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A 2000-yr-long multi-proxy lacustrine record from eastern Baffin Island, Arctic Canada reveals first millennium AD cold period

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ABSTRACT

We generate a multi-proxy sub-centennial-scale reconstruction of environmental change during the past two millennia from Itilliq Lake, Baffin Island, Arctic Canada. Our reconstruction arises from a finely subsectioned ^{210}Pb- and ^{14}C-dated surface sediment core and includes measures of organic matter (e.g., chlorophyll *a*; carbon–nitrogen ratio) and insect (Diptera: Chironomidae) assemblages. Within the past millennium, the least productive, and by inference coldest, conditions occurred ca. AD 1700–1850, late in the Little Ice Age. The 2000-yr sediment record also reveals an episode of reduced organic matter deposition during the 6th–7th century AD; combined with the few other records comparable in resolution that span this time interval from Baffin Island, we suggest that this cold episode was experienced regionally. A comparable cold climatic episode occurred in Alaska and western Canada at this time, suggesting that the first millennium AD cold climate anomaly may have occurred throughout the Arctic. Dramatic increases in aquatic biological productivity at multiple trophic levels are indicated by increased chlorophyll *a* concentrations since AD 1800 and chironomid concentrations since AD 1900, both of which have risen to levels unprecedented over the past 2000 yr.

Introduction

The Arctic plays a profound role in the global climate system. Yet, this role is complex and there remain many uncertainties regarding Arctic climate change. Snow and ice cover strongly influence the overall energy balance of the planet (Curry et al., 1995), and changes in mountain glaciers and the Greenland Ice Sheet have a significant impact on relative sea-level rise (Meier et al., 2007; Pfeffer et al., 2008; Berthier et al., 2010). As the Arctic continues to warm and sea-ice extent continues to decrease (Stroeve et al., 2007; Kaufman et al., 2009; Polyak et al., 2010), a more complete understanding of these impacts on the whole arctic system is needed. Part of this improved understanding will stem from records of arctic environmental change reconstructed from geological archives, which provide baselines for ongoing and future change. In addition, increasing the spatial density of reconstructions of environmental change improves our understanding of the arctic climate system, increases our knowledge of ecosystem response to climate change, and provides data for testing climate models.

Lake sediments are valuable archives of environmental change because lakes are widespread in the Arctic and their sediments are often continuous and datable (e.g., Wolfe et al., 2004; Kaufman et al., 2009). Furthermore, multiple chemical, physical and biological proxies can be extracted from lake sediments and analyzed to provide highly resolved, reliable indicators of past climate (Pienitz et al., 2004). High-resolution (e.g., annual- to sub-centennial-scale) climate proxy records spanning recent millennia are particularly sparse in the Arctic (Jansen et al., 2007). The number of highly resolved records of arctic environmental change spanning the past millennium is increasing (Overpeck et al., 1997; Kaufman et al., 2009; Journal of Paleolimnology special volume 41, 2009). However, the number of high-resolution records from the Arctic that extend further back in time are still relatively few.

According to millennial-scale quantitative Holocene climate records, Baffin Island, Arctic Canada experienced a warm early Holocene (10.5–8 ka), followed by gradual cooling (Briner et al., 2006; Francis et al., 2006; Michelutti et al., 2007; Axford et al., 2009a). This mid- to late-Holocene cooling is not reconstructed at sub-

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millennial resolution, except in the past millennium. The past millennium was characterized by cool temperatures punctuated by warm events, most notably between AD 1400–1700 and during the 20th century (Hughen et al., 2000; Moore et al., 2001; Wolfe, 2003; Michelutti et al., 2005; Thomas et al., 2008; Thomas and Briner, 2009). Few of these high-resolution records extend earlier than ~AD 1200. This study utilizes organic-rich sediments from Itilliq Lake, eastern Baffin Island (Fig. 1), to produce a continuous, sub-centennial scale record of environmental change spanning the past two millennia using multiple physical, geochemical and biological proxies. Our new record, combined with other records from Baffin Island, suggests a prominent climate reversal during the first millennium AD recognized in northwestern North America, which indicates that this climate event might be hemispheric in nature (Calkin et al., 2001; Hu et al., 2001; Reyes et al., 2006; Barclay et al., 2009). Furthermore, this record corroborates recent findings that lake ecosystem responses to Arctic change in the past few decades are unprecedented in the late Holocene (Kaufman et al., 2009) and even in the past 200,000 yr (Axford et al., 2009b).

Setting and methods

Itilliq Lake (informal name, 67°59.5′N, 65°07′W) is a small (0.08 km^2) shallow (maximum depth = 5.45 m) lake located at 9 m asl (above sea level) on the Qivitoo Highland, eastern Baffin Island (Fig. 1). The Qivitoo Highland is dominated by Precambrian crystalline bedrock, and the lakes in this region therefore have no old carbon reservoir derived from the underlying bedrock. The surface pH of Itilliq Lake in May 2005 was 5.72. Itilliq Lake is through-flowing with an ephemeral inflow, receiving most of its water from snowmelt. Lakes in this region experience extensive periods of snow and ice cover, with an ice-free season that lasts only 2 or 3 months (between July and September). The closest weather station is Qikiqtarjuaq (67°33′N, 64°01′W, 6 m asl, 67 km southeast of Itilliq Lake), where the mean July air temperature from AD 1995–2007 (the length of the record) was 5.0°C and mean annual air temperature was −10.7°C. Mean annual precipitation for the years AD 2005 and 2006 (the only years with complete data) was 349 mm water equivalent (Environment Canada, 2009).

A 51-cm-long surface core (05ITLSC) with an intact sediment–water interface was collected from the deepest part of the lake (5.45 m) with a 9.5-cm-diameter percussion–piston surface corer in May 2005. The core was subsectioned in the field at 0.25-cm increments from 0 to 25 cm and at 1-cm increments below 25 cm.

The chronology of core 05ITLSC is based on a ^{210}Pb profile and four accelerator mass spectrometry (AMS) ^{14}C measurements on humic acid fractions extracted from bulk sediment. Alpha spectroscopy at MyCore Scientific, Inc. was used to determine ^{210}Pb activity, and sediment age was calculated by applying the constant rate of supply (CRS) model to the unsupported ^{210}Pb inventory (Appleby and Oldfield, 1978). Bulk sediment samples for ^{14}C dating were freeze-dried at the University at Buffalo. The humic acid fraction was extracted and graphite targets were prepared at the INSTAAR Laboratory for AMS Radiocarbon Preparation and Research at the University of Colorado and measured at the W.M. Keck Carbon Cycle AMS Facility at the University of California, Irvine. Radiocarbon ages were calibrated using Calib version 5.0.2 using the IntCal04 calibration dataset (Reimer et al., 2004; Stuiver et al., 2005) and are reported throughout this paper as years AD.

Each sub-sampled section of 05ITLSC was weighed before and after freeze-drying for wet and dry bulk density and hydroscopic moisture calculations. Percent loss-on-ignition at 550°C (LOI) was measured on each sample ($n = 124$) down to 50 cm. Bulk samples from Itilliq Lake sediments were analyzed for organic carbon (%C) and nitrogen (%N), stable isotopes of carbon (δ^{13}C) and nitrogen (δ^{15}N), and biogenic silica (%BSiO$_2$) every 0.25 cm for the top 10 cm and every 0.5 cm from

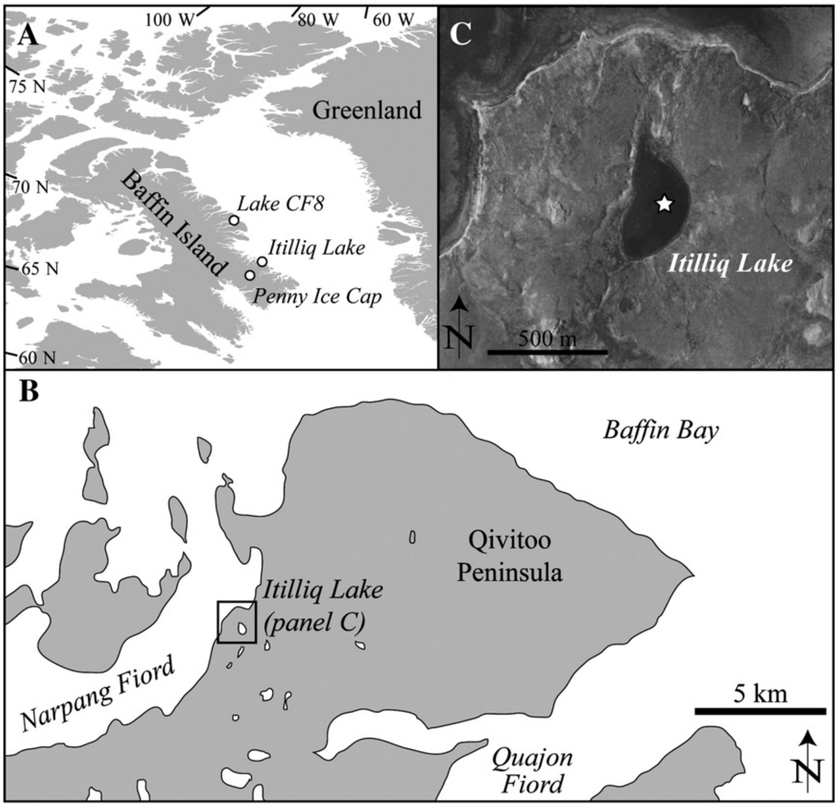

Figure 1. (A) Location of Itilliq Lake, eastern Baffin Island, and other sites mentioned in text. (B) Itilliq Lake lies near the coast on Qivitoo Peninsula. (C) Vertical air photograph of Itilliq Lake showing low-relief catchment and coring location (star).

10 to 25 cm ($n = 70$). For carbon and nitrogen analyses, an aliquot (15–25 mg) of each freeze-dried sample was combusted to CO_2 and N_2 at 1000°C in an online elemental analyzer (PDZEuropa ANCA-GSL) at the UC Davis Stable Isotope Facility. The gases were separated on a Carbosieve G column (Supelco, Bellefonte, PA, USA) before introduction to a continuous flow isotope ratio mass spectrometer (20–20 mass spectrometer, Sercon, Crewe, UK). Standards were analyzed (every 12th sample, $n = 19$) to evaluate analytical precision, which was 0.06‰ for $\delta^{13}C$, 0.3% for %C, 0.15‰ for $\delta^{15}N$ and 0.1% for %N, ($\pm 1\sigma$). An aliquot (50–75 mg) of each freeze-dried sample was analyzed for $BSiO_2$ at Northern Arizona University following the methods described by Mortlock and Froelich (1989). A HACH DR/2000 spectrophotometer was used to measure $BSiO_2$ concentrations, which were then converted to weight percent SiO_2 of dry sediments. Analytical precision of $BSiO_2$ measurements was 3% of the measured values. Finally, the relative absorption by chlorophyll *a* and its degradation products was measured on 28 sieved (125 μm) samples with an ASD Fieldspec Pro attached to an ASD High Intensity Muglight (light source and sensor) following the methods of Michelutti et al. (2005), using the reflectance trough from 650 to 750 nm.

Chironomids (non-biting midges, Diptera: Chironomidae) were analyzed every 1.0 cm ($n = 23$) in the top 22 cm of the sediment core, which covered the past two millennia, and at 30, 40 and 50 cm. Sediment samples for chironomid analysis were deflocculated with warm 5% KOH for 20 min and rinsed on a 100-μm mesh sieve. Head capsules were manually picked from a Bogorov sorting tray under a 40× power dissecting microscope, then permanently mounted on slides using Euparal. All samples contained at least 50 whole identifiable head capsules. Taxonomic identifications followed Brooks et al. (2007) with reference to Oliver and Roussel (1983) and Wiederholm (1983). Taxonomic designations were harmonized with Francis et al. (2006) prior to conducting the analyses described in the following paragraph.

July air temperature inferences were derived using the training set published by Francis et al. (2006), which adds 29 calibration sites from Baffin Island to a midge training set from across eastern Canada (Walker et al., 1991; 1997). We employ a weighted-averaging (WA) regression model with inverse deshrinking and square-root transformed species data, both with and without tolerance downweighting. The model has a cross-validated root mean squared error of prediction ($RMSEP_{jack}$) of 1.5°C (with tolerance downweighting, or 1.6°C without tolerance downweighting) for mean July air temperatures. Paleotemperatures were calculated using the computer program C2 v 1.4.3 (Juggins, 2003). Canonical correspondence analysis (CCA), an ordination technique useful for exploring relationships between community composition and environmental variables (Ter Braak, 1986), was used to assess whether downcore assemblage changes followed temperature gradients in the training set data. CCA was conducted on all of the training set samples compiled by Francis et al. (2006) using the statistical software program R v 2.5.1, with rare taxa downweighted, lake-area data square-root transformed, and lake-depth data log transformed. Downcore samples were then plotted passively with respect to the training set results.

Results[1]

The ^{210}Pb activity is unsupported above 7.0 cm depth. Above 4.5 cm, the ^{210}Pb activity is constant, indicating that bioturbation or some other form of sediment mixing might be homogenizing the sediment. As the sediments are not laminated and contain abundant benthic organisms (i.e., chironomids), bioturbation is a possibility. The sediment mixing is not enough to homogenize the sediment completely, however, since the paleoclimate proxies still show centimeter-scale changes. We therefore apply the ^{210}Pb CRS age model with caution and treat the resulting ages as minima, since mixing would bring young sediment with higher ^{210}Pb activity to greater depths. The ^{210}Pb CRS age model indicates that 7.0 cm depth corresponds to AD 1883 ± 32. The uppermost radiocarbon age of 465 ± 15 ^{14}C yr BP (510 ± 10 cal yr BP; AD 1440 ± 10) from 5.0 to 5.25 cm corresponds with a ^{210}Pb model age of AD 1941 ± 7 (Fig. 2). This indicates that the humic acid fraction has a radiocarbon reservoir equivalent to 500 yr, and we subtract this duration from all four calibrated humic acid radiocarbon ages. This humic acid reservoir correction is similar to offsets measured in lakes elsewhere on Baffin Island (Wolfe et al., 2004) and is attributed to the long residence time of organic material in permafrost landscapes prior to deposition in the lake. Nonetheless, the age–depth model and basal age assignment of ~2600 cal yr BP should be considered to be only broadly constrained beyond the ^{210}Pb-dated interval. We derive a chronology for our sediment sequence using a polynomial through the calibrated, corrected radiocarbon ages and the ^{210}Pb CRS model. The age–depth model reveals increasing sedimentation rates from the base of the record to the surface (Fig. 2; Table 1), a trend recorded in other Baffin Island lakes (e.g., Michelutti et al., 2005; Thomas et al., 2008). We do not have an age constraint for the samples below 25 cm, and refer to them hereafter as "middle Holocene" in age.

The productivity proxies (LOI, %C, %N and chlorophyll *a*) strongly co-vary throughout the record (Fig. 3). All begin at moderate values (LOI 13–17%, C 5–6%, N 0.46–0.6%, chlorophyll *a* 0.4) from 600 BC to AD 500, are low from AD 500–900, and are centered around their lowest value in the entire record (LOI 8%, C 4%, N 0.35%, chlorophyll *a* 0.25) from AD 650–750. These proxies increase thereafter to AD 1700, decline slightly until AD 1800, and then rise sharply to late 20th century values, which are the highest in this record (LOI 22%, C 9%, N 1.0%, chlorophyll *a* 0.75). The C:N ratio is relatively constant at 14.5 throughout most of the record, begins to decrease around AD 1200 to 13 at AD 1900, and more sharply declines after AD 1900 to present values of 11.5; values are slightly lower (around 14) from AD 500–900. The $\delta^{13}C$ values are stable (~28.0‰) for most of the record. They increase slightly to −27.8‰ when organic matter proxies decrease between AD 500–900, increase slightly to −27.5‰ around AD 1550, then increase steadily from ~AD 1800 to ~AD 1900, when they reach a maximum of −26.8‰ before decreasing slightly at the surface. Values of $\delta^{15}N$ increase from 1.8‰ to 2.6‰ from 600 BC to AD 300, then

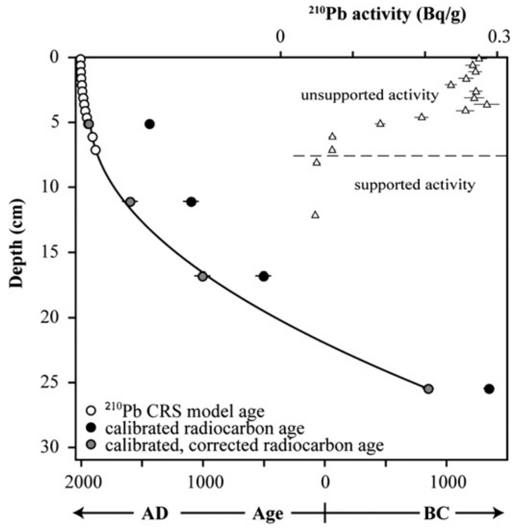

Figure 2. Age–depth information for core 05ITLSC. Error bars are shown, but are smaller than data points in most cases. Polynomial used for age–depth conversion below ^{210}Pb CRS model is: $age = 6.1893(depth)^2 - 53.967(depth) + 197.71$; $r^2 = 0.99$. ^{210}Pb activity shown with open triangles.

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[1] All geochronological and geochemical data and chironomid species counts are available online through the World Data Center for Paleoclimatology (ftp://ftp.ncdc.noaa.gov/pub/data/paleo/paleolimnology/northamerica/canada/baffin/itilliq2011.txt).

Table 1
Radiocarbon ages from 05ITLSC.

Lab number[a]	Midpoint depth (cm)	Fraction modern	$\delta^{13}C$ (% PDB)	Radiocarbon age (^{14}C yr BP)	Calibrated age (yr AD ± 1σ)[b]
8834	5.125	0.9439 ± 0.0017	−27.4	465 ± 15	1440 ± 10
8835	11.125	0.8901 ± 0.0013	−28.1	935 ± 15	1100 ± 60
8516	16.825	0.8256 ± 0.0013	−25	1540 ± 15	500 ± 60
8198	25.5	0.6828 ± 0.0010	−23.4	3065 ± 15	1350 ± 40

[a] CURL number from the INSTAAR Laboratory for AMS Radiocarbon Preparation.
[b] Calibrated using CALIB 5.0.2 with IntCal04 (Reimer et al., 2004; Stuiver et al., 2005).

decline steadily to 2.0‰ at AD 1700, and subsequently decline more rapidly toward present values of 1.6‰. Biogenic silica fluctuates throughout the record with no overall trend.

Chironomid head capsule concentrations change dramatically throughout this record (Fig. 4). The mid-Holocene samples have concentrations ranging from 60 to 250 head capsules g^{-1} dry sediment. From AD 0 to 1900, the head capsule concentrations are low (65–150 head capsules g^{-1} dry sediment). After AD 1900, chironomid head capsule concentrations increase to 419 head capsules g^{-1} dry sediment in AD 1941, drops to 226 head capsules g^{-1} dry sediment in AD 1966, and increases rapidly to 1367 head capsules g^{-1} dry sediment in AD 2005. We calculated head capsule accumulation rates for the ^{210}Pb-dated interval, because this dating method constrains sedimentation rates more precisely than relatively widely spaced radiocarbon ages. Because the sedimentation rate increases during the past century (Fig. 2), head capsule accumulation rates increase dramatically. Prior to AD 1900, accumulation rates are less than 5.0×10^3 head capsules m^{-2} yr^{-1}. Accumulation rates increase to 2.5×10^4 head capsules m^{-2} yr^{-1} in AD 1907, decline to 1.2×10^4 head capsules m^{-2} yr^{-1} in AD 1966, and reach a maximum of 2.4×10^5 head capsules m^{-2} yr^{-1} in AD 2005.

The chironomid assemblage in Itilliq Lake is dominated throughout by the Tanytarsini, including *Micropsectra*, *Tanytarsus lugens*/*Corynocera oliveri* type, and *Paratanytarsus*, and undifferentiated Tanytarsini (60–80% of total head capsules; Fig. 4). *Sergentia*, *Heterotrissocladius*, *Zalutschia*, *Chironomus*, *Orthocladius oliveri* type, and undifferentiated Orthocladiinae are also important in the Itilliq Lake record, reaching maximum relative abundances of 26.6%, 21.2%, 10.5%, 15.6%, 15.3%, and 5.4%, respectively. *Psectrocladius* has relative abundances less than 2% during the past 2000 yr, but reaches up to 7.9% relative abundance in the middle Holocene. Other taxa present include *Abiskomyia*, *Coronyneura*/*Thienemanniella*, *Cricotopus*/*Orthocladius*, Tribe Pentaneurini and *Orthocladius trigonolabis* type, none of which reach relative abundances greater than 3.5%.

Chironomid assemblages shift in relative abundance during the past 2000 yr and the mid-Holocene, but most taxa are present throughout the record. Middle Holocene chironomid assemblages are markedly different from the late Holocene in that *Psectrocladius*, *Heterotrissocladius* and *Tanytarsus lugens*/*Corynocera oliveri* type are more abundant, and *Sergentia* and *Chironomus* are less abundant than during the late Holocene. Assemblages from AD 0–1700 have the highest concentrations of Tanytarsini, with corresponding low abundances of *Sergentia*, *Zalutschia*, *Chironomus*, and *Orthocladius oliveri* type. Samples from AD 1700–2005 have higher concentrations of *Sergentia*, *Zalutschia*, *Chironomus*, and *Orthocladius oliveri* type, with corresponding lower concentrations of *Heterotrissocladius*, undifferentiated Tanytarsini, and *Tanytarsus lugens*/*Corynocera oliveri* type. *Corynoneura*/*Thienemanniella* is unique in the record, in that it is present at low abundances in the early part of the record, disappears after AD 750, and reappears after AD 2000 (2 uppermost samples).

Modeled chironomid-inferred July air temperatures were calculated with and without tolerance downweighting (Fig. 4). Tolerance downweighting assigns greater importance to taxa that display narrow temperature tolerances in the modern training set. Therefore, when tolerance downweighting is employed, the subset of samples containing *Abiskomyia* yield inferred temperatures up to 3°C cooler than samples without *Abiskomyia*. In contrast, when tolerance downweighting is not used, inferred July air temperatures show little variation, ranging between 9 and 10°C throughout the record. CCA Axis 1 is strongly correlated with air and water temperatures, reflecting the predominant gradients within the training set (Fig. 5). Axis 2 more strongly correlates with lake depth and surface area.

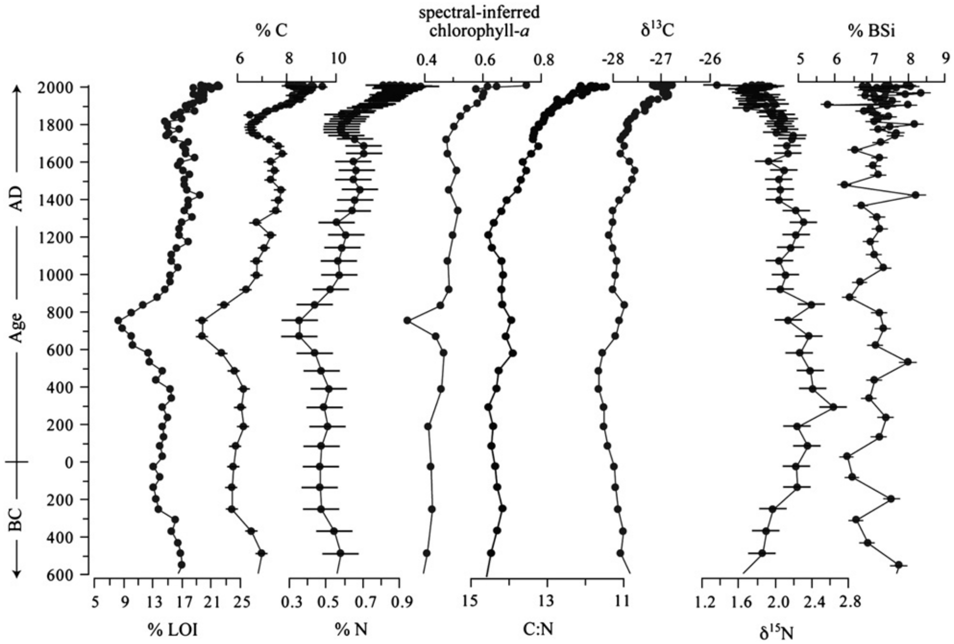

Figure 3. Biogeochemical proxies from 05ITLSC. %LOI, %C, %N, and %BSi, percent loss-on-ignition, carbon, nitrogen, and biogenic silica. C:N, carbon to nitrogen ratio. Error bars are one sigma analytical error, smaller than the symbols for $\delta^{13}C$, and error bars are not shown for %LOI, spectral-inferred chlorophyll *a*, or C:N.

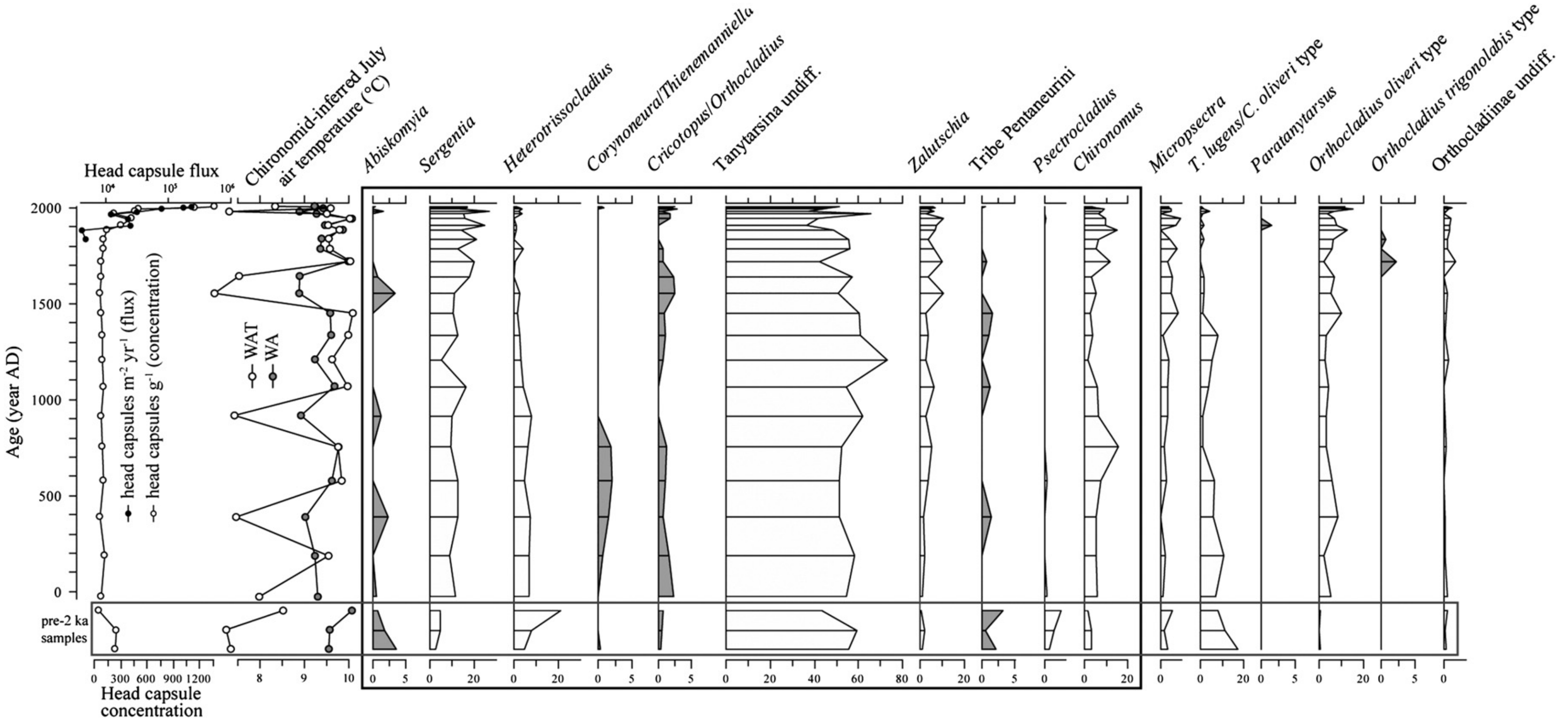

Figure 4. Chironomid head capsule concentrations (white) and fluxes (black), chironomid-inferred July air temperature (white symbols indicate the model using tolerance downweighting, gray symbols indicate the model without tolerance downweighting), and relative abundances of select chironomid taxa from 05ITLSC (rare taxa <2% are not shown). Taxa within box are arranged according to their temperature optima (based on Francis et al., 2006) with colder optima on the left. Note different *x*-axis scales, as indicated by gray versus white plots.

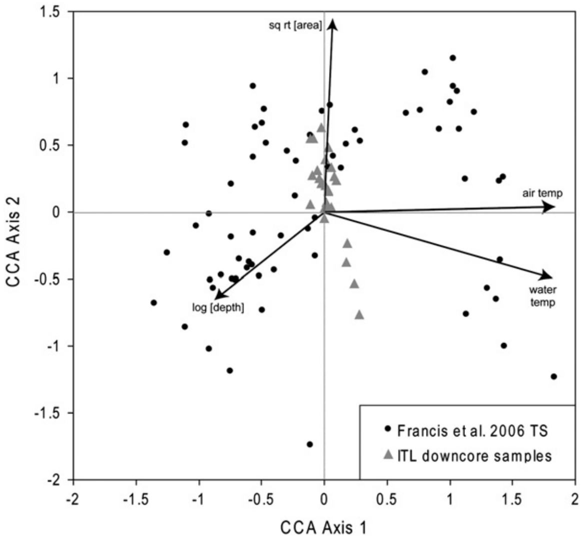

Figure 5. Ordination diagram showing CCA results. CCA site scores for chironomid assemblages in surface-sediment samples of the eastern Canada training set are shown as black circles (sites and samples described by Walker et al., 1997 and Francis et al., 2006). Vectors represent environmental variables in the training set, namely summer lake-water temperature, July air temperature, lake depth, and lake surface area. Downcore samples from Itilliq Lake (gray triangles) are plotted passively.

Downcore samples, which are plotted passively with respect to the training set data, show little variation along Axis 1; differences between downcore samples are more strongly expressed along Axis 2.

Discussion

Interpreting organic matter proxies

The multiple proxies from Itilliq Lake sediments reveal relatively stable environmental conditions through the first millennium AD with the exception of a significant drop in organic matter content between AD 500 and AD 900. The second millennium AD is similarly stable until AD 1700, when organic matter content declines for about a century before increasing to the maximum values of the record in the past century. The two proxies most directly indicative of changes in biological productivity within the lake—chlorophyll *a* and chironomid concentrations—increased to unprecedented values after AD 1800 and 1900, respectively, compared to the previous two millennia. The recent increase in chlorophyll *a* at Itilliq Lake is similar to 20th century chlorophyll *a* increases documented in other Canadian Arctic lakes (Michelutti et al., 2005; Michelutti et al., 2007) and, as has been argued for those lakes, likely records an increase in primary productivity. Michelutti et al. (2010) demonstrated that trends in chlorophyll *a* track primary productivity and do not represent diagenetic signals. Other lakes in the Canadian Arctic also contain direct evidence for recent increases in within lake primary productivity (e.g., diatom test concentrations and chryosphyte stomatocysts; Wolfe and Perren, 2001; Smol et al., 2005; Smol and Douglas 2007). It is unclear to us why $BSiO_2$ does not show similar trends as chlorophyll *a*, as $BSiO_2$ is also a product of primary productivity (Fig. 3). The dramatic 20th century increase in chironomid head capsule concentrations indicates that the increase in primary productivity was accompanied by changes at higher trophic levels, although the heterotrophic chironomids seem to respond to changes approximately a century later than autotrophs (Figs. 3 and 4).

The trends in organic-matter content in Itilliq Lake sediments most likely represent primary environmental changes, rather than effects of differential preservation. One possible cause for the recent dramatic changes in organic matter and δ^{13}C and δ^{15}N in arctic lakes could be greater post-depositional utilization of sedimentary organic matter by microbes or benthic fauna. If this were the case, we would expect to observe an enrichment of carbon and nitrogen isotopes, coincident with a decline in %C and %N as the light isotopes are preferentially remineralized. We also would expect the C:N ratio to increase, since nitrogen is likely a limiting nutrient in this system (Ogbebo et al., 2007), and nitrogen would therefore be remineralized more rapidly than carbon. In fact, the opposite is true for these proxies in Itilliq Lake (Figs. 3 and 6). The %C and %N increase in the upper 9 cm of the sediment and carbon and nitrogen isotopes remain constant or become slightly depleted in the upper 5–10 cm. Finally C:N decreases in the upper 10 cm, which is the opposite of the expected response in a system that is likely nitrogen-limited, and instead we interpret this change as indicative of an increase in aquatic relative to terrestrial productivity (see below). Furthermore, we would expect differential preservation to affect sediments from similar lakes in similar ways. Compared to sediments from Lake CF8, a similarly small, oligotropic lake on Baffin Island, ~320 km northwest of Itilliq Lake (Fig. 1), the changes in %C, C:N, and ∂^{13}C occur at different depths, but at the same time (Fig. 6). Also, these three proxies decline slightly in the upper 1–

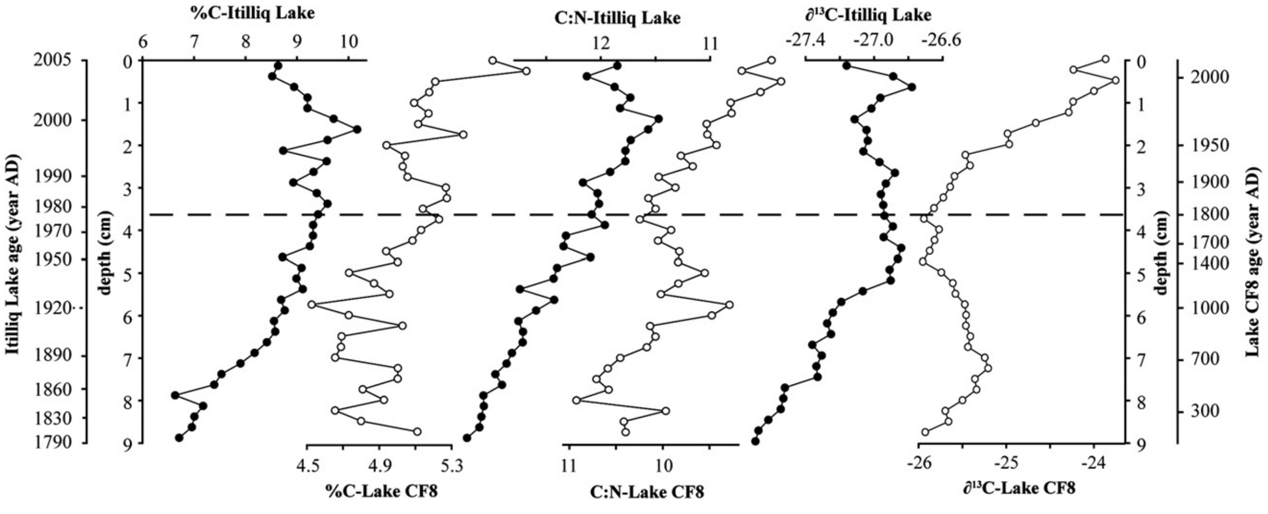

Figure 6. Organic matter data from Itilliq Lake (black circles) and Lake CF8 (open circles; Thomas et al., 2008), plotted by depth down to 9 cm, with age axes (Itilliq Lake age on left, CF8 age on right). Itilliq Lake %C, C:N, and ∂^{13}C begin to increase at 9 cm, which corresponds to ~AD 1800, while Lake CF8 %C, C:N, and ∂^{13}C begin to increase at 3.75 cm (dashed line), which also corresponds to AD 1800.

2 cm of the Itilliq Lake record, but continue to increase in Lake CF8. We therefore conclude that organic matter content in Itilliq Lake reflects changes in organic matter production rather than post-depositional alteration.

The C:N ratio, interpreted in this type of lacustrine setting to reflect changes in the relative contribution of aquatic versus terrestrial organic matter (lower ratio = more aquatic contribution; Meyers and Teranes, 2001), reveals a slowly increasing contribution of aquatic organic matter initiating at ~AD 1300, followed by more rapid contribution after AD 1850, coinciding with the recent rise in chlorophyll *a*, organic matter content, and chironomid concentrations. Increasing δ^{13}C values in the recent two centuries are also consistent with an increase in aquatic productivity over this interval, since photosynthetic utilization of the inorganic carbon pool reduces the ability of aquatic flora to fractionate against the heavy isotope (Meyers and Teranes, 2001).

Changes in organic matter content (LOI, %C, and %N) can be driven either by changes in biological productivity or by changes in inorganic input (e.g., dust or runoff) to the lake. Whereas the major changes in organic matter content during the past two centuries at Itilliq Lake coincide with changes in aquatic primary productivity (as inferred from chlorophyll *a* and δ^{13}C), the drop in LOI, %C, and %N from AD 500–900 does not exhibit changes in δ^{13}C or C:N. If we interpret this portion of the record purely as a decline in primary productivity, this drop in organic matter content would signify a cold interval from AD 500–900. However, if aquatic productivity were declining, we would expect δ^{13}C to decline and the C:N ratio to increase (if terrestrial productivity did not change simultaneously). Neither occurs during this interval. Instead, we postulate that the interval from AD 500–900 had increased inorganic sediment inputs. Several mechanisms could increase inorganic sediment inputs to Itilliq Lake, including dustier or wetter conditions with more runoff from the surrounding catchment. Increased inorganic inputs would dilute the LOI, %C, and %N, and would likely increase sedimentation rates, but would not change the C:N or δ^{13}C ratios. Given our relatively low-resolution chronology, there is no noticeable change in sedimentation rate during this interval.

Primary productivity has been correlated with summer temperature in similar small, shallow, oligotrophic lakes elsewhere in the Arctic (Willemse and Tornqvist, 1999; Michelutti et al., 2005, 2007; Thomas et al., 2008). Assuming aquatic productivity and organic sedimentation correlate with summer temperatures at Itilliq Lake through the late Holocene, these sediments register relatively cool summer temperatures throughout the first millennium AD, a more recent cold period between ~AD 1700 and ~AD 1850 (late Little Ice Age), and relatively warm summer temperatures in the past century. Proxies at Itilliq Lake do not register the gradual insolation-driven late Holocene cooling that is well documented at many sites around the Arctic (Kaufman et al., 2009 and references therein), suggesting that proxies may be responding to environmental drivers other than summer temperature on millennial timescales.

Chironomid taxa

Although subfossil chironomid assemblages are often useful as paleotemperature proxies (e.g., Larocque and Hall, 2003; Walker and Cwynar, 2006), this is not appropriate for every site (e.g., Velle et al., 2010). Late Holocene chironomid assemblage changes at Itilliq Lake are not straightforward to interpret in terms of temperature. For example, the increase in relatively thermophilic taxa after AD 1500, including *Chironomus* and *Zalutschia*, would appear to suggest warming temperatures; but the corresponding increase in *Sergentia*, which has a much lower temperature optimum in the modern training set developed for eastern Canada (Francis et al., 2006), appears to contradict this interpretation. The presence of *Psectrocladius* and abundance of *Chironomus* during the latter half of the first millennium AD could be interpreted as indicating relative warmth, whereas the abundance of *Heterotrissocladius* through this interval suggests relatively cool temperatures. Several minor types which lump together multiple species within a morphotype exhibit broad temperature tolerances in the modern training set (e.g., >4°C for both *Corynoneura*/*Thiennemaniella* and *Cricotopus*/*Orthocladius*; Francis et al., 2006), and as such are not ideal temperature indicators. *Abiskomyia* exhibits a narrower temperature tolerance (0.8°C; Francis et al., 2006) so could be a useful temperature indicator (e.g., Axford et al., 2009b), but fluctuates abruptly between 0 and 3.5% abundance in the Itilliq Lake record without displaying coherent trends.

Modeled July air temperatures based on the chironomid assemblages (Fig. 4) show no significant trends. The few samples containing small percentages of *Abiskomyia* yield reconstructed temperatures up to 3°C cooler than the surrounding samples when tolerance downweighting is employed, but this pattern is very unlikely to reflect real paleotemperature trends. CCA results lend further support to the notion that chironomid assemblages at this site are not responding primarily to temperature changes: CCA Axis 1 is strongly correlated with both air and water temperature gradients within the training set, yet downcore samples show little variation along Axis 1 (Fig. 5). CCA Axis 2 correlates strongly with lake area and lake depth, but it is unlikely that these variables changed much during the past two millennia. The limited number of environmental variables included in the training set probably precludes attributing assemblage shifts to a particular environmental factor, but we can conclude more generally that late Holocene chironomid assemblage shifts at Itilliq Lake were predominantly in response to environmental factors other than temperature.

Many environmental factors, such as changes in lake water chemistry, trophic status, oxygen availability and macrophyte abundance, are known to influence chironomid distributions (e.g., Velle et al., 2005, 2010; Langdon et al., 2010). Consistent with this interpretation (and in contrast with some other sites, e.g., Thomas et al., 2008), inferred 20th century warming at Itilliq Lake has not been associated with clear changes in chironomid species assemblages, despite the recent dramatic increase in overall abundance of chironomid remains.

Comparison with other late Holocene climate reconstructions on Baffin Island

There are striking similarities between the record from Itilliq Lake and Lake CF8 (Fig. 1), the nearest lake from which similar proxies have been measured at comparable resolution (Thomas et al., 2008). Both lakes are from near-coastal sites along eastern Baffin Bay, and have generally similar present-day climate. The two lakes have similar trends in organic matter content, C:N values, and δ^{13}C values (Fig. 6). For example, the Lake CF8 record also shows a significant drop in organic matter content during the first millennium AD, and a smaller drop between ~AD 1700 and ~AD 1900, followed by increasing values in the past century. Similarly, the C:N values in both cores decrease by ~2 in the past century. Several varve-based records of summer temperature from Baffin Island have been produced that span the past millennium. These records similarly show summer temperature increases of at least 1°C in the past century, following cooler summer temperatures during the Little Ice Age (~AD 1600–1900; Hughen et al., 2000; Moore et al., 2001; Thomas and Briner, 2009; Fig. 7). The indicators of warming over the past century or two, inferred from both varve-based and organic matter-based records from Baffin Island, are part of a broader trend across the entire Arctic of significant warming in the past century (Fig. 7; Kaufman et al., 2009).

First millennium AD climate change

Prior to the past century, the most significant change in organic matter content in Itilliq Lake and Lake CF8 occurs during the first

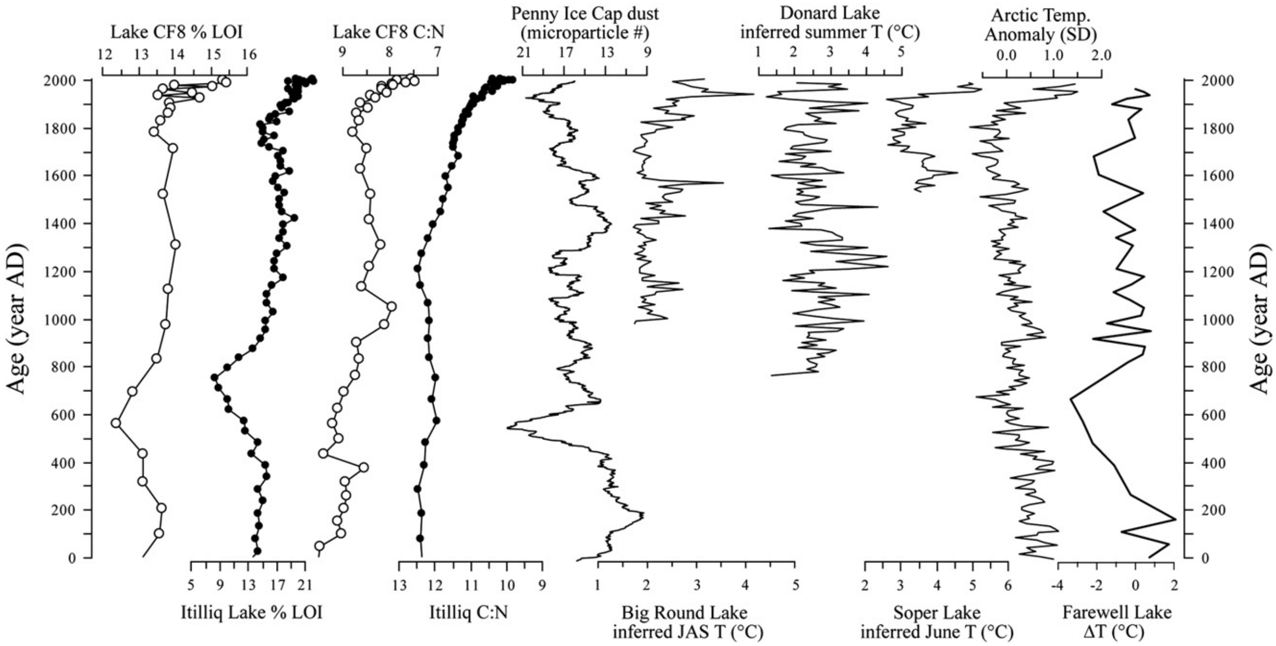

Figure 7. Downcore proxy data from Itilliq Lake (black circles) compared with the same parameters measured from Lake CF8 (open circles; Thomas et al., 2008), dust concentrations from the Penny Ice Cap (Fisher et al., 1998), varve-based records from Big Round Lake (Thomas and Briner, 2009), Donard Lake (Moore et al., 2001), and Soper Lake (Hughen et al., 2000), Arctic-wide compilation of summer temperature (Kaufman et al., 2009) and summer temperature recorded at Farewell Lake, Alaska (Hu et al., 2001).

millennium AD. Both lakes may be recording a decline in primary productivity, or increased inorganic sediment inputs may have caused the decline in organic matter content. Either way, the similar timing of these events in the two lakes indicates that this cool event was regional.

Few other records at high resolution exist during this interval from Baffin Island. The Penny Ice Cap, ~80 km to the southeast of Itilliq Lake, is one location where proxy data have been generated at comparable resolution and time scale (Fisher et al., 1998). The dust record (measured as microparticle number per gram of sediment) reveals a first-order trend of increasing dustiness over the past two millennia with significant centennial-scale variability (Fig. 7). Despite this variability, a pronounced increase in microparticle number occurs during the first millennium AD from AD 450 to 650. This episode of increased dust, and the decline in organic matter content in Lake CF8 and Itilliq Lake, which occur during the first millennium AD, are among the most significant changes in these records. Increased dustiness in the region may have even been the source of increased inorganic sediment input to Itilliq Lake. While acknowledging uncertainties in chronologies, we tentatively correlate these events, which suggest there was a significant cool anomaly on Baffin Island during the first millennium AD. It is difficult to know the precise timing of this event, but suggest (based upon regional correlations) that it is centered around AD 500–600, and that the Itilliq Lake chronology (the least reliable of the three due to the humic acid age offset) might be incorrect by a century or more.

We suggest that this first millennium AD cool period recorded on Baffin Island may be related to the first millennium AD climate event in Alaska and northwestern Canada. The climate event is recognized by Hu et al. (2001) in Farewell Lake as a ~3°C cool period centered at AD 600 (Fig. 7). The most pronounced manifestation of the event is registered as widespread advance of mountain glaciers throughout coastal mountains in British Columbia and southern Alaska (Calkin et al., 2001; Reyes et al., 2006; Barclay et al., 2009). Stratigraphic records of glacier change are abundant in northwestern North America, and are required to reconstruct first millennium AD glacier advances due to the obliterative nature of later, more extensive glacier advances during the Little Ice Age. There is currently no strong evidence for a glacier advance during the first millennium AD on Baffin Island (Briner et al., 2009), but stratigraphic records of glacier change are extremely rare on Baffin Island. One record of pre-Little Ice Age glacier change is available from radiocarbon-dated vegetation entombed beneath receding plateau ice caps on northern Baffin Island (Anderson et al., 2008). The radiocarbon ages indicate the timing of glacier advance, and a cluster of ages centered at AD 400 may signify glacier expansion on Baffin Island coeval with glacier expansion in northwestern North America (Anderson et al., 2008). Regardless of the glacial record, it seems plausible that a pronounced cool climate episode occurred both in northwestern and northeastern North America during the middle of the first millennium AD.

A North American Arctic cool climate episode may have been forced by similar mechanisms that caused quasi-periodic climate changes elsewhere in the world throughout the Holocene (Bond et al., 1997; Mayewski et al., 2004). Although the Itilliq Lake record is not long enough to assess millennial-scale variability, the first millennium AD cool interval at Itilliq Lake corresponds to a cool episode observed in records that demonstrate periodicity seen elsewhere in the Northern Hemisphere (Bond et al., 1997) and the Arctic (Hu et al., 2003; Reyes et al., 2006). Solar irradiance was at an extreme low at AD 650 (Steinhilber et al., 2009), which is within the dating error of the peak of the cool interval in eastern Arctic Canada (Fig. 7). As suggested in previous studies of Holocene climate periodicity (Hu et al., 2003; Mayewski et al., 2004), low solar irradiance might have forced the middle first millennium AD cool episode, in concert with amplifying mechanisms (Lean, 2010; Miller et al., 2010).

Conclusion

The multi-proxy results from Itilliq Lake presented here provide a new reconstruction of environmental change in Arctic Canada spanning the past 2000 yr. Shifts in organic matter content, likely reflecting changes in summer temperature, indicate a cool period during the late Little Ice Age (~AD 1700–1850 in Itilliq Lake) and a period of warming during the past century at Itilliq Lake. These same periods of inferred summer temperature change have been observed in other climate reconstructions from Baffin Island. For example, the industrial-era increase in the production of aquatic organic matter observed throughout Baffin Island (e.g., Michelutti et al., 2005; Thomas et al., 2008) is unprecedented in recent millennia. Furthermore, the environmental conditions of Baffin Island lakes during the 20th century appear to be unique within the past ~200,000 yr (Axford et al., 2009b), and may be part of changes that are occurring throughout the Arctic (Kaufman et al., 2009).

When combining the few high-resolution climate proxy records that exist from Baffin Island that span the first millennium AD, there appears to be a period of significant cooling on Baffin Island centered on ~AD 600. This episode may be the same cold climate anomaly observed in lacustrine and glacier records in northwestern North America (Calkin et al., 2001; Hu et al., 2001; Reyes et al., 2006; Barclay et al., 2009). At this point, it is difficult to know if a distinct episode of cool climatic conditions is pervasive across the North American Arctic or not. Why do some records show a distinct climate perturbation at AD 600 (Hu et al., 2001), whereas others show a broader period of cooling (Loso et al., 2006; McKay and Kaufman, 2009; Porinchu et al., 2009), and still others show no obvious anomaly during the first millennium AD (e.g., MacDonald et al., 2009)? The answer remains unresolved due to the paucity of records with sufficient resolution to characterize the climate of the first millennium AD. Regardless, these new climate proxy data from Baffin Island add to a growing number of high-resolution records spanning recent millennia from the Arctic. Records like these are important for investigating the history of Arctic climate change and for assessing regional similarities and differences across the Arctic.

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