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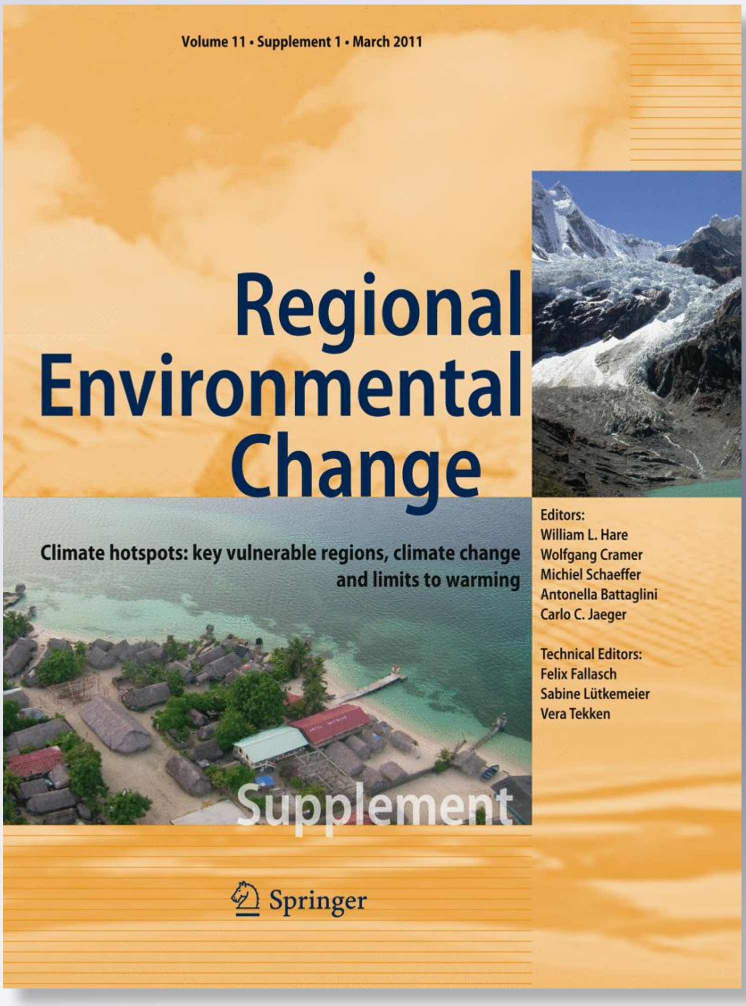
Regional Environmental Change

ISSN 1436-3798
Volume 11
Supplement 1

Reg Environ Change (2010)
11:249-264
DOI 10.1007/s10113-010-0180-y



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ORIGINAL ARTICLE

Climate vulnerability of ecosystems and landscapes on Alaska's North Slope

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Accepted: 26 October 2010

Abstract Alaska's North Slope is especially vulnerable to climatic change because higher latitudes are subject to positive snow- and sea ice-atmosphere feedbacks under warming conditions and because the dynamics of frozen seascapes and landscapes are tightly determined by thermal regime. Shifts in timing and magnitude of freeze–thaw processes are observed to have or expected to have non-linear, threshold-crossing impacts on sea ice, landforms, and biota. Observed changes in North Slope surface air temperatures and precipitation were non-monotonic over the last century, but have trended upward for the last several decades. These changes are linked to hemispheric climate dynamics, reflected in North Pacific and Arctic Oscillation circulation indices. Projected anthropogenic climate changes—with the possibility of continued warming, increased storm frequency and intensity, and decreased insulating snow cover—portend an uncertain future for this domain. Current or foreseen physical system shifts include: (1) declining seasonal and permanent sea ice extent and character, (2) rapid coastal erosion due to storm exposure over a longer near-shore ice-free season, (3) deeper soil active layer over warmer permafrost, along with altered thermokarst processes—contributing to thaw lake expansion, surface drainage re-organization, and hillslope instability. Biogeophysical responses encompass (1) modified surface-atmosphere energy balance from snow cover, vegetation, and hydrologic change and (2) shifted soil and wetland biogeochemical dynamics, including accelerated carbon efflux. Climate-driven plant community shifts on the North Slope result from the interplay of climate, vegetation response, and landscape processes. Some transitions involve stabilizing, others destabilizing plant-permafrost feedbacks. Impacts on caribou, migratory avifauna, and freshwater biota are through direct effects of climate on organism physiology and reproductive biology and indirectly through disruption of habitat mosaics (including along migratory routes) and shifts in competition and trophic linkages. The North Slope's physical and biological vulnerabilities to shifting climate and observed leading indicators of change are compelling reasons for land managers to consider climatic instability as a threat in conjunction with other known stressors while seeking strategies for protection of this domain's natural heritage and ecosystem services.

Keywords North American Arctic · Recent climate change · Recent ecological change · Permafrost-thaw lake-tundra feedbacks · Mammal and avifauna response to climate change · Freshwater responses to climate change

Introduction

We present a synthesis of peer-reviewed studies on climate change effects on seascape, landscape, and ecosystem

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processes as they relate to vegetation, terrestrial mammal, migratory bird, and freshwater communities of Alaska's North Slope (USA). We review the current state of knowledge regarding: How has recent climate change altered these processes and communities? How might such responses unfold in the future under projected climate change? And, finally, how are some climate impacts amplified or mitigated as they propagate through the ecosystem?

Located entirely above the Arctic Circle, the North Slope extends 340 km north from the Brooks Range to the Arctic Ocean (to the Beaufort and Chukchi seas) and 1,030 km from west to east (Fig. 1). In spite of harsh winters (Fig. 2a) and a short growing season, the North Slope's vast landscapes, spanning ~24.5 million ha, are year-round home to many large mammals and the seasonal breeding grounds of migratory birds from around the temperate world. Its ecosystems underpin indigenous peoples' subsistence lifestyles, offer widely recognized wilderness values, and influence the Earth's global carbon budget and climate.

Climate change is currently, and is projected to continue to be, greater toward the poles than toward the Equator, reflecting the especially high vulnerability of polar, perennially frozen environments to climate change (IPCC 2007). Changes in solar radiation, atmospheric and oceanic chemistry, and ocean heat transport that drive Arctic air, water, and soil temperatures above the freeze/thaw threshold have disproportionately large effects on sea ice, snow, glaciers, permafrost, tundra ecosystems, and biological diversity.

Arctic warming began mid-19th century and accelerated in the last half of the 20th century (ACIA 2005). Alaska has warmed ~2°C on average since the 1950's (ACRC 2008). Experimental evidence has measured the impact of recent warming on Arctic physical processes, species, and ecosystems. Indigenous peoples of the Arctic report numerous changes in the environment over recent decades (Box 1). Warming, on the face of it, may seem like an "improvement" to Arctic conditions, but its consequences are complex in ways unique to frozen environments and highly disruptive to ecosystems and the many people living and working in the region.

Climate variability and change

Broad climate patterns

Hemispheric and regional climate processes define North Slope climate and its sensitivity to altered forcing. These processes are reflected in a marked seasonal cycle in temperature and precipitation (Fig. 3a, b) (Olsson et al. 2003). Extremely cold winters (e.g., January mean minimum temperatures <−28°C) result from southward flow of cold, dry air formed over the polar ice cap and High Arctic continental

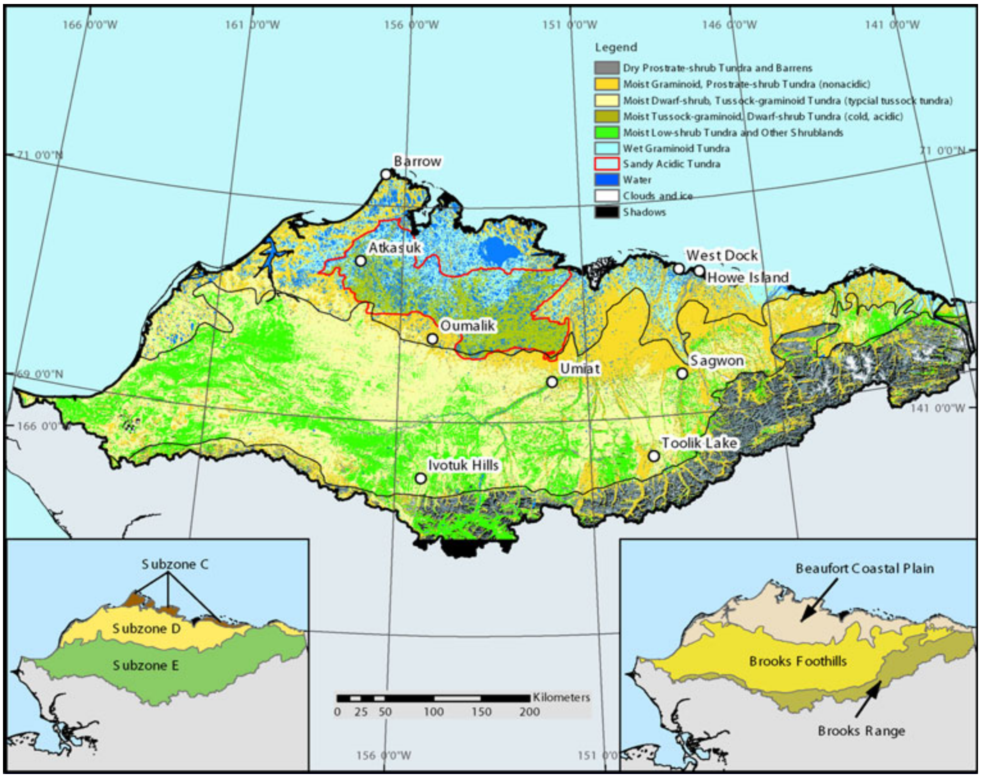

Fig. 1 Landcover map of Alaska's North Slope (Muller et al. 1999) with respect to the physiographic provinces of the Alaska–Yukon Arctic ecoregion. (*Lower left insert*) Bioclimatic subzones of the Arctic (CAVM Team 2003): *C* is High Arctic, *D* and *E* are Low Arctic bioclimates. (*Lower right insert*) Physiographic provinces of the Alaska–Yukon Arctic ecoregion (Nowacki et al. 2002)

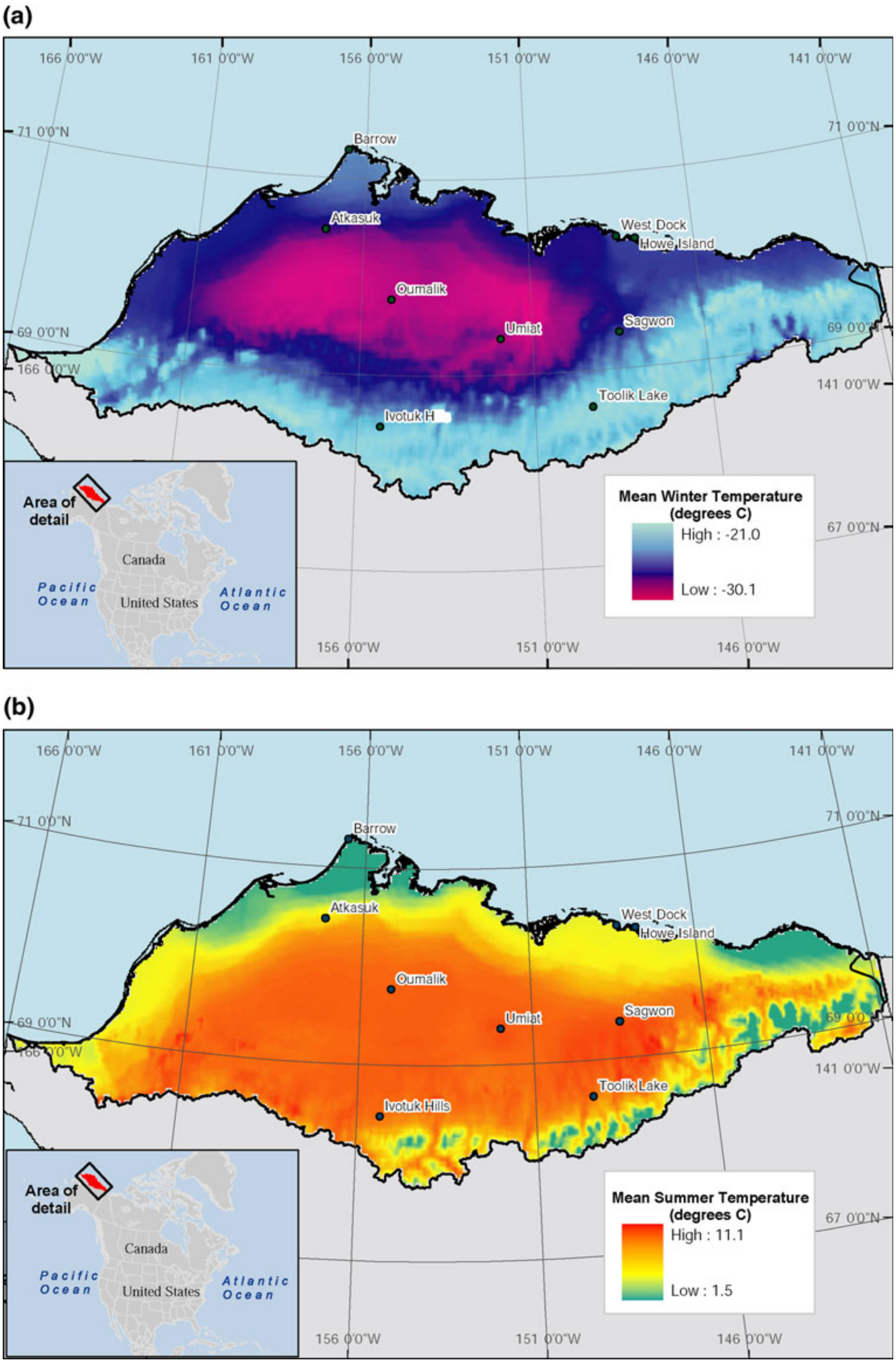

Fig. 2 Historical (1961–1990) climatology for **a** Mean winter (January, February, and March) temperature and **b** Mean summer (June, July, and August) temperature for the North Slope of Alaska (data from OSU-SCAS 2002; Daly et al. 2002)

regions (Fig. 2a). Spring is a critical transition period, during which increasing solar input and air temperatures drive snow melt and breakup of sea and river-ice. These changes result in a rapid decrease in surface albedo and, consequently, increased absorption of solar radiation and surface temperatures—further speeding snow melt and opening of rivers and the coastal ocean. This self-reinforcing thawing process, referred to as the "snow-albedo feedback" and "ice-ocean–atmosphere feedback," makes North Slope climate particularly sensitive to altered radiative and thermal forcing.

In summer, the adjacent Arctic Ocean is relatively ice-free and the North Slope coastal plain becomes influenced by a more maritime (moist and less cold) version of the

Box 1 Climate change indicators observed by the Inuit peoples as reported by the International Institute for Sustainable Development (Ashford and Castleden 2001)

Birds—Changes in species composition, numbers, and behavior and higher incidence of deformed geese eggs

Marine animals—Changes in fish populations and fish size, and increases in seldom seen fish and deformed fish. Less sea ice, leading to young bearded seals being separated from mothers and starving, despite the perception of seal populations being higher. Bowhead whales more abundant

Land animals—Populations of caribou smaller, and fewer large males. Increase in musk ox populations but more deformed individuals. Polar bears leaving lairs earlier and moving away from community. Wolf population higher, while decreases in number of rabbits observed. New kinds species of foxes (black and red) observed (vs. Arctic fox)

Insects—Increase in number of insects and longer mosquito season. Occurrences of new beetles and sand flies

Weather patterns—Milder winters, but stronger winter winds. Earlier arrival of spring. Bigger waves in harbors. Warmer summers, with more intense summer sun, but also the occurrence of thunder and lightening; increased rain and hail. Shorter fall and slower, later freeze-up

Harvests—Difficulty hunting seals and polar bears on thinner and less abundant sea ice. Melting permafrost creates difficult conditions for overland travel making for harder harvest and transport of land animals

Health—Increase in number of health problems such as skin rashes, skin problems related to sun and wind, and increased allergic reaction to white pine pollen. White pine observed to be moving northward

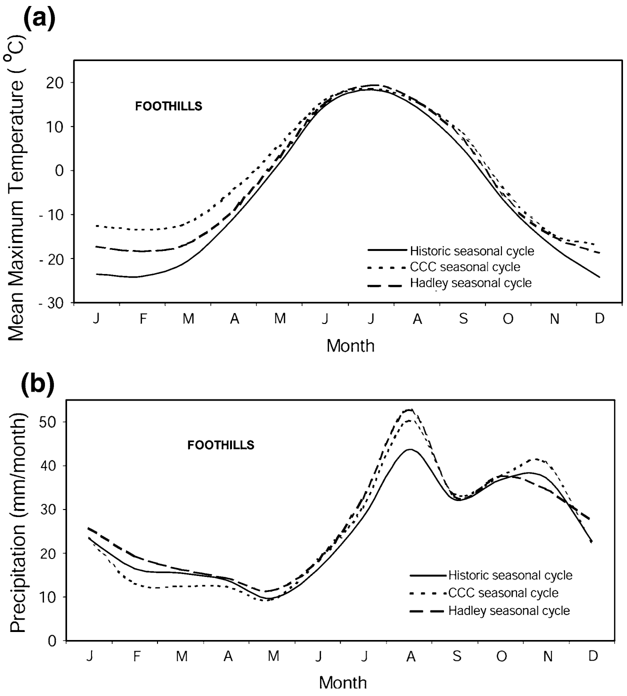

Fig. 3 Seasonal cycle of **a** mean maximum temperature and **b** precipitation for a foothills location on the North Slope (68.75°N, 156°W) for the historical period and CCC and Hadley future climate scenarios (data from Kittel et al. 2002; Kittel et al. 2004). Climate scenarios are based on GCM climate sensitivity experiments under elevated greenhouse gas and sulfate aerosol emission scenarios (+1%/year) from the Canadian Centre for Climate Modeling and Analysis (CCC, Boer et al. 2000) and the Hadley Centre for Climate Prediction and Research (Hadley, Mitchell et al. 1995)

polar air mass. Maritime air keeps the coastal plain markedly cooler than the more inland Brooks Foothills (Figs. 2b, 4a: June-Sept). The meeting of northward-flowing warmer and moist air from the northern Pacific Ocean with the Arctic air mass generates and intensifies high-latitude cyclonic storms. These storms produce precipitation and further facilitate circulation of warmer air to the North Slope (Fig. 3a, b: June-Sept). Northward flow of Pacific air is, however, partly blocked by the west–east trending Brooks Range (e.g., Fig. 4b, June–September), which tends to isolate the North Slope from Pacific and other warm air masses (Fig. 4a) maintaining the southern extent of the Arctic air mass.

Observed trends in temperature, precipitation, and snow cover

Observed centennial and multidecadal climate changes provide insights into behavior of North Slope climate and its sensitivity to future global forcing. While long-term records are sparse, there is enough information from a variety of sources to assess how inland and coastal climates changed over the last century. Best estimates are that North Slope annual mean surface air temperature increased by 1–2°C over the 20th century (Folland et al. 2001). In Barrow (Fig. 1), historic records indicate a 2.4°C increase in mean annual temperature during the period 1949–2008 (ACRC 2008). The centennial pattern, however, was not monotonic. Early century warming was interrupted by cooling from mid-1940s through mid-1970s, followed by a strong increase into the 21st century (Fig. 5a). From 1966 to 1995, regional temperatures increased +0.5°C/decade, dominated by winter and spring increases of 1.0–1.5°C/decade (Serreze et al. 2000), especially concentrated in spring when snow-albedo and sea ice feedbacks are strongest. High magnitude late 20th century North Slope temperature change is consistent with (1) temperature changes across the North American and Eurasian Arctic (Folland et al. 2001) and (2) with northern high-latitude shifts in circulation patterns and regional feedbacks that enhanced hemispheric warming (Wallace et al. 1996). Changes in these areas rank among the highest globally, reflecting the Arctic's high climate sensitivity.

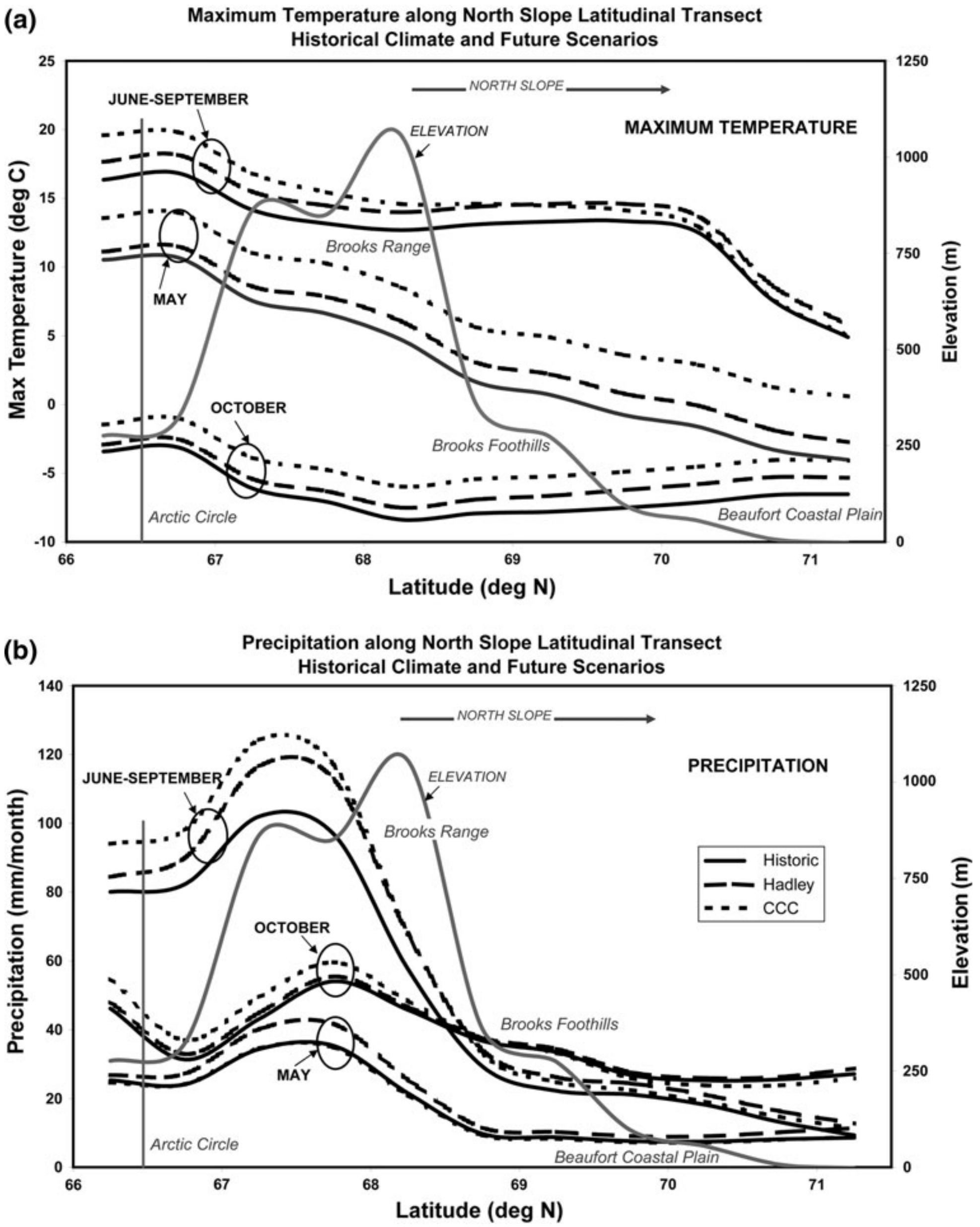

Fig. 4 Seasonal mean **a** maximum temperature and **b** precipitation along a North Slope latitudinal transect at 156°W longitude for the historical period and climate change scenarios, as in Fig. 3. Seasons represented (as groups of *lines*): spring transition (May), warm season (June–September), and fall transition (October). Averages are for 1922–1996 for the historical period, 1997–2100 for CCC, and 1997–2099 for Hadley (see legend in **b**). Elevation along the south–north transect is also shown (*right vertical axis*)

Precipitation increased throughout the Arctic during the 20th century (Dai et al. 1997; Serreze et al. 2000). At Barrow, and for Alaska in general, the multidecadal trend was, as for temperature, non-monotonic. Annual precipitation decreased from 1950 to late 1960s, followed by an upward trend (∼+13%/decade for Barrow since 1976; Fig. 5b) (Greenland and Kittel 2002). The upward trend is consistent with late 20th century increases in the frequency of cold- and warm-season cyclonic storms in the western and central North American Arctic (Serreze et al. 1997). The trend toward warmer years from 1970s to 1990s corresponded to a 5–15% decrease in spring and summer North Slope snow cover relative to earlier, colder years (Groisman et al. 1994). This reduction in snow cover during a period of increasing precipitation reflects both higher snow melt rates and less precipitation falling as snow from spring through fall (Karl et al. 1993).

Modes of hemispheric and North Slope climate variability

At the hemispheric scale, the Earth's climate system has modes of interannual and multidecadal variability. Each characteristically oscillates between two distinct ("negative" and "positive") phases on interannual scales and tends to favor regimes of one phase over the other on multidecadal scales. The North Pacific Index (NPI) captures dynamics of the semipermanent Aleutian low-pressure center (in the northern North Pacific) linked to weather of adjacent North America (Trenberth and Hurrell 1994) (Fig. 5b, right

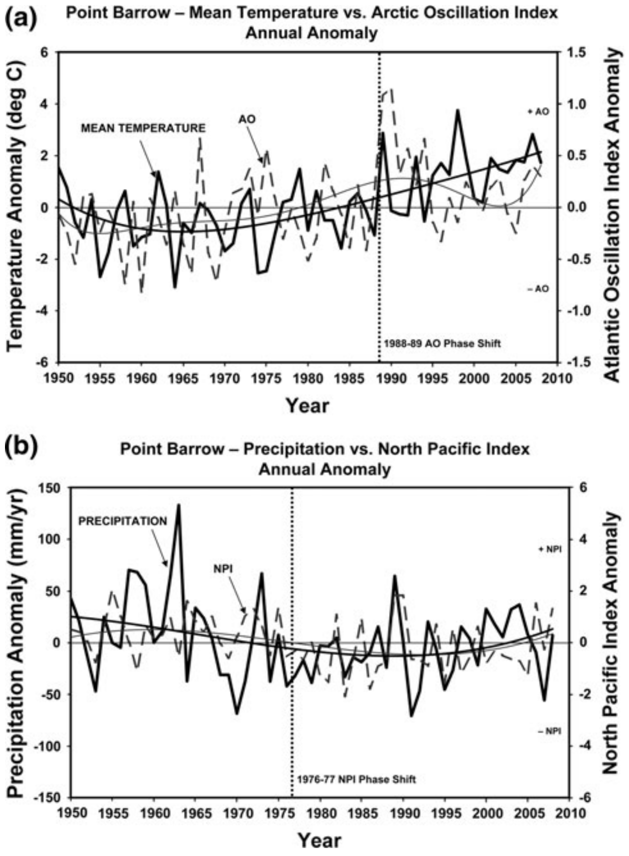

Fig. 5 Comparison of variability in climate at Barrow, Alaska, and hemispheric circulation indices 1950–2008. **a** Barrow annual mean temperature anomaly (*solid line*) and annual Arctic Oscillation index (*long-dashed line*, AO, Thompson and Wallace 1998). **b** Barrow annual precipitation anomaly (*solid line*) and North Pacific Index anomaly (*long-dashed line*, NPI, Trenberth and Hurrell 1994). Thinner timelines are polynomial fits, vertical short-dashed lines mark key regime changes. Anomalies are relative to period long-term means. Addendum: 2009 Barrow temperature and precipitation anomalies were +1.8°C and +41 mm/year, respectively. Barrow data are from the Western Regional Climate Center (http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ak0546), AO from the NOAA Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/monthly.ao.index.b50.current.ascii.table), and NPI from the National Center for Atmospheric Research (http://www.cgd.ucar.edu/cas/jhurrell/indices.data.html#npmon)

vertical axis). NPI's negative phase is associated with a deeper Aleutian Low and an intensified atmospheric circulation that drives warm air into Alaska, resulting in warmer winter temperatures as far as the North Slope (Hurrell 1996). Also during the negative phase, net hydrologic input (precipitation less evaporation) over the western Arctic is reduced in winter and spring and increased in summer (Rogers et al. 2001).

Another mode in northern high latitudes is the Arctic Oscillation (AO)—an oscillation in sea level pressure between the Northern Hemisphere's high and mid-latitudes (Thompson and Wallace 1998) (Fig. 5a, right axis). In its positive phase, a winter decrease in pressure in the Arctic Basin accompanies intensified Polar Vortex westerlies. North Slope annual mean temperatures are higher (Fig. 5a, left axis), though seasonal patterns diverge: winter air temperatures are lower and spring air temperatures higher. Springtime net hydrologic inputs over the western Arctic also increase (Overland et al. 2002).

Since the late 1960s, the AO moved toward a positive regime (generally warmer for the North Slope), with a substantial shift in 1988–89, while the NPI tended toward a negative regime (also generally warm for the North Slope) with a step change in 1976–77 and has remained predominantly in that phase (though most recently tending to positive) (Fig. 5). It is not clear if these shifts are part of a global climate change signal attributable to anthropogenic forcing (IPCC 2007). However, there is an indication in global circulation model (GCM) experiments under 20th century elevated greenhouse gases for a shift to hemispheric circulation phases favoring warm anomalies over the North Slope (Wallace et al. 1996).

Projected anthropogenic climate change

Global anthropogenic forcings that influence North Slope climate include global land surface changes and altered atmospheric composition (Chase et al. 2001; Pielke et al. 2009). GCM-based climate change scenarios under increased greenhouse gases and sulfate aerosols suggest that the pace and severity of climate change will increase throughout the Arctic in the 21st century. The rate of change in historical warming noted earlier for Barrow (2.4°C/60 years) is the same order of that projected by GCMs for 2000–2060 (Fig. 6).

Modeled changes include altered seasonality (Fig. 3) and geography (Fig. 4) for not only temperature and precipitation, but also the full suite of climate variables including cloudiness, humidity, solar radiation, and wind. An additional important lesson from these model experiments is the high uncertainty in future climates, captured only in part by the spread of outcomes for a range of emission scenarios simulated by selected GCMs (Fig. 6).

On the North Slope, climate responses will be amplified locally by snow-albedo and ice-ocean–atmosphere feedbacks and expressed in complex linked changes in temperatures, storm frequency and intensity, precipitation, snow cover, as well as coastal sea ice, permafrost dynamics, and surface hydrology—discussed next.

Changing seascapes and landscapes

Sea ice changes and coastal erosion

Although extent and thickness of perennial sea ice in the Arctic are highly variable, both have decreased in the last

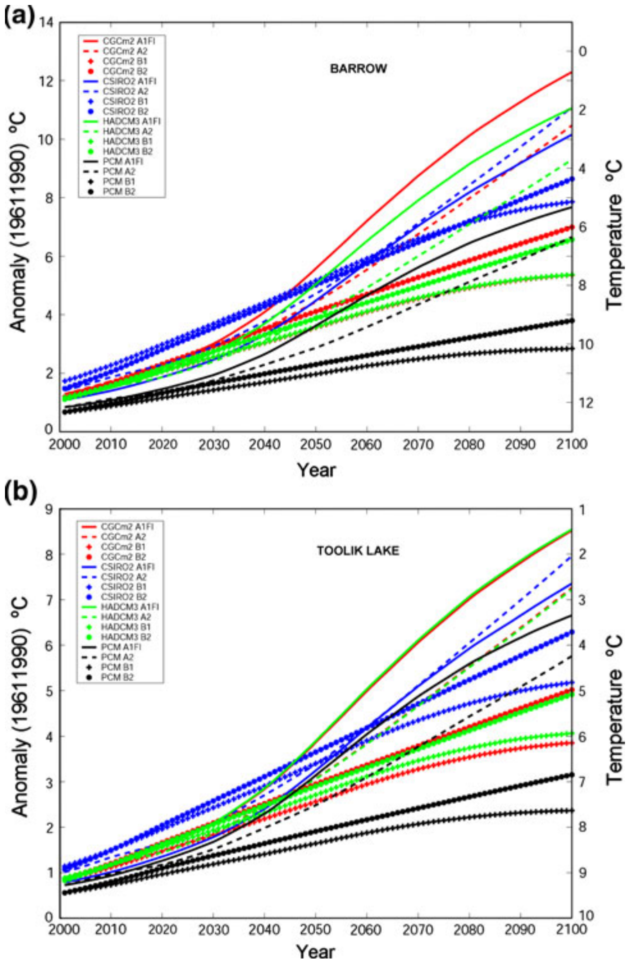

Fig. 6 Mean annual temperature anomaly (relative to 1961–1990 climatology) from four general circulation models (CGCm2, CSIRO2, HadCM3, and PCM) under four IPCC (Nakicenovic and Swart 2000) emission scenarios (A1FI, A2, B1, and B2) for **a** Barrow, AK and **b** Toolik Lake, AK (Data from Mitchell et al. 2004)

50 years. In September 2007, the extent (4.1 10^6 km^2) of the Arctic sea ice reached an unprecedented minimum (for 1978–2010), 24% less than the previous record set in September 2005 (Comiso et al. 2008; Maslanik et al. 2007). Total sea ice, seasonal as well as perennial ice, is also rapidly declining with a long-term (1978–2007) trend of $-3.7 \pm 0.2\%$ per decade. However, in 1996, there was a shift, steeping the rate of decline. For 1978–1996, the decline was $-2.2 \pm 0.4\%$ per decade, followed by $-10.1 \pm 0.7\%$ per decade during the period 1996 through September 2007 (Comiso et al. 2008). The rapid shift leading to the anomalously low ice extent in 2007 was due to a preconditioning of the perennial ice pack, from a decadal decline in multiyear ice and increase in younger and thinner pack to the point that not even 10% of pack ice was older than 2 years (Comiso et al. 2008; Maslanik et al. 2007). This is a consequence of warming and Arctic Oscillation-connected shifts in ocean drift patterns (Overland et al. 2008).

The most dramatic changes ice-free waters have occurred in the Beaufort, Chukchi, East Siberian, and Laptev seas (Comiso et al. 2008). Along the North Slope coast, ice-free period increases have been affected not only by sea surface and sea ice temperatures but also by a higher frequency of cyclonic storms in the western Arctic (Comiso et al. 2008). Along the coast, a longer ice-free period (1) increases spring and fall ground temperatures in coastline tundra, increasing its erosional instability and (2) increases shore exposure to wave erosion during severe storms at times normally protected by sea ice. These effects, in combination with increased storm frequency, resulted in coastal erosion at a rate of 5–9 m/decade at Barrow over last 50 years (Syvitski et al. 2003).

Permafrost soil and surface hydrology

North Slope soils are characterized by continuous permafrost generally ranging in thickness from 300 m near the foothills to over 600 m near the coast (Osterkamp and Payne 1981). Overlaying the permafrost is a seasonal thaw soil layer ("active layer") maintained by complex interactions among climatological, hydrologic, biotic, geologic, and oceanographic factors which influence heat, moisture, and solute transfers to and from the permafrost (Smith and Riseborough 2002). Permafrost temperature and active layer thickness generally increase with distance from the coast (Zhang et al. 1997). Both are directly proportional to the thawing index (cumulative number of degree-days above 0°C) and summer air temperature (e.g., Hinkel and Nelson 2003), with active layer thickness exhibiting more pronounced spatial and temporal variability (Anisimov et al. 2002; Zhang et al. 1997).

Permafrost temperatures are changing in many places in the Arctic (Nelson 2003). Rising air temperatures and increased solar radiation since the 1980s raised permafrost temperatures (by >3°C) and active layer thaw depth in some areas of the North Slope (Zhang et al. 2003; Osterkamp 2007). Warming and deepening of the active layer will alter water storage, downslope drainage, sediment in surface runoff (Osterkamp and Romanovsky 1997), and key biogeochemical and ecological processes (discussed later). Such changes will push landscapes in different parts of the North Slope in opposite directions. In ice-rich soils with poor soil drainage, warming will lead to an increase in thermokarst activity (ground-surface subsidence) and short-term increases in runoff, with water impounded in resulting surface deformations (Rouse et al. 1997). This may lead to development and expansion of wetlands and thaw lakes (discussed next). In contrast, on well-drained soils in uplands and hillslopes, permafrost degradation is likely to improve drainage by melting barriers, leading to drainage of thaw lakes and wetlands and to drier soils

(Rouse et al. 1997), as well as hillslope failure, already seen in the Brooks Foothills (Gooseff et al. 2009).

Thaw lakes

Thaw lakes and drained thaw-lake basins occupy much of the Beaufort Coastal Plain (Fig. 1). For example, on the Barrow Peninsula, thaw lakes cover 22% and drained thaw-lake basins 50% of land area (Fig. 7) (Hinkel et al. 2003). Thaw lakes develop as small water entrapments coalesce. Self-reinforcing feedbacks between summer warming and ablation of ground ice promote further subsidence and expansion of thaw lakes (Hinkel et al. 2003).

Thaw-lake depth is controlled by air temperature, winter lake ice thickness, and snow cover (Ling and Zhang 2003). Due to snow's insulating properties, its cover and depth exert a much greater influence on ice thickness than air temperature alone (Zhang and Jefferies 2000). These features determine which lakes freeze completely to the bottom each winter. Climate shifts that increase temperature and alter snow duration and depth will consequently alter lake water storage and unfrozen water availability (Bowling et al. 2003). Consequent changes in surrounding ground soil temperatures, permafrost, and the ratio of frozen to unfrozen ground (*taliks*) will accelerate methane efflux and alter energy fluxes to the atmosphere (Ling and Zhang 2003)—a positive feedback magnifying the pace and severity of landscape responses to destabilizing climate change.

Soil and thaw lake carbon flux

Carbon (C) deposition, decomposition, distribution, and feedbacks to the climate system have been the focus of many studies on the North Slope (McGuire et al. 2002). Methane (CH_4) and carbon dioxide (CO_2) fluxes in carbon rich soils are closely correlated with local variations in soil pH, soil temperature, thaw depth, nutrient cycling, growing season length, and water table depth. These factors in turn are all strongly mediated by changes in vegetation and landscape position (Bockheim et al. 2004). In general, colder, poorly drained soils on the Beaufort Coastal Plain have accumulated more carbon than relatively warmer, better drained upland soils in the Brooks Foothills (Michaelson et al. 1996; Bockheim et al. 1999).

Observed temporal variability in carbon fluxes reflects long-term climatic patterns. The warming that began in the mid-1970s and associated lowering of the water table caused wet sedge tundra on the coastal plain to switch from being an annual net C sink to a net source (Oechel et al. 2000). The spatial and temporal variability of C fluxes demonstrates that North Slope carbon pool is highly sensitive to local and regional environmental change. Climate shifts trigger numerous and complex interactions among ecosystem processes, altering the flux of these greenhouse gases into the atmosphere (Walker et al. 2004). For example, water-logged soils (over permafrost) and thaw lakes are primary CH_4 sources. With warming, thaw lake expansion and permafrost

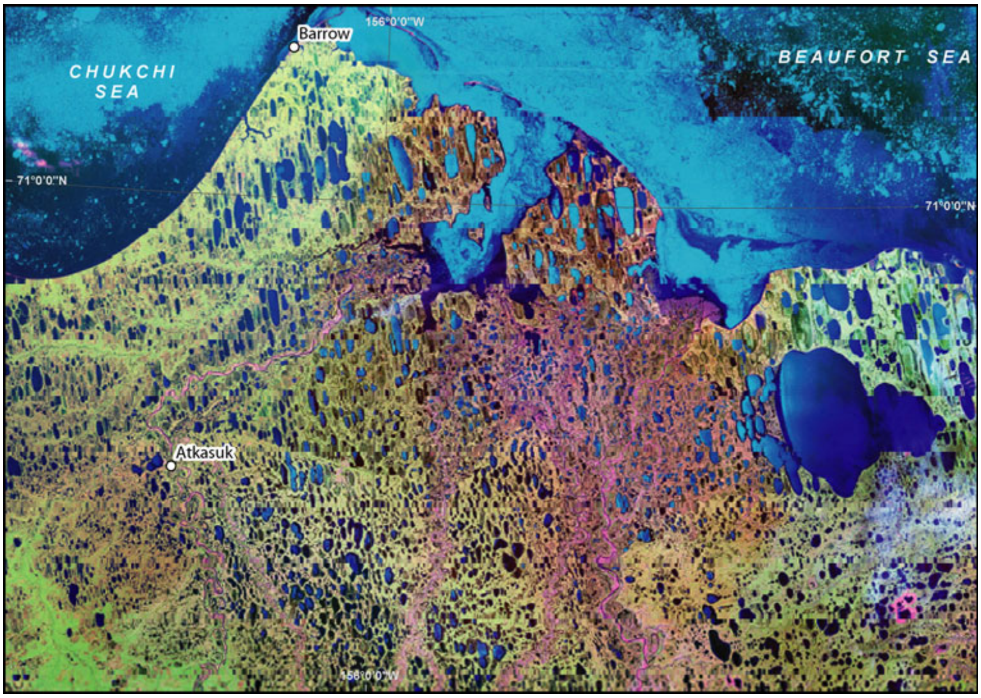

Fig. 7 Landsat 7 Enhanced Thematic Mapper image (GeoCover 2000) of thaw lakes and drained thaw-lake basins on the Beaufort Coastal Plain near Barrow, AK

degradation can lead to channeling that drain these sites and dry soils, reducing CH_4 production in favor of CO_2 efflux (Zhuang et al. 2009). Understanding future shifts in North Slope carbon balance will be crucial for estimating this strong positive biogeochemical feedback to climate. However, long-term controls and feedbacks to the atmosphere remain poorly understood and remain unpredictable (Hobbie et al. 2000).

Response of biological communities

Changing climate and consequent changes in landscapes and seascapes will impact North Slope biota. As with abiotic and biogeochemical processes described above, biological communities will respond in ways that vary greatly in space and time. Plants and animals show direct physiological responses to climate change. They also respond indirectly to climate impacts on their habitat and on population dynamics of other species with which they interact through competition and trophic linkages.

Climate change is expected to alter the nature of extreme events and interannual variability, as well as more often considered changes to seasonal means—climatic timescales with impacts on populations and communities. For example, changing frequency and intensity of sustained (week-long) low temperatures, high rainfall, and high wind events linked to high-latitude circulation oscillations (as the AO) affect survivorship of animals and plants during crucial periods of over-wintering, migration, or dormancy break, as well as growth and reproduction (e.g., Hallett et al. 2004).

Terrestrial vegetation

The vegetative growing season is short across the North Slope: for example, the median frost-free period at Umiat, Alaska, in the lower foothills is only 27 days (WRCC 2003). The growing season has been affected by warmer temperatures: remote sensing studies over recent decades show an increasing growing season length closely correlated with vegetation changes (Verbyla 2008; Stow et al. 2004). While warm-season precipitation is low (<60 mm month^{-1}, Fig. 3b), growing season conditions are generally moist, because precipitation and snow melt exceed evaporation. Cold temperatures additionally limit plant productivity through effects on nutrient availability (Shaver et al. 1998). Warmer soil temperatures, due to increased air temperatures or increased thermal insulation (from changes in vegetation cover, organic layer depth, snow depth, soil moisture, and proximity to thaw lakes), stimulate microbial activity and promote nitrogen mineralization (Starr et al. 2004).

Well over half of the North Slope is occupied by moist tundra, with the remaining area split among shrub tundras, wetlands, and lakes (Fig. 1) (Muller et al. 1999). North–south climate and physiographic (coast to mountain) gradients are the major broad scale drivers of vegetation structure across the region (Fig. 1). At the landscape level, other key factors are active layer depth, water storage, nutrient availability, soil pH, and soil temperature (e.g., van Wijk et al. 2004). Climate-driven shifts in major vegetation transitions on the North Slope result from the interplay of climate, vegetation response, and landscape processes—we discuss these dynamics for four such transitions in the next sections.

High Arctic: dry shrub tundras versus wet/moist non-tussock graminoid tundra

Along the northern coast, vegetation structure and ecosystem processes are controlled by the High Arctic's cold, dry climate (Fig. 1; Subzone C, left inset) (Epstein et al. 2004). On well-drained mineral soils, for example on Howe Island (Fig. 1) and much of the Canadian High Arctic, vegetation is typically dominated by hemi-prostrate dwarf shrubs, graminoids, mosses, lichens, and forbs. Communities have open plant canopies and low plant density (<200 g m^{-2}) and occur on soils with deep active layers (65 cm) (Walker et al. 2003). In contrast, on poorly drained sites (such as at Barrow and West Dock, Fig. 1), extreme cold maintains near-surface permafrost which in turn provides moist ice-rich soils. Here, the vegetation is wet and moist non-tussock graminoid tundras (Fig. 1), dominated by mosses, lichens, and graminoids with low shrub biomass and a higher total biomass (~ 400 g m^{-2}) (Walker et al. 2003).

Under warmer air temperatures and longer growing seasons, areas with sparse vegetation, mineral soils, and deep active layers may develop a thicker and more widespread layer of moss (Epstein et al. 2004). The insulation moss provides may serve as a negative feedback, keeping soil cooler in summer, thereby limiting active layer thaw depth (Beringer et al. 2001). On the other hand, moist non-tussock tundra, responds to warming as noted earlier for low-slope permafrost environs, with conversion to wetlands and expanding thaw lakes as the active layer deepens and ground subsides.

Low Arctic: moist non-acidic graminoid tundra versus moist acidic tussock tundra

Moist non-acidic graminoid tundra is characterized by non-tussock-forming sedges, erect dwarf shrubs, and minerotrophic mosses, which occur on calcareous loess deposits. Soils have a thin organic layer and a thick active layer. It is the dominant Low Arctic tundra of the Beaufort Coastal Plain (Fig. 1). On the other hand, moist acidic tussock tundra consists of tussock-forming sedges, dwarf deciduous and evergreen shrubs, and *Sphagnum* mosses. It occurs on moderately drained acidic soils with a deeper soil organic layer and thinner active layer (Walker et al. 2003). It is a dominant Low Arctic vegetation type throughout the Brooks Foothills (Fig. 1). The transition from moist non-acidic tundra to acidic tundra along the northern boundary of the foothills (Fig. 1) is primarily controlled by regional processes such as climate, with intra-zonal transitions strongly influenced by parent material, topographic position, microclimate, and natural disturbances (Epstein et al. 2004; Walker et al. 1998).

Mid-Holocene (~9,000–11,000 years BP) paleoenvironmental studies support the conclusion that climatic change has the potential to alter current boundaries between moist non-acidic tundra and moist acidic tundra with warming favoring moist acidic tundra (Kaufman et al. 2004). This conversion occurs as moist non-acidic tundra moss biomass develops a thick insulating carpet-like layer, which leads to warmer wintertime and cooler summertime soil temperatures, decreased active layer thaw depth, and increased water storage. This eventually leads to leaching of base cations, creating a more acidic soil environment and promoting colonization of moist acidic tundra species (Walker et al. 2003). While results from GCM scenarios (Fig. 6) suggest that even low end warming projections for 2050 will approach mid-Holocene temperatures (+2–3°C from present, Nelson and Carter 1987), it is unclear how quickly such a conversion could occur. The paleo-shift from non-acidic to acidic tundra took on the order of centuries to millennia (Oswald et al. 2003); we lack evidence of rapid decadal shifts in moist non-acidic tundra species composition (Epstein et al. 2004).

Moist acidic tussock tundra versus moist low shrub tundra

Moist acidic tussock tundra just discussed and moist low shrub tundra are the dominant Low Arctic vegetation in the Brooks Foothills (Fig. 1). Major structural differences between these tundras are that birch (*Betula nana*) and willow (*Salix planifolia* ssp. *pulchra*) dwarf shrubs are larger and more abundant and non-vascular biomass reduced in low shrub tundra (Epstein et al. 2004). Increased temperatures are seen to promote shrub expansion, suggesting that moist tussock tundra would give way to moist low shrub tundra. In field manipulation experiments, warming alone (+3°C) was sufficient to cause shifts in birch aboveground biomass and significant net redistribution of N favoring birch, helping it to gain canopy dominance (Bret-Harte et al. 2001; Hobbie and Chapin 1998b). This shift is self-reinforcing—increased litter fall and shading from birch are hypothesized as being responsible for a loss of mosses and lichens (Shaver et al. 2001). Shrub expansion on the North Slope has been observed coincident with warming over recent decades from field studies and through repeat photography (Chapin et al. 1995; Shaver et al. 1998; Strack et al. 2007). Shrub expansion is also promoted by a "snow-shrub feedback loop" (Sturm et al. 2001). In a positive feedback, shrub canopy and growth form are both fostered by and contribute to snow pack accumulation and duration.

North Slope woodlands and possibility of treeline expansion

The role of future warming on treeline within the Arctic is uncertain. Currently, balsam poplar (*Populus balsamifera*) occurs on the North Slope in small clonal populations restricted to floodplains and south-facing slopes (Bockheim et al. 2003). On the North Slope, cold Arctic air limits establishment of balsam poplar and other treeline species (*Betula papyrifera*, *Picea glauca*, *Populus tremuloides*, and *Alnus crispa*)—of these last four, white spruce (*Picea glauca*) is currently the most likely to survive were it to become established in Brooks Foothills upland tundra (Hobbie and Chapin 1998a). Climatic warming and associated increases in nutrient availability would enhance the probability of white spruce surviving on the North Slope. However, spruce pollen in the paleorecord over the past 9,000 years indicates that the Brooks Range is an effective barrier to northward migration and expansion of this species (e.g., Kaufman et al. 2004).

Terrestrial mammals

Much of what we know of recent wildlife change on the North Slope comes to us from indigenous people's observations (Box 1, Ashford and Castleden 2001). Most climate change scientific literature regarding Alaskan Arctic mammals focuses on caribou. Four herds (Western Arctic, Teshekpuk, Central Arctic, and Porcupine) occupy parts of the North Slope and adjacent areas at various times of the year. All are directly vulnerable to climate change and indirectly vulnerable to climate change impacts on their forage plants. Caribou have several life cycle stages particularly sensitive to climate variability. Earlier springs, warmer summers, and more winter precipitation as snow would influence caribou survival by altering forage availability, migration conditions, insect harassment, and ability to escape predation (Griffith et al. 2002).

Warmer wetter winters accompanied by deeper and denser snow fall and more frequent formation of an ice layer over snow seriously impede caribou foraging (Gunn and Skogland 1997). Rain falling on snow creates an impenetrable layer of ice and cause severe weight loss, starvation, or death (Aanes et al. 2000). Griffith et al. (2002) postulated that the 1990s population decrease in the

Porcupine caribou herd may have been the result of more intense freeze–thaw cycles on transitional and winter ranges in eastern Alaska and western Canada.

Shifts and losses of vegetation found in climate manipulation field experiments could have profound effects on caribou survival as well as other herbivorous mammals (Chapin et al. 1995; Gough et al. 2008). Forb inflorescences, which are nutritionally important and selectively grazed by caribou during lactation, were lost or strongly reduced in treatments simulating climatic warming (Jefferies and Bryant 1995). Biomass of lichens, critical to caribou nutrition levels when over-wintering (White and Trudell 1980), was also reduced.

Warmer summers, which increase thermokarst activity and so the amount of standing water, create ideal conditions for increased populations of mosquitoes (*Cuculidae*) and flies of the family *Oestridae* which harass caribou (Griffith et al. 2002). Climate change may further affect insect harassment by altering wind speed and direction. Though effects of insect harassment are not well studied, adjacent Porcupine and Central Arctic caribou herds appear to cope with it differently. The Central Arctic herd tends to move along the coastline during times of potential insect harassment, while the Porcupine herd tends to move to higher sites on the coastal plain or into the foothills and mountains of the Brooks Range (Griffith et al. 2002).

After human hunters, the main caribou predators are wolves (*Canus lupus*), grizzly bear (*Ursus arctos*), and golden eagles (*Aquila chrysaetos*) (Young et al. 2002). If increased caribou predation coincided with higher mortality and decreased fecundity (from climate-related reduced forage quality and quantity and elevated insect harassment), population decline would accelerate. In the absence of other (stable) sources of prey, a decline in predator populations would follow (Gunn and Skogland 1997).

Avifauna

A warmer climate on the North Slope will modify migratory bird breeding habitats, food webs, molting areas, home ranges, and migratory pathways with consequent changes to community composition and populations, possibly leading to local extirpation of some species (Root et al. 2003). Sea level rise, flooding, earlier spring, longer breeding seasons, higher air temperatures, altered precipitation, and greater insect populations will all affect avian reproduction. Responses to climate change will be highly variable across taxa and habitats.

A longer growing season will promote a longer breeding window benefiting single-clutch determinate layers (birds whose clutch size is determined at start of laying), especially if earlier springs improve adult body condition and lead to larger clutches (Davies and Cooke 1983). Even without changes in body condition and clutch size, the young will have more time to forage before fall migration. Longer breeding seasons may also enhance reproductive success via more regular breeding, e.g., for rough-legged hawks (*Buteo lagopus*) (Johnson and Herter 1989), or production of replacement clutches by indeterminate layers, e.g., northern pintail (*Anus acuta*) (Duncan 1987).

Deeper spring snow pack and excessive warming during late breeding can cause brood failure and adult mortality (Gaston et al. 2002). In addition, if spring melt and runoff exceed current natural variability, inundation could flood out breeders using tundra pond islands, such as loons (*Gavia* spp) and long-tailed ducks (*Clangula hyemalis*) (Johnson and Herter 1989), as well as those using gravel bars, beaches, and stony river ridges, including semipalmated plover (*Charadrius semipalmatus*) (Sutton and Parmelee 1955) and ruddy turnstone (*Arenaria interpres*) (Johnson and Herter 1989).

Unlike much of the Eurasian and Canadian Arctic, Alaska's North Slope has no adjacent land where tundra and associated avifauna could retreat northward. Open upland tundra birds are at particular risk to climate-related shifts to more woody-dominated habitats. These include lesser golden plover (*Pluvialis dominica*), Baird's sandpiper (*Calidris bairdii*), and long-tailed jaeger (*Stercorarius longicaudus*) (Salter et al. 1980; Johnson and Herter 1989). Expanding woody habitats and flooding due to rising water tables (Nicholls et al. 1999) could further diminish upland habitat for these species. On the other hand, birds preferring shrub habitat for breeding may benefit.

The northern Alaska coastline has no large seabird breeding colonies (Johnson and Herter 1989). However, reduced area of or accessibility to ice edges, leads, and large polynyas (open seawater surrounded by sea ice) could harm birds that forage heavily in these habitats (Divoky 1976; Stirling 1997). Retreating pack ice could actually create more open water habitat for exogenous migrants that fare poorly in ice-covered seas, e.g., short-tailed shearwater (*Puffinus tenuirostris*) (Bailey 1948). Rapidly rising sea level, greater freshwater runoff, or higher spring tides (coupled with greater spring storm intensity) could injure coastal birds on low offshore spits, barrier islands, and river deltas (Hansen 1961). Coastal flooding causes mortality, nest failures, and greater interannual variability in reproductive performance of brant (*Branta bernicula*), common eider (*Somateria mollissima*), and black guillemot (*Cepphus grylle*) (Barry 1986).

Increased insect abundance and more varied insect community composition are expected to accompany Arctic climate change (Danks 1992; Hodkinson and Bird 1998), providing energy-dense diets for insectivorous passerines including bluethroat (*Luscinia svecica*), Arctic warbler

(*Phylloscopus borealis*), and various sparrows (*Emberizidae*). Other impacts of climate change on Arctic birds are more difficult to gauge. New microhabitats caused by warming may alter the prey base and predator dynamics in unpredictable ways. Barrier island-lagoon systems provide important molting sites, staging grounds, and migratory pathways (Woodby and Divoky 1982). Increasing fetch and wave height may render these systems unsuitable breeding grounds along portions of Alaska's Beaufort Sea coastline.

Freshwater systems

The impacts of climate change on the hydrologic characteristics of Arctic Alaska are complex and somewhat unpredictable (Hinzman and Kane 1992). Expected hydrologic responses of rivers include earlier onset and later termination of snow melt-water peaks. Flows may be higher or lower, depending on precipitation patterns (Hinzman and Kane 1992). Higher flows from glacial activity (Arendt et al. 2002) and deeper active permafrost layer will increase base flow of streams and create new springs (Vörösmarty et al. 2001). Greater glacial melting will also deliver more silt and cold water to streams (Oswood et al. 1992). Higher flows from snow melt would destabilize riverbanks and raise sediment levels, changing channel morphology, stability, substrate composition, and habitat complexity (Oswood et al. 1992). Increases in turbidity and sediment loading of rivers and streams will lead to decreases in primary productivity and macroinvertebrate densities and to altered species compositions (Oswood et al. 1992). Fishes requiring clear water will decrease or become absent in reaches with increased turbidity. The effects of climate change on freshwater carbon dynamics are unclear (Oswood et al. 1992).

Climate change impacts on lakes are also complex. In recent decades, lake systems around the globe have had later onset and earlier breakup of surface ice (Magnuson 2002). This pattern has been observed in Arctic lakes, resulting in higher July water temperatures in the shallow littoral zone of Toolik Lake (MacDonald et al. 1996). Changes in water levels and nutrient concentrations in lakes will depend on precipitation levels (MacDonald et al. 1996) and watershed biogeochemical and geomorphic processes.

Thermal shifts in surface waters, whether warming or cooling, will affect developmental times and bioenergetic requirements of different taxa and life stages (Oswood et al. 1992; MacDonald et al. 1996). The effects of changes in the timing of developmental stages of biota and subsequent persistence of freshwater taxa in Arctic waters will be mixed. Colder water results in longer developmental times, warmer water shortens developmental times. The effects of shortened developmental times on riverine fishes are not clear, but the consequences of warming on bioenergetic requirements can be dramatic. MacDonald et al. (1996) indicated that young-of-the-year lake trout in Toolik Lake would experience a greater than eightfold increase in bioenergetic requirements with a 3°C increase. However, productivity in the lake is not expected to increase sufficiently to support this need, leading to age-class failures.

Climate change will affect the distribution, abundance, and life history characteristics of freshwater biodiversity on the North Slope and potentially allow colonization of new species into the region (Oswood et al. 1992). However, unlike other Arctic freshwater landscapes, where colonization from extraregional sources is likely, zoogeographic isolation of Arctic Alaskan rivers and lakes precludes trophic replacements of extirpated fish species by new arrivals (MacDonald et al. 1996). Riverine fishes from western Alaskan waters would have to colonize via brackish environments. Significantly warmer streams could be colonized by fish species with migratory marine life stages, such as sturgeon, lamprey, and salmonids such as brook trout, cutthroat trout, and rainbow trout (Poff et al. 2001), but the extreme winters may still limit their success. Many macroinvertebrates have flying adult stages and are so not limited in their range expansion by drainage boundaries. Macroinvertebrate species may colonize from the south as climate extremes are ameliorated, increasing species diversity (Oswood et al. 1992). The long-term ecological consequences of altering both macroinvertebrate and vertebrate freshwater community composition are impossible to predict.

Summary and conclusion

Real changes in climate, landscapes, and biotic communities have taken place on Alaska's North Slope over the past 50 years. Further warming of the magnitude simulated by GCMs will have profound implications for North Slope ecosystems and for humans living there. These changes will be mediated through complex interactions and are not likely to be uniform across the North Slope. Climate-related changes across the North Slope will depend on the magnitude and direction of temperature and precipitation shifts, but also on other weather elements such as storm and high wind event frequency and intensity. How these changes play out across the region also depends on local landform and soil processes determining drainage, erodibility, permafrost dynamics, and existing carbon stocks—the interplay of climate and landform offers a useful framework for projecting the spatial pattern of ecosystem responses to climate change. On poorly drained sites, warmer temperatures generally promote melting of permafrost and expansion of wetlands and thermokarst lakes—until expansion erodes channels that drain and dry soils. On well-drained terrain, warming may, on the other hand, promote increases in plant cover and stabilization of frozen layers.

A future climate resembling the warmer, wetter regime experienced in the early Holocene would promote peat formation and shrub expansion. However, a warmer and drier climate may have the opposite effect, fostering drier upland tundra landscapes. Warming promotes CH_4 emissions where soils become wetter and anaerobic vs. CO_2 emissions where soils become drier. Changes in the duration, extent, and depth of snow cover also have profound effects on the thermal and hydric regime of permafrost and thaw lakes, with positive and negative feedbacks among soil temperature, erosion and drainage, nutrient cycling, and vegetation dynamics. Altered dynamics of these systems trigger feedback mechanisms—many of them positive, and so reinforcing trends.

Changing climate regimes will have direct physiological effects on terrestrial, avian, and freshwater wildlife. However, many of the strongest climate impacts will be indirect through changes to landforms, surface hydrology, and vegetation that determine habitat distribution and quality. Landscape and biological community changes already observed are leading indicators of abrupt change. These and our understanding of system vulnerabilities to climate change give North Slope scientists, land managers, and policymakers some early warning, and hence, the opportunity to enhance the ability of Arctic Alaskan ecosystems to adapt. "Least regrets" strategies are needed—strategies that reduce the vulnerability of ecosystems to rapid climate change using an integrated multistressor approach and without reliance on specific future climate scenarios (Pielke and de Guenni 2004). Such action is nonetheless limited by the magnitude and rate of climate change, threshold dynamics of these landscapes, and geographical limits to poleward retreat for organisms. Regardless, these Arctic landscapes will be transformed.

Acknowledgments This work was funded in part by a grant from BP Exploration (Alaska, Inc). We would like to thank Bill Streever, Environmental Studies Leader for BP in Alaska, for making this work possible. In addition, we would like to thank Terry Chapin, Larry Hinzman, and George Divoky (University of Alaska Fairbanks) and Peter Kareiva (The Nature Conservancy) for their review and helpful comments on an earlier version of the manuscript. We are grateful to Chris Daly (Oregon State University) for providing PRISM climate data and Nan Rosenbloom (National Center for Atmospheric Research) for providing VEMAP data sets. Lastly, we would like to thank Gwen Kittel (NatureServe) and Joel Smith, Christina Thomas, Sam Hitz, Russ Jones, Amy Gage, and Sheila DeMars (Stratus Consulting) for their help with earlier versions of this manuscript.

References

Aanes R, Saether BE, Øritsland NA (2000) Fluctuations of an introduced population of Svalbard reindeer: the effects of density dependence and climatic variation. Ecography 23(4):437–443

ACIA (ed) (2005) Arctic climate impact assessment. ACIA scientific report. Cambridge University Press, New York

ACRC (2008) Temperature change in Alaska. Climate Research Center, University of Alaska. http://climate.gi.alaska.edu/ClimTrends/Change/TempChange.html

Anisimov OA, Shiklomanov NI, Nelson FE (2002) Variability of seasonal thaw depth in permafrost regions: a stochastic modeling approach. Ecol Model 153:217–227

Arendt AA, Echelmeyer KA, Harrison WD, Kingle CS, Valentine VB (2002) Rapid wastage of Alaska glaciers and their contributions to rising sea level. Science 297:382–386

Ashford G, Castleden J (2001) Inuit observations on climate change: final report. International Institute for Sustainable Development

Bailey AM (1948) Birds of Arctic Alaska. Colorado Museum of Natural History, Denver

Barry TW (1986) Eiders of the western Canadian Arctic. In: Reed A (ed) Eider ducks in Canada. Canadian Wildlife Service, Ottawa, pp 74–80

Beringer J, Lynch AH, Chapin FS III, Mack M, Bonan GB (2001) The representation of arctic soils in the Land Surface Model: the importance of mosses. J Clim 14:3324–3335

Bockheim JG, Everett LR, Hinkel KM, Nelson FE, Brown J (1999) Soil organic carbon storage and distribution in Arctic Tundra, Barrow, Alaska. Soil Sci Soc Am J 63(4):934–940

Bockheim JG, O'Brien JD, Munroe JS, Hinkel KM (2003) Factors affecting the distribution of *Populus balsamifera* on the North Slope of Alaska, U.S.A. Arc Antarct Alp Res 35(3):331–340

Bockheim JG, Hinkel KM, Eisner WR, Dai XY (2004) Carbon pools and accumulation rates in an age-series of soils in drained thaw-lake basins, arctic Alaska. Soil Sci Soc Am J 68:697–704

Boer GJ, Flato GM, Ramsden D (2000) A transient climate change simulation with historical and projected greenhouse gas and aerosol forcing: projected climate for the 21st century. Climate Dyn 16:427–450

Bowling LC, Kane DL, Gieck RE, Hinzman LD, Lettenmaier DP (2003) The role of surface storage in low-gradient Arctic watershed. Water Resour Res 39(4):1087

Bret-Harte MS, Shaver GR, Zoerner JP, Johnstone JF, Wagner JL, Chavez AS, Gunkelman RF IV, Lippert SC, Laundre JA (2001) Developmental plasticity allows *Betula nana* to dominate tundra subjected to an altered environment. Ecology 82(1):18–32

Chapin FS III, Shaver GR, Giblin AE, Nadelhoffer KJ, Laundre JA (1995) Responses of arctic tundra to experimental and observed changes in climate. Ecology 76(3):694–7111

Chase TN, Pielke Sr RA, Zhao M, Pitman AJ, Kittel TGF, Running SW, Nemani RR (2001) Relative climatic effects of landcover change and elevated carbon dioxide combined with aerosols: A comparison of model results and observations. J Geophys Res 106(D23):31685–31692

Comiso JC, Parkinson CL, Gersten R, Stock L (2008) Accelerated decline in the Arctic sea ice cover. Geophys Res Lett 35:L01703

Dai A, Fung IY, Delgenio AD (1997) Surface observed global land precipitation variations during 1900–88. J Clim 10(11):2943–2962

Daly C, Gibson WP, Taylor GH, Johnson GL, Pasteris P (2002) A knowledge-based approach to the statistical mapping of climate. Climate Res 22:99–113

Danks HV (1992) Arctic insects as indicator of environmental change. Arctic 45:159–166

Davies JC, Cooke F (1983) Annual nesting productivity in Snow Geese: prairie droughts and arctic springs. J Wildl Manag 47:291–296

Divoky GJ (1976) The pelagic feeding habits of ivory and Ross' gulls. Condor 78:85–90

Duncan DC (1987) Nesting of northern pintails in Alberta: laying date, clutch size, and renesting. Can J Zool 65:234–246

Epstein HE, Beringer J, Gould WA, Lloyd AH, Thompson CD, Chapin FS III, Michaelson GJ, Ping CL, Rupp TS, Walker DA (2004) The nature of spatial transitions in the Arctic. J Biogeogr 31(12):1917–1933

Folland CK, Karl TR, Christy JR, Clarke RA, Gruza GV, Jouzel J, Mann ME, Oerlemans J, Salinger MJ, Wang S-W (2001) Observed climate variability and change. In: Houghton JT, Ding Y, Griggs DJ et al (eds) Climate change 2001: The scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 99–181

Gaston AJ, Hipfner MJ, Campbell D (2002) Heat and mosquitoes cause breeding failures and adult mortality in an Arctic-nesting seabird. Ibis 144:185–191

GeoCover (2000) Orthorectified landsat enhanced thematic mapper (ETM+) compressed mosaics. NASA Earth Science Enterprise Scientific Data Purchase Program. https://zulu.ssc.nasa.gov/mrsid/

Gooseff M, Balser A, Bowden WB, Jones JB (2009) Effects of hillslope thermokarst in northern Alaska. Eos Trans Am Geophys Union 90:29–31

Gough L, Shrestha K, Johnson DR, Moon B (2008) Long-term mammalian herbivory and nutrient addition alter lichen community structure in Alaskan dry heath tundra. Arct Antarct Alp Res 40(1):65–73. doi:10.1657/1523-0430(06-087)[gough]2.0.co;2

Greenland D, Kittel TGF (2002) Temporal variability of climate at the US Long-Term Ecological Research (LTER) sites. Climate Res 19:213–231

Griffith BD, Douglas DC, Walsh NE, Young DD, McCabe TR, Russell DE, White RG, Cameron RD, Whitten KR (2002) The Porcupine caribou herd. In: Douglas DC, Reynolds PE, Rhode EB (eds) Arctic Refuge coastal plain terrestrial wildlife research summaries, Biological Science Report USGS/BRD/BSR-2002-001. U.S. Geological Survey, Biological Resources Division, pp 8–37

Groisman PY, Karl TR, Knight RW, Stenchikov GL (1994) Changes of snow cover, temperature, and radiative heat-balance over the northern-hemisphere. J Clim 7:1633–1656

Gunn A, Skogland T (1997) Response of caribou and reindeer to global warming. In: Oechel W, Callaghan T, Gilmanov T et al (eds) Global change and arctic terrestrial ecosystems. Springer, New York, pp 187–200

Hallett T, Coulson T, Pilkington J, Clutton-Brock T, Pemberton J, Grenfell B (2004) Why large-scale climate indices seem to predict ecological processes better than local weather. Nature 430:71–75

Hansen HA (1961) Loss of waterfowl production to tide floods. J Wildl Manag 25:242–248

Hinkel KM, Nelson FE (2003) Spatial and temporal patterns of active layer thickness at Circumpolar Active Layer Monitoring (CALM) sites in northern Alaska, 1995–2000. J Geophys Res 108(D2):8168

Hinkel KM, Eisner WR, Bockheim JG, Nelson FE, Peterson KM, Dai X (2003) Spatial extent, age, and carbon stocks in drained thaw lake basins on the Barrow Peninsula, Alaska. Arct Antarct Alp Res 35(3):291–300

Hinzman LD, Kane DL (1992) Climate change impacts on northern water resources in Alaska. In: Prowse TD, Ommanney CSL, Ulmer KE (eds) 9th International Northern Research Basin Symposium, 1992. NHRI Symposium No. 10

Hobbie SE, Chapin FS III (1998a) An experimental test of limits to tree establishment in arctic tundra. J Ecol 86:449–461

Hobbie SE, Chapin FS III (1998b) The response of tundra plant biomass, aboveground production, nitrogen, and CO_2 flux to experimental warming. Ecology 79(5):1526–1544

Hobbie SE, Schimel JP, Trumbore SE, Randerson JR (2000) Controls over carbon storage and turnover in high-latitude soils. Global Change Biol 6:196–210

Hodkinson LD, Bird J (1998) Host-specific insect herbivores as sensors of climate change in Arctic and alpine environments. Arctic Alpine Res 30:78–83

Hurrell JW (1996) Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperature. Geophys Res Lett 23(6):665–668

IPCC, 2007: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 976pp

Jefferies RL, Bryant JP (1995) The plant-herbivore interface in arctic ecosystems. In: Chapin FS III, Körner C (eds) Arctic and alpine biodiversity: Patterns, causes and ecosystem consequences. Springer, Berlin, pp 271–281

Johnson SR, Herter DR (1989) The birds of the Beaufort Sea. BP Exploration (Alaska) Inc, Anchorage, Alaska

Karl TR, Groisman PY, Knight RW, Heim RR Jr (1993) Recent variations of snow cover and snowfall in North America and their relation to precipitation and temperature-variations. J Clim 6(7):1327–1344

Kaufman DS, Ager TA, Anderson NJ, Anderson PM, Andrews JT, Bartlein PJ, Brubaker LB, Coats LL, Cwynar LC, Duvall ML, Dyke AS, Edwards ME, Eisner WR, Gajewski K, Geirsdóttir A, Hu FS, Jennings AE, Kaplan MR, Kerwin MW, Lozhkin AV, MacDonald GM, Miller GH, Mock CJ, Oswald WW, Otto-Bliesner BL, Porinchu DF, Rühland K, Smol JP, Steig EJ, Wolfe BB (2004) Holocene thermal maximum in the western Arctic (0–180°W). Quat Sci Rev 23:529–560

Kittel TGF, Rosenbloom NA, Royle JA, Aulenbach S, Fisher HH, Kaufman C, Daly C, Schimel DS, VEMAP2 Participants (2002) The VEMAP Phase 2 Dataset for Alaska and adjacent Canada: gridded historical (1922–1996) and future scenario climates. NCAR. http://www.cgd.ucar.edu/vemap/datasets.html

Kittel TGF, Rosenbloom N, Royle J, Daly C, Gibson W, Fisher H, Thornton P, Yates D, Aulenbach S, Kaufman C, McKeown R, Bachelet D, Schimel D, VEMAP2 Participants (2004) The VEMAP Phase 2 bioclimatic database. I: a gridded historical (20th century) climate dataset for modeling ecosystem dynamics across the conterminous United States. Climate Res 27:151–170

Ling F, Zhang T (2003) Impact of the timing and duration of seasonal snow cover on the active layer and permafrost in the Alaskan Arctic. Permafrost Periglac Process 14:141–150

MacDonald ME, Hershley AE, Miller MC (1996) Global warming impacts on lake trout in Arctic lakes. Limnol Oceanogr 41: 1102–1108

Magnuson JJ (2002) Signals from ice-cover trends and variability. In: McGinn NA (ed) American Fisheries Society Symposium No 32. American Fisheries Society, Bethesda, pp 3–14

Maslanik JA, Fowler C, Stroeve J, Drobot S, Zwally J, Yi D, Emery W (2007) A younger, thinner Arctic ice cover: increased potential for rapid, extensive sea-ice loss. Geophys Res Lett 34:L24501

McGuire AD, Wirth C, Apps M, Beringer J, Clein J, Epstein H, Kicklighter DW, Bhatti J, Chapin FS III, de Groot B, Efremov D, Eugster W, Fuduka M, Gower T, Hinzman L, Huntley B, Jia GJ, Kaisischke E, Melillo J, Romanovsky V, Shvidenko A, Vaganov E, Walker D (2002) Environmental variation, vegetation distribution, carbon dynamics and water/energy exchange at high latitudes. J Veg Sci 13:310–314

Michaelson GJ, Ping CL, Kimble JM (1996) Carbon storage and distribution in tundra soils of arctic Alaska. Arctic Alpine Res 28:414–424

Mitchell JFB, Johns TC, Gregory JM, Tett SFB (1995) Climate response to increasing levels of greenhouse gases and sulfate aerosols. Nature 376(6540):501–504

Mitchell T, Carter T, Jones P, Hulme M, New M (2004) A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901–2000) and 16 scenarios (2000–2100). Working Paper, vol 55. Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, UK

Muller SV, Racoviteanu AE, Walker DA (1999) Landsat MSS-derived land-cover map of northern Alaska: extrapolation methods and a comparison with photo-interpreted and AVHRR-derived maps. Int J Remote Sens 20:2921–2946

Nakicenovic N, Swart R (eds) (2000) Emissions scenarios. 2000 Special report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK

Nelson FE (2003) (Un)frozen in Time. Science 299(5613):1673–1675

Nelson RE, Carter LD (1987) Paleoenvironmental analysis of insects and extralimital *Populus* from an early Holocene site on the Arctic Slope of Alaska. Arctic Alpine Res 19:230–241

Nicholls RJ, Hoozemans FMJ, Marchand M (1999) Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses. Global Environ Change 9:S69–S88

Nowacki G, Spencer P, Brock T, Fleming M, Jorgenson T (2002) Unified ecoregions of Alaska: 2001. U.S. Geological Survey, Reston

Oechel WC, Vourlitis GL, Hastings SJ, Zulueta RC, Hinzman L, Kane D (2000) Acclimation of ecosystem CO_2 exchange in the Alaskan Arctic in response to decadal climate warming. Nature 406:978–981

Olsson PQ, Sturm M, Racine CH, Romanovsky V, Liston GE (2003) Five stages of the Alaskan Arctic cold season with ecosystem implications. Arct Antarct Alp Res 35(1):74–81

Osterkamp TE (2007) Characteristics of the recent warming of permafrost in Alaska. J Geophys Res 112:F02S02. doi:10.1029/2006jf000578

Osterkamp TE, Payne MW (1981) Estimates of permafrost thickness from well logs in northern Alaska. Cold Reg Sci Technol C5:13–27

Osterkamp TE, Romanovsky VE (1997) Freezing of the active layer on the coastal plain of the Alaskan Arctic. Permafrost Periglac Process 8:23–44

OSU-SCAS (2002) PRISM 1961–1990 mean monthly minimum and maximum temperature and precipitation grids for Alaska. Spatial Climate Analysis Service, Oregon State University. http://www.prism.oregonstate.edu/

Oswald WW, Brubaker LB, Hu FS, Kling GW (2003) Holocene pollen records from the central Arctic Foothills, northern Alaska: testing the role of substrate in the response of tundra to climate change. J Ecol 91(6):1034–1048

Oswood MW, Milner AM, Irons JG III (1992) Climate change and Alaskan rivers and streams. In: Firth P, Fisher SG (eds) Global climate change and freshwater ecosystems. Springer, New York, pp 192–210

Overland JE, Wang MY, Bond NA (2002) Recent temperature changes in the Western Arctic during spring. J Clim 15(13): 1702–1716

Overland J, Turner J, Francis J, Gillett N, Marshall G, Tjernström M (2008) The Arctic and Antarctic: Two faces of climate change. Eos Trans Am Geophys Union 89(19). doi:10.1029/2008EO190001

Pielke RA Sr, de Guenni LB (2004) How to evaluate vulnerability in changing environmental conditions. In: Kabat P, Claussen M, Dirmeyer PA et al (eds) Vegetation, water, humans, and the climate. Springer, New York, pp 483–544

Pielke R Sr, Beven K, Brasseur G, Calvert J, Chahine M, Dickerson R, Entekhabi D, Foufoula-Georgiou E, Gupta H, Gupta V, Krajewski W, Krider E, Lau W, McDonnell J, Rossow W, Schaake J, Smith J, Sorooshian S, Wood E (2009) Climate change: the need to consider human forcings besides greenhouse gases. Eos 90:413. doi:10.1029/2009EO450008

Poff NL, Angermeier SD, Lake KD, Fausch KD, Winemiller KO, Mertes LAK, Oswood MW, Reynolds J, Rahel FJ (2001) Global biodiversity in a changing environment. In: Chapin FS III, Sala OE, Huber-Sanwald E (eds) Fish diversity in streams and rivers. Springer, New York

Rogers AN, Bromwich DH, Sinclair EN, Cullather RI (2001) The atmospheric hydrologic cycle over the Arctic Basin from reanalyses. Part II: interannual variability. J Climate 14(11): 2414–2429

Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA (2003) Fingerprints of global warming on wild animals and plants. Nature 421(6918):57–60

Rouse WR, Douglas MSV, Hecky RE, Hershey AE, Kling GW, Lesack L, Marsh P, McDonald M, Nicholson BJ, Roulet NT, Smol JP (1997) Effects of climate change on freshwaters of arctic and subarctic North America. Hydrol Process 11:873–902

Salter RE, Gollup MA, Johnson SR, Koski WR, Tull CE (1980) Distribution and abundance of birds on the Arctic coastal plain of the northern Yukon and adjacent Northwest Territories: 1971–1976. Can Field Nat 94:219–238

Serreze MC, Carse F, Barry RG, Rogers JC (1997) Icelandic low cyclone activity: climatological features, linkages with the NAO, and relationships with recent changes in the Northern Hemisphere circulation. J Clim 10(3):453–464

Serreze MC, Walsh JE, Chapin FS III, Osterkamp T, Dyurgerov M, Romanovsky V, Oechel WC, Morison J, Zhang T, Barry RG (2000) Observational evidence of recent change in the northern high-latitude environment. Climatic Change 46:159–207

Shaver GR, Johnson LC, Cades DH, Murray G, Laundre JA, Rastetter EB, Nadelhoffer KJ, Giblin AE (1998) Biomass and CO_2 flux in wet sedge tundras: responses to nutrients, temperature, and light. Ecol Monogr 68(1):75–97

Shaver GR, Bret-Harte MS, Jones MH, Johnstone JF, Gough L, Laundre J, Chapin FS III (2001) Species composition interacts with fertilizer to control long-term change in tundra productivity. Ecology 82(11):3163–3181

Smith MW, Riseborough DW (2002) Climate and the limits of permafrost: a zonal analysis. Permafrost Periglac Process 13:1–15

Starr G, Neuman DS, Oberbauer SF (2004) Ecophysiological analysis of two arctic sedges under reduced root temperatures. Physiol Plant 120:458–464

Stirling I (1997) The importance of polynyas, ice edges, and leads to marine mammals and birds. J Mar Syst 10:9–21

Stow DA, Hope A, McGuire D, Verbyla D, Gamon J, Huemmrich F, Houston S, Racine C, Sturm M, Tape K, Hinzman L, Yoshikawa K, Tweedie C, Noyle B, Silapaswan C, Douglas D, Griffith B, Jia G, Epstein H, Walker D, Daeschner S, Peterson A, Zhou L, Myneni R (2004) Remote sensing of vegetation and land-cover change in arctic tundra ecosystems. Remote Sens Environ 89(3):281–308

Strack JE, Pielke RA Sr, Liston GE (2007) Arctic tundra shrub invasion and soot deposition: consequences for spring snowmelt and near-surface air temperatures. J Geophys Res 112:G04S44. doi:G04s4410.1029/2006jg000297

Sturm M, McFadden JP, Liston GE, Chapin FS III, Racine CH (2001) Snow-shrub interactions in arctic tundra: a hypothesis with climatic implications. J Clim 14:336–344

Sutton GM, Parmelee DF (1955) Breeding of the semipalmated plover on Baffin Island. Bird Band 26:137–147

Syvitski JPM, Manley WF, Peckham SD, Dyurgerov M, Lestak L, Maslanik J (2003) Arctic coast erosion: a regional to local perspective. 3rd Arctic Workshop, April 3–5. Tromsø, Norway

Team CAVM (2003) Circumpolar arctic vegetation map (scale 1:7, 500, 000) Conservation of Arctic Flora and Fauna (CAFF) Map No. 1. Map No. 1 edn. U.S. Fish and Wildlife Service, Anchorage, AK

Thompson DWJ, Wallace JM (1998) The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. Geophys Res Lett 25(9):1297–1300

Trenberth KE, Hurrell JW (1994) Decadal atmosphere-ocean variations in the Pacific. Climate Dyn 9:303–319

van Wijk MT, Clemmensen KE, Shaver GR, Williams M, Callaghan TV, Chapin FS III, Cornelissen JHC, Gough L, Hobbie SE, Jonasson S, Lee JA, Michelsen A, Press MC, Richardson SJ, Rueth H (2004) Long-term ecosystem level experiments at Toolik Lake, Alaska and at Abisko, Northern Sweden: generalizations and differences in ecosystem and plant type responses to global change. Global Change Biol 10:105–123

Verbyla D (2008) The greening and browning of Alaska based on 1982–2003 satellite data. Glob Ecol Biogeogr 17(4):547–555. doi:10.1111/j.1466-8238.2008.00396.x

Vörösmarty CJ, Hinzman LD, Peterson BJ, Bromwich DH, Hamilton LC, Morison J, Romanovsky VE, Sturm M, Webb RS (2001) The hydrologic cycle and its role in Arctic and global environmental change: a rational strategy for synthesis study. Arctic Research Consortium of the United States, Fairbanks

Walker DA, Auerbach NA, Bockheim JG, Chapin FS III, Eugster W, King JY, McFadden JP, Michaelson GJ, Nelson FE, Oechel WC, Ping CL, Reeburg WS, Regli S, Shiklomanov NI, Vourlitis GL (1998) Energy and trace-gas fluxes across a soil pH boundary in the Arctic. Nature 394:469–472

Walker DA, Jia GJ, Epstein HE, Raynolds MK, Chapin FS III, Copass C, Hinzman LD, Knudson JA, Maier HA, Michaelson GJ, Nelson F, Ping CL, Romanovsky VE, Shiklomanov N (2003) Vegetation-soil-thaw-depth relationships along a low-arctic bioclimatic gradient, Alaska: synthesis of information from the ATLAS studies. Permafrost Periglac Process 14:103–123

Walker DA, Epstein HE, Gould WA, Kelly AM, Kade AN, Knudson JA, Krantz WB, Michaelson G, Peterson RA, Ping CL, Raynolds MK, Romanovsky VE, Shur Y (2004) Frost-boil ecosystems: complex interactions between landforms, soils, vegetation, and climate. Permafrost Periglac Process 15:171–188

Wallace JM, Zhang Y, Bajuk L (1996) Interpretation of interdecadal trends in Northern Hemisphere surface air temperature. J Clim 9:249–259

White RG, Trudell J (1980) Habitat preference and forage consumption by reindeer and caribou near Aktasook, Alaska. Arctic Alpine Res 21:511–529

Woodby DA, Divoky GJ (1982) Spring migration of eiders and other waterbirds at Point Barrow, Alaska. Arctic 35:403–410

WRCC (2003) Western U.S. historical summaries, Alaska. Western Regional Climate Center, University of Nevada, Reno and U.S. Department of Commerce. http://www.wrcc.dri.edu/summary/climsmak.html

Young DD, McCabe TR, Ambrose R, Garner GW, Weiler GJ, Reynolds HV, Udevitz MS, Reed DJ, Griffith B (2002) Predators. In: Douglas DC, Reynolds PE, Rhode EB (eds) Arctic Refuge coastal plain terrestrial wildlife research summaries, Biological Science Report USGS/BRD/BSR-2002-0001. U.S. Geological Survey, Biological Resources Division, pp 51–53

Zhang T, Jefferies MO (2000) Modeling interdecadal variations of lake-ice thickness and sensitivity to climatic change in northernmost Alaska. Ann Glaciol 31:339–347

Zhang T, Osterkamp TE, Stamnes K (1997) Effects of climate on the active layer and permafrost on the North Slope of Alaska. USA Permafrost Periglacial Process 8:45–67

Zhang Y, Chen W, Cihlar J (2003) A process-based model for quantifying the impact of climate change on permafrost thermal regimes. Journal of Geophysical Research 108(D22):4695–4710

Zhuang Q, Melack JM, Zimov S, Walter KM, Butenhoff CL, Khalil MAK (2009) Global methane emissions from wetlands, rice paddies, and lakes. Eos Trans Am Geophys Union 90(5):37–44