4

Unprecedented Change to Arctic Hydrological Systems

Change is an inherent property of the Arctic, with the paleoclimatic record providing ample evidence of the enormous changes experienced by the region since the last glacial maximum (Mayewski et al. 1994, Alverson, Oldfield, and Bradley 2000). The system has alternately experienced extensive and thick ice sheets, the blockage of northward flowing rivers, exposed coastal shelf regions, giant catastrophic floods, and most recently the complex signature of human-induced climate change. High-resolution paleo-records indicate that arctic climate can move rapidly from one regime to another, resulting in the anomalous persistence of warm temperatures, shifts in seasonality, extreme events, and changes in ocean circulation (e.g., Bond et al. 1999, Douglas et al. 1994). These and many other paleoclimate studies provide an understanding of arctic hydrologic variability and are needed to place the recent observations of Arctic system change into appropriate context (Stein 1998). Although changes to many environmental variables have occurred previously throughout geologic time, the rate of changes observed within the last few decades to century are quite likely unprecedented and indeed have evoked a sense of urgency within the community (Overpeck et al. 1997, Overpeck 1996, SEARCH SSC 2001, Serreze et al. 2000).

The multiagency SEARCH Science Plan (SEARCH SSC, 2001) provides an in-depth analysis of the spatial and temporal extent of recent changes to the arctic system. Many significant changes are observable from what is admittedly an incomplete and in many cases fragmentary record. The review given below focuses on the arctic system as well, but highlights those changes related specifically to the arctic water cycle.

Changes to the Land-Based Hydrologic Cycle

A wide range of changes in terrestrial arctic hydrology has been detected, and many of these changes started, or accelerated, in the mid-1970s. The arctic hydrologic system is particularly sensitive to changes in the magnitude and timing of rain and snowfall, freeze-up and thaw, and the intensity and seasonality of storm activity that reflect changes in large-scale atmospheric circulation rather than simple responses to temperature increases. Although historical changes in these fields are poorly known and characterized by enormous spatial and temporal variability, observations suggest that the arctic hydrologic system may be entering a state that is unprecedented, at least over a historical timeframe (Serreze et al. 2000, Lammers et al. 2001).

Integrated measures of hydrological status, such as glacier mass balance studies that record both summer and winter precipitation, indicate that over the last 30 years, smaller glaciers in the Arctic have experienced decidedly negative mass balances (Dyurgerov and

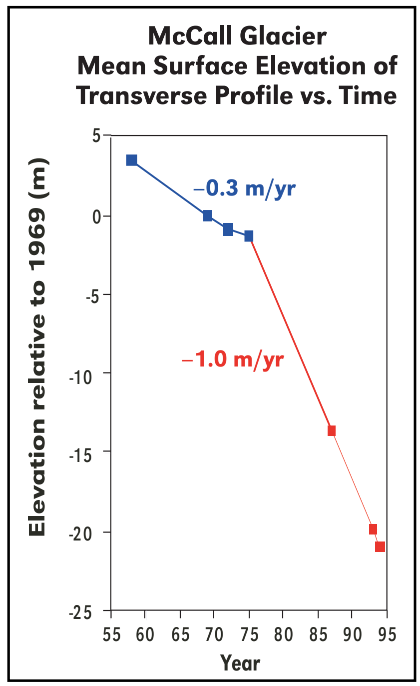


Figure 4-1. The McCall Glacier in the Romanzof Mountains of Arctic Alaska has been losing mass since measurements began in 1957, with accelerated losses over the last two decades (Rabus et al. 1995).

Meier, 1997). The 1957 to 1995 record for McCall Glacier in arctic Alaska (Figure 4-1) shows that the mass balance has not only been negative, but the rate of down-wasting has increased dramatically since 1976 (Rabus et al. 1995). The Greenland Ice Sheet has also increased in melt area throughout the 1980s (Abdalati and Steffen 1997), and the associated reduction in volume is about equal to those of all the smaller glacier systems in the Arctic (Dyurgerov and Meier 1997).

Observed responses of arctic river systems to changes in temperature and precipitation reflect a complex set of spatial patterns, including a mean delay of nine days for freeze-up and a ten-day earlier ice breakup date for lakes and rivers, comparing conditions 150 years ago to today (Figure 4-2; Magnuson et al. 2000). Trend analysis of river outflow has been inconclusive. Shiklomanov et al. (2000) suggest very little change in mean annual discharge for large rivers over the last several decades, whereas Semiletov et al. (2000) document increases for several Eurasian rivers. Changes in the seasonal pattern of discharge in many Arctic rivers have occurred (Savelieva et al. 2000), but these changes are challenging to detect because of large natural variations. Changes in the base flow, such as the increases in the Yenisei River between 1936 and 1995 (Figure 4-3) (Yang et al. in review), are more distinct and thought to reflect increased groundwater infiltration coupled to reductions in permafrost and an increase in active layer thickness due to warmer temperatures (Figure 4-4). A recent analysis of discharge records from several hundred stations distributed across the pan-Arctic (Lammers et al. 2001) indicates there has been an increase in winter flow in several Siberian river basins during the 1980s. Such hydrologic changes can impact stream habitat, increase icing, and elevate the export of sediment and solutes to the ocean.

Changes to the Atmosphere

Within the atmosphere, evidence of unprecedented change is documented in the instrumental record of precipitation and temperature as well as in changes in synoptic scale circulation and variability. The paleo perspective extends the relatively short instrumental

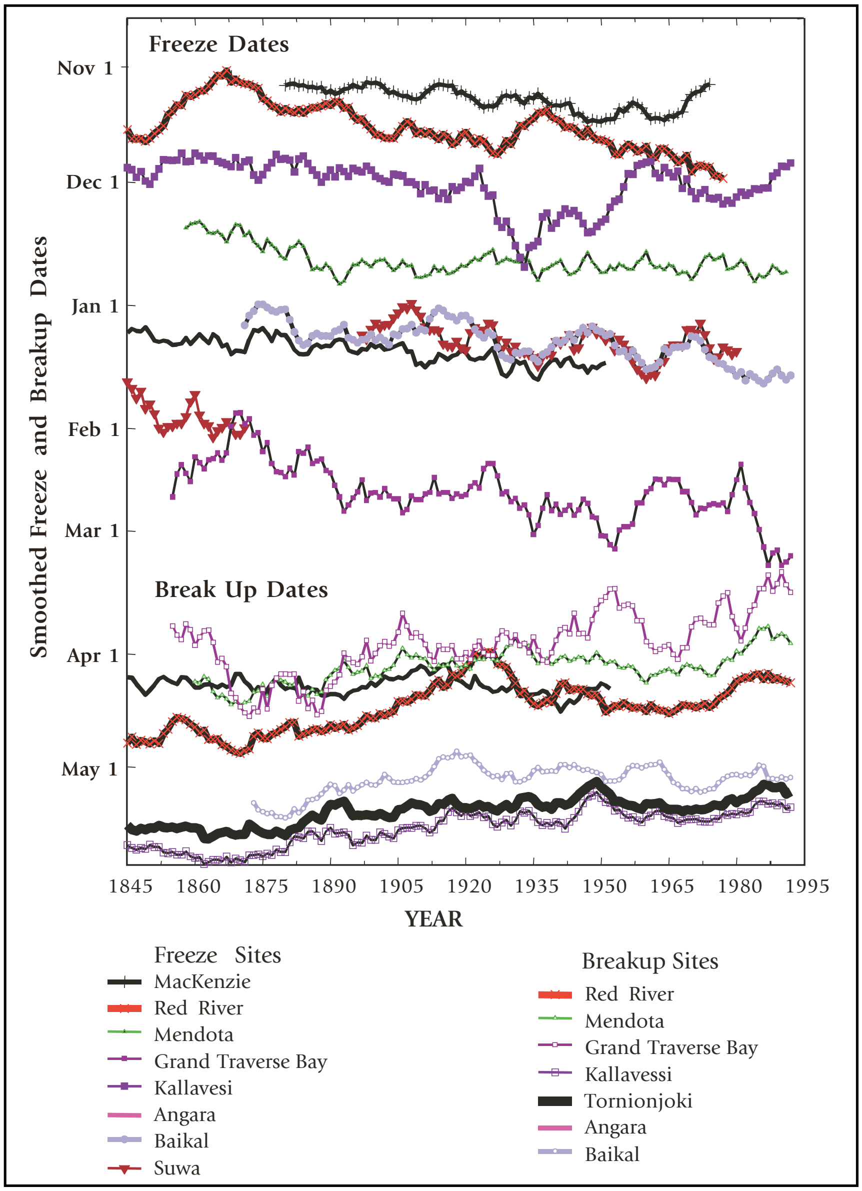


Figure 4-2. With increasing temperature, there have been noticeable changes in the dates of freeze up and ice breakup in many lakes and rivers of the Arctic. The average change over the 150-year period was nearly nine days later for freeze up dates and almost 10 days earlier for ice breakup dates of rivers and lakes in the Northern Hemisphere (Magnuson et al. 2000).

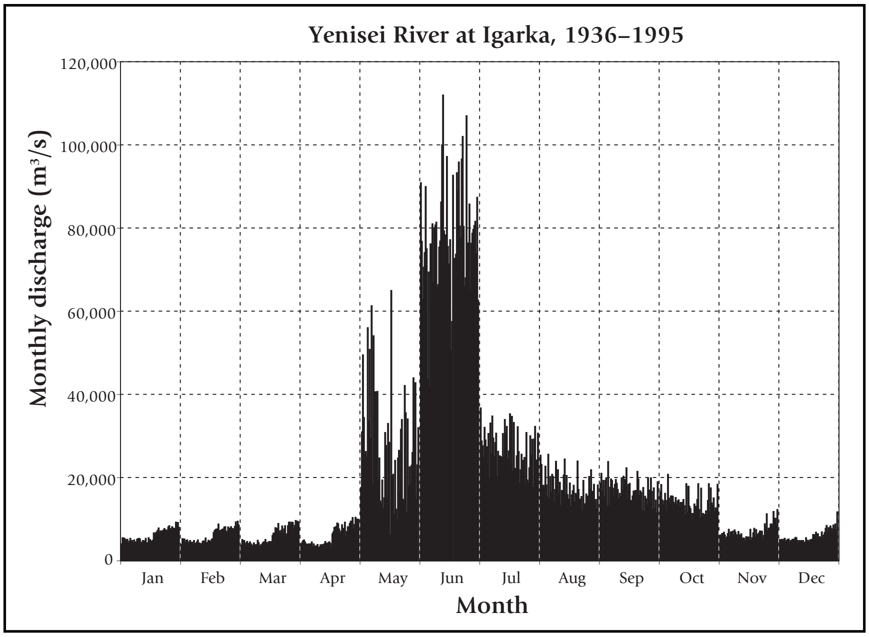


Figure 4-3. The base flow (non-surface runoff) of the Yenisei River increased markedly over the period from 1936 to 1995. For each month the plot shows the average conditions for each sequential year. This change is postulated to arise from increased groundwater infiltration coupled with permafrost degradation, which itself is a response to climate warming (Yang et al., in review). The construction of large artificial impoundments may also contribute to these changes.

Figure 4-4. Springs represent an important connection between groundwater and surface water, often forming at the permafrost boundary. Presence of well-developed minerotrophic vegetation indicates the spring has existed for many years. As permafrost degrades, the connections between groundwater and surface water increase, allowing springs to form or in some cases ponds to shrink (photo by L. Hinzman).

period and thus provides a more complete context for interpreting recent hydrologic variability and change. Overpeck et al. (1997) used a multiproxy regional synthesis to determine that arctic summer air temperatures of the 20th century have been the highest in the last 400 years, despite showing both positive and negative shorter term temperature trends. One warm period began in the 1920s and extended to the late 1940s; a second, still underway, started in the 1970s (Figure 4-5). The instrumental record of change in the Arctic indicates that high northern latitudes have increased in mean annual temperature by ~1˚C, with the largest increase in winter temperatures (~2˚C), whereas summer temperatures increased by ~0.5˚C (Lugina 1999, Lugina et al. 2001). Serreze et al. (2000) confirm that temperature changes are spatially complex, with warming in northern Eurasia and western North America but cooling in eastern Canada and southern Greenland (Figure 4-6).

Instrumental precipitation records document a significant increase over northern Eurasia (Groisman 1991) over the last 50 years across northern North America (Groisman and Easterling 1994), whereas in eastern Russia over the same period there has been a decrease in summer precipitation (Sun and Groisman 2000). This decrease in eastern Russia over the last 50 years has been accompanied by a replacement of stratiform clouds with convective clouds. Overall, across much of Russia there has been an increase in convective cloudiness associated with an increase in the number of days with heavy precipitation (Sun et al. 2001).

The primary modes and variability of the North Atlantic Oscillation (NAO), and the closely related Arctic Oscillation (AO), determine interannual precipitation variations over Eurasia and eastern North America whereas western North America responds to variability in the North Pacific Ocean. Consistent with intensification of the NAO/AO over the last two decades, winter precipitation amounts and surface air temperatures have been increasing in northern Eurasia, decreasing in southern Eurasia, and decreasing in northeastern Canada in response to enhanced storm activity in northern latitudes (Serreze et al. 2000). Over the same period that winter precipitation has increased, there has been a dramatic decline in northern hemisphere snow cover (Robinson 1999) (Figure 4-7). Eurasian snow cover extent has decreased over the past 20 years (primarily in the spring and summer; Groisman et al. 1994). The same is true for Alaska where during the past 50 years a general retreat of spring snow cover was reported (Groisman et al. 2001). Most of this retreat has occurred during the past two decades, resulting in an earlier onset of spring by approximately two weeks.

These climate trends are consistent with greenhouse warming, however, uncertainty remains whether these phenomena reflect natural climate variability, anthropogenic forced (i.e., "global warming") or a combination. Changes in rainfall, snowfall, and the recycling of water back to the atmosphere through evaporation and sublimation are difficult to assess from the instrumental record because the network of stations is sparse and data collection difficult (Black 1954; Woo et al. 1983; Yang et al. 1999, 2001). Summer precipitation trends, determined from computing precipitation (P) minus evaporation (E) from numerical weather prediction model reanalysis (Walsh et al. 1994, Serreze et al. 1995, Cullather et al. 2000), reveal little systematic change over the past 30 years. Site-specific studies often yield less ambiguous results. In locations where direct land-

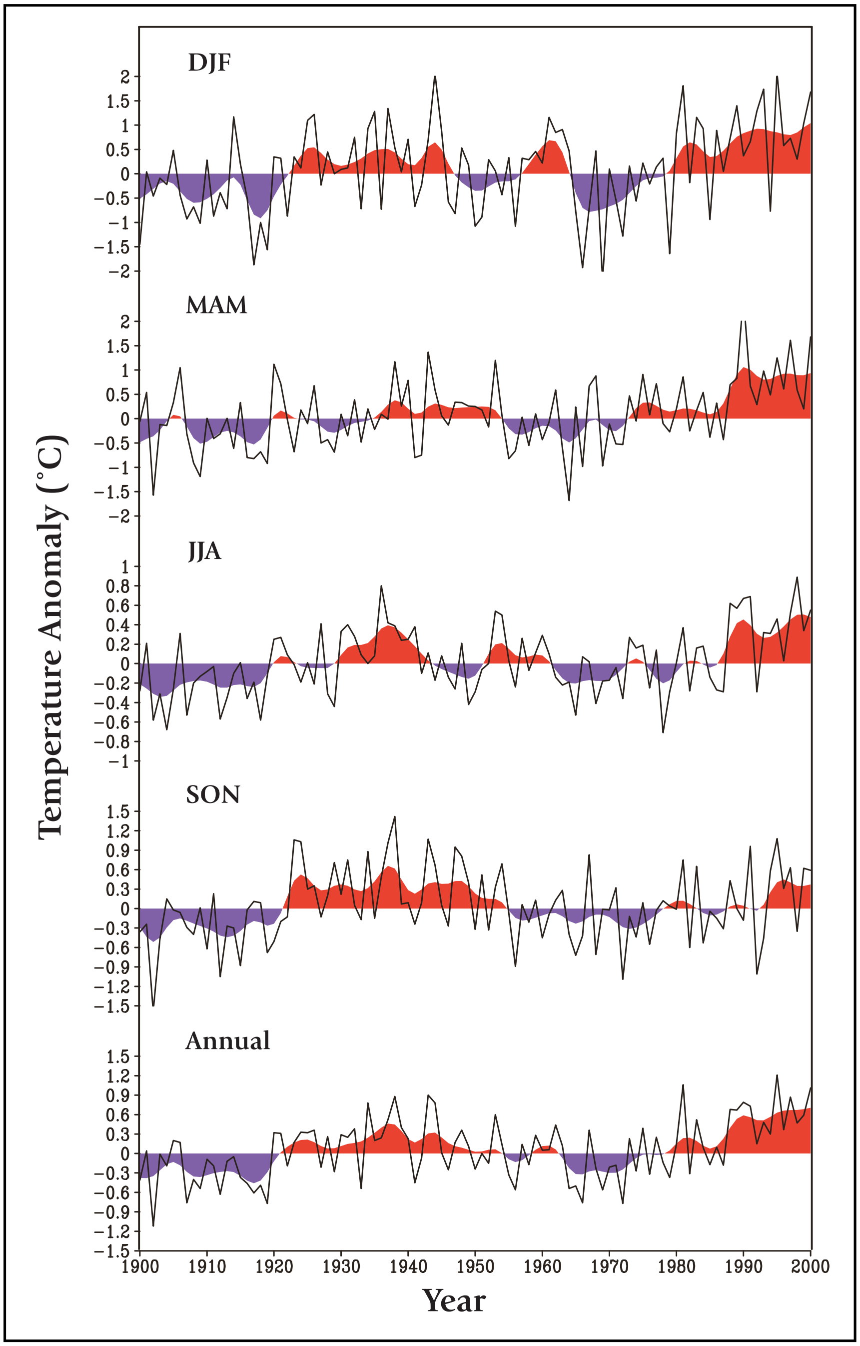


Figure 4-5. Time series of temperature anomalies for the 20th century for the Northern Hemisphere from 55° to 85° N (based on update to Eischeid et al. 1995).

based measurements have been available (Oechel et al. 2000), an observed trend toward increasing summer precipitation (1960 to 1998) has been offset by increasing air temperature and evapotranspiration, resulting in a net gain of water vapor to the atmosphere and drying of the soil (Figure 4-8).

Although pan-arctic data sets of critical hydroclimatic variables can be assembled at relatively high resolutions using state-of-the-art interpolation and gridding techniques (Price et al. 2000, Willmott and Rawlins 1999), accuracy is limited by a deteriorating network of ground-based monitoring stations. Intercomparison tests (Rawlins 2000) suggest that not only are new techniques still

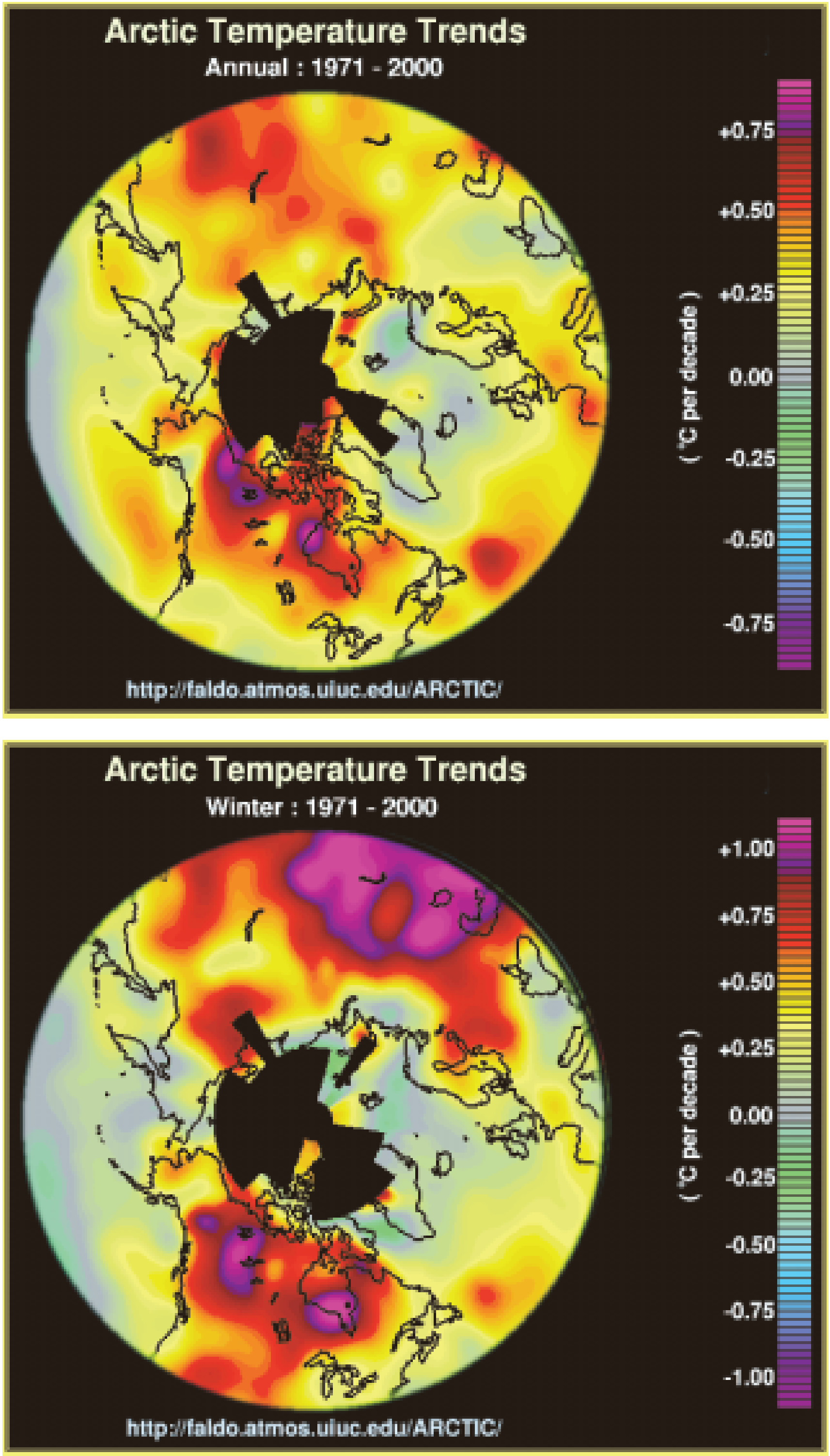


Figure 4-6. The geography of recent circumarctic temperature change. Updated from Chapman and Walsh (1993).

Figure 4-7. Understanding the processes controlling the variability of snowpack properties and snow cover distribution are critically important to understanding the current hydrologic regime and in predicting potential responses to climate change (photo by L. Hinzman).

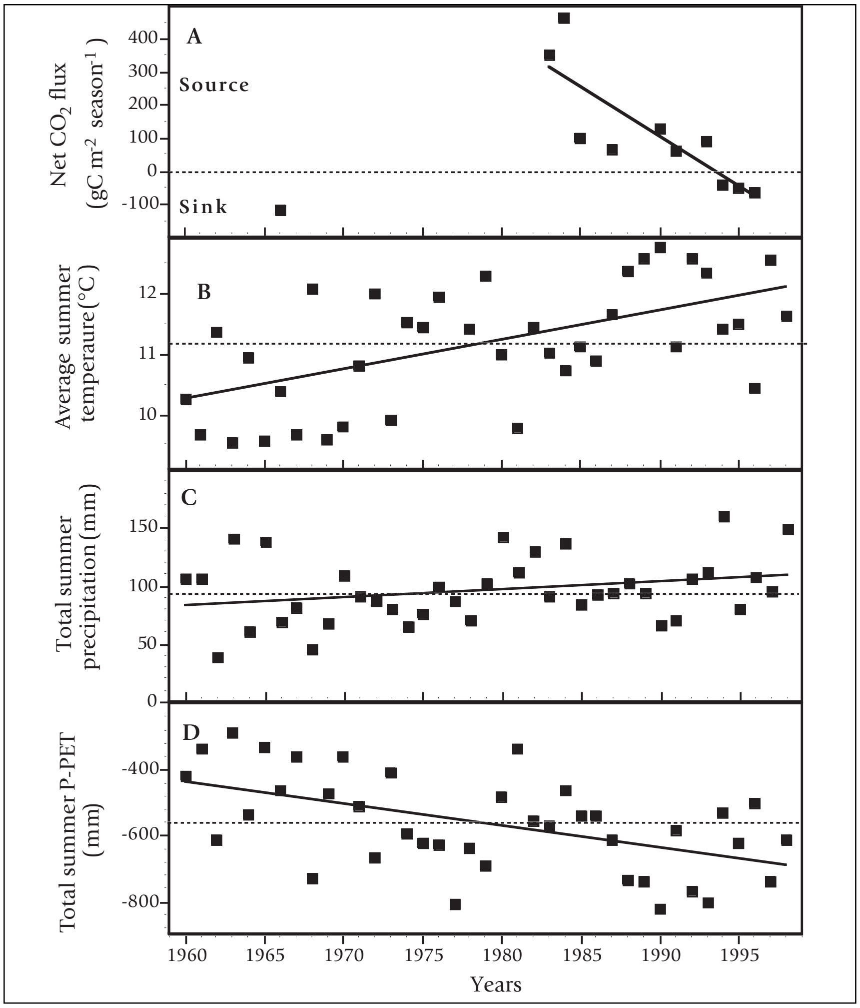
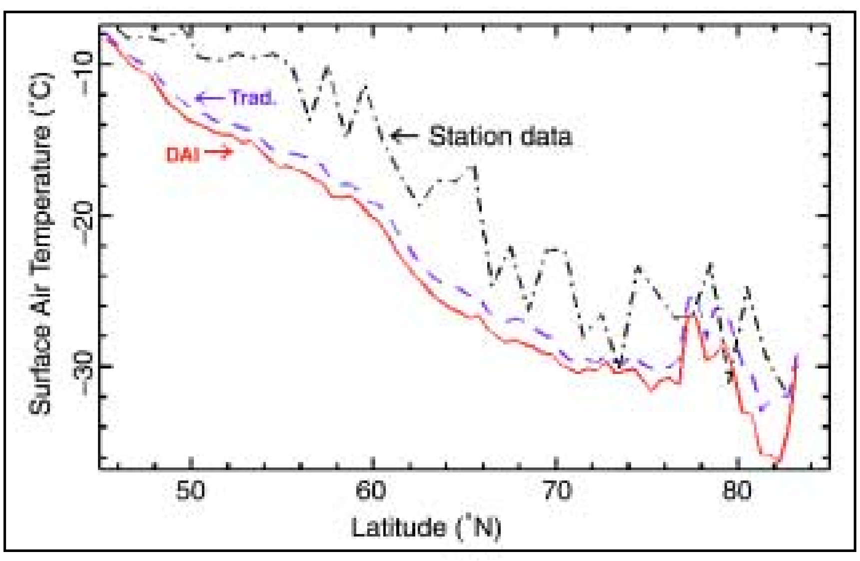


Figure 4-8. Changes in precipitation (P), potential evapotranspiration (PET), and their difference, a measure of net water available for soil water recharge and runoff. These data represent measurements made at four sites in northern Alaska. A net change in CO_2 flux is also tabulated as terrestrial primary productivity and ecosystem respiration are linked closely to moisture availability at these sites during the growing season (Oechel et al. 2000).



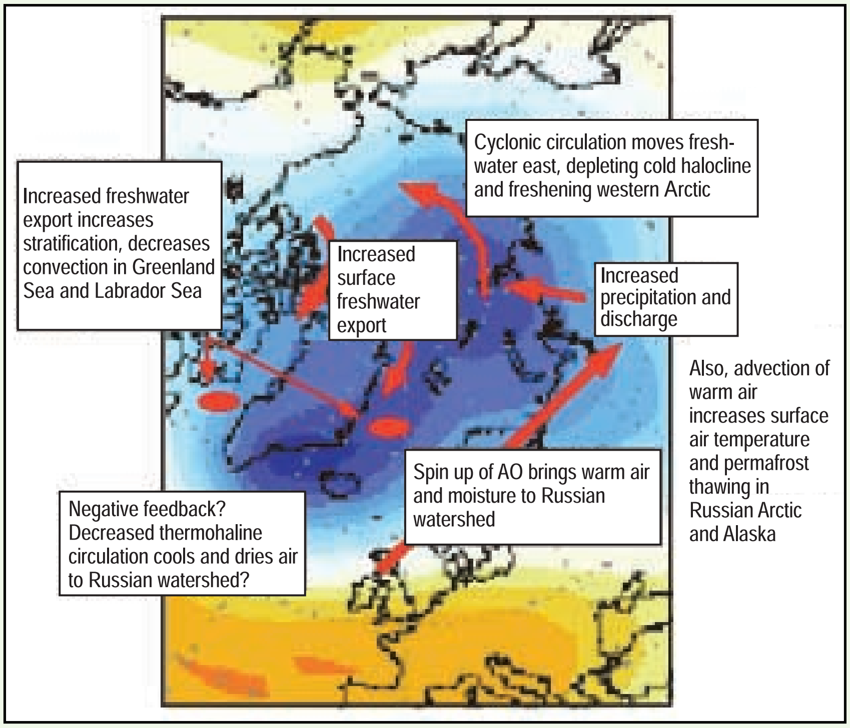
necessary to narrow the substantial gaps in our detection of climate warming but a substantial upgrading of station holdings remains critical (Figure 4-9).

The Changing Arctic Ocean and its Regional Seas

Recent hydrologically related changes within the Arctic Ocean system include increased salinity in the central region, shrinking of the cold halocline layer, and decreased surface salinity off of western North America (SEARCH SSC, 2001). Specific hydrological observations include changes in ice drift pattern, decreased sea ice extent, and decreased sea ice thickness. Arctic sea ice extent decreased by 2.9 +/- 0.4% per decade over the last 30 years (Cavalieri et al. 1997) and analyses of passive microwave time series from satellites indicate that ice reductions have been accompanied by an increased length of ice melt season (Smith 1998). Arctic sea ice thickness measured by U.S. Navy submarines over the last 20 years record an average 43% reduction in thickness for the central Arctic Ocean (Rothrock et al. 1999). The yearly average pressure maps indicate a shift in the

Figure 4-9. Impact of interpolation technique on the resulting bias in pan-arctic temperature climatologies. Latitudinally averaged (over 30′ latitude bands) mean surface temperature for winter is shown for traditional spherical interpolation versus Digital topography-Aided Interpolation (DAI) (Rawlins 2000). This graphic highlights the need to address systematic errors in our monitoring of hydrologically relevant variables across the pan-Arctic.

Box 4-1. The Arctic Oscillation and Hypothesized Connections to the Water Cycle



Based on extensive oceanographic observation, critical changes in the Arctic Ocean and changes to the land-based hydrologic cycle are hypothesized to relate closely to the onset of the Arctic Oscillation (AO) (Thompson and Wallace 1998). The working hypothesis is that as the AO index rises, the strength of the polar vortex increases, and the surface pressure in the Arctic Basin decreases, weakening the Beaufort high (Walsh et al. 1996). This applies positive vorticity to the sea ice and ocean circulation (Proshutinsky and Johnson 1997), resulting in reduced convergence in the Beaufort Gyre. This in turn results in more open water, greater radiative heat input, increased summer melt, and decreased Beaufort Sea surface salinity (McPhee et al. 1998). The change in circulation may also account for the decreased ice cover on the Siberian shelves (Maslanik et al. 1996). Increasing surface air temperatures are also thought to influence land-based freeze-thaw with potential acceleration of the terrestrial water cycle.

Steele and Boyd (1998) argue that the change in circulation reroutes Siberian river runoff to the east rather than allowing it to mix with Atlantic water, cool, and move cross-shelf to form cold halocline water. It is thereby responsible for thinning the cold halocline layer. The shift of Siberian runoff to the east may also be in part responsible for the freshening of the upper layers of the Beaufort Sea (McPhee et al. 1998, Macdonald et al. 1999). The increased cyclonic vorticity added to the Arctic Ocean may also act to draw surface water from the lower salinity, western region of the basin and increase the amount of fresh surface water flowing out through Fram Strait. This could increase stratification in the Greenland Sea and contribute to the weakened deep convection observed there in recent years (Aagaard et al. 1991, Schlosser et al. 1991).

An intriguing possibility is that reduced thermohaline circulation imposes a negative feedback on this system by causing less northward ocean heat flux into the Nordic seas and thereby cooling northern Europe and Russia, with important consequences for terrestrial ecosystems and human society.

These complex interconnections argue strongly for synthesis studies of the entire coupled arctic system. Integrated monitoring and simulation—at the heart of the overall Arctic-CHAMP initiative—will be essential to future progress in understanding these geophysical processes.

position of the Beaufort high, usually centered over 180° longitude before 1988–1989, to a more western position and weakening thereafter. These pressure anomalies are linked to changes in ocean circulation patterns and therefore the distribution of sea ice, terrestrially derived runoff, and salinity.

Collectively these changes represent some of the most compelling lines of evidence for arctic environmental change and suggest a substantial reorganization of the Arctic Ocean system, with important implications for ice cover, the ice-albedo feedback, and the terrestrial water cycle. These changes also highlight the integrative nature of the hydrologic cycle, linking land, atmosphere, and ocean. Box 4-1 describes some of the hypothesized links between the Arctic Ocean and freshwater dynamics. The full impact of the unfolding changes to the Arctic Ocean hydrologic system remains unknown, but the dramatic changes evident in numerous paleoclimate records underscore the importance of understanding both the magnitude and consequences of contemporary hydrological changes across this climatically sensitive region (Stein 2000).

Central Question: Are the Observed Changes in Arctic Hydrology Part of the Natural Variability or Are They Related Uniquely to Human-forced Global Warming?

Key Gaps in Current Understanding and Needed Studies:

- Design and implementation of long-term, coherent observational programs for water-related variables over land, atmosphere, ocean, and cryosphere
- Historical and paleo studies to establish benchmarks by which contemporary change can be measured
- Quantify the underlying processes controlling the natural variability and the observed unprecedented changes
- Studies that identify the causal agents of observed changes to arctic hydrosystems
- Trend analysis for early detection of global climate change