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ORIGINAL PAPER

Climate of the past millennium inferred from varved proglacial lake sediments on northeast Baffin Island, Arctic Canada

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Abstract This study uses $^{239+240}$Pu-dated varved sediments from Big Round Lake, a proglacial lake on northeast Baffin Island, Arctic Canada to generate a 1000-year-long, annual-resolution record of past climate. Varve thickness is positively correlated with July–August–September temperature measured at Clyde River, 70 km to the north of the lake ($r = 0.46$, $p < 0.001$). We therefore interpret the variability and trends in varve thickness to partially represent summer temperature. The coolest Little Ice Age temperatures occurred in this record from 1575 to 1760 AD and were approximately 1.5°C cooler than today (average from 1995 to 2005 AD) and 0.2°C cooler than the last millennium (average from 1000 to 2000 AD). Pre-twentieth-century warmth occurred during two intervals, 970–1150 AD and 1375–1575 AD; temperatures were approximately 1.2°C cooler than today, but 0.1°C warmer than the last millennium. The Big Round Lake varve-thickness record contains features similar to that reconstructed elsewhere in the eastern Canadian Arctic. This high-resolution quantitative record expands our understanding of arctic climate during the past millennium.

Keywords Varves · Late Holocene paleoclimate · Arctic · Lake sediments · Air temperature proxy · Paleolimnology

Introduction

Current changes in the global climate system are occurring rapidly: global average temperatures are reaching levels unprecedented in at least the past 1000 years, summer sea-ice extent in the Arctic during 2007 was smaller than ever before recorded in the 50-year-long record, and land-based ice is retreating rapidly and contributing to global sea level rise (Jones and Mann 2004; Osborn and Briffa 2006; Meier et al. 2007; Shepherd and Wingham 2007; Stroeve et al. 2008). Comparison with annual-resolution paleoclimate places these recent changes in the context of past climate variability. Because the number of annual-resolution temperature records decreases dramatically back in time (Mann et al. 1999; Jansen et al. 2007), our understanding of the magnitude and spatial extent of past climate variability is limited. The past millennium encompassed a range of well documented but not widely quantified natural climate variability, including the spatially and temporally variable Medieval Warm Period (~950–1200 AD) and the more tightly

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This is one of fourteen papers published in a special issue dedicated to reconstructing late Holocene climate change from Arctic lake sediments. The special issue is a contribution to the International Polar Year and was edited by Darrell Kaufman.

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constrained Little Ice Age (LIA; 1550–1850 AD; Bradley 2000; Bradley et al. 2003; Hunt 2006). The Arctic is particularly sensitive to present and past climate change, partly due to positive cryosphere-albedo feedbacks associated with sea ice, snow, glacier and boreal forest extent (Moritz et al. 2002; Arctic Climate Impacts Assessment 2005; Chapin et al. 2005). Obtaining a more dense network of annual-resolution quantitative paleoclimate records in the Arctic for the past millennium is important to increase our understanding of the magnitude, timing and spatial extent of natural variability in this sensitive region, and to better understand the role of mechanisms that drive climate change.

This study utilizes sediments from Big Round Lake, a proglacial lake on northeast Baffin Island, Arctic Canada (Fig. 1), to produce a varve thickness record for the past millennium. By correlating varve thickness with the nearby climate station at Clyde River, we reconstructed late summer (July–August–September) temperature at subdecadal-resolution. Our record adds to the limited number of high-resolution arctic paleoclimate records that allow us to place recent climate changes in a longer-term context and better understand local and regional climate variability.

Setting

Big Round Lake (informal name, 69°52′ N, 68°50′ W, 180 m asl) is located between Inugsuin and

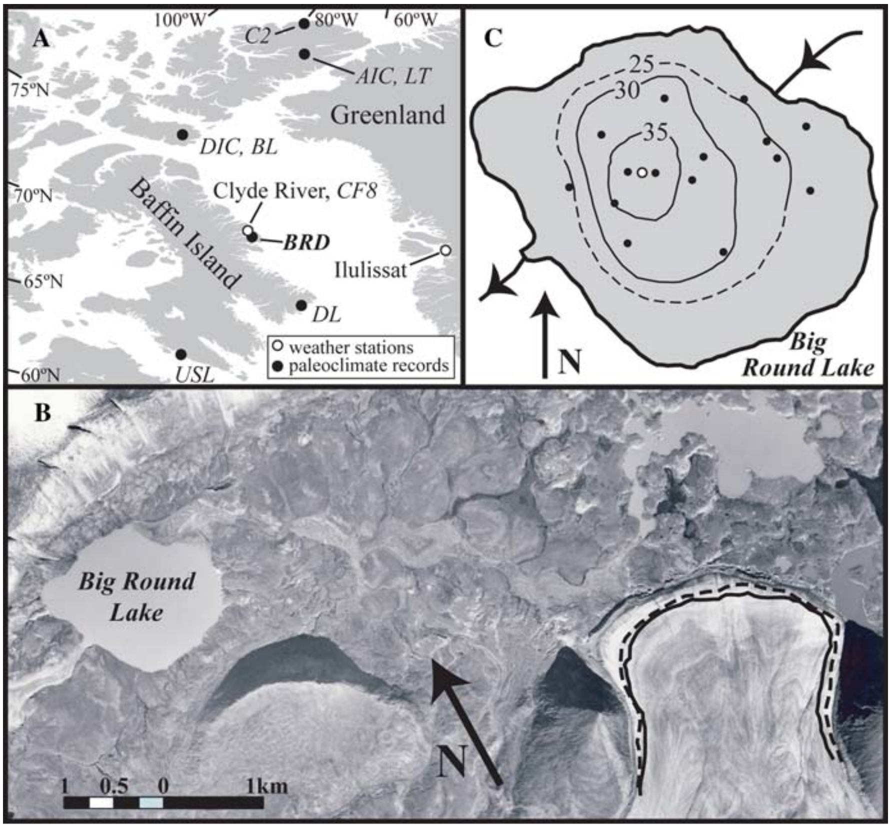

Fig. 1 **a** Map of eastern North American Arctic, showing location of paleoclimate records and weather stations mentioned in text. *AIC* Agassiz Ice Cap; *BL* Bear Lake; *BRD* Big Round Lake (this study); *C2* Lake C2; *CF8* Lake CF8; *DIC* Devon Ice Cap; *DL* Donard Lake; *LT* Lake Tuborg; *USL* Upper Soper Lake. **b** Vertical aerial photograph of the glacier and the proglacial stream that feeds Big Round Lake on September 1, 1960 (reproduced with the permission of Natural Resources Canada 2008, courtesy of the National Air Photo Library). Dashed line on glacier indicates 1990 extent; solid line indicates 2000 extent (mapped from Landsat TM and ETM+ images). **c** Bathymetry of Big Round Lake. Black dots are depth measurements; white dot in the central basin is where both cores were retrieved

McBeth fjords on northeast Baffin Island (Fig. 1a). Big Round Lake is 70 km south of Clyde River, the closest town with a weather station (in operation since 1946). The 1.3 km^2 lake sits on crystalline bedrock in a hummocky landscape. A 150-m-high hill 700 m to the south and 500-m-high cliffs 300 m to the north likely contribute colluvial sediment to the lake. Sediment is also delivered to Big Round Lake via a single 5-km-long proglacial stream emanating from a large outlet glacier (Fig. 1b). This glacier has retreated ~250 m in the past 50 years, a small distance compared to the total distance between the glacier and the lake. Big Round Lake has a single outflow channel and a single-basin geometry that is 36 m deep at the deepest point near the lake's center (Fig. 1c).

Because temperatures remain below freezing from September to late May (Environment Canada 2007), ice covers the lake for ~9 months of the year and is ~2 m thick by the end of the winter season. A moat around the edge of the lake begins to form in late June or July and the lake is usually ice-free for the months of July, August, and September. Sediment input to the lake is therefore confined to the summer months from late June to September.

Methods

Sediment coring

In May 2006 a 34-cm-long surface sediment core (06BRDS2, herein referred to as "surface core") with an intact sediment-water interface was collected using a Universal Corer from the deepest basin of Big Round Lake (36.3 m depth; Fig. 1c). A 270-cm-long sediment core (06BRDP1, herein referred to as "long core") was collected using a sled-mounted percussion coring system (Nesje 1992) a few meters from the surface core location. Fine (millimeter-scale) silt and clay laminations were visible through the clear surface core tube. The surface core was kept vertical and dewatered for several days, and both cores were packed with foam and kept cool until shipment.

Physical parameters

Subsamples were collected, weighed wet, freeze-dried, and weighed again for moisture content from each core (0.5 cm increments in the surface core, every other centimeter in the long core). Loss-on-ignition at 550°C (LOI) was measured on an aliquot (~100 mg) of each sample. An aliquot (50 to 75 mg) of each sample was analyzed for biogenic silica (BSi) concentration at Northern Arizona University following the methods described by Mortlock and Froelich (1989). Magnetic susceptibility (MS) was measured every 0.5 cm on the split core faces using a Bartington MS2E Surface Scanning Sensor connected to a Bartington MS2 Magnetic Susceptibility Meter.

Lamination analysis

The surface core was cut into thin sections at the Quaternary Sediments Lab at Mt. Holyoke College in South Hadley, MA following methods similar to Lamoureux (1994) and Francus and Asikainen (2001). A section of the long core (23.5–78.5 cm) was cut into thin sections at Texas Petrographics Services, Inc. in Houston, TX. These thin sections are thinner than the surface-core thin sections cut at Mt. Holyoke College. Therefore, when the thin sections were scanned using a transparency scanner at 1600 dpi (e.g. Lamoureux and Gilbert 2004), the surface-core thin sections appeared darker than the long-core thin sections. This resulted in some initial differences in lamination identification between the two cores. These differences were identified and eliminated by examining the sections where the two cores overlap and matching the criteria for lamination identification between cores. Laminated couplets were identified, marked and counted in Adobe Illustrator and lamination thicknesses were measured perpendicular to the laminations using ImageJ software.

$^{239+240}Pu$ dating

Plutonium ($^{239+240}Pu$) is a radionuclide that was introduced into the atmosphere with atmospheric nuclear testing in 1952. Atmospheric concentrations of $^{239+240}Pu$ peaked at the height of testing in 1963. $^{239+240}Pu$ is used to identify chronostratigraphic events in lake sediments because its fallout record is well-constrained and it is generally well-preserved in lake sediments worldwide (e.g. Ketterer et al. 2004a). Dried aliquots (0.5 g) of the top 8 cm of the surface core (0.5 cm increments, $n = 16$) were analyzed at Northern Arizona University for $^{239+240}$Pu concentrations using ICP-MS analysis following the methods of Ketterer et al. (2004b).

Results and discussion[1]

Core stratigraphy and sedimentology

Big Round Lake sediments are minerogenic and composed of clay to fine sand. The surface core is dominated by distinct silt-clay couplets. The upper 58 cm of the long core are also dominated by silt-clay couplets interspersed with fine sand layers. Below 58 cm, the long core is composed mostly of fine sand and contains fewer and more diffuse laminations, all of which lack the distinct normal grading and clay caps seen in the upper sediments. This indicates that conditions led to couplet deposition only in the late Holocene, potentially due to several factors such as glacier proximity and the duration of seasonal lake-ice cover.

In thin section, the laminations are normally graded: silt fining upwards into a clay cap and a sharp contact between each clay cap and the overlying silt layer (Fig. 2). The laminations typically range from 0.1 to 5 mm thick; most are <1 mm thick. They are intermittently interspersed with layers of fine sand (2–5 mm thick). The sand layers are easily visible because they are composed of light-colored grains and appear within the dark, fine-grained upper portion of a couplet (Fig. 2). A sand layer is not found within every couplet, and two distinct sand layers can exist within a single couplet.

Lamination number and thickness

Sediment consolidation can produce depth-dependent trends in varve thickness, particularly at the surface where the sediment is not compacted (Hughen et al. 2000). Moisture content (a measure of porosity) in the surface core does not decrease dramatically down-core as it would if the surface were not consolidated, but rather covaries with organic-matter content (see below; Menounos 1997). This is probably because the core was dewatered in the field, a process that drove most of the water out of the uppermost sediments. We therefore do not account for changes in porosity in our uppermost lamination measurements.

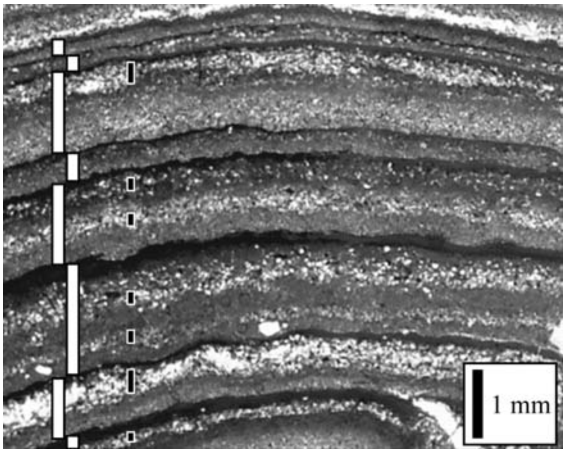

Fig. 2 Scanned thin section (1,600 dpi) from the Big Round Lake long core (06BRDP1). White boxes delineate laminations; black boxes delineate sand layers. The variability in lamination and sand-layer thickness across the thin section increases uncertainty in our comparisons with the Clyde River instrumental record

Initial lamination counts revealed 500 laminations in the surface core and 641 laminations in the finely laminated portion of the long core (Fig. 3a, b). In the section where the two cores overlap, there was a ~10% difference in the number of laminations after the initial counts (87 in the surface core, 79 in the long core). This was probably because the surface-core thin sections were thicker than the long-core thin sections and therefore looked different (less contrast) after scanning. Misidentified laminations were located by close comparison of the thin sections from the two cores. Lamination misidentification was most often attributable to a sand layer overlain by a clay cap incorrectly identified as a silt-clay couplet. The laminations were counted and measured a second time and care was taken to ensure that the fine sand layers were not misinterpreted as silt layers. Following this remeasurement, the overlapping sections had the same number of laminations with similar thicknesses (Fig. 3a, b). The final counts revealed 495 laminations in the surface core and 628 laminations in the long core, indicating that there was a within-core error of 1–2% in lamination counts and in the

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[1] The data presented in this paper are available on-line at the World Data Center for Paleoclimatology (ftp://ftp.ncdc.noaa.gov/pub/data/paleo/paleolimnology/northamerica/canada/baffin/big-round2008.txt).

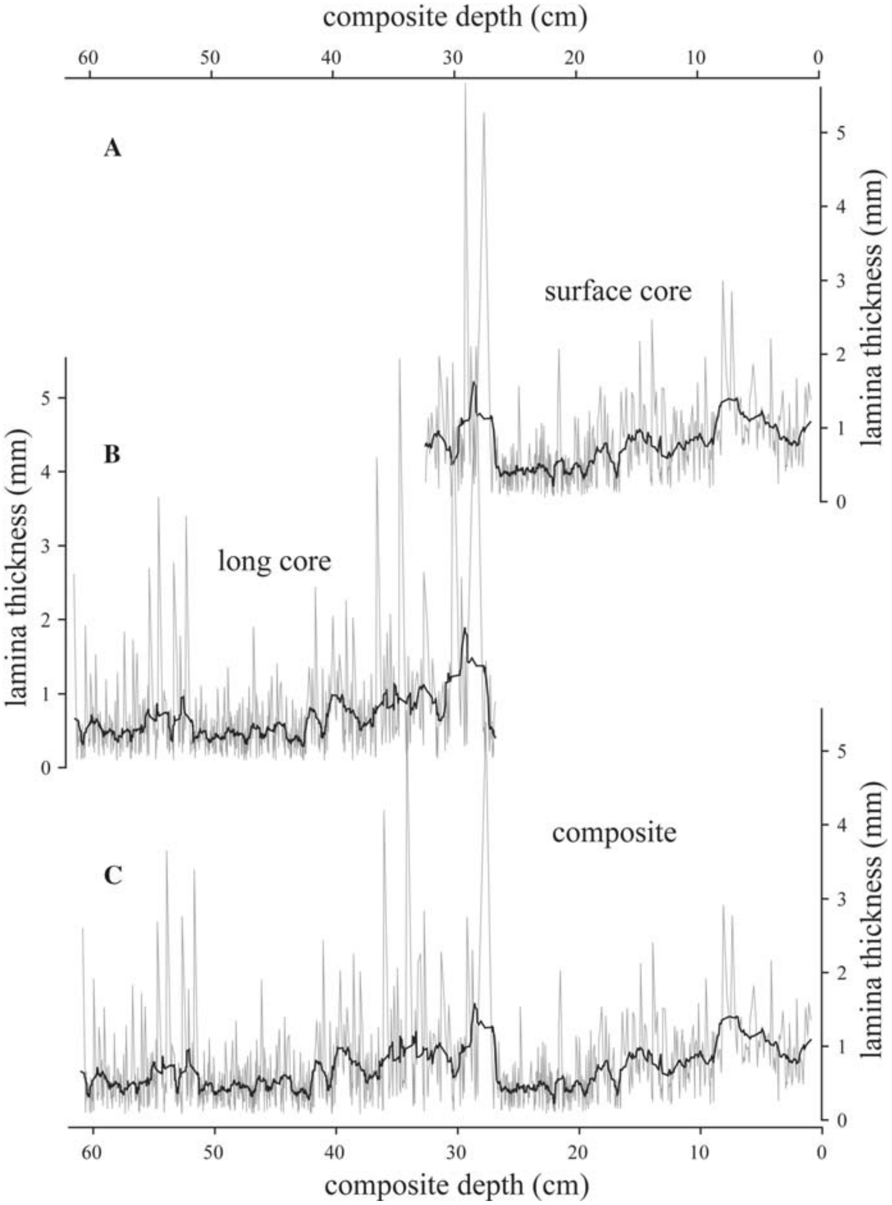


Fig. 3 Lamination thicknesses from Big Round Lake sediment plotted against composite depth for **a** the surface core, **b** the long core, and **c** a composite of the two cores. Gray lines are thicknesses of individual laminations; black lines are 15-point running means

final age model. Lamination thicknesses were averaged for the overlapping sections to create a composite lamination thickness record containing 1,033 laminations (Fig. 3c).

Chronology

The surface core $^{239+240}$Pu profile shows an onset of $^{239+240}$Pu deposition (1952) at 5.0–5.5 cm and peak $^{239+240}$Pu concentrations (1963) at 3.5–4.0 cm (Fig. 4a). These depths correspond to surface-core lamination numbers 30–33 and 41–46, respectively (Fig. 4b). Hence, $^{239+240}$Pu dates the core to within a few years. Because the laminations are millimeter-scale, the uppermost surface-core laminations were likely disturbed during dewatering, packing, and transport of the core. We therefore used an independent method to determine which year the uppermost intact lamination represents, as follows. Elsewhere on Baffin Island, varve-thickness records have positive correlations ($r > 0.5$) with summer temperature records from nearby climate stations (Hughen et al. 2000; Moore et al. 2001). The normally-graded silt-clay couplets and distinct boundaries between clay

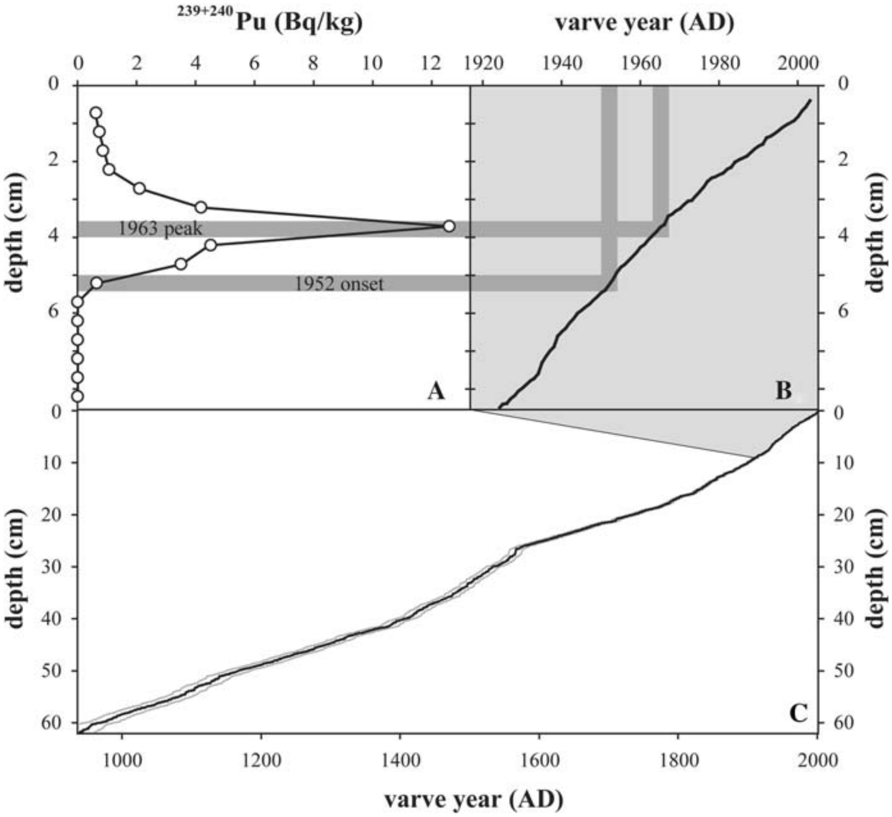


Fig. 4 **a** $^{239+240}$Pu profile from Big Round Lake surface core. Onset and peak of $^{239+240}$Pu deposition labeled with horizontal gray bars. **b** Lamination year plotted against composite lamination depth for the uppermost 8 cm. Gray bars mark depth intervals of known age based on the $^{239+240}$Pu profile. **c** Lamination year plotted against composite lamination depth for the top 60 cm (the finely laminated section). Gray lines illustrate the interval of 2% error in lamination counts, estimated from the difference between initial and final counts

caps and overlying couplets in Big Round Lake sediments suggest that the Big Round Lake laminations may have been deposited annually (e.g. Moore et al. 2001; Lamoureux et al. 2002). We therefore compared Big Round Lake lamination thickness to Clyde River summer temperature for the years 1946–2005. To determine which year the uppermost lamination most likely represents, we calculated correlation coefficients between the two datasets, with the uppermost lamination representing a range of years from 1997 to 2005. The best correlation results when the uppermost intact lamination represents 2003 AD ($r = 0.46$, $p < 0.001$, $n = 58$). This evidence suggests that the top intact lamination was deposited in summer 2003, which corroborates the $^{239+240}$Pu data: lamination numbers 30–33 and 41–46 correspond to years 1952–1955 and 1963–1968, respectively (Fig. 4b). Based on these independent lines of evidence (stratigraphy of the laminations, correlation to climate and radiometric dating), we conclude that the laminations in the Big Round Lake cores are varves.

A composite depth scale was generated by summing varve thickness down core. Cumulative depth plotted against lamination year (Fig. 4c) yielded an age-depth model that we applied to measurements of physical parameters down core.

Physical parameters of the sediment

Sediment moisture content ranges from 24–42% throughout both cores and covaries with LOI (Fig. 5a, b). LOI is low throughout the record (2.0–5.5%; Fig. 5b). BSi also remains low (6.5–9.2%, measured only in the surface core; Fig. 5c). The low concentrations of organic matter in Big Round Lake indicate low productivity in the lake and/or minor inputs of allochthonous organic material. Organic material visible in the thin sections appears to be leaf fragments with few aquatic macrofossils, indicating that most of the organic input to Big Round Lake is allochthonous. The MS record has opposite trends to the organic-matter proxies (Fig. 5d) and has trends similar to the varve-thickness record (see below).

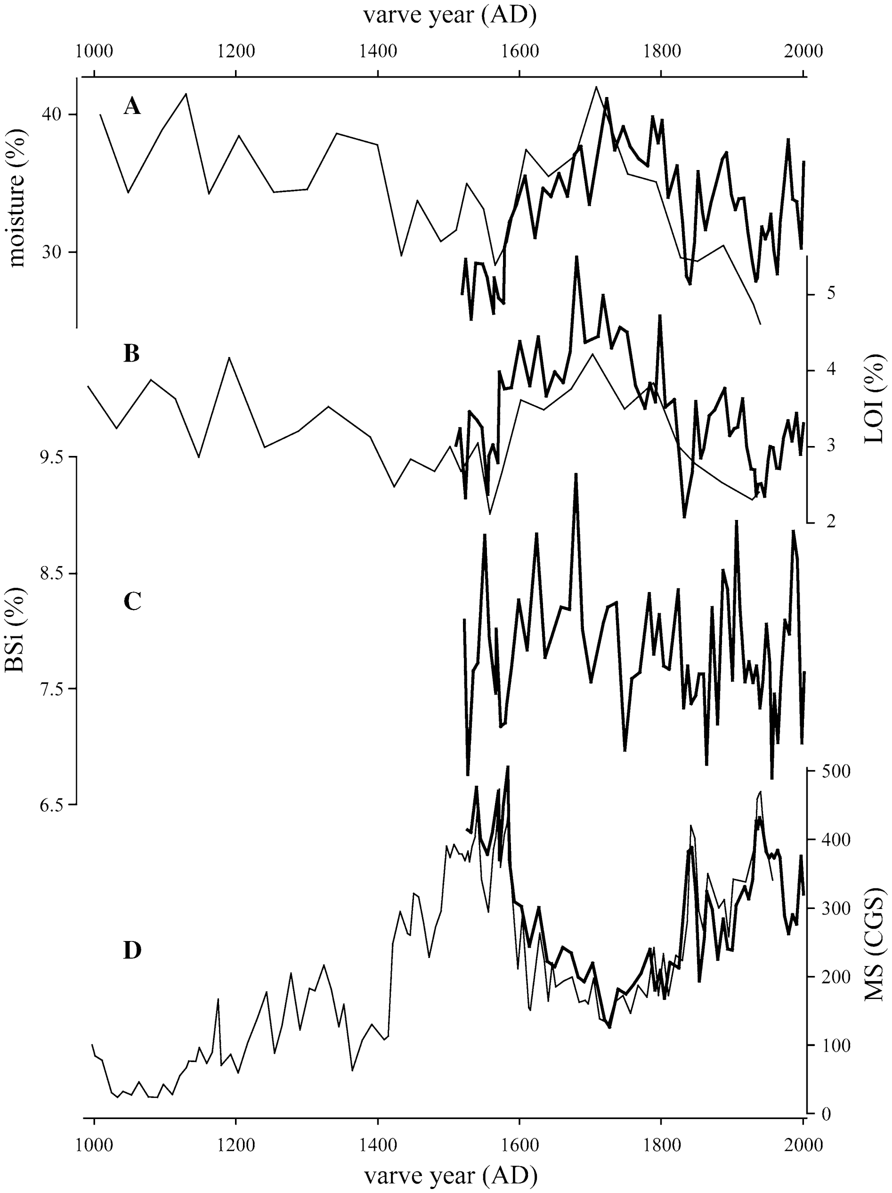


Fig. 5 Physical parameters of the Big Round Lake sediment cores plotted against age. Fine lines are data for the long core; bold lines are data for the surface core. **a** Moisture content. **b** Organic content measured by loss-on-ignition (LOI). **c** Biogenic-silica (BSi) content. **d** Magnetic susceptibility (MS)

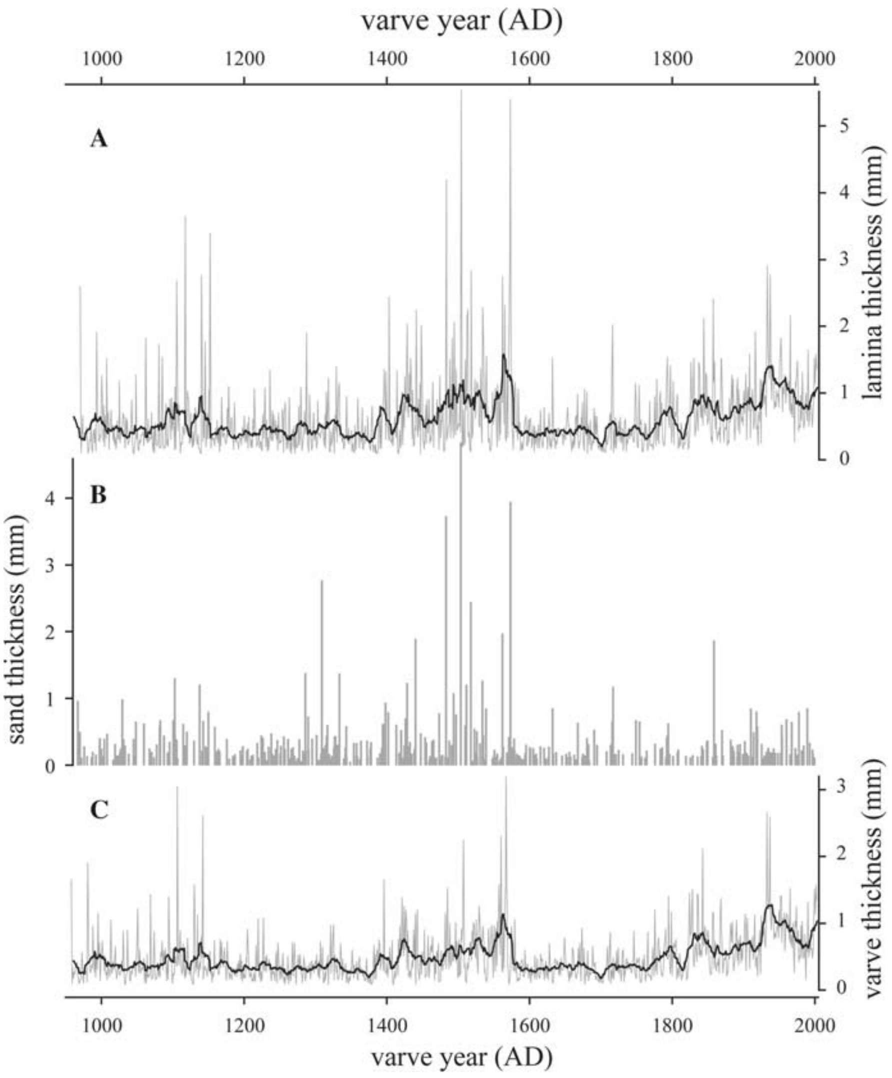
The peak in LOI and BSi in the eighteenth century occurs during a period of thin varves (Fig. 6), and LOI and BSi were low in the nineteenth and twentieth centuries, when the thickest varves were present. These results are counterintuitive because lacustrine primary productivity decreases in response to cooler temperatures (Wolfe 2003), which would also result in thin varves. The input of minerogenic material during cold periods may have decreased more dramatically than the organic input, resulting in an apparent increase in organic matter content. Similarly, during warm periods, minerogenic input likely increased more than organic input to the lake, resulting in an apparent decrease in organic matter content. The opposite signals between the organic proxies and the MS (Fig. 5) supports the hypothesis that organic matter is diluted by minerogenic input to the lake.

Varve thickness and climate

Sand layers

Some studies in the eastern Canadian Arctic have explored whether sand layers (Moore et al. 2001) or

Fig. 6 The Big Round Lake varve record plotted against varve year (AD). Gray lines are thicknesses of individual laminations; black lines are 15-point running means **a** Lamination thickness. **b** Sand-layer thickness. **c** Varve thickness



sand grains (Lamoureux and Gilbert 2004) are controlled by climatological factors (e.g. precipitation, niveo-aeolian transport; Moore et al. 2001; Lamoureux and Gilbert 2004). The sand layers that interrupt normally-graded couplets throughout Big Round Lake sediments may have been deposited during stochastic environmental events (e.g. Lewis et al. 2002). Because the sand layers most often appear in the fine-grained upper portion of a couplet (Fig. 2), they are likely deposited in the late summer or fall before the lake freezes over. The Clyde River climate record indicates that the months of August, September, and October have more precipitation than the rest of the year (Environment Canada 2007). We found a moderate correlation ($r = 0.45$, $p = 0.05$, $n = 19$) between Big Round Lake sand-layer thickness and August precipitation at Clyde River (Table 1). Sand-layer occurrence and thickness in Big Round Lake therefore may be partially controlled by precipitation. The lack of a stronger correlation may be due to the complex pattern of precipitation in mountainous regions. The thickest sand layers (many >1 mm, and several >2 mm) were deposited from 1375 to 1575 AD (Fig. 6). The thinnest (<0.5 mm) and fewest sand layers were deposited during the LIA from 1575 to 1850 AD, indicating that the LIA was drier than other intervals during the past millennium.

Table 1 Correlation coefficient and *p*-values for various comparisons of Big Round Lake lamination thickness and Clyde River instrumental climate

Clyde River vs. sand thickness (annual)

	r	*p*
Precipitation		
All years included		
Total annual	0.01	0.917
March–April–May (spring)	0.02	0.893
June–July–August (summer)	0.09	0.491
September–October–November (fall)	0.09	0.508
December–January–February (winter)	0.04	0.777
June	0.12	0.351
July	0.15	0.265
August	0.03	0.820
September	0.12	0.363
October	0.02	0.854
Only sand layers		
Total annual	0.04	0.855
March–April–May (spring)	0.01	0.964
June–July–August (summer)	0.17	0.486
September–October–November (fall)	0.17	0.489
December–January–February (winter)	0.08	0.742
June	0.12	0.624
July	0.12	0.634
August	0.45	0.054
September	0.07	0.780
October	0.04	0.866

Clyde River vs. varve thickness (annual)

	r	*p*
Temperature		
Mean annual T	0.10	0.469
March–April–May (spring)	0.08	0.529
June–July–August (summer)	0.38	0.003
September–October–November (fall)	0.19	0.159
December–January–February (winter)	0.13	0.343
July–August–September (ice free)	0.46	<0.001
Precipitation		
Total Annual	0.13	0.349
March–April–May (spring)	0.06	0.655
June–July–August (summer)	0.17	0.215
September–October–November (fall)	0.06	0.669
December–January–February (winter)	0.04	0.749

Varves

Because sand layers represent deposition from stochastic precipitation events, we generated a varve-thickness record by subtracting sand-layer thickness from total lamination thickness (Fig. 6). The resulting record spans 1033 years from 970 to 2003 AD, and individual varve thickness ranges from 0.1 to 3 mm (Fig. 6). Varve thickness had high interannual variability from 970 to 1150, 1375 to 1575, and 1760 to 2003 AD. Thin varves with low interannual variability were deposited from 1150 to 1375 and 1575 to 1760 AD. Sustained thick varves were deposited from 1375 to 1575 AD and during the nineteenth and twentieth centuries. During the 1920s, average varve thickness increased abruptly from 0.6 to 1.2 mm, and the most consistently thick varves were deposited during the 1930s. The nineteenth and twentieth centuries are unique in the Big Round Lake varve thickness record for two reasons: 1. Average varve thickness was greater than at any other time in the record, and 2. Minimum varve thickness was greater than at any other time in the record (i.e. the minimum thickness measured throughout the record was ~0.1 mm, but during the nineteenth and twentieth centuries the minimum thickness increased to 0.2–0.7 mm).

Significant correlations with climate have been established for varve thickness throughout the eastern Canadian Arctic (e.g. Hughen et al. 2000; Lamoureux and Gilbert 2004). We compared Big Round Lake varve thickness to temperature and precipitation for different seasons at Clyde River, 70 km from Big Round Lake (Fig. 7; Table 1). The best correlation was obtained with July–August–September (JAS) temperature (Table 1), the months when the lake is ice-free. Varve thickness and Clyde River JAS temperature (1946–2005) are positively correlated with a high level of significance ($r = 0.46$, $p < 0.001$, $n = 58$; Fig. 7b). Varve thickness correlations are strongest with late summer temperatures probably because this is the only time when the lake is at least partially ice-free, the glacier is melting and sediment can be transported to and deposited in the lake. An increase in summer temperature would therefore lead to longer ice-free time and more glacier melt, resulting in more sediment transported

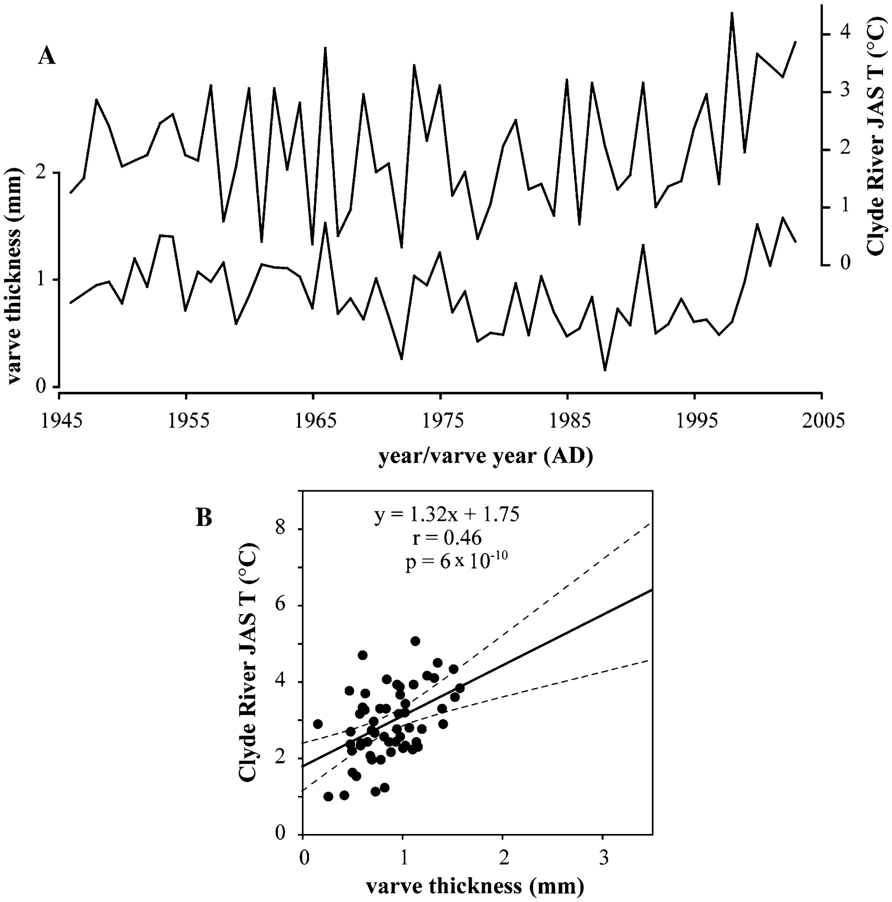


Fig. 7 **a** Big Round Lake varve thickness and the Clyde River instrumental temperature record shown for the period during which these records overlap (1945–2003). **b** Scatter plot of these two records. Solid black line is the regression (equation, coefficient of correlation, and *p*-value shown). Dashed curves represent uncertainty (2σ) on the regression

to and deposited in Big Round Lake and thus, the creation of thick varves.

Other influences on varve thickness

As Hodder et al. (2007) point out, factors other than temperature can influence varve thickness. Leonard (1997) demonstrated that changes in glacier activity and position relative to the lake influence varve thickness. The Big Round Lake varve record is probably not influenced by changes in glacier position, at least during the twentieth century. The maximum Holocene extent of the glacier was likely attained in the late nineteenth century (Briner et al. in press). The glacier remained at this maximum position until the mid-twentieth century (Fig. 1b) and has retreated ~250 m since 1960 AD, a small distance compared to the size of the glacier (~2 km across) and the 5-km-long proglacial stream. We cannot determine pre-twentieth-century glacier position, however, and therefore do not know whether greater changes in glacier position occurred from 1000 to 1900 AD that would have influenced the Big Round Lake varve record. This adds uncertainty to our varve-inferred temperature reconstruction prior to the twentieth century. Furthermore, we cannot determine changes in subglacial sediment storage that would influence varve thickness.

The sedimentation regime in Big Round Lake changed dramatically around 970 AD (58 cm depth in the long core). Neoglaciation initiated on Baffin Island ~3 ka (Briner et al. in press), and the glacier likely was farther from the lake before this time. The distance between the glacier and Big Round Lake likely was changing around 970 AD, and may have caused the change in sedimentation at the lake. Although the transition from coarse, weakly laminated sediments to varves appears to be rapid, the early part of the varve record may be influenced by the transition and may contain hiatuses. There also may be hiatuses throughout the Big Round Lake varve record due to changing depositional/erosional environments that were not identifiable from this single core site. These factors could potentially be accounted for by future work on several cores from throughout the deep basin of Big Round Lake.

Events that are more stochastic, including hillslope activity, sediment storage and release upstream of Big Round Lake and transport of sediment by lake ice, also may influence varve thickness in Big Round Lake. We cannot quantify the influence of these factors, however, due to the lack of sediment process monitoring in Big Round Lake. Finally, the correlation of varve thickness and summer temperature may be further complicated by the distance between Big Round Lake and the instrumental weather station. Big Round Lake is in an inland alpine environment, whereas the Clyde River temperature data are from a coastal lowland area. These factors may influence varve thickness and chronology, and thus decrease the correlation between summer temperature and varve thickness.

Temperature reconstruction

The positive correlation between varve thickness and Clyde River JAS temperature indicates that summer temperature has some influence on Big Round Lake varve thickness. We therefore used this relationship to infer past summer temperature from 970 to 2003 AD. We smoothed the reconstructed temperature to 3-year resolution because it accounts, to some degree, for the non-climate-related influences on varve thickness (Fig. 8). The inferred temperatures must be treated with caution, especially in the pre-instrumental period, because of the non-climatic factors that can influence varve thickness. We present the reconstructed temperatures with an estimate of error based on the 2σ confidence intervals of the least-squares regression between varve thickness and JAS temperature (Fig. 7b). The errors are typically ±0.2 to 1.6°C. Log-transformation of varve thicknesses does not improve the correlation with summer temperature. The Durbin-Watson statistic is $d = 2.1$ for this regression, indicating that it is not significantly influenced by autocorrelation in the time series. The instrumental temperature record from 1995 to 2005 (average JAS temperature: 3.7 ± 0.8°C at Clyde River), and the average of the last millennium (2.4 ± 0.5°C) are used as the baselines for comparison (Fig. 8). During the LIA (1575–1760 AD), varve-inferred Clyde River JAS temperature was 1.5 ± 0.2°C cooler than today and 0.2 ± 0.2°C cooler than the last millennium (Fig. 8). The warmest pre-twentieth century period in this 1000 year record, 1375–1575 AD, was characterized by temperatures 1.2 ± 0.6°C cooler than today and 0.1 ± 0.2°C warmer than the last millennium.

The past 1000 years in the eastern Canadian Arctic

Comparison of the Clyde River varve-inferred temperatures to other paleoclimate records in the eastern Canadian Arctic reveals regional climate patterns. The 150-year-long instrumental record from Ilulissat, Greenland (Figs. 1, 9) exhibits pronounced warming, particularly during the 1920s and 1930s (Vinther et al.

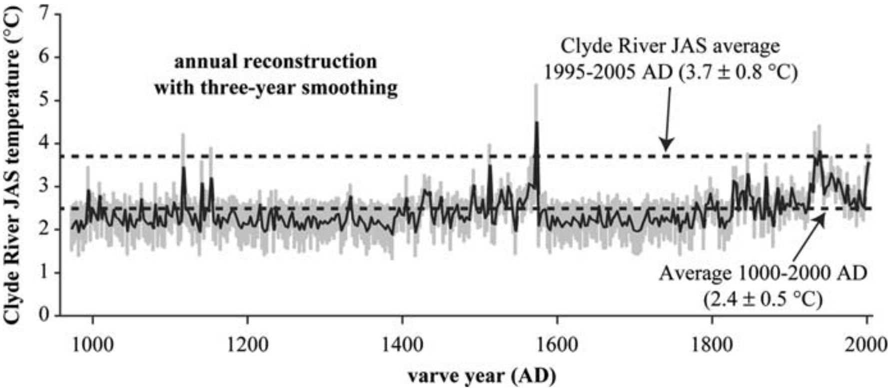


Fig. 8 Clyde River JAS temperature for the past millennium inferred from Big Round Lake varve thickness. Black curve is the 3-year smoothing of the annual reconstruction; gray shading is the uncertainty (2σ) on the regression derived from data shown in Fig. 7b. Dashed lines are the average instrumental JAS temperature at Clyde River from 1995 to 2005 AD and the average varve-inferred JAS temperature at Clyde River from 1000 to 2000 AD

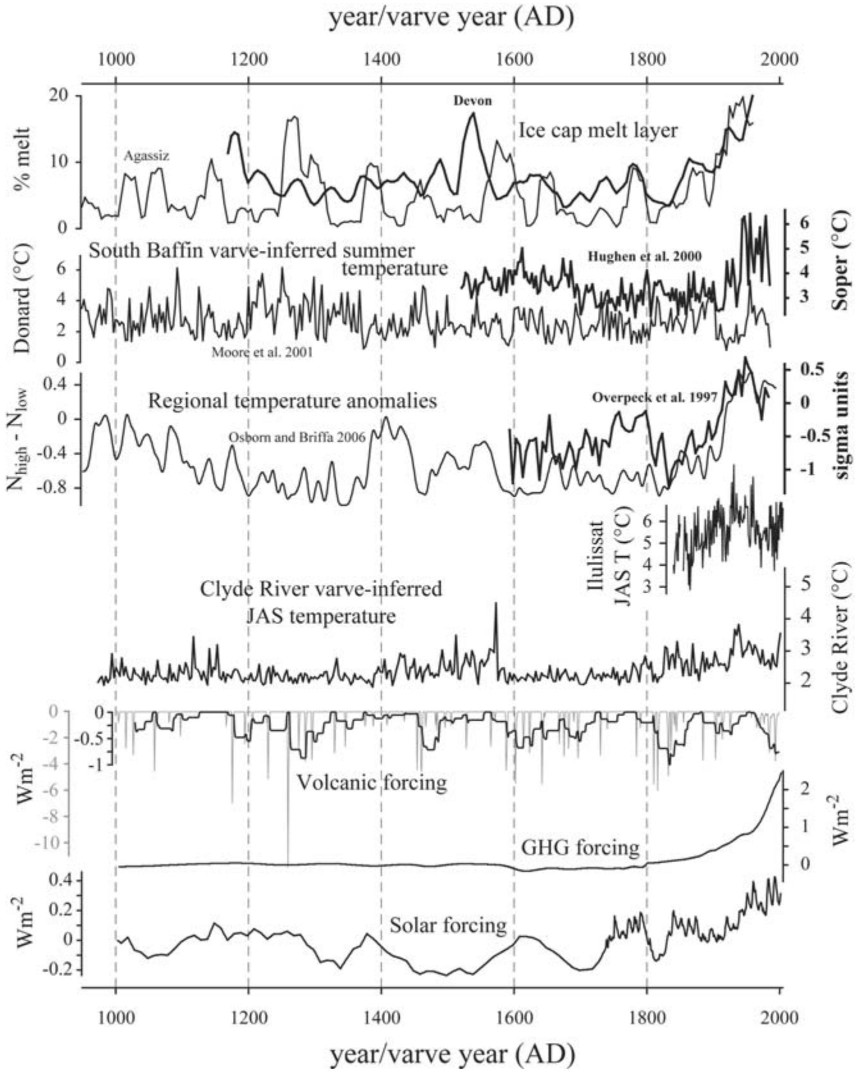


Fig. 9 Clyde River varve-inferred temperature, regional paleoclimate records, and volcanic, solar, and greenhouse gas (GHG) forcing. Ice cap melt-layer records: Agassiz (fine) and Devon Ice Cap (bold) are 5-point running means of 5-year-resolution records (Fisher 1979; Fisher and Koerner 1994; Fisher et al. 1995). South Baffin varve-inferred summer temperature records: Donard (fine) and Upper Soper (bold) are 15-point running means of annual-resolution data (Hughen et al. 2000; Moore et al. 2001). Regional temperature anomalies: Northern Hemisphere compilation (fine) is at annual resolution with a 20 year filter (Osborn and Briffa 2006); Arctic summer temperature compilation (bold) is at 5-year resolution (Overpeck et al. 1997). Ilulissat, Greenland instrumental temperature is at annual resolution (Vinther et al. 2006). Clyde River varve-inferred JAS temperature is at 3-year resolution, shown without uncertainties. Climate forcing: fine gray lines are raw volcanic forcing inferred from Greenland ice core acidity (Hammer et al. 1980; Crowley et al. 1993; Langway et al. 1995; Zielinski 1995) and compiled by Crowley (2000), bold black lines are the raw data averaged over 25 years (plotted at youngest age of the 25-year window) and scaled by a factor of four to make the patterns more visible. Pre-1850 GHG forcing from Etheridge et al. (1996); post-1850 GHG forcing from Crowley (2000). Solar forcing inferred from radiocarbon measurements from tree rings (Stuiver and Braziunas 1993) and contemporary solar monitoring (Lean et al. 1995); the two records were spliced by Crowley (2000)

2006). The greatest increase in Clyde River varve-inferred temperature also occurs during this two-decade interval (Fig. 9). A 500 year varve-thickness record from non-glacial Upper Soper Lake provides an annually resolved record of June temperature from south Baffin Island (Figs. 1, 9; Hughen et al. 2000).

The lowest temperatures at Upper Soper Lake (early eighteenth to nineteenth centuries) occurred later than the lowest temperatures at Big Round Lake, but on average are 1°C cooler than twentieth century average temperatures, similar to the LIA temperature difference inferred from Big Round Lake. Both records exhibit an abrupt increase in temperature in the first part of the twentieth century, synchronous with the strongest warming recorded at Ilulissat. Varve thicknesses from proglacial Donard Lake on southeast Baffin Island were used to reconstruct subdecadally resolved summer temperature during the past 1200 years (Figs. 1, 9; Moore et al. 2001). Despite similar depositional environments, the Donard Lake and Big Round Lake records are generally dissimilar, except for an increasing temperature trend in the early nineteenth century (Fig. 9).

Varve-thickness records from the Canadian High Arctic contain variability similar to the Big Round Lake record. Bear Lake, Lake Tuborg, and Lake C2 (Fig. 1, not shown in Fig. 9) all contain thin varves during the seventeenth and eighteenth centuries, and increasing varve thickness during the twentieth century, much like Big Round Lake (Hardy et al. 1996; Lamoureux and Bradley 1996; Lamoureux and Gilbert 2004; Smith et al. 2004).

The Big Round Lake varve-thickness record is broadly similar to the Devon and Agassiz ice cap melt records (Figs. 1, 9; Fisher 1979; Fisher and Koerner 1994; Fisher et al. 1995). This is expected given that they are controlled by similar processes: glacier melt produces water that transports sediment to Big Round Lake and that refreezes as melt layers on top of the ice caps. All three records exhibit pronounced increasing temperatures in the nineteenth and twentieth centuries and low temperatures in the seventeenth and eighteenth centuries. Furthermore, all three records contain peaks in percent melt/varve-inferred temperature during the sixteenth century.

Studies of lacustrine biological paleoclimate proxies (e.g. diatoms, chironomids) in the eastern Canadian Arctic demonstrate that dramatic ecological changes, likely driven by climate, occurred in the late twentieth century (e.g. Douglas et al. 1994; Wolfe 2003; Michelutti et al. 2005, 2006; Smol et al. 2005; Smol and Douglas 2007a, b). Chironomid assemblages from nearby Lake CF8 (Fig. 1; not shown in Fig. 9) indicate that dramatic ecological and chironomid-inferred temperature changes began in 1970 AD in this region (Thomas et al. 2008). This contrasts with varve thicknesses at Big Round Lake: the most dramatic varve-thickness-inferred warming occurred in the 1920s, and was followed by cooling until a warming trend began in the 1990s. The disparity between these two records indicates that either the ecology of small Arctic lakes responds more slowly to changes in climate than varve thickness, or that bioturbation in Lake CF8 sediments mutes the signal of rapid ecological changes or that one or both of these proxies is controlled by other factors (cf. Walker and Cwynar 2006; Hodder et al. 2007).

Overpeck et al. (1997) synthesized multiple paleoclimate records (mostly annual resolution) into an Arctic-wide temperature record for the past 400 years (Fig. 9). The Big Round Lake record contains similarities to this synthesis: the strongest warming occurs in the late nineteenth and early twentieth centuries, and both records exhibit a brief cooling in the mid-twentieth century followed by a warming trend that continues today. The timing of the coldest LIA temperatures differs between Big Round Lake (1575–1760 AD) and the arctic synthesis (mid-nineteenth century), although the arctic synthesis does contain cooler temperatures from ~1600 to 1750 AD (Overpeck et al. 1997). Osborn and Briffa (2006) compiled proxy records of Northern Hemisphere temperature change for the past 1200 years (Fig. 9). The Big Round Lake varve-inferred temperatures are similar to this reconstruction: the twentieth century is anomalously warm, the eleventh to twelfth centuries, and fourteenth to sixteenth centuries are cooler than but similar to the twentieth century, and the expression of the LIA is synchronous (late sixteenth to eighteenth centuries).

Finally, we compared the Big Round Lake varve thickness record with climate-forcing mechanisms for the past millennium (Fig. 9; Crowley 2000). Periods of low volcanic activity generally coincide with the highest varve-inferred temperatures (e.g. late sixteenth and early twentieth centuries). A prolonged interval of volcanic activity beginning in the late sixteenth century is synchronous with the LIA in the Big Round Lake record (1575–1760 AD). Prolonged volcanic activity from the late twelfth to early thirteenth centuries also corresponds with low varve-inferred temperatures (1150–1375 AD). The Big Round Lake record seems to match solar variability from the early seventeenth century to present: varve-inferred temperatures during the Maunder (eighteenth century) and Dalton solar minima (early nineteenth century) are particularly low, and periods of increasing temperatures in the nineteenth and twentieth centuries correspond to increases in solar forcing (Fig. 9). Although we can make no strong claims about regional climatic forcing based on this single record, it does appear as if Clyde River varve-inferred temperature was controlled to some extent by volcanic and solar forcing during the past millennium.

The striking similarities between the Big Round Lake record and independent records from throughout the eastern Canadian Arctic and the Northern Hemisphere in general indicate that climate variability was similar throughout the eastern Canadian Arctic (and broader trends were similar throughout the Arctic and the Northern Hemisphere) during at least the past 1000 years. Dissimilarities in timing of specific climatic events, or even with entire records (e.g. Donard Lake), indicate that, despite broad regional coherence, climate also varied on the local scale throughout the past millennium. Alternatively, differences in timing between records could be a result of imperfect chronological control.

Conclusions

Although the Arctic is particularly sensitive to changes in climate, the instrumental climate record is spatially and temporally sparse compared to other regions of the world. The significant correlation of Big Round Lake varve thicknesses with JAS temperature at Clyde River allows us to quantify temperature at near-annual resolution for northeast Baffin Island during the past millennium. This helps to expand the spatial and temporal understanding of arctic climate variability. The twentieth century was unique in this record in terms of high average varve-inferred temperatures (Figs. 8, 9). The LIA (1575–1760 AD) was 1.5 ± 0.2°C cooler than today and 0.2 ± 0.2°C cooler than the last millennium. The warmest pre-twentieth century interval (1375–1575 AD) was 1.2 ± 0.6°C cooler than today and only slightly (0.1 ± 0.2°C) warmer than the average for the last millennium, but is not necessarily synchronous with other records of the spatially and temporally variable Medieval Warm Period (Bradley 2000; Bradley et al. 2003).

Long-term varve-thickness trends and variability captured in the Big Round Lake record are corroborated by individual paleoclimate records and by regional paleoclimate syntheses. Big Round Lake is the third varve record (second proglacial varve record) produced from Baffin Island that has a significant correlation with summer temperature (Hughen et al. 2000; Moore et al. 2001). This indicates that Baffin Island may be a good location for summer temperature-modulated varve formation. Further investigations of proglacial lakes as paleoclimate archives may increase the number of high-resolution climate records in Arctic sites.

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