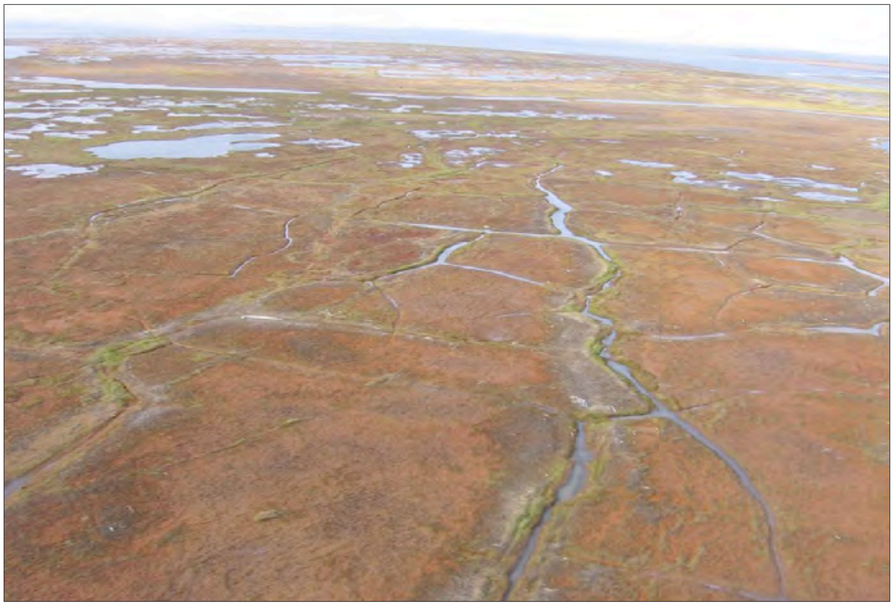


Figure 4.2 (above). The effects of a major storm with strong west winds on Barter Island in August 2008. The undercutting of thermoerosional niches and the collapse of large blocks helps fragment and accelerate the rate of coastal erosion along ice-rich portions of the Beaufort Sea coast. Below the human figure, a cross section of the thin active layer and an ice wedge is clearly visible. Photo by Mitch Osborne, USFWS.
Figure 4.3 (below): Salt-killed tundra is prevalent along low-lying portions of the coast that have been inundated by storm surges. After inundation by salt water, iron staining and a white salt crust at the surface are common. Photo by M.T. Jorgenson.

Sea level rise measured at nine tide stations in Siberia averaged 2–3 mm per year from 1954–2007 (Richter-Menge et al. 2008). Global sea level rise in the period since 1993 is estimated to have occurred at a rate of 3 mm per year, and projections for cumulative rise by the end of the 21st century range from 0.18–0.59 m, but do not account for potential changes in ice flow of the Greenland and Antarctic ice shelves (IPCC 2007). Some researchers believe that accelerated ice sheet melt will result in mean sea level rise exceeding 1 m by the end of this century (http://climatecongress.ku.dk/newsroom/rising_sealevels/, retrieved March 14, 2009).

Sea-surface temperature trends for the Arctic Ocean over the past century are characterized by a period of cooling from 1930–1965, followed by a period of warming, particularly pronounced since 1995 (Steele et al. 2008). Sea-surface temperatures for the Beaufort and Chukchi seas have been especially warm in this decade, e.g. 2–3°C higher in 2007 than the average for the previous 25 years (Richter-Menge et al. 2008).

The combined effect of sea level rise, increased frequency of storm surges, and increased water temperature has already resulted in a substantial increase in erosion rates on the Beaufort Sea coast (Jorgenson and Brown 2005, Jones et al. 2009). Lunar tides along the Beaufort Sea coast are only on the order of 20 cm, but water levels are strongly affected by wind direction, with west winds associated with higher tidal stage (Jorgenson 2009). Strong winds can raise water levels as much as 2 m (Reimnitz and Maurer 1979), and these storm surges can result in very rapid coastline erosion, particularly in sectors characterized by exposed ice-rich peat bluffs. Erosion of ice-rich bluffs involves formation of a thermoerosional niche (Figure 4.2) and subsequent collapse of bluff materials (Reimnitz and Maurer 1979). Unlike coastlines in temperate areas, erosion is affected by thawing as well as mechanical processes. Erosional rates of 1–2 m per year are typical for many sectors of the Beaufort coast, excluding river deltas, where accretion is occurring. The 60-km section north of Teshepuk Lake is retreating much more rapidly, however, with mean annual erosion rates having increased from an average of 6.8 m per year (1955–

1979) to 13.6 m per year (2002–2007). For most shoreline types the rate was even higher—18 m per year—in the most recent period (Jones et al. 2009). If this rate were to remain constant over the next century, a coastal retreat of 1.8 km would be expected, representing a loss of 8% of the Teshekpuk Lake Goose Molting Area (see box 5.1 on page 72).

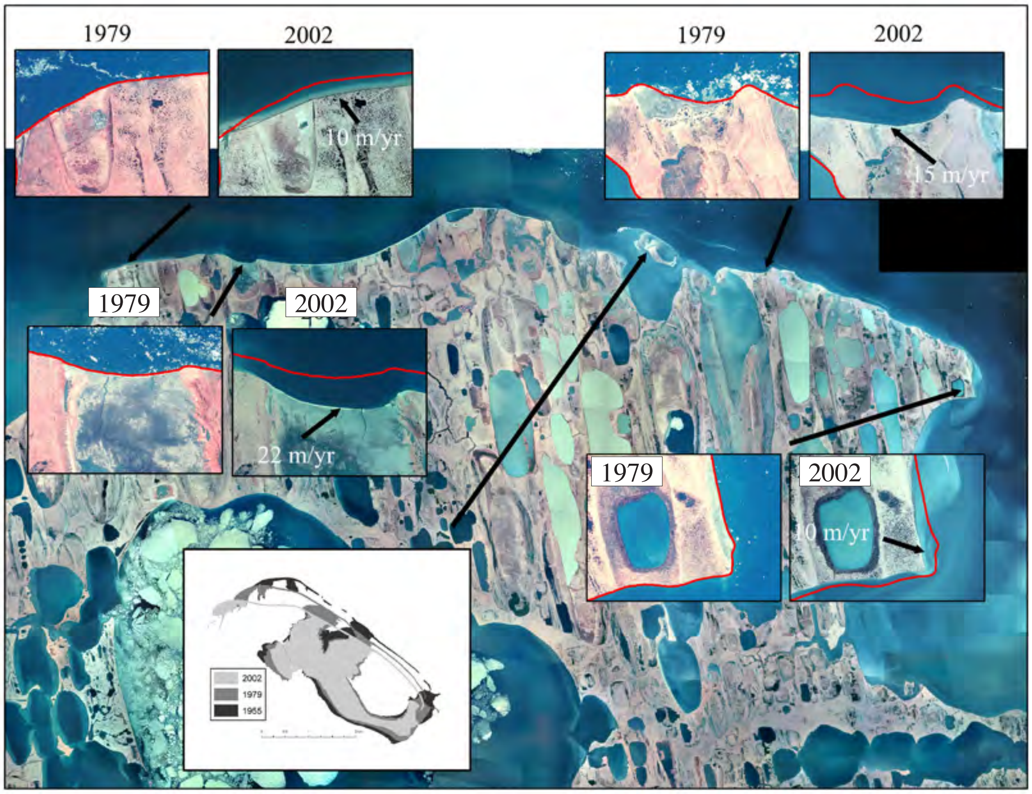
By comparison, the coastal reach between the Colville and Sagavanirktok rivers (within which most of the North Slope oil and gas infrastructure is located) retreated at a historic rate of less than 2 m per year (Jorgenson and Brown 2005). At a hypothetical higher rate of 4 m per year held constant over the next century, the resultant 200 m retreat would represent a loss of less than 1% of the Arctic Coastal Plain terrestrial habitats in this sector.

In addition to accelerating shoreline erosion, increased storm heights accompanied by the projected sea level rise will cause additional flooding and salinization of low-lying terrain. Inundation with salt water may kill the existing vegetation, resulting in relatively barren patches of salt-killed tundra (Figure 4.3). A distinctive coastal wet sedge tundra community characterized by salt tolerant species (e.g., *Puccinellia phryganodes* and *Carex subspathacea*) may develop in wetter areas (Flint et al. 2008). Coastal wet sedge tundra is currently rare, and its future abundance will reflect the equilibrium between loss from erosion and inundation and increase due to colonization in salinized terrain.

The persistence of coastal delta environments depends on the degree to which sedimentation keeps pace with sea level rise. Information on the baseline rates of sedimentation for North Slope rivers is very limited. On the Colville River Delta, a large breakup or precipitation event can result in accumulation of 10 cm or more, and an average nearshore deposition rate of 1 kg/m/year was estimated (Brown and Jorgenson 2005). In general, sediment discharge in arctic rivers is much less than the global average, due to watershed characteristics that include a thin weathering crust, low precipitation, extensive permafrost, low temperatures, wetland-dominated landscape, and low level of human activity (Gordeev 2006). Models predict a 30% increase in sediment load for every 2°C of warming in the drainage basin, and a 10% increase in sediment transport for a 20% increase in discharge (Syvitski 2002, Morehead et al. 2003). Projected increases in temperature and precipitation in arctic Alaska suggest a trend toward increased rates of sedimentation. The increased supply of sediment to river deltas may compensate for, or outpace, the effect of sea level rise.

The barrier island-lagoon system provides important summer feeding habitat and migration corridors for waterfowl and anadromous fish. The barrier islands are believed to be erosional remnants of ancient mainland shores and composed of materials not generally supplied by modern depositional processes (Hopkins and Hartz 1978, Morack and Rogers 1981). Some retain remnant vegetated tundra underlain by permafrost, but most are constructional islands largely devoid of vegetation and in a continual state of migration (westward and towards the mainland) and morphological

Erosion along a segment of the Beaufort Sea coastline based upon vertical aerial photography captured in 1955, 1979, and 2002. Image from B. Jones, USGS.



change. These islands are typically less than 1 m in elevation and no higher than 3 m (Hopkins and Hartz 1978) and, therefore, are subject to overwash during storm events. Storm-associated erosion commonly breaches the islands and splits them into smaller pieces, which may later coalesce due to longshore transport and redeposition of sediments. Ice-push events, during which gravel is dredged and deposited by wind-driven ice floes, may play an important role in maintaining the islands by periodically concentrating materials in a discrete zone.

Preliminary evidence suggests that the Beaufort Sea barrier island system may be disintegrating. For example, Narwhal Island, which is east of Prudhoe Bay, has greatly diminished in surface area since 1955, and the migration rate from 1990–2007 (24 m/yr) greatly exceeds that from 1955–1990 (5 m/yr). Total surface area of barrier islands in the central Beaufort Sea (Colville River to Point Thomson) has decreased approximately 4% from the 1940s to the 2000s, and the rate of change is greater during the period since 1980 (Gibbs et al. 2008). A longer period of open water and increased occurrence of larger waves is at least partially responsible for this acceleration. Ice-push events require the coincidence of strong onshore winds and a high density of broken ice, and this may occur less frequently as sea ice retreats farther offshore in summer. Warming ocean temperatures also may play a role, however, as even the constructional islands may be partially composed of ice-bonded sediments (Morack and Rogers 1981), which inhibit longshore sediment transport (Thomas Ravens and William Lee, University of Alaska Anchorage, personal communication). These trends suggest that the deterioration or disappearance of the existing system of barrier islands is possible over a relatively short period.

The coastline is a dynamic environment subject to continual change. Climate change may affect the equilibrium among various coastal processes, however, and result in a net change in habitat availability. The linkages among coastal processes, as affected by temperature and precipitation changes, are illustrated in a conceptual model (Figure 4.4).

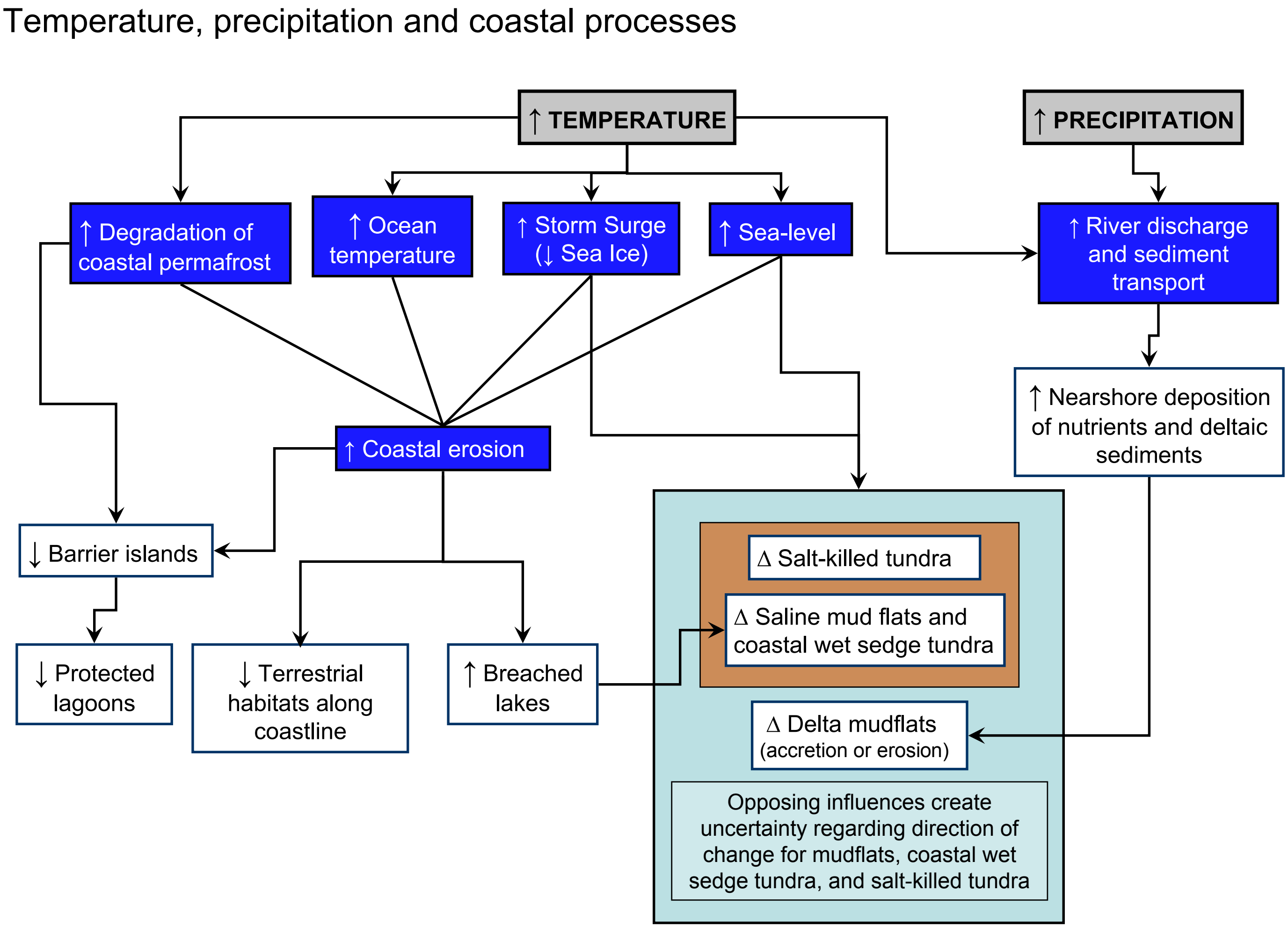


Figure 4.4. Conceptual model illustrating linkages between physical processes and coastal habitat. Grey boxes identify climate drivers, blue boxes indicate physical processes, and white boxes indicate landscape responses. The light-blue box contains habitats for which we are less certain of the direction of the habitat change.

Arctic Coastal Plain

Regional differences in the distribution of late-Pleistocene surficial deposits (Figure 4.5) strongly influence the presence and characteristics of lake basins. Ice-rich deposits, such as delta and glacio-marine deposits, are associated with abundant thaw lakes and drained basins. Lakes in ice-poor deposits, such as eolian sand and slightly pebbly till, formed in low-lying swales during the early Holocene and expanded through erosion of fine-grained sediments (Jorgenson and Shur 2007) because the volume of ground ice was insufficient to allow thaw lake development.

The development and expansion of a drainage network during the Holocene has resulted in drainage of many large lakes, particularly over the past 5,000 years (Hinkel et al. 2003, Jorgenson and Shur 2007). Lake drainage may be triggered by a variety of processes, such as ice wedge erosion, headward stream erosion, tapping, bank overflow, or coastal erosion. Once lakes are drained, the relatively warm water in deep waterbodies that promotes talik formation is lost, and the exposed sediments are once again subject to permafrost aggradation. The sandy margins tend to aggrade little ice, while ice segregation and ice wedge development in the organic-rich silty centers is prevalent. This differential ice accumulation typically causes the drained centers to dome up and shift water to the lower lying sandy margins. Small ponds created by this hydrologic shift are abundant around the margins. These typically fill in with limnic sediments in the center and sedge peat around the margins. Stabilization of a drained lake basin and re-establishment of polygonal terrain is a process that may take centuries to millennia (Jorgenson and Shur 2007).

The response of Coastal Plain deposits to a warmer and wetter environment is expected to have a dramatic effect on the stability of ice wedges accompanied by redistribution of water on the landscape. Because ice wedges are formed just below the active layer and are in close equilibrium with the existing climate, an abrupt warming will cause nearly all ice wedges to degrade (Box 4.1, Figure 4.6). The redistribution of water, however, will depend on whether the site is a water-shedding slope or a water-gathering basin.

In low-lying basins, the water of deep lakes and shallow ponds will be fully recharged by spring snow melt with excess water running off, assuming constant or increased winter precipitation. Under a warming scenario where summer precipitation is insufficient to compensate for increased evapotranspiration, deeper midsummer draw-down may be expected in lakes and ponds, but water levels should increase again with fall rains and spring melt in the following year. Shallow ponds and wet sedge meadows, which are dependent on direct precipitation for water input, would be most sensitive to a negative shift in water balance; if drier summer conditions become prevalent, desiccation of these wetlands may occur (Smol and Douglas 2007).

Effects of ice wedge thawing are already evident on the Arctic Coastal Plain. A large increase in both area and density of degrading ice wedges has been observed in study areas near the Colville River Delta (Jorgenson et al. 2006). The accelerated thermokarst degradation, probably associated with record

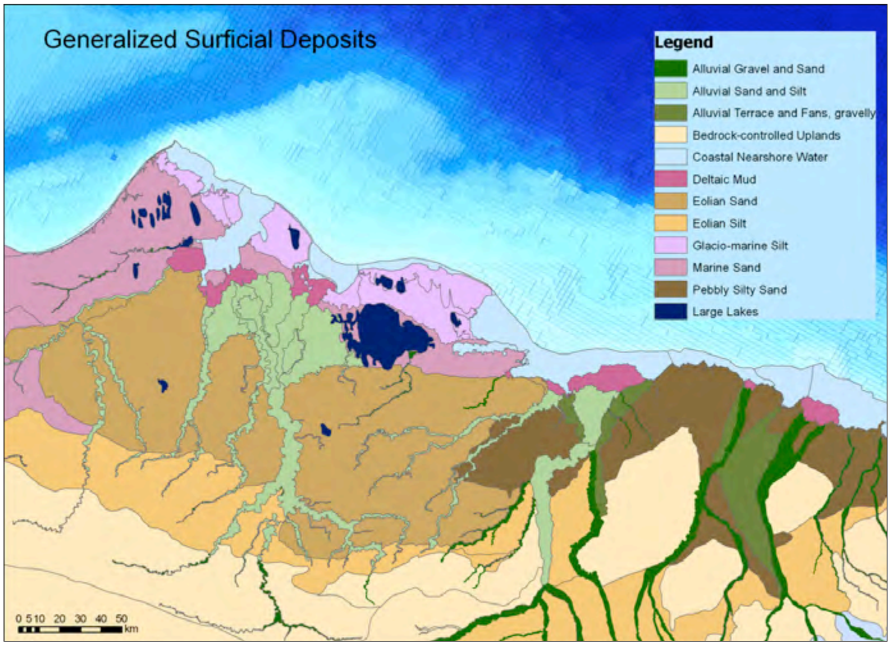


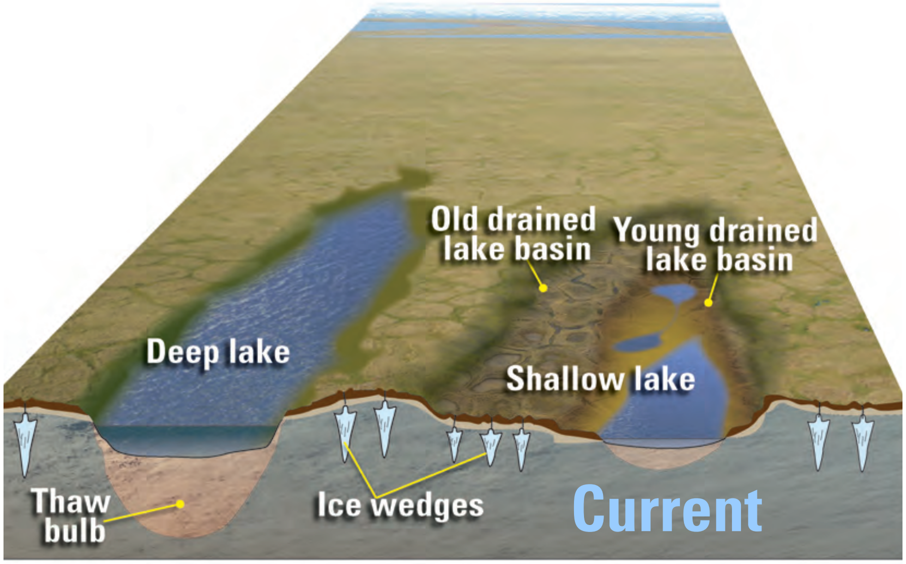
Figure 4.5. Regional differences in the distribution of surficial deposits, all of late Pleistocene origin, are a reflection of various past processes. The coastal areas are characterized by glaciomarine pebbly silt, glacial deposition of slightly pebbly silty sand from a northern ice sheet, and deposition of marine sand by marine transgression. The western portion of the Arctic Coastal Plain is covered by an eolian sand. The lower portion of the Arctic Foothills is blanketed by thick loess (silt). The upper Foothills are underlain by bedrock near the surface; ridges typically have rocky residual soils, slopes are mantled with organic-rich colluvium (accumulations of sediment transported downslope by gravity), and basins are filled with organic-rich fine-grained colluvium. From Jorgenson et al. 2009.

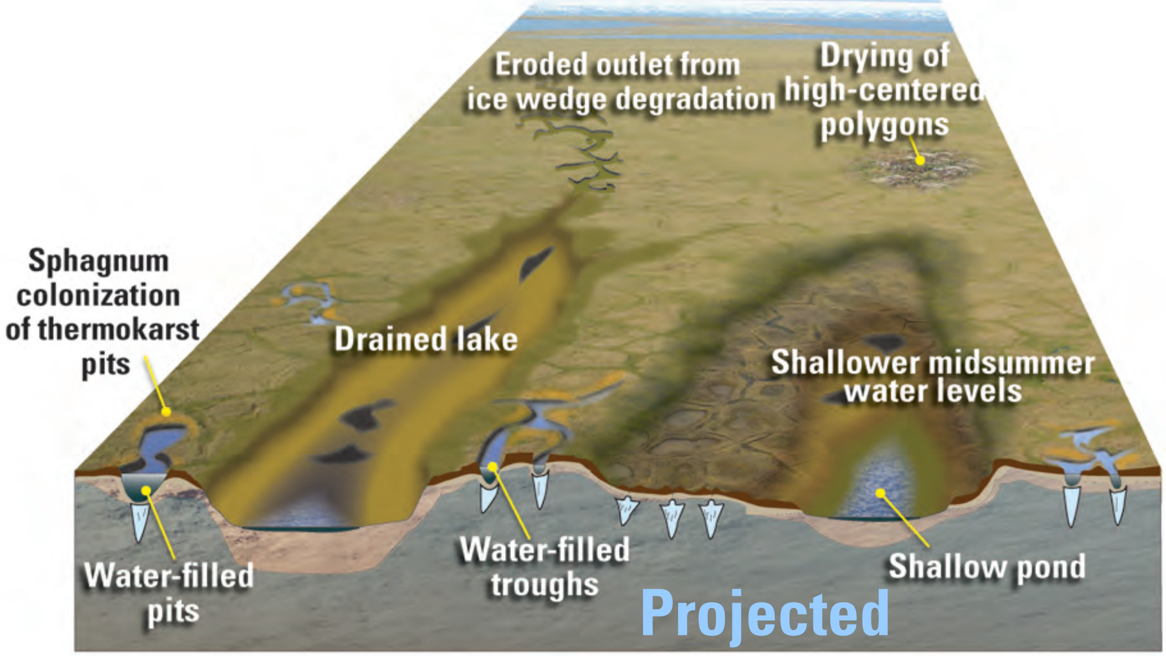
warm temperatures from 1989–1998, has resulted in a deepening network of water-filled thermokarst troughs and pits and drying polygon centers. Based on the general distribution of ice-rich soils, surface changes of this type could potentially affect 10–30% of arctic lowland landscapes.

Thermokarst lakes within the lower latitude zone of discontinuous permafrost may drain as a result of a deepening talik that completely penetrates the permafrost, as documented on Alaska's Seward Peninsula (Yoshikawa and Hinzman 2003). On the North Slope, however, continuous deep permafrost would preclude this mechanism. In continuous permafrost environments, studies have concluded that the surface area of large lakes is either stable to increasing (Smith et al. 2005, Riordan et al. 2006, Mars and Houseknecht 2007) or too sensitive to short-term variability in precipitation regime to allow detection of a long-term trend (Plug et al. 2008). Large, deep lakes are expected to continue to expand in surface area, due to shoreline erosion by wind-driven waves and lake expansion from thermokarst. Erosion rates averaged 0.08 m/yr for large (>20 ha), deep (>1.5 m) lakes at three study sites on the Coastal Plain west of the Colville River Delta (Jorgenson et al. 2003), while shorelines of small or shallow (≤1.5 m) lakes eroded at rates averaging <0.04 m/yr. Based on extrapolation from Jorgenson et al. (2003), the increment in lake area due to expansion may comprise ~1–3% of the landscape by the end of the century, although this underestimates the effect if rates of lake expansion increase significantly due to a longer ice-free season and warmer water.

Most drained lake basins formed during a period of extensive drainage during the mid-Holocene (Jorgenson and Shur 2007) and contemporary lake drainage is uncommon. With expected warming, however, degrading ice wedges may progressively integrate into drainage channels with a lower base elevation resulting in increased frequency of lake-tapping (sudden drainage) events. Where ice-rich soils and a topographic gradient exist (e.g., adjacent to a stream or the coast), sequential lake tapping could occur (McGraw 2008).

Figure 4.6. Schematic of Arctic Coastal Plain landscape, current (above) and projected (below). The projected landscape illustrates elements likely to change as a result of climate warming. Figure by R. Mitchell/Inkworks for WildREACH from cited sources.



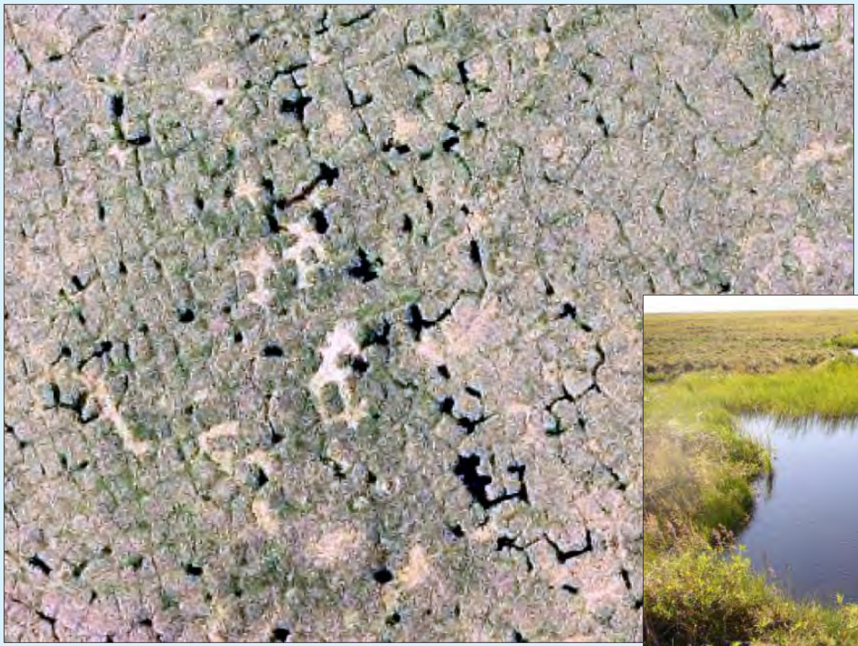


Box 4.1. Permafrost Degradation

The susceptibility of arctic landscapes to thermokarst processes depends on ground ice content, and this varies according to the surficial geology and geomorphic setting. Ground ice may occur as segregated ice (smaller stuctures interspersed within the permafrost) or massive bodies such as ice wedges, and the relative abundance of each type affects how the surface will respond to warming, at both the landscape scale and over distances of a few meters. On the Arctic Coastal Plain, mean segregated ice volume in the upper 2 m ranged from 45% in inactive sand dunes to 71% in alluvial-marine deposits (Jorgenson et al. 1998, 2003). The mean volume of ice wedges in the upper 2 m varied from less than 1% in ice-poor margins of lakes to a high of 33% in ice-rich lake centers (Jorgenson and Shur 2007). Understanding how the type and amount of ground ice varies across the landscape is essential to forecasting how habitats may change in response to warming temperatures.

Above: This polygonal terrain is located in the Niguanak Lowlands on the coastal plain of the Arctic National Wildlife Refuge. The bright green polygon troughs are associated with the reticulate-patterned network of subterranean ice wedges. The wet troughs support lush sedge vegetation, in contrast to the drier polygon centers. Photo by M.T. Jorgenson.

Ice wedges, with top surfaces located just 30-40 cm beneath the surface, are particularly sensitive to warming air temperatures (Jorgenson et al. 2006). Melting of the tundra surface results in varying amounts of ground settlement, with ice wedges melting faster than the intervening polygon centers. The subsiding surface overlying the melting ice wedges forms water-filled troughs with deeper pools at the intersections (see photos). As the trough system develops and deepens, a steeper drainage gradient redistributes water from broad polygon centers into narrow, deep troughs. The landscape may shift from a more uniform mesic state to one of alternating patches of dry polygon centers and flooded troughs. In settings with sufficient topographic gradient, which occur commonly in the transitions from upland ridges to lake basins and floodplains, deepening troughs can develop into a drainage network that promotes runoff, lowers the water table, and results in more widespread drying. In contrast to the upland setting, ice wedge degradation in topographic basins will create more capacity for water storage but should have little effect on water levels.



Left: Aerial view of polygonal pools formed by ice wedge degradation west of the Colville River Delta. Below: Ground level view of the same location. Both photos by M.T. Jorgenson.

Arctic Foothills

The upland ecosystems of the Arctic Foothills have three major distinctive geomorphic environments: 1) rocky residual soils on ridges, 2) gentle slopes mantled with ice- and organic-rich colluvium (material deposited at slope-bottom by gravity) over bedrock, and 3) Pleistocene loess on the lower Foothills (Figure 4.7). Response of each Foothills terrain condition is discussed separately below.

The rocky residual soils are well-drained, have deep active layers, and are relatively thaw stable. Rocky ridges probably will undergo little geomorphic change under a warmer and wetter climate. The soils will remain well drained and thaw stable. The active layer will likely increase and taliks may develop on some south-facing slopes, but this will have little effect on surface hydrology. Under drying conditions, little change is expected.

The colluvium-mantled hillsides are likely to be very sensitive to climate warming. The soils on colluvium, typical of mid- to lower slopes, tend to be highly organic, saturated, and have abundant ice wedges and segregated ice near the permafrost table. Because the active layer is underlain by ice-rich permafrost, thaw slumps are likely to become abundant on the sloping surfaces (Gooseff et al. 2009). The slumping will create new thaw lakes, expose new soil to plant colonization, and increase sediment transport in runoff (Figure 4.7). Gullies are likely to become common where water flow through ice wedge networks causes the ground surface to collapse. The gullies then contribute to channelization of flow and drying of lakes and intervening ridges. In some areas, water tracks may deepen without deeper gully formation but still serve to channel suprapermafrost groundwater flow. On very gentle slopes, ice wedges are likely to degrade without prominent gully formation.

Landscapes characterized by the presence of extremely ice-rich loess (yedoma) of late Pleistocene origin are highly sensitive to warming and have the potential for drastic change.

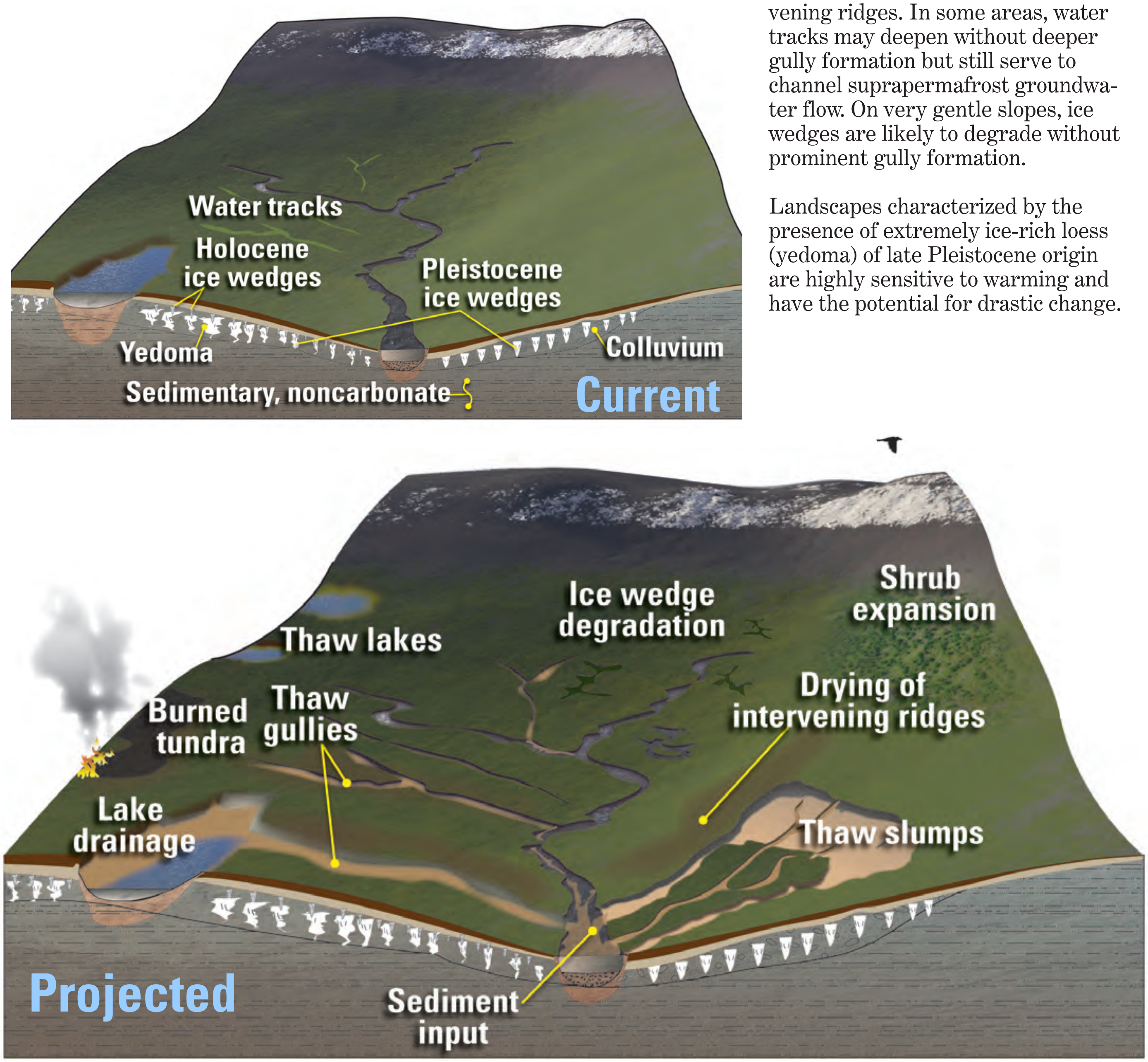


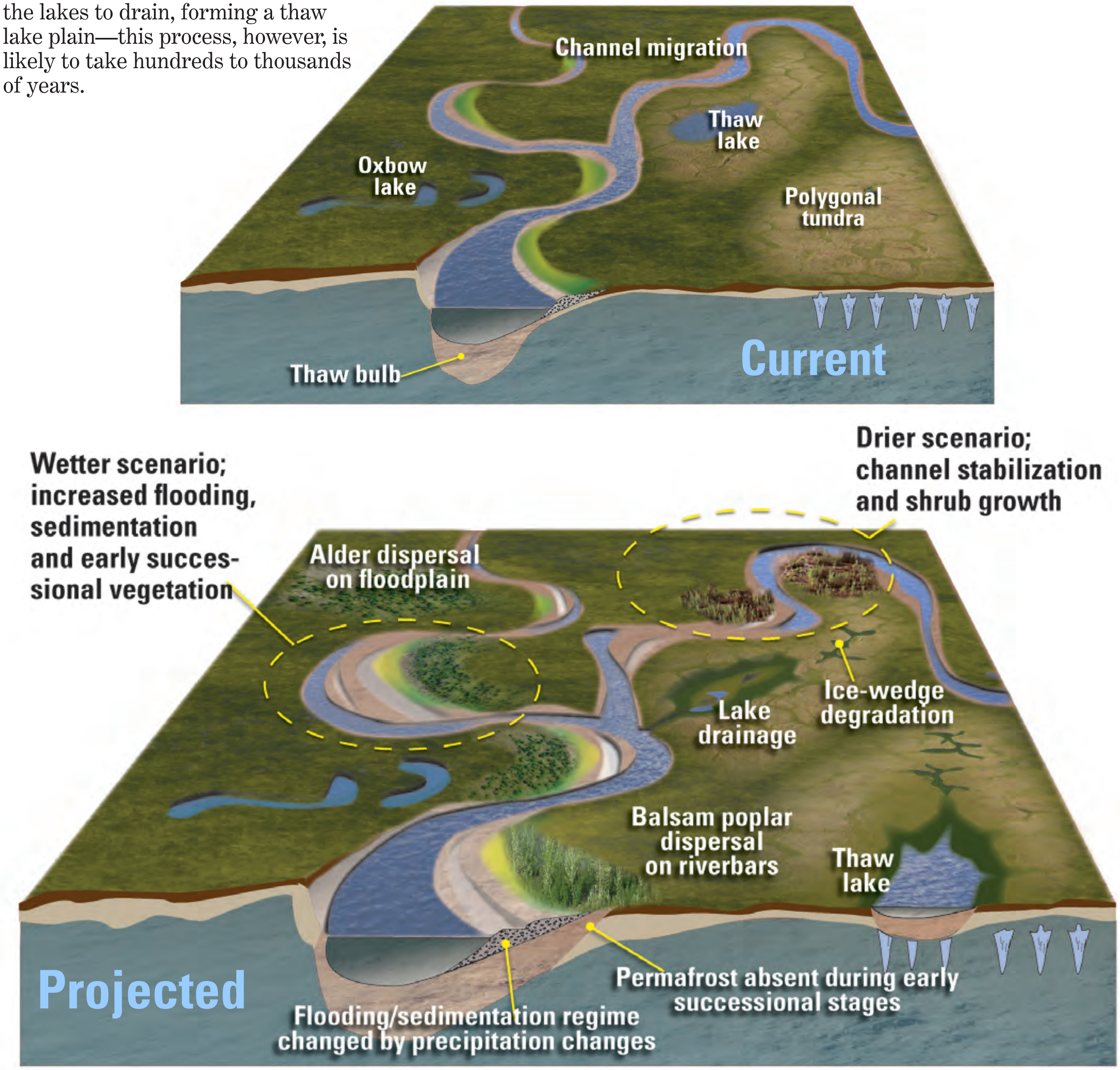
Figure 4.7. Schematic of Arctic Foothills landscape, current (above) and projected (below). The projected landscape illustrates elements likely to change as a result of climate warming. Figure by R. Mitchell/ Inkworks for WildREACH from cited sources.

Yedoma is abundant across the lower foothills and may occupy roughly 20% of the overall foothills landscape (Carter 1988). In this type of terrain, masses of ice can extend to depths of up to 30 m (Carter 1988). Along the lower Colville River, the yedoma has only 0.5–1 m of soil covering 10–25 m of ice. Because of the massive ice, deep thermokarst lakes are common on this terrain. The degraded yedoma landscape of the Seward Peninsula may provide a good analog of how the arctic landscape could be altered by widespread ice degradation. First, thermokarst develops in the network of shallow Holocene ice wedges near the surface of the permafrost. Next, the thermokarst troughs and pits expand into thermokarst ponds and lakes that thaw into the underlying massive ice. Finally, expansion of the thermokarst lakes and drainage networks causes the lakes to drain, forming a thaw lake plain—this process, however, is likely to take hundreds to thousands of years.

Floodplains

Floodplains are active geomorphic environments because of sedimentation caused by flooding, erosion caused by channel migration, and deposition of wind-blown sand from barren river bars (Figure 4.8). The varying flooding regime creates a sequence of deposits that include massive or crossbedded sand in the active channel; rippled interbedded sands and fine-grained material (fines) with distinctive detrital organics that are the remains of peat banks eroded upstream; layered fines caused by vertical accretion of silts during overbank flooding; layered organics and silts created by the accumulation of organic matter between infrequent flooding events; and massive organics that accumulate on higher floodplains that are rarely flooded (Shur and Jorgenson

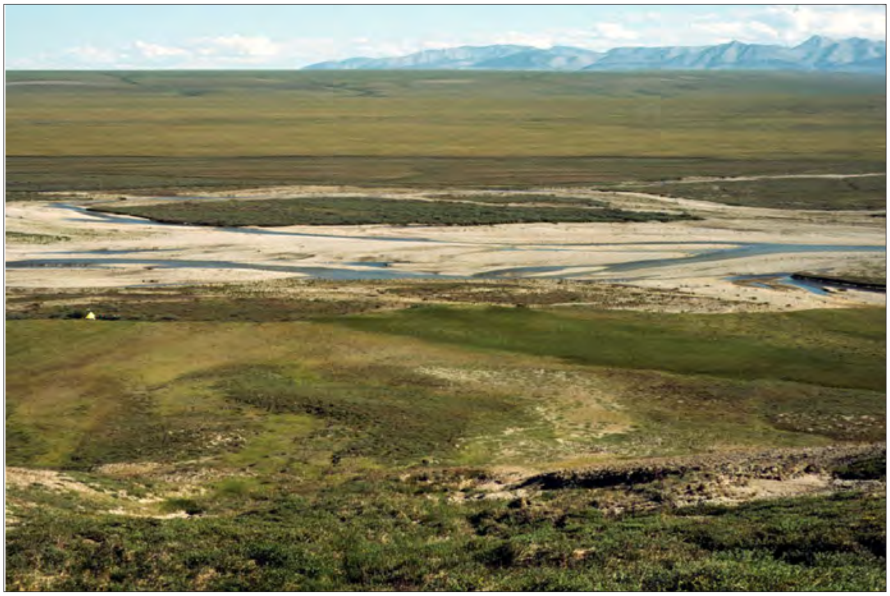
Figure 4.8. Schematic of arctic floodplain landscape, current (above) and projected (below). The projected landscape illustrates elements likely to change as a result of climate warming. Figure by R. Mitchell/Inkworks for WildREACH from cited sources.



1998). During floodplain evolution, the deposits are modified by the aggradation of segregated and wedge ice, which deforms the surface, affects water runoff, and increases the susceptibility of older terrain to thermokarst. These deposits support a successional sequence of ecotypes from river to riverine barrens, tall shrub, low shrub, dwarf shrub, and wet sedge meadows. Riverine ecosystems are not abundant, comprising ~8% of the Coastal Plain and ~4% of the Foothills. They are highly productive ecosystems, however, serving as conduits of water, sediments, and nutrients, and are used by a wide range of species.

Riverine ecosystems could respond to climate change in a variety of ways depending on the amount of warming and the balance between evapotranspiration and precipitation. In response to warming, permafrost aggradation will be retarded in the barren portions of active floodplains, and degradation will be accelerated on the inactive and abandoned floodplains. Ice wedges formed in the later stages of floodplain development will degrade, thus lowering the water table and instigating formation of drainage networks that will accelerate drainage of riverine lakes. The consequences of altered precipitation (amount, seasonality, and frequency of extreme events), discharge, flooding, sedimentation, and erosion are more uncertain. Many of these processes are more sensitive to extreme events rather than to average conditions. A scenario of increased precipitation will be accompanied by increased flooding, sedimentation, and erosion. This, in turn, should favor more productive early successional ecosystems. In contrast, decreased runoff associated with drying during midsummer may lead to increased channel stability and increased shrub growth on the stabilized active floodplain.

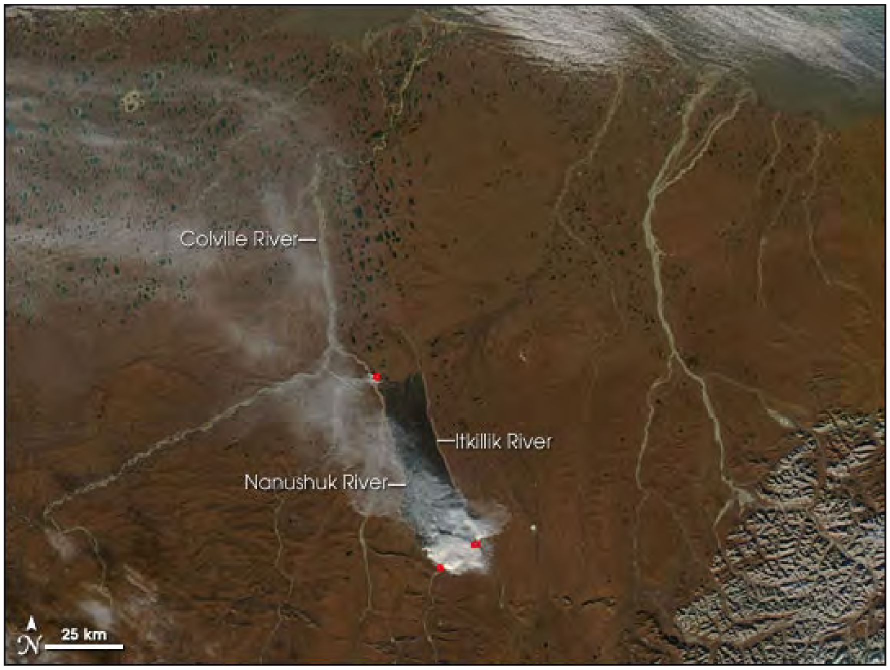
Floodplain lakes include oxbow and thaw lakes. These lakes are important to fish and bird species and play an important role in trapping sediments and the biogeochemical processing of water before it is discharged to the ocean. Fish access, as well as nutrient status, is related to the degree of connectivity with river systems, the duration of which can vary from constant (all summer) to a transitory connection limited to high-water events (especially spring flood). For example, when flow from upstream snow melt begins before the onset of melt downstream, ice dams may spread water over vast areas in arctic river deltas, reconnecting and recharging lakes. In the MacKenzie River Delta, the degree to which lakes are connected depends on their distance from the nearest active channel and elevation. During low-water years, associated with decreased ice-dam flooding, lakes greater than 4 m above sea level are not recharged or connected to riverine source waters (Lesack and Marsh 2007). If changes in freeze-thaw cycles cause years with little ice-damming to become more frequent, these lakes may dry, sediment transport to river deltas may increase, and biogeochemistry of river water discharged to the ocean may be altered.



Above: A male Wilson's warbler (Wilsonia pusilla) *singing during the breeding season. Songbird species may move into expanded shrub habitats if active arctic floodplains stabilize in drier summers. Photo by Ted Swem, USFWS. Below: The floodplain of the Katakturuk River in the Arctic National Wildlife Refuge shows the effects of past flooding and erosion events on the vegetation community. USFWS photo.*

Historically, tundra fires have been rare on the North Slope, with only 10 known occurrences north of 69°N from 1956 to 2007 (Racine and Jandt 2008). In the fall of 2007, however, coinciding with an anomalously warm and dry season, a 1,000 km^2 area burned between the Itkillik and Nanushuk rivers in the central Arctic Foothills; this is the largest North Slope fire on record (Racine and Jandt 2008). This event underscores the potential for more frequent, larger tundra fires under a climate scenario of warmer, drier summers. A severe fire reduces surface albedo and combusts the insulating surface organic layer, increasing soil thermal conductivity and heat flow into the ground (Yoshikawa et al. 2002). Post-fire soil moisture increases in the short term (Liljedahl et al. 2007), which also increases soil thermal conductivity and promotes warming. Soil warming is accompanied by at least a temporary thickening of the active layer and, if the soils are ice-rich, can stimulate thermokarst. In some settings, long-term change in active layer thickness and a change in vegetation community (decreased moss cover and increased shrub cover) ensues, reinforcing a shift toward warmer, drier near-surface soils (Yoshikawa et al. 2002). On the Seward Peninsula, active layer thickness diminished to pre-fire levels within a few decades on flatter terrain, but a thickened active layer persisted on steeper slopes (Racine et al. 2004). The post-fire warming and drying on slopes promoted a shift to willow shrub vegetation on the steeper slopes, but tussock sedge recovered well on the poorly drained sites. *Sphagnum* moss and lichen failed to recover after 24 years, except for *Sphagnum* in a wet meadow site (Racine et al. 2004).

Fire frequency on the Seward Peninsula is greater than that on the North Slope (Racine and Jandt 2008). The two regions are similar, however, with respect to frequency of lightning strikes (http://geology.com/articles/lightning-map.shtml, retrieved April 2009) and vegetation. Differing soil moisture, therefore, most likely accounts for the difference in fire frequency. In Barrow, under near-average summer conditions, polygon rims and troughs remained >80% saturated after late June (Liljedahl et al. 2009). The water table on tussock tundra hillsides in the upper Kuparuk River watershed typically remains within 10 cm of the ground surface (Hinzman et. al. 1993), whereas soils at 10 cm depth at a Seward Peninsula tussock site declined to ~40% saturated after the spring peak (Liljedahl et al. 2007). Predicting the future North Slope fire regime, therefore, is closely linked with projection of summer water balance.



The Anaktuvuk Fire ignited on July 16, 2007, and burned until early October. This MODIS satellite image was obtained on September 25, 2007, and the red dots indicate areas still burning on that date (NASA, http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=19139&oldid=14550).

Vegetation

Current Vegetation Communities

The North Slope of Alaska comprises less than 3% of the circumpolar arctic region mapped by the CAVM Team (2003) but contains 26% of the area classified as sedge, moss, dwarf-shrub wetland, primarily on the Coastal Plain, and 24% of the area classified as tussock-sedge, dwarf-shrub, moss tundra, mostly in the Foothills (Figure 4.9). Ecoregional differences in vegetation reflect differences in climate, topography, and parent material (Table 4.1, Figure 4.9, 4.10, Appendix 2).

The Coastal Plain landscape is a mosaic of low-lying lacustrine (lake-related) basins separated by intervening higher terrain. Lacustrine ecosystems include deep (>1.5 m) lakes, shallow (<1.5 m) lakes and ponds, lacustrine grass marsh (dominated by *Arctophila fulva* in water >0.3 m deep), lacustrine sedge marsh (*Carex aquatilis* and *Eriophorum angustifolium* in water 0.1–0.3 m deep), and lacustrine wet sedge tundra (*C. aquatilis*, *E. angustifolium*, forbs and mosses in water <0.1 m deep). The older, higher terrain between basins also supports lowland wet sedge tundra in swales, lowland moist sedge-shrub tundra on lower slopes, and upland tussock tundra on upper slopes and gentle ridges. Prostrate willows and *Dryas* (a small flowering shrub) occur on moist sedge-shrub tundra, but typically comprise <35% cover.

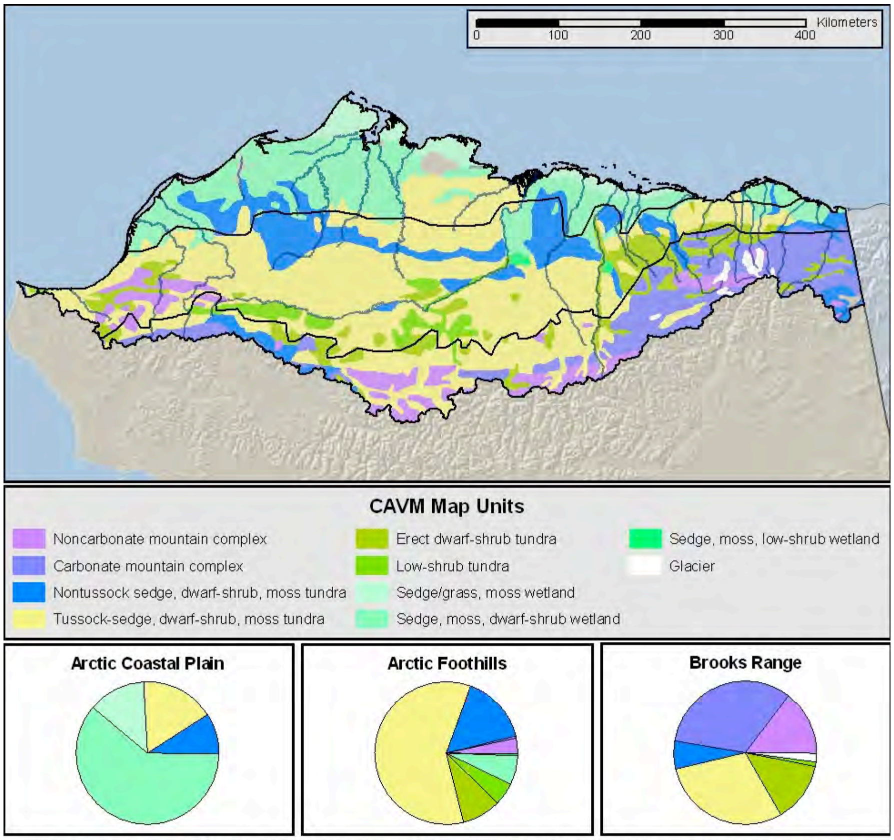


Figure 4.9 (left). Vegetation of arctic Alaska based on the Circumpolar Arctic Vegetation Map (CAVM 2003). Map by FWS, based on CAVM data. Available online at http://data.arcticatlas.org/geodata/circumpolar/cavm/.

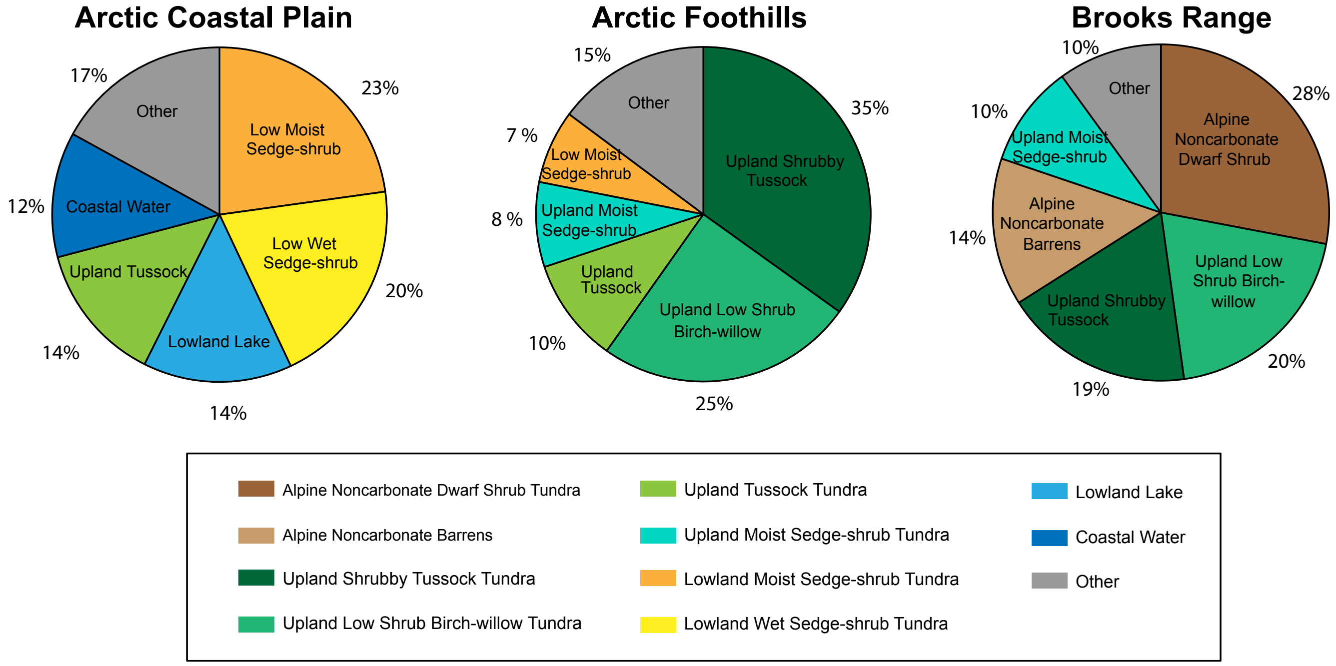


Figure 4.10. Distribution of ecotypes among ecoregions of the North Slope, after Jorgenson and Heiner 2003.

Uplands in the Foothills are characterized by shrub-dominated vegetation. Dominant ecotypes include upland *Dryas* and ericaceous dwarf shrub on dry rocky ridges, upland low birch-willow shrub (*Betula nana, Salix. planifolia, S. glauca*) on better drained soils, upland shrubby tussock tundra (*B. nana, S. planifolia, E. vaginatum*) and upland tussock tundra (*E. vaginatum*) on saturated organic-rich soils, and upland moist sedge-shrub tundra (*C. bigelowii, D. integrifolia*) on circum-alkaline soils. Less common are lowland wet sedge tundra and lowland low birch-willow shrub in swales, toe-slopes, and basins.

Upland tall alder shrub occurs on mid- to upper slopes of the Brooks Range but is <1% of the landscape. Tall alder-willow shrub occurs in riverine settings in both the Foothills and the Brooks Range, but is <0.1% of the landscape in either ecoregion.

Table 4.1 Distribution of ecotypes[1] among ecoregions of the North Slope. More abundant (>5% of area) ecotypes are highlighted in bright yellow.

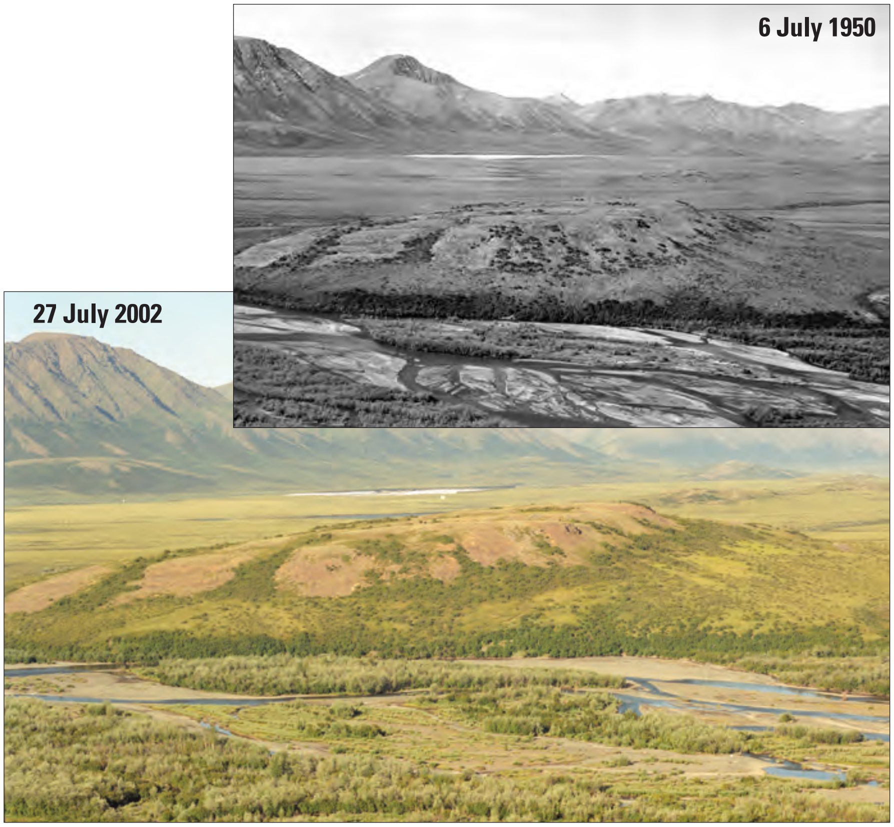
Ecotype	Coastal Plain		Foothills		Brooks Range		North Slope (total area)	
	Area (km²)	%	Area (km²)	%	Area (km²)	%	Area (km²)	%
Coastal Barrens	507.7	0.9	9.5	0.0	0.0	0.0	517.2	0.2
Coastal Wet Sedge Tundra	1253.8	2.3	40.9	0.0	0.0	0.0	1294.7	0.6
Coastal Water	6741.6	12.1	301.4	0.3	0.0	0.0	7043.0	3.4
Coastal Grass and Dwarf Shrub Tundra	1320.0	2.4	79.2	0.1	0.0	0.0	1399.2	0.7
Riverine Barrens	548.4	1.0	921.1	1.0	228.3	0.4	1697.8	0.8
Riverine Willow Shrub Tundra	75.9	0.1	920.9	1.0	146.9	0.3	1143.7	0.5
Riverine Moist Sedge-Shrub Tundra	1374.4	2.5	2948.2	3.1	579.5	1.0	4902.1	2.3
Riverine Wet Sedge Tundra	951.3	1.7	914.4	1.0	135.3	0.2	2000.9	1.0
Riverine Waters	554.2	1.0	610.9	0.6	132.1	0.2	1297.2	0.6
Riverine Dryas Dwarf Shrub Tundra	0.0	0.0	4.8	0.0	270.2	0.5	275.0	0.1
Riverine Spruce Forest	0.0	0.0	0.0	0.0	1.8	0.0	1.8	0.0
Lowland Wet Sedge Tundra	11239.0	20.2	3511.4	3.7	643.6	1.1	15394.0	7.4
Lowland Lake	7983.2	14.4	1665.3	1.7	246.3	0.4	9894.9	4.7
Lowland Moist Sedge-Shrub Tundra	12671.0	22.8	6923.7	7.2	0.0	0.0	19595.5	9.4
Lowland Low Birch-Willow Shrub	683.2	1.2	1293.7	1.4	297.6	0.5	2274.6	1.1
Lowland Spruce Forest	0.0	0.0	0.0	0.0	11.5	0.0	11.5	0.0
Upland Tussock Tundra	7480.6	13.5	9682.7	10.1	0.0	0.0	17163.7	8.2
Upland Dryas Dwarf Shrub Tundra	891.5	1.6	551.7	0.6	1089.5	1.9	2532.9	1.2
Upland Shrubby Tussock Tundra	17.6	0.0	33469.3	34.9	10448.6	18.2	43938.2	21.0
Upland Low Shrub Birch-Willow Tundra	1199.5	2.2	23831.6	24.9	11357.8	19.8	36390.4	17.4
Upland Moist Sedge-Shrub Tundra	18.1	0.0	7869.5	8.2	5621.5	9.8	13510.1	6.5
Upland Tall Alder Shrub	0.0	0.0	0.0	0.0	211.8	0.4	211.8	0.1
Upland Spruce Forest	0.0	0.0	0.4	0.0	41.2	0.1	41.6	0.0
Alpine Glaciers	0.0	0.0	0.0	0.0	198.6	0.3	198.6	0.1
Alpine Non-carbonate Barrens	0.0	0.0	62.7	0.1	8133.0	14.2	8195.8	3.9
Alpine Carbonate Barrens	0.0	0.0	0.0	0.0	103.2	0.2	103.2	0.0
Alpine Mafic Barrens	0.0	0.0	0.0	0.0	103.1	0.2	103.1	0.0
Alpine Non-carbonate Dwarf Shrub Tundra	0.0	0.0	51.5	0.1	16060.3	28.0	16112.0	7.7
Alpine Carbonate Dwarf Shrub Tundra	0.0	0.0	0.0	0.0	129.5	0.2	129.5	0.1
Alpine Mafic Dwarf Shrub Tundra	0.0	0.0	0.0	0.0	185.4	0.3	185.4	0.1
Riverine Alder-Willow Shrub	0.0	0.0	0.0	0.0	2.0	0.0	2.0	0.0
Cloud, Snow, and Ice	5.4	0.0	123.7	0.1	1071.7	1.9	1200.8	0.6
Total	**55516.4**	**26.6**	**95788.7**	**45.9**	**57450.1**	**27.5**	**208762.5**	**100**

1. Source: Jorgenson and Heiner (2003).

Projected Changes in Vegetation Communities

Treeline

The Arctic Climate Impact Assessment (ACIA 2005, p. 332) predicted very likely replacement of tundra by forest, and some continent-scale biome shift models predict that a taiga environment will replace North Slope tundra by the year 2100 (Gonzalez et al. 2005). Although northward shift of the spruce treeline has been observed (Lloyd et al. 2002), modeling studies focused on the Alaska forest-tundra ecotone predict that a shift from upland tundra to spruce forest (5% tree cover) would take >150 years (Chapin and Starfield 1997, Rupp et al. 2000a). Furthermore, the position of the Brooks Range coincides with the latitudinal treeline and is expected to pose a significant topographic barrier to forest establishment on the Alaska North Slope (Rupp et al. 2000b). Conversion of North Slope tundra to spruce forest is therefore considered an unlikely scenario within the century time frame.



A systematic comparison of photos of Alaska's North Slope taken in the mid-20th century with recent photos of the same locations reveals an increase in shrub vegetation over time (Sturm et al. 2001). In 2002, alder shrubs cover more of the landscape along the Nimiuktuk River, a tributary of the western Noatak River, compared to conditions in 1950. The vegetation of the western Brooks Range and North Slope appears to be responding to changes in climate, with implications for surface energy exchange and carbon flux. Photos courtesy of Ken Tape.

Patches of balsam poplar forest occur in scattered locations across the northern Brooks Range and Foothills, in floodplain settings with year-round groundwater flow (Bockheim et al. 2003). They also occur in numerous small patches on floodplains and hillsides in northwestern Alaska where mean annual air temperatures are -6 to -8 °C (Jorgenson et al. 2004). Because these trees release highly mobile wind-dispersed seeds and are adapted to growing on well-drained, early successional habitats, balsam poplar should be able to rapidly advance down floodplains across arctic Alaska in response to warming temperatures.

Shrub Expansion

Shrubs can have dramatic effects on local microclimates and may provide a positive feedback that contributes to global warming (Sturm et al. 2001, Pomeroy et al. 2006). Shrubs trap snow and can increase winter soil temperatures, and the snow cover change can affect the timing and magnitude of all surface energy balance components during the melt and increase runoff late in the snowmelt period (Liston et al. 2002).

Within the Brooks Range and Foothills, an expansion of shrub tundra into areas formerly dominated by sedge is evident over the time scale of a half century. Increased abundance of alder, willow, and dwarf birch is detectable via comparison of historical oblique aerial photos (1940s) with modern photography (Sturm et al. 2001, Stow et al. 2004, Tape et al. 2006). The study sites are located in the Brooks Range and Arctic Foothills, primarily in the Colville River watershed. Expansion of alder is most conspicuous in the photographs, but field observations confirm that willow and shrub birch cover has increased as well. These results pertain mainly to hill slopes and valley bottoms.

Vegetation on the broad interfluve areas of the Foothills is primarily tussock-shrub tundra, with the tussock-forming sedge *Eriophorum vaginatum* codominant with low shrubs, principally dwarf birch *Betula nana* and willow *Salix pulchra*. Plot experiments conducted at Toolik Field Station suggest that relative cover and canopy height of shrubs (principally *B. nana*) will increase under conditions of warmer summer temperatures and deeper snow (Wahren et al. 2005). These results are consistent with increased shrub and graminoid height and cover after artificial warming at 10 other international experimental tundra biome sites (Walker et al. 2006). Increased birch cover could promote fire spread, because shrub birch is relatively flammable compared with other shrubs and graminoids (Higuera et al. 2008).

Remote sensing methods, most notably the normalized difference vegetation index (NDVI) have also been used to assess vegetation trends in the Arctic. NDVI values are a measure of "greenness" and correlate well with above-ground plant biomass. Retrospective studies show an increase in NDVI in arctic Alaska over the periods 1981–2001 (Jia et al. 2003) and 1990–1999 (Stow et al. 2004). Increasing NDVI values could reflect increased shrub cover and stature, but this interpretation is not straightforward. A 22-year record analyzed by Verbyla (2008) demonstrated a significant positive trend in the annual maximum NDVI on the Arctic Coastal Plain and Arctic Foothills, with no significant trend in the Brooks Range. Increasing biomass on the Arctic Coastal Plain is not likely to be associated with shrub increase, as shrubs constitute a very low proportion of the cover. The only available study from the Coastal Plain based on field measurements (Jorgenson and Buchholtz 2003) reported a small but significant decline in non-vascular plant cover, but no significant change in vascular plant cover or shrub height in plot studies covering the period 1984–2002. On the wet and lowland moist sedge tundra of the Arctic Coastal Plain, therefore, the increasing NDVI values reported by Verbyla (2008) might be indicative of more robust graminoid growth. Anecdotal evidence of shrub invasion in this ecoregion includes the establishment of alders (*Alnus* spp.) on polygon rims in the Colville River Delta (M.T. Jorgenson, ABR Inc., personal communication; see image page 37). There is no strong evidence, however, for widespread shrub expansion on the Arctic Coastal Plain.

Paludification

Paludification refers to the process of establishment of peat-forming plant communities on both dry lands and in bodies of water (bog formation from water-body infilling may be considered a distinct process, terrestrialization, but here we refer to all bog formation as "paludification"). Klinger (1990) proposed that mosses such as *Sphagnum* play a key role in driving this successional process. Initially, according to this hypothesis, organic acids released by moss cause mortality of fine roots in vascular plants, setting in motion a shift in plant species composition, with an increasingly acidic and moss-dominated bog as the stable climax community. In the boreal and arctic environment, conditions created by *Sphagnum* normally produce a positive feedback that enhances paludification by providing cooler, increasingly acidic soils leading to increased peat formation, a thinner active layer, and permafrost aggradation (Auerbach et al. 1997). Extrinsic disturbance that results in drier soils and/or higher alkalinity leads to conditions less favorable for *Sphagnum* growth (Spatt and Miller 1981).

Present-day acidic tussock tundra that dominates the Arctic Foothills may have evolved from arid grass-forb communities that were prevalent during the late Pleistocene, through paludification in the warmer, moist Holocene environment (Walker et al. 2001). Tussock tundra communities are characterized by plants that are relatively unpalatable to herbivores, with high concentrations of toxic secondary compounds, and thus offer less favorable habitat for herbivores. Conversion of

Figure 4.11. Thermokarst pits on the Hulahula Lowlands, Arctic National Wildlife Refuge. Orange coloration on trough margins are patches of Sphagnum *moss. Photo by M.T. Jorgenson.*

shallow water and sedge tundra on the Arctic Coastal Plain to acidic bog habitats would have profound ecological implications, given that acidification impedes nutrient availability, lowers productivity, and creates favorable conditions for slower-growing sedges and heath shrubs (Szumigalski and Bayley 1997, Thormann and Bayley 1997).

In the northern hemisphere, *Sphagnum* reaches peak abundance in the climate zone featuring 630–1,300 mm annual precipitation and -2°C to -6°C MAAT (Gajewski et al. 2001), both warmer and wetter than current conditions in arctic Alaska. In contrast to the Arctic, wet drained lake basins in the warmer environment of the Seward Peninsula (MAAT of -6 °C) are characterized by vegetation co-dominated by sedges and *Sphagnum* moss (Jorgenson et al. 2004). If the Seward Peninsula coastal climate is a reasonable analog for the future climate of the Coastal Plain, we may expect increased abundance of *Sphagnum* in the Arctic and potential conversion of wet sedge tundra to bog meadow (M.T. Jorgenson, ABR Inc., personal communication). The rate at which peatlands might develop on the Coastal Plain is unknown. Holocene peatland formation in northern Canada developed over a period >1,000 years (Kuhry et al. 1992), but *Sphagnum* has been observed to fill thermokarst pits (Figure 4.11) on the Arctic Coastal Plain over the past half century (M.T. Jorgenson, ABR Inc., personal communication).

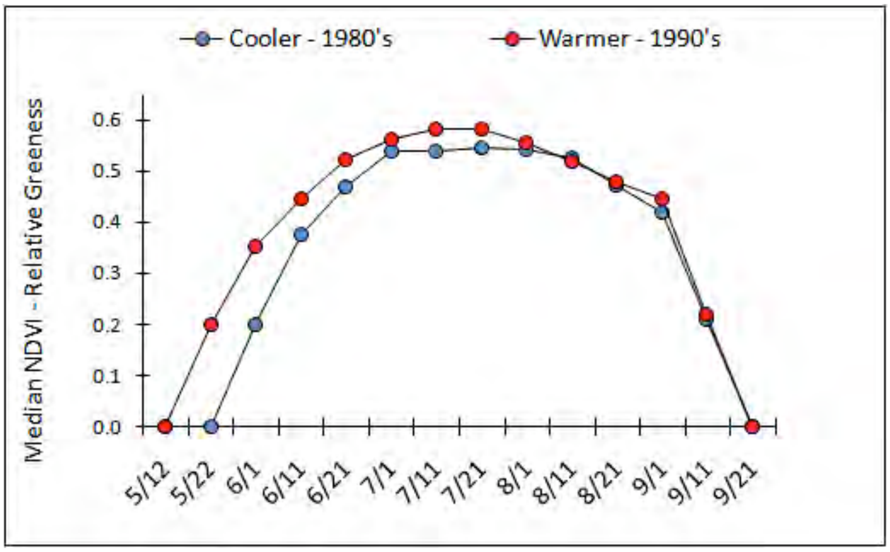


Figure 4.12. Median normalized difference vegetation index (NDVI) within the late July concentrated use area of satellite-collared adult females from the Porcupine caribou herd in the 1980s (1985–1989) compared to the 1990s (1990–2001). Source: Brad Griffith, USGS, Alaska Cooperative Wildlife Research Unit, unpublished data.

Phenology

Growth and photosynthetic activity commences almost immediately after snowmelt exposes plants in spring and the ground thaws. Data collected as part of the International Tundra Experiment (ITEX) suggest that experimental warming of tundra can produce "small to moderate" advance in green-up (Arft et al. 1999). Similarly, NDVI data from northeast Alaska spanning 12 years (Figure 4.12) shows that in warmer years (1990s), green-up is advanced approximately two weeks on the Coastal Plain. Peak greenness occurs in mid-July regardless of mean temperature, but biomass averages higher in the warmer years. Absent other influences, warming air temperatures are projected to advance spring thaw an average of 8–11 days by the end of the century, and as indicted by the ITEX results, may advance the onset of annual plant growth and development. Deepening of the snowpack and greater cloud cover in spring, however, could offset the effect of increased air temperature, slowing snow ablation and possibly delaying onset of green-up.

Senescence in plants is a highly regulated, species-specific process controlled by both endogenous (e.g., nutrient drain, plant hormones) and exogenous (e.g., photoperiod, temperature) factors (Kelly et al. 1988). The potential impacts of increased temperature on plant senescence are not well understood. Indeed, experimental warming of tundra has produced conflicting results. The ITEX experiment reported little effect on timing of senescence, indicating that photoperiod might play a more important role in late-season phenology (Arft et al. 1999). In contrast, an experiment in northeast Greenland using an alternate warming technique showed that warmer temperatures postponed the onset of senescence (Marchand et al. 2004). In further contrast, NDVI data from northeast Alaska indicated that the decline in senescence began earlier in the warmer years (Figure 4.12). Given the conflicting evidence and the complexity surrounding onset and control of plant senescence, it cannot be assumed that warmer fall temperatures will extend the period of greenness.

Contaminants

Contaminants generated throughout the globe are deposited across the arctic landscape through atmospheric deposition and ocean currents, in addition to local sources. Climate change may increase both transport and mobilization of these contaminants to fish, wildlife, and their habitats. For example, climate change may increase contaminant mobilization from previously contained sources. Coastal erosion and sea level rise may breach or erode sewage lagoons, landfills, dumps, tailing ponds, drilling mud pits, and oil-contaminated soils (AMAP 2003), releasing contaminants into the nearshore environment. Shoreline fuel delivery, storage, and pipeline systems may also be damaged or destroyed; in 2007, Newtok, Alaska, lost its barge landing and a 1,000-gallon fuel tank in a storm (CCAAG 2008). Increased discharge from large river systems and the associated increases in sediment transport also will bring additional contaminant mobilization. For example, mercury concentrations were positively correlated with river flow and were greatest during spring freshets and high flow events in the Mackenzie River Delta (Leitch et al. 2007); increased mercury concentrations may in part reflect increased surface inundation and bank erosion. Contaminants currently contained within glacial ice, multi-year sea ice, and permafrost, including persistent organic pollutants and mercury, will almost certainly be mobilized to aquatic ecosystems as these systems melt. Additionally, long-range atmospheric transport will continue to be a source of contaminants to the Arctic.

Increased number or intensity of fires could result in additional mercury inputs to the arctic tundra. Turetsky et al. (2006) evaluated climate-related changes in fire incidence and associated mercury emissions. They found that mercury formerly sequestered in cold, wet peat soils is released to the environment during fires in Canadian boreal forests and present a growing threat to sensitive aquatic habitats and northern food chains as the climate warms. Estimates of circumboreal mercury emissions presented in this study are 15-fold greater than estimates that did not account for mercury stored in peat soils. Weidinmeyer and Friedli (2007) estimated mercury emissions from wildfires in Alaska and the lower 48 states to average 44 metric tons per year from 2002–2006. This amount is roughly equivalent to 30% of the total mercury emissions permitted by the U.S. Environmental Protection Agency in 2002. While emissions due to fire were quite variable in Alaska, it is notable that in 2004 fire-related mercury emissions in Alaska (32 metric tons) exceeded the combined total amount from the lower 48 states (23 metric tons). In 2005, mercury emissions from fires in Alaska (22 metric tons) were only slightly lower than the total for the other states (28 metric tons).

Mercury concentrations in fish have been shown to increase following fires in Alberta, Canada, both by increasing mercury inputs and by restructuring food webs; top predators switched from invertebrate prey to smaller fish (Kelly et al. 2006). Collectively, these studies suggest that these fire-related mercury emissions will continue, assuming fire incidence remains constant or increases with a warming climate. If wetland area increases as predicted by some climate models, the area available for methylation of mercury will also increase. Increased mercury mobilization and methylation will cause mercury levels in all trophic levels to increase; already, mercury is a major contaminant of concern for arctic biota.

Top: The Anaktuvuk Fire of 2007 was by far the largest fire ever recorded north of the Brooks Range. Photo courtesy Arctic Long Term Ecological Research program.
Bottom: Debris from a dump at the abandoned military site at Nuvagapak Point in the Arctic National Wildlife Refuge. Coastal erosion is exposing buried industrial and household waste. USFWS photo.

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Caribou (Rangifer tarandus) *foraging near Toolik Field Station; the animals' ability to access vegetation under snow is key to their overwinter survival. Photo by Øivind Tøien.*

Chapter 5
Climate Effects on Fish and Wildlife

In the previous chapter, important physical and biological agents that will alter arctic habitats in response to climate change were described. In this chapter, we explore likely pathways by which fish and wildlife populations will be affected.

The WildREACH workshop participants worked in breakout sessions (see Appendices 3–5) to consider the mechanisms by which climate-related changes in habitat would affect fish and wildlife. Workshop participants acknowledged the immense uncertainty associated with climate projections and the manner in which physical and ecological systems will respond to an altered thermal regime. Against this background, participants were cautious to avoid poorly supported predictions regarding fish and wildlife response. For each taxonomic group of wildlife (i.e., birds, fish, and mammals) graphic and narrative conceptual models were developed that represent hypotheses linking climate change, habitat change, and biological effects. It is important to recognize that these models are intended as **hypotheses to be tested through observation and experiment**, rather than evidence-based conclusions.

The models are not intended as an exhaustive catalog of all possible effects; rather they represent a selection based on our judgment of both plausibility and magnitude of effect. We focus attention on changes associated with physical processes and vegetation change. Trophic interactions are considered at the community and system level, but an assessment of other multi-species interactions is largely deferred. We acknowledge that climate change is likely to result in novel species assemblages accompanied by altered competitive interactions, predator-prey relationships, and parasite-host relationships. Predicting the nature of these changes was considered too speculative at this stage.

Hydrologic Process Models

Hydrologic processes are found to be a critical link between climate change and habitat suitability. Issues of water balance, precipitation, and surface water distribution were of paramount concern for all species groups. Two simple conceptual models are presented (summer [Figure 5.1] and winter [Figure 5.2]), outlining pathways by which changes in air temperature and precipitation regime will affect aspects of surface hydrology most relevant to fish and wildlife habitat. These models provide the foundation for the taxon-specific models that follow later in this section. Summer and winter seasons are considered separately since winter constitutes most of the year in the Arctic, yet the short summer growing season is critical to reproduction and body condition for most species.

Summer Processes

1. Evapotranspiration is the primary means by which surface and soil water loss occurs and thus is a key factor in controlling arctic hydrology (Kane 1997, Bowling et al. 2003). There is evidence that portions of the Coastal Plain are

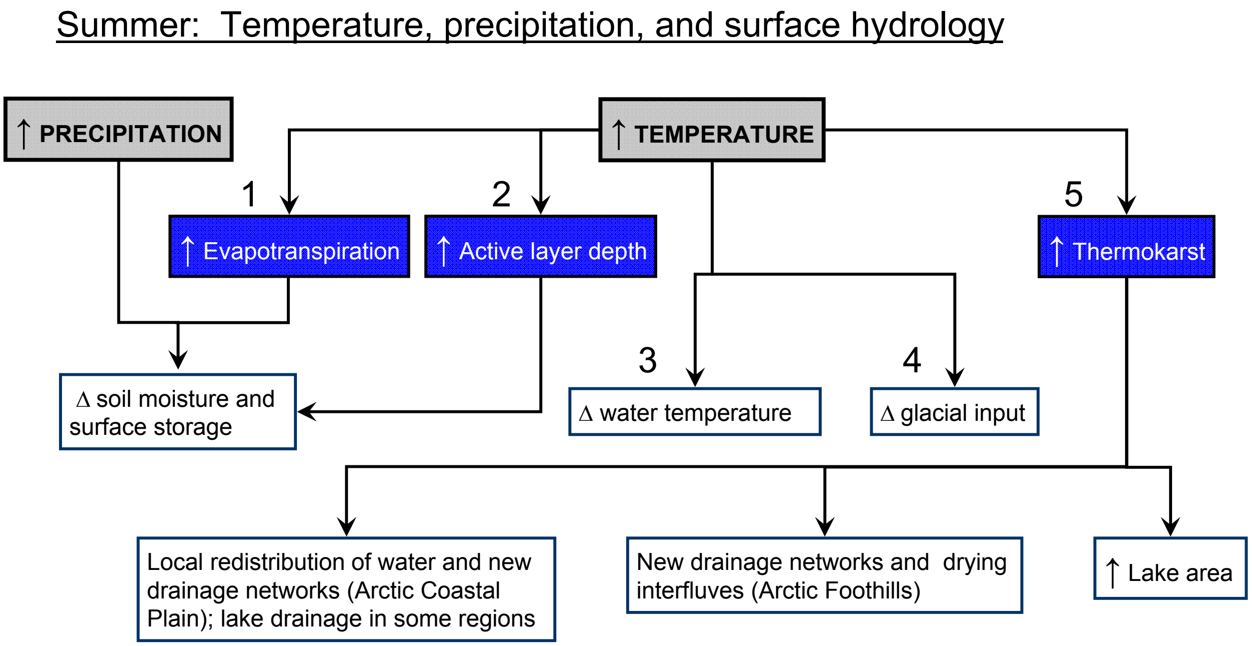


Figure 5.1. Conceptual model illustrating the effects of increased summer air temperature and precipitation on aspects of surface hydrology relevant to habitat change. Gray text boxes identify climate drivers, blue boxes identify physical processes, and white boxes represent habitat effects.

already experiencing increasingly drier conditions as precipitation fails to compensate for evapotranspiration (Hinzman et al. 2005). While increasing temperatures will promote evapotranspiration, it is important to recognize that the actual rate of evapotranspiration can be either water- or energy-limited. If projected increases in summer precipitation do not compensate for increased evapotranspiration, then summer drying will occur earlier and to a greater degree than currently. Fall evapotranspiration tends to be limited by available energy, as well as by the onset of plant senescence. Soil saturation and surface water storage at the onset of winter is sensitive to changes in rainfall, which tends to occur in late summer and fall.

2. Warmer soil temperatures and earlier onset of active layer thaw will increase the depth of seasonal thaw. As active layer thickness increases, the soil storage capacity will increase and water may percolate downward, resulting in drying at the surface. Streamflow records from gauges in the Canadian Northwest Territories and portions of the Yukon River show increases in baseflow during winter, which has been attributed to permafrost degradation (St. Jacques and Sauchyn 2009, Walvoord and Striegl 2007). In the Foothills, a longer warm season may prolong the time available for soil moisture to move down gradient and into drainage networks. This may lead to drying of shallow soils in late summer and early fall, while baseflow increases due to additional shallow groundwater flow. Fall and winter drainage may be less important on the Coastal Plain because soil moisture distribution is largely determined by microtopography. Deepening of the active layer and subsequent redistribution of water, however, should reduce surface storage (e.g., lower lake levels) and produce drier near-surface soils.

3. A warming climate combined with increased snow cover is expected to have a significant impact on the annual heat budget of arctic lakes (for review see Schindler and Smol 2006). Increased snow cover will insulate lakes and result in thinner ice. Thinner lake ice will melt faster in spring, leading to earlier ice-out and earlier seasonal rise in water temperature. There is a paucity of long-term temperature records for arctic lakes and streams, but what data are available suggest a warming trend. Toolik Lake, located within the Foothills, shows a 3°C warming of the epilimnion (upper layer of lake) from 1975 to 1992 (O'Brien et al. 1997). Warming of water in the Arctic is not limited to lakes, as large rivers, such as the Lena River in Siberia, also show a warming trend (Yang et al. 2002). Milner et al. (1997) reported that daily maximum temperatures in a tundra stream reached as high as 21°C, although the maximum monthly temperature was 13.5°C. If these data are representative, it suggests that water temperature in arctic Alaska lakes and streams is highly sensitive to climate change.

4. As the rate of ice loss continues to increase for Brooks Range glaciers (Nolan et al. 2006), these glaciers are expected to disappear in the next 100–200 years (Weller et al. 2007). Initially the magnitude and temporal extent of glacial runoff will increase, leading to increased sediment delivery to deltaic mud flats and the ocean and greater connectivity to floodplain lakes. When ice loss reaches the point at which meltwater outflow decreases or ceases, glacial-fed systems will show reduced flow rates, lower turbidity, and altered water quality. These changes will be particularly important in the eastern portion of the North Slope where glaciers exert strong controls over flow regime, habitat suitability, and formation of coastal deltas.

5. Recent observations in arctic Alaska suggest that permafrost is warming (Romanovsky and Osterkamp 1997, Osterkamp and Jorgenson 2006, Clow 2008) and that warming temperatures can accelerate thermokarst processes at mean annual ground temperatures well below 0°C (Jorgenson et al. 2006). Permafrost temperatures are likely to continue to increase under the expected scenario of increasing air temperature and precipitation. This in turn will likely accelerate the formation of thermokarst features. Types of thermokarst features and ecological implications of permafrost degradation will vary depending on location, landscape position, soils, hydrology, and amounts and types of ice (Jorgen-

son and Osterkamp 2005). In areas with little topographic relief, such as portions of the Coastal Plain, ice wedge degradation can produce water-filled pits and troughs that drain water from flooded polygon centers (Jorgenson et al. 2006). Where topographic gradients are large enough to allow for rapid drainage, suprapermafrost groundwater flow can deepen the active layer and produce features known as water tracks (Jorgenson et al. 2008). Similarly, thermokarst gullies can form when surface water becomes channelized, deepens the active layer, and thaws ice-rich permafrost (Jorgenson et al. 2008). Thermokarst lakes, common across the western portion of the Coastal Plain, will also respond to a warming climate. Lakes can undergo lateral expansion by the process of thermal and mechanical erosion (Jorgenson and Shur 2007, Jorgenson et al. 2008). As permafrost warms and begins to degrade, lake area will likely increase as shorelines become more susceptible to erosion.

Winter Processes

1. Snow acts as an insulator between relatively warm soil and cold air throughout the winter. Temperature records from the Kuparuk River basin show that snow cover attenuates average winter air temperature by 34–47% and diurnal air temperatures by 40–96% (Taras et al. 2002). Where snow is deep, soil temperatures are warmer, and, in extreme cases, deep snowdrifts can prevent soils from freezing (Sturm et al. 2005). Using a model developed for the Kuparuk basin, Taras et al. (2002) estimated that increasing snow depth by 15 cm would increase temperatures at the soil/snow interface by 0.5–3°C. It follows that warmer winter air temperatures in combination with increased snow depth will likely produce warmer soil and subnivean (air layer between the snow and the soil surface) temperatures.

2. Increased snowpack depth will likely produce higher snow water equivalent (SWE) values.

3. Control of timing and duration of snowmelt is complex. In general, snowmelt is advanced in warm, wet springs and delayed under cool and dry conditions (Zhang et al. 2001). Therefore, under a scenario of warming air temperatures it is possible that spring melt will occur earlier in the year. Snow cover records from Barrow suggest that the snowmelt date is becoming increasing variable and has advanced by 10 days since 1941 (Hinzman et al. 2005), suggesting that a shift to an earlier onset of spring is already occurring.

4. On the North Slope, mid-winter freeze-thaw cycles and rain-on-snow events can occur but are rare (Kane et al. 2000). Warmer temperatures during winter could result in more frequent thaw-freeze cycles and rain-on-snow events. If these icing events become increasingly common, the snowpack will become denser and grain size will increase. Such a change would likely have profound consequences for a number of mammals.

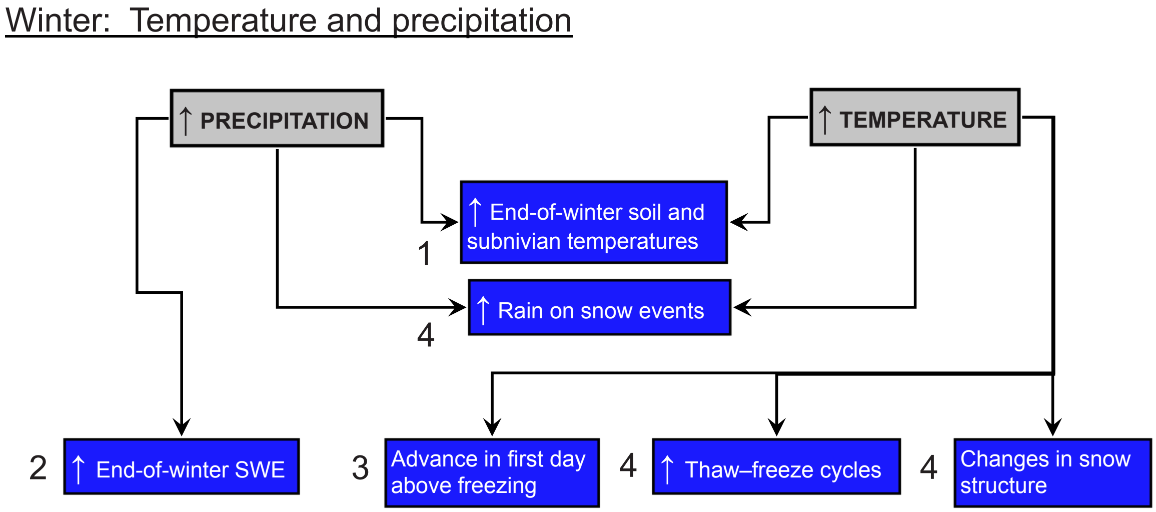


Figure 5.2. Conceptual model illustrating the effects of increased winter air temperature and precipitation on aspects of surface hydrology relevant to habitat change. Gray text boxes identify climate drivers and blue boxes identify physical processes.

Birds

Over 200 species of birds have been observed on the North Slope, but many are of casual occurrence. Over 90 species (Table 5.1) regularly use terrestrial and freshwater habitats for nesting, brood rearing, and fall staging. Nearly all are migratory, occupying the region for some portion of the summer season (May to September). A few species, including rock and willow ptarmigan, common raven, snowy owl, and American dipper (Johnson and Herter 1989), are known to occur on a year-round basis.

The avifauna of arctic Alaska is dominated numerically by waterfowl and shorebirds that are dependent on a variety of wetland habitat types distributed broadly across the Coastal Plain. All of the waterfowl (21 species), loons (4 species), grebes (1 species), and gulls/terns (4 species) that regularly occur in arctic Alaska are dependent on open-water habitats for foraging, brood rearing, and/or molting (Bergman et al. 1977, USFWS 1993). Shorebirds (25 species) vary in their breeding habitat preference, with some species using moist upland tundra and others dependent on aquatic or semi-aquatic habitats (Cotter and Andres 2000, Troy 2000, Brown et al. 2007). While wetland-dependent species are most prevalent on the Coastal Plain, the diversity of perching birds is greatest in the Brooks Range and Foothills, where shrub-associated species with taiga affinities reach the northern limits of their ranges (Johnson and Herter 1989, Poole 2005).

Many species of waterfowl and shorebirds use coastal habitats (mainland beaches, river deltas, protected lagoons and their shorelines, and barrier islands) for brood rearing, molt, and staging prior to fall migration (Connors et al. 1979, Connors et al. 1981, Johnson and Richardson 1982, Connors 1984, Gill et al. 1985, Johnson et al. 1993, Fischer and Larned 2003). Mainland and barrier-island beaches are used by high densities of staging shorebirds (e.g., red and red-necked phalaropes), likely attracted by marine invertebrates concentrated by wind-driven water currents (Connors et al. 1979). Barrier islands are used by nesting common eiders to the virtual exclusion of other habitats (Johnson and Herter 1989, Dau and Larned 2007). Coastal wet sedge (also known as arctic salt marsh) is used preferentially by many brood-rearing and post-breeding waterfowl and shorebirds, particularly brant and snow geese (Johnson 2000, Sedinger and Stickney 2000). River-delta mudflats provide important pre-migration habitat for shorebirds (Connors et al. 1979, Andres 1994, Alaska Shorebird Group 2008). Lake basins breached by coastal erosion may provide especially favorable staging habitat for post-breeding shorebirds (Audrey Taylor, University of Alaska, unpublished data).

Several waterfowl species perform a post-breeding molt migration to specific North Slope sites at which they complete wing molt, remaining flightless for several weeks. Notably, tens of thousands of geese of four species converge on the large lake area north of Teshekpuk Lake each year from breeding areas in northern and western Alaska, arctic Russia, and Canada (King and Hodges 1979, Derksen et al. 1979). Similarly, large numbers of long-tailed ducks use nearshore waters of Beaufort Sea coastal lagoons for molting (Johnson and Richardson 1981, Johnson 1985).

Diets vary among species groups, but many arctic birds rely heavily on invertebrate prey. Of the 94 species listed in Table 5.1, 37 species (39%) are entirely dependent on invertebrate prey, and 72 species (77%) rely at least to some degree on invertebrates. Insects are a particularly important component of the diet for juveniles of widely divergent taxonomic groups, ranging from dabbling ducks to sparrows. Herbivorous species are few but include geese and ptarmigans, which are of special management significance because of their importance to subsistence and sport hunters. Piscivory is also uncommon, with loons and terns the most prominent examples. Twelve species rely significantly on bird and mammal prey, including hawks, falcons, eagles, owls, jaegers, and gulls.

Predation is a major cause of nest failure among arctic-breeding waterfowl and shorebirds (Day 1998, Troy 2000, Sovada et al. 2001, Meltofte et al. 2007), likely influencing productivity and population sizes for some species, particularly colonial nesters. Arctic foxes are the most important predator of bird eggs and young (Day 1998, Burgess 2000, Troy 2000, Bety et al. 2001), and they also take adults of some species. Other important predators include glaucous gulls, jaegers, common ravens, and brown bears (Day 1998, Troy 2000, Bety et al. 2002, NRC 2003). Foxes, gulls, and jaegers rely heavily on microtine rodents (lemmings and voles), and predation on tundra-nesting birds appears to be inversely related to the abundance of mammalian prey (Day 1998, Bety et al. 2001, 2002, ACIA 2005: 301, Meltofte et al. 2007).

Table 5.1. Bird species occurring regularly in terrestrial and freshwater habitats of arctic Alaska (Johnson and Herter 1989) classified by diet (Poole 2005) and habitat association (The Nature Conservancy [TNC] and ABR, Inc., unpublished data).

			Habitat Associations[2]								
			Wetlands				Shrubs		Coastal		
Common Name	**Scientific Name**	**Diet[1]**	**Lake**	**Emergent Marsh**	**Wet Sedge**	**Moist Sedge-Shrub**	**Tall**	**Low**	**Barrens**	**Wet Sedge**	**Water**
Waterfowl											
Tundra Swan	*Cygnus columbianus*	H	3	3	3	3				2	
Greater White-fronted Goose	*Anser albifrons*	H	3	3	3	2				2	
Snow Goose	*Chen caerulescens*	H		2	2					2	
Brant	*Branta bernicla*	H	3	3	3				3	3	2
Canada Goose	*Branta canadensis*	H	2	2	2	3					
American Wigeon	*Anas americana*	H, I	2	2	2					2	
Mallard	*Anas platyrhynchos*	H, I	2		2						
Northern Shoveler	*Anas clypeata*	H, I	2	2	2					2	
Northern Pintail	*Anas acuta*	H, I	2	3	3	3			2	2	
Green-winged Teal	*Anas crecca*	H, I	2	2	2	2					
Greater Scaup	*Aythya marila*	H, I	2	2	2						2
Lesser Scaup	*Aythya affinis*	I	2								
Steller's Eider	*Polysticta stelleri*	I	2	2							3
Spectacled Eider	*Somateria fischeri*	H, I	3	3	3					2	2
King Eider	*Somateria spectabilis*	H, I	2	3	3	2				2	2
Common Eider	*Somateria mollisima*	I			2				3		2
Harlequin Duck	*Histrionicus histrionicus*	I					2	2			
Surf Scoter	*Melanitta perspicillata*	I									2
White-winged Scoter	*Melanitta fusca*	I	2								3
Long-tailed Duck	*Clangula hyemalis*	H, I	3	3	3	2			2	2	3
Red-breasted Merganser[3]	*Mergus serrator*	I, P									
Grouse											
Willow Ptarmigan	*Lagopus lagopus*	H			3	3	2	2			
Rock Ptarmigan	*Lagopus muta*	H			3	3		2			
Loons											
Red-throated Loon	*Gavia stellata*	P	3	3	3					2	2
Pacific Loon	*Gavia pacifica*	P, I	3	3	3	2				2	2
Common Loon	*Gavia immer*	P									2
Yellow-billed Loon	*Gavia adamsii*	P	3	2						2	
Grebes											
Red-necked Grebe[3]	*Podiceps grisegena*	P, I									

Continued next page

Table 5.1. Continued

Common Name	Scientific Name	Diet[1]	Habitat Associations[2]								
			Wetlands				Shrubs		Coastal		
			Lake	Emergent Marsh	Wet Sedge	Moist Sedge-Shrub	Tall	Low	Barrens	Wet Sedge	Water
Hawks, Eagles, Falcons											
Northern Harrier[3]	*Circus cyaneus*	C									
Rough-legged Hawk[3]	*Buteo lagopus*	C									
Golden Eagle[3]	*Aquila chrysaetos*	C									
Merlin[4]	*Falco columbarius*	C									
Gyrfalcon[3]	*Falco rusticolus*	C									
Peregrine Falcon[3]	*Falco peregrinus*	C									
Cranes											
Sandhill Crane[3]	*Grus canadensis*	H, I, C									
Shorebirds											
Black-bellied Plover	*Pluvialis squatarola*	I			3	3			2		
American Golden-Plover	*Pluvialsi dominica*	I			3	3				2	
Semipalmated Plover	*Charadrius semipalmatus*	I							2		
Spotted Sandpiper[4]	*Actitis macularius*	I									
Wandering Tattler[3]	*Tringa incana*	I									
Upland Sandpiper[3]	*Bartramia longicauda*	I									
Whimbrel	*Numenius phaeopus*	I, F				2					
Bar-tailed Godwit	*Limosa lapponica*	I, F			3	2			3		
Ruddy Turnstone	*Arenaria interpres*	I		2	2	2			3	2	
Surfbird[3]	*Aphriza virgata*	I									
Red Knot	*Calidris canutus*	I, H			2	2			3		
Sanderling	*Calidris alba*	I			2				3		
Semipalmated Sandpiper	*Calidris pusilla*	I			3	3			3	2	
Western Sandpiper	*Calidris mauri*	I				3			3		
Least Sandpiper	*Calidris minutilla*	I			2	2		2	2		
White-rumped Sandpiper	*Calidris fuscicollis*	I			3	3				2	
Baird's Sandpiper	*Calidris bairdii*	I			2	3			2	3	
Pectoral Sandpiper	*Calidris melanotos*	I		2	3	3			2	2	
Dunlin	*Calidris alpina*	I			3	3			2	2	
Stilt Sandpiper	*Calidris himantopus*	I			3	3				2	
Buff-breasted Sandpiper	*Tryngites subruficollis*	I		2	3	3				2	
Long-billed Dowitcher	*Limnodromus scolopaceus*	I		2	3	3			2	2	
Wilson's Snipe	*Gallinago delicata*	H, I		2	3	2				2	

1. Diet categories: H=herbivore (shoots, leaves), F=herbivore (fruit), S=herbivore (seeds), I=invertebrates, C=carnivore (mammals/birds), P=piscivore, A=anthropogenic.

2. Habitat associations: 2=medium, 3=high, based on review of habitat use by 89 species (TNC/ABR). Only habitat use indices of 2 and 3 are reported, regardless of data quality. Alpine, Dwarf Shrub, Forested, Bluff and Riverine Water habitats are not presented here because few species exhibited medium or high use of these habitats. Some TNC/ABR habitats are combined here: Emergent Marsh includes both Lacustrine Marsh and Riverine Marsh categories presented in TNC/ABR; Wet Sedge includes Lowland Wet Sedge Tundra and Riverine Wet Sedge Tundra categories; Moist Sedge-Shrub includes Upland Moist Sedge-Shrub Tundra, Lowland Moist Sedge-Shrub Tundra, and Riverine Moist Sedge-Shrub Tundra categories; Tall Shrubs includes Upland Tall Alder Shrub and Riverine Tall Alder-Willow Shrub categories; and Low Shrubs includes Upland Low Birch-Willow Shrub Tundra, Upland Shrubby Tussock Tundra, Lowland Low Birch-Willow Shrub, and Riverine Low Willow-Shrub Tundra categories.

3. Species reviewed in TNC/ABR, but none have index ≥ 2 for habitats presented in this table.

4. Species not reviewed in TNC/ABR.

Table 5.1. Continued

			Habitat Associations[2]								
			Wetlands				Shrubs		Coastal		
Common Name	Scientific Name	Diet[1]	Lake	Emergent Marsh	Wet Sedge	Moist Sedge-Shrub	Tall	Low	Barrens	Wet Sedge	Water
Shorebirds, continued											
Red-necked Phalarope	*Phalaropus lobatus*	I	3	2	3	3				2	
Red Phalarope	*Phalaropus fulicarius*	I	2		3	3			2		
Gulls and Terns											
Glaucous Gull	*Larus hyperboreus*	C, P, A	3	2	2	2			3		3
Mew Gull[4]	*Larus canus*	C, P, A, I									
Sabine's Gull	*Xema sabini*	H, I, P	3	3	3	2			3	3	2
Arctic Tern	*Sterna paradisaea*	I, P	2		2	2			3	3	2
Jaegers											
Pomarine Jaeger	*Stercorarius pomarinus*	C			2						2
Parasitic Jaeger	*Stercorarius parasiticus*	C			3	2					
Long-tailed Jaeger	*Stercorarius longicaudus*	C, I			3	3					
Owls											
Snowy Owl[3]	*Bubo scandiacus*	C									
Short-eared Owl	*Asio flammeus*	C			2						
Perching Birds											
Say's Phoebe[4]	*Sayornis saya*	I									
Horned Lark[4]	*Eremophila alpestris*	I, S									
Cliff Swallow[4]	*Petrochelidon pyrrhonota*	I									
Common Raven[3]	*Corvus corax*	H, C, P, A									
Gray-headed Chickadee[4]	*Poecile cincta*	I, S									
American Dipper[3]	*Cinclus mexicanus*	I, P									
Arctic Warbler[4]	*Phylloscopus borealis*	I									
Bluethroat	*Luscinia svecica*	I					2	3			
Northern Wheatear[3]	*Oenanthe oenanthe*	H, I									
Gray-cheeked Thrush	*Catharus minimus*	I, F					3	3			
American Robin[4]	*Turdus migratorius*	I, F									
Eastern Yellow Wagtail	*Motacilla tschutschensis*	I					2	3			
American Pipit[3]	*Anthus rubescens*	I									
Northern Shrike	*Lanius excubitor*	I, C					3	3			
Yellow Warbler[4]	*Dendroica petechia*	I									
Wilson's Warbler[4]	*Wilsonia pusilla*	I									
American Tree Sparrow	*Spizella arborea*	I					3	3			
Savannah Sparrow	*Passerculus sandwichensis*	I, S				3					
Fox Sparrow	*Passerella iliaca*	I					3	3			
White-crowned Sparrow	*Zonotrichia leucophrys*	I, S					3	2			
Lapland Longspur	*Calcarius lapponicus*	I, S			3	3		2	2		
Smith's Longspur	*Calcarius pictus*	I, S			3	2		3			
Snow Bunting	*Plectrophenax nivalis*	I, S			3				3		
Common Redpoll	*Carduelis flammea*	I, S					2	3			
Hoary Redpoll	*Carduelis hornemanni*	I, S					2	3			

Effects of Climate Change on Birds of Arctic Alaska

Many bird species characteristic of high latitudes have broad circumpolar distributions. Within Alaska, the breeding range of some tundra-associated species extends along the Chukchi Sea coast and as far south as the Yukon-Kuskokwim Delta (e.g., tundra swan, common eider, black-bellied plover, bar-tailed godwit, and western sandpiper). Other species are widely distributed across Alaska, including alpine areas and wetlands in the boreal forest zone (e.g., Pacific loon, long-tailed duck, American golden plover, arctic tern, and Lapland longspur). Considering only the Alaska portion of their range, populations of several species are concentrated in the Arctic. These include: yellow-billed loon, snow goose, king eider, spectacled eider, Steller's eider, red phalarope, stilt sandpiper, ruddy turnstone, red knot, white-rumped sandpiper, pectoral sandpiper, buff-breasted sandpiper, long-billed dowitcher, glaucous gull, pomarine jaeger, snowy owl, and Smith's longspur (Poole 2005). While arctic Alaska may serve as a refugium for species with more southerly distributions, these arctic specialists are likely the most vulnerable to climate warming.

The potential for warmer summers and delayed freeze-up would likely improve reproductive success for some bird species. For example, there is evidence that shorebird chick growth and survival is constrained by cold weather conditions (Soloviev et al. 2006), thus a warming climate could increase productivity in these species. A longer open-water season should also improve fledging success for species like red-throated loons, for which early freezing temperatures are a significant source of juvenile mortality (Dickson 1993).

If warmer summers result in drying of wetlands, however, species that rely on shallow water and wet meadow habitats could be profoundly affected. A long-term drying trend would likely lead to changes in vegetation community composition and productivity of invertebrates, affecting herbivorous species as well as those dependent on arthropods. Widespread paludification (expansion of bogs and peat-forming environments, see page 53) could reduce habitat quality for wetland-dependent species across the Arctic Coastal Plain. Shrub expansion on the North Slope, if it results in displacement of open moist and wet sedge tundra habitats, would similarly reduce habitat quality and availability.

Increased temperatures and longer open-water and growing seasons are likely to increase primary and secondary productivity in aquatic and semi-aquatic systems, thus increasing food abundance for invertebrate-dependent species and herbivores. Changes in seasonal patterns of food availability and quality, however, could be detrimental if birds cannot adjust migration, breeding, and molting schedules to optimize exploitation of food resources. This could result in a "trophic mismatch," in which the seasonal timing of life cycle events is out of phase with that of critical food resources (Coppack and Both 2002). At present, the timing of breeding activities for many species of arctic birds appears closely linked to peak insect emergence (Hurd and Pitelka 1954, Holmes 1966, MacLean 1980). If birds are unable to respond to climate-mediated changes in these peak events, breeding success and population size will likely be affected (Both et al. 2006, Moller et al. 2008, Tulp and Schekkerman 2008). Similarly, changes in plant phenology and increased plant growth may reduce the availability of high-quality forage for geese. This could reduce gosling growth and survival (Dickey et al. 2008) and restrict nutrient uptake among molting geese (Schmutz et al. unpublished).

The presence or absence of fish in arctic lakes heavily influences the invertebrate community (Stross et al. 1980) and, therefore, prey availability for aquatic birds. Changes in flow regimes that prevent fish from entering lakes would be detrimental to piscivores, but reduced competition for invertebrate prey will likely benefit other bird species. Additionally, in northern Alaska, species diversity of soil invertebrates increases substantially along a climatic gradient away from the colder coastal zone (MacLean 1975), suggesting that longer summer seasons will result in range shifts and changes in the composition of the soil invertebrate fauna. The potential effects of such changes on birds are unclear and would depend on their ability to exploit these new resources.

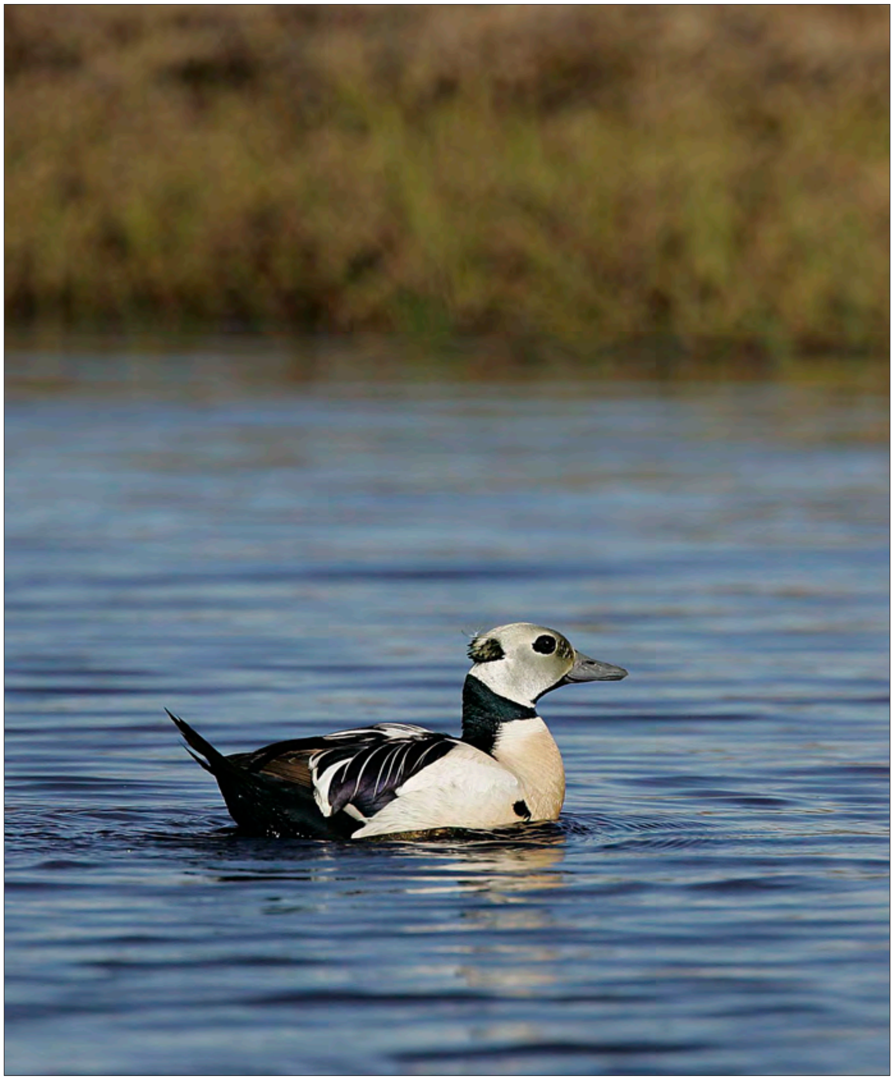
Changes in coastal habitats will affect availability of bird habitat. Coastal erosion, accompanied by lake-breaching and salinization of adjacent low-lying areas, may result in changes in vegetation that influence habitat suitability differentially for birds (Flint et al. 2008). Increased stream sediment loads may result from increasing drainage basin surface temperatures (Syvitski 2002) and thermokarst-associated bank erosion (Walsh et al. 2005); the persistence of deltaic mud-flat habitat is dependent on the balance of deposition rate and inundation from sea level rise.

Climate warming may affect the relationship between arctic birds and their predators in several ways. Population cycles of lemmings and other small rodents affect productivity of waterfowl and shorebirds because these bird species (especially at egg and chick stages) serve as alternate prey when rodent populations are low (Bety et al. 2001, 2002, ACIA 2005: 301). The inverse relationship between lemming abundance and nest success is less apparent on the North Slope than the Eurasian Arctic (Day 1998). Nevertheless, climate-related changes in rodent population cycles (Ims and Fuglei 2005, Kausrud et al. 2008) could indirectly influence bird productivity and abundance.

Warming may lead to further increases in human economic activity (e.g., increased shipping and offshore oil development), and this activity may further influence abundance or distribution of predators. Arctic foxes, glaucous gulls, common ravens, and brown bears tend to concentrate in areas of human activity on the North Slope (Day 1998, NRC 2003). Increased development could increase localized densities of predators, although population-level effects on birds are unknown and could likely be at least partially mitigated (Liebezeit et al. in press). Further increases in human economic activity may also result in increased industrial contamination, including oil spills.

Finally, there is anecdotal evidence that red foxes may be increasing in number on the North Slope and documentation of competition between the arctic fox and the larger red fox, with the latter dominating (Pamperin et al. 2006). The effect on breeding birds of increasing red fox numbers and their potential exclusion of arctic foxes is unclear. Red foxes would likely occur at lower densities during the breeding season, but they are more capable of killing or chasing off large adult waterfowl that often succeed at defending nests and deterring predation attempts by the smaller arctic fox.

*A red fox (*Vulpes vulpes*) carrying a spectacled eider (*Somateria fischeri*) near Prudhoe Bay, Alaska. Climate warming may allow red fox populations to expand in arctic Alaska. Photo by Bryan Collver, BryLyn Collver Art.*



Conceptual Models: Potential Climate-mediated Impacts to Arctic Birds

Four conceptual models were developed describing potential climate-mediated habitat changes on North Slope birds. Narratives describing elements of each model are presented below.

Abundance and Distribution of Surface Water (Figure 5.3)

1. Aquatic and semi-aquatic habitats of the North Slope support large numbers of birds, both herbivores and invertebrate-dependent species (Bergman et al. 1977, Derksen et al. 1981, Martin and Moitoret 1981, Meehan and Jennings 1988, USFWS 1993, TERA 1994). Persistently dry summer conditions could result in conversion of aquatic marsh and wet sedge meadow to moist sedge meadow, and moist sedge meadow to tussock tundra. Widespread loss of aquatic and semi-aquatic habitat across the Arctic Coastal Plain would likely decrease invertebrate productivity and availability. This alteration would represent a loss of habitat quantity and quality, leading to changes in bird distributions as well as decreases in productivity and abundance, with population-level effects possible for some species.

Above: A male Steller's eider (Polysticta stelleri) *near Barrow; the species is listed as threatened under the Endangered Species Act. Photo by Ted Swem, USFWS.*
*Below: Long-billed dowitchers (*Limnodromus scolopaceus) *at Prudhoe Bay, Alaska, flocking in August prior to migration. Photo by Bryan Collver, BryLyn Collver Art.*

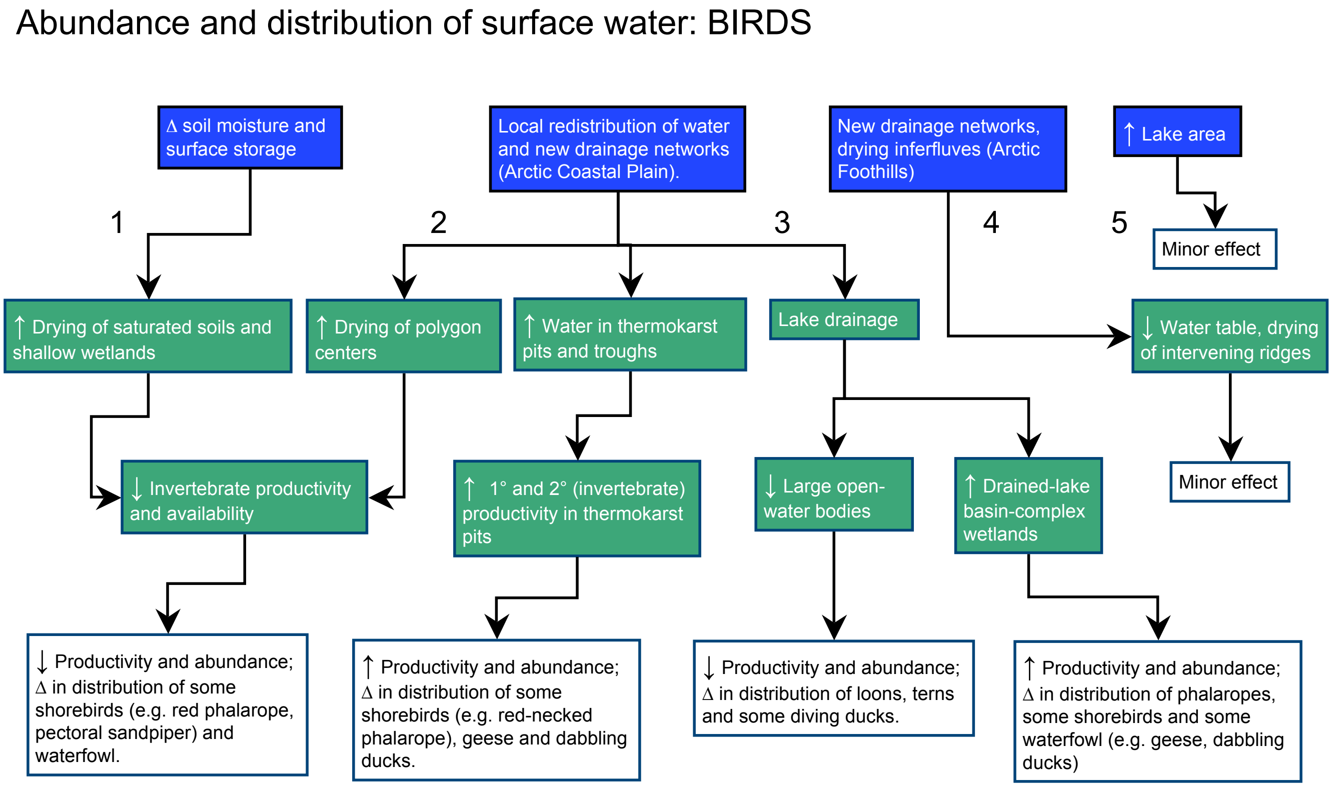
2. Permafrost degradation in polygonal terrain will continue to drive local redistribution of surface water from shallow polygon centers to deeper polygon troughs. Loss of productivity in drying polygon centers would likely be offset by increased primary and secondary productivity of expanding thermokarst pits, including higher biomass of aquatic insects (MacLean 1980, Martin 1983). Habitat heterogeneity characteristic of thermokarst terrain has been linked to higher local-scale nest density for species such as American golden plover, semipalmated sandpiper, and red-necked phalarope (Troy 2000) and higher general use by some waterfowl such as greater white-fronted goose (Troy 1991). It is unclear, however, whether landscape-wide acceleration of thermokarst would be a net benefit to these or other species.

3. The formation of new drainage networks could cause increased lake drainage in some landscapes, resulting in a loss of open-water habitats. Depending on the extent to which this occurs, it could affect the distribution, productivity, and abundance of species such as loons, terns, and some diving ducks. Lake drainage can also result in the development of productive drained lake-basin complex wetlands with stands of water sedge *Carex aquatilus* and emergent pendant grass *Arctophila fulva*. Emergent *Carex* and *Arctophila* stands have high primary productivity (Alexander et al. 1980) and support high densities of aquatic invertebrates (Bergman et al. 1977). *Arctophila* wetlands are preferred habitat for Pacific and red-throated loons, tundra swans, black brant, northern pintails, long-tailed ducks, white-winged scoters, king eiders, and both red and red-necked phalaropes (Derksen et al. 1981, Troy 1988), and are also important to threatened spectacled and Steller's eiders (Quakenbush et al. 1995, USFWS 1996).

4. In the Foothills ecoregion, development of new drainage networks and drying of intervening ridges may result in transition from tussock tundra to dwarf birch vegetation. The effects on birds of such a transition are uncertain and perhaps minor.

5. Large, deep lakes unaffected by new drainage networks are expected to continue expanding due to thermokarst and shoreline erosion by wind-driven waves. This will likely affect only a small portion of the Coastal Plain landscape and will have only minor effects on bird distribution and abundance.

Figure 5.3. Conceptual model of how changes in abundance and distribution of surface water could impact birds. Blue text boxes identify physical drivers, green boxes identify habitat effects, and white boxes summarize biological implications of habitat change.



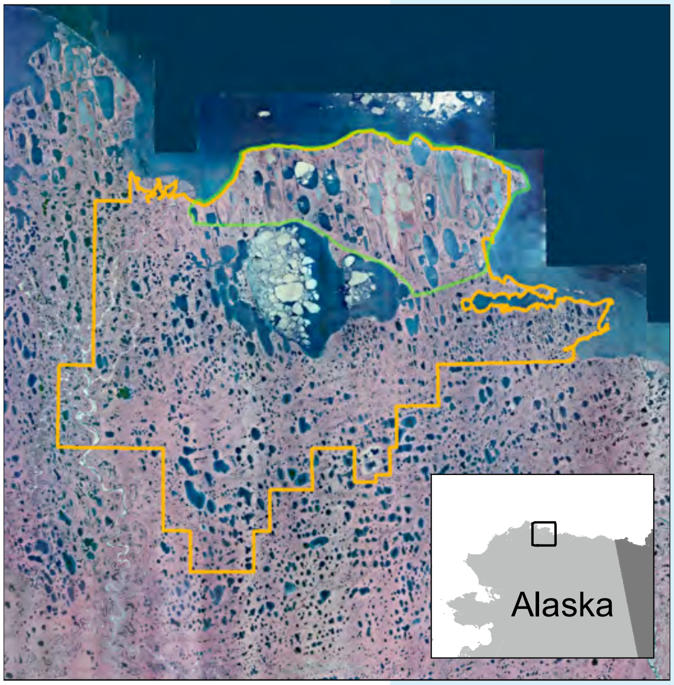
Box 5.1 Avian Population Response to Ecological Change Along the Arctic Coastal Plain

The Teshekpuk Lake Special Area (TLSA), northeast of Teshekpuk Lake in the National Petroleum Reserve–Alaska, represents one of the most important goose molting habitats in the circumpolar arctic (Flint et al. 2008). To understand how variability in the physical environment may manifest biological change, the U.S. Geological Survey (USGS) investigated the extent to which goose distribution has changed over time, whether such change was a consequence of habitat change, and what physical and biological processes were responsible. Managers need this understanding to better predict future distributions of molting geese, thereby improving land management decisions.

The USGS analyzed survey data collected by the U.S. Fish and Wildlife Service since 1976 and discovered that goose distribution has changed. In particular, black brant shifted from inland lakes to coastal habitats while greater white-fronted geese concurrently increased in numbers. The change in distribution could either have been related to habitat change or interspecific competition could have forced brant to use suboptimal habitats. Examination of a time-series of aerial imagery confirmed that high rates of coastal erosion combined with periodic storm surges have led to saltwater intrusion into freshwater habitats, and the associated changes in salinity may have altered foraging conditions for geese in the coastal zone (Jones et al. 2009).

The results from multiple lines of inquiry suggested that the change in distribution has not been detrimental to brant. There was no difference in body condition between birds molting in traditional inland habitats compared to those molting along the coast. Moreover, body condition appears to have improved in recent years compared with birds measured in the 1980s. Analyzing forage plant species across a range of habitats within the TLSA revealed that salt-tolerant plant species, most commonly found along the coast, tended to have higher nitrogen content than species sampled along inland lakes, an indicator of higher nutritional quality. Interestingly, in the warmer year (2006) plant productivity was higher in terms of net biomass, but nutrient quality was lower in terms of percent nitrogen and the carbon-to-nitrogen ratio.

These results demonstrate the difficulty in predicting how climate change may impact habitat and wildlife. On the surface, a change in distribution from historical molting grounds seems troubling. However, changes in goose distribution at TLSA that are correlated with climate change suggest that geese have shifted habitats in response to improving conditions along the coast. This redistribution of birds from inland lakes likely reduced interspecific competition, resulting in overall improvements in body condition across all habitats. We anticipate further shifts in wildlife distributions and changes in plant forage species productivity and nutrient composition as warming patterns continue to alter the landscape.



Above: Location of the Teshekpuk Lake Special Area (orange outline) and area used by concentrations of molting geese (green outline). Map by USFWS from Bureau of Land Management data.
Below: Brant (Branta bernicla) *are exclusively high arctic breeders that depend on particular coastal vegetation communities to feed young goslings. Following breeding, brant congregate at specific areas such as Teshekpuk Lake where they molt in large flocks before fall migration. Photo by Stephanie Clemens, USFWS.*

Vegetation Community Changes (Figure 5.4)

1. Increased shrub abundance could have variable effects, depending on the landscape setting. Increased abundance of tall shrubs in riparian or hillslope settings would permit range expansion and increased abundance of a variety of songbirds with affinities for tall shrub. At present, tall shrub habitat is exceedingly scarce (<1% of the landscape), and thus an increase would have the net effect of increasing regional biodiversity. Conversion of tussock tundra to shrubby tussock tundra in the Foothills and Coastal Plain, particularly in the form of increased stature and density of dwarf birch (*Betula* spp.), would have uncertain consequences for bird distribution and abundance. Broad-scale expansion of shrub communities at the expense of wet sedge tundra and moist sedge-shrub tundra on the Coastal Plain would reduce habitat availability for a broad suite of wetland-adapted species (Table 5.1). The threshold at which shorebird and waterfowl production would be reduced, however, and the likelihood of reaching that threshold are not well understood.

2. The extent to which paludification may impact bird populations and distribution depends on the rate at which this process may occur and the degree to which diminished primary productivity influences the availability of invertebrate prey. Acidification may reduce diversity and biomass of aquatic invertebrates (Hendrey et al. 1976).

3. Only a few species of birds are herbivorous during the summer season. For herbivorous geese, forage quality rather than quantity is thought to be limiting, and forage quality affects gosling growth rates and subsequent survival (Lindholm et al. 1994, Sedinger et al. 1995). Preliminary studies near Teshekpuk Lake (Schmutz et al. unpublished) suggest that warmer temperatures during the growing season result in greater plant biomass but diminished forage quality. There is evidence suggesting that reduced gosling size in years of higher spring temperatures may be attributed to a mismatch between hatching dates of goslings and timing of the peak forage quality (Dickey et al. 2008).

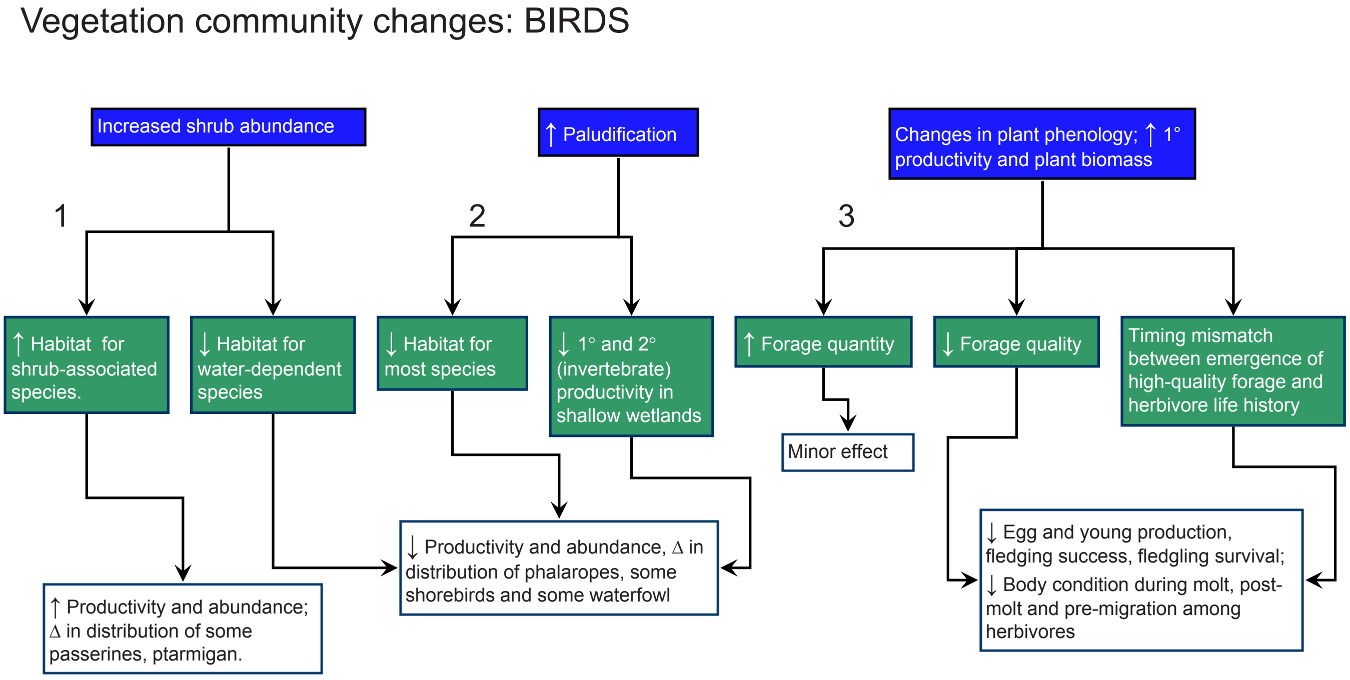


Figure 5.4. Conceptual model of how vegetation community changes could impact birds. Blue text boxes identify physical drivers, green boxes identify habitat effects, and white boxes summarize biological implications of habitat change.

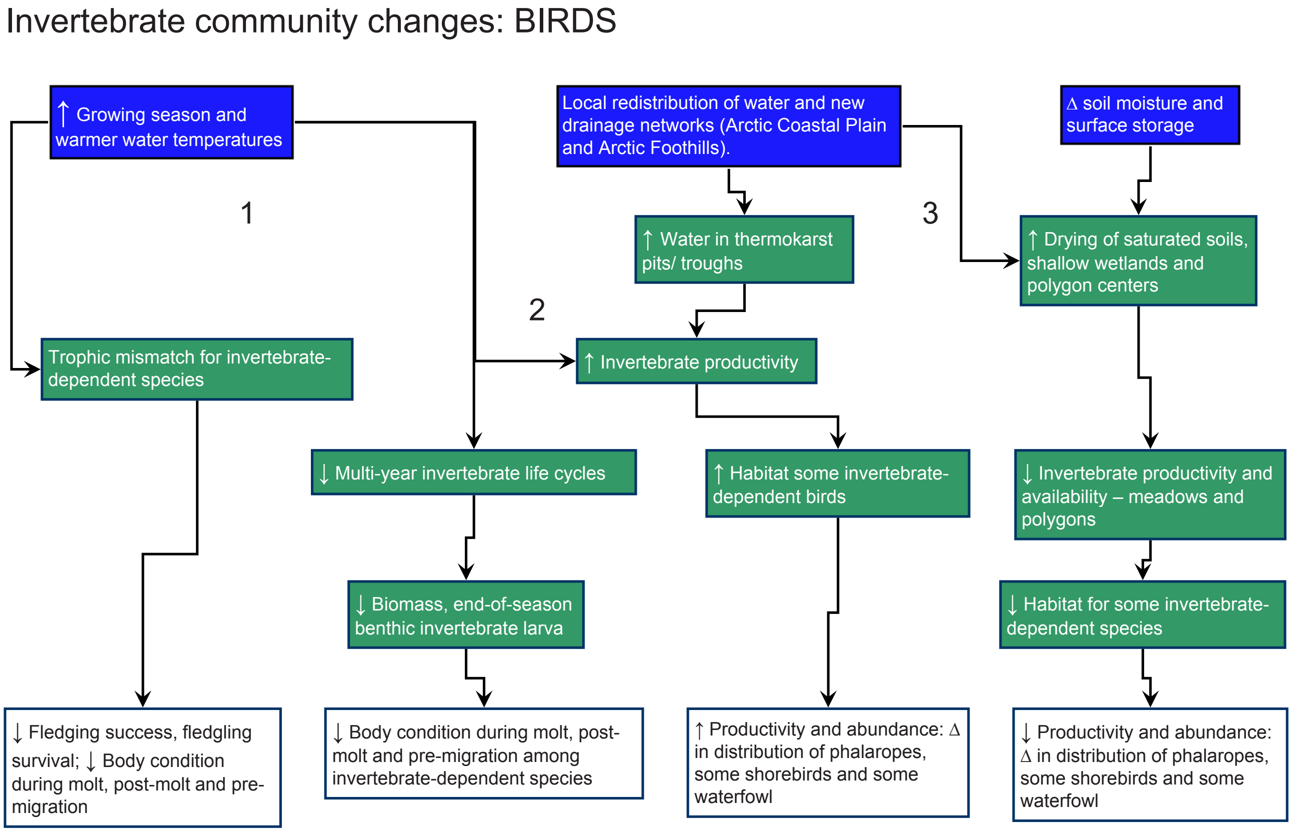
Invertebrate Community Changes (Figure 5.5)

1. The timing of insect emergence is closely related to the timing of snowmelt, and might advance with warmer spring temperatures (Høye and Forchhammer 2008, Tulp and Schekkerman 2008). If warming alters the timing and patterns of insect emergence and peak abundance, and birds are unable to compensate for these changes, "trophic mismatches" may result. If birds cannot alter their migration and breeding schedules accordingly, nest success, fledgling survival, and pre-migration body condition will likely decline.

   Beyond short-term phenological response to changing climate, seasonality may have profound long-term consequences for the distribution and abundance of arctic arthropods. Multi-year life cycles occur in many arctic invertebrates (MacLean 1980, Chernov 1985) and the prevalence of multi-year life cycles results in a large standing biomass of larval invertebrates available to predators throughout the summer season. A shift to shorter, even annual, life cycles could substantially influence the larval biomass available to birds during portions of the breeding season, although the relationship is complex (MacLean 1980). A decrease in availability of benthic invertebrate larvae could affect brood-rearing waterfowl and pre-migration body condition of shorebirds, perhaps resulting in reduced juvenile survival among both, with subsequent declines in recruitment and, ultimately, population size.

2. Other things equal, warmer temperatures and longer growing seasons should result in increased productivity of soil and aquatic invertebrates. Increases in production associated with increased temperatures, permafrost degradation, and longer open-water and growing seasons may initially lead to increased primary and secondary productivity in both pelagic and benthic habitats. If birds are able to exploit these increases in prey abundance, the result should be improved habitat quality that would translate into increased productivity and abundance, and perhaps higher densities and expanded distributions among shorebirds and invertebrate-dependent waterfowl and passerines. Increased nutrient input into lakes, however, may lead to eutrophication which would decrease light penetration and could ultimately lead to a decline in benthic primary production (Vadeboncoeur et al. 2003). This decline may translate into decreased benthic invertebrate biomass/production

Figure 5.5. Conceptual model of how invertebrate community changes may impact birds. Blue text boxes identify physical drivers, green boxes identify habitat effects, and white boxes summarize biological implications of habitat change.



and/or a change in benthic invertebrate community composition that may negatively impact both birds and fish.

3. If warming results in broad-scale drying of moist and shallow wet habitats, a decline in soil and aquatic invertebrates would be expected across the North Slope. This would reduce habitat quality and availability for all shorebirds and most waterfowl, with associated decreases in productivity and abundance as well as changes in distributions for many species.

Coastal Processes and Habitats (Figure 5.6)

1. A warming Arctic may cause a number of changes in barrier islands of the Beaufort and Chukchi seas. Potential changes include reduced size, increased rates of migration and erosion, and a greater likelihood of overwashing and breaching by storm surges. Most of the 2,000–3,000 common eiders that breed along the Beaufort and Chukchi sea coasts (Johnson and Herter 1989, Dau and Larned 2007) nest on coastal barrier islands, and loss of this specialized habitat would likely lead to substantial reduction in this population. More frequent or severe overwash events would reduce nest success through direct egg mortality, as well as diminished nesting habitat suitability, due to removal of sheltering driftwood, detritus, and vegetation clumps (Dau and Larned 2007).

   Loss or major reduction of barrier islands would likely cause changes in nearshore temperature and salinity regimes, perhaps reducing invertebrate abundance and, therefore, the quality of foraging habitat for species such as long-tailed ducks. Loss of barrier islands would also reduce shoreline foraging habitat for shorebirds such as phalaropes because their planktonic prey frequently becomes concentrated along island water lines.

2. The increase in coastal erosion projected over the next century is not expected to result in a significant loss of terrestrial habitats along much of the coast; however, the potential loss of 8% or more of the goose molting area north of Teshekpuk Lake could have significant consequences for the tens of thousands of geese that molt there annually.

3. Climate-induced changes in coastal processes could potentially affect other coastal habitats, including coastal wet sedge tundra, salt-killed tundra, and delta mud flats. Coastal wet sedge and deltaic mud flats currently are sparsely distributed but important habitats, and any loss would be considered detrimental to waterfowl and shorebirds. Salt-killed tundra is of low value as nesting habitat because of limited plant cover so an increase of this type at the expense of more productive habitat would be detrimental. The total area affected, however, is expected to be relatively minor on a regional scale.

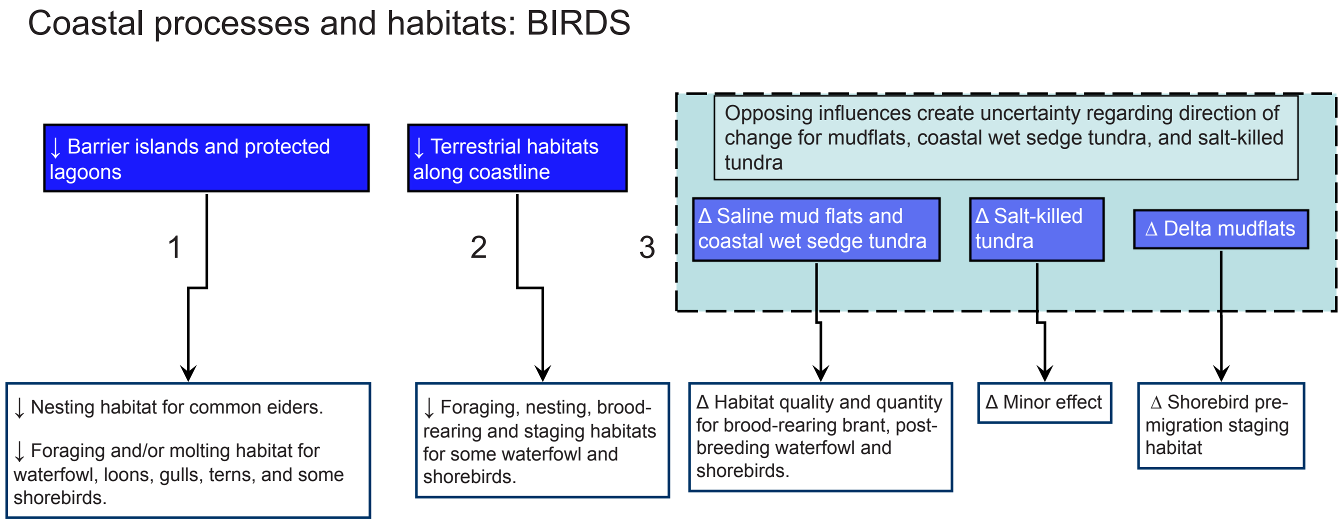


Figure 5.6. Conceptual model of how changes in coastal processes and habitats could impact birds. Blue text boxes identify physical drivers and white boxes summarize biological implications of habitat changes.

Fish

Aquatic Habitats of the North Slope of Alaska

Aquatic habitats on the North Slope are characterized by low average temperatures, low prey densities, short open water periods each year, and limited overwintering areas. Many fish populations are reliant on seasonal movements among habitats (Craig 1989). North Slope streams can be categorized by ecoregion, size, and origin (Craig and McCart 1975, Craig 1989). Mountain streams originate in the Brooks Range and Arctic Foothills, are prevalent east of the Colville River, and are characterized by glacial and clear water systems of variable size, with flows derived mostly from springs and surface runoff (Craig and McCart 1975). These streams are typically cooler and have higher discharges than other waterbodies in the region and typically freeze to the bottom in winter, with only spring areas and deep pools containing liquid water in the winter (Craig 1989). As the largest mountain stream and the largest drainage on the North Slope, the Colville River intercepts smaller mountain streams across the western Brooks Range. West and north of the Colville, most streams originate on the Coastal Plain. These Coastal Plain streams are typically smaller, warmer, and slower-moving, and many do not contain liquid water in winter (Craig 1989); the larger of these drainages, however, contain liquid water in deep pools and springs throughout the year (Morris et al. 2006). Many Coastal Plain streams meander through lake networks with their discharges dependent on surface runoff. These systems also include the smaller tundra streams that typically occur as tributaries across the Coastal Plain.

Lakes across the North Slope can also be categorized as mountain lakes or Coastal Plain lakes, based on ecoregion, size, and origin (Hobbie 1973). Mountain lakes are uncommon, occupying only 1.7% of the Foothills and 0.4% of the Brooks Range ecoregions (Jorgenson and Heiner 2003) and are typically of glacial origin, formed by moraines, scour, or deposited ice blocks (kettle lakes; Hobbie 1973). Many of these lakes are large and deep with recharge associated with surface runoff and groundwater sources. Because of their depth, most of these lakes do not freeze to the bottom. Coastal Plain lakes are abundant, occupying approximately 14% of the Coastal Plain ecoregion (Jorgenson and Heiner 2003). The area they encompass is considered to be the second largest lake district in Alaska (Arp and Jones 2008). Many Coastal Plain lakes are derived from thermokarst processes (Hobbie 1973) and are relatively shallow (<9 m), including Teshekpuk Lake, the largest lake on the North Slope (NRC 2003). Smaller and shallower (<2 m) lakes typically freeze to the bottom and only contain liquid water during the warm season. Coastal Plain lakes are dependent on surface runoff for recharge and are subject to substantial evaporative loss during summer (Miller et al. 1980). Although landlocked lakes are present on the Coastal Plain, many lake systems are seasonally linked by shallow streams, forming complex networks of connected habitats.

Marine and estuarine environments on the North Slope are no less extreme than freshwater habitats. Many areas of the North Slope coast are characterized by barrier islands that form shallow lagoon systems and by large river deltas, both of which provide important fish habitat (NRC 2003). During summer and depending on prevailing winds, topography, and nearshore currents, freshwater flows from North Slope rivers mix with coastal waters to produce a narrow nearshore band of relatively warm, brackish water (Craig 1984). During winter when freshwater input is minimal, nearshore water may become hypersaline due to concentrated salts from ice formation, and the temperature of under-ice water can reach -2°C or colder (Griffiths et al. 1977). These cold waters are not suitable habitat for anadromous or freshwater fish. Tidal fluctuations are on the order of 20 cm and do not play a major role in mixing and exchange between brackish and marine waters (Griffiths et al. 1977).

Freshwater Resident and Anadromous Fish of the North Slope of Alaska

Species in the family Salmonidae are perhaps the most diverse group of fishes that use North Slope freshwater habitats. They include lake trout (*Salvelinus namaycush*) and Arctic char (*S. alpinus*), which live exclusively in freshwater lake systems (Morrow 1980, Reist et al. 1997). Arctic grayling (*Thymallus arcticus*) and round whitefish (*Prosopium cylindraceum*) live in lakes and rivers and are rarely encountered in coastal waters. Most Dolly Varden (*S. malma*) populations are anadromous, while others are resident and live entirely in freshwater. Similarly, both anadromous and freshwater resident populations of least cisco (*Coregonus sardinella*) occur on the North Slope (Seigle 2003, Moulton et al. 1997). Broad whitefish (*C. nasus*) and humpback whitefish (*C. pidschian*) populations are typically anadromous, although freshwater populations may exist in certain lakes or in upstream reaches of the Colville River (Craig 1989). Arctic cisco (*C. autumnalis*) encountered on the North Slope of Alaska are entirely anadromous and return to the Mackenzie River in northern Canada to spawn (Fechhelm et al. 2007). Chum salmon (*Oncorhynchus keta*), pink salmon (*O. gorbuscha*), and other Pacific salmon species occur in low numbers in nearshore coastal waters of the Beaufort Sea each summer (Stephenson 2005). Small numbers of spawning chum and pink salmon are regularly observed in the Colville River and occasionally observed in other streams as well. Aside from chum salmon in the Colville River, it is not clear whether Pacific salmon observed in North Slope rivers are members of self-sustaining populations or strays from populations in drainages of the Chukchi Sea or farther south.

A number of non-salmonid fishes of several families have also adapted to aquatic habitats on the North Slope. Ninespine stickleback (*Pungitius pungitius*) populations can be either resident or anadromous (Morrow 1980). They are found in freshwater and nearshore habitats across the North Slope, and they play a critical role in the food webs of piscivorous birds (Poole 2005) and fish. Burbot (*Lota lota*) are common in stream and lake habitats of the western North Slope (Morris 2003), but they are rarely captured in coastal waters. Alaska blackfish (*Dallia pectoralis*), northern pike (*Esox lucius*), slimy sculpin (*Cottus cognatus*), and longnose sucker (*Catostomus catostomus*) are also found in freshwater habitats of the western North Slope. Habitat use for a subset of fish species is summarized in Table 5.2.

Table 5.2. Generalized life history and seasonal habitat use by common North Slope freshwater and anadromous fish.

		Habitat Use[2]								
		Open-water Season						Ice-cover Season		
		Streams		Lakes		Coastal Water		Streams		Lakes
Species	Life History Strategy[1]	Large	Small	Deep	Shallow	Near-shore	Ocean	Large	Small	Deep
Least Cisco	A	X		X	X	X		X		
	R			X						X
Arctic Cisco	A	X				X	X	X		
Round Whitefish	R	X	X	X				X	X	X
Broad Whitefish	A	X	X	X	X	X				
Humpback Whitefish	A	X		X	X	X		X		X
Lake Trout	R			X						X
Arctic Char	R			X						X
Dolly Varden	A	X	X			X	X	X	X	
	R	X	X					X	X	
Pink Salmon	A	X				X	X	X		
Chum Salmon	A	X				X	X	X		
Arctic Grayling	R	X	X	X	X			X	X	X
Ninespine Stickleback	A	X	X	X	X	X		X	X	X
	R	X	X	X	X	X		X	X	X

1. *Life history strategies: A=Anadromous, R=Resident. Least cisco, Dolly Varden, and ninespine stickleback have populations in both categories.*
2. *Habitat Definitions: Large streams have sufficient flow to allow instream (springs and deep areas) and estuarine (river delta) overwintering habitat. Small streams have insufficient flow to develop estuarine habitats, but some of these streams may provide instream overwintering habitat in the form of springs and deep pools. Deep lakes do not freeze to the bottom allowing year-round use by fish. Shallow lakes do not provide overwintering habitat but may be used by fish during the open water season if there is access. Coastal water (near-shore) is marine water that is somewhat warmer and of lower salinity than the ocean in summer, due to freshwater inflow during the open water period; these habitats take on fully marine characteristics of salinity and temperature during winter, which precludes their use by freshwater or anadromous species during that season. Coastal water (ocean) is fully marine habitat that does not allow overwintering of any salmonid species because of low water temperature.*

Effects of Climate Change on Fish of Arctic Alaska

The Intergovernmental Panel on Climate Change (IPCC) and the Arctic Climate Impact Assessment (ACIA) both identified the Arctic as an area where climate change effects will be observed most readily (IPCC 2007, ACIA 2005). Furthermore, aquatic systems within the region are expected to act as key indicators of the timing, rate, intensity, and effects of the change. Fish response to climate change is difficult to quantify due to the lack of basic biological information and the incomplete understanding of climate effects on ecological processes of freshwater systems (ACIA 2005). There is little doubt, however, that a changing climate has the potential for widespread consequences for the physical, chemical, and biological processes that are key components of fish habitat in arctic Alaska (Reist et al. 2006a). Reduced flow and increased air temperatures that cause higher water temperatures may also have direct effects on individual fitness and population resilience (Svenning and Gullestad 2002).

A warming climate is likely to increase ecosystem productivity, resulting in increased biomass and yields of many species (Reist et al. 2006b). The magnitude of change in ecosystem productivity and biomass will depend on local conditions and population tolerances. Freshwater resident fish in lakes may show increased production in comparison to those populations in flowing water. Increased productivity in nearshore areas could boost returns of anadromous fish. However, increased productivity in freshwater and estuarine systems could be offset if water temperatures rise past optima. Higher than optimum water temperatures could result in decreased biomass and yield, leading to altered rates and locations of colonization, extinction, competition, and productivity (Tonn 1990). Increasing temperatures will have a direct effect on available habitats, including populations reliant on colder water below the thermocline in lakes (Reist et al. 2006a). Increased air temperature and duration of the ice-free season may promote thermal stratification in lakes that currently remain unstratifed due to wind-mixing, short ice-free season, and low air temperatures. Over the past 40 years, presence and strength of late summer thermal stratification in several large deep lakes in the Brooks Range has increased dramatically (G. Burkart, National Park Service, personal communication). Juvenile fish constrained to the warm epilimnion (surface layer) may experience lower growth rates because greater food availability may not compensate for higher metabolic rate, while adult fish seeking thermal refuge in the hypolimnion (deep layer) may experience anoxic conditions due to the increae in pelagic productivity in the warmer surface waters.

Longer term changes may also lead to a disturbance of synchronized environmental cues, such as photoperiod and water temperature, which may drive major life history actions, including gonadal maturation and fertilization success (Reist et al. 2006a). Changes in groundwater flows may affect the type and amount of instream sediment and substrate, alter chemical composition, and change the temperature of the water, leading to increased physiological stress for populations not adapted to these new conditions. Changes to the physical and chemical properties of water may reduce incubation success and the availability of overwintering habitat. In addition, groundwater can alter the timing, extent, and duration of ice cover, which may lead to changes in habitat structure. Changes in both groundwater and precipitation runoff may affect the flow regimes of rivers and streams and disrupt the migration patterns of freshwater and anadromous fish (Prowse et al. 2006). An increase in sea level and coastal erosion may also disrupt traditional migration patterns or make current habitats unavailable (ACIA 2005).

Dolly Varden char (Salvelinus malma malma) *in arctic Alaska can be found in both anadromous and resident populations. Photo by Fred DeCicco, Alaska Department of Fish and Game.*

Access to Spawning and Overwintering Habitats
Periods of low stream flow and low water levels in lakes could have significant effects on migratory patterns of many fish populations (Reist et al. 2006a, 2006b). Sufficient flows during particular seasons are critical to fish movements and also reduce stranding events (Power et al. 1999).

The degree to which changes in water balance impact fish will depend in part on the type of watershed they occupy and the time of year. Anadromous and many freshwater resident fish populations on the North Slope are highly migratory and are reliant on corridors with sufficient discharges to complete their annual life cycle. While anadromous populations move between freshwater and marine environments (Craig 1989), freshwater residents move among individual lakes and streams, as well as within lake and stream systems (Morris 2003). During the spring freshet (water flow resulting from sudden rain or melting snow), anadromous populations move from overwintering areas in freshwater to summer feeding areas in marine water. These populations then leave marine waters in late summer and ascend rivers to spawn and overwinter. Freshwater residents that spawn in the spring are also dependent on the freshet when they move from overwintering areas to spawning areas. After spawning, they move to summer feeding areas, and in late summer and fall return to overwintering areas. Freshwater residents that spawn in the fall move directly from overwintering to feeding areas in the spring, and in late summer and fall return to spawning and overwintering areas. Because the freshet is driven by snowmelt, sufficient flows during spring are expected to be available for fish to move to preferred habitats, regardless of their life history strategy.

Key impacts could occur in late summer and early fall, however, when warmer air temperatures and increased evapotranspiration reduce the amount of water stored at the surface, causing a drying effect that may limit access to spawning and overwintering habitats. Even in those areas where stream baseflow is likely to increase or be maintained (Kane 1997), hot, dry summers could result in at least a temporary loss of connectivity. For example, Deegan and Peterson (1992) described a case in the summer of 1990 where water levels in the upper Kuparuk River were low, many riffles were nearly dry, and many of the deeper pools were isolated. A similar instance was noted in the upper John River near Anaktuvuk Pass in the Brooks Range (G. Burkart, National Park Service, personal communication). Arctic grayling in several areas of the stream became stranded, and only after a heavy rain event in September were water levels high enough to allow these fish to migrate to overwintering areas. If similar circumstances become more common across the North Slope, fish may be delayed in their migrations, and they may not be able to access spawning or overwintering areas prior to freeze-up, with direct mortality likely.

Increased Water Temperatures
Periods of low stream flow and low water levels in lakes could also have significant effects on the temperature regimes of the habitats required by many fish populations (Reist et al. 2006a). Fish seek out habitats with water temperatures that fall within their thermal preference (Coutant 1987). These habitat areas can be dispersed, and the availability of water at the preferred temperatures limit seasonal and spatial fish distribution. As such, water temperatures influence migration patterns (Svenning and Gullestad 2002), can pose a barrier to movement, and influence the availability of pathways to access preferred habitats (Coutant 1987). Water temperature also affects physiological processes, including growth, gonadal maturation, and egg incubation, as well as population productivity and survival (Reist et al. 2006a). Warmer waters may also increase the prevalence of diseases and parasites (Reist et al. 2006b) and increase the uptake and toxicity of contaminants (Schiedek et al. 2007).

If streams on the North Slope become shallower, fish may be unable to access seasonal habitats such as overwintering areas. Photo by Larry Hinzman.

Conceptual Model: Effects of Changed Surface Hydrology and Water Temperature

We developed a conceptual model describing potential effects of changed surface hydrology and water temperature on North Slope fish (Figure 5.7). Narratives describing elements of the model are presented below.

1. As soil moisture and surface storage change, baseflow in mountain streams during summer and fall will likely increase and may be sufficient to maintain the physical connections among required habitats within a watershed; if increased precipitation is insufficient to compensate for increased evapotranspiration, however, loss of connectivity is probable. Moreover, surface flow may also be controlled by thaw depth beneath the channel, and a deeper active layer may allow more underground flow and drying at the surface. Water levels in mountain lakes may decrease, but should remain sufficient in most cases to support populations of lake trout and Arctic char. In settings where fish move between deeper overwintering lakes and productive shallow lakes for summer foraging, however, a loss of connectivity could result in reduced food availability or stranding.

   A shift from surface storage to soil storage of water could lower water levels in coastal streams and lakes and reduce connectivity among these waterbodies. Species that rely on these connections to access critical habitats, such as broad whitefish, least cisco, Arctic grayling, and ninespine stickleback (Moulton 2007), may be forced into less preferred habitats (Wrona et al. 2006). A lack of connectivity between streams and their deltas may also affect the amount of overwintering habitat available and the timing of annual migrations for resident species. For anadromous species, the loss of connectivity may restrict access to spawning and overwintering areas as fish return from summer feeding in estuarine and marine waters.

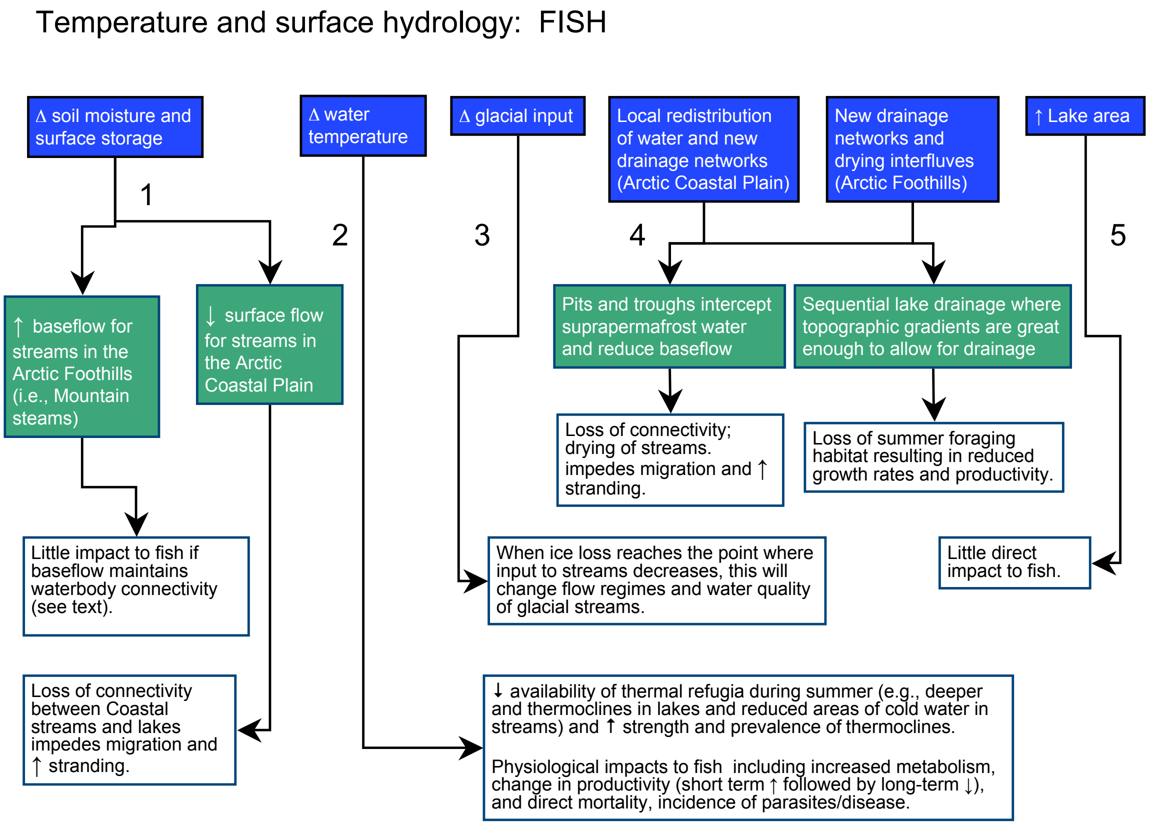


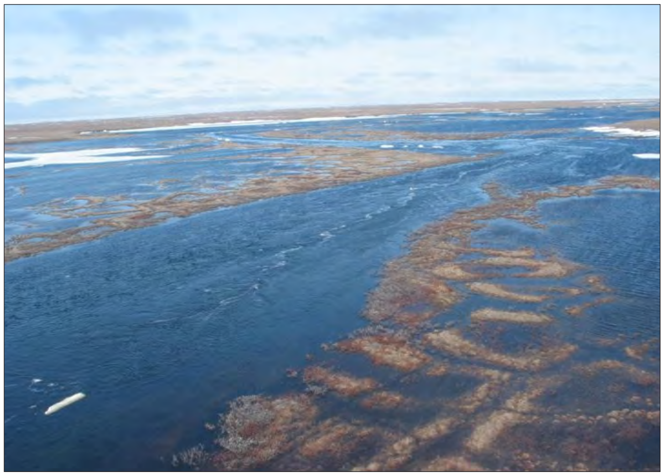
Figure 5.7. Conceptual model describing potential effects on changes in surface hydrology and water temperature on North Slope fish. Blue text boxes identify physical drivers, green boxes identify habitat effects, and white boxes summarize biological implications of habitat change.

2. Increased water temperatures in late summer may prevent fish from reaching spawning and overwintering areas after summer feeding. The magnitude of temperature change and loss of thermal refugia will differ among stream systems, with those systems fed by springs or glaciers (see element 3) likely having cooler water that will allow normal fish movements. Fish inhabiting mountain lakes, such as lake trout and Arctic char, may be confined to deeper waters as water temperatures increase (Reist et al. 2006c), and may be restricted from moving into shallow areas and summer feeding areas along the shoreline. Migratory fish that use Coastal Plain streams and lakes may be the most affected by increases in water temperatures. Although migratory fish may be able to find suitable temperatures in deep portions of these waterbodies, warmer temperatures at the surface may interfere with emigration. Also, warmer temperatures in streams may constrain movements and result in fish becoming stranded in isolated pockets of cooler water (Power 1999). Increased water temperatures could lead to higher metabolism and higher productivity, but will likely result in long term decreases in yield (Tonn 1990). Consistently high temperatures could also lead to direct mortality.

3. Migratory fish rely on sufficient late summer discharge to reach spawning and overwintering habitats. Glacial stream systems and the fish that use them are likely to be significantly impacted by a warming climate. As the rate of ice loss continues to increase for Brooks Range glaciers (Nolan et al. 2006), these glaciers are expected to disappear in the next 100–200 years (Weller et al. 2007). When ice loss reaches the point at which meltwater input decreases, sufficient discharge may not be available to allow Dolly Varden and other species that use glacial systems to complete their migrations from summer feeding areas to spawning and overwintering habitats. The decrease in amount of meltwater may also change turbidity and other water quality characteristics to which these populations have adapted.

4. As air temperatures increase, the distribution of surface water on the Coastal Plain is likely to change due to both local redistribution of water and formation of new drainage networks (McGraw 2008). Newly formed pits and troughs can intercept subsurface flows, decreasing baseflow into streams and reducing connectivity among streams and lakes. Where topographic gradients are large enough, new drainage networks may form, resulting in the loss of connectivity among previously used corridors, potentially disrupting migration.

5. Increased thermokarst along lakeshores will cause soils to slump into the lakes (Prowse et al. 2006), expanding lake surface area and increasing the amount of shoreline habitat. Provided that lake expansion does not result in breaching of the lake margins, this will result in a slight increase in fish habitat availability.



Ublutuoch River during spring breakup (above) and mid-summer (below). Strong seasonal variation in flow regime is a characteristic of Coastal Plain streams that could be accentuated by climate change. Photo by Richard Kemnitz, Bureau of Land Management.

Terrestrial Mammals

Twenty-eight species of terrestrial mammals live in arctic Alaska from the crest of the Brooks Range north to the Beaufort Sea (Bee and Hall 1956, Wilson and Ruff 1999, Table 5.3). Polar bears are usually classified as marine mammals, but, because they use terrestrial habitats for birthing dens and scavenging carcasses, they are included here. Some arctic species are restricted to very narrow ecological niches, using only one type of tundra and/or a very specific diet; others have broad niches, using a wide variety of habitats and/or foods. Species vary in their geographic distributions from those that are endemic to northern Alaska, to those found worldwide throughout the northern hemisphere (Table 5.3). For many broadly distributed species, arctic Alaska includes the northern limit of their geographic range.

Table 5.3. Species, habitats, and geographic range of mammals found in arctic Alaska, north of the Brooks Range mountains.

Common name	Scientific name	Habitats (niche breadth)	Range
Red-backed vole	*Myodes rutilus*	Forest + tundra (3)	6
Singing vole	*Microtus miurus*	Tundra dry shrub (2)	3 N
Tundra vole	*Microtus oeconomus*	Tundra taiga moist graminods (3)	6
Collared lemming	*Dicrostonyx groenlandicus*	Arctic tundra shrub (1)	2
Brown lemming	*Lemmus trimucronatus*	Arctic+ subarctic graminoids (2)	4
Snowshoe hare[1]	*Lepus americanus*	Forest + tundra (3)	5 N
Alaskan hare[1]	*Lepus othus*	Tundra (1)	1 N
Porcupine	*Erethizon dorsatum*	Forest + tundra (3)	5 N
Arctic ground squirrel	*Spermophilus parryii*	Forest, tundra, meadows (3)	3 N
Alaska marmot	*Marmota broweri*	Tundra alpine rocks (1)	1 N
Dall's sheep	*Ovis dalli*	Arctic+subarctic alpine rocks (1)	3 N
Caribou	*Rangifer tarandus*	Tundra + open woodlands (3)	6
Muskox	*Ovibos moschatus*	Tundra graminoid + shrub (2)	2
Moose	*Alces americanus*	Forest + tundra shrub (3)	6
Barren-ground shrew	*Sorex ugyunak*	Tundra graminoid+shrub (2)	2
Tundra shrew	*Sorex tundrensis*	Forest+tundra graminoid shrub (3)	5
Dusky shrew	*Sorex monticolus*	Forest+tundra wet areas (3)	5 N
Alaska tiny shrew	*Sorex yukonicus*	Forest, riparian shrub (3)	2
Least weasel	*Mustela nivalis*	Forest, prairies, tundra (3)	6
Ermine	*Mustela erminea*	Forest, meadows, tundra (3)	6
Mink	*Neovison vison*	Streams, lakes, marshes (2)	5 N
Arctic fox	*Vulpes lagopus*	Arctic tundra and coasts (2)	4
Red fox	*Vulpes vulpes*	Forests, deserts, tundra (3)	7
River otter	*Lontra canadensis*	Rivers + lakes: fish (2)	5 N
Wolverine	*Gulo gulo*	Forests, taiga, tundra (3)	6
Wolf	*Canis lupus*	Forests, tundra: ungulates (2)	7
Grizzly bear	*Ursus arctos*	Forests, taiga, tundra, deserts (3)	6
Polar bear[2]	*Ursus maritimus*	Arctic sea ice: ice seals (1)	4

Niche breadth (number of habitats/types of food): 1=few; 2=moderate; 3=many. Geographic range: 1=endemic, arctic/west Alaska; 2=arctic Alaska/Canada; 3=Alaska/northern Canada; 4=circumpolar arctic; 5=Alaska through west or south U.S.; 6=circumpolar-boreal north to mid-latitudes; 7=most of northern hemisphere; N=northern extent of range. Species are grouped as in Tables 5.4, 5.5. Scientific names and ecological information from Wilson and Ruff (1999) and Wilson and Reeder (2005). Geographic distribution and other ecological information summarized from MacDonald and Cook (2008) and the IUCN Red List 2008 (www.iucnredlist.org).

[1] *Both species have been recorded on the North Slope. The range of* L. othus *evidently has contracted from the North Slope in the past century;* L. americanus *is known to occur today along the Colville River. Despite some taxomonic uncertainty,* L. othus *appears to be a distinct species (Waltari and Cook 2005).*

[2] *Polar bears use terrestrial habitats for natal dens and scavenging carcasses.*

Arctic mammals can be grouped by diet, body size, winter survival strategies, and reproductive strategies (Table 5.4). Arctic mammals eat plants (herbivores), other animals (carnivores), or a mixed diet of plants and animals (omnivores). Terrestrial mammals range in size from the 10-g tundra shrew to the 600-kg polar bear. Arctic mammals can be classified as small (<0.1 kg), medium (0.5–10 kg), large (50–90 kg), or very large (>150 kg), based on the average mass of adult females (Wilson and Ruff 1999).

Reproductive strategies play an important role in the fitness of arctic mammals (Table 5.4). Most arctic mammals are blind, naked, and helpless (altricial) at birth and need shelter and parental care that can last from a few weeks to ≥2 years. In contrast, some medium-sized herbivores (e.g., hares and porcupines) and large ungulates (e.g., caribou, Dall sheep, muskoxen, and moose) produce more mature (precocial) offspring. All young mammals obtain their initial nutrition from milk produced by their mothers, and

Table 5.4. Arctic mammals grouped by body size, diet, and life history strategies.

		Group characteristics		
Group	**Common name**	**Body size and diet**	**Winter strategy**	**Reproductive strategy**
H1	Red backed vole Singing vole Tundra vole Collared lemming Brown lemming	Small herbivores <0.1 kg	Subnivian (active beneath snow) Store food	Altricial offspring Short gestation, lactation, parental care Multiple medium to large litters
H2a	Snowshoe hare Alaskan hare Porcupine	Medium-sized herbivores 0.5–10 kg	Active	Precocial offspring Short to long gestation, lactation, parental care Single & multiple small to large litters
H2b	Arctic ground squirrel Alaska marmot	Medium-sized herbivores 0.5–10 kg	Dormant in den (hibernation) Fatten before denning Use body reserves	Altricial offspring Short to medium gestation, short lactation, social groups Single small to medium litters
H3	Dall sheep Caribou Muskox Moose	Large/very large herbivores (ungulates) 50–200 kg	Active Adapted to cold & less food Use body reserves	Precocial offspring Long gestation, lactation, parental care Single birth of 1–2 offspring
C1	Barren-ground shrew Tundra shrew Dusky shrew Least weasel Ermine	Small carnivores <0.1 kg	Active and/or subnivean	Altricial offspring Short gestation & lactation; short to medium care Single/multiple medium to large litters Delayed implantation in mustelids (weasels)
C2	Mink Arctic fox Red fox River otter Wolverine Lynx Wolf	Medium/large carnivores 0.5–45 kg	Active Adapted to cold	Altricial offspring Short to medium gestation & lactation; short to long care Single small to large litters
C3	Grizzly bear Polar bear	Very large carnivores/omnivores >200 kg	Dormant in den Fatten before denning Use body reserves	Altricial offspring Delayed implantation, medium gestation, very long lactation & care Single small litters

Ecological information summarized from Wilson and Ruff (1999) and various authors from IUCN Red List 2008 (www.iucnredlist.org).

lactation is a major energetic cost for reproductive females (Vaughan et al. 2000, Persson 2005). The length of gestation, lactation, and parental care ranges from a few weeks to ≥2 years (Wilson and Ruff 1999). Most arctic mammals reproduce once per year, and litter sizes vary from 1 to >20. Some small and medium-sized mammals (e.g., shrews, lemmings, voles, snowshoe hares, and least weasels) can have >2 litters per year. In contrast, some very large herbivores and carnivores, e.g., muskoxen and grizzly bears, have few offspring at intervals of 2 or more years (Wilson and Ruff 1999).

Unlike most birds that are present in the Arctic only during the brief summer season, most mammals remain year-round. Therefore, winter survival strategies are critical (Table 5.4). Arctic mammals survive the long winter by:

1. adapting to cold temperatures and low food availability and living in the arctic landscape year-round (surface active);
2. storing food and remaining active in winter beneath insulating snow cover (subnivean); or
3. putting on large fat reserves and spending the winter in dens in true hibernation or a torpid (dormant) state (Blix 2005).

Even species that typically migrate, such as caribou, move only short distances relative to most birds and are therefore exposed to severe winter conditions, requiring specific adaptations to cold and resource shortages.

The previously identified mammal groups (Table 5.4) also vary with respect to their habitat and physiological requirements for survival and reproduction (Table 5.5). Identification of these essential elements is a useful starting point for developing hypotheses regarding species' vulnerability to climate-related habitat change. During the short growing season, mammals must have access to adequate food to replace body reserves lost the previous winter and depleted during pregnancy and lactation. They must also accumulate body fat to survive the coming winter. In winter, mammals must conserve energy, access stored food or fat reserves, and find appropriate shelter. Females that are pregnant and lactate during the winter season require additional body reserves and natal nests or dens to shelter helpless offspring.

Table 5.5. Seasonal requirements of arctic mammals.

Group	Mammals	Winter season needs	Growing season needs
H1	Microtines (lemmings and voles)	Access to stored food Hoar frost layer Snow for insulation Natal nests	Abundant green forage Food to store for winter Natal and post natal nests Runways + escape cover
H2a	Hares and porcupines	Winter forage Shelter for offspring Escape cover	Abundant green forage Shelter for offspring Escape cover
H2b	Ground squirrels and marmots	Winter dens Snow for insulation	Abundant green forage Burrows for escape/sleep Large pre-winter body reserves
H3	Large ungulates (sheep, caribou, muskoxen, moose)	Adequate winter forage Escape terrain (sheep) Soft shallow snow	Abundant green forage Escape terrain (sheep, moose) Pre-winter body reserves
C1	Shrews and small mustelids (weasels)	Invertebrate/microtine prey Natal nests Snow for insulation	Invertebrate/microtine prey Nests
C2	Medium/large mustelids, foxes, lynx, wolves	Winter prey or carcasses Natal and/or permanent dens	Summer prey or carcasses Dens/shelter
C3	Bears	Natal and/or winter dens Adequate snow for insulation	Access to food Large pre-winter body reserves

Effects of Climate Change on Mammals of Arctic Alaska

Climate change will have different effects on arctic mammals in different seasons. Winter is the dominant season in the Arctic, lasting for 8–9 months of the year. Although temperatures below 0°C and snow can occur any time of the year, these conditions generally exist from September through May. As a result of climate change, temperatures and precipitation are expected to increase, primarily in winter. Warmer winter temperatures will likely affect amounts of precipitation, the density and hardness of snow, and will likely increase the frequency of rain-on-snow or “icing” events.

The growing season in the Arctic occurs from early to mid-June through early to mid-August. Although this is a relatively short period in the annual cycle, the growing season is key to survival. Herbivores and omnivores depend on the high digestibility and nutritional value of green plants to replace body reserves used up during the long winter, to meet the demands of pregnancy and lactation, and to fatten before the next long winter season. Several species, like muskoxen, do not breed until body mass reaches a minimum threshold (White et. al 1997).

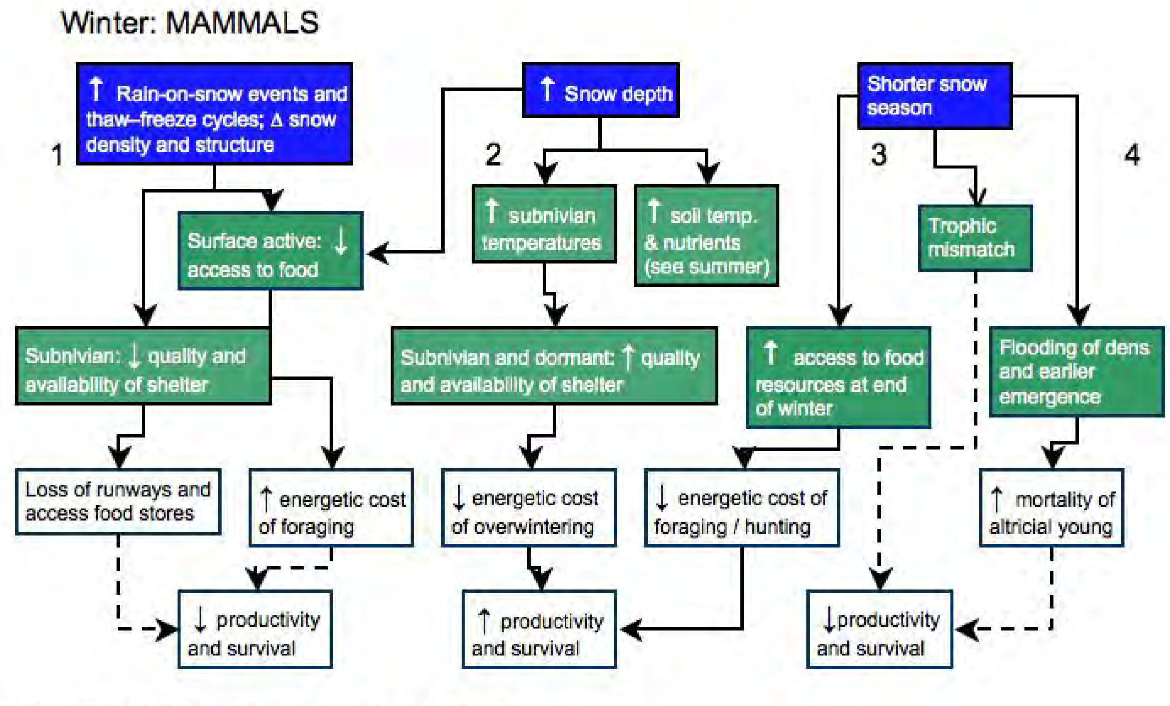
Conceptual Models: Changes in Winter and Growing-season Conditions

Two conceptual models were developed summarizing potential effects of changing conditions on arctic mammals during winter and during the short growing season (Figures 5.8, 5.9). We assumed a scenario of increasing temperatures and precipitation, primarily in winter (Walsh et. al 2008, IPCC 2007). Numbered elements within the model are described more fully below.

Winter

1. Warmer temperatures in winter will likely result in an increase in thaw-freeze cycles and the number of rain-on-snow (icing) events. Denser, harder snow and the formation of ice layers within the snow pack or at ground level will reduce accessibility to forage and increase energetic costs for ungulates and other mammals active throughout the winter. A severe icing event in October 2003 resulted in the deaths of thousands of muskoxen on Banks Island (Grenfell and Putkonen 2008). Ice layers and changes in snow structure may cause the loss of nests and runways and could decrease access to stored food used by subnivean herbivores. The effect of ice layers on the transportation of oxygen and carbon dioxide through snow is unknown, but this may be important for denning and subnivean mammals.

Figure 5.8. Conceptual model illustrating possible effects of changing conditions during the winter season (September–May) on arctic mammals. Blue text boxes identify physical drivers, green boxes identify habitat effects, and white boxes summarize biological implications of habitat change.



Dashed lines indicated a negative impact to energy balance.

2. Deeper, harder snow will be energetically costly to ungulates and possibly some predators who must travel through snow or dig through snow to find food. Deeper snow could benefit some species, however. For example, deeper snow would provide additional insulation for denning and subnivean mammals and might create additional denning habitat for polar bears. The insulative effect of deeper snow will also increase winter soil temperatures, potentially enhancing microbial activity and nutrient availability for plants (see *Growing Season* below).

3. Warmer winter temperatures and a shorter snow season would result in the early emergence of some plants. This would provide early green forage and reduced energetic costs for some ungulates and possibly other species, but this shift could also disrupt the seasonal synchrony between herbivores and the plants upon which they feed. Emerging plant species have higher forage quality than do plants at later phenological stages (Jorgenson et al. 2002). Herbivores such as caribou migrate to calving areas and give birth when tussock sedges are emerging. Earlier emergence may result in forage of lesser quality being available during calving and peak lactation when nutritional demands reach a yearly maximum (Griffith et al. 2002).

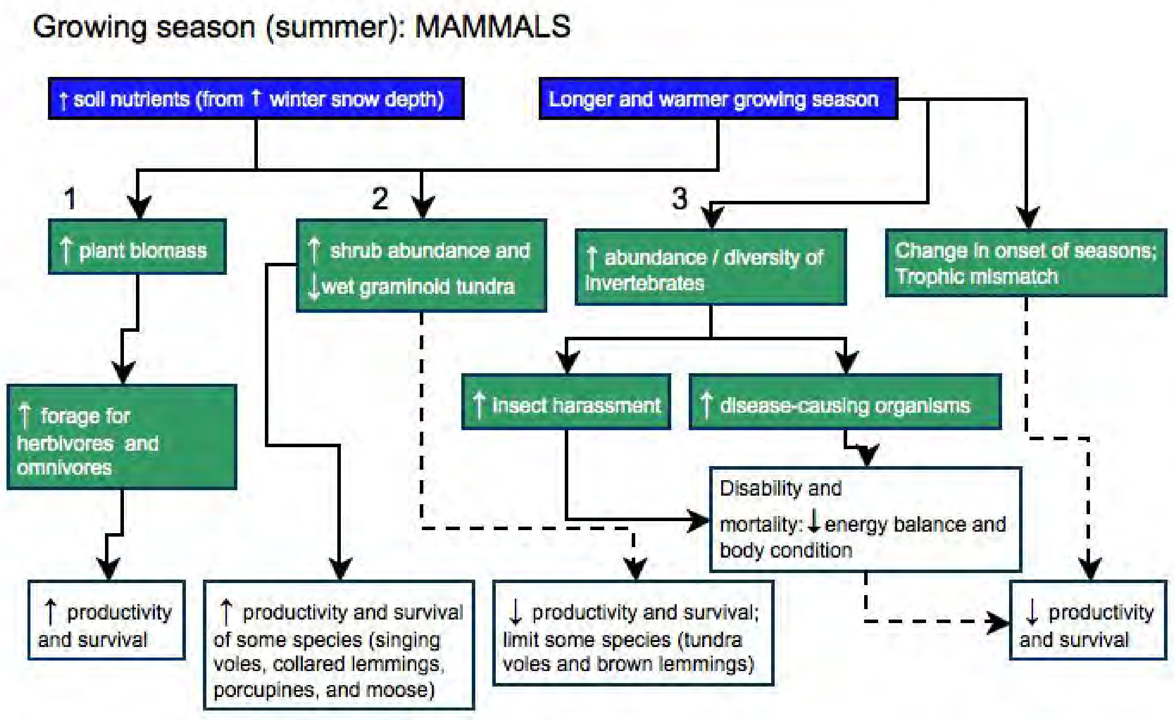
4. Warmer temperatures will result in a shorter snow season and reduced snow extent in late winter. Earlier breakup and flooding may affect subnivean mammals and mammals in winter dens. Warmer temperatures will likely result in early emergence from winter dens and the subsequent death of altricial neonatal offspring like bear cubs, canid (wolves, foxes) pups, and young rodents.

Growing Season

1. Improved nutrient availability, as a result of warmer winter soil temperatures, could increase overall primary productivity/for age availability, but also may contribute to a shift toward a more shrubby environment (Sturm et al. 2005), with divergent effects on mammal populations (see below).

2. With a longer, warmer growing season, plant biomass will likely increase, providing more forage for large and small herbivores, including lemmings, voles, squirrels, and large ungulates. In experiments, cool overcast summers were accompanied by lower productivity of grasses and forbs (Lenart et al. 2002, Rachlow and Bowyer 1998), but a long-term trend toward warmer and drier conditions may result in a shift to increased shrub cover. Shrubby tundra and boreal forests are expanding northward

Figure 5.9. Conceptual model illustrating possible effects of changing conditions during the growing season (June–August) on arctic mammals. Blue text box identifies physical drivers, green boxes identify habitat effects, and white boxes summarize biological implications of habitat change.



Dashed lines indicated a negative impact to energy balance.

and up mountain slopes (Sturm et al. 2001, Danby and Hik 2007). If wet graminoid tundra is replaced by drier shrubbier tundra, singing voles, collared lemmings, snowshoe hares, porcupines, barren ground shrews, and moose could benefit, and brown lemmings, tundra voles, and tundra and dusky shrews may not. The diversity of arctic-adapted species will likely decline if some arctic habitats disappear, but overall diversity may increase as additional species shift their ranges northward.

3. Warmer temperatures and a longer growing season will likely increase the abundance of invertebrates, parasites, and disease organisms that could potentially negatively affect all arctic mammals. For example, life cycles of protostrongylid nematodes (*Umingmakstrongylus pallikuukensis* in muskoxen and *Paralaphostrongylus odocoilei* and *P. stilesi* in Dall's sheep) shorten as temperatures warm and the frost-free season lengthens, increasing the incidence of disease (Kutz et al. 2004, Jenkins et al. 2006). Increases in biting insects like bot and warble flies will likely cause stress and declines in body condition in caribou and other species (Thomas and Kilaan 1990). If drier summer conditions prevail, soil invertebrate communities will change; shrews would likely benefit if there were an overall increase in invertebrate abundance.

*Above: A group of muskoxen (*Ovibos moschatus*) on the North Slope. Although the species was extirpated from Alaska in the late 19th century, it was successfully reintroduced in the 20th century. Photo by Richard Flanders. Below: A Dall's sheep ram (*Ovis dalli*) in the Brooks Range. Photo by Ken Whitten.*

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Hatching snowy owls (Bubo scandiacus). *Snowy owls breed across the circumpolar Arctic. Photo by Elizabeth Eubanks (PolarTREC 2008), courtesy of ARCUS.*

Chapter 6

Working Groups' Summaries: Common Themes and Research Gaps

This chapter synthesizes the discussions of the WildREACH working groups for birds, fish, and mammals.

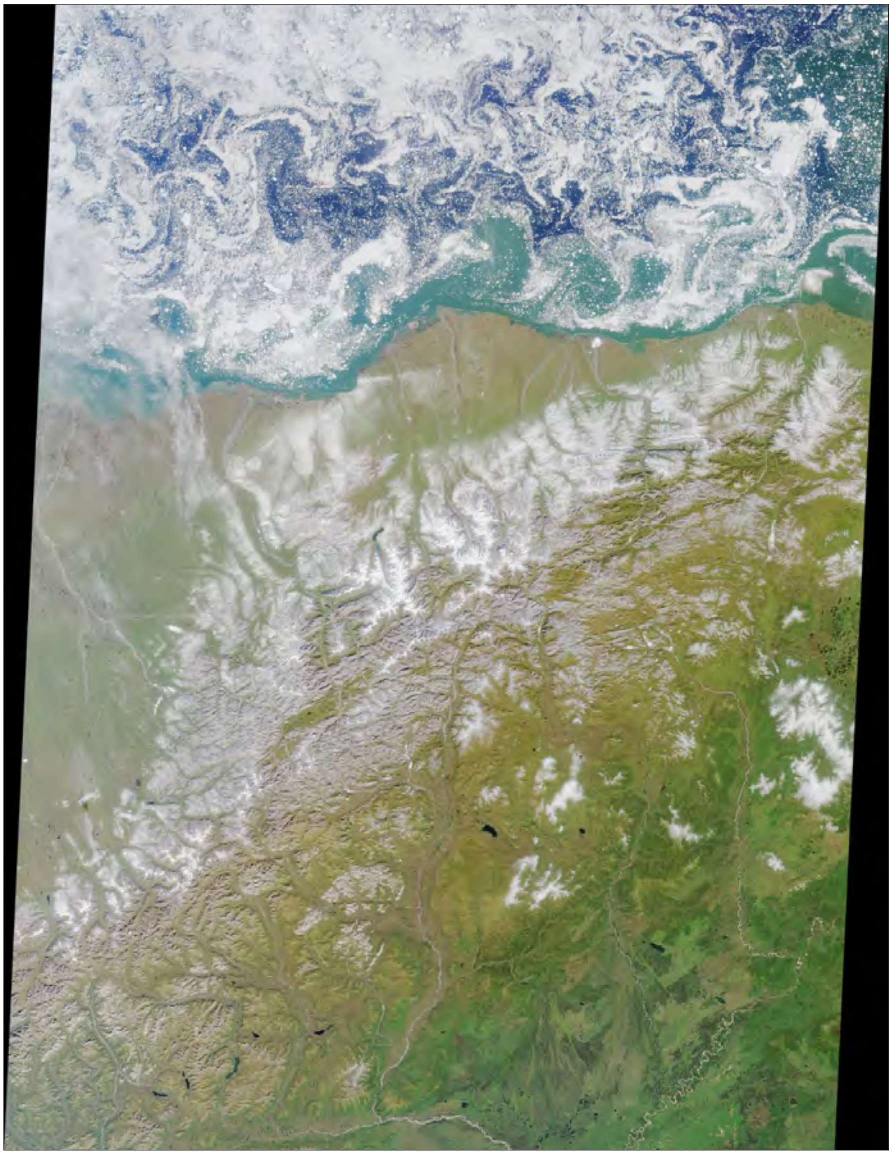
The working groups were multidisciplinary groups of scientists and multi-organization groups of managers (see Appendix 5). The working groups' findings are organized into four sections:

Integrated Research and Monitoring. All working groups emphasized the importance of interdisciplinary studies and recognized that collaboration between geophysical and biological specialists is paramount.

Common Themes Across Species Groups. Specific information gaps varied among species groups, but most fell into four crosscutting themes: 1) changes in precipitation and hydrology; 2) changes in vegetation communities and phenology; 3) changes in abundance and timing of invertebrate emergence; and 4) coastal dynamics.

Fish and Wildlife Ecology Data. All working groups emphasized that information available on life history, habitat requirements, distribution, abundance, and demography is inadequate for many arctic species. More complete information on basic life history is needed to refine hypotheses and improve our predictions regarding species' response to environmental change.

Focal Species in the Context of Climate Change. All working groups developed a preliminary list of focal species perceived to be sensitive indicators of climate change.



Above: Image of the Arctic National Wildlife Refuge and the Beaufort Sea acquired by the Multi-angle Imaging SpectroRadiometer's nadir (vertical-viewing) camera on August 16, 2000, during Terra orbit 3532. The area represented by the image is approximately 380 km x 540 km. Image Credit: NASA/GSFC/LaRC/JPL, MISR Team.
Below: Arctic grayling (Thymallus arcticus) *have highly variable life history strategies depending on location. Some populations are highly migratory while others are relatively sedentary. Wikimedia Commons photo.*

Need for Integrated Research and Monitoring

We cannot accurately predict the effects of climate change on organisms without sufficient information about the underlying biological and physical processes that drive terrestrial and aquatic ecosystem functions (Wrona et al. 2006). Acquiring this understanding will require additional effort in three complementary areas:

1. Long-term monitoring of physical and biological parameters;
2. Field observations and focused process studies to clarify the mechanisms by which environmental variables influence fish and wildlife populations; and
3. Interdisciplinary synthesis modeling.

This approach is consistent with that proposed by Vörösmarty et al. (2000) in their assessment of the needs for developing a synthetic understanding of the arctic hydrologic cycle. The strong linkages and feedbacks between climate, permafrost, hydrology, and habitat conditions highlight the critical need for comprehensive, cross-disciplinary monitoring and research programs. Integrated long-term data sets from representative locations are needed to test hypotheses regarding the mechanisms by which climate affects habitat conditions and to parameterize models of landscape change. Similarly, moving toward more specific predictions regarding specific fish and wildlife responses to habitat change will require both long-term monitoring and focused research approaches.

Long-term data sets are particularly scarce in Alaska, where organized scientific programs are recent, and access to remote areas is difficult and expensive. Initial investment should be placed in “rescue” and assembly of legacy data to be used for retrospective analyses. These data sets may be limited by resolution and spatial scale; however, they may provide valuable insights into:

1. the extent, spatial scale, and intensity of monitoring efforts necessary to develop efficient and relevant approaches for long-term data collection and modeling needs,
2. mechanisms of change and their relative importance to fish and wildlife populations, and
3. additional gaps in data not addressed during this workshop.

Future approaches should include establishment of integrated long-term data sets at multiple scales. Satellite-based remote sensing approaches are essential for assessing attributes such as snow cover, green-up, and surface water on a regional scale. Processing and archiving these data sets in a readily usable form will require multi-agency coordination. At an intermediate scale (e.g., watershed), high-resolution satellite or aircraft-mounted sensors can provide elevation data for digital elevation models or detailed stream and landcover mapping. These remote sensing efforts combined with spatial and retrospective analyses will better inform planning efforts for costly long-term monitoring and process studies conducted on the ground. Cost considerations will likely limit ground-based efforts to relatively few sites, thus careful site selection will be important.

Multidisciplinary monitoring programs, integrated with research, will provide the best opportunity for developing a mechanistic understanding of climate-related habitat change. In this framework, intensive *in situ* research and monitoring would be scaled up to the landscape and regional level through modeling informed by remote sensing technologies. Monitoring and research should include replication across dominant environmental or ecological gradients using a distributed network of sites that are sampled at a lower intensity.

There are some existing long-term monitoring efforts on the North Slope of Alaska, which provide a limited foundation and baseline data for an integrative approach to long-term monitoring of fish, wildlife, and key environmental variables. For example, existing facilities at Toolik Lake and Barrow should serve as “flagship observatories” (Shaver et al. 2004) around which a research and monitoring program could be built. An essential element of an observatory is a sustained observational time series consisting of measurements of a core set of environmental variables. The Arctic Long Term Ecological Research (LTER) site at Toolik Lake provides the best example of integrated monitoring in northern Alaska (http://ecosystems.mbl.edu/ARC/Datatable.html, retrieved April 10, 2009), but data pertaining to higher trophic-level organisms are largely absent from the existing program, with the exception of freshwater fish. Suitable models for integration of fish and wildlife monitoring with environmental data exist, however, at sites such as Zackenburg Research Station, northeast Greenland (Meltofte et al. 2008). The National Park Service's Arctic Network Inventory and Monitoring Program provides an example that emphasizes the use of fish and wildlife as "vital sign" indicators of ecosystem function (http://science.nature.nps.gov/im/units/arcn/, retrieved 10 April 2009). These existing programs provide useful models, but data collection at the temporal and spatial scale necessary to effectively address climate change issues will require implementation of monitoring at multiple sites, and strong collaboration among federal, state and local agencies, academic institutions, conservation organizations, and private industry.

Much of the uncertainty in projecting future habitat conditions stems from an insufficient understanding of arctic hydrologic systems. In the Arctic, the thermal and hydrologic regimes are uniquely linked through changes in the active layer (the ground layer that experiences seasonal freeze and thaw), so coordinated study of the coupling between permafrost dynamics, soil moisture, and ecological systems is fundamental to predicting the extent and magnitude of habitat change. High priority must be placed on establishing a distributed network of watershed-based study sites to collect data essential to improved synthesis modeling of environmental change. A proposed set of measurements for hydrological study sites (modified from Vörösmarty et al. 2000) is provided in Box 6.1. Some of these parameters have been measured in the Kuparuk River watershed, beginning as early as 1985. We recommend establishing a long-term hydrological observatory within the Kuparuk River watershed and at least two additional watersheds to better represent variability across the North Slope. Data obtained at hydrologic observatories will be instrumental in creating predictive models that will help land managers better understand and manage fish and wildlife habitat in a rapidly changing climate.

Because climate modelling forms the basis for projections of habitat change, continued effort to improve the reliability of down-scaled climate models is crucial, and would likely benefit from an expanded network of meteorological stations with coordinated data storage and analysis. In considering climate effects, we are constrained to some degree by the ways in which we aggregate data. Projections of future climate conditions tend to focus on metrics describing annual or seasonal averages. While practical and often useful, evaluation of potential climate change effects based solely on average conditions overlooks the importance of extreme events on fish and wildlife populations. For instance, events such as rain-on-snow in winter (which have killed thousands of muskoxen and caribou) and major floods in summer (which have killed dozens of muskoxen, and likely caribou and moose) have a potential to devastate populations if they occur with increased frequency. Greater attention must be paid to modeling variability in climate conditions. Similarly, conditions during the seasonal transition periods (spring thaw, freeze-up) can be more critical for fish and wildlife populations than the relatively stable mid-winter or summer periods. Greater consideration of the key issues related to seasonal transitions is warranted.

Box 6.1. Examples of the coordinated set of measurements that might be made at an arctic hydrologic observatory study site. After Vörösmarty et al. (2000).

Hydrologic and other geophysical measurements
- Precipitation amount (year round)
- Evapotranspiration and sublimation
- Solar flux and surface energy measurements
- Snow pack
- Snow redistribution
- Snow melt
- Soil thermal properties and their variation
  - Temperature profiles
  - Active layer depth
  - Permafrost temperature
  - Thermal conductivity
- Infiltration on frozen and unfrozen soils
- Soil moisture
- Runoff flow paths
- Stream and large river discharge
- High-resolution and accurate digital elevation models
- Distribution of surface waters, including seasonal flooding and connectivity between lakes and rivers
- Timing of freeze-thaw cycles

Biological and biogeochemical measurements
- Precipitation chemistry
- Vegetation surveys (ecotype maps and community composition)
- Soil mapping, including ice content
- Monitoring of vegetation, soil, and groundwater chemistry
- Physical, chemical, and biological parameters in stream, river, and lake ecosystems
- Isotope and other tracers for discharge entering the Arctic Ocean

Common Themes Across Species Groups

Although climate change effects will differ among species and among taxonomic groups, a common set of environmental drivers and processes will affect habitat suitability for a broad suite of species. Four major themes emerge as relevant to a diversity of fish and wildlife species groups:

1. Hydrologic processes, including precipitation, water balance, and distribution of surface water;
2. Vegetation, including community composition and phenology;
3. Invertebrates (primarily aquatic or semi-aquatic forms), including productivity and phenology; and
4. Coastal dynamics, including the interacting effects of erosion, sedimentation, stream discharge, inundation, and plant successional processes.

Within these four general areas, there are specific needs for improving understanding of the physical processes that drive habitat change and the associated ecological responses, summarized in Table 6.1 and further elaborated below.

Hydrologic Processes: Precipitation, Water Balance, and Distribution of Surface Water

Understanding water balance and partitioning of water among habitat units is a key issue, with important direct and indirect implications across all fish and wildlife taxa. The changes associated with the projected wetter and warmer winter environment will have important implications for resident mammals (see below) but minimal direct consequences to birds because most are migratory and absent in winter. For arctic fish populations, overwintering habitat availability is currently limiting, and a warmer, wetter winter environment would most likely relax that constraint. The consequences of a hypothetical summer drying regime, however, are perceived as a greater threat to fish and birds. High priority is assigned to addressing the following questions:

- How reliable are the projections for increasing precipitation and evapotranspirtion?
- How will the annual precipitation input on the Coastal Plain and Foothills be allocated between winter (snow pack) and summer?
- How will changes in precipitation, evapotranspiration, and active layer depth alter summer surface water availability in shallow-water and mesic/wet tundra habitats?
- How will changing patterns of seasonal runoff affect stream flow?
- What is the contribution of groundwater in various systems, and is it sufficient to maintain year-round flow?
- Will drought conditions and changes in drainage patterns decrease water body connectivity?

Lakes may be susceptible to draining as a result of newly developed thermokarst drainage networks, thus:

- Which Coastal Plain lakes are susceptible to draining and on what time scale?

Increasing temperatures and precipitation in winter will affect food acquisition and energy balance of non-denning and subnivean mammals. For mammals, the quantity and nature of winter precipitation is of paramount interest, with a particular focus on the following questions:

- What are expected changes in snowpack characteristics (depth, density, presence of ice layers) and how might these vary on a regional and local scale?
- How much change will occur in the timing of snow melt and snow onset?
- How will the frequency of rain-on-snow and severe winter storm events change?

A collared lemming (Dicrostonyx groenlandicus) *in a subnivean runway. Lemmings spend the majority of the year in subnivean spaces, and the characteristics of the snowpack are likely to be critical to their survival and reproduction. Photo by Jean-Louis Klein and Marie-Luce Hubert.*

Vegetation Community Change

Changes in vegetation have important implications for several ecosystem processes. Vegetation exerts an important influence on soil moisture and temperature, active layer thickness, and permafrost stability, and vice versa. Changes in both plant phenology and the relative abundance of forage species will affect the palatability, nutritional quality, and quantity of available food for herbivores (primarily mammals in arctic Alaska). Changes in primary productivity will directly affect the carrying capacity of habitat for aquatic and terrestrial herbivores, and indirectly affect higher trophic levels. Vegetation is a primary component of habitat structure, which may affect suitability for some species independent of trophic effects.

Vegetation change will affect fish indirectly, primarily through export of terrestrial productivity into the aquatic system in the form of leaves and insects. This input could increase with increased floodplain shrub growth, with potential implications for invertebrate community composition and productivity. Shoreline stability and water temperature is also influenced by the vegetation adjacent to water bodies. For birds and mammals, the influence of changing vegetation communities is more direct, with the following issues considered highest priority:

- How will changes in temperature and precipitation affect plant community composition, including changes in habitat structure and nutritional quality of available forage (i.e., digestibility, nutrient content)?
- What is the expected rate of shrub increase, and how will this vary by species/growth form (low vs. tall shrub) and ecoregion?

Table 6.1. Pathways by which climate-influenced habitat change could influence arctic fish and wildlife, categorized by major themes.

Theme	Habitat Change Pathway	Affected Species Groups
Water: Precipitation, water balance, and distribution of surface water	Lake drainage due to development of new drainage networks	Birds, Fish
	Drying of shallow-water and mesid/wet tundra habitats	Birds
	Changes in flow regimes, as influenced by water source	Fish
	Drought-related loss of connectivity between water bodies	Fish
	Change in snowpack characteristics, e.g., depth and density	Mammals
	Change in the length and timing of the snow season	Fish, Mammals
	Change in the frequency and timing of extreme events, i.e., rain-on-snow events and major winter storms	Mammals
	Changes in aquatic trophic systems, including potential shift from benthic to pelagic production in lakes	Birds, Fish
Vegetation: Seasonality and community composition	Change in plant phenology, accompanied by change in the timing of forage nutritional quality	Birds, Mammals
	Change in plant community composition:	
	−Change in forage quantity and quality, at community level	Birds, Mammals
	−Shrub expansion	Birds, Mammals
	−Paludification and consequences for both herbivore and detritus-based trophic systems	Birds
	Increased primary productivity of terrestrial vegetation and export of nutrients into aquatic systems	Fish
	Change in riparian vegetation, as influenced by flow regime and frequency/severity of flooding	Birds, Fish, Mammals
Invertebrates: Phenology and abundance	Change in productivity, abundance, and seasonality of life cycles for aquatic and semi-aquatic invertebrates	Birds, Fish
	Change in timing of emergence and abundance of biting insects, parasites, and disease vectors	Mammals
Coastal Dynamics: Interactions of coastal erosion/deposition, river discharge, sedimentation, inundation, succession	Degradation of barrier island systems and alterations to physical/chemical environment of lagoons	Birds, Fish
	Increased fog/clouds and subsequent effects on evapotranspiration, snow melt, and plant phenology	Birds, Mammals
	Change in availability of coastal habitats, specifically coastal wet sedge and deltaic mud flats	Birds, Mammals
	Change in availability of deep-channel habitat in major river deltas	Fish

- How will changes in the length and timing of the growing season influence plant phenology, including seasonal changes in nutritional quality?
- What is the likelihood of widespread conversion from sedge and sedge-shrub meadow to bog meadow (paludification), and how would this affect herbivore and detritus-based trophic systems?
- How will changes in the seasonality of stream discharge and occurrence of flood events influence development of riparian vegetation communities?

Invertebrate Populations: Temperature and Seasonality Influences
Most species of birds and fish in arctic Alaska are predators of aquatic and semi-aquatic macroinvertebrates (e.g., insects, crustaceans, gastropods) and are therefore vulnerable to changes in productivity, abundance, and seasonality of life cycle stages. This is an exceptionally poorly studied aspect of arctic ecology, and experimental research and monitoring efforts to address the following areas are a high priority:

- How does earlier spring thaw affect timing of invertebrate life cycle events and peak availability to predators?
- How does temperature affect growth and development of aquatic insects?
- What climate-related changes are likely in community composition of macroinvertebrates in stream, lake, and saturated soil environments?
- How will changes in the distribution and quality of surface waters and shifts from pelagic to benthic productivity in deep lakes affect availability of macroinvertebrates to fish and wildlife?

For most mammals, invertebrates are more important in their role as parasites and vectors of disease, rather than prey. Related priority questions include:

- How will warming and changing seasonality affect abundance and peak activity periods of biting insects, and what are the bioenergetic consequences for caribou?
- How will warming and changing seasonality affect the prevalence of parasites and disease vectors (e.g., nematode parasites of muskoxen and Dall's sheep)?

Coastal Dynamics
Loss of summer sea ice, increased coastal erosion, rising sea level, warmer ocean waters, changing seasonality of river discharge, and altered sedimentation rates interact to affect coastal habitats. Coastal lagoons of the Beaufort and Chukchi seas are important summer feeding habitat and migration corridors for birds and fish, while deltas and coastal wet sedge tundra are important foraging habitats for shorebirds and waterfowl. Although coastal habitats are dynamic by nature, climate change may cause directional change that alters the availability of some habitats. Related priority questions include:

- Will higher water temperatures, sea level rise, and retreat of summer sea ice cause degradation of the barrier island systems of the Beaufort and Chukchi seas?
- Will alluvial deltas continue to build or will rising sea levels outpace potential increases in sedimentation rates?
- How quickly will shoreline retreat result in newly breached lake basins?
- To what extent will coastal erosion, in combination with sea level rise, cause salinization of low-lying coastal areas?
- Will coastal wet sedge meadows establish at a rate equal to loss of this habitat through erosion and inundation?

A longer ice-free season will strongly influence climate in the coastal zone. A longer open water season may increase the prevalence of fog, which will have a cooling effect in spring while a warming effect in fall.

- Will increased fogginess/cloudiness exert a negative or positive feedback effect on air temperature in the coastal zone? What would be the expected spatial extent of this effect?

*The USFWS has determined that listing the yellow-billed loon (*Gavia adamsii*) as a threatened or endangered species is warranted under the Endangered Species Act, but that listing is precluded by other higher priority species. The "warranted but precluded" finding was published in the Federal Register on March 25, 2009. The yellow-billed loon is now designated as a candidate species. Photo by Ted Swem, USFWS.*

With the exception of a few well-studied species, such as caribou, our knowledge of life history, habitat requirements, distribution, abundance, and demography is incomplete or poor for most arctic species; additional basic biological data are needed for all but the most general forecasts regarding species response to a warming climate. Because the region is remote, basic knowledge of status and distribution is often inadequate, as illustrated in the following examples:

- Little is known about the distribution and natural history of the Alaska marmot, an alpine-adapted species that has a limited and disjunct population.
- The Alaska Tiny Shrew is a newly described species (discovered in 1997) with only a few dozen specimens collected to date, two of which are from the North Slope.
- Spawning and overwintering areas are known for some populations of Dolly Varden in the eastern North Slope and broad whitefish in the Teshekpuk Lake region, but the extent of inter-drainage movement and the habitats used at different life stages for these and other species are poorly known.
- Little is known about the factors that limit Pacific salmon populations on the North Slope and the potential for range expansion into arctic waters.
- Knowledge of bird distribution is heavily biased toward the coastal areas, with very sparse data from the Foothills and northern Brooks Range, particularly west of the Dalton Highway.
- Habitat models that reliably predict bird species occurrence and/or abundance on the basis of measurable habitat parameters are lacking.

Alaska marmots (Marmota broweri) *are endemic to mountains north of the Yukon River (Gunderson et al. 2009); evidence suggests that these highly social animals hibernate in groups. Photo by Jake Schaas, Toolik Field Station.*

Cost constraints and practicality argue for conducting biological and life history investigations on focal species or related species groups, chosen on the basis of criteria that includes consideration of climate impacts; this topic is explored below.

Because species respond individualistically to climate drivers, it is expected that novel assemblages of species will arise. Given the difficulty inherent in predicting the composition of new species assemblages, consideration of interspecific interactions is largely deferred, except at the broad level of trophic dynamics. In specific instances, however, observed changes in other arctic regions suggest promising avenues for investigation:

- In most portions of the Arctic, lemming populations exhibit strong cyclicity, but observations in Eurasia over the past few decades indicate that lemming cycles are becoming less regular and of lesser amplitude (Ims and Fuglei 2005, Kausrud et al. 2008). A breakdown in the cyclicity of population highs could influence nutrient cycling, plant community composition, avian and mammalian predator population dynamics, and productivity of shorebirds and waterfowl. It is not known whether lemming population dynamics in arctic Alaska are similar to those reported from Eurasia.
- The Fennoscandian population of arctic fox is considered endangered (Angerbjörn et al. 2008). Competition with red fox, along with the influence of warming on prey (lemming) availability, has been suggested as contributing to the non-recovery of this arctic fox population (Frafjord 2003, Killengreen et al. 2006). Anecdotal evidence from northern Alaska documents interspecific competition (Pamperin et al. 2006) but is insufficient to demonstrate broad-scale displacement of the arctic fox. The relative abundance of the two species may be a useful early indicator of a climate related shift in predator-prey dynamics.

*The arctic fox (*Vulpes lagopus*), found across the circumpolar Arctic, is an important predator of small mammals and birds in summer and ranges out onto the sea ice in winter. Photo by Ken Whitten.*

Choosing Focal Species in the Context of Climate Change

Developing a better understanding of the physical processes that influence ecosystem function is an essential foundation for managing fish and wildlife populations affected by climate change. Basic biological information, however, such as seasonal habitat requirements, is deficient for many species. Understanding the response of arctic fish and wildlife to climate change requires improved understanding of physical and ecological processes, as well as enhanced knowledge of natural history and population ecology of arctic species.

Practical considerations dictate that resource management agencies choose a subset of species to actively study and manage—traditionally, those species whose numbers have or will decline without management intervention or which have significant public recreational or commercial value. Choosing these "focal species" is a challenging task, best undertaken in a structured fashion based on objective criteria. In the context of the Fish and Wildlife Service's "Strategic Habitat Conservation" approach, it has been suggested that these criteria reflect the importance of the species relative to its ecological significance, management significance, legal mandates, and feasibility of implementing long-term, landscape-based adaptive management.

Above: Both species of phalarope found in northern Alaska —red phalaropes (Phalaropus fulicarius) *and red-necked phalaropes* (Phalaropus lobatus)*—may be good indicator species for climate change effects. Photo by Stephanie Clemens, USFWS.*
Below: This polar bear (Ursus maritimus) *ranged about 125 miles inland along the Dalton Highway in October 2002 before returning to the coast. Photo by Richard Flanders.*

Climate change adds complexity to the process of selecting focal species. While existing lists (e.g., endangered species listing, NatureServe heritage ranking, International Union for Conservation of Nature [IUCN] Red List) reflect population response to past events, consideration of climate change forces us to consider a future in which over 40% of species are at risk of extinction globally (IPCC 2007), and the arctic tundra region may experience up to 74% turnover in species assemblage (Lawler et al. 2009). Intrinsic life history traits that may be associated with greater extinction risk in a changing climate may be incorporated into a ranking process (Foden et al. 2008). An example of an application of this approach to arctic terrestrial mammals is provided in Box 6.2. While a valuable first step, this approach does not incorporate specific projections of habitat change on a local or regional scale.

The uncertainties surrounding scenarios of climate-associated habitat change exacerbate the difficulties in choosing appropriate focal species for conservation planning. Our approach has been to develop hypotheses regarding projected habitat change in the form of conceptual models (Chapter 5). For each model, we have proposed reasonably foreseeable fish and wildlife responses. Here, we propose monitoring priorities based on selection of species/parameters believed to be sensitive indicators of the hypothesized habitat changes (Table 6.2). The resulting list includes both common and rare species—some that would benefit from a warming climate and some for which negative effects are postulated. In this framework, focal species are selected, at least in part, on the basis of their perceived value as tests of specific models of habitat change. This list should be considered preliminary and should be refined through a further structured decision-making process. A second additional criterion to consider when refining selection of focal species is the timescale on which different processes of change occur. Some processes will alter habitats relatively quickly, while others operate on much longer timescales (Table 6.3). As the priority list develops, it may be necessary to add or remove species. The process must be undertaken in full awareness that initial projections of future habitat condition may be inaccurate (thus understanding of species' vulnerability limited), but this should not deter us from initiating biological monitoring. As data are collected and synthesized, conceptual models can be adjusted to reflect changes in our understanding or changes in processes and species/environmental responses.

A common eider (Somateria mollisima) *sits on her nest on a barrier island. Common eiders breed colonially, and females commonly return to their natal islands. Current evidence suggests that the existing system of barrier islands in northern Alaska may deteriorate or diminish in a relatively short time frame. Photo by James Zelenak, USFWS.*

Box 6.2. Ranking arctic terrestrial mammals by resilience to climate change

Effects of climate change on terrestrial mammals of the Arctic depend on the individual species' relative vulnerability or resistance to change (resilience). Resilience is a function of geographic distribution and niche breadth. Mammals that have a broad geographic range, are habitat generalists, and/or eat a variety of foods are more likely to survive changing environmental conditions than those that are highly specialized for the current arctic environment and are found only in the circumpolar north or in northern Alaska. For example, an endemic species like Alaska marmots that occurs only in northern and central Alaska is more likely to be adversely affected by climate change than red-backed voles, which live throughout Alaska and northern Canada. Arctic-adapted species like polar bears, muskoxen, and arctic foxes are more vulnerable to warming temperatures than species like grizzly bears and red foxes that are found throughout the northern hemisphere in a variety of habitats (see Table 5.3). Montane species (e.g., Alaska marmots, Dall's sheep) may be particularly vulnerable to changes occurring along elevational gradients that essentially shrink their available habitat.

In contrast, species like moose that are broadly distributed and have recently expanded their distribution into the Arctic likely have an advantage as temperatures warm. We estimated relative resilience scores for representative species living in the Alaskan arctic based on geographic range, niche breadth, population status, and life-history strategies (Table). Our results suggest that polar bears and Alaska marmots are likely to be most vulnerable to expected changes in climate.

Group	Species	Index of potential resilience
C3	Polar bear	7
H2b	Alaska marmot	7
H3	Dall sheep	8
C1	Barren-ground shrew	9
H1	Collared lemming	9
H2a	Alaskan hare	9
H3	Muskox	9
C2	Arctic fox	11
H1	Singing vole	11
H2b	Arctic ground squirrel	11
C2	Mink	12
C2	River otter	12
C2	Lynx	12
C3	Grizzly bear	12
H1	Brown lemming	12
H2a	Porcupine	12
H3	Moose	12
C1	Tundra shrew	13
C1	Dusky shrew	13
H3	Caribou	13
C2	Least weasel	14
C2	Ermine	14
C2	Wolverine	14
H2a	Snowshoe hare	14
C2	Red fox	15
C2	Wolf	15
H1	Red backed vole	15
H1	Tundra vole	15

Less resilient

More resilient

Arctic mammals sorted by their relative vulnerability to climate change. An index of relative resilience was calculated from world-wide geographic range (Table 5.3), breadth of ecological niche (Table 5.3), status under the Endangered Species Act and IUCN Red List (1=threatened, 2=of least concern) and life history strategies (1=low reproducing carnivores [bears], 2=low reproducing herbivores [ungulates and porcupines], 3=moderate reproducing carnivores [shrews, mustelids, canids, felids] and herbivores [squirrels], and 4=high reproducing herbivores [microtines and hares]). Polar bears were the only species considered threatened; wolverines are listed as "near threatened" under IUCN criteria, but Alaska populations are not threatened.

Table 6.2. Proposed indicators of climate change effects on fish and wildlife.

Species or Species Group	Parameter to Measure	Projected Change in Habitat	Positive or Negative Effect	Rationale for Response to Projected Habitat Change
Birds				
Yellow-billed loon	Distribution, fledging success	Changes in fish availability, lake drainage	+ or -	Warming lakes could increase productivity, but loss of connectivity could inhibit fish migration
Pacific loon	Fledging success	Increased productivity in warmer lakes	+	Warming could improve availability of macroinvertebrates fed to chicks; longer ice-free season allows more time to fledge
Red phalarope, pectoral sandpiper	Abundance, distribution	Drying of wet sedge meadow	-	Loss of preferred foraging habitat and/or decreased food availability
Red-necked phalarope	Abundance, distribution	Drying of wet sedge meadow, increased thermorkarst	+ or -	Loss of preferred foraging habitat in lowlands (drying of wet sedge meadow), but increased thermokarst could allow expansion into upland areas
Geese (black brant, greater white-fronted)	Gosling growth rates	Change in plant phenology	-	Growth rates are sensitive to forage quality during the fledging period
Shorebirds	Timing of arrival and nesting; chick growth and survival	Change in timing of aquatic insect life cycle stages	-	Potential trophic mismatch if timing of shorebird migration and nesting does not match temperature-regulated timing of insect abundance
Perching birds (sparrows. warblers, etc.)	Abundance, distribution	Increased shrubbiness	+	Shrub-associated species will expand their range and local abundance as shrubs increase
Common eider	Abundance, nest success	Loss of barrier islands, increased storms	-	Reduced availability of gravel islands limits nesting habitat and/or increased frequency of storm overwash increases nest loss
Long-tailed duck	Abundance and distribution during molt stage	Change in lagoon systems	-	Loss of barrier islands reduces availability of habitat for resting and disrupts trophic system of lagoons
Fish				
Arctic grayling	Growth rate, productivity, age at maturity, within-drainage distribution	Increased water temperature (associated with availability of food)	+ (until upper lethal temperature is reached)	Sensitive, ubiquitous
Broad whitefish	Growth rate, productivity, age of maturity, within-drainage distribution	Increased water temperature; loss of waterbody connectivity	-	Fish passage will depend on connectivity between lakes, small streams, and other habitats
Dolly Varden	Population estimates	Increased water temperature; habitat fragmentation	-	High site fidelity; specific habitat requirements
All salmon	Regional distribution	Increased water temperature	+	Assume that expansion of range would have a positive effect
Arctic char and lake trout	Regional distribution	Changes in water quality and increasing temperatures	-	Perhaps narrow range of temperature tolerance
Aquatic insects/ invertebrates	Species abundance and composition	Changes in water quality; changes in pH (resulting from acidification of terrestrial habitats)	+ or -	Rapid changes in response to environmental changes; easily sampled

Continued next page

Table 6.2. Continued

Species or Species Group	Parameter to Measure	Projected Change in Habitat	Positive or Negative Effect	Rationale for Response to Projected Habitat Change
Mammals				
Polar bear	Use of onshore habitats/denning	Loss of summer sea ice and principle prey	-	Shift in distribution, decline in abundance are likely to occur as sea ice disappears
Alaska marmot	Distribution, life history	Loss of alpine habitats	-	Limited distribution; little is known about this endemic species that has a limited and disjunct population
Dall's sheep	Trends in abundance, distribution	Loss of alpine habitats; more rain-on-snow events, deeper snow, warmer summers	-	Higher energetic costs, more parasites and diseases, changes in plant phenology and communities
Muskox	Trends in abundance, distribution	More rain-on-snow events, deeper snow, warmer summers, more shrubs	-	Arctic-adapted species lives in arctic Alaska year-round. Less access to winter forage, higher energetic costs, more diseases and parasites may offset positive aspects of increasing summer biomass
Caribou	Trends in abundance, distribution	More rain-on-snow events, deeper snow, warmer summers, fewer lichens, changes in plant phenology and community structure	-	Less access to winter forage, loss of lichens from increased fire or competition with other vegetation, timing of migration uncoupled from optimal foraging, more insect harassment, parasites, and diseases, and increased energetic costs may offset positive aspects of increases summer biomass
Lemmings and barren ground shrews	Distribution and relative trend	Changes in distribution and population cycles	+ or -	Arctic-adapted species likely to be affected by changes in food and shelter; important in food webs; little known about barren ground shrews (may be difficult to study)
Arctic fox	Distribution and relative trend	Changes in abundance and distribution	-	Arctic-adapted carnivore; possible competition with red foxes and disappearance of sea ice may affect distribution and abundance; important predator of birds.

Table 6.3. Relative timeline of climate-driven processes of change.

Timeline	Process
Annual to decadal	Erosion, construction, and migration of barrier islands Ecosystem phenology and productivity Expansion of lake shorelines (due to erosion) Thermokarst, pond formation, and gully formation
Decadal to century	Change in fire regime Change in species composition Change in length of ice-free season Change in sea-surface temperatures Lake tapping Shrub advance
Century to millennial	Formation of a thaw lake plain Loss of continuous permafrost Stabilization of drained lake basin Re-establishment of polygonal terrain
Unknown (decadal to millennial)	Paludification

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An arctic ground squirrel (Spermophilus parryii) *emerges from his burrow in spring after hibernating for more than six months underground. Photo by Øivind Tøien.*

Chapter 7
Conclusions and Recommendations

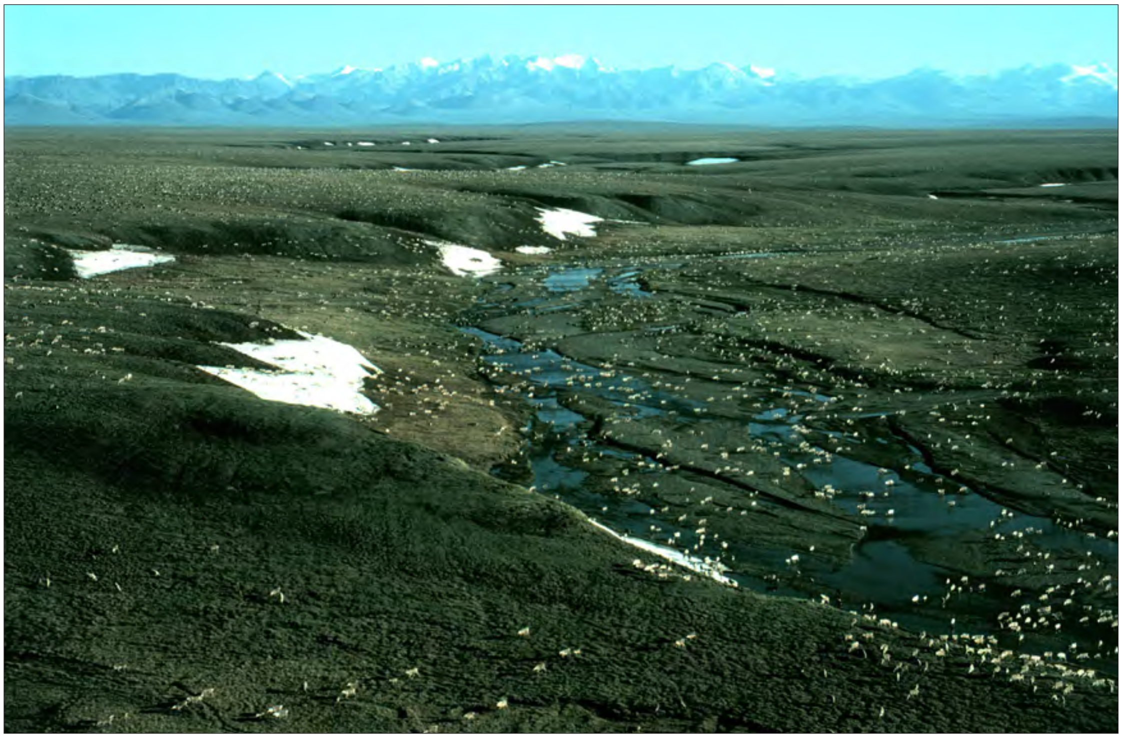
Land and resource managers know that climate change will strongly affect the future landscape of America's Arctic. Under a mid-range carbon emissions scenario, mean annual air temperature for the North Slope is projected to rise ~7°C by the end of the century, and precipitation is projected to increase by up to 50% in coastal areas. Despite the expected increase in precipitation, warmer summers are expected to result in significant drying.

Arctic aquatic and terrestrial habitats are shaped by the complex interactions among climate, soils, permafrost, hydrology, and vegetation. Arctic habitats are among the most sensitive to warming because of the pivotal role played by permafrost, which can only persist at low temperature. Some arctic-adapted species will respond to habitat change through range shifts, but other species may be vulnerable to extirpation from the North Slope if suitable refugia are not available.

Climate change requires that managers of arctic species and landscapes anticipate the future condition of habitats and populations, but they cannot do this at present because too little is known about the linkages between climate, habitat, and organisms. Global Circulation Models, down-scaled to the North Slope region, are beginning to paint a clearer picture of the magnitude of climate change that may be expected within the century; these projections, however, are subject to large uncertainty. Our ability to translate climate change projections into specific forecasts of habitat condition is currently rudimentary. Indeed, it is not yet possible to link climate scenarios to fish and wildlife population status with the level of confidence needed to support development and implementation of conservation plans.

The WildREACH workshop and related discussions have identified important scientific priorities and activities required to improve our ability to forecast—and thus respond to—climate change effects on arctic fish and wildlife.

A male spectacled eider (Somateria fischeri) *near Barrow; the species is listed as threatened under the Endangered Species Act. Photo by Ted Swem, USFWS.*



The Porcupine caribou herd (Rangifer tarandus) *crosses the 1002 area of the Arctic National Wildlife Refuge. Photo by Chuck Young, USFWS.*

Scientific Priorities

Workshop participants identified important information gaps in our understanding of climate change effects on birds, mammals, and fish populations. The specific gaps varied among species groups, but most fell into four cross-cutting thematic areas and underlying research questions (see Chapter 6 for more details):

A pectoral sandpiper (Calidris melanotos) *near Barrow. Photo by Ted Swem, USFWS.*

1. Precipitation, Water Balance, and Distribution of Surface Water

a. How reliable are the projections for increasing precipitation and evapotranspiration?

b. How will the annual precipitation input on the Coastal Plain and Foothills be allocated between winter (snow pack) and summer?

c. How will changes in precipitation, evapotranspiration, and active layer depth alter summer surface water availability in shallow-water and mesic/wet tundra habitats?

d. How will changing patterns of seasonal runoff affect stream flow?

e. What is the contribution of groundwater in various systems, and is it sufficient to maintain year-round flow?

f. Will drought conditions and changes in drainage patterns decrease water body connectivity?

g. Which Coastal Plain lakes are susceptible to tapping (rapid drainage) and on what time scale?

h. What are the expected changes in snowpack characteristics (depth, density, presence of ice layers), and how might these vary on a regional and local scale?

i. How much change will occur in the timing of snow melt and snow onset?

j. How will the frequency of rain-on-snow and severe winter storm events change?

2. Vegetation Community Composition and Phenology

a. How will changes in the length and timing of the growing season influence plant phenology, including seasonal changes in nutritional quality?

b. How will plant species composition shift in response to long-term climate change, and what are the implications for habitat structure and quality of the prevalent available forage (i.e., digestibility, nutrient content)?

c. What is the time scale of expected shrub increase, and how will this vary by species/growth form (low vs. tall shrub) and ecoregion?

d. What is the likelihood of widespread conversion from sedge and sedge-shrub meadow to bog meadow (paludification) and how would this affect herbivore and detritus-based trophic systems?

e. How will changes in the seasonality of stream discharge and occurrence of flood events influence development of riparian vegetation communities?

3. Abundance and Phenology of Invertebrates

a. How does earlier spring thaw affect timing of life cycle events and peak availability to predators?

b. How does temperature affect growth and development of aquatic insects?

c. What climate-related changes are likely in community composition of macroinvertebrates in stream, lake, and saturated soil environments?

d. How will changes in the distribution and quality of surface waters and shifts from pelagic to benthic productivity in deep lakes affect availability of macroinvertebrates to fish and wildlife?

e. How will warming and changing seasonality affect abundance and peak activity periods of biting insects, and what are the bioenergetic consequences for caribou in particular?

f. How will warming and changing seasonality affect the prevalence of parasites and disease vectors (e.g., nematode parasites of muskoxen and Dall's sheep)?

4. Coastal Dynamics

a. Will higher water temperatures, sea level rise, and retreat of summer sea ice cause degradation of the barrier island systems of the Beaufort and Chukchi seas?

b. Will alluvial deltas continue to build or will rising sea levels outpace potential increases in sedimentation rates?

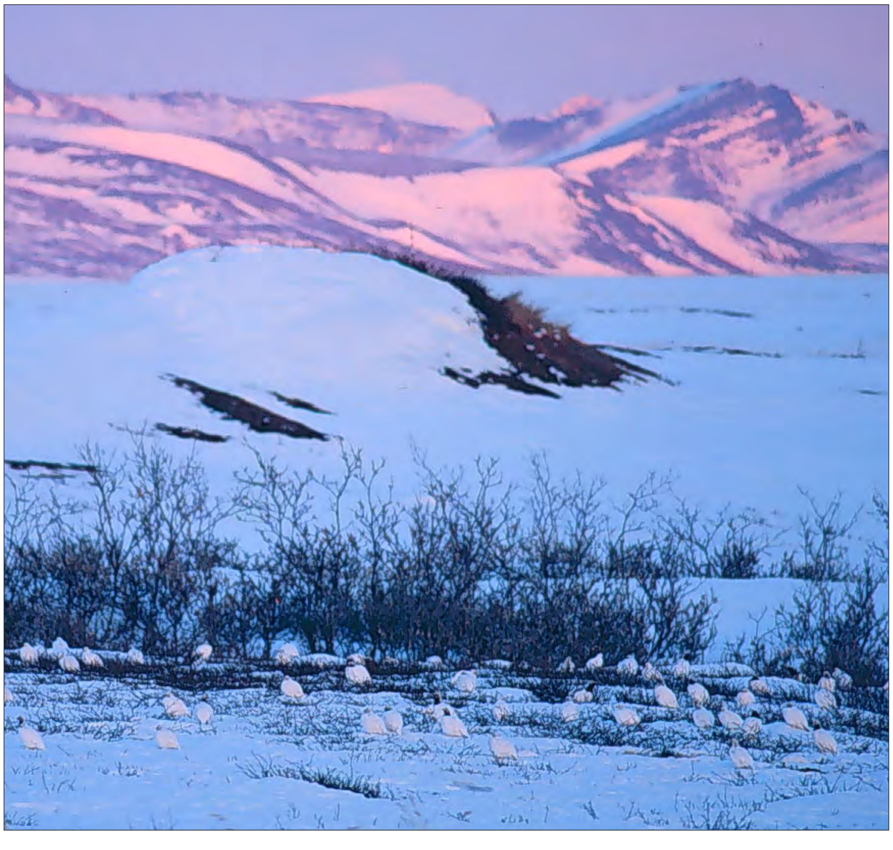
c. How quickly will shoreline retreat result in newly breached lake basins?

d. To what extent will coastal erosion, in combination with sea level rise, cause salinization of low-lying coastal areas?

e. Will coastal wet sedge meadows establish at a rate equal to loss of this habitat through erosion and inundation?

f. Will increased fogginess/cloudiness exert a negative or positive feedback effect on air temperature in the coastal zone? What is the expected spatial extent of this effect?

Relevant to all of the four major themes above, the study and modeling of hydrologic processes emerged as critical to understanding habitat change. Furthermore, hydrologic data and models are needed by a broad constituency of user groups, including engineers and infrastructure planners.



Ptarmigan (Lagopus *sp.) are nomadic in winter, moving in flocks from one sheltered slope or patch of food to another from November to March. Photo by Øivind Tøien.*

Recommended Research Activities

The scientific priorities previously listed should be addressed by activities including: monitoring of physical and biological parameters; field observations and focused research activities designed to clarify the mechanisms by which environmental variables influence fish and wildlife populations; and development and refinement of arctic process models that integrate physical and biological parameters. More specific research activity recommendations are detailed below.

Hydrologic Research

Hydrologic data are sparse for the North Slope, principally due to the cost of acquisition. Recognizing that cost sharing among agencies and others is necessary, we recommend four initiatives in this area:

1. Establishment of at least three long-term observatories on the North Slope to collect integrated hydrologic, climate, and geophysical data. The central mission of these observatories should be to develop an understanding of the response of permafrost (active layer dynamics), hydrologic, and ecological systems to changes in thermal regime. To ensure applicability to fish and wildlife biology, water budgets should be estimated for key ecotypes.
2. Intensive observations at the observatory sites should be supplemented by instrumentation (e.g., meteorology, radiation, stream discharge, soil moisture) at dispersed sites arrayed across important environmental gradients.
3. Modeling that dynamically couples soil thermal and hydrologic regimes, and biological systems at appropriate spatial and temporal scales.
4. Centralized data storage and interpretation for the mutual benefit of multiple end-users.

A flock of long-tailed ducks (Clangula hyemalis) *migrating along the coast near Barrow. Photo by Ted Swem, USFWS.*

Development of Habitat Change Models

We recommend immediate attention to developing habitat change models, focusing initially on processes that are ongoing and occurring on a short (decadal) time scale. Priority topics include:

- Coastal processes (e.g., erosion, storm surge, deposition, succession);
- Seasonality (e.g., plant phenology, animal migration, life stages of aquatic invertebrates);
- Shrub advance;
- Fire regime (as a function of interactions among climate, permafrost, and vegetation); and
- Thermokarst effects on surface water and lake drainage.

Selection of Indicator Species and Parameters

Deficiencies in our knowledge of basic natural history and ecology of arctic species currently hinder our ability to assess responses to climate change. We suggest choosing focal species that reflect sensitivity to hypothesized climate change effects. The WildREACH working groups made progress toward this goal, but we recommend additional work in this area. Specifically, the Service should engage the U.S. Geological Survey (USGS) and others in a structured decision-making process to refine the selection of indicator species/parameters as components of a long-term climate monitoring program. Upon reaching consensus, management agencies should seek stable funding for monitoring these species/attributes.

Agency Coordination and Collaboration

Climate change is transformative. The challenge of conserving fish and wildlife populations in the face of climate change already exceeds the capacity of any single entity. The scale and scope of climate change demands change in the way that resource agencies do business—we must pool already constrained human and financial resources. The future of conservation lies in landscape approaches that are developed and implemented with other federal, state, and non-governmental organization (NGO) partners. We recognize that there is no overarching business model that fits all agencies' mandates, but there is ample common ground for agencies and NGOs to engage in collaborative conservation. Conservation partnerships will provide efficiencies through strategic targeting of financial resources and provide an opportunity to co-develop an adaptive, landscape-level response.

Since the WildREACH workshop, the Service has promoted conservation partnerships across landscapes that align with Bird Conservation Regions (BCRs). These Landscape Conservation Regions (LCRs) will be supported by Landscape Conservation Cooperatives (LCCs) that house the technical expertise from multiple partners to address the science needs of each LCR. The Service has designated America's Arctic as Alaska's first LCR, affirming the high priority to be placed on developing partnerships and research plans and implementing conservation for the Arctic LCR. The Arctic LCR will be supported by the Northern Alaska LCC located in Fairbanks. The Northern Alaska LCC will work with USGS, through its National Climate Change and Wildlife Science Center and/or Regional Climate Science Hub, and other partners to establish the technical and organizational capacity to address the science needs of the Arctic LCR.

Engaging in the broad scope of scientific inquiry recommended by workshop participants will require financial commitment from a coalition of organizations and the formation of teams of specialists representing multiple disciplines. Toward those ends, the U.S. Fish and Wildlife Service is committed to improving communication and collaboration with the arctic research community. The Service will:

1. Work with the National Science Foundation (NSF) to define priorities for basic and applied research programs targeted toward climate research relevant to resource management agencies;
2. Seek opportunities to collaborate with academic institutions to frame grant proposals in ways that address the priorities of fish and wildlife managers;
3. Participate in planning and implementation of the interagency Study of Environmental Arctic Change (SEARCH) Program to ensure inclusion of research relevant to resource management agencies;
4. Work with arctic science program managers in the research agencies (e.g., National Science Foundation, USGS, National Oceanic and Atmospheric Administration) to identify funding sources to address priority questions; and
5. Promote a collaborative approach to acquire, process, archive, and disseminate essential satellite-based remote sensing data products (e.g., snow cover, green-up, and surface water) needed for regional-scale monitoring.

The Service is currently working with other federal and state managers to develop mechanisms to facilitate coordinated interagency planning, budget implementation, and data-sharing on a statewide basis via the Climate Change Roundtable. The State of Alaska's Governor's subcabinet (http://www.climatechange.alaska.gov/) is also working to identify priority tasks to address mitigation and adaptation within the context of social and economic factors. As we designate LCRs and build the LCCs that support them, resource management agencies, research institutions, and NGOs must implement interagency agreements that commit resources to coordinated long-term research and monitoring, biological planning, and conservation design and delivery.

Climate change presents an unprecedented challenge to managers of arctic natural resources. The complexity with which interacting systems may respond to changing climate forces us to accept an uncomfortable level of uncertainty, and the time scales of change are long relative to the normal management cycle. We have the opportunity and obligation, however, to lay the foundation of information needed to inform future management decisions. The WildREACH workshop was successful in identifying priority information gaps and activities needed to provide the basis for adaptive management of arctic fish and wildlife resources. Adopting these recommendations will greatly strengthen our capacity to form anticipatory responses to climate-related habitat change, and will help us identify the most promising strategies to protect arctic fish and wildlife populations.

Candle ice (small, icicle-shaped pieces of lake ice) is rapidly blown to shore on a lake on the Ikpikpuk Delta in July, crumpling the soft lake margin. It took only 4–5 minutes for the ice to come ashore. Photo by Leslie Pierce (TREC 2005), courtesy of ARCUS.

Appendix 1: Methods for Climate Projections

Climate Data Sets

Temperature and precipitation projections were based on the downscaled General Circulation Model (GCM) output distributed by the University of Alaska Scenarios Network for Alaska Planning (SNAP; http://www.snap.uaf.edu/about), based on the work of Walsh et al. (2008). Output from each model contains spatially explicit mean temperature (°C) and total precipitation (mm) grids for every month of every year for 120 years (1980–2099) for the entire state of Alaska. These data were downloaded to the Department of Atmospheric Sciences at the University of Illinois from the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset. The five models used were:

- ECHAM5/MPI from the Max Planck Institute for Meteorology in Germany;
- GFDL-CM2.1 produced by the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory, a unit of the Department of Commerce, in the U.S.;
- MIROC3.2MedRes produced by the Center for Climate System Research at the University of Tokyo, the National Institute for Environmental Studies, and the Frontier Research Center for Global Change, a unit of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), in Japan;
- UKMO-HadCM3 produced by the Hadley Centre for Climate Prediction and Research and the Met Office in the U.K.; and
- CGCM3.1 produced by the Canadian Centre for Climate Modelling and Analysis in Canada.

More documentation on each model is available at the CMIP3 website (http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php). Walsh et al. (2008) objectively evaluated 15 models over Alaska—the above five models were ranked highest and provided output that most closely matched actual Alaska climate data for the years 1958–2000 (SNAP; http://www.snap.uaf.edu/about). The best performing models in that analysis tend to be the models that project the most change in climate. Limiting the analysis to only the best performing models is one approach to narrowing the uncertainty of the projected climate change (Walsh et al. 2008).

Each model run is based on the Intergovernmental Panel on Climate Change (IPCC) A1B greenhouse gas emission scenario (IPCC 2007), which assumes fast economic growth, an eventual decline in global population, development of more efficient technology, and the continued use of fossil fuels for some, but not all, energy sources. The A1B scenario is considered a "middle-of-the-road" scenario among those presented by the IPCC. The A1B, B1 (slow greenhouse gas increase), and A2 (more rapid greenhouse gas increase) scenarios differ little by mid-century but diverge by 2100. The projected climate changes are generally proportional to the respective increases of greenhouse gas concentrations, so the B1 and A2 changes of climate can be scaled to the A1B changes. The projections used in this report are derived from a composite of the five model outputs.

Baseline temperature and precipitation data were derived from the Parameter-Elevation Regression on Independent Slopes Model (PRISM) dataset created by the PRISM Group (Oregon State University, www.prism.oregonstate.edu). These data consist of 12 gridded mean maximum temperature, mean minimum temperature, and total precipitation files at 2-km resolution, one for each month averaged over 1961–1990 for the state of Alaska. This dataset was created using observation data from weather stations across Alaska and spatially interpolated over intervening areas using weighted regression incorporating elevation and terrain effects on climate (Daly et al. 2002, Simpson et al. 2005). Walsh et al. (2008) calculated GCM baseline values for each of the five selected models using mean monthly outputs for 1961–1990. They then calculated differences between projected GCM values and baseline GCM values for each year and created "anomaly grids" representing these differences. The anomaly grids were added to the PRISM baseline to create fine-scale (2-km) grids for monthly mean temperature and precipitation projections out to 2099.

Temperature and Precipitation Projections

The Nature Conservancy calculated the projected decadal mean for each month of the year, for both temperature and precipitation. Monthly values were averaged (for temperature) or summed (for precipitation) across months to yield seasonal and annual values. Mid-century and end-of-century intervals were selected to represent projected change. Mid-century (2051–2060) and end-of-century (2091–2100) grids were generated by calculating the differences between projected values from the PRISM baseline value (temperature) or the percent change from the PRISM baseline value (precipitation). A spatial mean was then calculated to produce the summaries by ecoregion. For this document, summer is defined as June through September and winter as October through May.

Freeze-Up, Thaw, and the Frost-Free Season Projections

The Wilderness Society generated data for onset of freeze-up, thaw, and length of frost-free season. Data were analyzed using the open source application R (R Development Core Team 2005) and ArcGIS 9.3 (ESRI, Redlands, California). Climate data were monthly means and totals, but freeze-up and spring thaw dates are often variable within days; therefore, a ramp function was used to linearly interpolate the day of freeze-up and thaw for the 1980–2099 composite (Euskirchen et al. 2007). A 12 x 120 matrix (12 months, 120 years) of spatial mean values was developed and assumed to represent the value for the 15th day of that month. The slope between these values was calculated and added to each progressive day beyond the 15th until the 15th of the next month was reached. This procedure was repeated for each month. For the purposes of these analyses, freeze-up was defined as the first day of the year when the interpolated value fell below 0°C, and thaw was defined as the first day above 0°C. The number of days between these two dates was defined as the frost-free season, calculated for all 120 years and plotted over time. Rate of change over time was calculated using a linear regression. This analysis is not indicative of the actual dates of freeze-up and thaw or the natural variability surrounding them (e.g., several freezing and unfreezing events may occur), however, it does give an indication of how much these actual dates may be delayed or advanced under each scenario of climate change.

Potential Evapotranspiration and Water Availability Projections

The Wildness Society calculated potential evapotranspiration (PET) for each of the three North Slope ecoregions using a modified version of the Priestly-Taylor method adapted to a monthly time step using energy balance equations from Allen et al. (1998). The two time slices used for PET projections are different than those used for temperature and precipitation and are centered around 2035–2044 and 2075–2084. Climate variable inputs included mean monthly temperature (T_{mean}), mean monthly minimum temperature, (T_{min}), mean monthly maximum temperature (T_{max}), and percent cloud cover. Spatial averages for each ecoregion were derived from the baseline PRISM dataset for each ecoregion. Mean monthly minimum and maximum temperature grids were created by subtracting the corresponding PRISM T_{mean} grids from the projected T_{mean} grids to obtain monthly anomalies from the baseline PRISM climatology. These anomaly grids were then added to the PRISM T_{max} temperature grids and subtracted from the PRISM T_{min} grids to create 12 projected T_{max} and 12 projected T_{min} temperature grids for the two time periods. For months with mean temperatures below 0°C, PET is assumed to be zero. Mean cloudiness, as percent sky cover, for each ecoregion was estimated using station data available at the Alaska Climate Research Center (ACRC) website (http://climate.gi.alaska.edu/Climate/index.html) and assumed to remain constant throughout future projections. Additional inputs included ordinal date and latitude. The 15th of January served as an initial ordinal date and progressed through the year at a 30-day time step. For example, the ordinal date used for the month of February was the 45th, and for August it was the 225th. The latitude coordinates used for the Arctic Coastal Plain, Arctic Foothills, and Brooks Range were 70.37°N, 69.42°N, and 68.80°N, respectively.

Growing season months ($T_{mean} > 0°C$) used for the Coastal Plain and Foothills analysis remained consistent throughout future projections, spanning the months of June through September. The growing season in the Brooks Range expanded, however, from the historical June–August to include September by 2035–2044 and May by 2075–2084. Sparse cloud cover data made it necessary to interpolate regional values. Cloud cover data for the Coastal Plain are averages of ACRC weather station data from Barrow and Barter Island (the only stations available for the region). Values for the Brooks Range are assumed to be the same as those measured in Bettles (the closest high-altitude station available). Because none of the weather stations located within the Arctic Foothills contained cloud cover measurements, cloud cover data for this ecoregion is represented by an average of value from Barrow, Barter Island, and Bettles.

Monthly estimates of PET were subtracted from total monthly precipitation (P) values for each time period to estimate changes in the mean growing season water balance (P-PET) for each ecoregion over time. These analyses were restricted to months with average temperatures exceeding 0°C and did not include the additional days expected to contribute to a longer growing season as determined by the separate frost-free season regression analyses.

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Appendix 2: Description and Distribution of Northern Alaska Ecotypes

Terrestrial habitat types adapted from the ecotypes described by Jorgenson and Heiner (2003) are described in Table A2.1. The distribution of ecotypes is depicted in Figure A2.1.

Table A2.1. Description of terrestrial habitat types found in northern Alaska. From Jorgenson and Heiner (2003).

Class	Description
	ALPINE ECOTYPES
Alpine Glaciers	Perennially frozen snow and ice at high elevations in the Brooks Range, typically on north-facing slopes.
Alpine Non-carbonate Barrens	Barren (<5% plant cover) to partially vegetated (5–30%) areas on non-carbonate bedrock and talus slopes above treeline in the Brooks Range. Bedrock includes felsic intrusive (e.g., granite, granodiorite), non-carbonate metamorphic (e.g., slate, schist), and non-carbonated sedimentary (e.g., conglomerate, sandstone, shale) rocks that generally have low calcium and sodium and high aluminum concentrations that lead to acidic soils. Soils are rocky, excessively drained, lacking in surface organic accumulations, and strongly acidic (pH <5.5). At high elevations, common species include *Geum glaciale, Saxifraga bronchialis, S. flagellaris, S. nivalis, S. eschscholtzii,* and crustose and fruticose lichens. Lower elevations have species similar to Alpine Non-carbonate Dwarf Shrub Tundra.
Alpine Carbonate Barrens	Barren (<5% plant cover) to partially vegetated (5–30%) areas on carbonate bedrock and talus slopes above treeline in the Brooks Range. Bedrock includes both sedimentary (limestone, dolostone) and metamorphic (marble) carbonate rocks. Soils are rocky, excessively drained, lacking in surface organics, and alkaline (pH >7.3). Common pioneering plants include *Dryas integrifolia, D. octopetala, Saxifraga oppositifolia, Potentilla uniflora, Oxytropis nigrescens, O. arctica,* and *Carex rupestris*.
Alpine Mafic Barrens	Barren areas on intermediate, mafic, and ultramafic plutonic rocks above treeline in the Brooks Range that typically have dark-colored mineral assemblages with abundant iron and magnesium. Soils are rocky, excessively drained, lacking in surface organic accumulations, and are neutral to alkaline. Some areas have high levels of trace metals. Areas usually are devoid of vegetation.
Alpine Non-carbonate Dwarf Shrub Tundra	Areas on noncarbonate bedrock and talus slopes above treeline in the Brooks Range with dwarf shrub vegetation. Soils are rocky, excessively drained, have very thin surface organic accumulations, and are strongly acidic. Vegetation is dominated by dwarf shrubs including *Dryas octopetala* (mostly south slopes), *Salix phlebophylla, S. arctica, Loiseleuria procumbens, Diapensia lapponica, Arctostaphylos alpina, Empetrum nigrum, Vaccinium uliginosum,* and *Cassiope tetragona* (north slopes). Other species include *Carex podocarpa, C. bigelowii, Hierochloe alpina, Cladina mitis, C. rangiferina,* and *Rhizocarpon geographicum*.
Alpine Carbonate Dwarf Shrub Tundra	Areas on carbonate bedrock and talus slopes above treeline in the Brooks Range with dwarf shrub vegetation. Soils are rocky, excessively drained, rich in humus, and alkaline. Vegetation is dominated by dwarf shrubs including *Dryas integrifolia* (mostly south slopes), *D. octopetala, Cassiope tetragona* (north slopes), *Salix arctica,* and *Arctostaphylos alpina.* Other species include *Carex rupestris, C. bigelowii, Saxifraga oppositifolia, Potentilla uniflora, Oxytropis nigrescens, O. arctica, Nephroma arcticum, Rhytidium rugosum, Flavocetraria cucullata,* and *Thamnolia vermicularis.*
Alpine Mafic Dwarf Shrub Tundra	Areas on intermediate, mafic, and ultramafic plutonic rocks above treeline in the Brooks Range with dwarf shrub vegetation. Rocks have dark-colored mineral assemblages with abundant iron and magnesium. Soils are rocky, excessively drained, lacking in surface organic accumulations, and are neutral to alkaline. Some areas have high levels of trace metals. Vegetation is poorly described for this type but it probably is similar to that described for Alpine Non-carbonate Dwarf Shrub Tundra.

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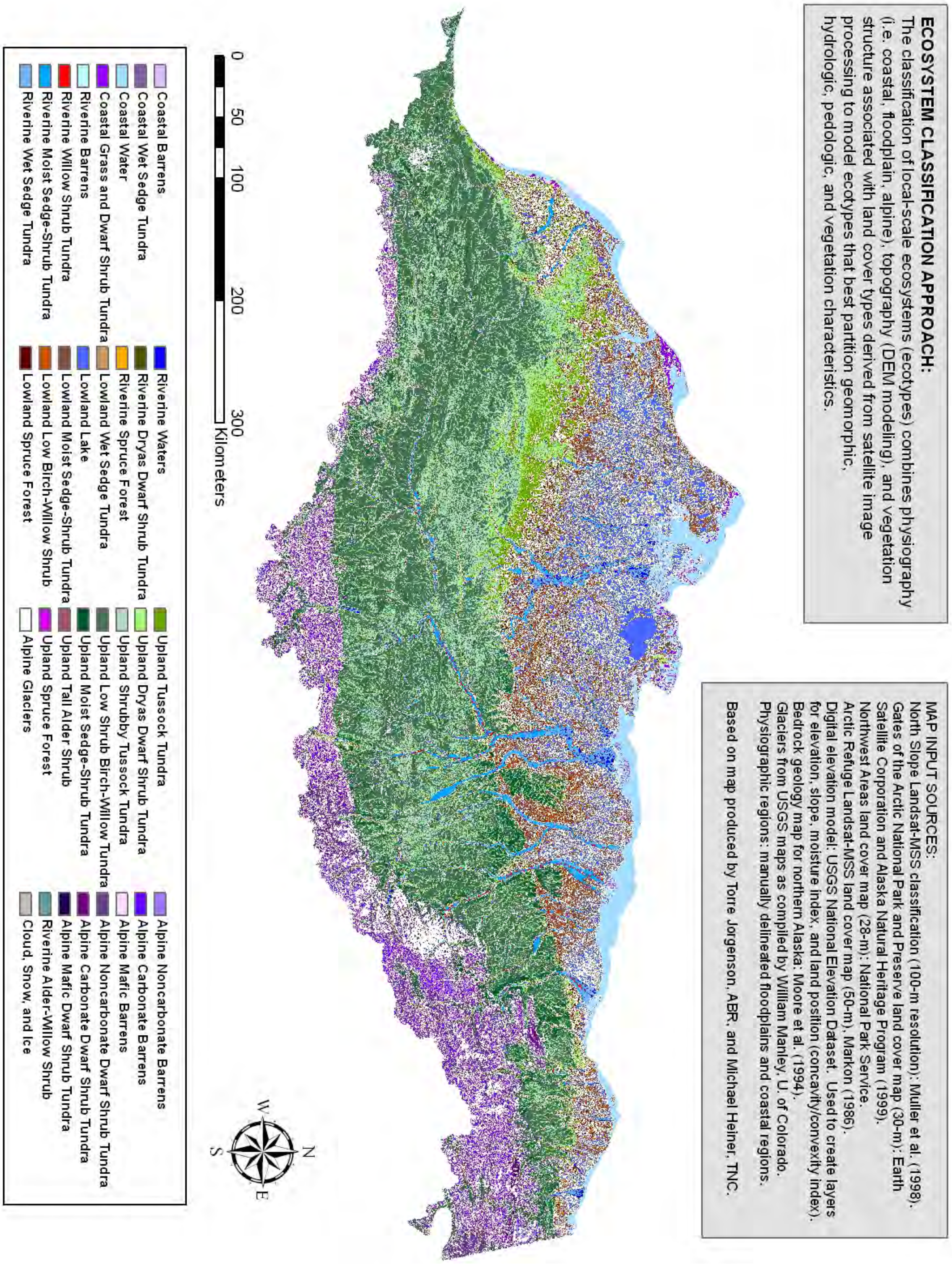

ECOSYSTEM CLASSIFICATION APPROACH:
The classification of local-scale ecosystems (ecotypes) combines physiography (i.e. coastal, floodplain, alpine), topography (DEM modeling), and vegetation structure associated with land cover types derived from satellite image processing to model ecotypes that best partition geomorphic, hydrologic, pedologic, and vegetation characteristics.

MAP INPUT SOURCES:
North Slope Landsat-MSS classification (100-m resolution): Muller et al. (1998).
Gates of the Arctic National Park and Preserve land cover map (30-m): Earth Satellite Corporation and Alaska Natural Heritage Program (1999).
Northwest Areas land cover map (28-m): National Park Service.
Arctic Refuge Landsat-MSS land cover map (50-m), Markon (1986).
Digital elevation model: USGS National Elevation Dataset. Used to create layers for elevation, slope, moisture index, and land position (concavity/convexity index).
Bedrock geology map for northern Alaska: Moore et al. (1994).
Glaciers from USGS maps as compiled by William Manley, U. of Colorado.
Physiographic regions: manually delineated floodplains and coastal regions.

Based on map produced by Torre Jorgenson, ABR, and Michael Heiner, TNC.

Figure A2.1. Distribution of ecotypes in northern Alaska (Jorgenson and Heiner 2003).

Table A2.1. Continued

Class	Description
	UPLAND ECOTYPES
Upland Spruce Forest	Upland areas on mid- to upper slopes on weathered bedrock, colluvium, and glacial till with vegetation dominated by needleleaf trees. Soils are loamy to rocky, well-drained, have moderately thick organic horizons, are acidic, and may or may not have permafrost. This late-successional forest is dominated by an open to closed canopy of *Picea glauca*, but can include minor amounts of *Betula papyrifera* and *P. mariana*. Understory plants include *Alnus crispa, Vaccinium vitis-idaea, Ledum groenlandicum, Empetrum nigrum, Rosa acicularis, Cornus canadensis, Shepherdia canadensis, Spiraea beauverdiana, Linnaea borealis, Calamagrostis canadensis, Hylocomium splendens,* and *Pleurozium schreberi*.
Upland Birch-Aspen-Spruce Forest	Upland areas on mid- to upper slopes on weathered bedrock, colluvium, and glacial till with vegetation co-dominated by broadleaf and needleleaf trees. Soils are well-drained, have thin organic horizons, are moderately acidic, and usually lack permafrost. This mid-successional mixed forest is dominated by an open to closed canopy of *Betula papyrifera, Populus tremuloides,* and *Picea glauca.* Understory plants include *Alnus crispa, Salix glauca, Vaccinium vitis-idaea, Ledum groenlandicum, Rosa acicularis, Cornus canadensis, Shepherdia canadensis, Linnaea borealis, Calamagrostis canadensis,* and feathermosses.
Upland Birch-Aspen Forest	Upland areas on mid- to upper slopes on weathered bedrock, colluvium, and glacial till with vegetation dominated by broadleaf deciduous trees. Soils are loamy to rocky, well-drained, have thin organic horizons, are acidic, and usually lack permafrost. The mid-successional forest is dominated by an open to closed canopy of *Betula papyrifera* and *Populus tremuloides.* Understory plants include *Alnus crispa, Salix glauca, Vaccinium vitis-idaea, Ledum groenlandicum, Rosa acicularis, Cornus canadensis, Shepherdia canadensis, Spiraea beauverdiana, Linnaea borealis, Calamagrostis canadensis*, and feathermosses.
Upland Tall Alder Shrub	Upland areas on mid- to upper slopes on weathered bedrock, colluvium, and glacial till with vegetation dominated by tall shrubs. Soils are loamy to rocky, well-drained, have thin organic horizons, are acidic, and usually lack permafrost. Vegetation is dominated by an open to closed canopy of *Alnus crispa,* although *Salix pulchra, Salix glauca,* and *Betula glandulosa* occasionally are abundant. Understory species include *Vaccinium uliginosum, Vaccinium vitis-idaea, Betula nana, B. glandulosa, Ledum groenlandicum, Empetrum nigrum, Equisetum arvense, Spiraea beauverdiana, Calamagrostis canadensis,* and *Petasites frigidus*. Mosses include *Sphagnum* spp., *Hylocomium splendens*, and *Dicranum* spp.
Upland Low Birch-Willow Shrub Tundra	Upland areas on mid- to upper slopes on weathered bedrock, colluvium, and glacial till with vegetation dominated by low shrubs. Soils are loamy to rocky, well-drained, have moderately thick organic horizons, are acidic, and usually have permafrost. Vegetation has an open to closed canopy of *Betula nana* and/or *Salix pulchra*. Other species include *Salix glauca, Vaccinium uliginosum, V. vitis-idaea, Ledum decumbens, Empetrum nigrum, Arctostaphylos alpina, Dryas octopetala, D. integrifolia, Salix reticulata, Equisetum arvense, Carex bigelowii,* and the mosses and lichens *Hylocomium splendens, Tomentypnum nitens, Sphagnum* spp., *Aulacomnium palustre, Dicranum* spp., *Cladina rangiferina,* and *Flavocetraria cucullata.*
Upland *Dryas* Dwarf Shrub Tundra	Upland windswept ridges and upper slopes on weathered bedrock, colluvium, inactive sand dunes, and coastal plain deposits with vegetation dominated by dwarf shrubs. Soils are well-drained, loamy to rocky, have thin organic horizons, and are circumneutral to acidic. Common dwarf shrubs include *Dryas octopetala* (mostly south slopes), *D. integrifolia, Salix phlebophylla, S. arctica, S. reticulata, Loiseleuria procumbens, Diapensia lapponica, Arctostaphylos alpina, Empetrum nigrum, Vaccinium uliginosum, Ledum decumbens,* and *Cassiope tetragona* (north slopes). Other common species include *Carex bigelowii, C. scirpoidea, Arctagrostis latifolia, Equisetum variegatum, Tomentypnum nitens, Hylocomium splendens,* and *Cladina stellaris.*
Upland Shrubby Tussock Tundra	Gently sloping uplands and ridges on loess and colluvium over bedrock and glacial till, primarily within the Brooks Foothills (>120 m elevation), with vegetation co-dominated by tussock-forming sedges and low shrubs. Soils are somewhat poorly drained, loamy, have moderately thick surface organics, are acidic, and are underlain by ice-rich permafrost. The open low shrub canopy of *Betula nana* and *Salix pulchra* usually overtop the *Eriophorum vaginatum* tussocks. Other dominant plants include *E. angustifolium, Carex bigelowii, Ledum decumbens, Vaccinium vitis-idaea, V. uliginosum, Rubus chamaemorus, Hylocomium splendens, Sphagnum* spp., *Aulacomnium palustre, Cladina rangiferina, C. arbuscula, C. mitis,* and *Flavocetraria cucullata.*
Upland Tussock Tundra	Gently sloping uplands and ridges on loess, colluvium, and coastal plain deposits, primarily within the Beaufort Coastal Plain (<120 m elevation), with vegetation dominated by tussock-forming sedges. Soils are moist, somewhat poorly drained, loamy, and have moderately thick surface organics, are circumneutral to acidic, and are underlain by ice-rich permafrost. Vegetation is dominated by *Eriophorum vaginatum.* On circumneutral soils, *Carex bigelowii, Dryas integrifolia, Salix pulchra, Cassiope tetragona, S. reticulata, Tomentypnum nitens,* and *Hylocomium splendens* are common. On acidic soils, dominant plants include *E. angustifolium, Betula nana, Salix pulchra, Ledum decumbens, Vaccinium vitis-idaea, Rubus chamaemorus, Hylocomium splendens, Sphagnum* spp., *Aulacomnium palustre,* and *Cladina rangiferina.*

Class	Description
Upland Moist Sedge-Shrub Tundra	Upland ridges and upper slopes on weathered bedrock, loess-mantled bedrock, colluvium, and glacial till, with vegetation co-dominated by sedges and low and dwarf shrubs. Soils are loamy to rocky, somewhat poorly drained, have moderately thick surface organics, and are alkaline to acidic depending on substratum. On acidic soils more common in the upper foothills and mountains, dominant plants include *Betula nana, Salix pulchra, Carex aquatilis, Eriophorum angustifolium,* and *Sphagnum* spp. On circumneutral to alkaline soils more common on the coastal plain and lower foothills, dominant plants include *Salix lanata richardsonii, Dryas integrifolia, S. reticulata, Arctostaphylos rubra, Rhododendron lapponicum, Equisetum arvense, Carex bigelowii, Tomentypnum nitens,* and *Thamnolia vermicularis*.
LOWLAND ECOTYPES	
Lowland Spruce Forest	Low-lying flats and gentle slopes on colluvium and abandoned floodplains with vegetation dominated by needleleaf forests. Soils are wet, somewhat poorly drained, have moderately thick surface organics, are acidic, and usually are underlain by permafrost. The open tree canopy (usually 5–10 m high) is dominated by *Picea mariana,* although *P. glauca, Larix laricina,* and *Betula papyrifera* occasionally can be present in small amounts. In the wettest areas the trees can be very stunted. Common understory plants include *Salix pulchra, Betula nana, Vaccinium uliginosum, Ledum groenlandicum, Potentilla fruticosa, Rubus chamaemorus, Equisetum arvense, and Carex bigelowii*. Mosses and lichens include *Sphagnum* spp., *Hylocomium splendens, Pleurozium schreberi, Cladonia* spp., *Nephroma* spp., *Cetraria* spp., and *Peltigera* spp.
Lowland Low Birch-Willow Shrub Tundra	Low-lying flats and lower slopes on drained lake basins, abandoned floodplains, colluvium, and coastal plain deposits with vegetation dominated by low shrubs. Soils typically are poorly drained, loamy, have moderately thick surface organics, are acidic, and are underlain by permafrost. The open to closed low shrub canopy is dominated by *Salix pulchra* and *Betula nana.* On acidic soils other common species include *Ledum decumbens, Vaccinium uliginosum, V. vitis-idaea, Empetrum nigrum, Petasites frigidus, Rubus chamaemorus, Eriophorum angustifolium, Carex aquatilis, Calamagrostis canadensis,* and *Sphagnum* spp. On circumneutral to alkaline soils, *Salix lanata richardsonii, S. reticulata, Dryas integrifolia, Arctostaphylos rubra, Equisetum arvense, Eriophorum angustifolium, and Carex aquatilis* are common.
Lowland Moist Sedge-Shrub Tundra	Low-lying flats and gentle slopes on drained lake basins, abandoned floodplains, colluvium, and coastal plain deposits, particularly on the Beaufort Coastal Plain, with vegetation co-dominated by sedges and low or dwarf shrubs. Soils are saturated at intermediate depths (>15 cm), loamy with moderately thick surface organics, are circumneutral to alkaline, and are underlain by ice-rich permafrost. Sites generally are free of surface water during summer. Vegetation is dominated by *Carex aquatilis, C. bigelowii, Eriophorum angustifolium,* and *Dryas integrifolia.* Other common species include *Salix lanata richardsonii, S. pulchra, S. reticulata, Tomentypnum nitens,* and *Hylocomium splendens*. Acidic vegetation could not be adequately differentiated from non-acidic vegetation on the Beaufort Coastal Plain.
Lowland Wet Sedge Tundra	Low-lying flats and drainages on drained lake basins, abandoned floodplains, colluvium, and coastal plain deposits, particularly on the Beaufort Coastal Plain, with vegetation dominated by sedges. Soils are poorly drained, have moderately thick to thick (10–50 cm) surface organics over silt loam, usually circumneutral, and are underlain by ice-rich permafrost. Ice wedge development in older landscapes creates distinctive low-centered polygons. The surface generally is flooded during early summer (depth <0.3 m) and drains later, but soils remain saturated ≥15 cm from the surface throughout the growing season. Vegetation is dominated by *Carex aquatilis* and *Eriophorum angustifolium*, while willows, including *Salix lanata richardsonii* and *S. pulchra*, often are present but usually not co-dominant. Other common species include *Dryas integrifolia, S. reticulata, C. bigelowii,* and *Equisetum scirpoides* on higher microsites and polygon rims.
Lowland Lake	Shallow (<1.5 m) ponds and deep (≥1.5 m) lakes resulting from thawing of ice-rich permafrost, primarily on the coastal plain and distal portions of abandoned floodplains. In shallow ponds, water freezes to the bottom during winter, thaws by early to mid-June, and is warmer than water in deep lakes. In deep lakes, water does not freeze to the bottom during winter in deeper portions of the lake. Sediments are loamy to sandy. These lakes lack riverine influences (flooding), but they may have distinct outlets or connections to rivers.

Continued next page

Table A2.1. Continued

Class	Description
LACUSTRINE ECOTYPES	
Lacustrine Barrens (not mapped)	Barren or partially vegetated (<30% cover) areas on newly exposed sediments in recently drained lake basins. The surface form generally is nonpatterned due to the lack of ice wedge development. Soils are saturated to well-drained, sandy to loamy, lack surface organics, and are alkaline. Typical colonizers are *Arctophila fulva, Carex aquatilis, Dupontia fisheri, Scorpidium scorpioides,* and *Calliergon* spp. on wet sites and *Poa alpigena, Senecio congestus, Salix ovalifolia,* and *Salix arctica* on drier sites.
Lacustrine Marsh (not mapped)	Shallow (<1 m), permanent waterbodies with emergent aquatic sedges and grasses. Water and bottom sediments freeze completely during winter, but the ice melts in early June. The sediments range from sands to organics (10–50 cm deep) overlying silt loam. In deeper water (30–100 cm), *Arctophila fulva* can form sparse to dense stands and is the predominant vegetation. In shallower (<30 cm) water, *Carex aquatilis* and *Eriophorum angustifolium* are dominant, and *Utricularia vulgaris* is common. This ecosystem type is important to waterbirds but could not be mapped separately and is included in both Lowland Lakes and Lowland Wet Sedge Tundra.
RIVERINE ECOTYPES	
Riverine Spruce Forest	Flat areas on inactive floodplains subject to infrequent flooding with vegetation dominated by needleleaf trees. The late-successional forest has an open to closed tree canopy dominated by *Picea glauca*. Soils are well-drained, loamy to gravelly, have moderately thick surface organics, and are acidic. The understory is dominated by *Alnus crispa, Vaccinium uliginosum, V. vitis-idaea, Arctostaphylos rubra, Cornus canadensis, Viburnum edule, Rosa acicularis, Mertensia paniculata,* and feathermosses *(Hylocomium splendens, Rhytidiadelphus triquetrus,* and *Pleurozium schreberi)*.
Riverine Spruce-Balsam Poplar Forest	Flat areas on inactive floodplains subject to infrequent flooding with mixed forests co-dominated by needleleaf and broadleaf trees. The mid-successional forests have an open to closed tree canopy dominated by *Picea glauca* and *Populus balsamifera*. Soils are well-drained, loamy to gravelly, have moderately thick surface organics, and are circumneutral to acidic. The understory is dominated by *Alnus crispa, Vaccinium uliginosum, V. vitis-idaea, Arctostaphylos rubra, Cornus canadensis, Viburnum edule, Rosa acicularis, Equisetum arvense, Epilobium angustifolium, Calamagrostis canadensis,* and feathermosses *(Hylocomium splendens, Rhytidiadelphus triquetrus,* and *Pleurozium schreberi)*.
Riverine Balsam Poplar Forest	Flat areas on inactive floodplains subject to infrequent flooding and that have vegetation dominated by broadleaf forests. Soils are well-drained, loamy to gravelly, have thin surface organics, and are circumneutral. The mid-successional forest has an open to closed canopy dominated by *Populus balsamifera* or occasionally *Betula papyrifera*. The understory has *Alnus crispa, Rosa acicularis, Equisetum arvense, Epilobium angustifolium, Hedysarum alpinum, Calamagrostis canadensis, Galium boreale,* and *Rhytidiadelphus triquetrus*.
Riverine Tall Alder-Willow Shrub	Flat areas on active floodplains subject to frequent flooding that have vegetation dominated by tall shrubs in the boreal region. Soils are well-drained, loamy to gravelly, have very thin surface organics, and are circumneutral. The early succession community has an open to closed tall shrub canopy dominated by *Salix alaxensis, S. arbusculoides, S. monticola,* and *Alnus crispa*. The understory is dominated by *Vaccinium uliginosum, Artemisia tilesii, Calamagrostis canadensis, Petasites frigidus,* and *Equisetum arvense*. Mosses and lichens are not abundant.
Riverine Low Willow Shrub Tundra	Flat to gently sloping areas on active and inactive floodplains in arctic regions subject to variable flooding frequency and that have vegetation dominated by tall and low shrubs. On the narrow zone close to the river, soils are frequently flooded, well-drained, lack organic accumulations, and have vegetation dominated by open tall (>1.5 m) *Salix alaxensis, S. arbusculoides,* and *S. glauca. Alnus crispa* is uncommon. In the understory, *Equisetum arvense, Astragalus alpinus, Aster sibericus,* and *Festuca rubra* are common. On inactive floodplains, where soils have interbedded organic layers and are seasonally saturated, *Salix lanata richardsonii* and *S. pulchra* are dominant. Common understory species include *Salix reticulata, Arctostaphylos rubra, Dryas integrifolia, Arctagrostis latifolia, Equisetum* spp., legumes, *Tomentypnum nitens,* and other mosses.
Riverine Dryas Dwarf Shrub Tundra	Flat areas on inactive floodplains subject to infrequent flooding and that have vegetation dominated by dwarf shrubs. Soils are well-drained, sandy to rocky, have thin surface organics, are alkaline, and are underlain by ice-poor permafrost. The dwarf shrub *Dryas integrifolia* is dominant, and *Salix reticulata, S. lanata richardsonii, Carex bigelowii, Arctagrostis latifolia, Astragalus* spp., *Oxytropis deflexa,* and *Equisetum scirpoides* are common. *Tomentypnum nitens* and *Distichium capillaceum* are common mosses.
Riverine Moist Sedge-Shrub Tundra	Flat areas on inactive floodplains subject to infrequent flooding and that have vegetation co-dominated by sedges and low and/or dwarf shrubs. Soils are moderately well-drained, loamy, have moderately thick surface organics, are circumneutral and underlain by ice-rich permafrost. Vegetation is dominated by *Carex aquatilis* and *Eriophorum angustifolium* with *Dryas integrifolia, Salix lanata richardsonii, S. reticulata,* and *Carex bigelowii, Equisetum* spp., *Tomenthypnum nitens,* and *Campylium stellatum* as common associates.

Class	Description
Riverine Wet Sedge Tundra	Flat areas on active and inactive floodplains subject to frequent or infrequent flooding and that have vegetation dominated by sedges. Soils are poorly drained, loamy with moderately thick to thick surface organics, are circumneutral to alkaline, and are underlain by ice-rich permafrost. Surface forms vary from nonpatterned to low-relief, low-centered polygons; the latter are indicative of progressive ice wedge development. Vegetation is dominated by *Carex aquatilis* and *Eriophorum angustifolium*, although occasionally the willow *Salix lanata richardsonii* is a co-dominant. Other species include *Dupontia fisheri, Equisetum variegatum, Pedicularis sudetica, Campylium stellatum, Scorpidium scorpioides,* and *Limprichtia revolvens*.
Riverine Marsh (not mapped)	Shallow waterbodies (0.1–1.0 m) on active and inactive floodplains subject to occasional flooding with vegetation dominated by emergent aquatic grasses and sedges. Due to shallow water depths, the water freezes to the bottom in the winter, and the ice melts by early June. *Arctophila fulva* usually is found in deeper water while Carex aquatilis is usually found in very shallow water. *Hippuris vulgaris* occasionally is present.
Riverine Barrens	Barren or partially vegetated (<30% cover) areas on active river channel deposits associated with meandering or braided rivers. Frequent sedimentation and scouring restricts establishment and growth of vegetation. Soils are poorly to excessively drained, sandy to gravelly, lack surface organics, are alkaline, and usually have ice-poor permafrost in arctic regions and lack permafrost is boreal regions. Typical pioneer plants include *Salix alaxensis, Deschampsia caespitosa, Chrysanthemum bipinnatum, Epilobium latifolium, Artemisia arctica, Festuca rubra, Arctagrostis latifolia*, and *Trisetum spicatum*.
Riverine Waters	Permanently flooded channels of freshwater rivers and streams, and lakes on inactive floodplains that are subject to occasional flooding. Some stream water flows throughout the year. Peak flooding generally occurs during spring breakup, and the lowest water levels occur during mid-summer. Riverbed materials can be either sand or gravel. Shallow (<1.5 m) or deep lakes usually are associated with old river channels, point bars, and meander scrolls, although some result from thawing of ice-rich permafrost on large floodplains. Some may have connecting channels that flood during high water. Shorelines usually are smooth (lack polygonization).
COASTAL ECOTYPES	
Coastal Grass and Dwarf Shrub Tundra	Low-lying, salt-affected areas along the coast with vegetation dominated by either grasses or dwarf shrubs. Soils are well-drained, slightly saline, and alkaline. This class includes three vegetation types. On active dunes and beaches, vegetation includes *Elymus arenarius, Chrysanthemum bipinnatum, Puccinellia* spp., *Artemisia tilesii,* and *Salix ovalifolia*. Well-drained inactive tidal flats dominated by dwarf shrub vegetation have *S. ovalifolia, Stellaria humifusa, E. arenarius, Deschampsia caespitosa, Dupontia fisheri, Carex subspathacea,* and *A. tilesii*. Inactive dunes along the Chukchi Sea with slightly saline sandy soils have dwarf shrub vegetation dominated by *Empetrum nigrum, S. ovalifolia, E. arenarius, Lathyrus maritimus, C. bipinnatum*, and lichens. Substantial areas of this mapped class would have been more accurately mapped as Lowland Moist Sedge-Shrub Tundra but could not be adequately differentiated spectrally or by modeling.
Coastal Wet Sedge Tundra	Low-lying, salt-affected areas on tidal flats, deltas, and muddy beaches along the coast that are frequently flooded and have vegetation dominated by sedges. The surface is nonpatterned. Soils are poorly drained, clayey to loamy, usually lack surface organics, and are brackish and alkaline. The soils are underlain by ice-poor permafrost. Vegetation is dominated by *Carex subspathacea, Carex ursina,* and *Puccinellia phryganodes,* with *Dupontia fisheri, Puccinellia andersonii, Cochlearia officinalis,* and *Stellaria humifusa* also common. Non-vascular plants usually are absent. Substantial areas of Lowland Wet Sedge Tundra are included in these mapped areas but could not be adequately differentiated.
Coastal Barrens	Barren or partially vegetated, low-lying, salt-affected areas on tidal flats, deltas, and muddy beaches along the coast that are frequently flooded. Soils are poorly drained, clayey to loamy, usually lack surface organics, and are brackish and acidic to alkaline. The soils are underlain by ice-poor permafrost. Common colonizing plants include *Deschampsia caespitosa, Elymus arenarius, Salix ovalifolia,* and *Stellaria humifusa* in well-drained areas, and *Puccinellia phryganodes, Dupontia fisheri,* and *Carex subspathacea* in wetter areas. This class also includes tundra that has been killed by saltwater intrusions from storm surges and is being colonized by salt-tolerant plants. Newly deposited sediments typically are found on top of a thick organic horizon. These areas have low pH, high salinity, and shallow thaw depths. Common colonizing plants include *Puccinellia phryganodes, Stellaria humifusa, Cochlearia officinalis,* and *Salix ovalifolia*.
Coastal Water	Shallow (~<2 m) estuaries, lagoons, embayments, and tidal ponds along the coast of the Beaufort and Chukchi seas. Winds, tides, river discharge, and icing create dynamic changes in physical and chemical characteristics. Salinity ranges widely from nearly fresh near rivers to saline in unprotected areas. Tidal ranges normally are small (<0.2 m) along the Beaufort and moderate (0.5–1 m) along the Chukchi seas, but storm surges produced by winds may raise sea level as much as 2–3 m. Bottom sediments are mostly unconsolidated mud and sand. The ice-free period extends from July until October. Winter freezing generally begins in late September.

Continued next page

Table A2.1. Continued

Class	Description
OTHER ECOTYPES	
Marine Water (not mapped)	Deep (~>2 m) marine waters of the Beaufort and Chukchi seas outside of lagoons and barrier islands. Ice coverage is highly variable from permanent pack ice to seasonally ice free areas. Small areas of Marine Water are included in Coastal Water for mapping purposes.
Human Modified	Barren or partially vegetated areas resulting from human disturbance. As mapped, the human-modified areas are predominantly roads, pads, and mine pits and overburden.
Cloud, Snow, and Ice	Areas with clouds, snow, and ice. The Clouds and Ice Class was combined with the Shadow classes for the final map. Most of the original shadow classes in the input maps in the Brooks Range were recoded to alpine classes based on modeling. Remaining shadow areas are primarily due to clouds in the Brooks Foothills. Aufeis on rivers was classified as Riverine Barrens to avoid creation of a separate Riverine Ice class.

Appendix 3: WildREACH Workshop Agenda

Wildlife Response to Environmental Arctic Change (WildREACH): Predicting Future Habitats of Arctic Alaska

17–18 November 2008
Westmark Hotel, Fairbanks, Alaska

Day 1: Monday, 17 November 2008

Registration: 7:30 a.m.–9:30 a.m.
7:30 a.m. Arrival and Coffee Service
Plenary Session Held in Gold Room

8:00 a.m. Welcome
    Geoffrey Haskett, Regional Director, U.S. Fish and Wildlife Service
8:10 a.m. Introductions
    Philip Martin, U.S. Fish and Wildlife Service
8:30 a.m. Workshop Goals and Structure
    Philip Martin, U.S. Fish and Wildlife Service
8:50 a.m. Observed Climate Change in Northern Alaska
    Martha Shulski, University of Alaska Fairbanks
9:05 a.m. Projected Climate of Northern Alaska
    Peter Larsen, The Nature Conservancy
9:20 a.m. Coastal Processes
    David Atkinson, University of Alaska Fairbanks
9:35 a.m. Permafrost and Active Layer Dynamics
    Vladimir Romanovsky, University of Alaska Fairbanks
9:55 a.m. Permafrost-Influenced Geomorphic Processes
    Torre Jorgenson, ABR Environmental Services, Inc.
10:15 a.m. Plenary Discussion/Q&A
10:30 a.m. Break
10:50 a.m. Vegetation Change
    Eugenie Euskirchen, University of Alaska Fairbanks
11:05 a.m. Hydrologic Processes
    Amy Tidwell, University of Alaska Fairbanks
11:20 a.m. Hydrology Panel—Predicting Change
    Snow: Matthew Sturm, Cold Regions Research and Engineering Laboratory
    Water Balance: Doug Kane, University of Alaska Fairbanks
    Feedbacks: Larry Hinzman, University of Alaska Fairbanks
        Anna Liljedahl, University of Alaska Fairbanks
11:50 a.m. Plenary Discussion/Q&A
12:30 p.m. Lunch (on your own)
1:30 p.m. Integration – Potential Ecosystem Pathways
    Torre Jorgenson, ABR Environmental Services, Inc.
1:50 p.m. Charge to Working Groups
    Philip Martin, U.S. Fish and Wildlife Service
2:00 p.m. Working Groups Breakout Session I

Working Groups will be presented with scenarios of climate and landscape change that would affect landscape-scale habitat availability, e.g., broad scale conversion from one habitat type to another. What species (or species attributes) would be sensitive indicators of the hypothesized changes?

3:30 p.m. Break
4:00 p.m. Return to Plenary Session: Working Group Reports
    Bird Working Group
    Fish Working Group
    Mammal Working Group
    Managers Working Group
5:00 p.m. Summary of Day's Discussion; Plans for Day 2
5:15 p.m. Adjourn
5:30 p.m. Reception and Poster Session (light food and cash bar)

All participants are encouraged to bring a poster that describes synthesis research, data, and modeling needs within their area of interest, or relevant research findings from integrated projects.

Day 2: Tuesday, 18 November 2008

8:00 a.m. Arrival and Coffee Service

8:15 a.m. Review of Day 1 Discussion, Day 2 Goal, Workshop Products
8:25 a.m. Trophic Systems: Herbivores
Brad Griffith, University of Alaska Fairbanks
8:40 a.m. Trophic Systems: Aquatic
Mark Wipfli, University of Alaska Fairbanks
8:55 a.m. Charge to Working Groups
Philip Martin, U.S. Fish and Wildlife Service
9:10 a.m. Working Groups Breakout Session II
Climate-associated processes may lead to changes in habitat suitability which cannot easily be equated with change in availability. Examples include: changes in water temperature that affect physiological processes of fish, enhanced food availability due to increased primary and secondary productivity, changing seasonality that results in asynchrony between optimal food availability and critical life history phases. Based on the scenarios of climate change outlined in the previous Breakout, what are the most important mechanisms by which climate would affect habitat suitability? Express the relationships and mechanisms in the format of "box-and-arrow" conceptual models.
11:15 a.m. Return to Plenary Session: Report of Working Groups
Bird Working Group
Fish Working Group
Mammal Working Group
Managers Working Group
12:00 p.m. Lunch (on your own)
1:00 p.m. Return to Plenary Session
1:15 p.m. Bayesian Network Modeling
Erik Beever, U.S. Geological Survey
1:30 p.m. Empirical Temperature Downscaling: Improving Thermal Information Detail
David Atkinson, University of Alaska Fairbanks
1:45 p.m. Charge to Working Groups
Philip Martin, U.S. Fish and Wildlife Service
2:00 p.m. Working Groups Breakout Session III
Focusing on the conceptual models identified in the previous breakout session, what are the key areas where reducing uncertainty in physical process models would enhance our ability to predict habitat change? What would we most like modelers and researchers in other disciplines to work on?
4:00 p.m. Return to Plenary Session: Report of Working Groups
Bird Working Group
Fish Working Group
Mammal Working Group
Managers Working Group
4:30 p.m. Identify Areas of Commonality Among Working Groups
Panel Discussion: Working Group Leaders, Workshop Participants
5:00 p.m. Summary, Discussion, and Next Steps
Philip Martin, U.S. Fish and Wildlife Service
5:15 p.m. Workshop Adjourns

Day 3: Wednesday, 19 November 2008

U.S. Fish and Wildlife Service Conference Room, Federal Building

9:00 a.m. Invited Writing Group
U.S. Fish and Wildlife Service Staff & invited Workshop Participants
Synthesis of Key Results and Themes from Workshop
The third day is intended for a small group of participants who are willing to make a substantial commitment to drafting and reviewing the final document from this workshop. If you are interested in participating, please contact Philip Martin at 907-456-0325 or philip_martin@fws.gov.
12:00 p.m. Adjourn

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Appendix 5: Working Group Charges and Members

Working Group Breakout Session Charges

Sideboards and Assumptions
Geographic Scope: The geographic scope includes terrestrial and freshwater ecosystems from the crest of the Brooks Range northward. The boundary with the marine system is recognized as fuzzy; coastal processes are acknowledged to affect terrestrial and freshwater systems and vice versa. Processes that affect nearshore coastal environments may be considered for those species that cross ecosystem boundaries.

Priority Issues: It is recognized that climate change may influence organisms in multiple and complex ways. We intend to focus the discussion primarily on the following climate change effects:

- Change in relative abundance and distribution of habitat types on the landscape.
- Change in structural (including plant community structure) or physical characteristics of habitat.
- Change in trophic systems, including primary and secondary productivity, phenology, and forage/prey availability.

The importance of other potential effects of climate change—such as competitive interactions, invasive species, prevalence of disease, and contaminants—are recognized but are of secondary priority for this workshop.

Working Group Breakout Session I (Monday afternoon)
The goals of this session are to:

- Identify species or species groups that are expected to be sensitive indicators of the changes hypothesized in the climate scenarios and ecosystem pathway models.
- For each species, develop hypotheses regarding positive or negative response to changes in the availability of habitat, based on knowledge of species' life histories and habitat requirements.
- For each species, identify specific parameters (e.g., distribution, abundance, demography, body condition, growth rate, etc.) that would be affected.

Groups should focus on landscape-level changes in habitat availability. Species should be selected for their value as indicators of climate change. Groups should NOT feel constrained to only those species or parameters that are easily measured. This breakout session is an opportunity for discussion on any and all species in the region that will be affected by climate change. Later in the workshop, we will consider feasibility issues when prioritizing the research and modeling needs that arise from the breakout group sessions.

Working Group Breakout Session II (Tuesday morning)
The goal of this session is to refine draft conceptual models of climate effects on species, including processes that are not captured by habitat change models. Each working group will be presented with models drafted as a result of the scoping meetings. Groups are encouraged to consider "reasonable worst-case scenarios," i.e., scenarios that are within the expected range of potential change AND would have the greatest magnitude effects, thus most detectable. For example:

- Birds: Trophic system shifts for consumers of invertebrates, coastal habitat availability.
- Mammals: Forage quantity and quality in summer, snow conditions, forage availability in winter.
- Fish: Stream system flow regimes, availability of river delta overwintering habitat.

Working Group Breakout Session III (Tuesday afternoon)
The goal of this final breakout session is to review the products from the first two breakout sessions and identify the most critical gaps in data and modeling needed to predict future habitats of arctic Alaska. Gaps could be of at least two types:

- Models have not been constructed.
- Models exist but are not supported by adequate data.

Identified gaps should focus on the underlying ecological and physical processes that may affect species in all three groups of interest (birds, fish, and mammals). The goal is to go beyond identification of data gaps for arctic species biology and refine our thinking of what is needed to gain predictive ability of the system-level physical processes and ecosystem functions.

Breakout session results will form the core content for a five-year strategic plan that identifies the priority research, modeling, and synthesis activities needed to predict climate-related impacts to fish and wildlife populations in the Arctic.

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