Arctic Environmental Change of the Last Four Centuries

J. Overpeck,* K. Hughen, D. Hardy, R. Bradley, R. Case, M. Douglas, B. Finney, K. Gajewski, G. Jacoby, A. Jennings, S. Lamoureux, A. Lasca, G. MacDonald, J. Moore, M. Retelle, S. Smith, A. Wolfe, G. Zielinski

A compilation of paleoclimate records from lake sediments, trees, glaciers, and marine sediments provides a view of circum-Arctic environmental variability over the last 400 years. From 1840 to the mid-20th century, the Arctic warmed to the highest temperatures in four centuries. This warming ended the Little Ice Age in the Arctic and has caused retreats of glaciers, melting of permafrost and sea ice, and alteration of terrestrial and lake ecosystems. Although warming, particularly after 1920, was likely caused by increases in atmospheric trace gases, the initiation of the warming in the mid-19th century suggests that increased solar irradiance, decreased volcanic activity, and feedbacks internal to the climate system played roles.

Global climate change is likely amplified in the Arctic by several positive feedbacks, including ice and snow melting that decreases surface albedo, atmospheric stability that traps temperature anomalies near the surface, and cloud dynamics that magnify change (1–3). The Arctic, in turn, influences climate change at lower latitudes through changes in river runoff and effects on global thermohaline circulation, impacts on atmospheric circulation, and modulation of atmospheric CO_2 and CH_4 concentrations (1, 4). Although the Arctic is now one of the least disturbed regions on Earth, it may also be one of the most susceptible to both natural and human-induced climate change.

The instrumental record of Arctic climate change is brief and geographically sparse. The few records that extend back to the beginning of the 20th century suggest that the Arctic has warmed by about 0.6°C since that time, with peak temperatures (1.2°C more than in 1910) around 1945 (2). Although some areas of the Arctic have cooled recently—for example, as a result of dynamics within the North Atlantic (5)—the observed 20th-century Arctic-average temperature increase exceeds that of the hemisphere as a whole. The record is thus consistent with amplification of climate change through snow/ice radiation and other feedbacks (6, 7).

In this article, we use the paleoenvironmental record to assess the climate events of this century from the perspective of the last four centuries. We build on previous work (8–10) by compiling a variety of complementary paleoenvironmental indicators of climate from around the entire Arctic. This perspective permits the visualization of natural subdecadal to century-scale climate variability in the circum-Arctic region and allows us to examine the role that natural forcing mechanisms play in driving Arctic climate. Given the growing focus on Arctic environmental dynamics (4), we also examine the centuries-long paleoenvironmental perspective to determine whether the climate changes we infer have resulted in changes to the natural Arctic ecosystem.

The Paleoclimate Perspective

Proxy data from lakes, wetlands, ice cores, and marine sources demonstrate that Arctic

J. Overpeck is at the National Oceanographic and Atmospheric Administration (NOAA)–National Geophysical Data Center (NGDC) Paleoclimatology Program, 325 Broadway, Boulder, CO 80303, USA, and Institute of Arctic and Alpine Research (INSTAAR), University of Colorado, Boulder, CO 80309, USA. K. Hughen, A. Jennings, J. Moore, and A. Wolfe are at INSTAAR, University of Colorado, Boulder, CO 80309, USA. D. Hardy, R. Bradley, and S. Smith are in the Department of Geosciences, University of Massachusetts, Amherst, MA 01003, USA. R. Case and G. MacDonald are in the Department of Geography, University of California, Los Angeles, CA 90095, USA. M. Douglas is in the Department of Geology, University of Toronto, Toronto, Ontario M5S 3B1, Canada. B. Finney is at the Institute of Marine Science, University of Alaska, Fairbanks, AK 99775, USA. K. Gajewski is in the Department of Geography, University of Ottawa, Ottawa, Ontario K1N 6N5, Canada. G. Jacoby is at the Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA. S. Lamoureux is in the Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta T6G 2H3, Canada. A. Lasca and M. Retelle are in the Geology Department, Bates College, Lewiston, ME 04204, USA. G. Zielinski is at the Climate Change Research Center, University of New Hampshire, Durham, NH 03824, USA.

*To whom correspondence should be addressed. E-mail: jto@ngdc.noaa.gov

Table 1. Paleoclimate site information.

Map no.	Site name	Proxy type	Source
1	Svalbard Ice Core	Percent summer melt	(69)
2	Tornetrask	Tree ring widths	(22, 28)
3	Polar Urals	Tree ring widths	(22, 70)
4	Lena River	Tree ring widths	This article
5	Kolyma (Jack London Lake)	Tree ring widths	(71)
6	Site 412	Tree ring widths	(8, 9)
7	Arrigetch Peaks	Tree ring widths	(8, 9)
8	Dune Lake	^{13}C isotopes	This article
9	Sheenjek	Tree ring widths	(8, 9)
10	TTHH	Tree ring widths	(8, 9)
11	Eagle Fecal	Tree ring widths	(8, 9)
12	Franklin Mountains	Tree ring widths	(8, 9)
13	MacKenzie Mountains	Tree ring widths	(8, 9)
14	Coppermine	Tree ring widths	(8, 9)
15	Hornby Cabin	Tree ring widths	(8, 9)
16	Churchill	Tree ring widths	(8, 9)
17	Lake DV09	Varve thicknesses	(63)
18	Devon Island Ice Core	Percent summer melt	(27)
19	Lake C2	Varve thicknesses	(21)
20	Lake C3	Varve thicknesses	(65)
21	Lake Tuborg	Varve thicknesses	This article
22	Castle Peninsula	Tree ring widths	(8, 9)
23	Kuujuaq	Tree ring widths	(8)
24	Upper Soper Lake	Dark lamination thicknesses	(20)
25	Okak	Tree ring widths	This article
26	Salt Water Pond	Tree ring widths	(72)
27	Donard Lake	Varve thicknesses	This article
28	South Greenland Ice Core	Percent summer melt	(10, 73)
29	Nansen Fjord	Fossil foraminifera	(29)

interannual to century-scale environmental variability of the last 400 years is superimposed on longer-term changes of the Holocene (the last 10,000 years). Most of the Arctic experienced summers warmer (1° to 2°C) than today during the early to middle Holocene, but the timing of this Milankovitch-driven warmth (that is, warmth resulting from greater summer insolation) differed geographically because of the effects of local sea surface temperatures (SSTs) and land-ice cover (*11–13*). Decreases in summer insolation—perhaps coupled with other, more abrupt changes in climate forcing—led to successively cooler summers in the late Holocene; this trend culminated in the Little Ice Age, a period that began before 1600 (*14–17*) and evidently ended sometime in the last century (*11, 12, 14*).

Our compilation of paleoclimate records provides a 400-year view of Arctic variability that is superimposed on lower frequency Holocene trends. This view is based (*18*) on more than 20 records from the North American Arctic and substantially fewer records spread out across the Eurasian Arctic (Table 1 and Figs. 1 and 2). Although covariation among continental records in Alaska and western Canada (Fig. 2A) suggests that the Eurasian records may be broadly representative, a need for caution is highlighted by the differences among records from the eastern Canadian Arctic and Greenland (Fig. 2B), a region marked by geographic variability even in the instrumental period (*2*). Thus, although our compilation provides a much improved basis for understanding the patterns and causes of interannual to century-scale environmental variability in the circum-Arctic, future work will be needed to increase data coverage, particularly in Eurasia.

The most notable pattern of change revealed by most records across the Arctic is the near ubiquitous transition from anomalously cold conditions of the 19th century to peak warm conditions of the 20th century. This event can be seen even more clearly in a new proxy record of average Arctic temperature change over the last 400 years (*19*) (Fig. 3). Where quantitative estimates are available, it appears that the 19th- to 20th-century warming was 1° to 3°C locally (*8, 15, 20–25*) and averaged about 1.5°C across the Arctic. We thus confirm that the 20th-century warming observed in the instrumental record was only part of a more circum-Arctic climate event that began in the mid-19th century and marked the end of the Little Ice Age in the Arctic (*8, 26, 27*).

Another striking aspect of Arctic temperature change over the last 400 years is that most of the Arctic experienced cooling in the first part of the 19th century, resulting in the coldest temperatures of the Little Ice Age. In addition, although much of the Arctic was colder than today during parts of the 17th century, several of the records show temperatures nearly as warm as today during the 18th century (*9*). Arctic climate change before 1800 was more regional in nature than after this time. For example, many sites around the Arctic were warmer at some time between 1700 and 1820 than they were later in the 19th century, but the timing and duration of this warmth varied from region to region, as did the preceding 17th-century period of generally colder conditions.

The annually dated record of Arctic climate variability encompassing the last 1000 years has less spatial coverage than does the multiproxy record of the last 400 years. Sediment, ice core, historical, and tree ring data for this earlier period indicate that although Arctic summers of the 20th century were generally the warmest of the last 400 years, they may not have been the warmest of the last millennium (*21, 28–30*). The few time series of climate change spanning the last millennium also suggest that the Arctic was not anomalously warm throughout the so-called Medieval Warm Period of the 9th to 14th centuries (*31*).

Climate Forcing Mechanisms

The paleoclimate record of the Arctic reveals large variability over all of the last 400 years. Natural variability in most regions was as large before the 20th-century buildup of atmospheric trace gases as afterward (Figs. 2 and 3). Natural climate forcing mechanisms must therefore be considered before attributing some or all of the recent changes in the Arctic to human influences. The similarities of our new Arctic climate reconstruction (Fig. 3) to earlier reconstructions for the Northern Hemisphere (*8, 10*), and the coincidence of high inferred solar irradiance and warm Arctic temperatures in both the 18th and 20th centuries, suggest that solar forcing played a role (*32–36*). The strong recovery of high temperatures after the 1840s may also have been a partial response to high solar irradiance at that time. On the other hand, the lack of a distinct prolonged cold period associated with the 17th- to early 18th-century Maunder sunspot minimum period (*34*) argues against a dominant role for solar forcing over the past 400 years, as does the observation that changes in solar irradiance evidently did not lead climate warming into the 20th century.

Comparison of our temperature record with an Arctic volcanic sulfate record recently developed from the Greenland Ice
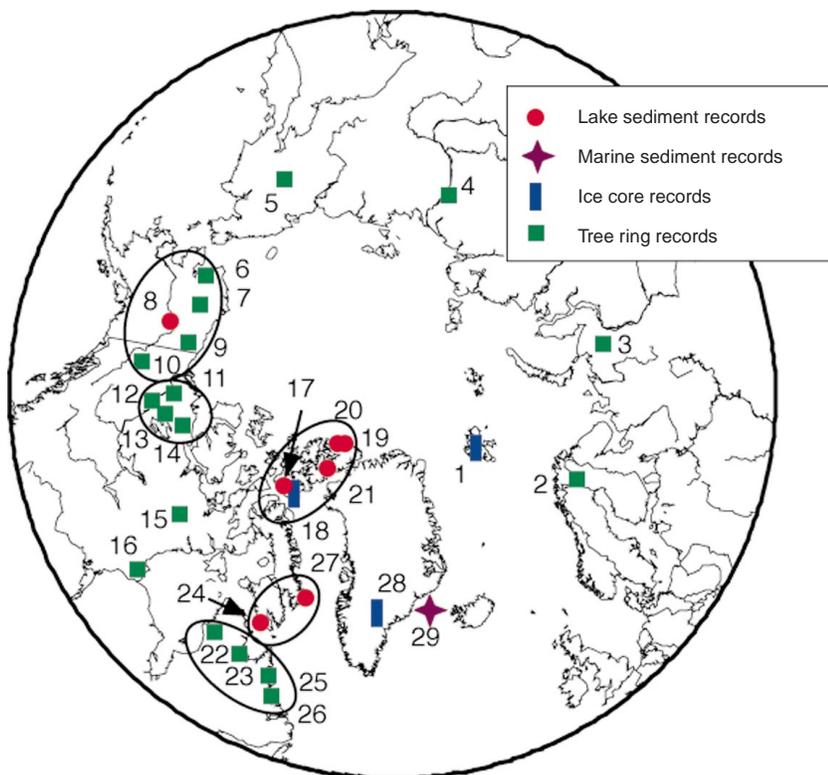

Fig. 1. Map showing locations of proxy climate records used in this study and listed in Table 1. Circles around groups of sites indicate the groups averaged before calculating the Arctic-wide temperature average. Isolated single sites not circled were averaged directly into the Arctic-wide series (*19*).

Sheet Project Two (GISP2) ice core (*37, 38*) indicates that most peaks in reconstructed atmospheric volcanic sulfate loading correspond to mean circum-Arctic cooling (Fig. 3). The repeated coincidence of high sulfate loading with the onset of Arctic cold events suggests that eruptions entrain positive ocean feedbacks capable of enhancing and prolonging Arctic cooling. For example, the anomalous early 19th-century period of frequent large sulfur-producing eruptions seems to have helped precipitate the drop into the coolest period of the Arctic Little Ice Age (*37, 39*). These findings agree with earlier evidence for volcanic forcing of Arctic temperatures over the last 100 years (*40*), as well as the more regional 200-year record of volcano-climate linkages for sub-Arctic North America (*41*) and earlier assertions that volcanic activity plays a role in modulating the climate of the Northern Hemisphere in general (*10, 42*). It is difficult to attribute the lack of a clear solar-climate correspondence, particularly during the period of the Maunder sunspot minimum (1650 to 1710), to counterbalancing by volcanic forcing. However, it is quite likely that the period of uncommonly low volcanic activity from 1935 to 1960

may have contributed to the peak Arctic summer temperatures at this time (*43, 44*), reducing the implied potential sensitivity of the climate system to solar forcing during this same period (*36*).

Variability internal to Earth's climate system, particularly in the ocean's thermohaline circulation, also can modulate climate over decades to centuries (*45, 46*). The variability evident in our 400-year Arctic compilation, although an order of magnitude smaller in scale than that driven by internal climate system processes over the last deglaciation (*47*), may relate to decadal-scale fluctuations in the state of the North Atlantic Oscillation (NAO) or to the transport of heat northward by thermohaline circulation. Such a forcing mechanism would leave a diagnostic pattern most obvious in, and downwind of, the North Atlantic (*46, 48*). The Nansen Fjord record from southeast Greenland (Fig. 2B), a proxy for North Atlantic SSTs (*49*), indicates that the range of North Atlantic variability over the past 400 years exceeds that of the recent instrumental record, and that the last century was marked by warming in the North Atlantic. However, comparison of this long proxy record of North Atlantic

SSTs with terrestrial temperature proxies from sites across the Arctic (Fig. 2) does not reveal clear evidence for strong Atlantic forcing of Arctic climate. The full role of NAO and thermohaline forcing of Arctic climate remains to be evaluated as more multicentury time series from the circum–North Atlantic region become available.

Half of the post-1840 warming (about 0.75°C) took place from 1840 to 1920, during a period in which concentrations of atmospheric CO_2 and CH_4 increased only by about 20 ppm and 200 parts per billion by volume (ppbv), respectively (Fig. 3). Given the current best estimates of climate sensitivity to trace-gas forcing [1.5° to 4.5° global mean warming for a 280-ppm increase in CO_2, and less for a doubling of CH_4 (*6, 46*)], trace-gas forcing alone might be able to explain only a small part (0.1° to 0.4°C) of the pre-1920 warming. The first half of the unprecedented 19th- to 20th-century increase in Arctic temperatures appears to be a natural readjustment as volcanic forcing weakened, and irradiance (and, to a lesser extent, greenhouse gases) increased, between 1840 and 1920. After 1920, both anomalously high solar irradiance and low volcanic aerosol loading likely

Fig. 2. (**A**) Standardized 400-year proxy climate records reflecting surface air temperature for sites from Arctic Europe east to western Canada (Fig. 1 and Table 1) (*18*). Red indicates temperatures greater than one standard deviation warmer than average for the reference period (1901–1960), whereas dark blue indicates at least one standard deviation colder than this average. (**B**) Same as (A) but for sites in Canada east to Greenland. All series are presented as 5-year averages except for sites 8 and 29, which are plotted at their original lower resolution. All time series represent surface air temperature except for site 29, which represents SST. All time series shown will be available at http://www.ngdc.noaa.gov/paleo/paleo.html.
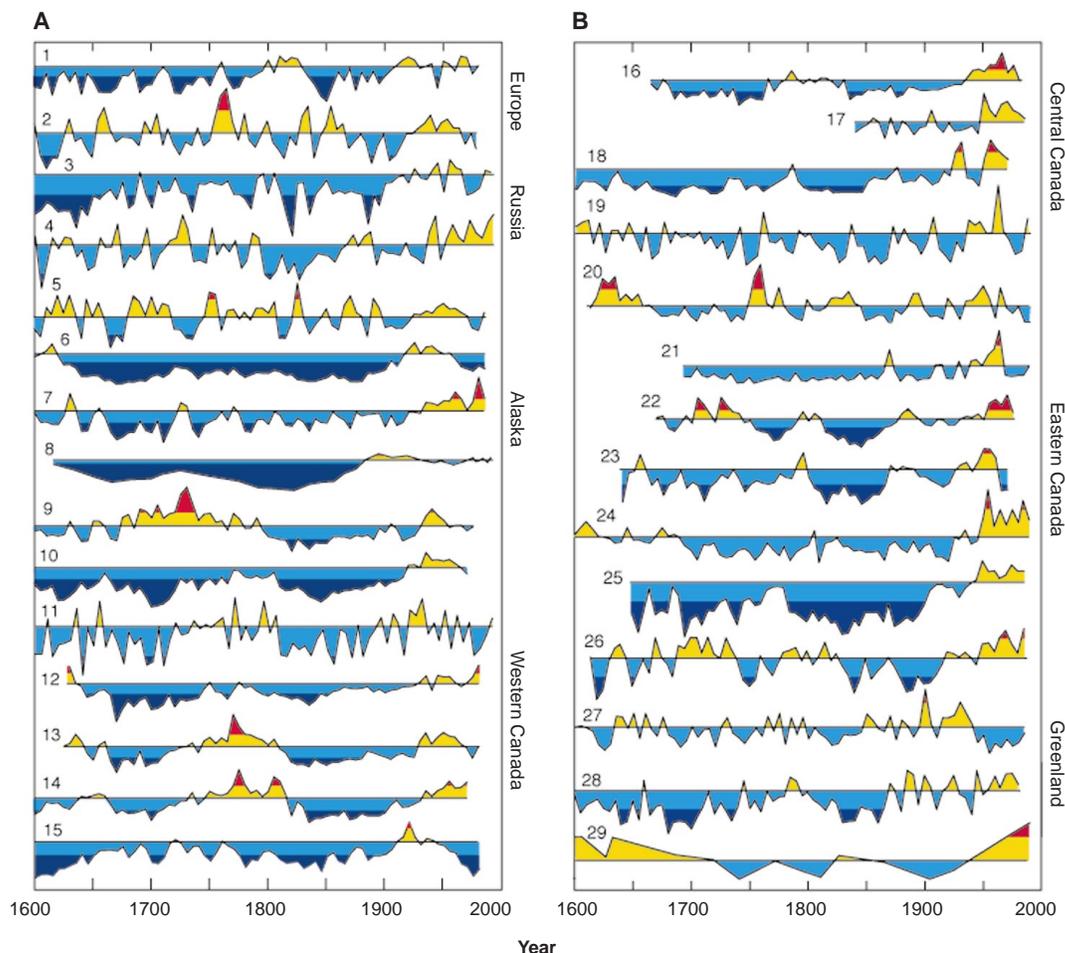
continued to influence Arctic climate, but exponentially increasing atmospheric trace-gas concentrations probably played an increasingly dominant role (36). More recently, the observed slowdown in warming from 1950 to 1970 (2) (Fig. 3) may have been influenced by the increase in Arctic tropospheric aerosols that occurred after 1950 (6, 50).

The Response to Arctic Climate Variability

With the emergence of a coherent picture of Arctic climate change over the last several centuries comes the realization that interannual to century-scale Arctic climate variability is the norm. This variability has affected many aspects of the Arctic environment. The primary implication is that today's Arctic cryosphere (glaciers and frozen ground) and biosphere (terrestrial, lacustrine, and marine) are not at steady state; they have changed and will continue to change in response to an evolving Arctic climate.

An obvious impact of recent climate change is the widespread retreat of glaciers

throughout the Arctic over the last century (51). On Baffin Island, retreats in glacial equilibrium-line altitudes (52) coincided with the 19th- to 20th-century warming observed in sediment, tree ring, and ice core records. Evidence for similarly large post–Little Ice Age glacial retreats can also be found farther east in Greenland, Iceland, Spitsbergen, and Scandinavia (14, 53), as well as to the north on Devon Island (27) and to the west in Alaska (25). Although it has been suggested that climate warming may be accompanied by an increase in snowfall sufficient to expand ice sheets (54), it appears probable that most Arctic glaciers will continue to melt if the Arctic continues to warm, as forecast by model simulations of the climate response to increasing greenhouse gas concentrations (6, 55). This inference may not apply to the Greenland Ice Sheet, whose modern mass balance is poorly known (51).

High-latitude permafrost conditions have also changed during the last 200 years. Where available (that is, North America), ground temperature records reconstructed from borehole temperature logs support the notion that large-scale warming has oc-

curred since the 19th century, but these records also indicate that high-latitude permafrost conditions have changed, and are likely to continue changing, as the Arctic warms (24). This future change in frozen ground will, in turn, likely affect construction, transportation, hydrology, ecology, and trace-gas fluxes in the Arctic (4).

The paleoenvironmental record of the last four centuries supports recent ecological studies (56) and indicates that, even if climate warming takes place at the low end of the range suggested by climate model simulations of the next 100 years (6), such warming is capable of driving changes in the Arctic biosphere that will likely rival any changes driven by nonclimate processes, including human land use. Tree growth correlates positively with temperature in many parts of the Arctic (Fig. 2), just as Arctic tree growth forms and fire disturbance regimes change with climate (57). Studies of recent seedling establishment and viability north of the present treeline (58, 59), together with evidence from annually dated fossil pollen records, suggest that Arctic plant species abundances and ranges have varied in response to varying temperatures (60).

The limnology of Arctic lakes will also likely continue to respond to climate change (61). Sediments from shallow ponds and lakes on Ellesmere (62) (Fig. 4) and Devon islands (63) show that warming since the mid-19th century caused acute shifts in diatom algal floras, including the recent establishment in some lakes of diatom populations previously too light-limited by perennial ice for their subsistence. Freshwater algae are sensitive recorders of environmental change and may also be harbingers of more profound ecological reorganizations, as changes in their populations may influence the structure of higher trophic levels. The paleoenvironmental record of the Arctic makes it clear that we should expect changes to occur in both terrestrial and aquatic ecosystems if the present Arctic warming persists.

Finally, our records confirm the hypothesis, originally based on a single high-Arctic ice core record of summer temperature variations (27), that the repeated failure of Europeans to find the Northwest Passage during the 19th century was likely a result of exceptionally severe summertime air temperature and sea ice extent (64). Conditions more amenable to Arctic sea travel, and to the discovery of the Northwest Passage, arose naturally after the turn of the century (27).

Implications for the Future

Our reconstruction of past environmental change in the Arctic suggests that natural

Fig. 3. Comparison of hypothesized external climate forcing (colored lines) and standardized proxy Arctic-wide summer-weighted annual temperature [gray lines, plotted as sigma units (18, 19)] for (**A**) atmospheric CH_4 (66), (**B**) atmospheric CO_2 (67), (**C**) solar irradiance (32), and (**D**) Greenland (GISP2) ice core volcanic sulfate. Eruptions known to be overrepresented in the GISP2 record are marked with an asterisk (37, 38).
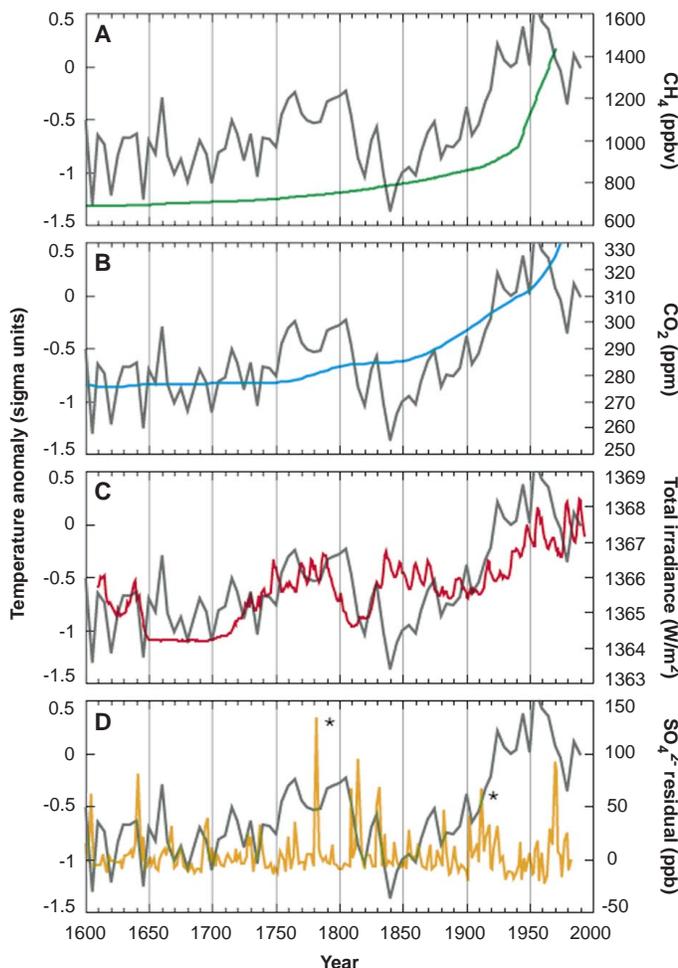
Fig. 4. Lake sediment records from climatically and limnologically contrasting regions of Ellesmere Island (*62, 68*), each showing abrupt changes in the composition of fossil diatom assemblages deposited within approximately the last 150 years. These biostratigraphic changes are unrelated to differential silica preservation and represent the greatest floristic shifts of the middle to late Holocene. Taxonomic diversification with greater representations of littoral and periphytic taxa (**A** to **C**), increased diatom algal biomass (C), and recent diatom recolonization (**D**) are all consistent with the abrupt 19th- to 20th-century shift toward longer summer growing seasons, reduced lake-ice severity, and greater habitat availability. The limnological consequences of the 19th- to 20th-century warming appear to be unprecedented in the context of pre–18th century natural variability. Except where noted, tick marks on horizontal axes represent 10% relative frequency intervals.

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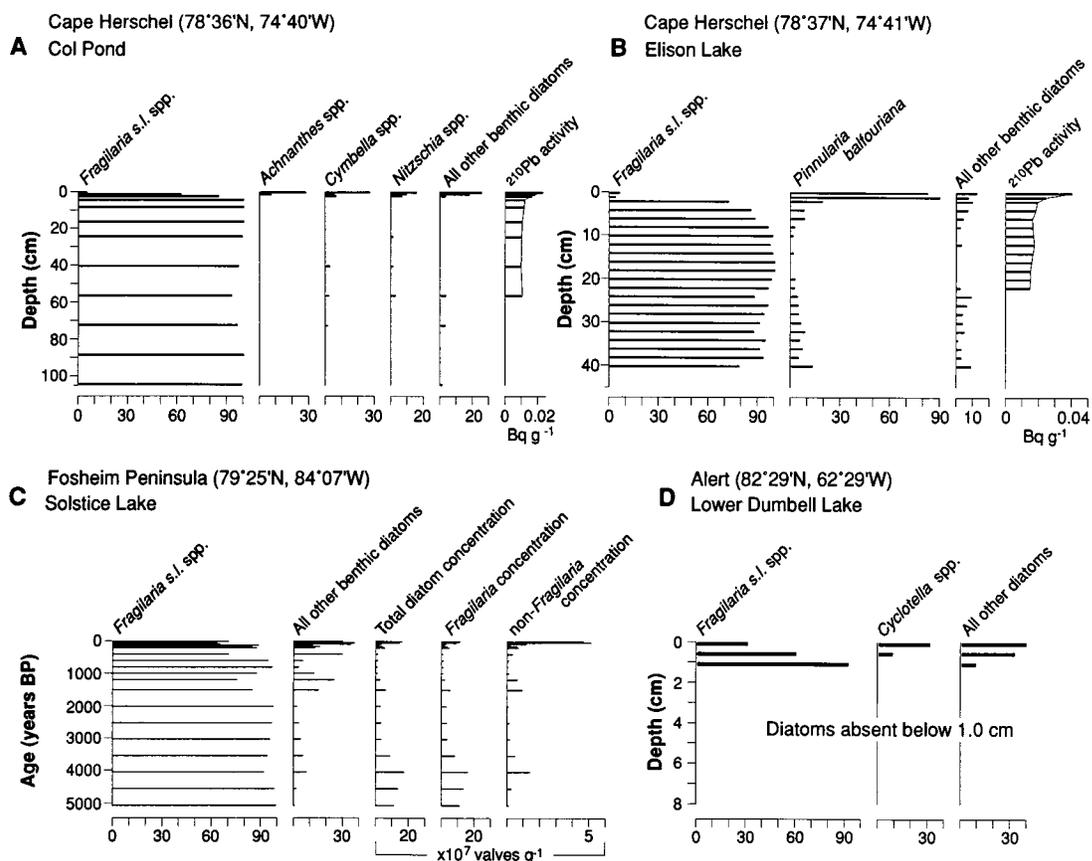
variability is large in this region and is working together with human forcing (through increased concentrations of atmospheric trace gases) to drive unprecedented changes in the Arctic environment. The complexity of natural and anthropogenic forcing highlights the probability that assumptions of climate stability, or efforts to simply extrapolate past patterns of change into the future, will ultimately fail to anticipate future Arctic climate change and its impacts. Reliable predictions of future change will require climate system models that prove effective in simulating past changes such as those reconstructed here. Even as these models are being developed and tested, however, the Arctic environment is likely to continue its pace of change.

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18. The proxy temperature time series in Fig. 2 were chosen because they were available in time series form. Most of the paleoclimate time series have been calibrated against instrumental data, but the scarcity of weather stations in the Arctic makes it necessary

to rely on similar records that have been calibrated directly against instrumental data, or to use theory, in order to define the nature of the climate signal represented in a few of the proxy records. For example, ice cores are commonly far from any instrumental station, but theory supports the interpretation of ice core melt layers as a proxy of summer temperature [whereas ice core stable isotopic variations are more complex on decadal time scales (*10*)]. Likewise, the selection of site characteristics ensures that tree ring chronologies correlate well with summer or annual temperatures where they can be compared with nearby instrumental records, reinforcing the likelihood that tree ring width also correlates well with summer or annual temperature at sites remote from any instrumental station (*8, 9, 26*). Theory and (in cases where nearby meteorological data are available) direct correlation with instrumental data support the assertion that the lake sediment records included in this study are also useful centuries-long proxies for early summer temperatures (*20, 21, 65*) [D. R. Hardy *et al.*, *J. Paleolimnol.* **16**, 227 (1996)]. Thus, although most of the time series summarized here have been calibrated quantitatively against summer temperature, it is more appropriate to plot raw proxy data (x) in terms of "sigma units" defined as normalized deviations (z) from the 1901–1960 mean (m): $z = (x - m)/s$, where s is the standard deviation of the raw series for the period 1901–1960. The reference period was selected to highlight the 20th century in the context of preceding centuries. Five-year averages are plotted to emphasize the lower frequency patterns of variability and to accommodate the ~1% temporal error that characterizes the sediment and ice core–based records. Tree ring chronologies generally are accurate at annual resolution, but they may be biased in Alaska after 1970 by moisture stress or new anthropogenic causes (*58*).

19. The 400-year Arctic average summer temperature series (Fig. 3) was generated by first averaging the

standardized 5-year–averaged series (Fig. 2) for each of the groups circled in Fig. 1 (to eliminate site density bias) and then averaging the group averages with the other single sites not circled in Fig. 1. Sites 8 and 29 were excluded because of their subdecadal resolution.

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34. In general, the reconstructed record of total solar irradiance (*32*) agrees well with independent records of solar activity inferred from ¹⁴C and ¹⁰Be cosmogenic isotopes (*35*). All three records agree that the lowest total solar irradiance of the last 400 years occurred in the interval 1650–1710. This period was characterized by Arctic temperatures that, although lower than at present, were not anomalously cold relative to the interval 1600–1650.
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36. Lean *et al.* (*32*) carried out a correlation analysis between reconstructed solar irradiance (the same used in our Fig. 3) and the Northern Hemisphere temperature reconstruction of Bradley and Jones (*10*). For the period 1610 to 1800, they found the solar temperature correlation to be 0.86. Assuming that the period 1610 to 1800 was influenced by natural climate forcing only, they used regression to define the solar-temperature relation and extrapolate it to the present, with the resulting inference that up to 50% of the Northern Hemisphere warming between 1860 and 1970 is attributable to solar forcing. When we repeated the analysis using Arctic temperature, we found that the 1610 to 1800 correlation between solar irradiance and Arctic temperature (Fig. 3) is less high at 0.47, whereas the correlation

between the volcanic activity (*38*) and Arctic temperature (Fig. 3) over the same period is higher (–0.21, calculated without any lags) than was suggested by the comparison with the Northern Hemisphere record (*32*). Extrapolation of the 1610 to 1800 relations to the present suggests that increasing atmospheric trace-gas concentrations have been the dominant influence on Arctic temperatures after 1920, but that solar and volcanic forcing also play a role.
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