PARCS: Paleoenvironmental Arctic Sciences

Taking the Long View of the Arctic System

This article was prepared by Glen MacDonald, Department of Geography, University of California at Los Angeles; Darrell Kaufman, Department of Geology, Northern Arizona University, Flagstaff; Matt Duvall, Department of Geology, Bates College, Lewiston, Maine; and Larry Coats, Department of Geology, Northern Arizona University, Flagstaff.

The importance of understanding the environmental history of the Arctic and placing recent and future environmental changes within the longer historical context has long been recognized as a crucial component of the NSF Arctic System Science initiative. The Paleoenvironmental Arctic Sciences (PARCS) program of ARCSS brings together a diverse community of natural scientists to identify the most important cross-cutting questions of how the Arctic system has evolved over time scales ranging from decades to millennia, and it generates research efforts to address those questions by acquiring and analyzing biological and physical records of past climate and environment. Without understanding the natural long-term variability of the Arctic environment, it is impossible to anticipate future conditions or demarcate when human-induced changes have exceeded the range of natural variability. Historical and instrumental environmental records, such as meteorological observations, are too short in duration and too sparse in geographic distribution to provide the needed long-term records of the Arctic environmental system. PARCS scientists develop and apply the research tools needed to produce and analyze records of climatic and environmental change that extend back far beyond the short time period covered by instrumental records.

The present PARCS program arose in 1999 from the amalgamation of the highly successful Greenland Ice Sheet Project (GISP2) and the Paleoclimate of Arctic Lakes and Estuaries (PALE) project. The creation of PARCS was guided by the global change imperatives of both the ARCSS program and the NSF Earth Systems History (ESH) program of the Atmospheric Sciences Division. The founding of PARCS, the creation of its structure, and the identification of a key set of research initiatives arose from a series of community-wide meetings held in 1998 and 1999 and are presented in the document *PARCS: Arctic Paleosciences in the Context of Global Change* (available at http://www.ngdc.noaa.gov/paleo/parcs/parcs.html).

Structure

The PARCS structure consists of a Science Steering Committee (SSC) with two co-chairs selected by community consensus and consultation with ARCSS. The SSC and its co-chairs are drawn from the ranks of PARCS principal investigators. The SSC oversees a science management officer and a data management officer. The latter is responsible for the timely archival of PARCS-generated data, distribution of data to PARCS and ARCSS researchers, and transmission of data to other national and international data centers. The SSC, its co-chairs, and the science and data management officers also foster and maintain ties to relevant international programs such as the International Geosphere–Biosphere Programme's PAGES paleoclimate program and Circumpolar Arctic PaleoEnvironments (CAPE) program. PARCS SSC and organizational activities are funded through grants from ARCSS. PARCS research is funded through several programs at NSF, primarily ARCSS and Arctic Natural Sciences. Most PARCS principal investigators submit grant proposals to the ESH program, where their Arctic-focused investigations are integrated into a broader network of similar research on a global scale.

General Research Imperatives

The PARCS founding document identified five general research imperatives that are fundamental to understanding the long-term functioning of the Arctic system and are of broad relevance to the wider ARCSS and global change communities. These imperatives are:

- Describe and understand the range of natural environmental variability in the Arctic at temporal and spatial scales relevant for anticipating future changes;
- Evaluate the impact and cause of climatic

"surprises" (that is, unexpected, extreme, and/or abrupt events) in Arctic climate system behavior;
- Determine and understand the sensitivity of the Arctic to altered forcings, both natural and anthropogenic;
- Document the history and controlling mechanisms of biogeochemical cycling of nutrients and environmentally sensitive species; and
- Evaluate the realism of state-of-the-art numerical models being used to predict future climate and environmental change on regional to global scales.

To address these research imperatives and to prioritize research needs, a community-wide meeting was held in 2000. Two research foci were developed to concentrate scientific efforts on the most critical questions needed to address the broader imperatives. The two current research foci are:

- Acquisition and analysis of paleoclimatic and paleoenvironmental records, linked with climate model experiments, to determine the causes and consequences of past warm episodes in Arctic climate; and
- Acquisition and analysis of high-temporal-resolution paleoclimatic records to determine the natural modes of climate variability that have impacted the Arctic over the past 2000 years and beyond.

Paleoclimatic and paleoenvironmental data from sources such as the Greenland ice cores, lake sediments, peat and soils, and other natural archives reveal that the Arctic has experienced periods when the climate was warmer than during the past 100 years. These intervals lasted from hundreds to thousands of years and took place during the present interglacial epoch (the Holocene, roughly the last 11,000 years) and during the height of the last interglacial period (some 130,000 years ago). The average summer temperatures during these warming events were 2–5°C higher than the twentieth century average. Such warm periods were caused by natural factors involving variations in the earth's orbital geometry that increased summer insolation at high latitudes. Although none of these past warm periods are a perfect analog for the warming anticipated to result from increased greenhouse gasses, they do provide evidence of the natural range of Arctic thermal variability and crucial insights into how the regional climates, ice and snow cover, permafrost conditions, and flora and fauna of the Arctic respond to prolonged and pronounced warming. Such insights are invaluable in anticipating and attempting to mitigate the future impacts of greenhouse warming.

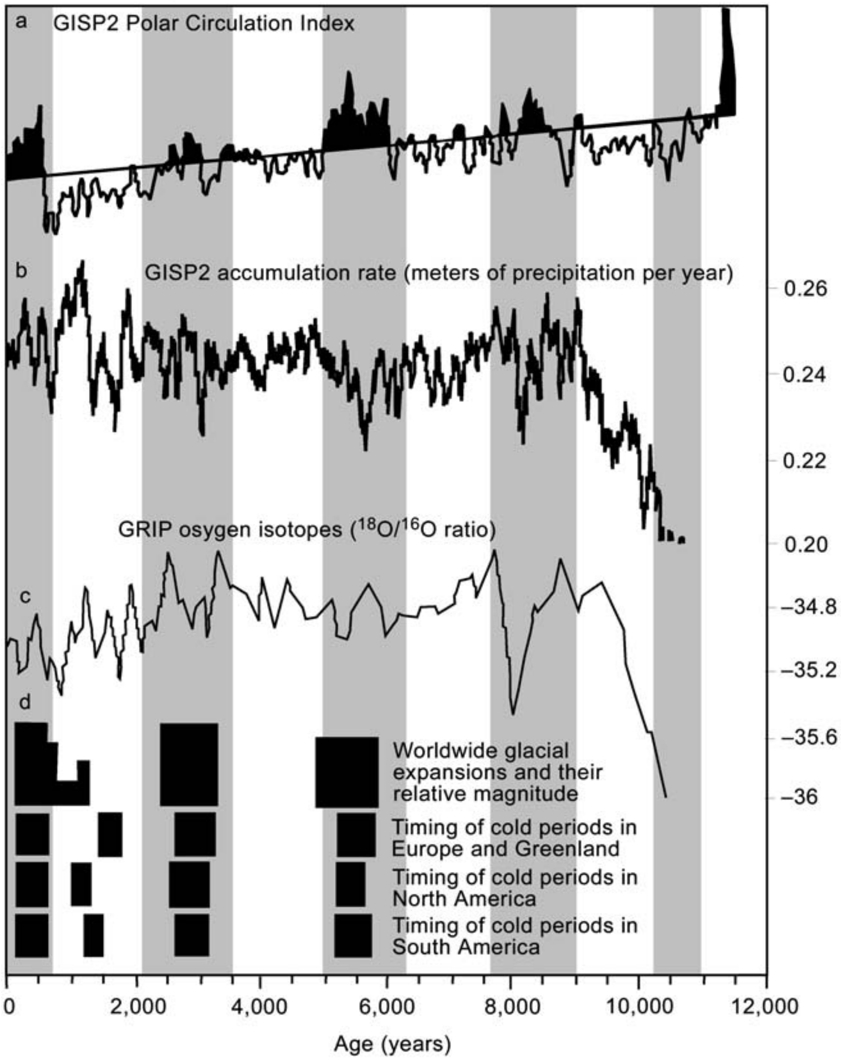
Some records of past climate, such as tree rings, lake sediments, and glacial ice, contain annual banding, allowing reconstruction of highly resolved records that have revealed natural decadal to centennial variations in Arctic climate. While the geographic patterns of these variations and their causes remain topics of intense research, we can anticipate that such natural variability will continue in the future. Understanding this long-term variability is necessary for detecting and predicting the impacts of greenhouse warming and for designing resource management strategies for the Arctic. The natural variability experienced over the past 2000 years provides a benchmark of what we may anticipate in the near future.

Recent and Current Activities

To effectively and efficiently address the two research foci, PARCS recently organized a series of working group meetings to:

- Synthesize existing data on past episodes of Arctic warming and high-frequency modes of Arctic climate variability;
- Combine these records with observational climate data and climate model experiments to help resolve the causes and impacts of past warming and high-frequency variability in climate;
- Determine the gaps in our data sets and theoretical knowledge regarding Arctic warm episodes and high-frequency climate variability; and
- Develop research synergy, strategy, and collaboration both nationally and internationally to fill the existing gaps over the next three to five years.

The first meeting was held in Maine in October 2002 and involved over 20 scientists examining the pronounced warming experienced during the height of the last interglacial period 130,000 years ago. The other two meetings were held simultaneously in Boulder, Colorado, in November 2002 and included over 30 scientists. One working group examined the timing and magnitude of maximum warming around the Arctic during the past 10,000 years, while the other working group synthesized annually resolved records of high-frequency variability in Arctic climate over the past 1000 years and compared



Paleoclimate information from Greenland ice cores. GISP2 PCI (a) is an index of polar atmospheric circulation intensity derived from analyses of major ion concentrations in the core. Rates of snow accumulation at the GISP2 core site (b) varied on decadal to centennial time scales. The relative concentration of the isotope ^{18}O in the Greenland ice cores (c) is related to air temperature, with lower values (top of scale) indicating warmer periods and higher values (bottom of scale) indicating cooler periods. Oxygen isotope analysis of the GISP2 core reveals increasing temperatures at the start of the Holocene and decreasing values after 4000 years ago. Superimposed on this general pattern are a number of shorter-term variations. Increased intensity of polar circulation and decreased snow accumulation on Greenland appear to be correlated with cooling and glacial advance around the globe (d).

this to known patterns of variability from instrumental meteorological records. These meetings spurred on a number of new research proposals and the preparation of five scientific manuscripts on the topics of natural warmth and variability in Arctic climate.

Examples of Recent Research Accomplishments

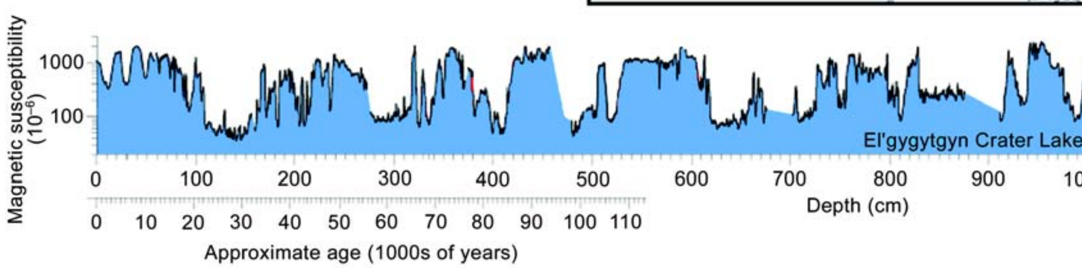
Paleoenvironmental scientists working in the Arctic have made major contributions to understanding Arctic climate dynamics and environmental response that are crucial to current research by a broad spectrum of ARCSS scientists and beyond. A few examples are discussed below.

The GISP2 ice cores from the summit of the Greenland Ice Sheet provided the premier records of regional to global climate change that extend back over 130,000 years. This research has resulted in hundreds of scientific publications that have revolutionized our understanding of climate variability. Oxygen isotope records from the ice cores capture cool and oscillating temperatures during

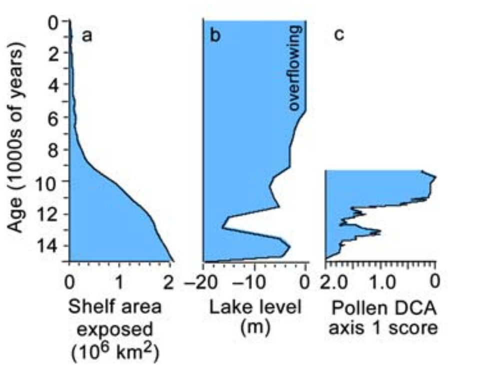
Researchers extracting an ice core at the GISP2 site.

the last glacial period and the general postglacial warming of the Arctic that commenced some 12,000 years ago. The ice cores also reveal natural changes in atmospheric concentrations of greenhouse gasses such as methane and show that the concentration of these gasses was never as high during the past 130,000 years as it is today. The ice cores show that both temperatures and precipitation rates varied abruptly and dramatically on decadal time scales. Thus, the ice cores encapsulate information on both long-term periods of warmth and shorter-term climatic fluctuations that can be compared with records from the Arctic and elsewhere. Aside from information on temperature, hydrologic balance, and atmospheric gasses, detailed chemical analyses of the ice cores have provided insights into phenomena such as past volcanic activity, biomass burning, sea ice extent, and intensity of polar atmospheric circulation.

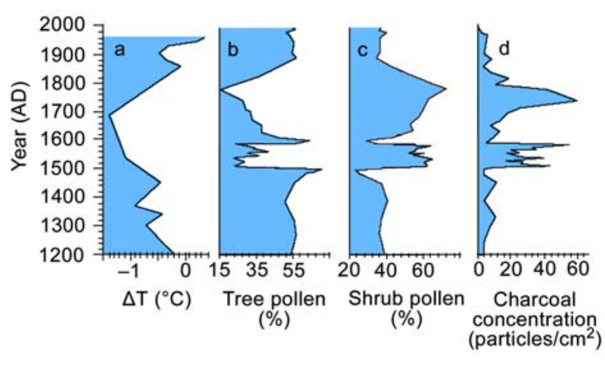
The Beringian region, encompassing Alaska and eastern Siberia, has long been a center of research by the former PALE program, which operated in tandem with the GISP2 project and was merged into current PARCS research. Recent discoveries have provided new insight into the impacts of natural climatic variability on time scales ranging from tens of thousands of years to decades across a region sensitive to fluctuations in the ocean–atmospheric circulation of the North Pacific basin. Unlike other high-latitude land areas, Beringia remained largely free of erosive glacial ice during past global glaciations, so unusually long records of paleoenvironmental changes are preserved. For example, an international team of scientists, including PARCS researchers, recently obtained a 300,000-year record from Lake El'gygytgyn in northeastern Siberia. Distinct fluctuations in a variety of physical and biological parameters indicate pronounced



Long records of paleoenvironmental change from Beringia. The graph shows the magnetic susceptibility of lake sediment from Lake El'gygytgyn, northeastern Siberia during the past two glacial-interglacial cycles. Changes in magnetic susceptibility reflect a complex system of deposition, preservation, and decomposition of organic matter and magnetic minerals.



Millennial-scale paleoenvironmental changes in Alaska. (a) Approximate extent of continental shelf area exposed as shorelines transgressed the Bering and Chukchi platforms, based on eustatic sea-level record and present-day bathymetry. (b) Lake-level changes at Birch Lake, interior Alaska, reflecting changes in effective moisture (Reprinted from Quaternary Research *53, Abbot et al., Lake level reconstructions and paleohydrology of Birch Lake, central Alaska, based on seismic reflection profiles and core transects, 154-166, 2000, with permission from Elsevier). (c) Detrended correspondence analysis (DCA) of pollen assemblages from Nimgun Lake, Ahklun Mountains, southwestern Alaska; DCA axis 1 is correlated with plant taxa associated with dry soils.*

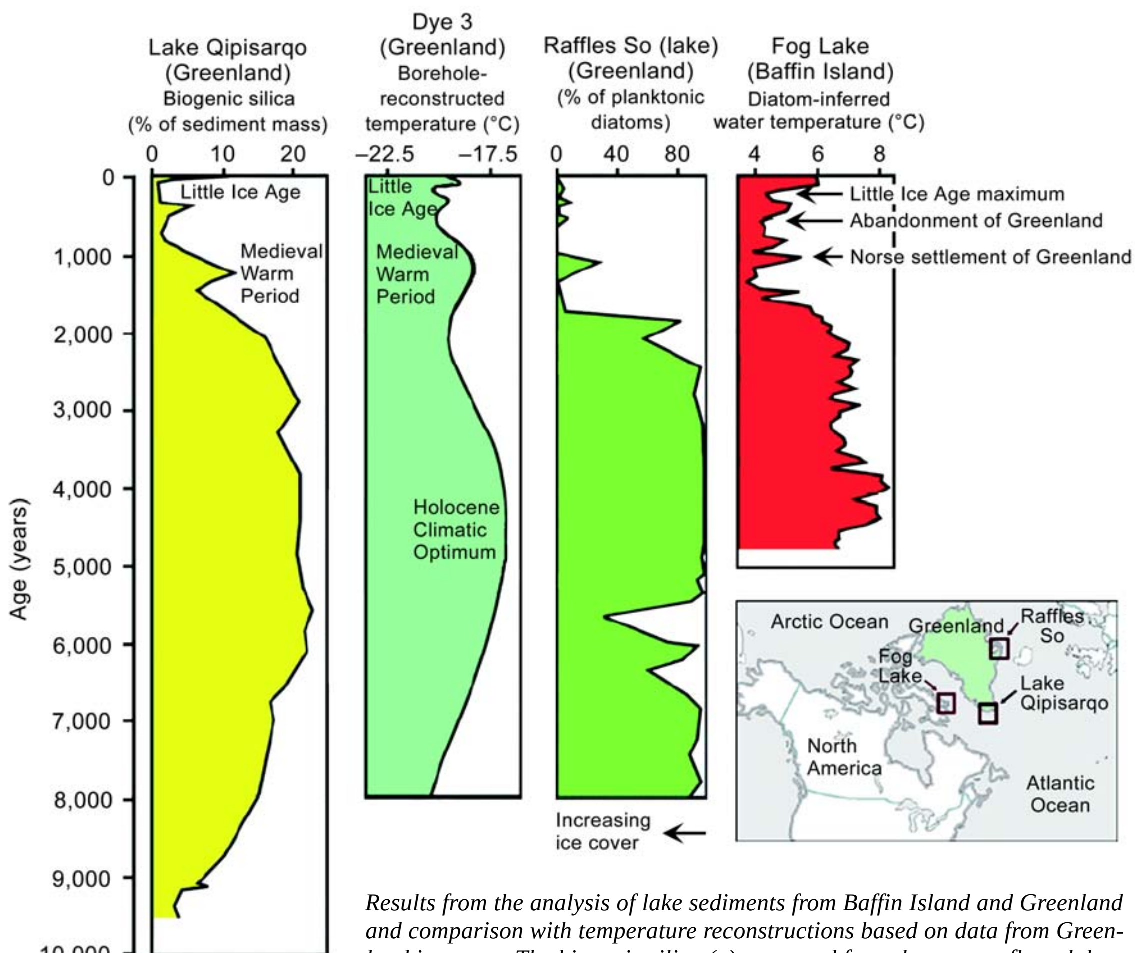


Centennial-scale paleoenvironmental records from Alaska. (a) Temperature change (ΔT) relative to the average for the twentieth century from Farewell Lake, northwestern Alaska Range, Alaska, based on oxygen-isotope analyses of abiotic and ostracode calcite. (b) Tree pollen percentage from Grizzly Lake, Alaska compared to (c) shrub pollen and (d) charcoal concentration. Wetter periods display a pattern of increased tree pollen, decreased shrub pollen, and lower fire frequency, while dryer periods show the opposite pattern.

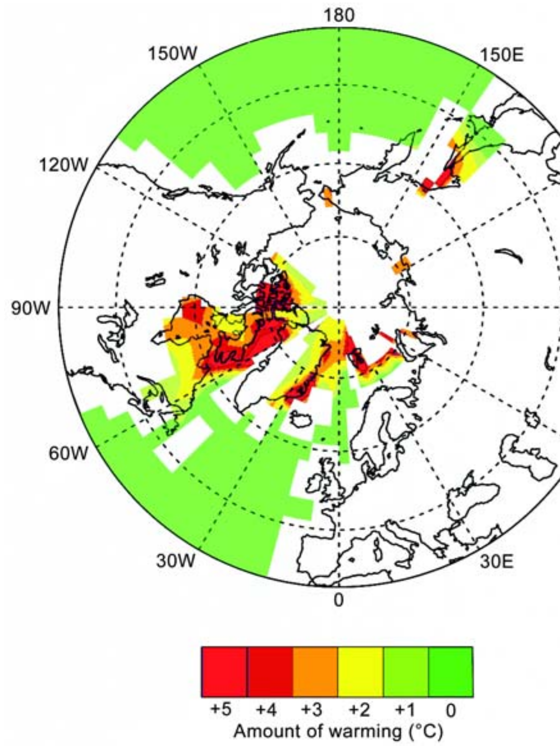
paleoenvironmental changes on millennial time scales. Variations in the magnetic susceptibility of lake sediment can be correlated in detail with oxygen isotope variations in marine sediment and glacier ice from the North Atlantic region, indicating that this is the longest continuous terrestrial record of climatic change from the Arctic.

Climatic fluctuations on centennial time scales during the last glacial-to-interglacial transition (15,000–10,000 years ago) are also now clearly documented in Alaska, where they occurred synchronously with rapid climate changes known from other high-latitude regions, suggesting a tightly coupled Arctic system. These climatic changes, along with the rise of sea level over the continental shelves of the Bering and Chukchi Seas, dramatically altered the moisture balance of terrestrial and aquatic systems across Beringia. All physical and biological aspects of the Arctic system were impacted by the dramatic climatic changes of the last glacial–interglacial transition, including the limnology of lakes, the composition of terrestrial vegetation, and the rates of land surface processes. For example, pollen data indicate that tundra plants responded rapidly to these abrupt events, indicating its sensitivity to climatic change.

Evidence for decadal-scale climatic fluctuations over the past two millennia has recently been revealed in southern Alaska. The climatic changes were more subtle than during the last



Results from the analysis of lake sediments from Baffin Island and Greenland and comparison with temperature reconstructions based on data from Greenland ice cores. The biogenic silica (a) measured from the cores reflects lake productivity and is positively related with summer temperatures (b). The amounts of planktonic diatoms (diatoms are microscopic algae that produce exoskeletons made of silica) relate to the persistence of ice cover on the lakes throughout the year (c). Changes in the diatom flora have been used to reconstruct temperature changes at Fog Lake, Baffin Island (d). The evidence indicates that warm conditions persisted during the early to mid-Holocene and that climate has become cooler and more variable during the past 4000 years. These variations permitted Norse settlement of Greenland during a warmer period, and forced abandonment when the climate cooled. Some lakes also show a pronounced increase in warmth during the twentieth century. (Reprinted from Quaternary Research *58, Kaplan et al., Holocene environmental variability in southern Greenland inferred from lake sediments, 149-159, 2002, with permission from Elsevier.)*



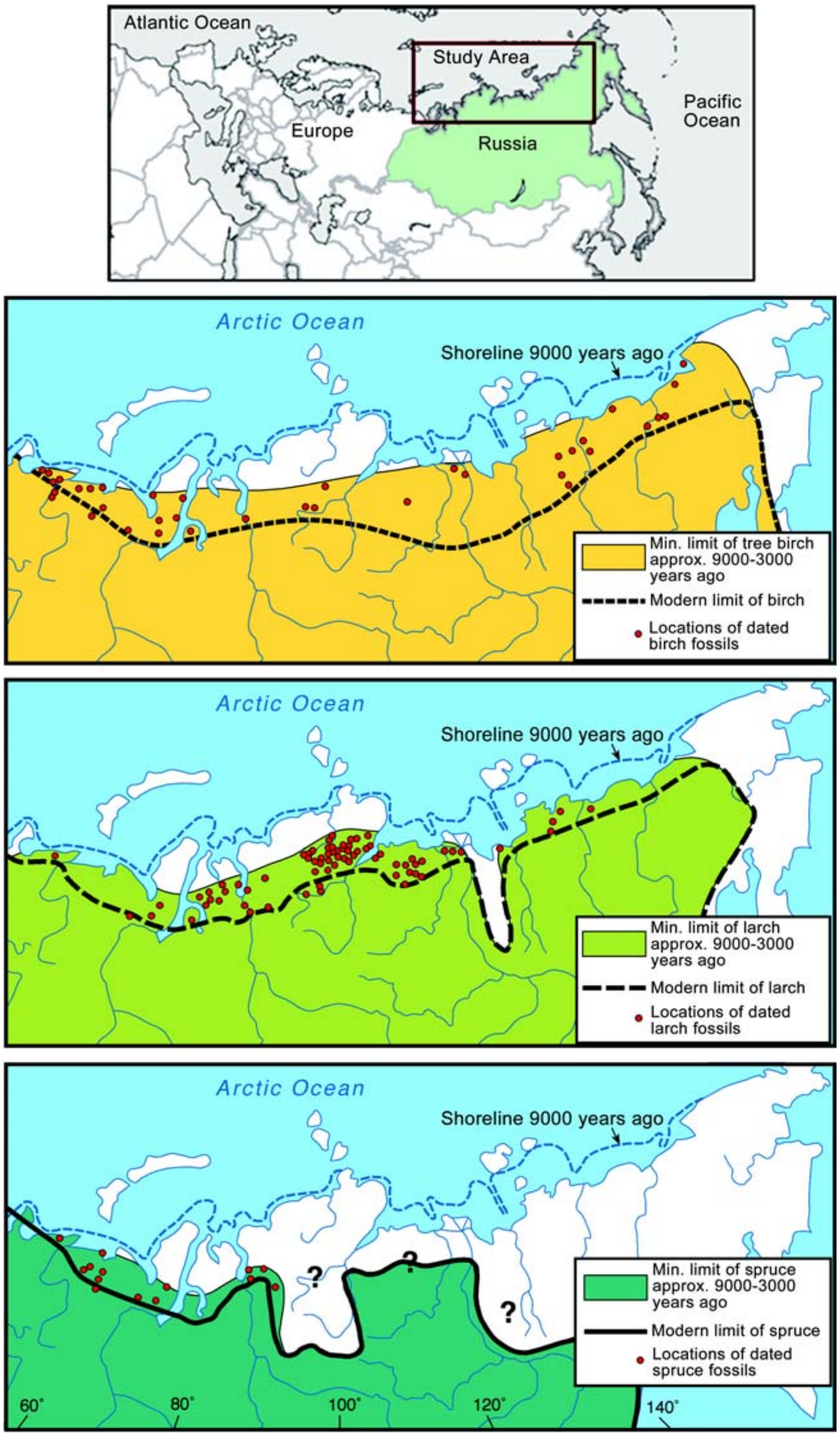
The effect of reducing the sea ice cover in a general circulation model. The map shows the amount of wintertime (December, January, February) warming caused by a 25% reduction in sea ice area during the winter, compared to the present-day extent of sea-ice. This reduction in sea-ice extent approximates the inferred middle-Holocene thermal maximum. This simulation shows warming of up to 5ºC concentrated over the northwest North Atlantic region. In contrast, the Pacific sector shows only a small response, despite equivalent reduction in sea ice in the North Atlantic. (Reprinted from Quaternary Science Reviews *22, Smith et al., Sensitivity of the Northern Hemisphere climate system to extreme changes in Holocene Arctic sea ice, 645-658, 2003, with permission from Elsevier.)*

interglacial–glacial transition; nonetheless, temperature fluctuations on the order of 1–2°C induced major changes in treeline vegetation, moisture balance, and glacial extent.

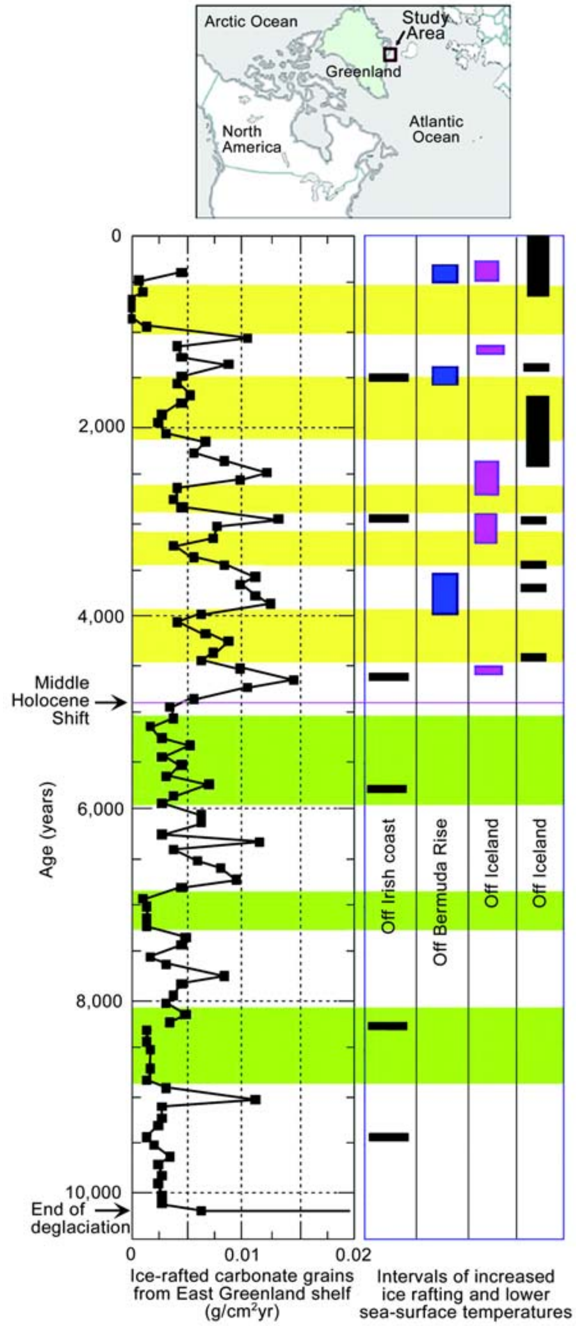
In eastern North America recent PARCS studies in the Baffin Island and southern Greenland region have provided key insights into both long-term climatic variability and the impact of such variability on the early Norse settlement and subsequent abandonment of Greenland. Sediment cores from a number of lakes have been studied for biogenic silica content, magnetic susceptibility, and diatom content to reconstruct past lake productivity and temperature. These records, which in some cases extend back over 9000 years, show that summers cooled by perhaps 2°C in the past 5000–2000 years. The lake sediment records compare well with paleotemperature estimates from the Greenland ice cores. This general cooling appears related to decreased summer insolation caused by natural changes in the earth's orbit. In addition, the last 2000 years are typified by increased climatic instability compared to previous millennia. Norse settlement in Greenland (approximately A.D. 985) coincided with an unusually warm interval within this period of climatic instability, while the abandonment (approximately A.D. 1350–1550) coincided largely with decreasing temperatures. Where temporal resolution is sufficient, the records depict considerable and rapid warming and related changes in the later twentieth century.

PARCS scientists have worked in close collaboration with researchers outside of North America to examine questions of past environmental change in all regions of the Arctic. Such international efforts are essential to understanding the Arctic as an integrated and coherent system from a circum-Arctic perspective. These efforts occur at a programmatic level, with PARCS participation in the IGBP's CircumArctic PaleoEnvironments (CAPE) program, and at a collaborative research level involving individual principal investigators from several countries. As part of this participation, PARCS was a major contributor to two recent CAPE meetings. The first, in 1997, addressed changes in Holocene climate around the Arctic by synthesizing paleoenvironmental conditions and comparing the results of these syntheses to climate model output (http://www.ngdc.noaa.gov/ paleo/cape/index.html). The second, in 2000, focused on sea ice and its role in the climate system. Over 50 researchers from 10 countries met in Iceland to review sea ice variability as reconstructed from the paleoenvironmental records and investigated in numerical models (http://www. ngdc.noaa.gov/paleo/cape/index.html). Sensitivity experiments were conducted for this meeting to evaluate the effect of sea ice extent on circum-Arctic temperature. By reducing the extent of sea ice from the present-day amount to an estimated minimum cover of the Holocene, the Atmospheric Global Climate Model at the National Center for Atmospheric Research (NCAR) showed warming effects concentrated in the North Atlantic region. Similarly, by increasing sea ice cover, the model simulated heightened effects in the North Atlantic.

Other examples of PARCS cooperative and integrative research with workers from the international community include collaborations with European colleagues on ocean circulation changes around the East Greenland/Iceland region, and reconstructions of northern treeline on the Eurasian continent. Stumps and other well-preserved remains of former trees from the Kola and Yamal Peninsulas of Russia collected by PARCS researchers have been combined with similar evidence collected by international and Russian research teams to reconstruct the postglacial history of the northern boreal forest treeline across



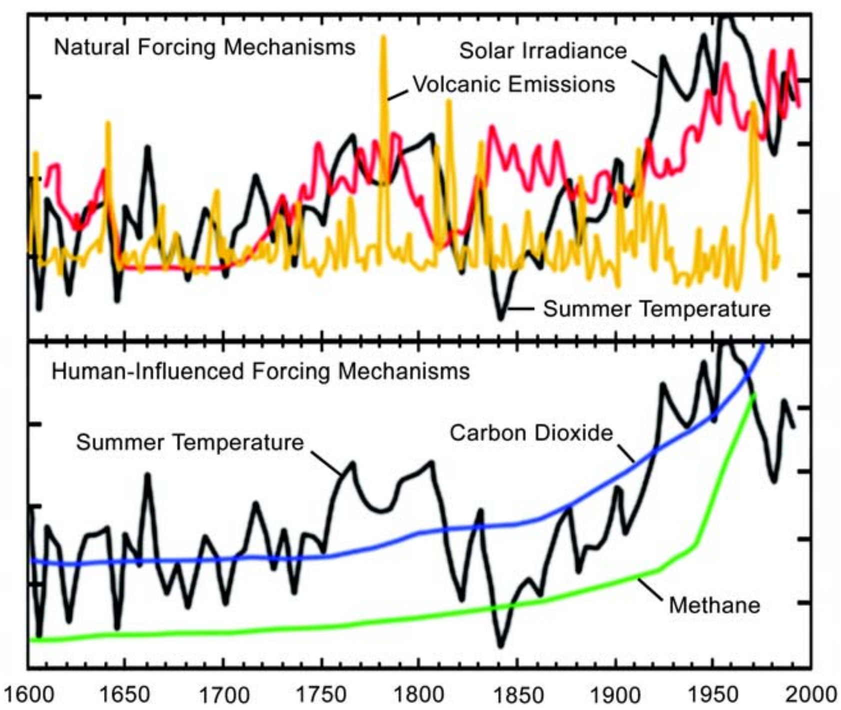
The collection of preserved stumps and other remains of trees from and beyond the modern treeline in northern Eurasia shows that the northern boreal forest extended as far north as the modern Arctic Ocean coastline between approximately 9000 and 3000 years ago and then retreated to its modern position. The initial development of the northern boreal forest and its northward expansion appears related to increased summer insolation and increased temperatures in the Nordic seas during the early to mid-Holocene. As insolation declined and the seas cooled, the treeline retreated. (Reprinted from Quaternary Research *53, MacDonald et al., Holocene treeline history and climate change across northern Eurasia, 302-311, 2000, with permission from Elsevier.)*



The flux of detrital carbonate measured in an ocean core from the East Greenland Shelf. The peaks in carbonate flux above the middle Holocene shift (white horizontal bars) are interpreted as sea-surface cooling episodes. These correspond with peaks in sea salt sodium and with lower sea-surface temperatures recorded in cores off Ireland, on the Bermuda rise, and off Iceland. Before the middle Holocene shift, intervals of low carbonate flux in the core correspond with intervals of elevated sea salt sodium, and the carbonate flux peaks do not correspond to coolings.

Eurasia. This study showed that the northern forest became established between 11,000 and 10,000 years ago across all of Eurasia except the Kola Peninsula, where it was delayed by about 1000 years. During the period 9000–3000 years ago the northern forest of Eurasia expanded significantly north of its modern position and reached as far as the present Arctic Ocean coastline in places. The retreat of the forest was synchronous across Eurasia, occurring at about 3000 years ago. The development and northward expansion of forest appears to be related to increasing summer insolation in the early Holocene due to natural variations in the earth's orbit and the warming of the Nordic seas. In addition, the changes in albedo (the reflection of solar radiation back into space from the earth) and heat transfer caused by the advance of the forest itself may have served as a positive feedback promoting the northward advance of trees. Decreasing insolation and ocean cooling generated the retreat of treeline in the later Holocene.

In the East Greenland/Iceland Shelf region of the North Atlantic Ocean, PARCS research has led to a greater understanding of ocean circulation dynamics during the past 5000 years. Marine and estuarine records from the region show that sea surface temperatures fluctuated with the amount of polar water present in the East Greenland Current during the past 4700 years. These temperature cycles correlate well with temperature fluctuations recorded in an ice core from Greenland and with cyclic changes in marine cores from the North Atlantic. Because the East Greenland Shelf is proximal to the source of polar water, it appears that these sites are more sensitive to changes and capture higher-frequency oscillations as well.



A circum-Arctic synthesis of summer temperature indicators from 29 records, including tree rings, lake and marine sediment cores, and ice cores, shows that the twentieth century has been characterized by an unusually prolonged period of high temperatures that appears unprecedented over the past 400 years. Some of the warming is likely related to natural variations in solar output and volcanic activity, but the magnitude and duration of the warming also suggests the impact of greenhouse gases on the Arctic climate.

One of PARCS' primary goals is to integrate paleoenvironmental records to provide comprehensive reconstruction and analysis of climatic change. To facilitate these syntheses and to provide a useful resource to the community, PARCS has developed an online "atlas" (http://www.ngdc.noaa.gov/paleo/parcs/atlas.html), which was initiated by the PALE program. The atlas displays the results of PARCS synthetic research and provides access to the primary data, the synthesized data, and the methods of synthesis. PARCS will continue to expand the atlas with the addition of data derived from its current two research foci. Another example of this approach from the PARCS community is the Alaska PaleoGlacial Atlas (http://instaar.colorado.edu/QGISL/ak_paleoglacier_atlas/), which provides an accessible, geospatial database of present and former glacier extents across Alaska.

In another important synthesis and analysis effort, PARCS researchers collated paleoclimatic records of summer temperatures from a variety of sources, including tree rings, lake sediments, and ice cores, to produce a circum-Arctic record of climatic change for the past 400 years. This reconstruction provided clear evidence that the magnitude and duration of warming in the Arctic during the twentieth century was unprecedented over the past 400 years. The study also concluded that, although much of this warming could be explained by natural forces, such as variability in solar radiation and volcanic activity, a significant portion is due to the impact of anthropogenically increased greenhouse gas concentrations.

These few examples of PARCS research demonstrate the considerable substantive, methodological, temporal, and geographical scope of the program. Despite the broad range of research topics and field areas, three common themes arise, each related to understanding the Arctic system and its response to future global warming.

PARCS scientists Al Werner, Darrell Kaufman, and students recover a lake sediment core from a floating platform on Sunday Lake, southwestern Alaska.

First, the Arctic system undergoes significant climatic and environmental variability at time scales ranging from annual to millennial; attempts to understand the biological and physical systems of the Arctic must consider this background of variability. Second, many of the natural forces that drive climate variability—some of which we understand, some of which we are still unraveling—will continue to impact the Arctic in the future and, unless their causes, periodicities, and impacts are understood, will obfuscate the detection of anthropogenic changes and confound efforts to mitigate those changes. Finally, an increasing body of evidence from paleoclimatic records attests to the unusual warmth in the Arctic during the twentieth century that appears to be the product of increased greenhouse warming.

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