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Twentieth-century warming revives the world's northernmost lake

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ABSTRACT

Although recent ecological changes are widespread in Arctic lakes, it remains unclear whether they are more strongly associated with climate warming or the deposition of reactive nitrogen (Nr) from anthropogenic sources. We developed a 3500-yr paleolimnological record from the world's northernmost lake to explore this question. Microfossils indicate that siliceous diatoms and chrysophytes were abundant initially, but disappeared 2400 yr ago in concert with Neoglacial cooling. Microfossils reappear in 20th-century sediments and reach unprecedented concentrations in sediments deposited after ca. A.D. 1980, tracking increasing summer temperatures in the absence of evidence for atmospheric nutrient subsidies. These results indicate that current warming in northern Greenland is unprecedented in the context of the past 2400 yr, and that climate change alone is responsible for the marked biological changes observed.

INTRODUCTION

Polar amplification of climate warming during recent decades is well documented, given that rates of Arctic surface temperature increases exceed the global average two- to three-fold over the past century (Trenberth et al., 2007; Serreze et al., 2009). Higher temperatures and longer growing seasons, coupled to altered snow and ice regimes, have potentially far-reaching ecological consequences, many of which are becoming evident across the circumpolar north (Post et al., 2009). In lakes, 20th-century shifts in algal and invertebrate communities suggest that recent climate change has induced ecological regime shifts across the Arctic (Smol et al., 2005). However, as the level of human interference with the global biogeochemical cycle of nitrogen accelerates (Gruber and Galloway, 2008), climate change is but one potential agent acting upon Arctic lakes, and its contribution to the total observed ecological change has not been unambiguously demonstrated.

Nitrogen stable isotopes ($\delta^{15}N$) in sediments from numerous Arctic lakes (Holtgrieve et al., 2011) and in nitrate from Greenland ice (Hastings et al., 2009) reveal progressive isotopic depletion in the 20th century, with an acceleration of this trend in the past ~40 yr. The similarity of this pattern to that in regions known to receive elevated reactive nitrogen (Nr) deposition (Wolfe et al., 2003) indicates that they chronicle long-range transport and deposition from anthropogenic sources. Although the amplitude of these isotopic shifts varies considerably due to site-specific processes, the near-synchronous timing and uniform direction of the shifts strongly support the notion that they represent a first-order proxy for anthropogenic Nr deposition. Together, climate warming and Nr deposition may form potent synergies leading to a range of ecological and biogeochemical changes in lakes (Hobbs et al., 2010). To date, however, it is has proven difficult to disentangle these effects in the absence of unambiguous end-member ecosystems that capture a signature purely mediated by climate change.

We explored this problem by undertaking paleolimnological analyses of Holocene sediments from Kaffeklubben Sø (unofficial name, 83°37′N, 30°47′W, 45 m above sea level [asl]; Fig. 1), the world's northernmost lake, on the north coast of Greenland and among the most remote regions of the Northern Hemisphere. Although previous Holocene paleoecological studies have been conducted in this region (Funder and Abrahamsen 1988; Olsen et al., 2012), our study is the first to present highly resolved analyses of surface sediments spanning the 20th century and place these within the context of late-Holocene natural variability. Kaffeklubben Sø is a small lake (area of 48 ha, maximum depth of 14.5 m) that remains ice-covered year-round, with a marginal ice-free moat forming in summer between the shore and the ice pan. Mean annual air temperatures are ~−18.0 °C, and current summer temperatures hover just above freezing (1980–1999 mean July temperature of 1.6 °C at Kap Morris Jesup, 30 km west of the lake). Average annual precipitation is 188 mm (at the nearest weather station, Station Nord), conferring polar desert conditions to the region (Cappelen et al., 2001).

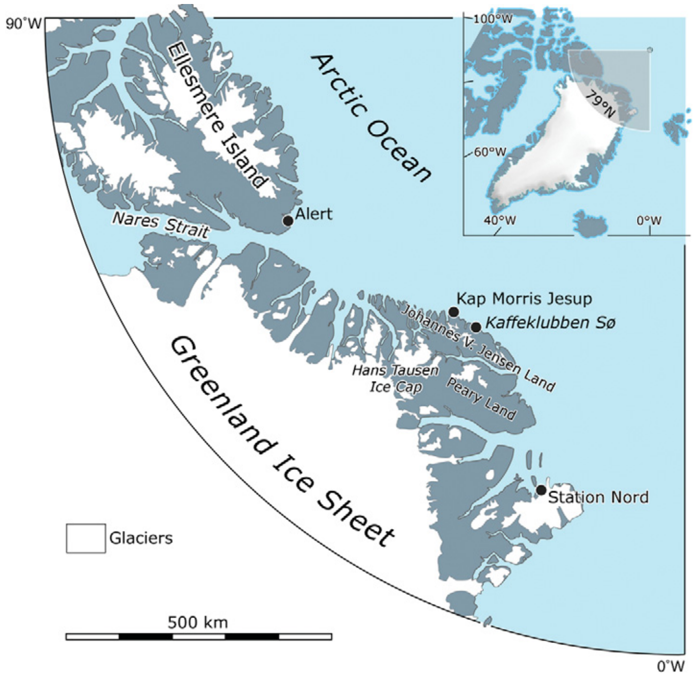

Figure 1. Location map of Kaffeklubben Sø on the north coast of Greenland. Site locations are those mentioned in text. Areas of glacier cover are white. Photographs of the area are available in the Data Repository (see footnote 1).

METHODS

A suite of lake sediment cores was extracted in July 2006 from the deepest part of Kaffeklubben Sø with a gravity coring device (Glew et al., 2001), capturing the entire late-Holocene organic sequence. Sediments were dated with excess (unsupported) ^{210}Pb and accelerator mass spectrometric ^{14}C dates on various organic matter fractions (see the GSA

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Data Repository[1]). Diatoms were prepared using standard methods for organic matter oxidation (Battarbee et al., 2001). Microfossil concentrations were determined by spiking digested slurries with an external marker (Wolfe, 1997), whereas diatom taxonomic richness was assessed using rarefaction analyses (Birks and Line, 1992) normalized to a count size of 200 valves (typical count size is >400 valves where present). Sediment carbon, and nitrogen content and $\delta^{15}N$ values, were obtained using a Costech 4010 elemental analyzer connected to a ThermoFinnigan MAT253 isotope ratio mass spectrometer. Combustion was achieved at 1000 °C in oxygen catalyzed by silvered cobaltous oxide to remove sulfur compounds, and reduced copper to convert NO_x to N_2. The evolved N_2 was introduced to the mass spectrometer in a He stream through an open split using a ConFlo III device. Precision of $\delta^{15}N$ analyses referenced to atmospheric N_2 is <0.2‰, based on measurements of internal reference materials (glutamic acid and bulk organic matter from salmon tissue) calibrated against IAEA-N1 and USGS32 standards. Carbon and nitrogen contents are reproducible to within ±0.1% (as percent total mass).

KAFFEKLUBBEN SØ PALEOLIMNOLOGICAL RECORD

The sediment record from Kaffeklubben Sø, which has been rigorously dated by ^{14}C and ^{210}Pb radiochronology (see the Data Repository), reveals three phases during the past 3500 yr (Fig. 2). Diatoms are present in the oldest sediments, and comprise a taxonomically depauperate community of pioneering benthic taxa belonging to the family Fragilariaceae. Non-fragilarioid diatoms and chrysophyte cysts are either rare or absent in this part of the record. Total diatom concentrations are relatively low, and after an initial rise, decrease monotonically until they disappear altogether, ca. 2400 calibrated (cal.) yr B.P. These sediments are overlain by a 47 cm interval representing ~2300 yr (Fig. 2) that is largely barren of siliceous microfossils, with episodic showings at very low concentrations at ca. 1980 yr B.P., ca. 1670–1630 yr B.P., and ca. 630–440 yr B.P. The occasional diatom valves present are well preserved, with no evidence of etching or pitting of valve walls (see the Data Repository). Therefore, their scarcity is attributed to low production by diatoms as a whole, and not to selective dissolution. Colonies of cyanobacteria belonging to the genus *Nostoc* occasionally are preserved in this interval and likely dominated lake primary production. Subsequently, beginning in ca. A.D. 1920, diatoms and chrysophytes reappear in the record and reach unprecedented concentrations in sediments deposited since A.D. 1980. Diatom taxonomic richness is as high, or higher, in these sediments as anywhere in the lower diatom-rich zone. Sediment accumulation rates broadly parallel diatom abundance patterns, declining during the inferred cold period when diatoms are rare or absent. Accordingly, diatom fluxes in recent decades are unprecedented in the context of the entire record.

Nitrogen stable-isotope values remain stable across these pronounced diatom community transitions (Fig. 2). Importantly, there is no evidence for directional decreases in sediment $\delta^{15}N$ or nitrogen concentration over recent decades, in contrast to both the Greenland summit ice-

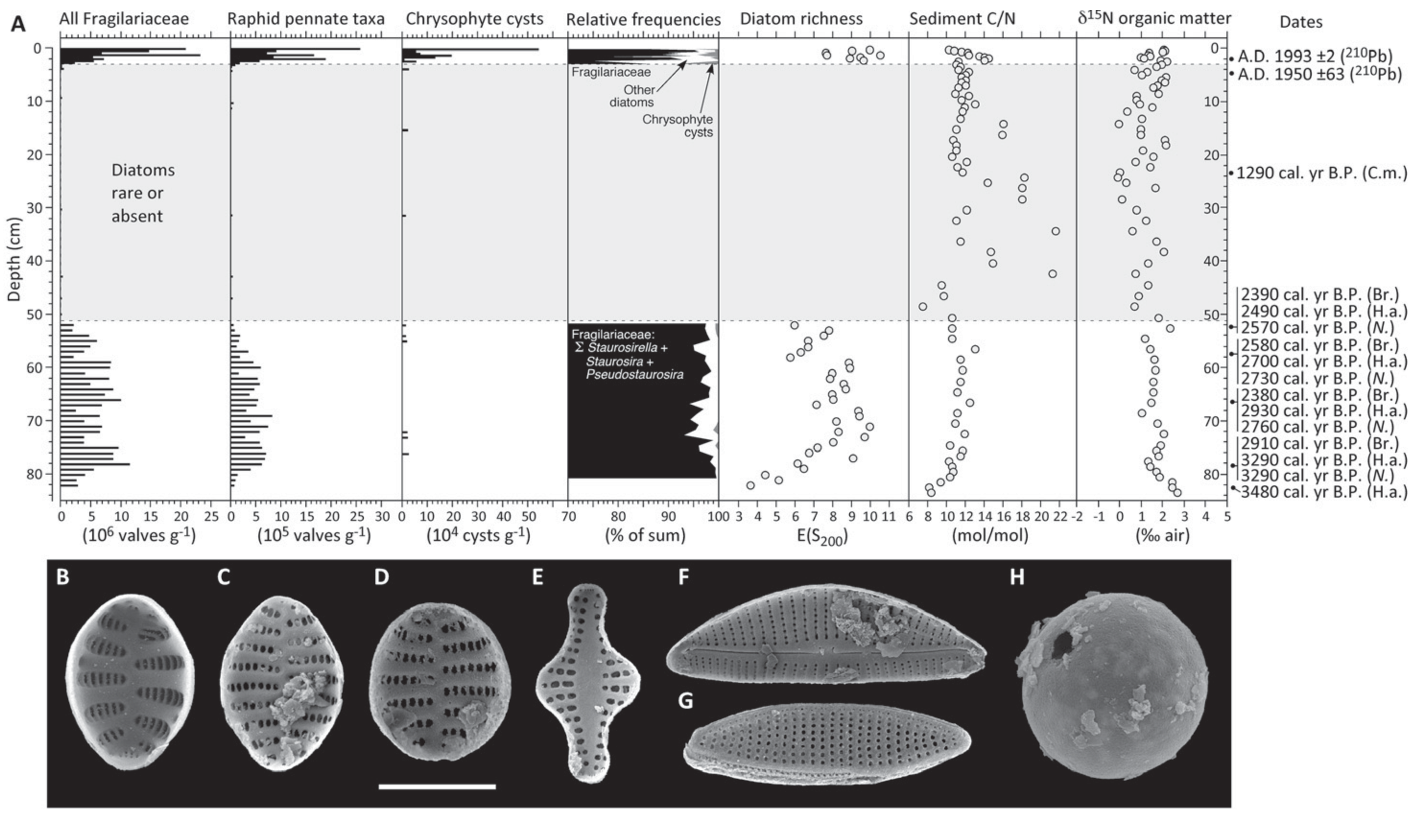

Figure 2. Late Holocene paleolimnology of Kaffeklubben Sø (northern Greenland). A: Stratigraphic profiles of concentrations of major siliceous microfossil groups, diatom taxonomic richness estimated by rarefaction analysis, relative frequencies of dominant siliceous microfossils, and sediment biogeochemical properties. Gray shading is the zone largely barren of diatoms. Taxonomic richness is normalized to a sum of 200 diatom valves [E(S_{200})]. Key dates (in calibrated yr B.P.) are shown on the right. Radiocarbon dating targets: C.m.—cyanobacterial mat; Br.—bryophytes; H.a.—humic acid extracts; *N.*—spherical *Nostoc* colonies. B–H: Field-emission scanning electron micrographs of representative microfossils. Scale bar is 5 µm. B: *Staurosirella pinnata*. C,D: Two morphotypes of *Staurosira venter*. E: *Pseudostaurosira pseudoconstruens*. F: *Encyonema minutum*. G: *Nitzschia perminuta*. H: A typical unornamented and collarless chrysophyte cyst.

[1]GSA Data Repository item 2012282, supplementary text and figures, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

core record and Arctic regions impacted by anthropogenic Nr deposition (Wolfe et al., 2006). The stability of lead stable-isotope ratios from recent Kaffeklubben Sø sediments lends further support to the contention that the lake is at present unaffected by atmospheric deposition (Michelutti et al., 2009), as do exceedingly low nitrogen deposition rates measured at Station Nord (<0.02 μg N m^{-2}; Hole et al., 2009). The greatest variability in down-core $\delta^{15}N$ and C/N molar ratios occurs during the interval largely barren of siliceous microfossils. This likely reflects variability in the sources of organic matter reaching sediments at these times, alternating between autochthonous sources associated with cyanobacteria when the lake was perennially frozen, and episodic inputs of terrestrial organics characterized by elevated C/N.

We interpret the Kaffeklubben Sø paleolimnological sequence as a record of limnological responses to past and ongoing climate change. Recent increases in siliceous microfossil accumulation rates (fluxes) correlate well with observed climate warming both locally (Fig. 3A) and regionally across northern Greenland (Fig. 3B). The association of July air temperatures at Kap Morris Jesup with sediment diatom flux confirms the nature of this diatom-temperature relationship. We hypothesize that diatoms and chrysophytes are not represented in Kaffeklubben Sø sediments when local July air temperatures fall below 0 °C. This provides a potentially powerful transfer function by which almost consistently frozen conditions can be inferred for the interval between ca. 2.4 kyr B.P. and A.D. 1920, sandwiched between periods of sustained summer melting. Perennial lake ice is strongly limiting to lake photoautotrophic communities dominated by diatoms and chrysophytes, whereas cyanobacteria are able to persist under conditions of perennial lake ice (Antoniades et al., 2009).

The evolution of late-Holocene climate on north Greenland produced a series of threshold responses in the siliceous algal communities of Kaffeklubben Sø (Fig. 2). Secular cooling over the past two millennia, culminating in the Little Ice Age, is a widely recognized pattern across the Arctic (Kaufman et al., 2009), with cold conditions persisting until the mid-20th century. Both the Greenland Ice Corp Project (GRIP) and Dye 3 ice cores register 2–3 °C of cooling between 4 and 2 kyr B.P. (Dahl-Jensen et al., 1998), which is believed to broadly reflect conditions on Greenland (Vinther et al., 2009). On the north coast, regional glacier equilibrium lines dropped substantially in this interval (Landvik et al., 2001), and ca. 2.5 kyr B.P., landfast ice became permanent on the north coast, precluding the penetration of driftwood to fiords (Funder et al., 2011). Brief reprises of driftwood penetration correspond with episodic diatom recurrences in Kaffeklubben Sø, although exceedingly low diatom concentrations during these periods imply that none of these intervals, even

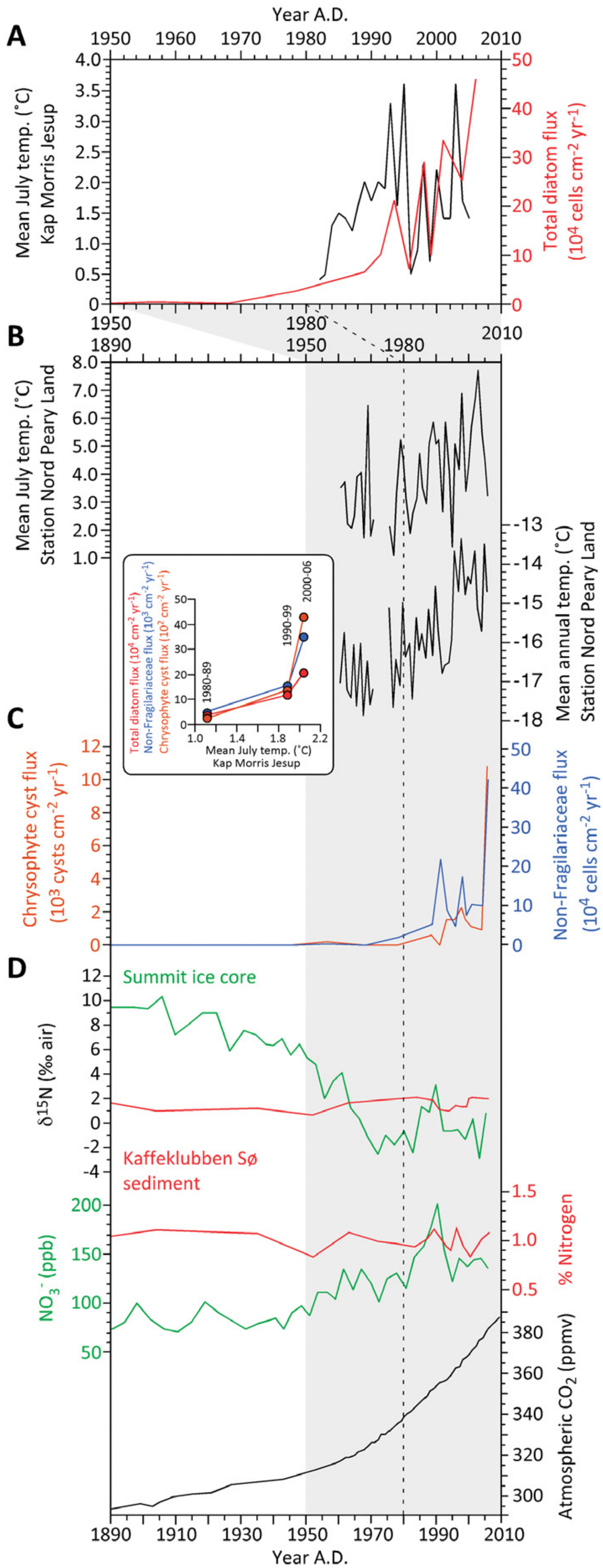

Figure 3. Correspondence between recent climate trends and biological changes in Kaffeklubben Sø (northern Greenland). A: Total diatom fluxes (red line), according to sediment ^{210}Pb chronology, track mean July temperatures at Kap Morris Jesup (black). B: Longer climate records from northern Greenland confirm unusual warmth of the most recent three decades and provide a broader temporal context for the Kap Morris Jesup temperature record (climate data compiled from Carstensen and Jørgensen, 2010). C: Trends in chrysophyte cyst (ochre) and non-fragilarioid diatom (blue) fluxes since ca. A.D. 1980. The inset relates decadally binned fluxes of the three siliceous microfossil categories to mean July temperatures at Kap Morris Jesup averaged over the same intervals (i.e., A.D. 1980–89, 1990–99, and 2000–2006). D: Ecological changes are decoupled from $\delta^{15}N$ and %N in Kaffeklubben Sø sediments (red lines), although $\delta^{15}N$ and NO_3^- concentrations from the summit of the Greenland Ice Sheet (green lines) reveal a clear signature of anthropogenic reactive nitrogen (Nr) deposition, particularly since A.D. 1950 (Hastings et al., 2009). Rising levels of atmospheric CO_2 (black line) from spliced ice core (Neftel et al., 1985) and measured (Tans, 2007) concentrations underscore the climatic and ecological changes of the late 20th and early 21st centuries.

during the Middle Ages, was comparable to current (post-A.D. 1980) warming. This finding is supported by the nearby Hans Tausen Iskappe record (Hammer et al., 2001). Finally, carefully vetted radiocarbon dates from archaeological sites scattered across the north coast document the termination of Independence II Paleoeskimo culture at 2.4 kyr B.P., following centuries of intermittent habitation (Grønnow and Jensen, 2003). It is plausible that climate deterioration influenced human survival on north Greenland at this time by curtailing terrestrial productivity and the availability of important resources such as muskoxen.

CONCLUSION

The revival of Kaffeklubben Sø's siliceous algal communities during recent decades, in complete absence of evidence for atmospheric Nr subsidies, represents a compelling example of the response of remote polar ecosystems to climate warming. Our results suggest that current summer temperatures in northernmost Greenland have not been experienced consistently since before ca. 2.4 kyr B.P. Given current and anticipated warming trajectories, ultimately influenced by enhanced anthropogenic greenhouse gas forcing (Meehl et al., 2007), these results portend even greater future biological changes and indicate that, even in absence of synergistic responses involving atmospheric deposition, profound ecological changes in High Arctic biomes will continue to accelerate.

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REFERENCES CITED

Antoniades, D., Veillette, J., Martineau, M.-J., Belzile, C., Tomkins, J., Pienitz, R., Lamoureux, S., and Vincent, W.F., 2009, Bacterial dominance of phototrophic communities in a High Arctic lake and its implications for paleoclimate analysis: Polar Science, v. 3, p. 147–161, doi:10.1016/j.polar.2009.05.002.

Battarbee, R.W., Jones, V.J., Flower, R.J., Cameron, N.G., Bennion, H., Carvalho, L., and Juggins, S., 2001, Diatoms, *in* Smol, J.P., Birks, H.J.B., and Last, W.M., eds., Tracking Environmental Change Using Lake Sediments, Volume 3: Terrestrial, Algal, and Siliceous Indicators: Dordrecht, Kluwer Academic Publishers, p. 155–202.

Birks, H.J.B., and Line, J.M., 1992, The use of rarefaction analysis for estimating palynological richness from Quaternary pollen-analytical data: The Holocene, v. 2, p. 1–10, doi:10.1177/095968369200200101.

Cappelen, J., Jørgensen, B.V., Laursen, E.V., Stannius, L.S., and Thomsen, R.S., 2001, The observed climate of Greenland 1958–1999 with climatological standard normals 1961–1990: Copenhagen, Danish Meteorological Institute Technical Report 00–18.

Carstensen, L.S., and Jørgensen, B.V., 2010, Weather and Climate Data from Greenland 1958–2009: Copenhagen, Danish Meteorological Institute Technical Report 10–08.

Dahl-Jensen, D., Mosegaard, K., Gundestrup, N., Clow, G.D., Johnsen, S.J., Hansen, A.W., and Balling, N., 1998, Past temperatures directly from the Greenland Ice Sheet: Science, v. 282, p. 268–271, doi:10.1126/science.282.5387.268.

Funder, S., and Abrahamsen, N., 1988, Palynology in a polar desert, eastern North Greenland: Boreas, v. 17, p. 195–207, doi:10.1111/j.1502-3885.1988.tb00546.x.

Funder, S., and 11 others, 2011, A 10,000-year record of Arctic Ocean sea-ice variability-view from the beach: Science, v. 333, p. 747–750, doi:10.1126/science.1202760.

Glew, J.R., Smol, J.P., and Last, W.M., 2001, Sediment core collection and extrusion, *in* Last, W.M., and Smol, J.P., eds., Tracking Environmental Change Using Lake Sediments, Volume 1: Basin Analysis, Coring, and Chronological Techniques: Dordrecht, Kluwer, p. 73–105.

Grønnow, B., and Jensen, J.F., 2003, The Northernmost Ruins of the Globe: Eigil Knuth's Archaeological Investigations in Peary Land and Adjacent Areas of High Arctic Greenland: Copenhagen, Danish Polar Center, 403 p.

Gruber, N., and Galloway, J.N., 2008, An Earth-system perspective of the global nitrogen cycle: Nature, v. 451, p. 293–296, doi:10.1038/nature06592.

Hammer, C.U., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, D., Gundstrup, N., and Steffensen, J.P., 2001, The paleoclimatic record from a 345 m long ice core from the Hans Tausen Iskappe *in* Hammer, C.U., ed., The Hans Tausen Ice Cap: Glaciology and Glacial Geology: Meddelelser om Grønland: Geoscience, v. 39, p. 87–95.

Hastings, M.G., Jarvis, J.C., and Steig, E.J., 2009, Anthropogenic impacts on nitrogen isotopes of ice-core nitrate: Science, v. 324, p. 1288, doi:10.1126/science.1170510.

Hobbs, W.O., Wolfe, A.P., Telford, R.J., Birks, H.J.B., Saros, J.E., Hazelwinkel, R.R.O., Perren, B.B., and Saulnier-Talbot, É., 2010, Quantifying recent ecological changes in remote lakes of North America and Greenland using sediment diatom assemblages: PLoS ONE, v. 5, p. e10026, doi:10.1371/journal.pone.0010026.

Hole, L.R., Christensen, J.H., Ruoho-Airola, T., Tørseth, K., Ginzburg, V., and Glowacki, P., 2009, Past and future trends in concentrations of sulphur and nitrogen compound in the Arctic: Atmospheric Environment, v. 43, p. 928–939, doi:10.1016/j.atmosenv.2008.10.043.

Holtgrieve, G.W.,and 18 others, 2011, A coherent signature of anthropogenic nitrogen deposition to remote watersheds of the Northern Hemisphere: Science, v. 334, p. 1545–1548, doi:10.1126/science.1212267.

Kaufman, D.S., and 29 others, 2009, Recent warming reverses long-term arctic cooling: Science, v. 325, p. 1236–1239, doi:10.1126/science.1173983.

Landvik, J.Y., Weidick, A., and Hansen, A., 2001, The glacial history of the Hans Tausen Iskappe and the last glaciation of Peary Land, North Greenland, *in* Hammer, C.U., ed., The Hans Tausen Ice Cap: Glaciology and Glacial Geology: Meddelelser om Grønland: Geoscience, v. 39, p. 27–44.

Meehl, G.A., et al., 2007, Global climate projections, *in* Solomon, S., et al., eds., Climate Change 2007: The Physical Science Basis: Cambridge, UK, Cambridge University Press, p. 747–845.

Michelutti, N., Simonetti, A., Briner, J., Funder, S., Creaser, R.A., and Wolfe, A.P., 2009, Spatial and temporal trends of pollution Pb and other metals in the Baffin Bay region inferred from lake-sediment geochemistry: The Science of the Total Environment, v. 407, p. 5653–5662, doi:10.1016/j.scitotenv.2009.07.004.

Neftel, A., Moor, E., Oeschger, H., and Stauffer, B., 1985, Evidence from polar ice cores for the increase in atmospheric CO_2 in the past two centuries: Nature, v. 315, p. 45–47, doi:10.1038/315045a0.

Olsen, J., Kjær, K.H., Funder, S.V., Larsen, N.K., and Ludikova, A., 2012, High-Arctic climate conditions for the last 7000 years inferred from multi-proxy analysis of the Bliss Lake record, North Greenland: Journal of Quaternary Science, v. 27, p. 318–327, doi:10.1002/jqs.1548.

Post, E., and 24 others, 2009, Ecological dynamics across the Arctic associated with recent climate change: Science, v. 325, p. 1355, doi:10.1126/science.1173113.

Serreze, M.C., Barrett, A.P., Stroeve, J.C., Kindig, D.N., and Holland, M.M., 2009, The emergence of surface-based Arctic amplification: Cryosphere, v. 3, p. 11–19, doi:10.5194/tc-3-11-2009.

Smol, J.P., and 25 others, 2005, Climate-driven regime shifts in the biological communities of arctic lakes: Proceedings of the National Academy of Sciences of the United States of America, v. 102, p. 4397–4402, doi:10.1073/pnas.0500245102.

Tans, P.P., 2007, Trends in atmospheric carbon dioxide: National Oceanic and Atmospheric Administration, Earth System Research Laboratory (NOAA/ESRL), http://www.esrl.noaa.gov/gmd/ccgg/trends/ (May 2012).

Trenberth, K.E., and 11 others, 2007, Observations: Surface and Atmospheric Climate Change, *in* Solomon, S., et al., eds., Climate Change 2007: The Physical Science Basis: Cambridge, UK, Cambridge University Press, p. 235–336.

Vinther, B.M., and 13 others, 2009, Holocene thinning of the Greenland ice sheet: Nature, v. 461, p. 385–388, doi:10.1038/nature08355.

Wolfe, A.P., 1997, On diatom concentrations in lake sediments: results of an interlaboratory comparison and other experiments performed on a uniform sample: Journal of Paleolimnology, v. 18, p. 61–73, doi:10.1023/A:1007920816271.

Wolfe, A.P., Cooke, C.A., and Hobbs, W.O., 2006, Are current rates of atmospheric nitrogen deposition influencing lakes in the Eastern Canadian Arctic?: Arctic, Antarctic, and Alpine Research, v. 38, p. 465–476.

Wolfe, A.P., Van Gorp, A.C., and Baron, J.S., 2003, Recent ecological and biogeochemical changes in alpine lakes of Rocky Mountain National Park (Colorado, USA): Geobiology, v. 1, p. 153–168, doi:10.1046/j.1472-4669.2003.00012.x.

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