EVIDENCE AND IMPLICATIONS OF RECENT CLIMATE CHANGE IN NORTHERN ALASKA AND OTHER ARCTIC REGIONS

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Abstract. The Arctic climate is changing. Permafrost is warming, hydrological processes are changing and biological and social systems are also evolving in response to these changing conditions. Knowing how the structure and function of arctic terrestrial ecosystems are responding to recent and persistent climate change is paramount to understanding the future state of the Earth system and how humans will need to adapt. Our holistic review presents a broad array of evidence that illustrates convincingly; the Arctic is undergoing a system-wide response to an altered climatic state. New extreme and seasonal surface climatic conditions are being experienced, a range of biophysical states and processes influenced by the threshold and phase change of freezing point are being altered, hydrological and biogeochemical cycles are shifting, and more regularly human sub-systems are being affected. Importantly, the patterns, magnitude and mechanisms of change have sometimes been unpredictable or difficult to isolate due to compounding factors. In almost every discipline represented, we show

Climatic Change (2005) 72: 251–298
DOI: 10.1007/s10584-005-5352-2

how the biocomplexity of the Arctic system has highlighted and challenged a paucity of integrated scientific knowledge, the lack of sustained observational and experimental time series, and the technical and logistic constraints of researching the Arctic environment. This study supports ongoing efforts to strengthen the interdisciplinarity of arctic system science and improve the coupling of large scale experimental manipulation with sustained time series observations by incorporating and integrating novel technologies, remote sensing and modeling.

1. Introduction

A recent synthesis of evidence from marine, terrestrial and atmospheric studies shows that the climate of the Arctic has warmed significantly in the last 30 years (Serreze et al., 2000). In terrestrial systems, the thermal regime controlling the abrupt threshold and phase change from ice to water at 0 °C limits a variety of biophysical processes, which operate at multiple spatial and temporal scales and may respond to change at varying orders of linearity. This paper synthesizes reports from a wide range of disciplines in order to address the consequences of this recent warming for arctic terrestrial ecosystems. Our definition of the Arctic includes the areas of high northern latitudes dominated by snow, ice and permafrost.

In the last 400 years a wide variety of changes within the Arctic system have been detected (Overpeck et al., 1997). In many cases, these changes started, or accelerated, in the mid-1970s. Some of the changes, such as later freeze-up and earlier break-up of arctic rivers and lakes (Magnuson et al., 2000), mirror arctic-wide and even global increases in air temperatures (Chapman and Walsh, 1993, as updated by Serreze et al., 2000). Others document more subtle or complex responses of the arctic system as it adjusts to current and longer-term trends in climate. Since the arctic system is particularly sensitive to changes in rain- and snowfall, timing of freeze-up and break-up, and the intensity of storm activity, it is likely that much of what has been documented to date, and will be observed in the future, arises from changes in these forcing fields. Unfortunately, compared with temperature, all other hydrological and meteorological time series variables are poorly known and/or measured. Regardless of the driving forces, however, the combined observations and documentation offer substantial evidence, although often diffuse, that the arctic system may be entering a state not seen in recent history. In this paper, we do not attempt to present an exhaustive review of the evidence currently accruing on biophysical processes in response to a changing climate but, rather, we attempt to synthesize inter-related responses to demonstrate that a warming climate will initiate a cascade of impacts that affect geophysical, hydrological, biological, and social systems in the far North.

The arctic biological, climatologic, hydrologic subsystems and their thermal regimes are fully coupled and cannot be completely understood or isolated individually. Plant cover is integral to soil moisture and permafrost dynamics. The ecosystem, in turn, provides feedback to both the local climate and the hydrology in many ways. No single piece of the system is independent, and to fully understand even a part of the system, we need to understand the whole. Because the Arctic is a vast and sparsely populated area, where integrated system studies are relatively new, there is much we do not know. Achieving an understanding at the system level, despite sparse data and the region's severe climate, is challenging. However, the very same factors that create difficulties also increase the value of that understanding. The Arctic is one of the few systems on Earth in which direct human influences are minimal. Studies of the response of the arctic terrestrial system to recent change yield broad and consistent evidence for rapidly changing physical, biological and social patterns.

Table I presents a summary of the evidence of environmental change that has been documented and will be described in this paper. It appears that first-order impacts to the terrestrial regions of the Arctic expected with a warming climate result from a longer thawing period combined with increased precipitation (Anisimov and Fitzharris, 2001). The longer snow-free season and greater winter insulation produces secondary impacts that could cause deeper thaw of the active layer or greater melt of permanently frozen ice in glaciers and permafrost, increased biological productivity and changes in vegetative communities. Tertiary impacts arise as animals, people and industry respond to the changing ecosystem. Throughout this simplified chronology, however, complex positive and negative feedbacks of one process influencing another over multiple spatial, temporal and organizational scales occur. The increased recognition of this complexity and coupling within Arctic system science is both an excellent indicator that there has been significant progress towards understanding how the Arctic functions as a system, and that there needs to be continued research, which examines the complexity of the system more closely and that is backed by long-term, integrated and multidisciplinary observational networks.

2. Methods

This paper attempts to present a synthesis of observed changes that have been documented in Arctic Alaska. In selecting which sources of evidence to include, emphasis was placed upon processes where documentation of a long-term change could be related to climate. There presently exist many other lines of evidence that were not included in this paper; however, we attempted to compile data on those variables that have important effects on the broader arctic system to demonstrate that the physical regime, the ecosystem and human society are intimately intertwined and interdependent. The primary geographic focus is on Alaska, however data from other parts of the Arctic have been utilized where necessary to provide a wider perspective that is not represented in the Alaskan datasets.

TABLE I
Summary of the evidence of environmental change

Theme	Location	Time frame	Evidence of change	Climate driver	Implications	Citation
Weather	North America	Recent decades	Greater variability, less predictable weather	Changed synoptic patterns	Increased mortality to plants and animals greater hazard in traveling	Krupnik and Jolly, 2002; Simpson et al., 2002; L'Heureux et al., 2004
Permafrost	Alaska	Since late 1800s, especially last decade	2–4 °C warming, thawing	Warmer air temperature, changes in snow	Thermokarst, infrastructure damage	Osterkamp and Romanovsky, 1999; Clow and Urban, 2002; Romanovsky et al., 2002
Thermokarst	Alaska	Late 1800s to present	Increased prevalence in interior Alaska	Warmer air temperature	Vegetation, landscape, and ecosystem change	Osterkamp et al., 2000
Thermokarst ponds	Seward Peninsula, Alaska	1951–2000	Decrease in area	Degradation of permafrost	Landscape and vegetation changes	Yoshikawa and Hinzman, 2003
Coastal erosion	Barrow Alaska	1949–2000	Increasing erosion rates	Shift of storm winds, active submarine erosion	Increased sediment and carbon flux to ocean, infrastructure damage	Brown et al., 2003
River	Lena, Ob, Yenisei Rivers, Russia	1936–1995	Increase in base flow, especially in winter	Reduction in permafrost leading to more groundwater flow	Changes in river flow, water chemistry	Peterson et al., 2002; Yang et al., 2002
Lake/River	Northern Hemisphere	1900s to present	Earlier breakup delayed freeze-up	Warmer air temperatures	Longer open water season changes in aquatic ecology riverine transportation	Magnuson et al., 2000; Rühland et al., 2003
Lake	Toolik Lake, Alaska	1975–2001	Increase in July water temperature	Warmer air temperature	Changes in lake ecology	Hobbie et al., 2003
Lake	Toolik Lake, Alaska	1975–2001	Increased alkalinity	Unclear	Changes in lake ecology	Hobbie et al., 2003
Soil Moisture	Interior and northern coastal Alaska	1960–2001	Decline in P-PET	Warmer air temperature	Vegetation and ecosystem changes	Oechel et al., 2000; Oechel et al., 1995
Ice Cap	Greenland	1993–1999	Thinning and recession on margins of ice sheet, reduced mass overall	Warmer air temperature	Rising sea level	Abdalati and Steffen, 2001

Glacier	Circum-Arctic	1960s to present	Reduced mass balance, areal extent	Warmer air temperature	Increased flow of freshwater, decreased albedo, rising sea level	Arendt et al., 2002; Dyurgerov and Meier, 1997; Nolan et al., in press
Snow	Barrow, Alaska	1950s to present	Snowmelt occurring ten days earlier	Warmer air, reduced winter precipitation	Reduced tundra travel, increased nesting period for birds, increased insect activity	Stone et al., 2002
Landcover	Northern Alaska	1949s to present	Increased shrubbiness	Warmer air and soil	Vegetation and ecosystem changes, albedo changes, feedbacks to climate	Sturm et al., 2001a and b
Landcover	North America	1980s to present	Longer growing season	Warmer air and soil	Vegetation and ecosystem changes	Stow et al., 2003; Jia et al., 2003
Treeline	Alaska	1900s to present	Advancing treeline	Warmer air and soil	Vegetation and ecosystem changes, albedo changes, feedbacks to climate	Lloyd and Fastie, 2002
Carbon	North Slope, Alaska	1960s to Present	Arctic tundra changed from a net sink for carbon (CO_2) to a major source to the atmosphere	Warming, decreased soil moisture	Loss of carbon stored in the tundra soils and released to the atmosphere	Oechel et al., 2000; Oechel et al., 1995; Oechel et al., 1993
Vegetation	Barrow, Alaska	1970s to present	Changed vegetation type	Warmer air, drier soil	Vegetation and ecosystem changes, reduced species diversity, reduction in carbon sink role	Hollister, 2003; Webber et al., personal communication
Birds	Alaska	Recent decades	Changed range	Longer growing season	Range extensions due to habitat changes	Kessel and Gibson, 1994; Meehan et al., 1999
Caribou	Northern Alaska and Canada	Recent decades	Improved calf survival reduced health, deaths from heat/icing	Warmer air, more insects/increased frequency of icing	Reduction in caribou herd fitness and population size	Griffith et al., 2002
Humans	Northern Alaska	Recent decades	Infrastructure degradation	Warmer permafrost, lost permafrost	Degradation of roads, runways, etc.; instability of buildings on pilings in permafrost	Krupnik and Jolly, 2002
Humans	Northern Alaska and Canada	1970s to present	Shorter period of frozen ground and sea ice	Warmer air	Reduction in season for tundra and sea ice travel related to subsistence and oil, mineral exploration	Riedlinger and Berkes, 2001

3. Synoptic Scale Change

The dynamic nature of the Arctic is framed by extremes: very cold winter temperatures, highly skewed annual cycle of solar radiation input, dominance of snow cover, and relatively low rates of precipitation, all of which result from its geographic position. Many of the unique features of the arctic terrestrial system arise from the extreme seasonality of the northern climate. There are essentially two seasons, one frozen and one thawed, with abrupt transitions between them. During the winter or frozen season, which lasts 7–10 months of the year, unfrozen surface water is rare, and a negative annual radiation balance is established (more radiation is lost to space as heat than comes in through solar heating). It is this negative radiation balance that creates the gradients that drive the arctic climate. Serreze et al. (2000) presented compelling evidence that the climate of the arctic region has indeed changed in the recent past. Long-time residents in the Arctic support this view from observations based on local knowledge (Krupnik and Jolly, 2002). A common testimonial relates to changing weather patterns and storm events and a decrease in the predictability of weather.

The climate of the Arctic has warmed substantially since the end of the Little Ice Age to present. From the mid-1800s to mid-20th century, the Arctic warmed to the highest temperatures in 400 years (Overpeck et al., 1997). It is difficult to quantify comparisons among regions that have experienced warming and cooling trends, particularly when the lengths of data records are inconsistent. The instrumental record of climate changes in the Arctic and subarctic is relatively short; few stations have been in operation for more than 100 years, with the notable exception of Yakutsk, Russia. One consistent finding amongst studies of hemispheric climate change is the marked difference among regions (Figures 1 and 2). Much of the Arctic experienced a cooling trend between 1940 and 1970. Western North America displays strong warming in the latter half of the 20th century while eastern Canada and Siberia have shown little change or in some instances cooled slightly. Cooling trends have also been reported over Greenland with slight warming over the Nordic Seas and Fenno-Scandia (Tuomenvirta et al., 2000). Maps of observed temperature change north of 50° N from 1970 to 2002 (Chapman and Walsh, 1993, updated) suggest predominant warming throughout the Arctic with greater warming occurring during the winter months. Most areas of the Arctic have also witnessed increases in precipitation. Spatial observations of precipitation changes also show, in general, broad scale increases primarily occurring during the winter (Serreze et al., 2003a, b; Kattsov and Walsh, 2000).

If weather patterns were indeed changing, we would expect this to be reflected in changes in the intensity or frequency of cyclonic storms. Over the 41-year time period 1959–2000, cyclone frequency and intensity in the Beaufort-Chukchi sector have not changed significantly on an annual basis (McCabe et al., 2001; Curtis et al., 1998; Lynch et al., 2004). Further, the proportion of storms that occur in each season has not shifted significantly. The only significant change discernible

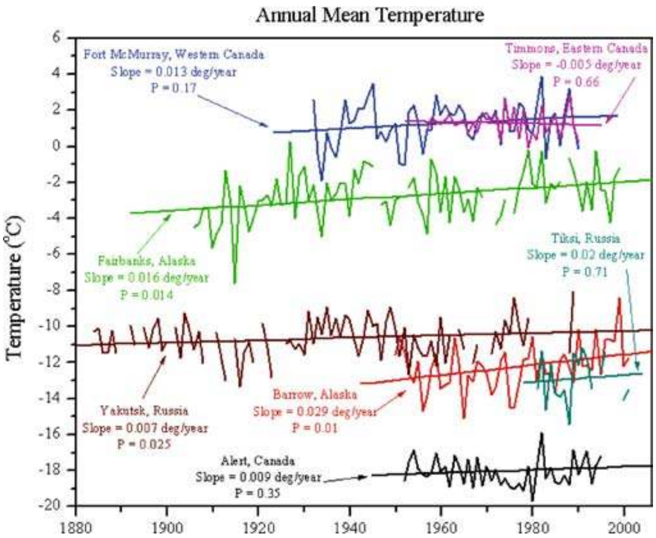

Figure 1. Climate stations around the Arctic, selected primarily for long time series, demonstrate increasing trends in air temperature. Although most long-term climate records in arctic regions do indicate increasing trends, some stations do show decreases in air temperature in recent years. The *p*-value represents a decreasing index of the reliability of a result (Brownlee, 1960). The lower the *p*-value, the more we can believe that the trend line is significantly different from zero. A *p*-value of 0.01 implies the slope of the trend line is significantly different from zero at the 99% confidence level.

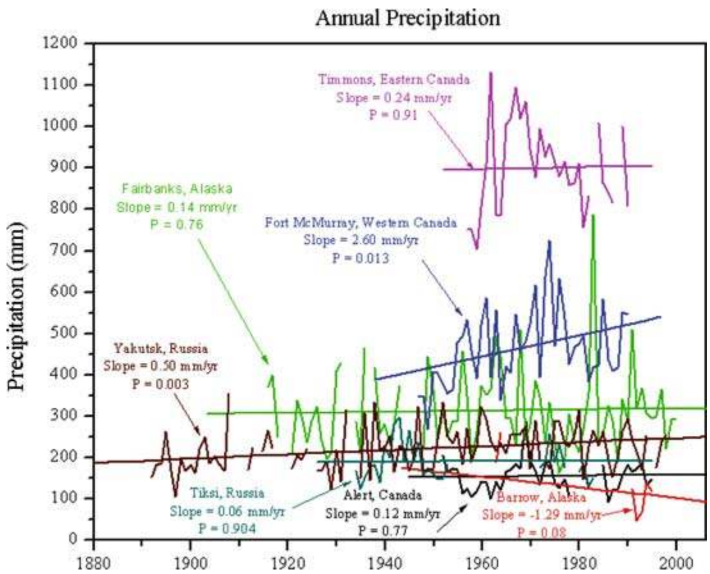

Figure 2. Several climate stations around the Arctic, selected primarily for long time series, demonstrate slight increasing trends in precipitation. Most of the increase has occurred during the winter months. Although most long-term climate records in arctic regions do indicate increasing trends, some stations do show decreases in precipitation in recent years. Only Fort McMurray, Canada and Yakutsk, Russia display strongly significant trends.

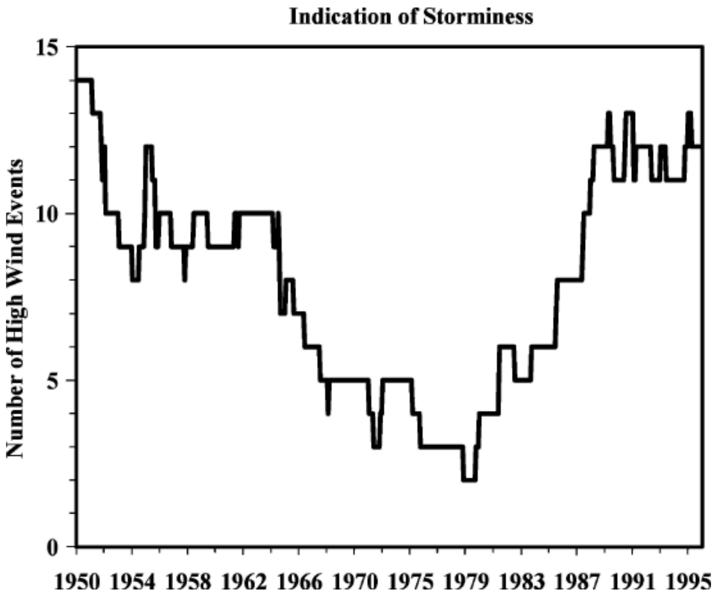

Figure 3. The number of high wind events decreased markedly in the mid-1960s. High winds were defined as those with peak wind gusts greater than 25 m/s, sustained wind (1 min) of greater than 20 m/s or daily average wind speed of greater than 13 m/s. The dramatic increase in wind events over the last two decades justifies residents' perceptions that the weather is indeed changing.

is the intensity of summer cyclones, which shows an increase of 0.5 Pa/m^2 per decade. This increase in summer cyclone intensity is manifest as an abrupt shift in cyclone intensity in 1971, an increase that has continued over the following 30 years. Analysis of the record in the context of the Arctic Oscillation (AO) or annular mode (Thompson and Wallace, 2001) found no relationship between cyclones in the Beaufort-Chukchi region and this large-scale teleconnection pattern.

However, not all high wind events in Barrow are associated with strong cyclones. High wind events specifically at Barrow can be linked to a range of different synoptic conditions, which may be characterized most generally by a Beaufort-Chukchi cyclone, an extremely large, strong Aleutian cyclone, or a strong Beaufort-Chukchi ridge. Although protocols in wind measurement have changed at Barrow throughout its history, it is apparent that the average wind speeds in Barrow have increased, particularly in winter, where a trend of 0.5 km/h per decade is evident. Figure 3 shows a 10-year moving average of high wind events in Barrow over the past 55 years, using available National Weather Service and Climate Monitoring and Diagnostics Laboratory observations. Dramatically apparent in the wind record is a relatively quiet period in all seasons from the late sixties to the early 1980s, with the lowest period in the late 1970s.

There are no long-term records of soil moisture in the Arctic. However, changes in water availability can be extracted from the surface water balance (precipitation

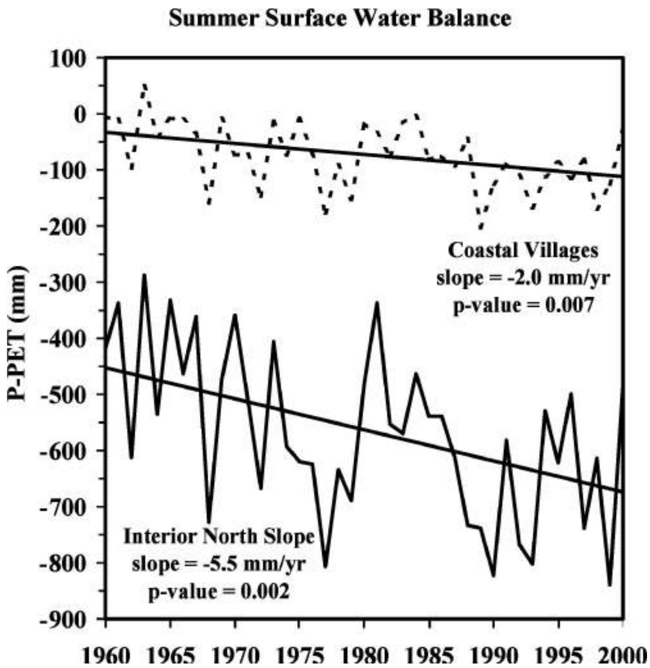

Figure 4. Time series of the summer (June–August) surface water balance (P-PET) for Alaskan North Slope villages between 1960 and 2001. Linear trends were estimated using least-squares linear regression and statistics correspond to the average change in the summer P-PET from 1960 to 2000. Summer (June–August) variations in the surface water balance for wet sedge and tussock tundra were estimated between 1960 and 2001 as the difference between precipitation (P) and the potential evapotranspiration (PET). Monthly values of PET were calculated as a function of the mean monthly temperature (Thornthwaite, 1948), which was derived from average daily values. These monthly estimates of P and PET were then summed to derive summer values of P-PET (Oechel et al., 2000). Temperature and precipitation data required for calculating the monthly estimates of P and PET were compiled for nine sites in northern Alaska (Barrow, Bettles, Kotzebue, Arctic Village, Chandalar Lake, Umiat, Barter Island, Prudhoe Bay, and Cape Lisburne). Coastal plain estimates of P-PET were calculated using data from Barrow, Kotzebue, Barter Island, Prudhoe Bay, and Cape Lisburne, while interior estimates of P-PET were calculated using data from Bettles, Arctic Village, Chandalar Lake, and Umiat. Missing data for coastal plain and interior sites were estimated using linear regression from the Barrow and Bettles datasets, respectively, which represented the most complete databases for the entire 41-year period (Oechel et al., 2000).

minus potential evapotranspiration). The surface water balance (P-PET) declined significantly for both the Alaskan coastal plain and interior regions between 1960 and 2001 (Figure 4). Although there was substantial interannual variation, P-PET for the Alaskan Arctic coastal plain declined on average 2.0 mm/yr ($p < 0.001$) while P-PET for interior regions declined on average 5.5 mm/yr (Figure 4). The two datasets are highly correlated with one another ($r = 0.75$), and time series analysis indicates a weak 20 year trend in P-PET for both regions. Interestingly, the larger rate of decline in P-PET estimated for the southern sites on the Alaskan

North Slope cannot be explained by regional differences in temperature and precipitation trends as compared to the sites on the arctic coast. For example, both regions experienced significant increases in the average summer temperature (0.04 °C/yr; $p < 0.001$, data not shown), while temporal trends in summer precipitation were lacking. However, large declines in P-PET in July, when air temperature is at a seasonal maximum, appeared to strongly influence the summer decline in P-PET, while for coastal plain sites, all summer months exhibited similar (low) declines in P-PET. These predictions calculated from climatic data are consistent with long-term drying trends noted by local residents but were not consistent with similar analyses of rawinsonde data using an aerological approach (Serreze et al., 2000). Changes in dominant vegetative communities in the Alaskan Arctic over the previous 8–13,000 years are believed to have been caused in a large part by changes in soil moisture (Mann et al., 2002). Pollen analyses from soil cores collected on the North Slope of Alaska indicate that peat accumulation increased along with rates of paludification after warmer and wetter conditions replaced the cooler and drier climate of the Younger Dryas. Soil moisture dynamics (particularly water table position) may be the most important factor influencing the trajectories of soil carbon flux under a warming climate. Saturated peatlands, under anaerobic conditions, may be large sources of methane (Friborg et al., 2003). Numerous studies have demonstrated that lowering the water table can markedly increase CO_2 emission rates from soil (Moore et al., 1998). At a certain soil redox potential, which in turn is a function of soil water content, CO_2 production declines and CH_4 production increases largely because CO_2 production is an aerobic process and CH_4 production is an anaerobic process (Oechel and Vourlitis, 1997; Vourlitis and Oechel, 1997). This is very important as the particular form of carbon from decomposition of organic soils has substantial effect on its effectiveness as a greenhouse gas.

4. Changes in Permafrost

Permafrost temperatures in boreholes displayed a 2–4 °C increase over the last 50–100 years on the North Slope of Alaska (Lachenbruch and Marshall, 1986) and there was a concurrent warming of discontinuous permafrost (Osterkamp and Romanovsky, 1999; Osterkamp, 2003). A comparison of deep bore-hole temperatures with earlier logs from an array of nine wells showed that permafrost on the Alaskan Arctic Coastal Plain and Alaskan Arctic Foothills warmed ∼3° C since the late 1980s (Clow and Urban, 2002). Long-term monitoring of deep wells in a north/south transect across the North Slope from Prudhoe Bay to the Brooks Range reveals variable warming with some cooling periods, over the last twenty-five years (Figure 5). Modeling indicates that continuous permafrost at Barrow cooled from 1950 until the later 1970s and has generally warmed since then (Romanovsky and Osterkamp, 2000); this is consistent with the broader-scale trends in air temperatures observed in northern Alaska (Figure 1). Permafrost temperatures along the

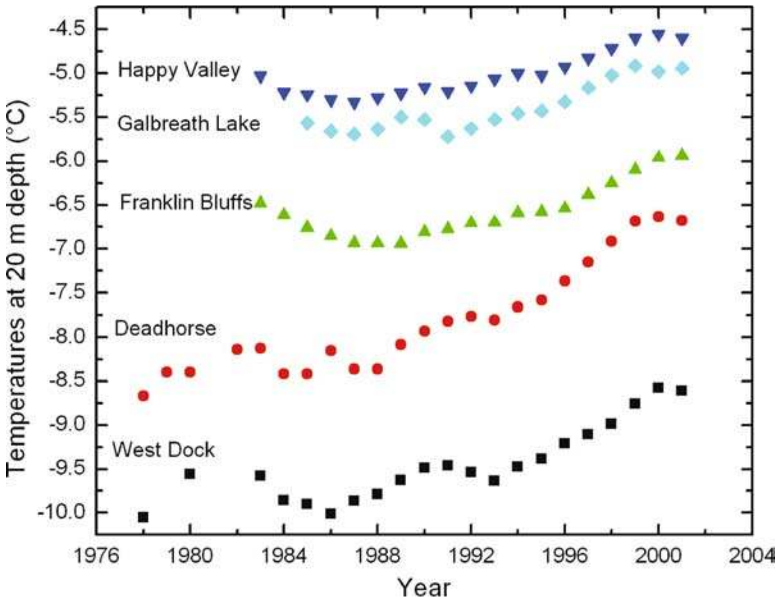

Figure 5. Temperatures measured at the 20 m depth in boreholes in permafrost on the North Slope of Alaska display broad scale warming over recent decades (Osterkamp, 2003).

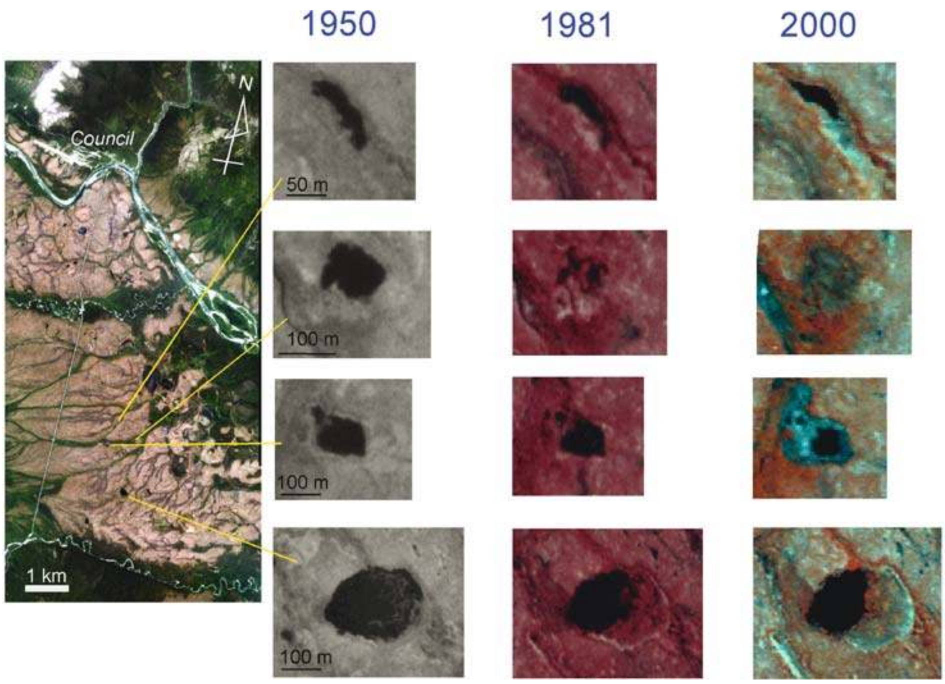

Figure 6. Numerous tundra ponds near Council, Alaska (64°51′N, 163°42′W) have decreased in surface area over the last 50 years. A probable mechanism for these shrinking ponds is internal drainage through the degradation of shallow permafrost (Yoshikawa and Hinzman, 2003).

Alaskan Arctic Coast indicate that the active layer and permafrost warmed about 2–3 °C near Prudhoe Bay since the mid-1980s (Romanovsky and Osterkamp, 1997; Osterkamp, 2003). This recent warming is about the same magnitude as predicted by GCMs for the next half-century (Giorgi et al., 2001).

Discontinuous permafrost is warming and thawing and extensive areas of thermokarst terrain (marked subsidence of the surface resulting from thawing of ice-rich permafrost) are now developing as a result of climatic change (Osterkamp and Romanovsky, 1999; Osterkamp et al., 2000). Estimates of the magnitude of the warming at the discontinuous permafrost surface are 0.5–1.5 °C. Warming rates near the permafrost surface were 0.05–0.2 °C/yr. In warm discontinuous permafrost, the thermal offset (due to a higher thermal conductivity of ice as compared to unfrozen water) allows mean annual temperatures at the permafrost surface to remain <0 °C even when the ground surface temperatures are positive, up to 2.5 °C. Thawing permafrost and thermokarst have been observed at several sites in interior Alaska. Thawing rates at the permafrost table at two sites of degrading permafrost were about 0.1 m/yr (Osterkamp et al., 2000).

Thermokarst is developing in the boreal forests of Alaska where ice-rich discontinuous permafrost is thawing (Osterkamp et al., 2000; Jorgenson et al., 2001). Thawing destroys the physical foundation (ice-rich soil) on which forests develop, causing dramatic changes in the ecosystem. Impacts on the forest depend primarily on the type and amount of ice present in the permafrost and on drainage conditions. In sites underlain by ice-rich permafrost, trees die when their roots are regularly flooded, causing wet sedge meadows, bogs and thermokarst ponds and lakes to replace forests. In the Tanana Flats near Fairbanks, Alaska, for example, ice-rich permafrost supporting birch forests is thawing rapidly and the forests are being converted to minerotrophic floating mat fens. At this site, an estimated 84% of 260,000 ha area was underlain by permafrost a century or more ago. About one half of this permafrost has partially or totally degraded and is characterized by thermokarst. These new ecosystems favor aquatic birds and mammals, whereas the previous forest ecosystems favored land-based birds and mammals. Thaw subsidence at the above sites is typically 1–2 m with some values up to 6 m (Osterkamp et al., 1998). Much of the discontinuous permafrost in Alaska is both warm and ice-rich, making it highly susceptible to thermal degradation if regional warming continues.

The active layer, defined as "the top layer of ground subject to annual thawing and freezing in areas underlain by permafrost" (Permafrost Subcommittee, 1988), is an important factor in cold-regions science and engineering, because most ecological, hydrological, biogeochemical, and pedogenic activity takes place within it (Hinzman et al., 1998; Kane et al., 1991; Osterkamp and Burn, 2002). The thickness of the active layer is influenced primarily by surface temperature and length of the thaw season and secondarily by several factors, including vegetative cover, thermal properties of the surface cover and substrate, soil moisture, and modes of heat transfer (Hinkel et al., 1997; Paetzold et al., 2000; Brown et al., 2000; Kane et al., 2001; Walker et al., 2003). Consequently, it displays substantial inter-annual and spatial variation. To date, there has been no conclusive evidence of increases in active layer thickness with increasing average annual air temperatures; however, the rate of active layer freezing has been slower on the North Slope of Alaska. Details on this process are presented in this paper in the section on human dimensions due to the important societal implications.

5. Hydrological Changes

The effects of a warming climate on the hydrological processes in the Arctic are already becoming apparent, with resulting effects on the ecology and geomorphology also becoming evident. It is expected that the effects of a warming climate will initially be most pronounced through atmospheric and near-surface processes and later through geomorphological evolution and hydrological responses to permafrost degradation. The broadest impacts to the terrestrial Arctic will occur as a result of changes in permafrost occurrence and distribution. The primary control on local hydrological processes in northern regions is dictated by the presence or absence of permafrost, but is also influenced by the thickness of the active layer and the total thickness of the underlying permafrost. As permafrost degrades, the interaction of surface and sub-permafrost ground water processes becomes more important. Ice-rich permafrost prevents surface water from infiltrating to deeper groundwater zones, causing surface soils to be very wet. However, in the slightly warmer regions of the subarctic, the permafrost is thinner or discontinuous. In permafrost-free areas, surface soils can be quite dry because infiltration is not restricted, impacting ecosystem dynamics, fire frequency, and latent and sensible heat fluxes. Other hydrological processes impacted by degrading permafrost include gradual or catastrophic drainage of lakes (Yoshikawa and Hinzman, 2003), increased winter stream flows (Bolton et al., 2000), decreased summer peak flows (Bolton et al., 2000), changes in stream water chemistry (Petrone et al., 2000), and other fluvial geomorphological processes (McNamara et al., 1999; Hinzman et al., 2003).

6. Rivers

Evidence of changes in watershed runoff is limited in Alaska primarily due to the small number of stations with long-term records of river discharge. Discharge was routinely monitored in few rivers prior to 1950 and, of those, regular monitoring has been maintained to the present on only a very few. Analyses of US Geological Survey data from nine stream monitoring stations in central to northern Alaska with long-term records (those with about 50 years of data) do reveal interesting, statistically significant, trends. Basins with a substantial glacial component consistently display increasing trends in runoff, presumably due to increases in glacier melt. River basins lacking large glaciers tend to show decreasing runoff, probably because evapotranspiration rates have increased faster than increasing precipitation. Three rivers on the North Slope of Alaska have continuous record lengths of only about 20–30 years (the Sagavanirktok, Putuligayuk, and Kuparuk). Although these are non-glacierized basins, they do display increasing trends in runoff over the period of record.

Changes have also been documented in the runoff regime of rivers in northwestern Canada (Janowicz, 2001). These increasing or decreasing changes again appear to be highly related to amount of glaciers within a watershed. Peak runoff in most Arctic, interior and northern Yukon Territory rivers has decreased in twenty-three of twenty-eight basins (record lengths vary between 18 and 50 years). In the glacierized watersheds of western Yukon, peak streamflow has increased in three of the four watersheds analyzed (record length 23–54 years).

Annual discharge of the major Siberian rivers (the Yenisei, Lena, Indigirka, Kolyma, Anabar and Ob) has increased markedly from the 1940s to recent times (Savelieva et al., 2000; Peterson et al., 2002; Yang et al., 2002), corresponding primarily with an increase in winter air temperature. During this period, precipitation has only slightly increased in Western Siberia and decreased in Eastern Siberia (Savelieva et al., 2000). The winter flows have displayed the greatest change, increasing by 13% in the Ob, 45% in the Yenisey and 25% in the Lena (Savelieva et al., 2000; Yang et al., 2002). Analyses of discharge records across the Lena basin demonstrated that large reservoirs do impact temporal runoff regimes in lower Lena, but cannot explain increases in winter runoff documented in many unregulated tributaries (Ye et al., 2003). Peterson et al. (2002) quantified this combined annual increase in total runoff as 2 ± 0.7 km^3/yr between 1936 and 1999.

Increased winter flow rates could have a wide range of impacts, including changes in stream chemistry and aquatic habitat, increased stream and river icing, and other uncertain implications on erosion and sediment flux. As permafrost becomes thinner and is reduced in spatial extent, proportions of groundwater input to streams will increase, and the proportion of surface runoff will decrease, increasing river and lake temperatures and altering chemical properties. The Arctic Ocean is surrounded almost entirely by continents and most of the freshwater that enters this ocean eventually exits to the North Atlantic and contributes to North Atlantic Deep Water (NADW) formation. If the increased discharge of Siberian Rivers is typical of freshwater input to the Arctic Ocean, the total export of arctic water to the North Atlantic could reach 0.06–0.15 Sv, (60,000–150,000 m^3/s) a value that ocean models suggest could destabilize NADW formation and thermohaline circulation, a major determinant of global climate (Peterson et al., 2002; Broecker, 1997).

7. Lakes

In response to some imposed disturbance, such as road construction, wildfire or climatic warming, permafrost can thaw differentially, creating irregular surface topography. Depressions, called thermokarsts, may appear as near-surface massive ice melts, allowing the surface to subside (Hinzman et al., 1997). Depending upon local terrain, small puddles or ponds may form, accelerating subsurface thaw through lower albedo and additional heat advected into the pond through runoff. Depending upon the local surface energy balance, the thawed ground may refreeze or the permafrost can continue to degrade. In time a talik (a layer of unfrozen soil above the permafrost and below the pond) may form as the depth of thaw becomes greater than the amount that can refreeze during the winter. If the permafrost is relatively thin (on the order of the diameter of the pond surface) the talik may penetrate the underlying permafrost and connect with subpermafrost groundwater. At that time, the pond may begin to fill or drain depending upon the direction of the hydraulic gradient beneath the lake.

Several thermokarst ponds on the Seward Peninsula were examined to determine if recent climate warming has impacted the dynamics of their development and degradation (Figure 6). These investigations included hydrological measurements, field studies through coring and thermal analyses, ground penetrating radar surveys and historical analyses of archived photographs, satellite imagery and long-term meteorological data collected in Nome, Alaska (Yoshikawa and Hinzman, 2003). The permafrost was quite thin in this area (between 15 and 50 m), and geophysical explorations near several ponds revealed taliks that completely penetrated the permafrost. Of the 24 ponds studied, 22 decreased in area between 1951 and 2000. Hydrological investigations demonstrated that the water surface elevations of these 22 ponds were higher than the normal groundwater level, while the water surface of two ponds in the flood plain were close to the same level as the normal groundwater elevation. The percentage of surface area lost in these 22 lakes ranged from 6 to 100%, with the average being 55%. The total area of lake surface lost was about 77,000 m^2 within the study area of 9.5 km^2, but the consistent decrease in almost all of the lakes in this area is indicative of a shift in the hydrological regime that will impact the local climate, ecology, wildlife habitat, and social structure of this area. Analyses of climate data collected in Nome, Alaska (approximately 120 km west) displayed a warming trend from 1907 to 1941, followed by a cooling period until 1976 when a marked warming occurred. The precipitation records demonstrate a stable trend prior to 1941, followed by a slight decrease in precipitation rates until 1976 after which the precipitation rate again increased. A comparison of meteorological records with lake dynamics indicates that other processes must be a factor in lake shrinkage. This analysis suggests that, in regions over thin permafrost, surface ponds may shrink and surface soils may become drier as the permafrost degrades. This depends upon regional hydraulic gradients (i.e., whether the region is a groundwater upwelling or downwelling zone). During the same time period, the situation was quite different in the Mentasta Pass area near Tok, Alaska. Significant lake area expansion occurred by erosion of the shorelines (Osterkamp et al., 2000).

Thermal degradation of ice-rich permafrost with coincident subsidence of the ground surface has recently resulted in extensive thermokarsting and creation of new water-filled surface depressions on the Beaufort Coastal Plain in northern Alaska (Jorgenson et al., 2003). Analysis of aerial photography from 1980 indicated that widespread ice wedge degradation had not yet occurred. Field observations and sampling showed that ice wedge degradation has been relatively recent as indicated by newly drowned vegetation. Despite the relatively cold average annual temperature of this northern permafrost, thermokarst was widespread on a variety of terrain conditions, but most prevalent on ice-rich centers of old drained lake basins and alluvial-marine terraces. Disturbance of the ground surface, which would have similar effect on ice wedges, was not evident so the natural degradation was attributed to warmer weather of the recent decades. Thermokarst can occur with warming even in very cold climates such as the North Slope of Alaska, because massive ice is very close to the ground surface. In interior Alaska where permafrost is warmer, deeper thaw, such as occurs after wildfire is required before thermokarst occurs, because massive ice has already been lost from near-surface soils.

Physical, chemical and biological parameters have been monitored weekly in Toolik Lake, north of the Brooks Range in Alaska (68°38′N and 149°43′W) during the ice-free season since 1975. During this period, there was an increase of more than 1.5 °C at a depth of 1 m (Figure 7) in Toolik Lake between 1975 and 2000. The very significant warming trend has decreased in recent years due to cooler summers. The July lake temperature displays a strong positive correlation ($r^2 = 0.75$) to the average of June and July air temperatures. The year-to-year variability in lake

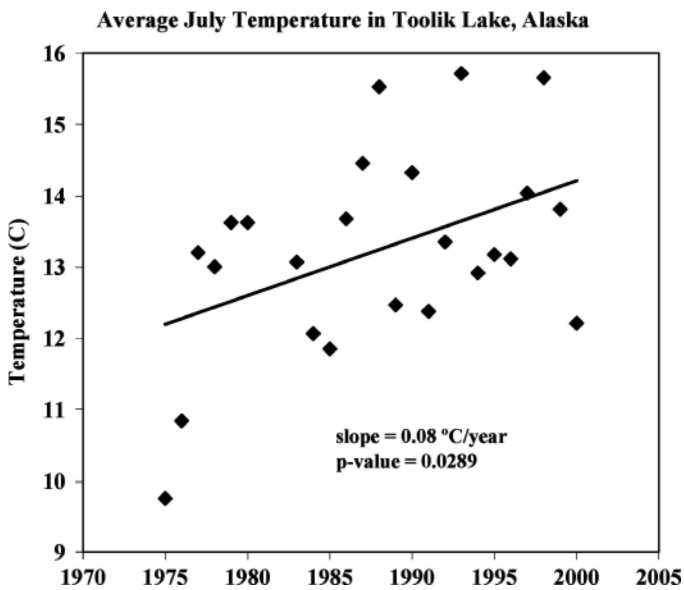

Figure 7. The average water temperature during July at 1 m depth in Toolik Lake displays an increasing trend from 1975 to 2001 (missing data 1981 and 1982). Recent years display a cooling trend, probably related to colder air temperatures and a thinner snow cover in those years.

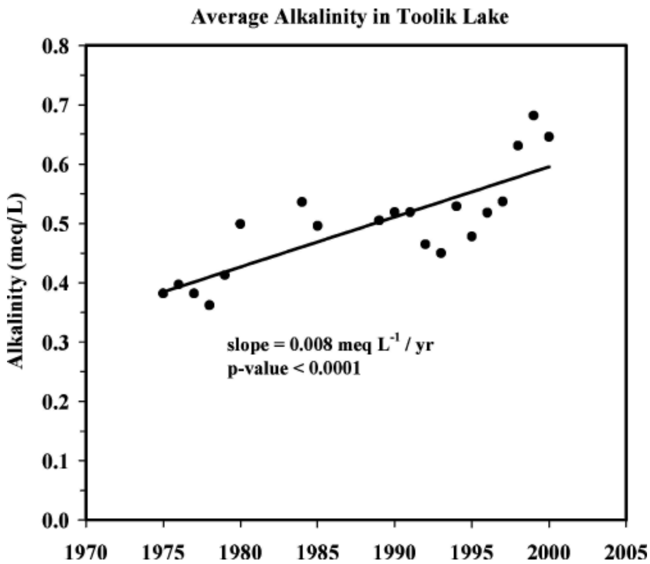

Figure 8. The average summer alkalinity in Toolik Lake from 1975 to 2000 (missing data 1983, 1986, 1987, 1988) displays an increasing trend, the reason for which is not completely understood.

temperature is quite large and is driven primarily by air temperature, snow depth and solar radiation.

As part of the long-term monitoring in Toolik Lake, weekly measurements of alkalinity or acid neutralizing capacity have been made, also during the ice-free season. Since 1975, the average summer alkalinity in Toolik Lake has doubled (Figure 8). Other lakes and streams in the area that have been monitored since 1990 show similar increases in alkalinity, balanced primarily by increases in calcium and magnesium. Similar processes occurring in these more remote lakes suggest this is not simply a response to increased development or road dust near Toolik Lake. The most likely cause of alkalinity increase is weathering of newly-unfrozen glacial till. One may consider atmospheric deposition as an explanation for this change, but neither the amount nor the chemical composition of the rainwater has shown equivalent changes (Arctic LTER Database). Other possible explanations include increases in the amount of subsurface flow through the active layer or changes in the spring snowpack water equivalent. Arctic LTER scientists are continuing to evaluate this phenomenon (Hobbie et al., 2003).

These field studies demonstrate that lakes and rivers are responding directly to the changing climate, but changes are also occurring in various components of the water balance causing tertiary responses in the aquatic ecosystem. Rouse et al. (1997) examined the impacts of warming climate on arctic aquatic systems and reported that growing season changes plus warmer temperatures would affect the chemical, mineral, and nutrient status, probably having a deleterious effect on the food chain. They determined warming has the most effect on predators, concluding that loss of predators will cascade through the food web, affecting the structure and function of planktonic and benthic communities.

8. Snow Cover

The annual end of snowmelt in Barrow, Alaska, shows increased variability over the last sixty years (Figure 9) and a trend toward markedly earlier snow free season. This analysis updates that of Stone et al. (2002) incorporating the most recent data from the NOAA/CMDL Barrow Observatory. Actual snowmelt date relates to the day when the snow depth is less than 2.5 cm and continues to melt or, since radiometric data have become available, the day when the surface albedo falls below 0.30 and does not recover to sustained higher values. The earlier melt is consistent with May air temperatures on the Alaskan North Slope, which show an abrupt and rapid increase in variability since 1990. Also, total snow accumulation in winter has decreased and March and April temperatures have increased in recent decades. Stone et al. (2002) attribute these changes to synoptic circulation changes that have affected the climate of the entire North Slope. Regression analysis indicates that the snowmelt date has advanced by about 10 days since 1941.

Earlier snowmelt permits plant growth to begin sooner, when water is plentiful and solar radiation is near the annual maximum. Lengthening the growing season

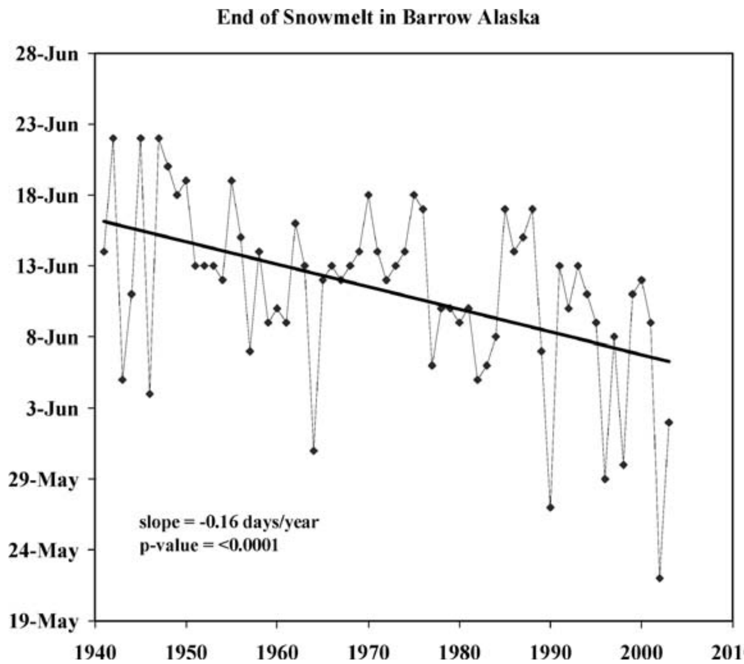

Figure 9. The disappearance of snow cover at Barrow, Alaska, presents a consistent trend of earlier snowmelt (updated from Stone et al., 2002). These data were compiled from direct observations and proxies estimated from radiometric (albedo) and air temperature measurements.

may be one of the most important impacts to the biological systems in arctic regions. Some arctic plants become photosynthetically active under the melting snowpack in early spring (Bilbrough et al., 2000). Earlier snowmelt also allows rapid warming of frozen soils and permits greater period of soil microbial activity (Fahnestock et al., 1998). Carbon emissions from soil microbes may be of greater consequence in response to later or warmer autumn periods as CO_2 and CH_4 released through decomposition may not be offset by photosynthetic uptake as plants maintain typical senescence in response to photoperiod limitations. Earlier snowmelt and later snow accumulation in autumn also facilitates an important positive feedback to climate warming (Chapin et al., 2000b; Eugster et al., 2000) as solar radiation, previously reflected due to the high albedo of the snow, is mostly absorbed on the darker surface warming the ground and the surface boundary layer.

9. Ice Sheets and Glaciers

Throughout Alaska, there is evidence that warming is causing a reduction in glacial ice mass. For instance, in the Kigluaik Mountains, of the Seward Peninsula, Alaska several glaciers has been decreasing in extent (Calkin et al., 1998). In this transitional maritime-continental climatic regime of western Alaska, the Grand Union glacier may completely disappear by the year 2035 if it continues to recede at its 20th century rate. There has been a 30% reduction in the glacier length between 1950 and 1990 (Calkin et al., 1998). These reductions in glacier size and extent are consistent with other studies that depict negative mass balances for the West Gulkana in the Alaska Range, as well as the Grizzly glacier and the McCall glacier (Figure 10) in the central and eastern Brooks Range, (Chambers et al., 1991; Rabus et al., 1995). Using airborne laser altimetery, Arendt et al. (2002) quantified the ice volume loss of 67 glaciers in northern, southern and southeastern Alaska and neighboring Canada. Most of the glaciers retreated and nearly all of the glaciers monitored displayed increased thinning during the 1995–2001 period as compared to measurements collected between 1950 and 1995. Glacial dynamics must be considered as well as response to climate in appraising glacial mass balance, but compared with the Greenland ice sheet and other sources, these glaciers contributed the largest single glaciological contribution to rising sea level (Arendt et al., 2002). Mountain glaciers (i.e. those not in the Greenland or Antarctic ice sheets) represent only about 3% of the glacierized area on earth, so the land area uncovered is probably of less significance than the tremendous volumes of water released and the importance of glaciers as integrated response to changing climate.

The Greenland ice sheet and glaciers on continents and archipelagoes in the Arctic constitute a substantial portion of the arctic landscape comprising about 2×10^6 km^2, which is about ∼30% of the total land area. These frozen bodies of fresh water are dynamic components of the arctic system (Pfeffer et al., 2000). The Greenland ice sheet and arctic glaciers are providing clear evidence that the

Figure 10. Photographs of the terminus of McCall Glacier in 1958 (upper photo ©Austin Post), and 2003 (lower photo ©Matt Nolan). This large reduction in ice mass began in about 1890 and continues today at a rate that has likely been increasing with time since then (Nolan et al., in press).

climate of the Arctic is indeed changing and that one very important consequence of global warming is the recent negative mass balance of portions of the Greenland ice sheet (Thomas, 2001). In 1993, NASA surveyed the entire Greenland ice sheet by airborne laser altimetry and the same flight-lines were again surveyed in 1999 (Krabill et al., 1999; Krabill et al., 2000). These investigators reported thinning and glacier recession along the margins of the ice sheet and, when taken as a whole, the surveyed region lost mass. The runoff from this mass loss is equivalent to one of the large Siberian rivers. This near-coastal thinning of the Greenland ice sheet along the east coast has been directly observed by Jones et al. (2000) near Thule, Greenland where entombed plants and soils are being uncovered, and significant amounts of CO_2 are being released to the atmosphere (Welker et al., 2002).

In general, the average balances for arctic glaciers have been negative over the past 40 years (Dowdeswell et al., 1997). Negative mass balances have been particularly strong for Svalbard, Asia and Alaska with a northern hemisphere reduction approaching 90 km^3/yr (Dyurgerov and Meier, 1997, 2000) (Figure 11). In the High Arctic, on Ellesmere and Devon Islands, additional evidence has been reported that glaciers and ice caps are responding to the warming climate. The Murry Ice Cap located on the Hazen Plateau of Ellesmere Island displayed a 28% reduction in the ice covered area from ~4.3 km^2 in 1959 to 3.1 km^2 in 2000 (Braun et al., 2001). In addition, the east lobe of the Twin Glacier near Alexandra Fiord receded at a rate of ~4 m/yr between 1960 and 1985 and at a rate of ~8 m/yr from 1985 to 1990 (Welker et al., 2002). In addition, there has been a reduction of the Devon Island ice cap by 338 km^2 between 1960 and 1999 (Burgess et al., unpublished paper).

The variation in mass loss rates in different regions appears to be consistent with variations in degrees and rates of observed warming, particularly the increased ablation rates in the late 1970s and early 1980s (Figure 11) correspond with increased warming observed in many locations (Figure 1 and Chapman and Walsh, 1993, updated). The consequences of these reductions in ice mass and associated increases in ice-free land surfaces are complex and numerous. The shift in albedo with the loss of glacial area could be important to the energy balance of the Arctic (Mitrovica et al., 2000). Increased freshwater delivery to the Arctic Ocean from reductions in ice sheets and glaciers result in rising sea levels (Arendt et al., 2002) and increases in coastal erosion. Other consequences of ice loss in the Arctic may be increases in inputs of dissolved organic C and sediments to the streams feeding coastal margins. In addition, greater inputs of freshwater from melting glaciers and ice sheets may affect the thermohaline circulation of the Arctic Ocean (Peterson et al., 2002) and patterns of climate in the Arctic and other regions.

American Arctic glaciers (B_{aa}) show the greatest mass loss (about 450 km^3) over the period (1961–1998) with increased ablation since the end of 1980s. Glaciers in the Russian Arctic (B_{ra}) demonstrate large losses as well (about 100 km^3 over the period). Glaciers in European Arctic (B_{ea}) show substantial increases in volume due to large influence of glaciers in Scandinavia and Iceland with positive balances. The entire Arctic system, B_{arctic}, has experienced substantial loss in volume, estimated at 400 km^3 over 1961–1998.

10. Land Cover Changes

The response of high latitude ecosystems to global change has the potential to significantly alter regional water and energy balance. Expansions of shrub tundra into regions now occupied by sedge tundra, and of boreal forest into regions now occupied by tundra, could reduce growing season albedo and increase spring energy absorption (Bonan et al., 1992; Thomas and Rowntree, 1992; Foley et al., 1994; McFadden et al., 1998; Chapin et al., 2000a, b). Decreased albedo due to changes in vegetation, the extension of snow-free and ice-free periods on terrestrial and lake surfaces, and reduction in the area occupied by glaciers and continental ice sheets in high latitudes may act as a positive feedback to radiative forcing and enhance atmospheric warming. Disturbance regimes that decrease the proportion of evergreen forests may reduce energy absorption and act as a negative feedback to atmospheric warming (Chapin et al., 2000b; Stocks et al., 2000). For example, fire disturbance often reduces albedo shortly after the fire and provides the opportunity for deciduous forests to develop, which generally raise albedo and increase the proportion of energy released to the atmosphere as latent rather than sensible heat.

Research by Pielke et al. (2002) has shown that land cover changes may be as important as changes in the concentrations of radiatively active gases in controlling climate change. Incorporation of improved information on albedo from the Boreal Ecosystem Atmosphere Study (BOREAS) in the recent European Center for Medium Range Weather Forecasting (ECMWF) re-analysis (Viterbo and Betts, 1999) resulted in a 2 °C January warm bias for northern hemisphere in comparison with a 13 °C January cold bias that was present in the prior ECMWF re-analysis. These results highlight the importance of improving the representation of land cover effects in climate re-analyses.

11. Growing Season and Phenology

Changes in land cover that are occurring include lengthening of the growing season in Alaska (Keyser et al., 2000), and a doubling of annual area burned in the boreal forest of North America during the last twenty years in comparison with earlier decades (Murphy et al., 2000). Analyses of northern hemisphere NDVI over the last two decades are consistent with expanding growing seasons, greater growth of trees, and expansion of shrub tundra (Myneni et al., 1997, 2001; Zhou et al., 2001; Lucht et al., 2002; Jia et al., 2003).

Using maximum NDVI values (Holben, 1986) and Shabanov et al. (2002) observed an increase in the onset and length of the growing season at latitudes north of 45 degrees for the period 1981–1994. These increases were attributed to the documented winter and annual warming of near-surface air temperature during this same period. When NDVI values are integrated seasonally, there is a weak increasing trend in the 1990s for the Kuparuk River watershed and entire North Slope of Alaska (Stow et al., 2003; Hope et al., 2003). Studies of the seasonal maximum NDVI demonstrate marked positive trends since the early 1980s (Figure 12) probably in response to increasing above-ground biomass (Jia et al., 2003).

12. Treeline

The boundary between tundra and boreal forest ecosystems may be highly sensitive to changes in climate because of the prominent role that temperature plays in determining the location of the forest-tundra ecotone. Conversely, studies with general circulation models indicate that the position of northern treeline has a substantial influence on global climate (Bonan et al., 1992; Foley et al., 1994; Thomas and Rowntree, 1992). On a large scale, the position of the forest-tundra ecotone is correlated with various measures of summer warmth (e.g., number of days with temperatures $> 10°$ C); physiological data suggest that temperature limits the growth and survival of trees at the forest boundary (e.g., Sveinbjörnsson, 2000; Sveinbjörnsson et al., 2002). The sensitivity of the forest-tundra ecotone to climate is also indicated by paleoecological data which suggest that treeline has covaried with temperature on long time scales, advancing northwards (and upwards in elevation) during warm intervals and retreating during cold intervals (e.g., Denton and Karlén, 1977; MacDonald et al., 2000; Pellatt et al., 2000). Although treeline advance correlates with climate warming, other parameters of climate change, particularly precipitation and wind (that vary widely regionally) also play primary roles in governing the rate of change of treeline.

Recent (e.g., 20th century) warming in Alaska has been accompanied by a widespread advance of trees into tundra ecosystems. The increase in density of white spruce has been documented at arctic treelines in northwest Alaska (Suarez et al., 1999). Expansion of white spruce range has been observed on the Seward Peninsula (Hopkins, 1972; Lloyd et al., 2002), in the Brooks Range (Cooper, 1986), the White Mountains (Lloyd and Fastie, 2003) and the Alaska Range (Lloyd and Fastie, 2003). The significant increase in tree density over time at all these sites is an important finding directly resulting from the warmer conditions allowing more trees to become established. If one compares the age of forests along transects that cross treeline, it is apparent that forest age becomes progressively younger as one crosses from forest into tundra, in essence, direct evidence for treeline advance. Although evidence for an advance of treeline in Alaska is ubiquitous, the timing of the advance varies substantially among sites. Treeline advance began earliest (mid to late 1800s) in the White Mountains in interior Alaska, and most recently (mid to late 1900s) in the Alaska Range. The most likely explanation for regional

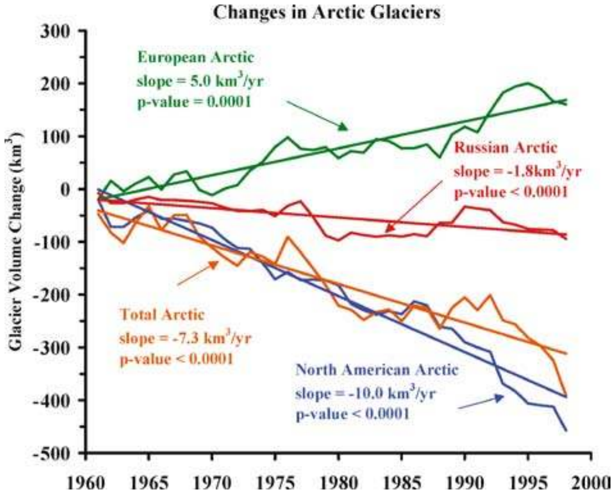

Figure 11. Volume change for Arctic Glaciers is calculated for three large regions plus the pan-Arctic (Dyurgerov and Meier, 1997, 2000): American Arctic (B_{aa}), with the entire area of 152,480 km^2 including the Canadian Arctic (151,758 km^2), Labrador Peninsula, (5 km^2), and Brooks Range (722 km^2); European Arctic (B_{ea}) with the entire area of 50,930 km^2 including Svalbard and Jan Mayen (36,612 km^2), Scandinavia (2942 km^2), and Iceland (11,260 km^2); Russian Arctic (B_{ra}) with the area of 56,892 km^2 including the Arctic Archipelagoes (56,125 km^2), Northeast Siberia (767 km^2) and Polar Ural (29 km^2); the entire area occupied by glaciers in the pan-Arctic (B_{arctic}) is 260,300 km^2 (about 70,000 km^2 of glacier area around the Greenland ice sheet are not included due to the lack of data).

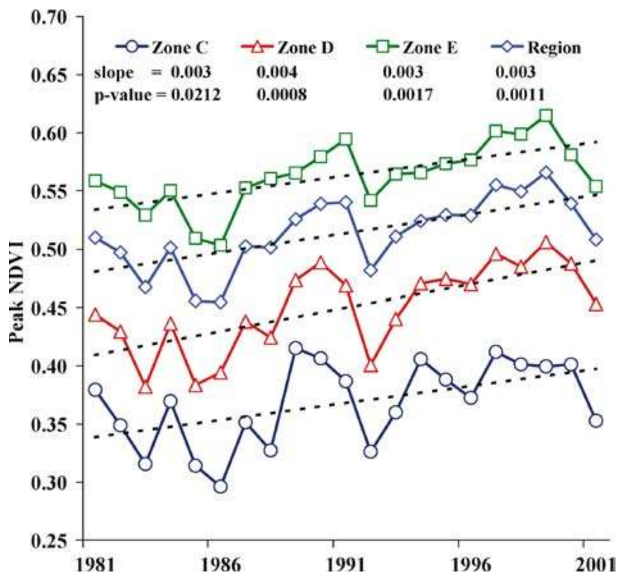

Figure 12. Peak NDVI (Normalized Difference Vegetation Index) in three bioclimate zones in northern Alaska, from the coastal plain to the northern foothills of the Brooks Range (as defined in Jia et al., 2003) confirm long-term positive trends in vegetation greenness indicating increases in above ground biomass.

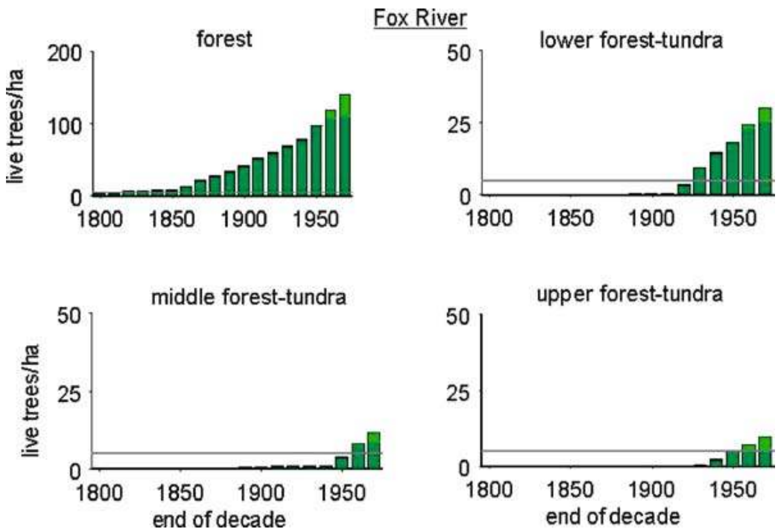

Figure 13. Density of live spruce in each decade from 1800 to 1970 at latitudinal treeline on the Seward Peninsula. Sites are located along a transect across the treeline boundary, from contiguous forest ("forest", upper left panel) to unforested tundra ("upper forest-tundra", lower right panel). Bar shading indicates the data source. Light green portions represent seedlings whose age was estimated from counts of annual rings; Dark green portions represent trees whose age was estimated from cores. A density threshold of 5 trees/ha (horizontal line on each panel) was used to identify the decade in which an ecologically significant density of trees established at a particular site.

variability in the timing of advance is variation in regional climate history (e.g., the onset of post-Little Ice Age warming). Despite the variation in the exact timing of response, the widespread nature of treeline advance in Alaska strongly suggests that this represents a directional response to regional climate change and not ongoing variability in within-site forest dynamics.

Although spruce appear to have advanced into tundra throughout Alaska, the area affected by this distributional shift is relatively small. At arctic treeline, the distributional limit of spruce has advanced by 10 km or more (Lloyd et al., 2002), while at alpine treelines in interior Alaska, the distance that spruce's distributional limit has shifted is probably <1 km at most sites (Lloyd and Fastie, 2003). Although the distributional change in spruce is an indicator that recent warming has affected the forest-tundra ecotone, the time scale on which ecosystem conversion occurs at this ecotone involves many decades to centuries (Figure 13). Modeling studies have predicted that this conversion would take >150 years (e.g. Chapin and Starfield, 1997; Rupp et al., 2000a,b). This estimate is supported by reconstructed stand dynamics at the forest-tundra ecotone based on tree-rings.

Patterns of growth of individual spruce trees at treeline, however, hint at a more complex response to climate. Increased warmth may be causing drought stress and thus leading to reduced growth and reduced forest productivity (Jacoby and

D'Arrigo, 1997; Barber et al., 2000; Lloyd and Fastie, 2002). Collectively, these data suggest that nonlinear responses to warming may be likely throughout the boreal forest and thus the magnitude and direction of future changes in the position of treeline may differ substantially from those observed during the past 100 years. Adding to the complexity of interpreting and projecting expected trends in treeline response to climate change is the difficulty in assessing how changes in wildfire regimes and insect and disease outbreaks that correlate with drought stress in spruce may affect changes in treeline (Juday et al., 1998).

13. Shrubs

In northern Alaska, expansion of shrub tundra is detectable with comparisons between historical (circa 1940s) and contemporary photographic imagery (Sturm et al., 2001a,b) and with Landsat imagery at decadal and sub-decadal resolution (Silapaswan et al., 2001). Regional modeling studies focused on Alaska have shown that the expansion of shrub tundra at the expense of sedge tundra may result in substantially warmer summers over tundra (Lynch et al., 1999; Chapin et al., 2000a). These modeling studies show vegetation change in the Arctic has the potential to influence climate and the magnitude and extent of the impact will depend on the temporal and spatial patterns of land cover change. Until the areal extent and magnitude of these land cover changes are documented, it will be difficult to assess the magnitude to which these land cover changes have contributed to the observed summer warming.

Manipulation experiments (Chapin et al., 1995; Doorman and Woodin, 2002; Hollister, 2003) and models of warming in Arctic Alaska suggest that one response will likely be an increase in the abundance and possibly the size of shrubs. Photographic comparisons between 1949 and 2001 at nearly 200 sites spanning the Arctic Slope confirm such an increase (Figure 14). The observed increase in shrub cover (predominately alder (Alnus crispa)) is consistent with anticipated increases in shrub cover due to a warmer climate (Sturm et al., 2001b). Dynamic vegetation modeling of the plant community response to climate warming predicted increases in shrubs (Epstein et al., 2000) and remote sensing analyses (Hope et al., 2003) confirm changes in shrub coverage on larger scales.

14. Tundra Plant Communities

Few studies have documented decadal time scale changes in tundra vegetation and land cover. Most of our knowledge of how tundra vegetation will change with climate change has been derived from manipulative, paleoecological and modeling studies. The International Tundra Experiment (ITEX) is a circumarctic network of sites using a common passive temperature manipulation to examine species

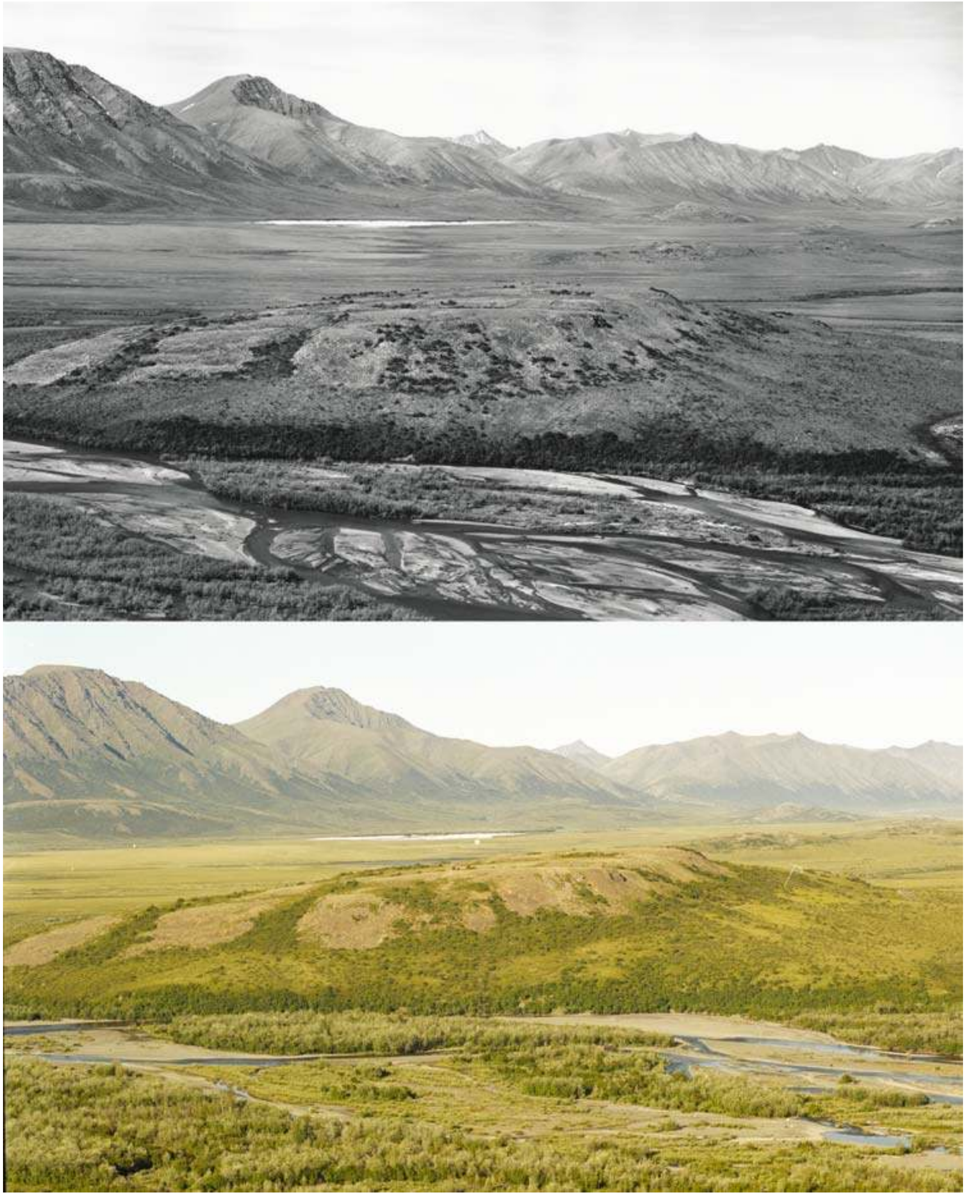

Figure 14. The proportion of shrubs has increased substantially in northern Alaska, causing subsequent changes in surface energy balance and snow distribution. These images, taken near the Nimiuktuk River in northwestern Alaska (upper, black and white photograph in July 1950 and lower, color photograph in August 2002), clearly demonstrate changes in the vegetative community. The photographs were taken from an aircraft located at 68°15.6′N, 159°53.1′W, with the camera aimed due west. Elevation above the ground was approximately 150 m (Sturm et al., 2001a).

specific responses to warming across climatic and geographic gradients of tundra ecosystems over the last decade (Henry and Molau, 1997; Arft et al., 1999). Tundra plants show immediate physiological and morphological responses to experimental warming (Welker et al., 1997). These geographically distributed experiments indicate that leaf bud burst and flowering are occurring earlier on warmed plots, but that there has been little affect on the termination of growth at the end of the growing season (Arft et al., 1999). While many of the species level responses to experimental warming have been site specific, there has been a general increase in vegetation stature and the cover of shrubs and graminoids and a decrease in the cover of mosses and lichens (Hollister, 2003).

In northern Alaska plots established in the 1970s were resampled between 1999 and 2001 to document plant community change. Plots were originally established as part of the International Biological Programme in Barrow, Alaska (Brown et al., 1980) and the Research in Arctic Tundra Environments (RATE) program in Atqasuk, approximately 100 km south of Barrow (Komárková and Webber, 1980). This long-term study of vegetation change found that the communities most vulnerable to change were wet and moist community types. Dry community types were the most stable over time. Changes in long-term plots at Barrow appear to be greater than those documented at Atqasuk. The assessment of land cover change in Barrow at a landscape-level grid (ca. 4.3 ha) showed patterns consistent with micro-grid (34 m^2) resampling and plot level (10 m^2) resampling. Dry community types have replaced wet and moist community types. There appears to have been increased fragmentation of community types at the landscape level, especially wet and moist community types. Changes in land cover at the landscape level are associated with an increase in active layer depth and a decrease in relative topographic range, although at the micro-grid level the relative range in elevation between polygon rims and troughs appears to have increased. The changes documented above are probably related to cumulative impacts and the result from interactions of multiple drivers of change. This region has undergone a warming and drying trend over the past few decades (Oechel et al., 2000), melts out earlier than surrounding tundra due to dust pollution, and has undergone significant hydrological change due to human-induced drainage (Brown et al., 1980). This re-sampling effort illustrates the relative propensity (i.e., direction and magnitude) that different vegetation and land cover types have to change.

15. Changes in Animal Populations or Behavior

Climate change will affect the timing of productivity among habitats, which are the proximal source of vertebrate population variability. Not all regions in the Arctic are warming, nor are regions that are warming doing so at a constant rate. Differential habitat use/selection/specificity by various vertebrate species and the resulting interactions among animal species will contribute additional heterogeneity to population responses. For resident species, climate warming may have a positive effect on habitats in summer and negative effects on ability of animals to access habitats in winter. For species that migrate long distances, climate change will have different effects across a species' global range, and it seems likely that change will be more pronounced across high-latitude breeding ranges (Myneni et al., 1997).

Arctic calving caribou provide an example of a species that is likely to be affected by climate change; yet long annual migrations and circumpolar distribution suggest that effects on populations will not be uniform. There are 13 major herds in North America, totaling 3–4 million animals, which are distributed from the warming western Arctic to the cooling eastern Arctic (Kofinas and Russell, 2004). Repeatable and frequent censuses are available only for the western herds. The western herds, with ranges entirely in Alaska, (Western Arctic, Teshekpuk, and Central Arctic) have increased 5–7-fold since the late 1970s while the Porcupine herd that spends substantial time in the Canadian Yukon Territory has shown both a two-fold increase and decrease during the same period. Hemispheric scale climate indices (e.g. NAO, AO) have been variously associated with population trends of Scandinavian ungulates (Post and Stenseth, 1999) and Svalbard reindeer (Aanes et al., 2002), and the population size of the Porcupine herd began to decline once the AO entered a predominantly positive phase in the early 1990s coincident with a phase shift in the PDO (Griffith et al., 2002). However, the three remaining western Alaska herds continued to increase after the AO entered the recent positive phase (Griffith et al., 2002).

Local effects of climate warming on the habitats and the numerical response of the Porcupine caribou herd illustrate the potentially counteracting effects of summer and winter warming. Temperatures on summer ranges have increased, the amount of green forage available to nursing females during peak lactation has increased concurrently, and calf survival during June has been positively associated with food available to females during the past 15–20 years (Griffith et al., 2002). During this warming period, however, the size of the herd began declining around 1990. A layer of ice in a snowpack affects the caribou's ability to crater through the snow to the underlying forage. These ice layers tend to form when the air temperature rises above freezing for a portion of the day, creating an icing within the snowpack when the temperature drops below freezing. The frequency of minor daily icing on spring and fall ranges of the Porcupine herd tended to be greater during the decline phase of the population than during the increased phase of the population (Griffith et al., 2002), but no increase in the frequency of icing has been observed on the winter ranges of the Alaskan herds that continued to increase throughout the 1990s. Icing events in spring, when animals are stressed, may increase mortality by elevating energetic costs of travel, reducing access to food, or increasing predation risk. Thus, there is a suggestion that the theoretical negative effects of winter warming nullified the positive effects of summer warming for the Porcupine caribou and that this effect has not been geographically uniform as evidenced by continued increases of western Alaska caribou herds. Conundrums such as this might be expected for other Arctic species.

For migratory species (particularly long distance migrants), their breeding ranges are most immediately affected by high-latitude climate change. Implications for distributions and population abundance and persistence will depend on the relative importance and availability of breeding, summering, and post-breeding high-latitude habitats. Among migratory birds, range shifts are already occurring and are certain to continue. Many long-distance migrants reach the terminus of their breeding distributions in Alaska and the Arctic, and these range limits are often dictated by the amount of time that these habitats are productive. At least some of these time-limited migrants are expanding their ranges in response to an increased length of high-latitude productivity.

Because of their mobility, birds are excellent and rapid indicators of environmental change. According to Icelandic Birding Pages, both the Mute and Tundra Swans have been observed more frequently in Iceland in recent years (http://www.hi.is/∼yannk/indexeng.html). Some species have shown range shifts in Alaska that are concordant with high-latitude warming and a longer growing season; e.g., Glaucous Gull (*Larus hyperboreus*; Winker et al., 2002) and Yellow-bellied Flycatcher (*Empidonax flaviventris*; Benson et al., 2000). Warming may also explain increased abundance and persistence of peripheral populations of resident species such as the Red-breasted Nuthatch (*Sitta canadensis*; Benson et al., 2000) in central Alaska (D. D. Gibson, personal communication). However, many changes in avian abundance and distribution in Alaska over the past century have not been due to warming (Kessel and Gibson, 1994). These include population declines among some species of long distance migrants that may be due to habitat changes (including anthropogenic) on distant wintering grounds. Declines have also occurred (for as yet unknown reasons) among Beringian eiders – to the point where two species have been listed as federally threatened, thus altering traditional human subsistence resource use. Numerous factors can impact avian population health in positive or negative aspects; these include changes in snowfree season, freezing rain, storminess, plant phenology and forage quality, insect life cycle, competition among species and mutualisms (Babcock et al., 1998). Complexities of life histories (e.g., resident, partial migrant, long distance migrant) and of habitat use will continue to produce heterogeneous responses to the effects of climate change among high-latitude birds (Figure 15).

16. Human Dimensions of Change

Humans in the Arctic are affected by climate in many ways. Strategies and materials for hunting, fishing, gathering, transportation, construction, and other activities are designed with particular conditions in mind (Fenge, 2001; Riedlinger and Berkes, 2001). Ecologically, climate helps determine the abundance and distribution of

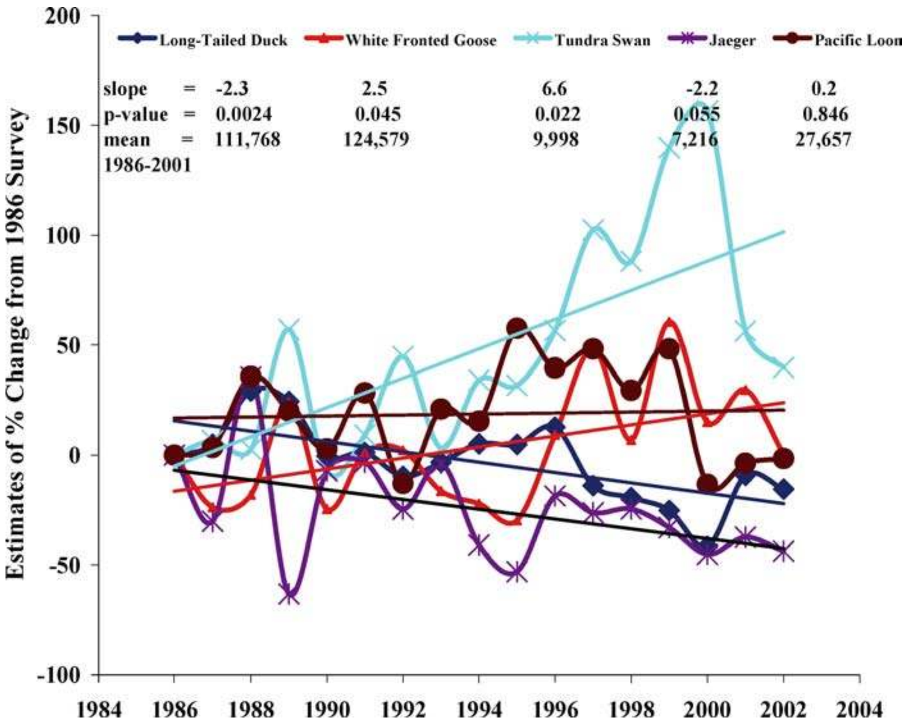

Figure 15. Estimates of bird populations, collected through aerial surveys, demonstrate the substantial differences among species in annual population dynamics and in longer-term trends (data from Mallek et al., 2003). Variations may reflect response to climate variations, but numerous other factors may also influence populations including changes in winter habitat, competition, disease or human interactions. Positive slopes indicate increasing populations.

animals that are hunted. Access to some hunting and fishing areas is constrained by the presence or absence of snow and ice. Sea ice, snow and ice roads provide a medium for community and industrial transportation. Permafrost presents a solid substrate, not only for structures such as buildings and pipelines, but also for terrestrial ecosystems. The interaction of these factors is critical in assessing the sustainability of arctic human communities. The identification and analysis of such changes, however, are hampered by the substantial interannual variability in many human activities, complicating the assessment of trends, and by the great societal and technological changes that have occurred over the past few decades across the Arctic (e.g., Ellanna, 1983; Huntington, 1992; Braund and Associates and Institute of Social and Economic Research, 1993; Peterson and Johnson, 1995).

Subsistence hunting and fishing are rooted in local ecological and environmental conditions. Certain aspects of subsistence hunting may be particularly vulnerable to climate change. Krupnik and Bogoslovskaya (1999) found that the harvest of walrus and seals in Chukotka, Russia, was strongly correlated with and highly sensitive to spring weather and sea-ice patterns, which influence both the presence of pinnipeds and the ability of hunters to reach them by boat or over the ice. Similar patterns have been documented in Greenland (Vibe, 1967), although the analysis can be complicated by socioeconomic factors (Jensen, 1987). Similar effects have also been demonstrated for land animals (Meldgaard, 1986).

In Barrow, Alaska, spring goose hunting is conducted at inland locations following the spring bowhead whale hunt, which is carried out from the sea ice. The ability to travel inland depends on the presence of snow, which has been melting earlier in Barrow in recent years. As hunters are required to go inland sooner if they want geese, whaling and goose hunting shift from being successive to being competing activities. Fall snow cover sufficient for traveling seems to be developing somewhat later now than in the past, which complicates efforts to complete fall caribou hunting and lake or river fishing through the ice before the days become too short. Factors such as increased time pressure, less experienced younger hunters, and even increased reliance on technological solutions such as GPS and search-and-rescue helicopters may contribute by increasing the degree of risk that is accepted when setting out on a trip. The decreased snow cover in Barrow differs from long-term meteorological observations collected at many (but not all) areas of the Arctic; however, spring snowpack surveys conducted in the Kuparuk watershed, North Slope Alaska (Kane et al., 2000) combined with snow precipitation measurements (NRCS, 1977–2003) do indicate a slight decreasing trend in maximum spring snowpack between 1977 and 2003. Increased snowpack may present different obstacles, including more difficult winter travel particularly through shrubby areas.

Similar changes have been noted in Canada's High Arctic. The absence of early season snow can leave inland trails impassable for snowmobile travel. Absent or thinner sea ice and water overflow on lakes and river is making travel more time consuming and in some cases unsafe (Ashford and Castledon, 2001). The floating sea ice cover of the Arctic Ocean shrank to extreme levels in the late summers of 2002, 2003 and 2004 continuing a trend of increasing sea ice losses over the past two to four decades (Serreze et al., 2003a,b). Changes in the timing of river break-up and freeze-up in areas where interception of migratory prey (e.g., caribou, waterfowl) is important may also have dramatic effects on subsistence harvesting patterns. For villages using traditional food caches for meat storage and drying during the fall to spring months, a decrease in the cold-weather season may lead to spoilage and economic hardship.

Changes in the distribution, abundance, and seasonal availability off subsistence fish and wildlife as a consequence climate change will be a function of the complexity of the associated adjustment of the dynamics of arctic ecosystems. These adjustments will vary in the rate of ecosystem response to climate driven change, and will add to the difficulty in anticipating or predicting availability of subsistence resources. As a consequence, systems for management of fish and wildlife resources aimed at supporting sustainable human harvest will need to be adaptable to the changes taking place in the Arctic and the associated responses of the fish and wildlife populations. Management systems in which local users of fish and wildlife share major responsibility for management of fish and wildlife resources with the regional resource management agency, can be structured to enable prompt adaptability of management to changes in availability of resources for harvest (Klein et al., 1999).

The construction and maintenance of infrastructure in the Arctic is greatly affected by climate. This is especially true in areas of permafrost, which both provides a useful foundation and raises the challenge of preventing thawing of ice-rich permafrost in order to avoid slumping of buildings, pipelines and roads (Osterkamp et al., 1998). In recent years, these impacts occur with increasing frequency throughout northern Alaska and the Northwest Territories. The runway serving the Prudhoe Bay oil fields, has been reconstructed due to settling from melting permafrost, which has warmed about 2–3 °C over the past decade. A general contractor in Barrow noted that the depths at which pilings for structures must be set have increased by several feet over twenty years (M. Aamodt, personal communication). Warming of permafrost prior to actual thawing can greatly reduce the load capacity of pilings, creating significant problems for buildings and pipelines (Osterkamp et al., 1998). Communities such as Tuktoyaktuk, Northwest Territories, and industrial sites such as several of the diamond mines in the Northwest Territories depend on winter ice roads for vehicle transportation to regional centers. Although monitoring in some areas has not detected trends, local residents have observed changes in the quality and thickness of ice.

On the Alaskan North Slope, the time period when travel by off-road vehicle is permissible (i.e., when the active layer is completely frozen and the vegetation is adequately protected by snow) has been gradually changing, resulting in a shorter time available for industrial or private transit. Although the closing date is substantial (changing by three weeks from late May in the early 1970s to early May in recent years, Alaska Department of Natural Resources, unpublished data), the date of opening has changed much more dramatically, from early November in the early 1970s to early January under the present climatic regime. Although closing of spring travel occurred concurrently with warmer spring air temperatures, thinner snowpack and earlier snowmelt as discussed previously, there is some question as to the consistency of the methods used to measure the bearing strength of the frozen soil. The marked delay in winter opening may be due to delayed active layer freezing resulting from relatively milder winters in recent years. The duration of permissible tundra travel has decreased from over 200 days in the early 1970s to just over 100 days in 2000s and has resulted in greater difficulty and environmental risk for mineral and oil exploration. This demonstrates the importance of society's need to adapt to a warming climate, maintaining environmental protection with resource development in a changing Arctic.

Increases in windiness have been noted in several areas. Residents of Norton Bay in western Alaska report that, compared with several decades ago, there are few calm days and winds change direction more suddenly (Huntington, 2000). A

U.S. Fish and Wildlife researcher working at Cape Lisburne, northwestern Alaska, reported that over the course of four years (2000–2003), the weather allowed boat travel on the ocean on only two days out of 114 spent at the field site in the months of July and August. In contrast, during the late 1990s, 10–15 boatable days per season were typical. Wind patterns and associated weather have also changed in that time (D. Roseneau, personal communication, 2003). The ability of subsistence hunters to travel under these conditions is, of course, greatly hampered, and may result in lower harvests, greater risks of injury and death, and shifts in the timing of harvests or the species harvested. For example, the traditional activity of gathering murre eggs (*Uria* spp.) in Point Hope, Alaska, was impossible in the summer of 2003 due to poor weather (E. Kingik, personal communication, 2003).

In addition to the specific changes and impacts noted so far in this section, a more generalized change is affecting people and their ability to plan. Increases in environmental variability are suggested in climate projections (Folland et al., 2001; Overland et al., 2002) and have been reported in many areas (Fox, 2002). Increased variability of conditions (e.g. more deep snow years, more low snow years, fewer mean snow years) confounds efforts to anticipate future conditions and results in greater uncertainty and risk for decision makers, be they policy makers or local hunters. Hunters in Nunavut, Canada, report changing travel habits due to less predictable weather (Fox, 2002). Infrastructure planning in Barrow, Alaska, is made more complicated by uncertainty about changes in frequency and severity of storms in the region (Brunner et al., in press). Thus, changes to known patterns of weather and other variables may be of similar significance to changes in specific environmental parameters.

Changes in traditional patterns of harvest of fish and wildlife by indigenous peoples may be necessary as distribution of species change with changes in habitat characteristics. For example, availability of moose may increase and caribou decrease in the northern boreal forest as a consequence of increased fire and insect epizootics. Anadromous fish may increase in arctic river systems, compensating somewhat for the reduced opportunity for fishing from an ice platform adjacent to coastal villages. Changes in traditional patterns of fish and wildlife harvest, however, may require new modes of travel to harvest sites and development of different methods for harvest and preservation of the fish and wildlife harvested. Adaptability will be a key element in living in a changing Arctic. An integrated assessment of Arctic community sustainability involving scientists and Native communities modeled possible forces for change, including a warming climate, to ascertain their implications to Old Crow, Yukon Territory, a small Gwich'in community with no road access that is highly dependent on Porcupine caribou (see www.taiga.net/sustain, Kruse et al., in press; Berman and Kofinas, 2004; Berman et al., 2004). Findings of the assessment offer several insights relevant to this discussion. A warming climate is likely to have a negative population effect on caribou availability by affecting access to hunting grounds. These conditions alone do not have a dramatic effect on harvesting, because the community has the capacity to consolidate local hunting resources and draw on existing institutions for resource sharing (e.g., more far-reaching hunts, more "community hunts" when caribou are within reach for hunting). The cumulative negative effects of a warming climate with industrial development that displaces animals from critical habitat suggest that future analyses need to integrate social, economic, and political variables. Some aspects of climate warming may produce positive results, such as lower winter home heating costs, increased monetary income from tourism, and increased abundance of certain animal species; however, socioeconomic changes cannot be evaluated without assessment of past and future climate change and ecosystem response.

17. Comparison of Science Record and Indigenous Reconstruction

There is a clear perception among residents of the North American Arctic that the climate of the region has changed in living memory (Ashford and Castledon, 2001; Krupnik and Jolly, 2002). For example, it has been reported that snowmelt onset at hunting camps is becoming unpredictable (K. Toovak, personal communication), the sun is feeling hotter (K. Toovak, personal communication), and the summer mosquito population is increasing (M. Carroll, personal communication). Careful examination of the climate records at Barrow generally supports these perceptions. A decrease in the amount and period of winter snow cover has been observed by residents and recorded in weather observations. Snow cover onset shows very little change, but snowmelt onset shows a significant trend towards earlier spring melt – almost ten days earlier over the last 50 years (Stone et al., 2002). Data on cloud cover and radiative fluxes are relevant to the perceptions that the sun is becoming more intense, but insufficient to support long-term analyses in this data-poor region. Annually, low cloud cover has decreased from an average of 6.5 tenths–5.5 tenths in Barrow (Curtis et al., 1998), although cloudiness has generally increased in winter and early spring (Stone, 1997). In all day-lit months except June, (1991–1996, Barrow, Alaska) Gurney (1998) found noontime ultraviolet irradiance measurements showed increases between 3 and 10% per year in the wavelengths known to cause biological damage.

Observations in other communities in the North American Arctic indicate that these changes are widespread. The basic observations of warmer temperatures, longer growing seasons, and thinner cover of sea ice have been observed repeatedly by indigenous people throughout the North American Arctic, even before the trends became statistically detectable in local instrument records (Fox, 2002; Jolly et al., 2002; Thorpe et al., 2002; Krupnik, 2002). More importantly, local residents note that weather and ice conditions are less predictable than in the past. The decline in predictability is at least as important to northern communities as is a change in average conditions, because traditional cues for predicting the weather no longer work. This "strips arctic residents of their considerable knowledge, predictive ability, and self-confidence in making a living from their resources. This may ultimately leave them as strangers in their own land" (Berkes, 2002). Thus, the departure from local knowledge systems resulting from climatic change renders arctic residents more vulnerable to these changes (Norton, 2002).

Arctic residents have also made many key observations that are not widely documented by western science. Ponds and wetlands are drying up near many communities across the North American Arctic (Fox, 2002; Jolly et al., 2002; Nickels et al., 2002). In some cases this appears to reflect changes in solar insolation rather than increased air temperature (Fox, 2002). The warmer, drier environment of ponds and wetlands is consistent with some published studies (Yoshikawa and Hinzman, 2003; Oechel et al., 2000). These associated changes in hydrology may account for new sightings of fish, insects, and birds. These northern extensions of range limits include sightings by residents of American Robins (*Turdus migratorius*), forest insects, and salmon (Fox, 2002; Thorpe et al., 2002; Jolly et al., 2002). Local residents have also observed changes in vegetation, for example, increased shrub abundance through a broad expanse of the North American Arctic (Nickels et al., 2002; Thorpe et al., 2002). These extend geographically the observations based on repeat photography in northern Alaska (Sturm et al., 2001a).

Changes in the behavior and health of caribou, a key subsistence species, have been observed in several communities (Thorpe et al., 2001; Kofinas et al., 2002). In northern Canada the health of caribou in some herds has declined, and bulls are reported to die from overheating, in some cases associated with increased mosquito harassment (Thorpe et al., 2002; Fox, 2002). In other herds, no consistent deterioration in the body condition of animals is observed (Kofinas et al., 2002). Changes in the timing and pathways of migration have also been observed repeatedly in many communities. These changes in movement patterns are often overlooked in satellite tracking of radio-collared caribou because of the small number of animals that can be monitored in this fashion (Kofinas et al., 2002). Altered movement patterns change the availability of animals to hunters. Local residents also report changes in the abundance of other key subsistence resources, such as the decline in cloudberries (*Rubus chamaemorus*) under dry conditions (Kofinas et al., 2002).

As a result of the numerous ways in which global warming has altered their lifestyle, northern communities have formed partnerships with scientists to document these changes and their societal consequences (Jolly et al., 2002; Kofinas et al., 2002; Krupnik, 2002). These partnerships provide new opportunities to share information and develop and explore new hypotheses.

18. Conclusions

We end where we began, by stressing the complexity and sensitivity of the response of the arctic terrestrial system to change. The combined record demonstrates that while climatic changes in regional and pan-arctic temperature and precipitation fields may be the dominant drivers of change, the nature and timing of weather events, the drastic threshold changes that occur as permafrost progresses through phase change, the spatial and temporal process variability, all have profound impacts on the system response. While documenting the subtle or even dramatic changes in an individual variable or process over time may convince us that the Arctic is a dynamic region, evaluating the important interdependence of physical, biological, and social processes demonstrates the critical connectivity and repercussions of climate warming in the Arctic.

At this time, it is difficult to reconcile all of the observed changes in physical and ecosystem processes to a simple response to warming temperatures. The degradation of glaciers or permafrost can exert conflicting responses in watershed runoff. Increases in precipitation may be offset by increases in evapotranspiration or increased infiltration to subpermafrost groundwater. Decreased sea ice may cause greater autumn snowfall, which in turn can slow the freeze-up of the active layer and insulate permafrost from cold winter air. Warmer winter and summer temperatures may be the cause of increased shrub growth, which may in turn trap more snow. The changes in vegetation may then affect foraging mammals and birds. Humans are an integral component of the system, influencing and responding to a changing climate and the consequent ecosystem dynamics. The accumulated evidence of changes among many components of the Arctic terrestrial system provides a diverse but consistent set of indicators of regional and global warming.

Documented changes are only a part of the changes likely to have occurred. Further changes are expected in the coming decades, emphasizing the need for expanded monitoring programs that will also help improve our understanding of the interdependence of physical, biological, and social processes in the Arctic. The complexity of the system may confound attempts at prediction, but it is already apparent that observed changes are influencing the landscape, the ecosystems, and the societies of the Arctic. Our growing ability to link observed changes to interdependent processes shows that we are making progress in understanding the arctic terrestrial system. Further progress requires extending the existing time series and new datasets especially in the biological and social realms, and more work in systemic analysis to quantify the relationships among primary drivers of change and key feedbacks.

Change is occurring in the Arctic, some of which is either directly or indirectly driven by global climate change. Increased understanding of the influence of climate change on the complexity of arctic systems is essential for the adaptation of human social, economic, and cultural systems to the changes taking place in the Arctic. The qualitative consistency of observed changes and their evident forcing by regional warming make a compelling case that we are seeing large-scale impacts of global processes. The breadth of impacts, including physical, biological, and social parameters, indicates tight coupling among the diverse components of the system and the likelihood of significant systemic impacts from further climate change.

Acknowledgments

Much of the research reported here was funded by the U.S. National Science Foundation Arctic System Science and Long Term Ecological Research programs. The authors would like to express their collective thanks for financial support provided through their many grants.

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Received 13 February 2003; accepted in revised form 29 July 2004