Recent changes in a remote Arctic lake are unique within the past 200,000 years

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The Arctic is currently undergoing dramatic environmental transformations, but it remains largely unknown how these changes compare with long-term natural variability. Here we present a lake sediment sequence from the Canadian Arctic that records warm periods of the past 200,000 years, including the 20th century. This record provides a perspective on recent changes in the Arctic and predates by approximately 80,000 years the oldest stratigraphically intact ice core recovered from the Greenland Ice Sheet. The early Holocene and the warmest part of the Last Interglacial (Marine Isotope Stage or MIS 5e) were the only periods of the past 200,000 years with summer temperatures comparable to or exceeding today's at this site. Paleoecological and geochemical data indicate that the past three interglacial periods were characterized by similar trajectories in temperature, lake biology, and lakewater pH, all of which tracked orbitally-driven solar insolation. In recent decades, however, the study site has deviated from this recurring natural pattern and has entered an environmental regime that is unique within the past 200 millennia.

chironomids | climate change | diatoms | paleolimnology | polar

Warming over the past century has caused widespread and rapid changes in the Arctic cryosphere, hydrosphere, and biosphere (1, 2). Many of these changes are incompletely documented due to the sparse coverage and short history of high-latitude monitoring networks. Paleoclimate proxy records provide opportunities both to document recent changes at remote sites and to assess their significance relative to natural variability (3, 4). Paleoclimate data from past interglacial periods in particular provide windows into naturally warmer climates and attendant changes in greenhouse gases, ice sheets, sea level, and ecosystems (5–9).

Terrestrial paleoclimate archives that record multiple interglacials are rare in the Arctic due to widespread glacial erosion, but recent research has revealed the preservation of ancient sediments in some glaciated terrains where ice sheets were minimally erosive (10). We have recovered intact lacustrine sediments predating the Last Glacial Maximum from Lake CF8 on Baffin Island, yielding a 200,000-year record of natural variations in the Arctic environment over three interglacial periods. The sediments also record 20th-century conditions at this remote site unaffected by direct human influences. The Lake CF8 sediment record predates, by approximately 80,000 years, the oldest stratigraphically intact ice core recovered from the Greenland Ice Sheet (11) and provides a long-term perspective on recent changes in the Arctic.

Cores recovered from Lake CF8 (Fig. 1; 70° 33.42′ N, 68° 57.12′ W, 195 m asl) contain four organic lake sediment units, which are separated by inorganic sands and record portions of the past three interglacial periods and one interstadial. Radiocarbon (^{14}C) ages from the uppermost organic unit span the Holocene, i.e., the past 11,000 years (12). Based upon ^{14}C and optically-stimulated luminescence (OSL) dating reported by

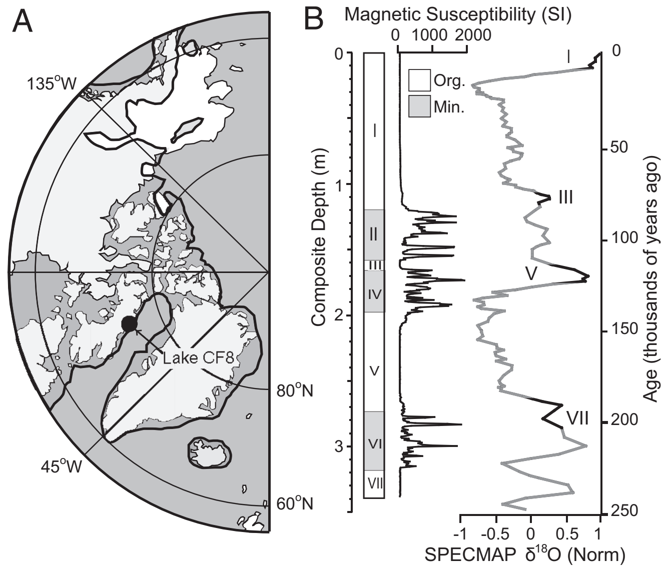

Fig. 1. Study site location and sediment stratigraphy. (*A*) Black dot shows location of Lake CF8 on Baffin Island in the Eastern Canadian Arctic. Bold line indicates approximate extent of ice sheets during the Last Glacial Maximum. (*B*) Stratigraphy and magnetic susceptibility of Lake CF8 sediments. Sediment units are represented as roman numerals I-VII [after (10); org. = organic-rich lake sediments; min. = minerogenic sediments]. Organic units are correlated with ice volume minima (interglacials/interstadials) in the global ice volume record of (13) based on the geochronology of (10).

(10), we assign the other major organic unit to the Last Interglacial [MIS 5e, ≈130,000–115,000 years ago (13)] and the deepest organic unit (of which we only recovered the upper portion) to a late phase of MIS 7, the prior interglacial period, which ended approximately 190,000 years ago. The thin organic unit between MIS 5e and the Holocene yields nonfinite ^{14}C ages on aquatic mosses, and is assigned tentatively to the MIS 5c or 5a interstadial (10). The three interglacial periods were separated by much longer glacial periods, during which organic sediments were not deposited and we infer that conditions were cold enough that the lake was either perennially frozen or covered by an ice sheet. Each glacial period is represented in the

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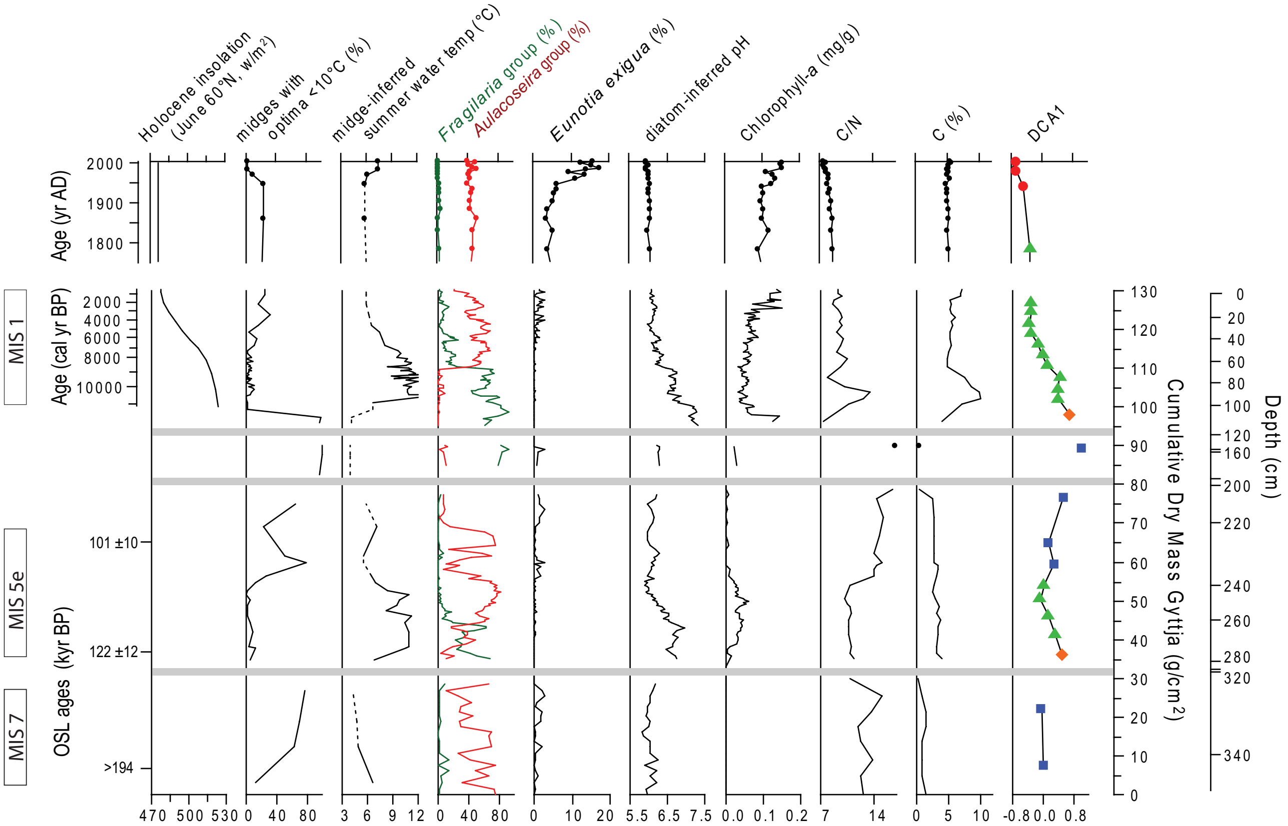

Fig. 2. Downcore proxy data. Percent of cold-stenothermous chironomid taxa with summer water temperature optima <10 °C; summer water temperature inferred from chironomid assemblages; percent abundance of the benthic diatom group *Fragilaria sensu lato* (green) and planktonic *Aulacoseira* group (red); percent abundance of the diatom *Eunotia exigua*; lakewater pH inferred from diatom assemblages; biogeochemical parameters measured on bulk sediment (abundance of chlorophyll-*a*, C:N ratio, and %C); and DCA Axis 1 scores. Colored symbols for DCA scores correspond with those in Fig. 3. Data from the long record are plotted versus cumulative dry mass, and data from the surface core are plotted versus time. Holocene chronology from (12, 14); OSL ages from (10). Temperature inferences shown as dotted lines are maximum estimates (12). June insolation is from (20).

stratigraphy by an unconformity (recording a hiatus in deposition) overlain by sands deposited by ice-marginal meltwater streams that flowed into the lake during deglaciation. This paper presents high-resolution multiproxy data from the four organic units, including the uppermost (20th century) sediments. The soft uppermost sediments were recovered and subsampled separately with a specialized coring device, and dated using excess ^{210}Pb (14).

Our study employs aquatic invertebrate and algal assemblages, augmented by sediment biogeochemistry, as proxies for climate and limnological change. The larvae of chironomids, or nonbiting midges (Chironomidae), have chitinous head capsules that are preserved in lake sediments. Chironomid species distributions are often temperature dependent, and subfossil assemblages are increasingly used for quantitative temperature inferences (15). Diatoms (Bacillariophyceae), unicellular algae with siliceous valves, are sensitive to water chemistry and regional climate (16). Chironomid and diatom assemblages have both shown sensitivity to recent Arctic warming (4). To assess aquatic conditions more generally, we inferred chlorophyll-*a* [a proxy for primary production (17, 18)] spectroscopically, measured percent organic carbon, and calculated the ratio of carbon to nitrogen [an indicator of organic material source (19)] in bulk sediments.

Results and Discussion

All proxies at Lake CF8 express considerable variability within each of the three interglacial periods (Fig. 2), which underscores the amplitude of natural variability experienced in the Arctic during warm-climate intervals. In general, the high-amplitude trends in lake-sediment proxies and of reconstructed temperature changes at this site are consistent with evidence for the strong sensitivity of Arctic climate and ecosystems to radiative forcing (1). Orbitally-driven summer solar insolation has been the primary forcing of interglacial climate evolution here, as evidenced by the similarity between trends in June insolation (20) and chironomid-inferred temperature and diatom-inferred pH at Lake CF8 over the well-dated Holocene (Fig. 2). Biological assemblages (and thus biologically-derived temperature and pH inferences) show similar trends through the Holocene and Last Interglacial, and trends within MIS 7 (presumably we have captured only its waning stages) are similar to those of the late Holocene. The lake biology followed a similar trajectory in response to changing climate through each of the past three interglacial periods, despite intervening continent-scale glaciation, species extirpations, and subsequent recolonizations.

Trends in diatom assemblages illustrate the points above: the dominant diatom taxa (e.g., the genera *Fragilaria sensu lato* and *Aulacoseira*) follow the same general trajectory within each interglacial period. At the onset of both the Last Interglacial and the Holocene the assemblage is dominated by small, benthic *Fragilaria* (Fig. 2). These alkaphilous taxa are common initial colonizers following deglaciation, because they benefit from alkalinizing base cations released from fresh sediments deposited by glaciers. These cations would have been quickly depleted around Lake CF8, where minimally-erosive ice-sheet advances deposited relatively little sediment (10), such that the continuing regulation of acid-base equilibria was governed by climate. As climate cooled with declining insolation in the latter part of each interglacial period, acidophilous *Aulacoseira* taxa increased (Fig. 2). Declining pH was likely a response to increasingly prolonged seasonal lake-ice cover, which simultaneously limited photosynthetic drawdown of limnetic CO_2 and trapped respired CO_2 within the lake (21, 22). Similar patterns of chemical and biological lake ontogeny have been recorded elsewhere over the Holocene on Baffin Island (21, 22).

Through the mid to late Holocene, declining summer insolation has caused progressive cooling in the Northern Hemisphere (23) and under natural forcing, climate would on average be expected to cool over coming centuries. Indeed, chironomids record cooling through the late Holocene at Lake CF8, as cold-tolerant taxa became increasingly dominant. But after approximately AD 1950, chironomid taxa with cold temperature optima abruptly declined (Fig. 2), matching the lowest abundances of the past 200,000 years. The two most extreme cold stenotherms, *Oliveridia/Hydrobaenus* and *Pseudodiamesa*, disappeared entirely (14). At the same time, aquatic primary production (inferred from chlorophyll-*a* and C:N) increased, as has been documented at other lakes in the region (16). Such evidence for 20th-century warming at Lake CF8 adds to mounting evidence from high-latitude northern sites suggesting that the natural late-Holocene cooling trajectory has been preempted in the Arctic (2, 24).

Although 20th-century warming is clearly recorded in the proxy data, Lake CF8 is not simply returning to the environmental regime seen during past warm periods (i.e., the early Holocene and MIS 5e). Rather, recent warm decades are ecologically unique. For example, there has been an unprecedented increase in the diatom species *Eunotia exigua*, which was present only intermittently through the preindustrial record (Fig. 2). This epiphytic species, commonly associated with aquatic mosses (25), may currently be responding to expanded habitat availability due to declining lake ice cover through the 20th century (26). Although *E. exigua* is relatively acidophilic, its increase does not imply recent acidification, as it has replaced other diatom taxa with similar pH optima (27); accordingly, there is no corresponding change in diatom-inferred pH (Fig. 2). Moreover, postindustrial acidification from long-range emissions is not a likely explanation for recent changes at Lake CF8 because acidic deposition is extremely low in this region (28). In fact, SO_4 concentrations in Lake CF8 ($< 25\ \mu eq\ L^{-1}$) are a fraction of those recorded in lakes affected by acidic deposition (29), and lower than other Baffin Island lakes, which have recorded increases in alkaliphilic taxa over the same period (22).

To place the complex 20th-century environmental changes objectively within the context of three interglacial periods, we used detrended correspondence analysis [DCA, an indirect ordination technique (30)] to summarize major trends across the range of biological and geochemical proxies. DCA axes can be viewed as latent variables that capture the major gradients within multivariate ecological data sets. DCA results from samples predating the 20th century fall within three distinct clusters reflecting the range of natural interglacial conditions experienced by the lake in the past 200,000 years (Fig. 3*A*): lake reinception following deglaciation, relatively warm full interglacial conditions, and descent into glacial conditions. DCA scores for 20th-century samples fall outside this broad range of natural variability, reflecting recent increases in lake productivity (inferred from chlorophyll-*a* and C:N), loss of cold-tolerant chironomid taxa, and changes in the diatom assemblage (Figs. 2 and 3). The lake has followed a trajectory through the 20th century toward increasingly exceptional environmental conditions with no natural analogues in the past 200,000 years. The 20th century is the only period for which all proxies show trends consistent

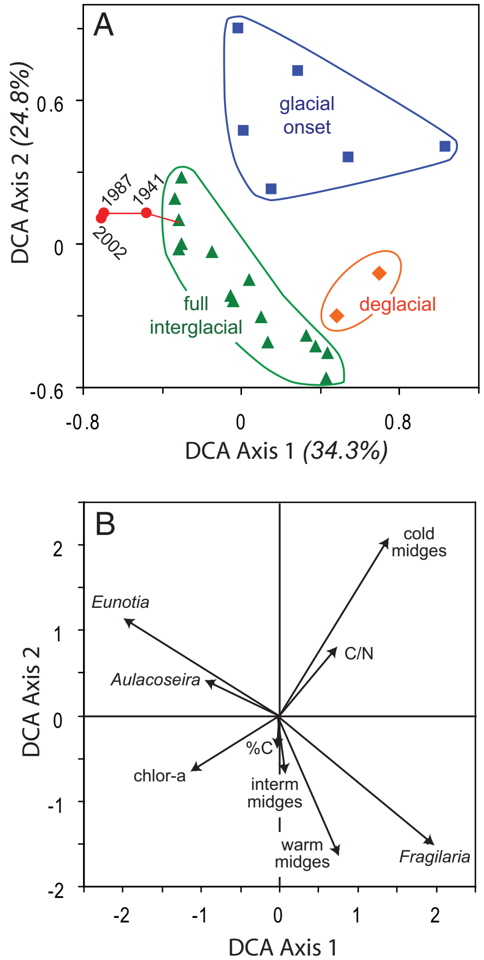

Fig. 3. Ordination results. (*A*) Sample scores from DCA of multiproxy data from interglacial and interstadial periods of the past 200,000 years. Numbers in parentheses are percentages of the variance explained. Colored symbols correspond with those in Fig. 2. Groupings are defined visually based upon the raw proxy data and stratigraphic position (Fig. 2). Twentieth-century samples (red circles) are labeled with ages in years AD. (*B*) Variable (species) scores from the same analysis. Downcore values for each variable included in the DCA are shown in Fig. S1.

with warming despite declining orbital forcing, which, under natural conditions, would cause climatic cooling. The timing of this shift coincides with widespread Arctic change, including warming attributed to a combination of anthropogenic forcings that are unprecedented in the Arctic system (1, 31). Thus, it appears that the human footprint is beginning to overpower long-standing natural processes even at this remote site.

The recent environmental changes at Lake CF8 are echoed across the Arctic, in dramatic 20th-century biological shifts documented in numerous Arctic lakes and ponds (4, 26, 32). The sediment record from Lake CF8 places these widespread changes in the context of multiple interglacial periods, and it suggests that ecosystems and environmental conditions in many lakes and ponds in the Arctic may now be outside the range of natural Quaternary variability. Lake ecosystems, which respond rapidly to climate and other environmental change, may be harbingers of similarly dramatic future changes in other parts of the Arctic system.

Materials and Methods

Lake CF8 (Z_{max} = 10 m; surface area = 0.3 km^2), on the coastal Clyde Foreland of northeastern Baffin Island, is a small through-flowing lake fed primarily by snowmelt. Mean annual temperature at nearby Clyde River is −12.8 °C and mean July temperature is +4.4 °C (33). Repeated field observations reveal that the lake is ice-covered for at least 9 months/year. The local bedrock is Precambrian granite and gneiss.

Chironomids were analyzed according to standard protocol (39), with a minimum of 50 whole head capsules enumerated per sample and following the taxonomy used by (34). Twenty-two different chironomid taxa were identified at this site. Temperature inferences used the weighted averaging model of (34), which incorporates data from (35) and has a root mean square error of prediction (RMSEP) of 2.2 °C. As with any transfer function, chironomid-inferred temperatures contain some statistical uncertainty (14, 34). Although absolute temperature values have a statistical uncertainty of ± 2.2 °C, reconstructed trends in past temperature at this site are likely robust because the amplitude of these trends exceeds the statistical uncertainty of the model; furthermore, these trends are supported by many other proxies from the region (36).

Diatom preparation followed standard protocol (38), with a minimum of 200 diatom valves enumerated per sample; taxonomy and pH inferences followed (16). A total of 123 diatom species from 36 genera were enumerated. Detailed results of paleoecological analyses are presented in theses (27, 37). Chlorophyll-*a* was inferred from reflectance spectra (650–700 nm) of freeze-dried bulk sediment samples using a FieldSpec Pro spectroradiometer (17). This spectral method captures both chlorophyll-*a* and the byproducts of its degradation, so diagenetic effects are not problematic (17, 18). C and N were measured on bulk sediment using a PDZEuropa ANCA-GSL elemental analyzer. C/N is reported as weight ratios. Downcore data are plotted versus cumulative dry mass (cumulative sediment thickness multiplied by dry density) to account for compaction.

DCA was conducted using R v 2.5.1 on the data matrix shown in Fig. S1. Raw data were averaged over 10-cm intervals of the long record and 0.5- to 1.0-cm intervals of the surface core to reduce all proxies to a common resolution. Data were normalized (divided by the maximum value for each proxy) and not downweighted. To compare 20th century samples with only preindustrial samples, the uppermost interval in the long record (which has not been dated with ^{210}Pb) was omitted from this analysis. Axes 1 and 2 had gradient lengths 1.74 and 1.46 and explained 34.3 and 24.8% of the variance, respectively.

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1. ACIA (2004) *Arctic Climate Impact Assessment* (Cambridge Univ Press, Cambridge, UK).
2. Trenberth KE, et al. (2007) in *Climate Change 2007: The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, eds Solomon S, et al. (Cambridge Univ Press, Cambridge, UK), pp 235–336.
3. Overpeck J, et al. (1997) Arctic environmental change of the last four centuries. *Science* 278:1251–1256.
4. Smol JP, et al. (2005) Climate-driven regime shifts in the biological communities of arctic lakes. *Proc Natl Acad Sci USA* 102:4397–4402.
5. EPICA Community Members (2004) Eight glacial cycles from an Antarctic ice core. *Nature* 429:623–628.
6. CAPE Last Interglacial Project Members (2006) Last Interglacial arctic warmth confirms polar amplification of climate change. *Quat Sci Rev* 25:1383–1400.
7. Hodgson DA, et al. (2006) Interglacial environments of coastal east Antarctica: Comparison of MIS 1 (Holocene) and MIS 5e (Last Interglacial) lake-sediment records. *Quat Sci Rev* 25:179–197.
8. Overpeck JT, et al. (2006) Paleoclimatic evidence for future ice-sheet instability and rapid sea-level rise. *Science* 311:1747–1750.
9. Blanchon P, Eisenhauer A, Fietzke J, Liebetrau V (2009) Rapid sea-level rise and reef back-stepping at the close of the last interglacial highstand. *Nature* 458:881–885.
10. Briner JP, Axford Y, Forman SL, Miller GH, Wolfe AP (2007) Multiple generations of interglacial lake sediment preserved beneath the Laurentide Ice Sheet. *Geology* 35:887–890.
11. NGRIP Project Members (2004) High-resolution record of Northern Hemisphere climate extending into the last interglacial period. *Nature* 431:147–151.
12. Axford Y, Briner JP, Miller GH, Francis DR (2009) Paleoecological evidence for abrupt cold reversals during peak Holocene warmth in Arctic Canada. *Quatern Res* 71:142–149.
13. Martinson DG, et al. (1987) Age dating and orbital theory of the ice ages: Development of a high-resolution 0 to 300,000-year chronostratigraphy. *Quatern Res* 27:1–29.
14. Thomas EK, Axford Y, Briner JP (2008) Rapid 20th-century environmental change on northeastern Baffin Island, Arctic Canada, inferred from a multi-proxy lacustrine record. *J Paleolimnol* 40:507–517.
15. Walker IR, Cwynar LC (2006) Midges and palaeotemperature reconstruction–the North American experience. *Quat Sci Rev* 25:1911–1925.
16. Joynt EH, III, Wolfe AP (2001) Paleoenvironmental inference models from sediment diatom assemblages in Baffin Island lakes (Nunavut, Canada) and reconstruction of summer water temperature. *Can J Fish Aquat Sci* 58:1222–1243.
17. Michelutti N, Wolfe AP, Vinebrooke RD, Rivard B, Briner J (2005) Recent primary production increases in Arctic lakes. *Geophys Res Lett* 32:L19715.
18. Michelutti N, et al. (March 20, 2009) Do spectrally inferred determinations of chlorophyll a reflect trends in lake trophic status? *J Paleolimnol*, 10.1007/s10933-009-9325-8.
19. Meyers PA, Teranes JL (2001) in *Tracking Environmental Change Using Lake Sediments*, eds Last WM, Smol JP (Kluwer, Dordrecht, The Netherlands), Vol 2, pp 239–270.
20. Berger A, Loutre MF (1991) Insolation values for the climate of the last 10 million years. *Quat Sci Rev* 10:297–317.
21. Wolfe AP (2002) Climate modulates the acidity of Arctic lakes on millennial time scales. *Geology* 30:215–218.
22. Michelutti N, Wolfe AP, Briner JP, Miller GH (July 19, 2007) Climatically controlled chemical and biological development in Arctic lakes. *J Geophys Res* (*G Biogeosci*) 112, G03002, 10.1029/2006JG000396.
23. Wanner H, et al. (2008) Mid- to Late Holocene climate change: An overview. *Quat Sci Rev* 27:1791–1828.
24. Kaufman DS, et al. (2009) Recent warming reverses long-term arctic cooling. *Science* 325:1236–1239.
25. Patrick R, Reimer CW (1966) *The Diatoms of the United States, Volume* 1 (Philadelphia, PA).
26. Smol JP, Douglas MSV (2007) From controversy to consensus: Making the case for recent climate change in the Arctic using lake sediments. *Front Ecol Environ* 5:466–474.
27. Wilson CR (2009) A lacustrine sediment record of the last three interglacial periods from Clyde Foreland, Baffin Island, Nunavut: Biological indicators from the past 200,000 years. M. Sc. thesis (Queen's University, Kingston, ON).
28. AMAP (2006) *Acidifying Pollutants, Arctic Haze, and Acidification in the Arctic* (Arctic Monitoring and Assessment Programme, Oslo, Norway).
29. Charles DF (1991) *Acidic Deposition and Aquatic Ecosystems. Regional Case Studies* (Springer-Verlag, New York).
30. Hill MO, Gauch HG (1980) Detrended correspondence analysis: An improved ordination technique. *Vegetatio* 42:47–58.
31. Shindell D, Faluvegi G (2009) Climate response to regional radiative forcing during the twentieth century. *Nature Geoscience* 2:294–300.
32. Douglas MSV, Smol JP, Blake W, Jr (1994) Marked post-18th century environmental change in high Arctic ecosystems. *Science* 266:416–419.
33. Environment Canada (2009) Canada's National Climate Archive. http://climate.weatheroffice.ec.gc.ca/.
34. Francis DR, Wolfe AP, Walker IR, Miller GH (2006) Interglacial and Holocene temperature reconstructions based on midge remains in sediments of two lakes from Baffin Island, Nunavut, Arctic Canada. *Palaeogeogr, Palaeoclimatol, Palaeoecol* 236:107–124.
35. Walker IR, Levesque J, Cwynar LC, Lotter AF (1997) An expanded surface-water paleotemperature inference model for use with fossil midges from eastern Canada. *J Paleolimnol* 18:165–178.
36. Briner JP, et al. (2006) A multi-proxy lacustrine record of Holocene climate change on northeastern Baffin Island, Arctic Canada. *Quatern Res* 65:431–442.
37. Axford Y (2007) Interglacial temperature variability in the high-latitude North Atlantic region inferred from subfossil midges, Baffin Island (Arctic Canada) and Iceland. Ph.D. dissertation (University of Colorado, Boulder, CO).
38. Battarbee RW, et al. (2001) in *Tracking Environmental Change Using Lake Sediments*, eds Smol JP, Birks HJB, Last WM (Kluwer, Dordrecht, The Netherlands), Vol 3, pp 155–202.
39. Walker IR (2001) in *Tracking Environmental Change Using Lake Sediments*, eds Smol JP, Birks HJB, Last WM (Kluwer, Dordrecht, The Netherlands), Vol 4, pp 43–66.