Quaternary Research 74 (2010) 188–198

Contents lists available at ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Autumn snowfall and hydroclimatic variability during the past millennium inferred from the varved sediments of meromictic Lake A, northern Ellesmere Island, Canada

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ARTICLE INFO

Article history:
Received 18 September 2009
Available online 31 July 2010

Keywords:
Varves
Laminae
Sedimentology
Paleoclimate
Snowfall
High Arctic

ABSTRACT

We examined the hydroclimatic signal in a record of annual lamina (varve) thickness from High Arctic Lake A, Ellesmere Island (83°00.00′N, 75°30.00′W). In this unglacierized catchment, nival melt is the dominant source for meltwater and transport of sediment to the lake, and autumn snowfall is highly influential on varve thickness through the amount of snow available for melt in the following year. For the period during which climatic data are available, varve thickness in Lake A was significantly correlated ($r = 0.50$, $p < 0.01$) with the cumulative snowfall from August to October (ASO) during the previous year and, to a lesser extent, ASO mean daily temperature ($r = 0.39$, $p < 0.01$) at Alert, Nunavut (175 km east). The varve thickness record, interpreted as a proxy record of ASO snowfall and, by extension, ASO temperature, indicated above-mean conditions during five periods of the past millennium, including most of the 20th century. These results corresponded well to other available high-resolution proxy climate records from the region, with some discrepancies prior to AD 1500 and during the period AD 1700–1900.

Introduction

The northernmost part of the Canadian High Arctic has undergone many notable recent environmental changes. Along the northern coast of Ellesmere Island, a formerly extensive ice shelf complex was reduced in size by 90% during the 20th century (Vincent et al., 2001) and the largest remaining Arctic ice shelf (Ward Hunt Ice Shelf) has had major recent fractures, which caused the drainage of an epishelf lake in Disraeli Fiord (Mueller et al., 2003). Most recently, the Ayles and Markham ice shelves disappeared in 2005 and 2008, respectively, while the Ward Hunt and Serson ice shelves, as well as coastal perennial sea-ice, were greatly reduced in extent in 2008 (Copland et al., 2007; Mueller et al., 2008; Vincent et al., 2009). Reductions in ice cover extent and thickness at nearby Lake A have been observed since AD 2000, and suggest that Lake A may be changing from a perennial to a seasonal ice cover regime (Mueller et al., 2009). These physical changes have been paralleled by a remarkable increase in aquatic productivity at Ward Hunt Lake during the past two centuries (Antoniades et al., 2007), and collectively, these indicators suggest substantial environmental changes are underway in the region.

Proxy climate indicators provide one method to extend instrumental climate records and put observed changes in a long-term perspective, but few annually resolved records are available from the Arctic (e.g., Lamoureux and Bradley, 1996; Hughen et al., 2000; Lamoureux and Gilbert, 2004). At the northern edge of the Canadian High Arctic, paleoenvironmental records exist for three adjacent chemically stratified (meromictic) lakes near Taconite Inlet (Bradley et al., 1996). This work revealed substantial changes in long-term melt season temperatures during the past 3300 yr (Lamoureux and Bradley, 1996). Similarly, recent work on northeastern Ellesmere Island by Besonen et al. (2008) provided a 1000-yr record of sedimentation rates and grain size and indicated general declines in both these variables during that period.

Lake A, located 35 km east of Taconite Inlet on Ellesmere Island and adjacent to the Ward Hunt Ice Shelf, provided the opportunity to build upon the initial paleoclimate research in the area and extend results across the region. Here we describe the development of a 989-yr varve thickness record from Lake A (Fig. 1) and investigate the causes of variability within the record. We used paleoclimatic interpretations of the varve thickness record to examine ongoing environmental change in the area and compared them with High Arctic counterparts to assess regional signals during the past millennium.

Study site

Lake A (unofficial name, 83°00.00′N, 75°30.00′W) is a meromictic lake located at ~4 m above sea level (a.s.l.) in a 36-km^2 unglacierized catchment on the northern coast of Ellesmere Island, Nunavut (Fig. 1). The monimolimnion of Lake A is comprised of anoxic, relict sea water, while the upper 10 m of the water column contains a freshwater mixolimnion. A sharp oxycline (10–16 m) and more gradual chemocline

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doi:10.1016/j.yqres.2010.06.005

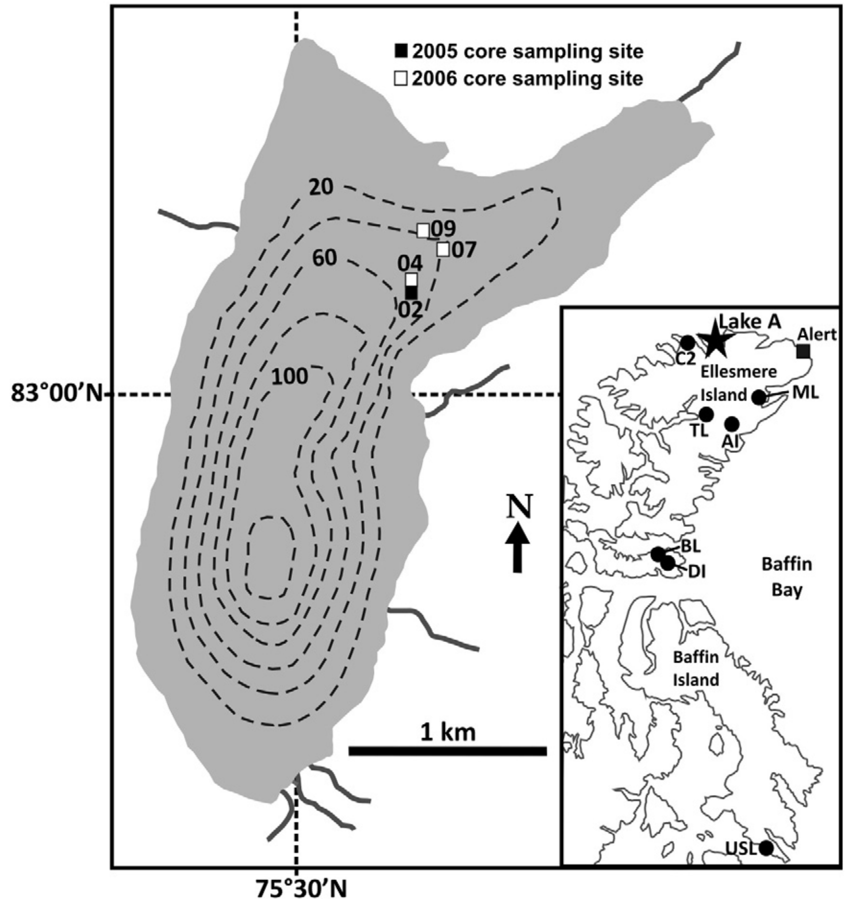

Figure 1. Lake A bathymetry (in metres) and location relative to meteorological records at Alert and other paleoclimate records discussed in the text (inset map; AI = Agassiz Ice Cap, BL = Bear Lake, C2 = Lake C2, DI = Devon Island Ice Cap, ML = Murray Lake, TL = Tuborg Lake and USL = Upper Soper Lake). Sampling locations of cores discussed in text are also shown.

(10–25 m) delineate the transition between the two water masses (Jeffries et al., 1984; Ludlam, 1996). The lake's near-perennial ice cover (mean thickness in June 2006: 1.25 m) prevents wind-mixing within the upper waters, which perpetuates anoxia in the monimolimnion and enhances preservation of microlaminated sediments below the oxycline (Tomkins et al., 2009b). The lake has a single basin with a surface area of 4.9 km^2 and a maximum known depth of 128 m. The lake has two main inlets and a single outlet into Rambow Bay, which is isolated from the Arctic Ocean by the Ward Hunt Ice Shelf.

Meteorological data are available from a weather station at Alert, located approximately 175 km east of the study site (Environment Canada, 2008). Local temperature records also exist from a Parks Canada (1995–2005) and SILA Network (Centre for Northern Studies, Laval University; 2005–present) 10-m tower weather station on Ward Hunt Island, located 15 km northeast of Lake A. Additionally, a 3-m weather station at Lake A provides recent temperature records (Vincent et al., 2009). The local records indicate that July and August are the only months with a mean temperature above the freezing point. At Alert, the mean annual temperature is −18°C and annual total precipitation is 154 mm (Environment Canada, 2008). Snow data from Alert and Ward Hunt Island show that most of the annual snowfall occurs during latter half of the year, particularly from August to November (see Fig. 5 in Vincent et al., 2009).

Methods

Field methodology

In May and June of 2005 and 2006, 21 sediment cores (12 to 78 cm long) were collected using Aquatic Research Instruments gravity and percussion coring systems. The locations of the four cores used in this study are shown in Figure 1. Coring locations were chosen based on previous research on the lake, lake bathymetry, and inlet and outlet positions. Most cores were collected from an area that was expected to have the longest, undisturbed sedimentary records in the lake and others were collected along a transect from deeper to shallower locations. All cores were stored vertically, unfrozen, and sealed with hydrophilic foam (2005) or gel (2006) prior to transport to the laboratory (Tomkins et al., 2008).

Laboratory methodology

Cores were cut lengthwise, and the exposed sediment face cleaned with a razor blade, logged, and photographed. Overlapping sediment slabs (7.0 × 1.5 × 0.3 cm) were sampled from all cores for thin section preparation following the methods of Lamoureux (1994, 2001). Detailed analyses of sedimentary structure and composition were conducted using transmitted light microscopy. Digital scans (2400 dpi) of the thin sections had insufficient resolution to clearly identify all laminae and examine the sedimentology. Hence, precision measurements (0.001 mm) of lamina couplet thickness were recorded using a Quick-Chek QC-1000 measurement system and dissecting microscope mounted on an Acu-Rite Absolute Zero II measurement stage. Couplets were counted and measured three to eight times between each pair of common marker beds, until consistent values were achieved. The final set of measurements was retained to create a record of lamina couplet measurements for each core.

Core A-02-05 was sampled for wet and dry density measurements, but no systematic changes in density were observed. The samples were weighed, dried for 24 hours in an oven (60°C), and weighed again to obtain the density data. Samples from the same core were taken for independent dating of the sedimentary record using radioisotopes (^{137}Cs and ^{210}Pb). For ^{137}Cs determinations, contiguous 3 cm^3 samples were collected at 0.5 cm intervals to a depth of 3 cm. The samples were dried for 24 hours at 60°C and crushed before radionuclide activity was measured using an ORTEC gamma counting system. To determine supported ^{210}Pb activity, 0.5 cm^3 samples were extracted at progressively larger depth intervals to 8.5 cm and from the base of the core. All samples were dried for 24 hours at 60°C and crushed before being measured by MyCore Scientific Inc. (Deep River, Ontario) using alpha spectroscopy.

Grain size was measured throughout core A-04-06 at contiguous 1-mm intervals. Organic material was removed from all samples through repeated applications of hydrogen peroxide (35%) at 40°C during a period of up to three weeks, before application of 1–2 ml of sodium hexametaphosphate (38 g L^{-1}) and sodium carbonate (8 g L^{-1}) solution to separate aggregates prior to measurement in a Beckman Coulter LS200 laser refraction particle size analyser. Three successive 60-second measurements were made with continuous sonication of each sample and the third set of measurements was retained after comparing all measurements for consistency.

Results

Sedimentary record

The most suitable cores for examination of the sedimentary record were found between 36.5 and 53 m water depth in the northern part of Lake A (Tomkins et al., 2009b). Diffuse sedimentary structures and apparent missing periods of sedimentation in cores collected at distal locations near or above the oxycline, and sand inclusions from

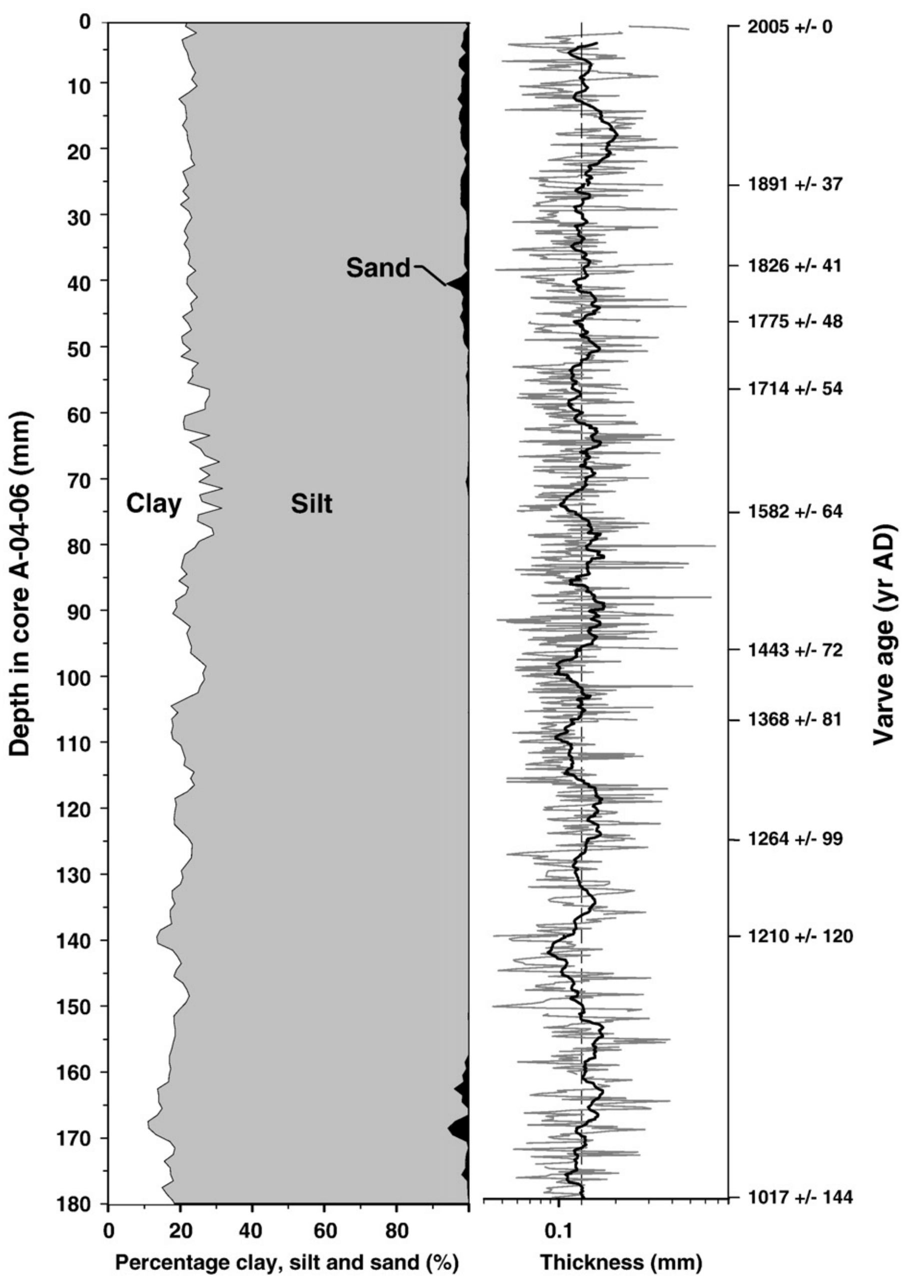

Figure 2. Grain size data from the varved section of core A-04-06. Dates are given for core A-04-06 by fitting the filtered composite varve thickness record to marker beds and date error estimates were derived from an age-depth model (Tomkins et al., 2009a). Mean varve thickness is denoted by the grey dashed line and varve thickness is plotted on a base-10 logarithmic scale.

disturbance along relatively steep slopes in the deep basin inhibited proper interpretation of cores from these areas.

The uppermost sediments (0–179 mm in core A-04-06) were microlaminated, with clearly defined lamina couplets. Below this facies, discrete sedimentary units became more diffuse with depth in all cores studied (Tomkins et al., 2009b). The upper facies was composed almost entirely of silt and clay (mean grain size = 6.8 μm), with the exception of limited fine sand inputs in the upper 50 mm and between 158 and 180 mm in core A-04-06 (Fig. 2). As described in Tomkins et al. (2009a), lamina couplets were counted and measured between common marker beds (designated A-M) in one 2005 core and all 2006 cores from 36.5 to 53 m depth, and radionuclide analyses corroborated the hypothesis that the lamina couplets were varves.

Development of the varve chronology and thickness record

In Lake A, the three cores with the longest varved sequences, best varve clarity, common marker beds and demonstrated similarity in varve measurements between marker beds were chosen to develop the varve thickness chronology. Two of the cores (A-07-06 and A-09-06) had identical mean varve thicknesses and standard deviations, whereas core A-04-06 had slightly thicker varves and higher variance (Table 1). Sedimentation rates were similar among the three cores to the depth of marker bed I, but sedimentation was notably higher in core A-04-06 between marker beds I and J (Fig. 3). This core had coarser sediments and more diffuse varves below marker bed J. Although not every varve could be cross-correlated among the three varve records, similarities in each varve record were apparent (Figs. 4 and 5). Divergence among the records was most notable in the uppermost marker bed interval, where core A-09-06 showed opposite trends to the other two cores, likely due to the influence of biogenic deposits on the uppermost sediments (Tomkins et al., 2009b).

Each thickness record was filtered for anomalously thick units, which appeared likely to be formed from geomorphic activity (e.g., subaqueous slumping), to produce unfiltered and filtered varve thickness records for each core. A thickness threshold of four standard deviations was chosen to characterize anomalously thick varves, as this value allowed for the removal of all suspected event deposits based on sedimentological observations. To create the filtered thickness record for each core, the anomalous unit thicknesses were removed from the data set; no values replaced the thickness values for these units.

Varve counts between marker beds in each core were similar (Table 2) but the differences in varve counts created offsets that were cumulative with depth. As such, the three records could not be averaged, as had been done in other studies (Lamoureux and Bradley, 1996; Hughen et al., 2000). The core with the highest number of varve counts for each marker bed interval was identified and the thickness measurements were retained for the final unfiltered and filtered varve composite records (Table 2). The retained segments were compiled into a single data set for statistical analyses prior to compiling the final composite records.

Mann–Whitney non-parametric tests were performed on both the unfiltered and filtered data sets and confirmed that the varve thickness values of the segments from each core could be considered to be from the same statistical population ($p<0.05$). Levene's tests were also conducted to test the equality of variances and indicated that the data from each of the three cores had statistically equal variance ($p<0.05$). As such, the records did not require standardization prior to amalgamation. Varve thickness measurements from each marker bed segment were then appended to each other to form the full unfiltered and filtered varve thickness composite records (Figs. 4 and 5). Each of the three cores contributed to these records, although core A-09-06 was most frequently used (Table 2, Figs. 4 and 5).

As described in Tomkins et al. (2009a), varve counting error estimates were derived for the section between each common marker bed within the microlaminated sedimentary record, following the methods of Sprowl (1993). Based on the age-depth model, the estimated counting error at the earliest marker bed in the varve thickness composite records (AD 1017) was ±144 yr, which represented a cumulative counting error of 15% (Tomkins et al., 2009a).

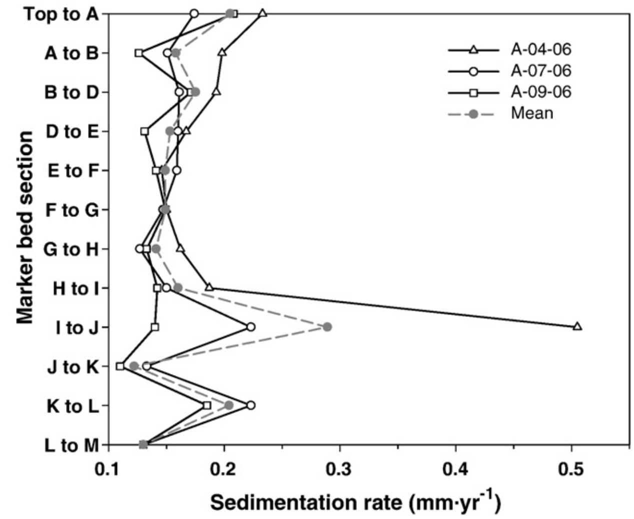

Figure 3. Sedimentation rates between marker beds in cores A-04-06, A-07-06, and A-09-06 and mean sedimentation rates for all three cores. Marker bed C was not included due to its close proximity to marker bed B and marker beds K and L in core A-04-06 were not clearly discernable.

Table 1
Descriptive statistics of the unfiltered and filtered varve thickness records from cores A-04-06, A-07-06, and A-09-06 during their period of overlap (top of core to marker bed J).

Core	Unfiltered			Filtered		
	n	Mean (mm)	SD (mm)	*n*	Mean (mm)	SD (mm)
A-04-06	728	0.19	0.28	725	0.18	0.16
A-07-06	728	0.15	0.10	720	0.15	0.08
A-09-06	728	0.15	0.10	723	0.14	0.08

The meteorological signal in the varve thickness composite record

Seasonal mean temperatures (AD 1995–2007) at Ward Hunt Island (WHI) are highly and significantly ($p<0.01$) correlated to those from Alert and are, on average, 1.3°C lower (Vincent et al., 2009). Snowfall records were not available from WHI for comparison with the Alert data, but both locations are located near sea level on the leeward side of the British Empire Range of northern Ellesmere Island, which influences air masses reaching the area from the south (Hardy, 1996), and should therefore show similarities in their snowfall trends.

The filtered varve thickness composite record was compared to Alert temperature (AD 1950–2005) and precipitation (AD 1951–1999) records to examine the climate signals recorded in the sedimentary record. The composite record was transformed using a base-10 logarithm to ensure normal data distribution for Pearson's correlation analysis. No summer temperature records had statistically significant relationships with the varve thickness series. For example, summer mean daily temperature (June-August) was not correlated with varve thickness ($r=-0.05$, $n=55$, $p=0.73$). By contrast, previous year cumulative August to October (ASO) daily snowfall had a statistically significant correlation ($r=0.50$, $n=48$, $p<0.01$) with log-normalized varve thickness (Fig. 6). Previous year cumulative August daily snowfall also correlated significantly with varve thickness ($r=0.41$, $n=48$, $p<0.01$), as did previous year ASO mean temperature ($r=0.39$, $n=54$, $p<0.01$; Fig. 6).

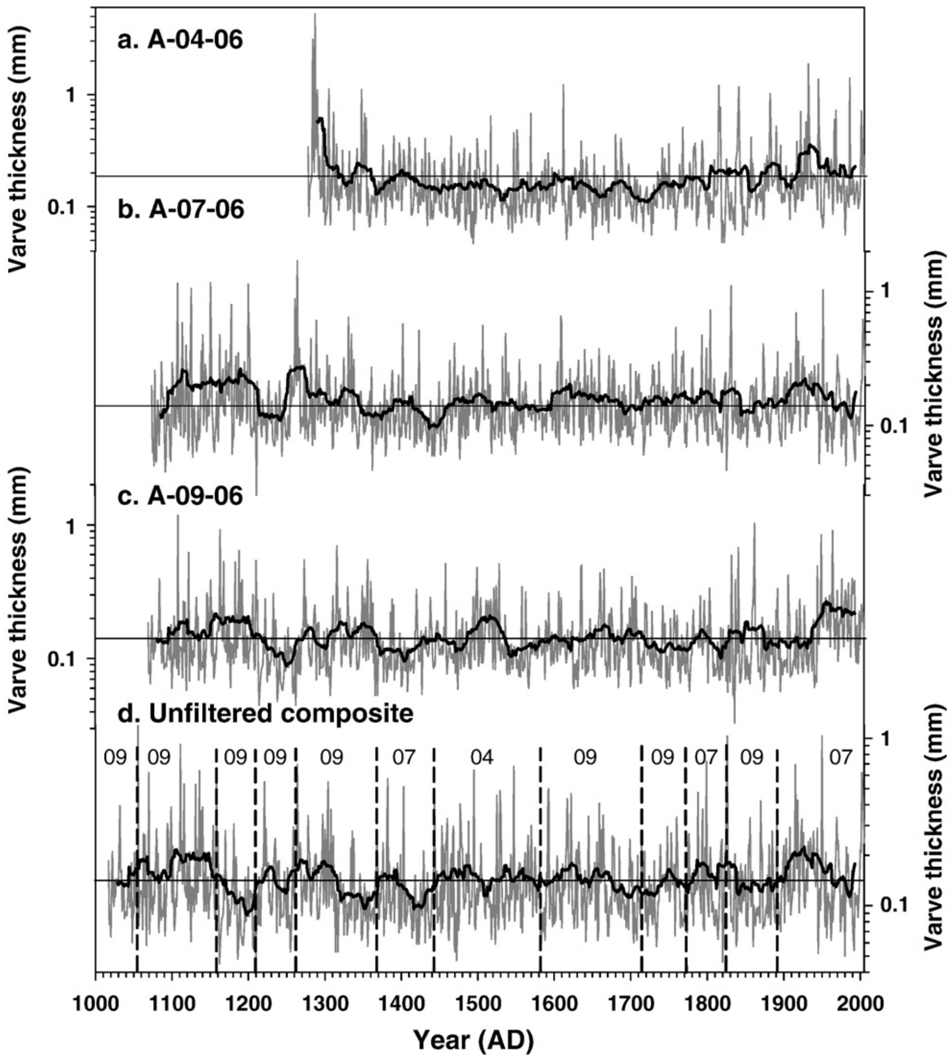

Figure 4. Unfiltered varve-thickness records from cores (a) A-04-06, (b) A-07-06, and (c) A-09-06 and (d) the unfiltered composite varve-thickness record that incorporates varve-thickness values from all three cores (indicated by 04, 07, and 09), plotted on a base-10 logarithmic scale. Dashed lines indicate marker beds, thin black lines indicate mean varve-thickness for each core and thick black lines indicate 25-yr unweighted moving means.

Discussion

Development of the varve chronology

No standard method exists for developing lacustrine varve chronologies. Most studies incorporate multiple cores into the final chronology to account for differences in sedimentation in different parts of a lake (e.g., Lamoureux and Bradley, 1996; Hughen et al., 2000), but varying methodologies are used to create multi-core composites of varve thickness. Lakes with low sedimentation rates have a greater possibility of missing varves compared to lakes with high sedimentation rates and it is possible for cores to be missing years of sedimentation (Sprowl, 1993; Lamoureux and Bradley, 1996; Lamoureux and Gilbert, 2004). Additionally, altered stream inflow and sediment dispersal within a lake may influence the varve thickness record by creating variability among cores from different areas of a lake (e.g., Lamoureux, 1999). The development of a composite varve chronology is therefore preferred whenever possible (Lamoureux, 2001).

In the High Arctic, several approaches have been used to develop composite varve-thickness records. At Donard Lake, Baffin Island, Moore et al. (2001) identified the core with the thickest, clearest varves and combined a floating varve thickness record with a surface core to develop a full varve chronology. Smith et al. (2004) developed a stacked mean varve-thickness record from Lake Tuborg, Ellesmere Island, by taking the mean of varve-thickness measurement from three cores. Hughen et al. (2000) standardized three varve-thickness chronologies from Upper Soper Lake, Baffin Lake, applied a correction for changes in porosity through the profiles and averaged the three chronologies for a final varve thickness record. At Lake C2, Ellesmere Island, Lamoureux and Bradley (1996) measured each varve among three different cores, used a non-parametric method of standardizing three varve thickness records by applying a linear detrending function, and then averaged the standardized values to create a varve-thickness index. Lamoureux and Bradley (1996) developed a filtered version of the index by removing anomalously thick units that were suspected to originate from geomorphic activity (e.g., subaqueous slumping) rather than hydroclimatic influences on sedimentation. Each of these methods strived to account for differences in sedimentation among cores that showed substantial chronological similarity but, in the case of Lake Tuborg and Upper Soper Lake, could not be reconciled on an annual basis.

Due to the extreme thinness of the varves in Lake A (mean thickness in core A-04-06: 0.2 mm) and resultant difficulties in correlating each varve between distinct marker beds, a new approach was developed to construct the Lake A varve-thickness composite record that incorporated components from several methodologies used in past studies. The use of multiple cores allowed for the identification of anomalous deposits and missing sections, while

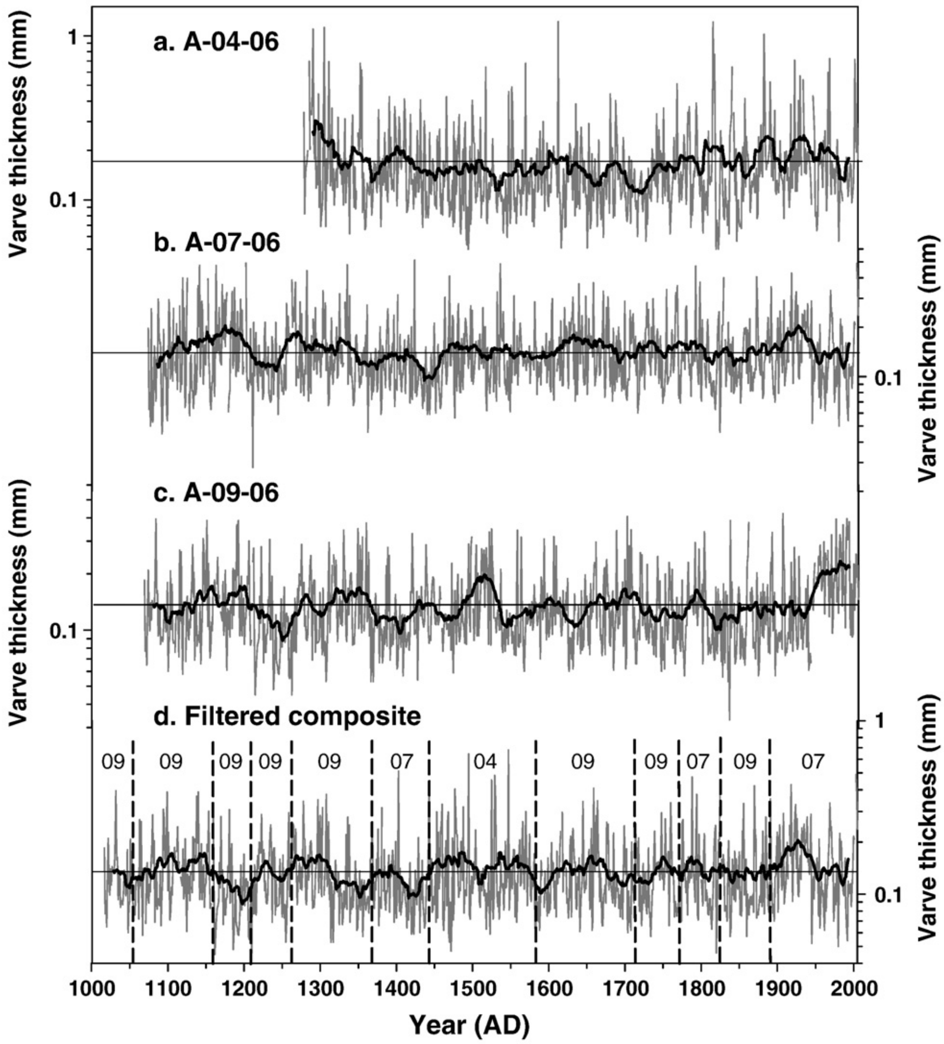

Figure 5. Filtered varve thickness records from cores (a) A-04-06, (b) A-07-06, and (c) A-09-06 and (d) the filtered composite varve thickness record that incorporates varve thickness values from all three records (indicated by 04, 07, and 09), plotted on a base-10 logarithmic scale. Dashed lines indicate marker beds, thin black lines indicate mean varve thickness for each core, and black lines indicate 25-yr unweighted moving means.

statistical analyses ensured that the varve thicknesses from each core segment used to develop the composite records could be amalgamated without introducing error through localized differences in sedimentation.

Table 2
Varve counts between marker beds in cores A-04-06, A-07-06, and A-09-06. Diffuse sedimentation between marker beds J and M in core A-04-06 prevented accurate varve counts for these sections. Bolded numbers indicate the highest varve count between a given marker bed interval and those counts used to develop the composite varve record.

Marker bed sections	Varve counts		
	A-04-06	A-07-06	A-09-06
Top to A	103	**115**	79
A to B	62	61	**65**
B to D	48	**51**	44
D to E	58	55	**61**
E to F	131	123	**132**
F to G	**139**	138	131
G to H	67	**75**	74
H to I	87	99	**104**
I to J	33	39	**54**
J to K	–	49	**51**
K to L	–	93	**103**
L to M	–	34	**39**

The hydroclimatic record from Lake A

A growing number of studies in non-glacial High Arctic catchments has demonstrated the importance of snow available for melt, often quantified as snow water equivalence (SWE), on influencing sediment transport processes, and a lesser role for melt season temperature influence (e.g., Braun et al., 2000; Forbes and Lamoureux, 2005; Lamoureux et al., 2006b; Cockburn and Lamoureux, 2008). Similar to other unglacierized High Arctic catchments (Lewkowicz and Wolfe, 1994; Forbes and Lamoureux, 2005; Cockburn and Lamoureux, 2008), snowmelt dominates sediment transport to Lake A. Suspended sediment concentrations in such catchments have been found to coincide with or lead maximum stream discharge (e.g., Lewkowicz and Wolfe, 1994; Cockburn and Lamoureux, 2008), which highlights the strong relationship between discharge magnitude and sediment transport in catchments with ample sediment supply. The magnitude and duration of peak discharge is controlled by snow availability and melt intensity (Cockburn and Lamoureux, 2008) and, as such, snowpack exhaustion can limit the amount of meltwater and sediment transport to a lake (Braun et al., 2000; Forbes and Lamoureux, 2005).

Most sediment transport occurs over only days to weeks during the relatively brief High Arctic melt season (Hardy, 1996), but catchment SWE rather than melt season temperatures and associated runoff intensity is the key hydroclimatic determinant of seasonal

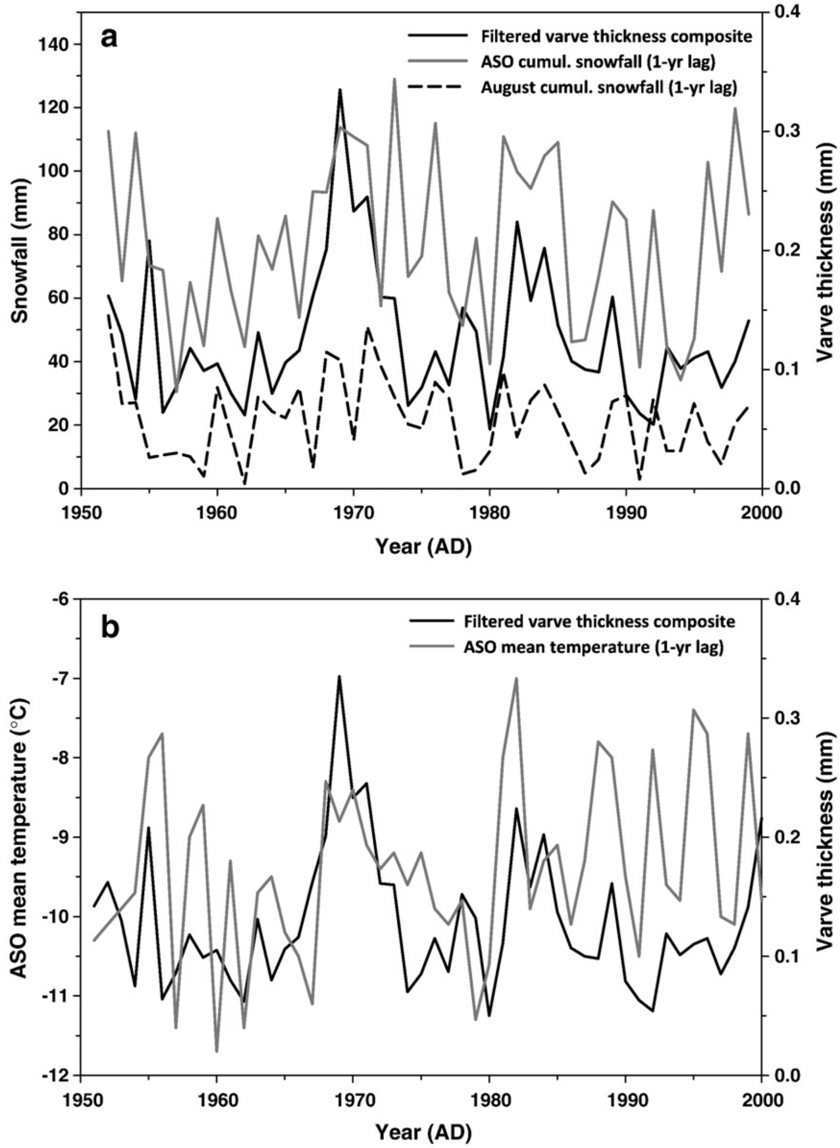

Figure 6. Comparison of the Lake A filtered varve thickness composite record with (a) August and combined August, September, and October (ASO) cumulative daily snowfall records (lagged 1 yr) and (b) the ASO mean daily temperature record (lagged 1 yr) from Alert, Nunavut.

suspended sediment transport to lakes in non-glacial catchments (Lamoureux et al., 2006b; Cockburn and Lamoureux, 2008). Sediment supply and interannual variations in runoff accessibility to sediment sources potentially further complicate downstream sediment yields and suggest that a direct relationship between melt season temperatures and varve sedimentation cannot be assumed in a non-glacial lake (Lamoureux et al., 2006a; Cockburn and Lamoureux, 2008).

Based on these studies, Lake A varve thickness was expected to be a function of the amount of snow available to melt, and to a lesser extent melt energy and sediment supply. No process studies have been conducted at Lake A to provide detailed information on nival melt processes and the relationship between stream discharge and suspended sediment transport, but such research was undertaken at nearby Lake C2 (Hardy, 1996; Retelle and Child, 1996). Discharge and suspended sediment transport were closely related in this catchment (Hardy, 1996) and the amount of energy available for snowmelt and, to a lesser extent, glacier ablation in the catchment was related to the warmest air mass to reach the area in summer (Hardy, 1996; Hardy et al., 1996). Although nival melt is important at both Lake A and Lake C2, catchment relief at Lake C2 is substantially greater (up to 1200 m) and a small glacier also influences sediment transport to the lake (Bradley et al., 1996). The extent of the relationship between snowpack and varve thickness was not explored at Lake C2 (Hardy, 1996), leaving uncertain its influence on sedimentation in the lake.

Other Arctic varve thickness records, particularly from proglacial or ice-contact lakes, have been correlated to spring or summer temperatures (e.g., Hughen et al., 2000; Moore et al., 2001; Francus et al., 2002; Smith et al., 2004; Hambley and Lamoureux, 2005). Conversely, the Lake A varve thickness record suggests a dominant hydroclimatic influence of the snowpack on sediment transport during the following summer. The varve record contains precipitation and temperature signals relating to the period of highest snowfall each year (August to October). Snowfall during these three months provides, on average, 41% of the annual total snowfall (Environment Canada, 2008). The influence of ASO mean daily temperature in the previous year likely reflects the influence of relatively warm autumn storm systems that generate snowfall along the northern Ellesmere Island coast; however, ASO cumulative daily snowfall and mean daily temperature are not significantly correlated ($r = 0.26$, $n = 48$, $p = 0.08$).

Sanagak Lake, Nunavut, located 1500 km southwest of Lake A, also contained an SWE signal in its varve thickness record due to the positive relationship between SWE, stream discharge and sediment transport in its main inflowing river (Forbes and Lamoureux, 2005; Lamoureux et al., 2006b). Additionally, at Bear Lake, Devon Island, located 900 km south of Lake A, the varve record corresponded most strongly with autumn snowfall at regional weather stations, and less strongly with autumn temperatures (Lamoureux and Gilbert, 2004). Relatively warm weather systems are common in Baffin Bay during autumn and provide snowfall to eastern Devon Island that, in subsequent summers, strongly influences varve formation in Bear Lake (Lamoureux and Gilbert, 2004). While sedimentation processes are likely markedly different in proglacial Bear Lake, Lake A records a similar signal, although not necessarily influenced by the same storm system pattern. The northern coast of Ellesmere Island is isolated from relatively warm southern weather systems in Baffin Bay due to the presence of the British Empire Range (Hardy, 1996). However, low pressure systems in the Atlantic, displaced northward during relatively warm periods from June to September, can move into the Arctic Ocean, strengthen along the Siberian coastline and bring precipitation to the Queen Elizabeth Islands, most notably to areas southwest of northern Ellesmere Island (Bradley and England, 1979).

Variations in melt season temperatures affect nival melt rates and thus sediment transport, but given the multitude of influences on sediment transport in non-glacial catchments, the importance of temperature may fluctuate over time (Lamoureux and Gilbert, 2004). Additionally, other influences on varve thickness, such as biogenic deposits, sediment supply, sediment supply, and past discharge history can change over time and, thus, affect the strength of hydroclimatic signals within a varve record (Menounos et al. 2005; Menounos and Clague, 2008; Tomkins et al., 2009b). The full range of environmental influences on the Lake A sedimentary record cannot therefore be assessed with the available data, but portions of the variance seen in the varve thickness record can be examined through linkages with instrumental climate records.

Climate variability during the past millennium recorded in Lake A

The filtered varve thickness composite record, interpreted primarily as an autumn (ASO) snowfall record, showed notable variability during the past millennium. Above mean ASO snowfall was inferred during most of the period between AD 1000 and the early 1300s (Fig. 7). The grain size record showed relatively coarse sedimentation during this period, including several fine sand deposits during the 1000s and 1100s (Fig. 2). Collectively, these results suggested above mean flow competency within the streams carrying sediment to Lake A. Above-mean varve thickness coinciding with coarser grain sizes may indicate an above-mean winter snowpack that would prolong the peak melt season and allow for more sediment influx than in years with below-mean snow covers (Francus et al., 2002; Forbes and Lamoureux, 2005). Conversely, the early 1200s and most of the period AD 1300–1450 were characterized by below-mean ASO snowfall. These intervals are interpreted to represent dry periods that restricted sediment transport to the lake through reduced meltwater production, which are also evident through finer sedimentary grain sizes.

Above-mean snowfall was inferred from AD 1450–1675 and the unfiltered varve record showed increased frequency of anomalously thick varves during this time (Fig. 4). Grain size was also relatively fine in this interval, which suggests below-mean runoff intensity (Fig. 2). The early 1700s and late 1800s were characterized by low autumn snowfall and few anomalously thick units. A period of above-mean ASO snowfall is interpreted to have occurred from the late 1700s to mid-1800s (Fig. 7). This period corresponds to Little Ice Age conditions in the Arctic when many glaciers reached their maximum extents (Bradley, 1990), although some regional variability in temperatures is apparent after AD 1800 (Overpeck et al., 1997). Fine sand was present in Lake A during the late 1700s to early 1800s, when several anomalously thick deposits were also notable (Fig. 4). Hence, while melt energy may have been relatively low during this period due to regionally cold conditions (Overpeck et al., 1997), coarse sediment deposits may indicate infrequent high melt years that resulted in sand transport and above-mean varve thickness. Relatively thick varves were observed during the same period in Nicolay Lake, Cornwall Island, and were interpreted to be caused by major summer rainfall, although increased runoff ratios due to reduced soil moisture storage could have also produced similar sediment yield signals (Lamoureux, 2000). Additionally, paleoecological records from some High Arctic ponds began to show changes in diatom species abundances and assemblages by the mid-1800s that have continued until the present (e.g., Douglas et al., 1994; Antoniades et al., 2005). Below-mean snow cover on regional lakes by the mid-1800s may have influenced interannual ice cover variability and increased light penetration into the water column, which altered species assemblages (Smol and Douglas, 2007).

While the highest ASO snowfall levels of the millennium were inferred during the early 1900s (Fig. 7), they are of comparable magnitude to conditions inferred during the 1100s. Relatively consistent sand inputs to the sedimentary record were evident after the late 1800s and they largely paralleled the inferred snowfall record for the 1900s. Above-mean snowfall, coupled with higher inferred regional temperatures during the first half of the 1900s (Overpeck et al., 1997; Tomkins et al., 2009a) creates a complex hydroclimate signal within the sedimentary record. Whether the variability in the grain size record is attributable to increased streamflow intensity during the first half of the 1900s or changed sediment sources remains unknown, but snowfall runoff magnitude likely also influenced the amount of sand that reached the lake during the 20th century. Additionally, sedimentary pellets deposited in Lake A sediments (Tomkins et al., 2009a) and a whole lake thermal model (Vincent et al., 2008) suggest reduced ice cover during the 1930s to 1940s. Instrumental temperature and precipitation records indicate that this period had above-mean temperatures during all seasons and above-mean summer precipitation in areas from 55 to 85°N (Serreze et al., 2000). Vincent et al. (2001) also suggested that this period was likely a time of enhanced ice shelf break-up along the northern Ellesmere Island coast. The post-1950 period was characterized by below-mean snowfall that in recent years has approached long-term mean levels.

Regional comparisons

The Lake A sedimentary record contained two complementary climate records. The varve thickness record can be interpreted from the perspective of ASO snowfall, while a record of ice-rafted sedimentary pellet frequency (Tomkins et al., 2009a) acts as an independent record of summer temperature from the same location. The two records were generally in agreement, with discrepancies most notable from AD 1000 to 1200 and during the 1700s and 1800s, possibly due to the lower temporal resolution of the sedimentary pellet record (Fig. 7). The two records corroborated each other during many periods likely due to the influence of snow cover on ice growth, as increased snow cover insulates lake ice when wind scouring is minimal and reduces ice growth in winter (Adams et al., 1989; Williams and Stefan, 2006). As such, winter ice thickening is reduced when snowfall is high, resulting in a thinner ice cover that is more susceptible to melt during the following summer.

Autumn snowfall was the most significant climatic influence on varve formation at Bear Lake, Devon Island (Lamoureux and Gilbert, 2004). The Lake A and Bear Lake varve thickness records correspond well to each other. The records showed below-mean snowfall during the early 1700s and last half of the 1800s and above-mean snowfall during the late-1200s, late-1300s, early 1600s, and much of the 1900s, with generally decreasing snowfall levels after mid-century (Fig. 7).

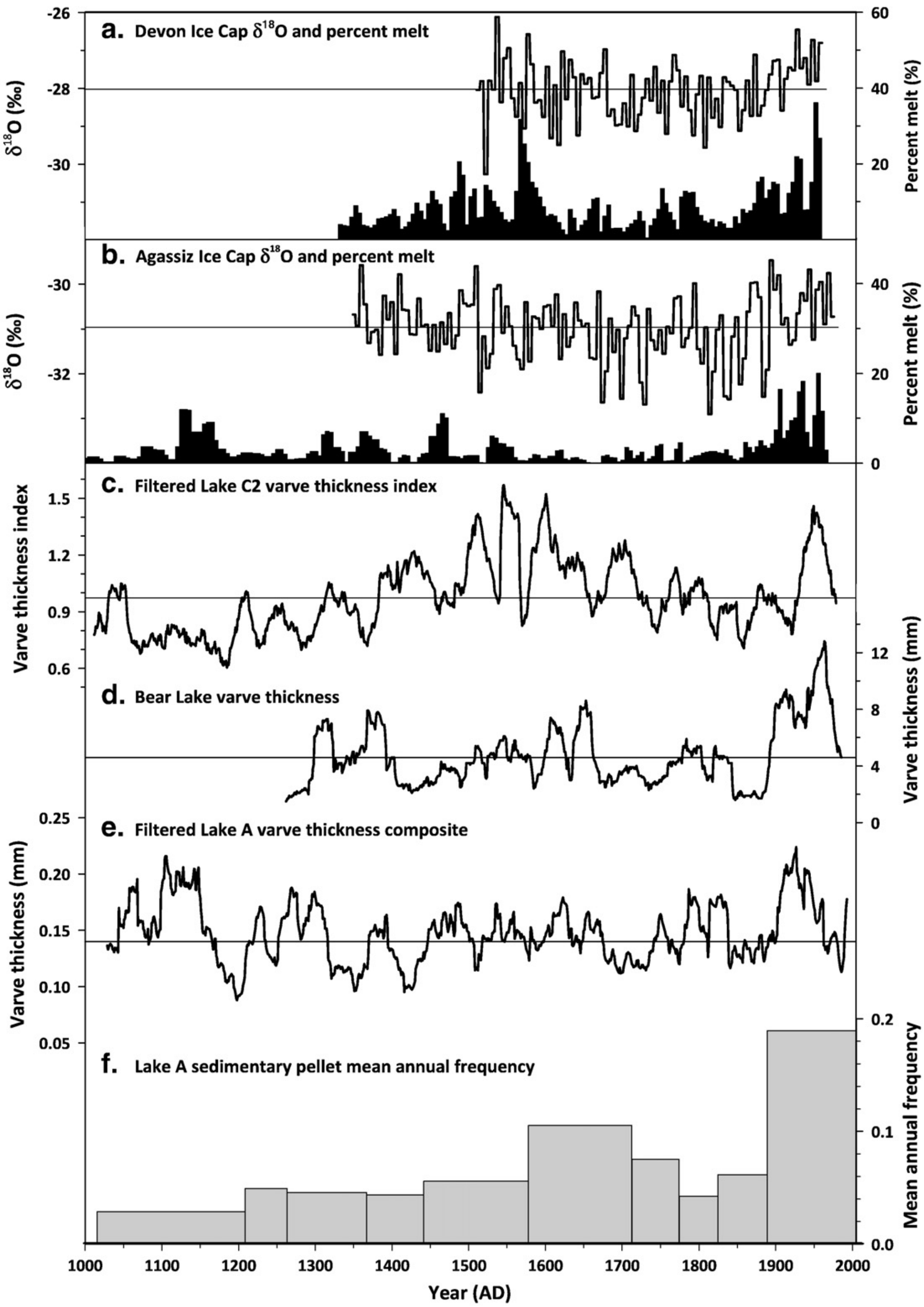

Figure 7. Comparison of regional paleoclimate records including (a) Devon Island Ice Cap $\delta^{18}O$ (annual and 25-yr unweighted moving mean) and percent melt records (5-yr means; core A77, Fisher and Koerner, 1994; Fisher et al., 1995), (b) Agassiz Ice Cap $\delta^{18}O$ (annual and 25-year unweighted moving average) and percent melt records (5-yr means; 1973 core, Fisher et al., 1983), (c) Lake C2 filtered varve thickness index (25-yr unweighted moving mean, Lamoureux and Bradley, 1996), (d) Bear Lake varve thickness (25-yr unweighted moving mean, Lamoureux and Gilbert, 2004), (e) Lake A filtered varve thickness composite (25-yr unweighted moving mean), and (f) Lake A mean annual ice-rafted pellet frequency (Tomkins et al., 2009b). Data for (a) and (b) was obtained from the IGBP PAGES/World Data Center for Paleoclimatology, NOAA/NGDC Paleoclimatology Program (http://www.ncdc.noaa.gov/paleo/data.html).

Although Canadian Arctic ice core records of $\delta^{18}O$ and melt percentage are dominantly a function of melt season temperature (Koerner, 1977), they are also influenced by accumulation and thus snowfall. Relatively high summer precipitation has been inferred on Devon Island during AD 1550–1620, the late-1800s and most of the 1900s and cold, dry conditions were suggested during the late-1600s to early 1700s and late-1700s to early 1800s (Alt, 1985). The Lake A varve thickness record suggests similar trends, with the exception of the late-1700s to early 1800s. The Devon Island Ice Cap record suggests that the coldest Little Ice Age conditions occurred during ca.

AD 1680–1730 and 1820–1860 (Koerner, 1977; Bradley, 1990), coincident with below-mean snowfall at Lake A. The Agassiz Ice Cap also suggests relatively cold conditions from ca. AD 1650–1900 and warm periods during the 1100s, late 1400s, and early 1500s (Fisher and Koerner, 1994; Fisher et al., 1995). These results generally correspond with above-mean ASO snowfall at Lake A during the inferred warm periods and below-mean snowfall during the cold periods (Fig. 7).

The inferred upper air summer temperature record at Lake C2 (Hardy et al., 1996) was similar to the Lake A sedimentary pellet signal (Tomkins et al., 2009a) and corresponded well with variability seen in the Lake A varve thickness record during much of the 1500s, 1600s, and 1900s (Lamoureux and Bradley, 1996; Fig. 7). Additionally, a June temperature reconstruction from Upper Soper Lake, Baffin Island, showed relative warmth during the 1500s, 1600s, and 1900s (Hughen et al., 2000) that broadly coincided with inferred warm summers and above mean autumn snowfall during these centuries at Lake A.

The Lower Murray Lake, Ellesmere Island, varve thickness record was not directly correlated to instrumental weather records but was inferred to represent melt season temperatures (Besonen et al., 2008). This record showed some correspondence to the Lake A varve record, most notably during times of relatively thick varve sedimentation (early 1100s to mid-1300s, 1500s, and 1900s). The grain size records from the two lakes both showed generally decreasing trends after the coarsest sediments were deposited early in the records (1100s and 1200s; Fig. 2). Besonen et al. (2008) interpreted this time as a warm period with increased runoff. The Lake A varve thickness and grain size records suggested above mean winter snowpack and extended melt seasons during at least the first half of the 1100s and most of the 1200s.

Conclusions

The approach used to develop the Lake A chronology and varve thickness record provides a new method for studies of varved Arctic sediments that builds upon previous methods. While a standard methodology for developing varve chronologies from High Arctic lakes may not be feasible considering the range of local environments studied and differences in sedimentation, common methodologies would aid in interpretation and comparison of varve records. The use of multiple sediment cores to develop varve thickness records remains an important strategy (Lamoureux, 2001), as multi-core studies have shown notable differences in sedimentation and varve clarity within the same lake that might result in errors if a single core is used (e.g., Lamoureux and Bradley, 1996; Zolitschka, 1996; Lamoureux and Gilbert, 2004; Tomkins et al., 2009a,b).

Several possible environmental influences affect sedimentation in Lake A and result in substantial unresolved variance in the varve thickness record, but the extent of their influences over time remains unknown. Despite these controls, the varves contain a quantifiable climate signal that demonstrates the influence of snowfall on runoff magnitude and hence sediment transport and varve thickness in the following year in this unglacierized catchment. Several other records in the Arctic show this signal, but most varve records have predominant melt season temperature signals, particularly in glacier-fed lakes. Lake A's varve record captures the most important period of snowfall on the northern Ellesmere Island coast each year and shows similarities to records developed from other studies conducted in unglacierized Arctic catchments where the amount of snow available for melt and runoff intensity are identified as more important influences on sediment transport to lakes than melt energy.

The Lake A varve thickness record corresponds well with the only other long-term, high-resolution proxy record of autumn snowfall in the Arctic, and both records appear to capture precipitation and temperature signals from different autumn air masses bringing snowfall to the Queen Elizabeth Islands. Similar to other proxy records in the High Arctic, the Lake A varve thickness and sedimentary pellet records indicate above mean melt season temperatures and autumn snowfall during portions of the 20th century, during which many significant environmental changes have been observed along the northern coast of Ellesmere Island. Continued joint comparison of Arctic proxy temperature and precipitation records will be important for providing a more complete view of recent and past climate variability in this changing region.

Acknowledgments

The authors gratefully acknowledge the support of the Natural Sciences and Engineering Research Council of Canada, ArcticNet, the Canadian Research Chair program and the International Polar Year program. Excellent logistical support was provided by Polar Continental Shelf Program (Natural Resources Canada; PCSP contribution number 006-10) and Parks Canada. Additional support from the Royal Canadian Geographical Society, the Canadian Northern Studies Trust, the Association of Canadian Universities for Northern Studies, the Northern Scientific Training Program, Queen's University and Le Fonds québécois de la recherche sur la nature et les technologies is gratefully acknowledged. Excellent field assistance by Jérémie Pouliot, Denis Sarrazin and Julie Veillette (Laval University), Eric Bottos (McGill University), and John Innis (Universal Helicopters) is greatly appreciated. Formal reviews and constructive comments from Brian Menounos and Bernd Zolitschka are appreciated.

References

Adams, W.P., Doran, P.T., Ecclestone, M., Kingsbury, C.M., Allan, C.J., 1989. A rare second year-lake ice cover in the Canadian High Arctic. Arctic 42, 299–306.

Alt, B.T., 1985. 1550-1620: A period of summer accumulation in the Queen Elizabeth Islands. In: Harrington, C.R. (Ed.), Climatic Change in Canada 5: Critical Periods in the Quaternary Climatic History of Northern North America. National Museum of Natural Sciences, Syllogeus No. 55, pp. 461–479.

Antoniades, D., Crawley, C., Douglas, M.S.V., Pienitz, R., Andersen, D., Doran, P.T., Hawes, I., Pollard, W., Vincent, W.F., 2007. Abrupt environmental change in Canada's northernmost lake inferred from fossil diatom and pigment stratigraphy. Geophysical Research Letters 34, L18708. doi:10.1029/ 2007GL030947.

Antoniades, D., Douglas, M.S.V., Smol, J.P., 2005. Quantitative estimates of recent environmental changes in the Canadian High Arctic inferred from diatoms in lake and pond sediments. Journal of Paleolimnology 33, 349–360.

Besonen, M.R., Patridge, W., Bradley, R.S., Francus, P., Stoner, J.S., Abbott, M.B., 2008. A record of climate over the last millennium based on varved lake sediments from the Canadian High Arctic. The Holocene 18, 169–180.

Bradley, R.S., 1990. Holocene paleoclimatology of the Queen Elizabeth Islands, Canadian High Arctic. Quaternary Science Reviews 9, 365–384.

Bradley, R.S., England, J., 1979. Synoptic climatology of the Canadian High Arctic. Geografiska Annaler, Series A, Physical Geography 61, 187–201.

Bradley, R.S., Retelle, M.J., Ludlam, S.D., Hardy, D.R., Zolitschka, B., Lamoureux, S.F., Douglas, M.S.V., 1996. The Taconite Inlet Lakes Project: a systems approach to paleoclimatic reconstruction. Journal of Paleolimnology 16, 97–110.

Braun, C., Hardy, D.R., Bradley, R.S., Retelle, M.J., 2000. Streamflow and suspended sediment transfer to Lake Sophia, Cornwallis Island, Nunavut, Canada. Arctic, Antarctic, and Alpine Research 32, 456–465.

Cockburn, J.M.H., Lamoureux, S.F., 2008. Hydroclimate controls over seasonal sediment yield in two adjacent High Arctic watersheds. Hydrological Processes 22, 2013–2027. doi:10.1002/hyp. 6798.

Copland, L., Mueller, D.R., Weir, L., 2007. Rapid loss of the Ayles Ice Shelf, Ellesmere Island, Canada. Geophysical Research Letters 34, L21501. doi:10.1029/2007GL031809.

Douglas, M.S.V., Smol, J.P., Blake, Weston Jr., 1994. Marked post-18th century environmental change in High-Arctic ecosystems. Science 266, 416–419.

Environment Canada, 2008. Adjusted Historical Canadian Climate Data. online. Website: <http://www.cccma.ec.gc.ca/hccd/>, Accessed: February 2008.

Fisher, D.A., Koerner, R.M., 1994. Signal and noise in four ice-core records from the Agassiz Ice Cap, Ellesmere Island, Canada: details of the last millennium for stable isotopes, melt and solid conductivity. The Holocene 4, 113–120.

Fisher, D.A., Koerner, R.M., Paterson, W.S.B., Dansgaard, W., Gundestrup, N., Reeh, N., 1983. Effect of wind scouring on climatic records from ice-core oxygen-isotope profiles. Nature 301, 205–209.

Fisher, D.A., Koerner, R.M., Reeh, N., 1995. Holocene climatic records from Agassiz Ice Cap, Ellesmere Island, NWT, Canada. The Holocene 5, 19–24.

Forbes, A.C., Lamoureux, S.F., 2005. Climatic controls on streamflow and suspended sediment transport in three large middle Arctic catchments, Boothia Peninsula, Nunavut, Canada. Arctic, Antarctic, and Alpine Research 37, 304–315.

Francus, P., Bradley, R.S., Abbott, M.B., Patridge, W., Keimig, F., 2002. Paleoclimate studies of minerogenic sediments using annually resolved textural parameters. Geophysical Research Letters 29, 1998. doi:10.1029/2002GL015082.
Hambley, G.W., Lamoureux, S.F., 2005. Recent summer climate recorded in complex varved sediments, Nicolay Lake, Cornwall Island, Nunavut, Canada. Journal of Paleolimnology 35, 629–640.
Hardy, D.R., 1996. Climatic influences on streamflow and sediment flux into Lake C2, northern Ellesmere Island, Canada. Journal of Paleolimnology 16, 133–149.
Hardy, D.R., Bradley, R.S., Zolitschka, B., 1996. The climatic signal in varved sediments from Lake C2, northern Ellesmere Island, Canada. Journal of Paleolimnology 16, 227–238.
Hughen, K.A., Overpeck, J.T., Anderson, R.F., 2000. Recent warming in a 500-year palaeotemperature record from varved sediments, Upper Soper Lake, Baffin Island, Canada. The Holocene 10, 9–19.
Jeffries, M.O., Krouse, H.R., Shakur, M.A., Harris, S.A., 1984. Isotope geochemistry of stratified Lake "A", Ellesmere Island, N.W.T., Canada. Canadian Journal of Earth Sciences 21, 1008–1017.
Koerner, R.M., 1977. Devon Island Ice Cap: core stratigraphy and paleoclimate. Science 196, 15–18.
Lamoureux, S.F., 1994. Embedding unfrozen lake sediments for thin section preparation. Journal of Paleolimnology 10, 141–146.
Lamoureux, S.F., 1999. Spatial and interannual variations in sedimentation patterns recorded in nonglacial varved sediments from the Canadian High Arctic. Journal of Paleolimnology 21, 73–84.
Lamoureux, S.F., 2000. Five centuries of interannual sediment yield and rainfall-induced erosion in the Canadian High Arctic recorded in lacustrine varves. Water Resources Research 36, 309–318.
Lamoureux, S.F., 2001. Varve chronology techniques. In: Last, W.M., Smol, J.P. (Eds.), Developments in Paleoenvironmental Research (DEPR) Volume 2—Tracking Environmental Change Using Lake Sediments: Physical and Chemical Techniques. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 247–260.
Lamoureux, S.F., Bradley, R.S., 1996. A late Holocene varved sediment record of environmental change from northern Ellesmere Island, Canada. Journal of Paleolimnology 16, 239–255.
Lamoureux, S.F., Gilbert, R., 2004. A 750-yr record of autumn snowfall and temperature variability and winter storminess recorded in the varved sediments of Bear Lake, Devon Island, Arctic Canada. Quaternary Research 61, 134–147.
Lamoureux, S.F., McDonald, D.M., Cockburn, J.M.H., Lafrenière, M.J., Atkinson, D., Treitz, P., 2006a. An incidence of multi-year sediment storage on channel snowpack in the Canadian High Arctic. Arctic 59, 381–390.
Lamoureux, S.F., Stewart, K.A., Forbes, A.C., Fortin, D., 2006b. Multidecadal variations and decline in spring discharge in the Canadian middle Arctic since 1550AD. Geophysical Research Letters 33, L02403. doi:10.1029/2005GL024942.
Lewkowicz, A.G., Wolfe, P.M., 1994. Sediment transport in Hot Weather Creek, Ellesmere Island, N.W.T., Canada, 1990-1991. Arctic and Alpine Research 26, 213–226.
Ludlam, S.D., 1996. The comparative limnology of high Arctic, coastal, meromictic lakes. Journal of Paleolimnology 16, 111–131.
Menounos, B., Clague, J.J., 2008. Reconstructing hydro-climatic events and glacier fluctuations over the past millennium from annually laminated sediments of Cheakamus Lake, southern Coast Mountains, British Columbia, Canada. Quaternary Science Reviews 27, 701–713.
Menounos, B., Clague, J.J., Gilbert, R., Slaymaker, O., 2005. Environmental reconstruction from a varve network in the southern Coast Mountains, British Columbia, Canada. The Holocene 15, 1163–1171.
Moore, J.J., Hughen, K.A., Miller, G.H., Overpeck, J.T., 2001. Little Ice Age recorded in summer temperature reconstruction from varved sediments of Donard Lake, Baffin Island, Canada. Journal of Paleolimnology 25, 503–517.
Mueller, D.R., Copland, L., Hamilton, A., Stern, D., 2008. Examining Arctic ice shelves prior to the 2008 breakup. Eos 89, 502–503.
Mueller, D.R., Van Hove, P., Antoniades, D., Jeffries, M.O., Vincent, W.F., 2009. High Arctic lakes as sentinel ecosystems: cascading regime shifts in climate, ice cover, and mixing. Limnology and Oceanography 54, 2371–2385.
Mueller, D.R., Vincent, W.F., Jeffries, M.O., 2003. Break-up of the largest Arctic ice shelf and associated loss of an epishelf lake. Geophysical Research Letters 30, 2031. doi:10.1029/2003GL017931.
Overpeck, J., Hughen, K., Hardy, D., Bradley, R., Case, R., Douglas, M., Finney, B., Gajewski, K., Jacoby, G., Jennings, A., Lamoureux, S., Lasca, A., MacDonald, G., Moore, J., Retelle, M., Smith, S., Wolfe, A., Zielinski, G., 1997. Arctic environmental change of the last four centuries. Science 278, 1251–1256.
Retelle, M.J., Child, J.K., 1996. Suspended sediment transport and deposition in a high Arctic meromictic lake. Journal of Paleolimnology 16, 151–167.
Serreze, M.C., Walsh, J.E., Chapin, R.S.I.I.I., Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W.C., Morison, J., Zhang, T., Barry, R.G., 2000. Observational evidence of recent change in the northern high-latitude environment. Climatic Change 46, 159–207.
Smith Jr., S.V., Bradley, R.S., Abbott, M.B., 2004. A 300 year record of environmental change from Lake Tuborg Ellesmere Island, Nunavut, Canada. Journal of Paleolimnology 32, 137–148.
Smol, J.P., Douglas, M.S.V., 2007. From controversy to consensus: making the case for recent climate change in the Arctic using lake sediments. Crossing the final ecological threshold in high Arctic ponds. Frontiers in Ecology and the Environment 5, 466–474.
Sprowl, D., 1993. On the precision of the Elk Lake varve chronology. In: Bradbury, J.P., Dean, W.E. (Eds.), Elk Lake, Minnesota: evidence for Rapid Climate Change in the North-Central United States. Geological Society of America Special Paper 276. Boulder, Colorado, pp. 69–74.
Tomkins, J.D., Antoniades, D., Lamoureux, S.F., Vincent, W.F., 2008. A simple and effective method for preserving the sediment-water interface of sediment cores during transport. Journal of Paleolimnology 40, 577–582.
Tomkins, J.D., Lamoureux, S.F., Antoniades, D., Vincent, W.F., 2009a. Sedimentary pellets as an ice-cover proxy in a High Arctic ice-covered lake. Journal of Paleolimnology 41, 225–242.
Tomkins, J.D., Lamoureux, S.F., Antoniades, D., Vincent, W.F., 2009b. Sedimentology of perennial ice-covered, meromictic Lake A, Ellesmere Island, at the northern extreme of Canada. Canadian Journal of Earth Sciences 46, 83–100.
Vincent, W.F., Gibson, J.A.E., Jeffries, M.O., 2001. Ice-shelf collapse, climate change, and habitat loss in the Canadian High Arctic. Polar Record 37, 133–142.
Vincent, A.C., Mueller, D.R., Vincent, W.F., 2008. Simulated heat storage in a perennially ice-covered high Arctic lake: sensitivity to climate change. Journal of Geophysical Research – Oceans 113, C04036. doi:10.1029/2007JC004360.
Vincent, W.F., Whyte, L.G., Lovejoy, C., Greer, C.W., Laurion, I., Suttle, C.A., Corbeil, J., Mueller, D.R., 2009. Arctic microbial ecosystems and impacts of extreme warming during the International Polar Year. Polar Science 3, 171–180.
Williams, S.G., Stefan, H.G., 2006. Modeling of lake ice characteristics in North America using climate, geography, and lake bathymetry. Journal of Cold Regions Engineering 20, 140–167.
Zolitschka, B., 1996. Recent sedimentation in a high Arctic lake, northern Ellesmere Island, Canada. Journal of Paleolimnology 16, 169–186.