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ORIGINAL PAPER

Five thousand years of sediment transfer in a high arctic watershed recorded in annually laminated sediments from Lower Murray Lake, Ellesmere Island, Nunavut, Canada

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Abstract Sediments in Lower Murray Lake, northern Ellesmere Island, Nunavut Canada (81°21′ N, 69°32′ W) contain annual laminations (varves) that provide a record of sediment accumulation through the past 5000+ years. Annual mass accumulation was estimated based on measurements of varve thickness and sediment bulk density. Comparison of Lower Murray Lake mass accumulation with instrumental climate data, long-term records of climatic forcing mechanisms and other regional paleoclimate records suggests that lake sedimentation is positively correlated with regional melt season temperatures driven by radiative forcing. The temperature reconstruction suggests that recent temperatures are ~2.6°C higher than minimum temperatures observed during the Little Ice Age, maximum temperatures during the past 5200 years exceeded modern values by ~0.6°C, and that minimum temperatures observed approximately 2900 varve years BC were ~3.5°C colder than recent conditions. Recent temperatures were the warmest since the fourteenth century, but similar conditions existed intermittently during the period spanning ~4000–1000 varve years ago. A highly stable pattern of sedimentation throughout the period of record supports the use of annual mass accumulation in Lower Murray Lake as a reliable proxy indicator of local climatic conditions in the past.

Keywords Varves · Holocene paleoclimate · Arctic · Lake sediments · Ellesmere Island

Introduction

The High Arctic, surrounded by sea ice and snow-covered much of the year, is a region where global climate changes are expected to be amplified by positive feedback processes (Holland and Bitz 2003).

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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The elevated climatic sensitivity of the Arctic makes it an ideal location for examining the causes and impacts of climate variability in the past, including both recent changes attributed to human activity and past changes associated with natural forcing mechanisms. However, our understanding of the climate system in the High Arctic is severely limited by a lack of long-term climate observations. In particular, the instrumental record is very short, generally less than 60 years in the Canadian Arctic, and provides limited spatial coverage. Additionally, limited daylight and severe temperatures reduce the potential for paleoclimate reconstructions based on biological proxies such as tree rings, pollen, and plankton assemblages. The few long-term proxy records that are available provide limited geographic coverage and typically demonstrate low temporal resolution (e.g. Gajewski and Atkinson 2003). Therefore, there is a significant need for additional high-resolution paleoclimatic data for the High Arctic.

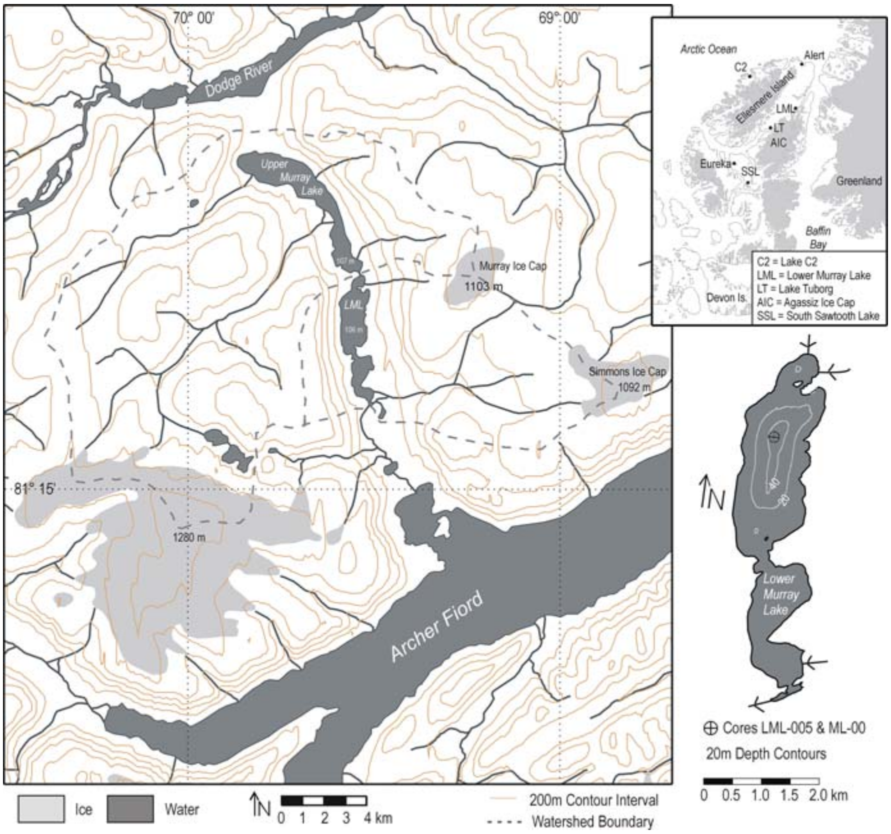
Due to their widespread occurrence, annually laminated (varved) lake sediments are increasingly being utilized as an important source of paleoclimatic information in the High Arctic. Climate reconstructions from laminated lake sediments are based on the relationship between the characteristics of an individual lamination, such as thickness or grain size, and some aspect of the weather during the corresponding year. Considerable effort has focused on correlating varve characteristics with instrumental climate records (Hughen et al. 2000; Moore et al. 2001; Francus et al. 2002; Hambley and Lamoureux 2006) and monitoring the meteorological and hydrological processes controlling sediment transfer and deposition in arctic lakes (e.g. Hardy 1996; Hardy et al. 1996; Cockburn and Lamoureux 2007, 2008). These studies have described and quantified process linkages between climatic conditions, stream flow, sediment transfer and lake sedimentation. However, they have also highlighted the complexity of the climate-sedimentation system and the uncertainty associated with paleoclimatic reconstructions based on laminae characteristics. Because varve-climate correlations are limited by the length of local instrumental observations and detailed process studies have been limited to only a few seasons of monitoring, one of the largest uncertainties in varve records relates to assumptions about the long-term stability of linkages between climate and sedimentation under varying climatic and geomorphic conditions.

In this paper, we report the results from a study of laminated sediments in Lower Murray Lake in the Canadian High Arctic, building upon results previously reported by Besonen et al. (2008). The results presented here extend the record of annual sedimentation in Lower Murray Lake through the past 5000+ years, making it the longest varve record yet produced from the High Arctic. This paper aims to identify how sediment delivery to the lake has varied through time and to evaluate the validity of inferred climate-sedimentation linkages over long time scales that include changes in external forcing mechanisms related to climate variability.

Study area

Lower Murray Lake is a relatively large (~5 km^2), deep (~47 m) lake located along the eastern margin of the Hazen Plateau, northern Ellesmere Island, Nunavut, Canada (81°21′ N, 69°32′ W; Fig. 1). The region is characterized by an extensive upland plateau that contains several small ice caps at an elevation of approximately 1000 m. Lower Murray Lake is one of two lakes occupying a glacially carved valley within the plateau region. The lake lies at an elevation of 106 m, which is above the local Holocene marine limit (England 1983), and most of its surface inflow is derived from the upper plateau. Lower Murray Lake has a total drainage basin of 261 km^2; however, the majority of this area (184 km^2) first drains into Upper Murray Lake, which is connected to the lower lake by a shallow spillway that is less than 1 m deep. Runoff associated with snow and ice melt in the upland areas drains into the lakes via several short, high-gradient streams. The main tributary into Upper Murray Lake drains a ~55 km^2 icecap located southwest of the lakes. Two small, stagnant ice caps drain directly into Lower Murray Lake at its extreme north and south ends. Apart from the spillway connecting the two lakes, the largest tributary enters Lower Murray Lake at its southeast corner, near its outflow stream. The southern portion of the lake is separated from the central, deep basin by a ~300-m-wide channel of unknown depth.

Fig. 1 Map of Lower Murray Lake and surrounding region. The lower right panel shows a close up of Lower Murray Lake, including approximate bathymetry and the location of the coring site. Inset shows Ellesmere Island and surrounding region



Climatically, the region is a polar desert with a mean annual temperature around −19°C, and mean annual precipitation, which occurs mostly in the form of snow, is less than 150 mm water equivalent (Maxwell 1981). Above-freezing temperatures occur from early June through late August, with daily maximum temperatures occasionally exceeding 15°C. The extreme seasonality of temperatures produces a brief period of runoff and sediment transfer into Lower Murray Lake and is highly conducive to the formation of annual laminations in the sedimentary record. A 1.5- to 2-m-thick (or thicker) ice cover lasts throughout much of the year, with open water generally occurring only from mid August through early September. This brief period of open water reduces wind and wave action and limits mixing of the water column leading to near anoxia at the sediment water interface (Besonen et al. 2008). In combination, these factors are highly conducive to the preservation of individual laminations in the lake sediments. Besonen et al. (2008) concluded that individual lamina in Lower Murray Lake were annual, and established a varve chronology for the past 1000 years from the upper ~55 cm of sediment.

Methods

Field work

Lower Murray Lake was visited in June 2005 and August 2006 to conduct coring and to survey the lake environment. A suite of cores was collected from the deepest basin (water depth 46.13 m) at 81.34175° N, 69.55204° W. Two overlapping, long cores were collected using an Uwitec piston corer (cores LML-05-C1 & LML-05-C2). Special care was taken to collect an undisturbed record of the upper-most sediment and to preserve an intact sediment-water interface using an Aquatic Research Instruments gravity corer (cores LML-05-C1-AR1 & LML-5-C1-AR2) and an Ekman dredge-type sampler (cores LML-05-C1-E4 & LML-05-C1-E5). Both the Aquatic Research and Ekman cores displayed clear water overlying the sediment, confirming that an undisturbed sediment-water interface was recovered. The Ekman samples were subsampled by inserting a 6-cm-diameter polycarbonate tube into the sediment and then sealing the ends of the tube.

Core analysis

All cores were split and photographed in the lab in order to identify the most complete and undisturbed sections suitable for further analysis. Dry bulk density of the sediment was measured at fixed intervals of 1 cm in core LML-05-C1-E4, and at 2-cm spacing in all other cores by extracting 1 cc samples using a cutoff syringe, drying the sediment for 16 h at 105°C, and then measuring the mass. Bulk density was calculated by dividing the dry mass of the sediment by the initial sampling volume. Organic carbon content was then estimated by percent loss-on-ignition (LOI) using the same samples analyzed for bulk density. Dried samples were placed in a preheated 550°C muffle furnace for 4 h, and then allowed to cool in a desiccator. Percent LOI was calculated by dividing the mass difference between the dry sediment sample and the post-ignition sample by the mass of the dry sample (Dean 1974; Heiri et al. 2001). Particle size was analyzed at 1 cm increments after pre-treating samples with a 30% hydrogen peroxide solution to digest organic material. Samples were analyzed using a Beckman Coulter LS200 particle-size analyzer. Paleomagnetic samples were recovered from the split cores using rigid u-shaped plastic channels with a 2 cm × 2 cm cross section. Paleomagnetic analyses were conducted at Institut des Sciences de la Mer de Rimouski, Québec, Canada. In order to analyze and interpret fine-scale laminations, thin sections of epoxy-impregnated sediment slabs were produced in a manner similar to that described by Francus and Asikainen (2001). Slabs of sediment were removed from the split core halves using 18 cm × 2 cm × 0.7 cm aluminum trays inserted into the sediment. Overlapping the trays provided continuous stratigraphic coverage. The slabs were then flash frozen in liquid nitrogen, dehydrated in a freeze dryer, and impregnated with epoxy under vacuum using a low viscosity resin. After the epoxy had cured, the slabs were cut into three sub-blocks from which 2.5 cm × 7.5 cm polished thin sections were prepared. Cutting the slabs at an angle across the laminations ensured that none of the sequence was lost to the saw kerf.

Detailed analysis of the laminations was carried out using digital images of the thin sections. Each thin section was scanned at 2400 dpi under plain transmitted and cross polarized light using an Epson V750 flatbed scanner. A composite sequence of images providing continuous coverage of the sediment record was created by selecting individual thin sections from the different cores which showed the least disturbance for that portion of the record. Counting and quantitative measurement of individual laminae was performed using image acquisition and analysis software developed at Institut National de la Recherche Scientifique, Québec. This software calculates and records the thickness and depth of individual laminae along a vertical axis. However, down-warping along the edges of the core barrel and/or misalignment of sediment slabs on the thin sections resulted in laminae that were not consistently oriented perpendicular to the measurement axis. In these cases the angle of the laminae was recorded and used to adjust the thickness measurements. The complete lamination sequence was counted and measured three times in an iterative manner, where the previous count was used as a starting point for refining further observations. An assessment of the reproducibility of the Lower Murray Lake lamination record was possible by comparing the results produced during this study with measurements previously reported by Besonen et al. (2008) who independently examined a different core, ML-00, collected at 81.3334° N, 69.54216° W from the same basin in Lower Murray Lake.

Radioisotope analysis

Surface core LML-05-C1-E5 was subsampled for ^{210}Pb and ^{137}Cs analysis by removing 0.5 cm slices of sediment from the split core tube. Sediment samples were freeze dried and powdered. Twelve samples spanning the upper 6 cm of the deposit were analyzed by gamma spectroscopy using a Canberra ultra-low background well-type germanium detector at the University of Florida.

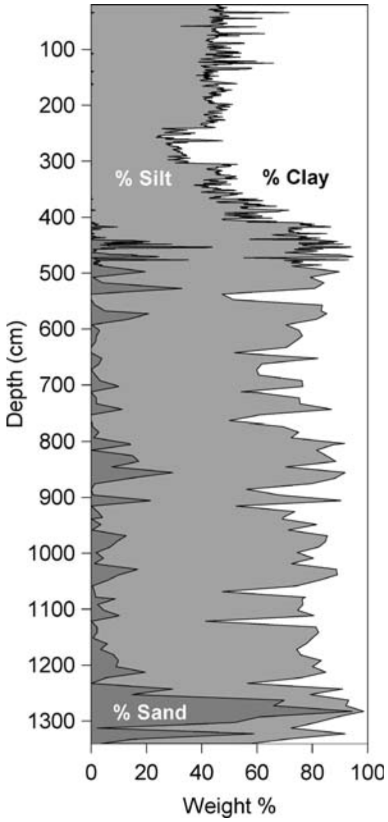


Fig. 2 Down-core variations in grain size in Lower Murray Lake sediments. The distinct transition that occurs at ~245 cm depth marks the beginning of the laminated portion of the sequence

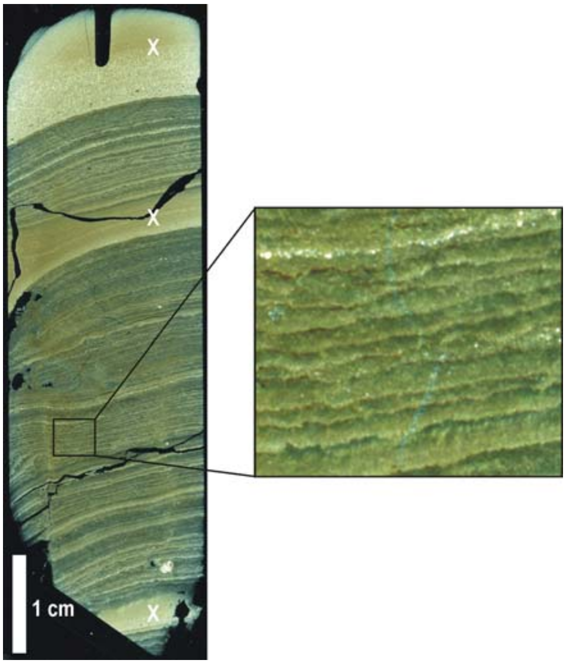


Fig. 3 Scanned image of a thin section under cross-polarized light showing fine-scale laminations punctuated by coarse-grained event deposits (marked X on thin section). Inset shows a sequence of fining-upwards silt and clay couplets that are characteristic of typical varves in Lower Murray Lake

Results[1]

Core stratigraphy

Core LML-05-C2, the longest core recovered from Lower Murray Lake, penetrated ~13.9 m. The bottom of this core consists of massive 5- to 10-cm-thick units of fine- to coarse-grained sand interspersed with silt and clay units (Fig. 2). The large grain size of these basal sediments suggests that they were deposited in a high-energy environment. We infer that the source of this energy was fluvial discharge from a locally receding glacier. This would suggest that core LML-05-C2 contains a nearly complete post-glacial lacustrine sedimentary sequence from Lower Murray Lake. The sediment sequence consists predominantly of fine-grained, silt- and clay-sized clastic material with very little organic matter. Mean loss-on-ignition was ~4.3%, although the actual organic content is likely lower because the dehydration of clay minerals continues at temperatures above 105°C (Dean 1974). The upper 245 cm of the core are characterized by fine laminations (<1 mm thick), consisting of alternating silt and clay couplets (Fig. 3). This upper portion of the core is punctuated by occasional, thicker units of silt and fine sand that are up to 1 cm thick (Fig. 3). Below 245 cm, laminations are less distinct and grain size is more variable. We interpret the transition to laminated sediments to reflect the retreat of glacial ice from the Murray Lakes valley and the evolution of the lake to its current water level. Relatively uniform grain size and lamination characteristics throughout the upper 245 cm suggest that the lake and its surroundings had reached steady-state conditions prior to this time. The remainder of this paper focuses only on the upper, finely laminated portion of

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[1] All data are available on-line through the World Data Center for Paleoclimatology (ftp://ftp.ncdc.noaa.gov/pub/data/paleo/paleolimnology/northamerica/canada/ellesmere/lower-murray2008.txt).

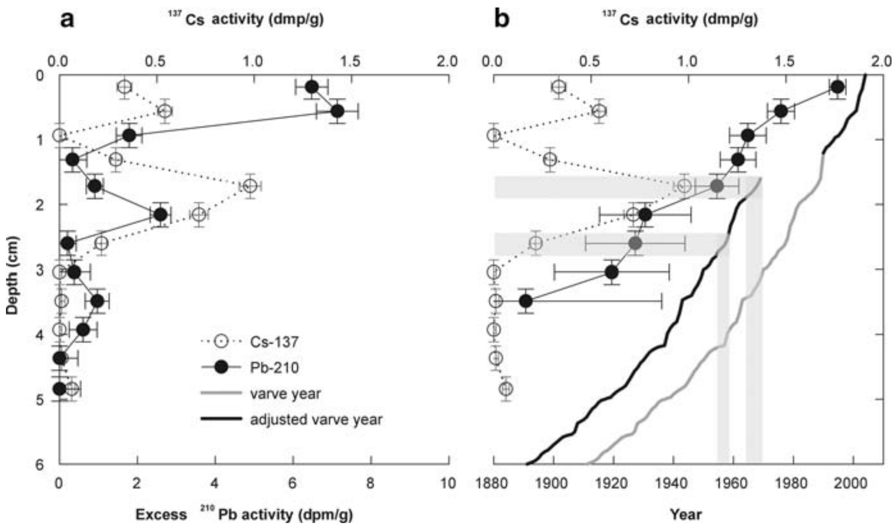

Fig. 4 **a** ^{210}Pb and ^{137}Cs activity versus depth for core LML-05-C1-E5. The ^{210}Pb minimum between ~1 and 1.5 cm depth suggests non-uniform deposition and is consistent with the depth of a turbidite observed in the sediment. **b** Comparison of the varve chronology with the ^{210}Pb age model (CRS model) and ^{137}Cs activity. Horizontal error bars are 1 σ uncertainties and vertical error bars represent the sampling interval. The gap in the varve chronology reflects suspected erosion resulting from a ca. 1990 turbidite, which likely contributes to the discrepancy between the varve and ^{210}Pb chronologies. Shaded regions indicate the first occurrence (~1954) and peak (1963) horizons of ^{137}Cs activity in the sediment, and their general agreement with the varve chronology

the record where lake sedimentation follows a consistent pattern.

Chronology

Due to the pronounced seasonality of the processes controlling sediment transfer and deposition in Lower Murray Lake, and to patterns of sedimentation that are consistent with varved deposits, including fining-upwards laminae topped by clay caps, we hypothesized that the silt-clay laminations observed in the sediments reflected annual units. Indeed, sediment cores collected in 2005 contained five additional laminae relative to those cores retrieved in 2000, confirming that recent laminae are annual. Further confirmation of this hypothesis was attempted by comparing ^{210}Pb and ^{137}Cs profiles to the varve chronology. However, disturbance from turbidity currents, bioturbation or mass movements can influence the inventory of ^{210}Pb in surface sediments (Wolfe et al. 2004). The application of ^{210}Pb dating in the Arctic is further complicated by very low ^{210}Pb activities in high-latitude lake sediments. Low radionuclide concentrations reflect a combination of reduced production because frozen soil retards the release of the parent isotope ^{222}Rn, and reduced deposition because persistent lake-ice cover limits the efficiency with which atmospheric ^{210}Pb is transferred to lake sediments (Wolfe et al. 2004). The Lower Murray Lake ^{210}Pb profile shows low activity levels characteristic of the Arctic, and erratic variations that likely reflect disturbance of the upper sediments (Fig. 4a). Visual inspection of the sediment confirms that an erosive turbidite layer was deposited during varve year 1990 (1.5 cm depth). Modeling of the sedimentation rate based on the ^{210}Pb profile using the constant rate of supply (CRS) model (Appleby and Oldfield 1978) produces an age-depth curve which is inconsistent with the varve chronology (Fig. 4b). The lowest sample in the ^{210}Pb age model assigns a date of 1890 to a depth of 3.5 cm, which corresponds to varve year 1944. This discrepancy would suggest large inaccuracies in the varve chronology which we believe are unreasonable and can more easily be explained by errors associated with low ^{210}Pb inventories in Arctic lake sediments, and by the erosive turbidite which would have removed and deposited elsewhere a portion of the radionuclide inventory.

The anthropogenic radionuclide ^{137}Cs provides two stratigraphic age horizons, corresponding to the onset of nuclear weapons testing ca. ~1954, and a peak in 1963 associated with maximum atmospheric fallout immediately prior to the implementation of the nuclear test ban treaty (Wolfe et al. 2004). The Lower Murray Lake radionuclide profile shows the first occurrence of ^{137}Cs at ~2.6 cm and a distinct peak at ~1.7 cm, corresponding to varve years ~1977 and 1988 respectively (Fig. 4). We propose that the discrepancy between the varve chronology and the known timing of these ^{137}Cs stratigraphic horizons was due to erosion of underlying varves associated with the turbidite in varve year 1990. Consequently the varve located in the middle of the interval of peak ^{137}Cs activity was assumed to be varve year 1963 and the varve chronology below the turbidite was reestablished from this point. The number of varves counted between the onset and subsequent peak in ^{137}Cs is consistent with the known age of these stratigraphic horizons. However, the large sampling interval used for radionuclide measurements relative to the low sedimentation rate in Lower Murray Lake precludes a precise determination of the number of laminae between the first occurrence and peak ^{137}Cs intervals. Counting varves upwards from the 1963 varve to the base of the turbidite suggests that varves from ~1970 through 1989 were eroded. This finding is consistent with the previous varve chronology established in Lower Murray Lake by Besonen et al. (2008)

Confident interpretation of the long-term sedimentary record in Lower Murray Lake requires validation of the consistency of the varve chronology throughout the time scale to be investigated. However, biological productivity in Lower Murray Lake is low both within the lake and in the surrounding drainage basin, and no suitable material for radiocarbon dating was identified in the lake sediments. Consequently, the long-term accuracy of the varve chronology was confirmed by comparing a record of paleomagnetic secular variation from Lower Murray Lake sediments in core LML-05-C2 with an independently dated paleomagnetic record from South Sawtooth Lake (Fig. 5). South Sawtooth Lake was cored as part of a separate study by coauthors of this paper. While analysis of the South Sawtooth record is ongoing, varve characteristics and limnological and sedimentary processes have been discussed in Francus et al. (2002, 2008). Despite differing rates of sedimentation, distinctive sedimentary characteristics and unique magnetic properties for each record, consistent patterns can be correlated among the different time series. In particular, both records show a large, coeval shift in declination and relative paleointensity and in-phase variations in the environmental magnetic ratio of anhysteretic remanent magnetization (ARM) after 30 mT demagnetization to the ARM before demagnetization. These similarities in the timing of paleomagnetic secular variations and environmental magnetic parameters help to confirm the accuracy of the individual chronologies.

Sources of error in varve chronologies can result from a number of factors including: (1) technical problems associated with coring and sub-sampling of the sediments; (2) unconformities caused by erosive events; (3) changes in varve preservation; and (4) either very high or very low sedimentation rates, which often make it difficult to distinguish seasonal events from the annual cycle (Zolitschka 2007). Technical problems in the Lower Murray Lake chronology were minimized by collecting multiple sediment cores and carefully selecting the least disturbed portions from each core to create a single composite varve sequence. All of the cores used in the composite record were from the same coring site, within a radius of <5 m, thus local variations in sedimentation should not be a factor. Although evidence for erosion during the ca. 1990 turbidite is unequivocal, only three other erosive turbidites were identified in the rest of the record. Additional unconformities may exist, but without further evidence, it seems likely that erosive events occur infrequently in this part of the lake. If erosive events were a common feature of the record, a continuously increasing offset would be expected between the timing of paleomagnetic variations in Lower Murray Lake sediments versus those in South Sawtooth Lake. However, this type of offset is not observed.

An estimate of the uncertainty associated with the subjective nature of varve identification and delineation was possible because Lower Murray Lake was the site of a previous varve study. Comparison of the overlapping portions of the varve records established in this study and by Besonen et al. (2008) demonstrates a high degree of consistency between chronologies established by separate individuals on different cores (Fig. 6). Despite relying on different sources of information (plain and cross-polarized scanned images in this study, and plain-light scans and backscattered SEM images in the previous study)

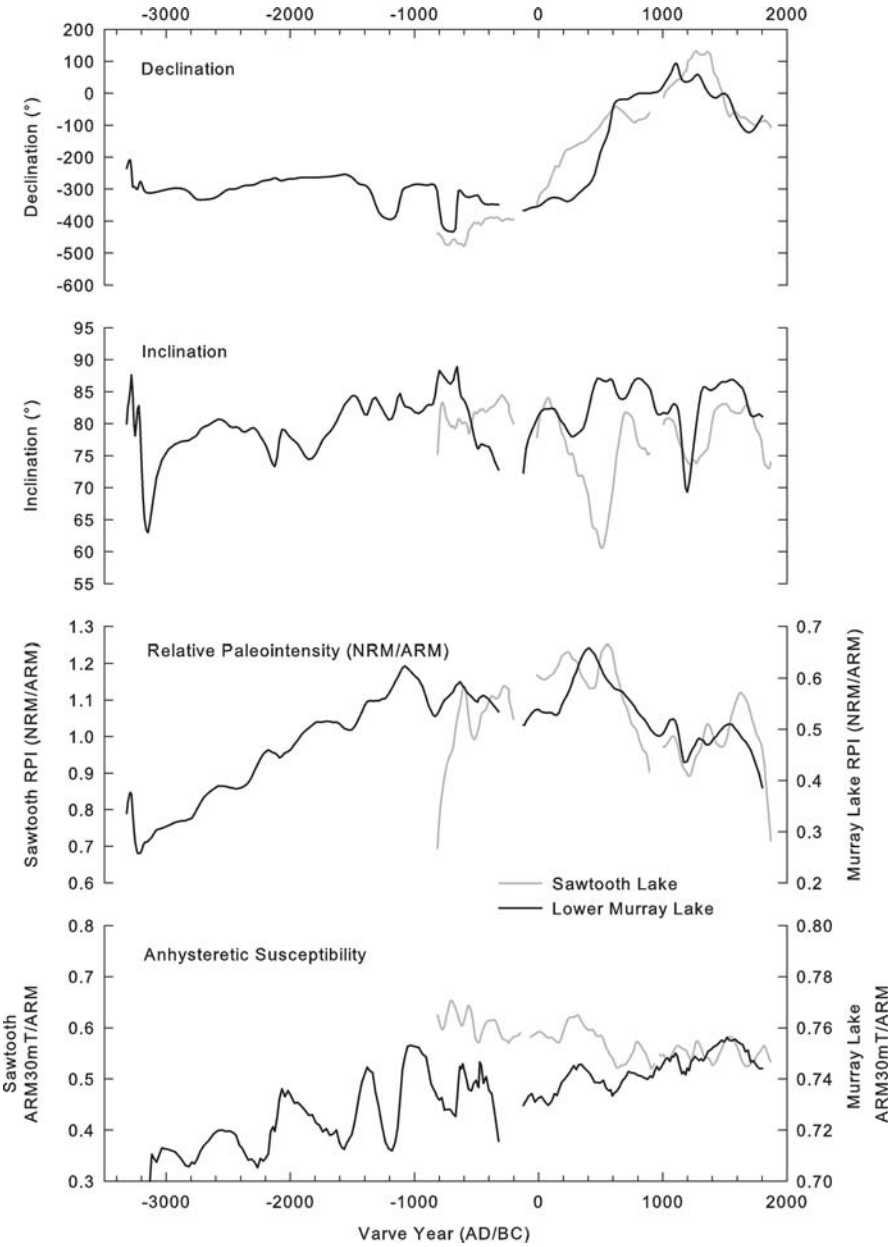

Fig. 5 Comparison of paleomagnetic secular variation records in sediment cores from Lower Murray Lake and South Sawtooth Lake on their independently derived varve-based chronologies. From top to bottom, the records include: the characteristic remanent magnetization (ChRM) declination; ChRM inclination; relative paleointensity estimated using the mean of the natural remanent magnetization (NRM) intensity normalized by anhysteretic remanent magnetization (ARM) over a range of progressive alternating field demagnetization steps; the ratio of ARM after 30 mT demagnetization to the ARM before demagnetization. See Stoner and St-Onge (2007) for further explanation of these measurements. Due to the higher rate of sedimentation in Sawtooth Lake, those data have been smoothed with a 20 point running mean filter

the two independent chronologies are offset by only 17 varve years at the end of the 1000 year period. Close examination of the individual chronologies isolated most of the offset to a single, short (~4 cm) portion of the record, between varve years 1550 and 1600 AD, where laminae were particularly diffuse and difficult to distinguish. There was no clear justification for favoring one chronology over the other, and as a result this discrepancy provides an error estimate of ~2% for the reproducibility of the varve chronology. The largest remaining sources of chronological error relate to either over-counting of sub-annual laminae, or under-counting eroded or poorly preserved laminae. Without more precise age control for the long record from either radiocarbon or tephra dating it is difficult to precisely quantify the full level of chronological uncertainty from all sources in the Lower Murray Lake varve record.

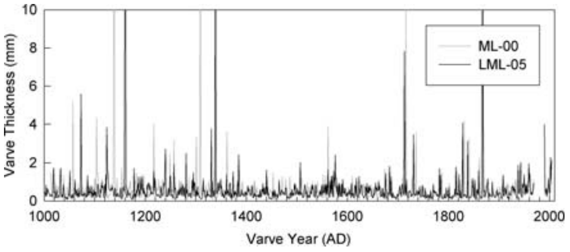

Fig. 6 Comparison of the independently derived varve chronologies from cores collected in 2005 (LML-05; this study) and 2000 (ML-00; Besonen et al. 2008). Offset between the two records illustrates the uncertainty in varve delineation and reflects error in both the chronology and thickness measurements. Total offset after 1000 varve years is <20 years or 2%. Most of the offset can be isolated within a single portion of the record where laminae are particularly diffuse and difficult to distinguish. Adjusting one record to match the other is difficult to justify

Lamina characteristics

A total of 5221 individual varves were identified. After accounting for the estimated ~20 varves eroded during the ca. 1990 turbidite, but without taking into account the additional uncertainties described above, the laminated portion of the Lower Murray Lake record spans the period from varve year 2004 AD through 3236 BC. No adjustment was made for the three additional erosive events because there was no way of determining how many laminae were removed. The composite time series of varve thickness is shown in Fig. 7. Mean laminae thickness throughout this period is 0.46 mm, although the record shows considerable high-amplitude variability. Typical laminae are characterized by a fining-upward silt unit topped by uniform clay caps. These units fit the classic description of clastic varves typical of cold environments (Sturm 1979; Zolitschka 2007). Punctuating this sequence are a number of anomalously thick (up to 1 cm), coarser grained (silt to fine sand), graded deposits, which occasionally contain planar sub laminae. The larger grain size of these deposits necessitates an alternative, higher-energy transport mechanism relative to the typical varves. The genesis of these deposits is difficult to decipher without additional process monitoring; however, similar deposits in other arctic lakes have been attributed to turbid underflows resulting from rain events and elevated stream flow (Lamoureux 2000; Hambley and Lamoureux 2006; Francus et al. 2008). A total of 124 of these anomalous beds were identified through visual inspection of the thin sections. To facilitate the interpretation of variations in mean sedimentation as

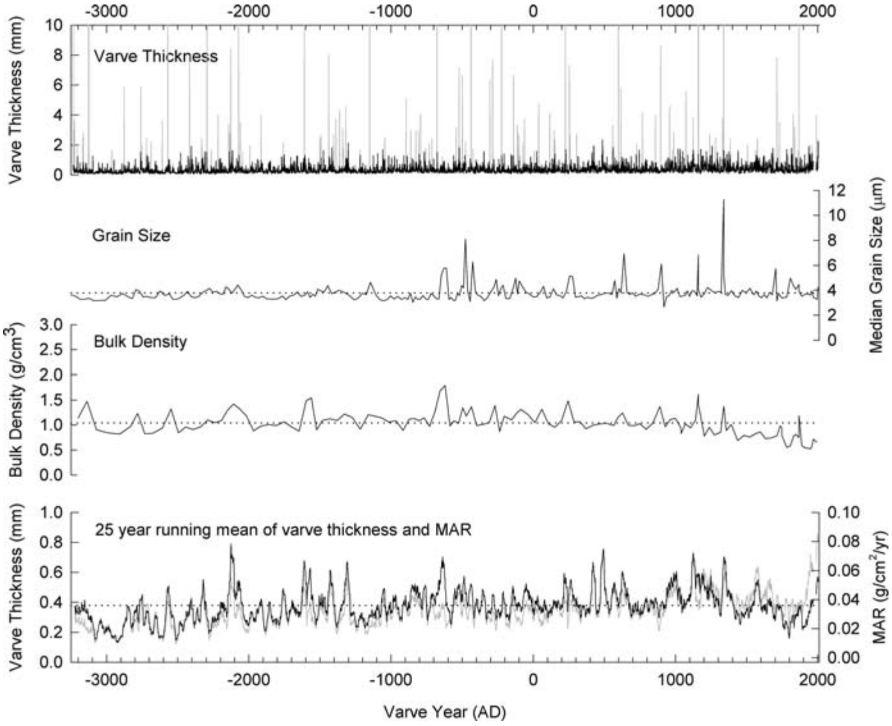

Fig. 7 Sedimentological results from Lower Murray Lake. Time-series data are a combination of the least disturbed sections of multiple cores. Top panel shows raw varve thickness measurements (*grey*) and varve thickness after anomalous depositional units have been removed (*black*). Bottom panel shows varve thickness (*grey*) and mass accumulation (*black*) after the data have been smoothed with a 25 year running mean filter. Mass accumulation is calculated from the varve thickness and bulk density measurements. Dotted lines in each panel reflect the series mean value

characterized by typical varves, the anomalous beds were removed from the time series and replaced by a unit equal in thickness to the series mean after excluding the graded beds (0.34 mm).

Evaluation of changes in sedimentation through time requires that varve thickness measurements are corrected for varying degrees of compaction. In general, sediment becomes more compacted with depth as it is compressed by the weight of the overlying material. In addition, differential compaction of sediments can occur during the coring process as sediment interacts with the surrounding sediment and core tube. This problem was addressed by converting varve thickness measurements to mass accumulation rates (MAR) using measurements of bulk density (Fig. 7). The average mass accumulation rate for the period of record was 0.049 or 0.036 g cm^{-2} year^{-1} if the anomalous event beds are excluded. Correcting for variations in bulk density effectively compensated for the trend toward increasing varve thickness observed in the uppermost sediments. However, comparison of the grain size, bulk density, varve thickness, and mass accumulation records indicate that isolated, coarse-grained deposits are responsible for some of the largest peaks in mass accumulation. This result highlights the difficulty of relating discrete bulk density measurements to higher-resolution varve thickness measurements (cf. Besonen et al. 2008). Thus, when comparing rates of sedimentation between different periods of the record it is important to evaluate how and why mass accumulation rates differ from varve thicknesses within a given interval.

Varve thickness and mass accumulation data were smoothed with a 25-year running mean filter to aid identification of periods of consistently higher or lower sedimentation (Fig. 7). The long-term record of mass accumulation shows distinct centennial-scale variations in addition to extended periods of reduced or enhanced mass accumulation relative to the long term mean. Twentieth-century mass accumulation rates fall at the upper end of the scale, and during the last 1000 varve years, were only exceeded in the twelfth and fourteenth centuries. A minimum in mass accumulation occurred around varve year 1800 AD; the only comparable period of low mass accumulation occurs from varve year 5200 BC through 4500 BC. Mass accumulation rates in the middle portion of the record, spanning varve years 2000 BC to 1000 AD, are predominantly near or above the 1000–2000 AD mean, and are characterized by considerable variability.

Discussion

Climatic controls on Lower Murray Lake sedimentation

Previous studies of High Arctic lake systems have demonstrated various quantitative relationships between lake sedimentation and meteorological conditions. In many cases, lake sedimentation and varve thickness are related to temperature during the summer melt season when the melting of ice and snow provides energy to transport sediment into lakes (Hardy 1996; Hardy et al. 1996; Gajewski et al. 1997; Braun et al. 2000b; Hughen et al. 2000; Moore et al. 2001; Francus et al. 2002; Hambley and Lamoureux 2006). In other systems, sediment delivery is controlled more by winter snow accumulation than by summer-melt conditions (Braun et al. 2000a; Lamoureux and Gilbert 2004; Forbes and Lamoureux 2005; Cockburn and Lamoureux 2007). Additional controls on lake sedimentation can include rain-induced erosion (Lamoureux 2000; Lamoureux et al. 2001), limited sediment availability (Braun et al. 2000a), spatial and temporal variations in the distribution of sediments within a lake (Lamoureux 1999), mass movements (Lewis et al. 2005), variations in sediment availability (Lamoureux 2002), and a variety of external catchment and within-lake processes that are often non-linear (e.g. Hodder et al. 2007).

We examined the relationship between annual sedimentation in Lower Murray Lake and climatic conditions by comparing the time series of mass accumulation to instrumental climate data recorded at the two nearest permanent weather stations located at Alert, which is 180 km away along the north coast of Ellesmere Island, and at Eureka which is located 320 km west in a more continental setting. Because the frequency distribution of annual mass accumulation rates was heavily skewed towards smaller values the data were log transformed. This process yields a time series consisting of more normally distributed values which are better suited for correlation with climatic data that typically exhibits a Gaussian distribution (cf. Rittenour et al. 2000). Only mass

Table 1 Coefficient of determination (R^2) values and their significance (p values) calculated for linear regressions between log-transformed Lower Murray Lake mass accumulation and assorted climatic data recorded at the Alert and Eureka weather stations

Variable	Alert R^2 (p value)	Eureka R^2 (p value)
June temp (°C)	0.02 (0.662)	0.01 (0.752)
July temp (°C)	0.15 (0.157)	0.06 (0.409)
August temp (°C)	0.23 (0.479)	0.13 (0.179)
Mean JJA temp (°C)	0.10 (0.240)	0.01 (0.767)
June 600 m temp (°C)	0.00 (0.992)	0.00 (0.961)
July 600 m temp (°C)	0.61 (<0.001)	0.50 (0.003)
August 600 m temp (°C)	0.02 (0.601)	0.02 (0.632)
Mean JJA 600 m temp (°C)	0.16 (0.136)	0.22 (0.080)
June rain (mm)	0.01 (0.732)	0.24 (0.023)
July rain (mm)	0.03 (0.582)	0.39 (0.017)
August rain (mm)	0.01 (0.732)	0.30 (0.041)
Total JJA rain (mm)	0.07 (0.446)	0.08 (0.323)
Total Sep-May snow (cm)	0.10 (0.102)	0.00 (0.479)

accumulation data from the years 1990 through 2004 were used in the statistical analysis because the certainty of the varve chronology decreases prior to the ca. 1990 turbidite. Table 1 lists r^2 values obtained from calculating linear regressions between Lower Murray Lake MAR and various climatic variables for the period 1990–2004. In general, r^2 values generated from correlation with surface meteorological conditions were very low. However, mass accumulation rates were significantly correlated to radiosonde measurements (Durre et al. 2006) of mean July temperatures at 600 m at both Alert ($r^2 = 0.61$) and Eureka ($r^2 = 0.50$; Fig. 8). Temperature data from 600 m were chosen for the analysis because this elevation corresponds to the approximate mean elevation of the Murray Lakes watershed.

A positive correlation between summer temperatures and sedimentation rates has been observed in several other lakes in the Canadian Arctic (e.g. Hardy et al. 1996; Hughen et al. 2000; Moore et al. 2001). In particular, Hardy et al. (1996) also identified a strong correlation between 600 m temperatures at Alert and daily sediment flux into Lake C2. Upper-air temperature measurements likely provide a better estimate of regional temperature conditions relative to surface measurements because they are not influenced by localized low-level temperature inversions which are common throughout the High Arctic. Furthermore, much of the runoff entering Lower Murray Lake is derived from snowmelt in the upper watershed which is at or above 600 m elevation. At other sites on northern Ellesmere Island where streamflow and sediment flux measurements have been recorded, peak streamflow and the majority of the seasonal sediment transport have occurred over a brief period of several days in July (e.g. Hardy et al. 1996; Braun et al. 2000b). Consequently, we suggest that sediment mass accumulation in Lower Murray Lake is dominantly influenced by July temperatures in the upper watershed which affect snowmelt, streamflow and sediment transport into the lake.

Because July air temperature at 600 m altitude at Alert showed the highest correlation with Lower Murray Lake mass accumulation, this relationship was used to calibrate the long-term record of MAR in terms of July temperature using the following equation:

$$\begin{aligned}&\text{Temperature} = 8.49 + 1.95 \times \ln(\text{MAR})\\&\quad \text{std. error} = \pm 1.04^\circ\text{C}\end{aligned} \tag{1}$$

The temperature calibration does not change the major features of the mass accumulation record, but

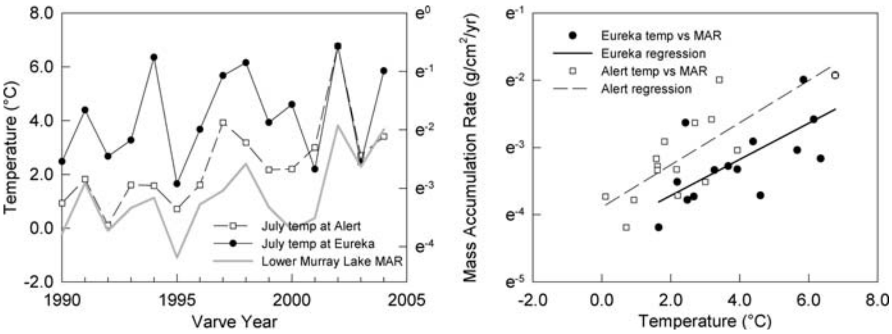

Fig. 8 **a** Time-series of Lower Murray Lake mass accumulation and 600 m temperatures recorded by radiosondes at Alert and Eureka. **b** Scatter plot showing the relationship between Alert and Eureka 600 m temperatures and mass accumulation rates in Lower Murray Lake

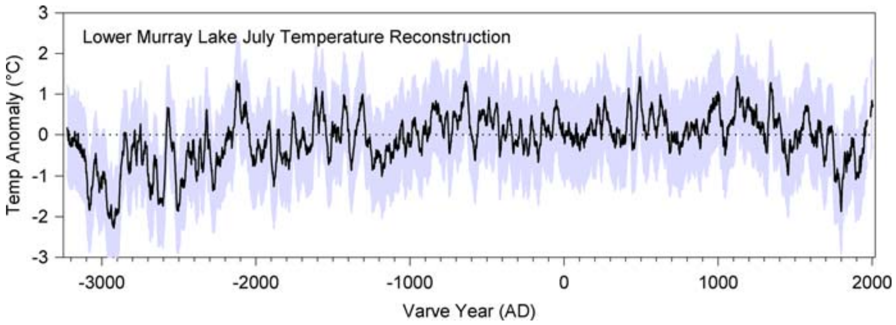

Fig. 9 Lower Murray Lake temperature reconstruction based on the calibration between mass accumulation rate and July 600 m temperatures at Alert. 25 year running mean temperatures are plotted as anomalies relative to the 1001–2000 AD mean. Shaded gray region reflects ±1.04°C standard error of the regression equation

provides a quantitative estimate of the range of past temperature variations at Lower Murray Lake (Fig. 9). The temperature reconstruction is plotted as anomalies relative to the 1001–2000 AD mean in order to account for differences in the absolute temperatures at Lower Murray Lake and the Alert calibration site. The 1001–2000 AD reference period, which is used in all subsequent figures and discussions, was chosen so that records of shorter duration could be compared to the Lower Murray Lake time series using a common interval as a reference for baseline conditions.

The temperature reconstruction suggests: (1) recent temperatures are ~2.6°C higher than minimum temperatures observed during the Little Ice Age, (2) maximum temperatures during the past 5,200 years exceeded modern values by ~0.6°C, (3) minimum temperatures observed approximately 2,900 varve years BC were ~3.5°C colder than recent conditions. The calibration period used to estimate these temperature changes is admittedly short and the distance between Lower Murray Lake and Alert adds additional uncertainty to the reconstruction that demands caution when interpreting the temperature calibration. Nonetheless, our confidence in the relationship between temperature and mass accumulation in Lower Murray Lake is enhanced by the similar relationships observed at Lakes Tuborg and C2 (Hardy et al. 1996; Braun et al. 2000b). The fact that MAR was significantly correlated to July temperatures at both Alert and Eureka suggests that sedimentation in Lower Murray Lake is responding to regional melt season temperatures. This allows us to compare the Lower Murray Lake time-series to independent proxy climate records and assess the veracity of inferred linkages between climate and sedimentation over long time scales.

As discussed previously, few high-quality paleoclimate reconstructions exist for the High Arctic. Therefore the sensitivity of Lower Murray Lake sedimentation to changes in temperature was evaluated by comparing the sedimentary sequence to records of climate forcing mechanisms known to contribute to changes in global temperatures (Fig. 10; Crowley 2000). Regional climate variations result from complex interactions among a variety of factors; nonetheless, changes in volcanic aerosols, solar output, and the concentration of greenhouse gases have a significant influence on temperature (Crowley 2000). Figure 10 indicates that periods of above average mass accumulation in Lower Murray Lake roughly coincide with periods of reduced volcanic activity, increased solar forcing, and increased greenhouse gas concentrations. In contrast, periods of below average mass accumulation generally coincide with periods of increased volcanic activity, reduced solar forcing, and reduced greenhouse gas concentrations. This relationship suggests that, over the last 1000 years decadal-scale variability in sedimentation in Lower Murray Lake is positively correlated with changes in regional temperatures that are driven by large-scale radiative forcing.

Over periods of several decades the relationship between temperature and sedimentation is likely strengthened by several factors specific to the Arctic. Przybylak (2002) demonstrated that, during the instrumental period, increased temperatures coincided with higher precipitation totals in most regions of the Canadian Arctic. Warm periods in the past were therefore likely associated with

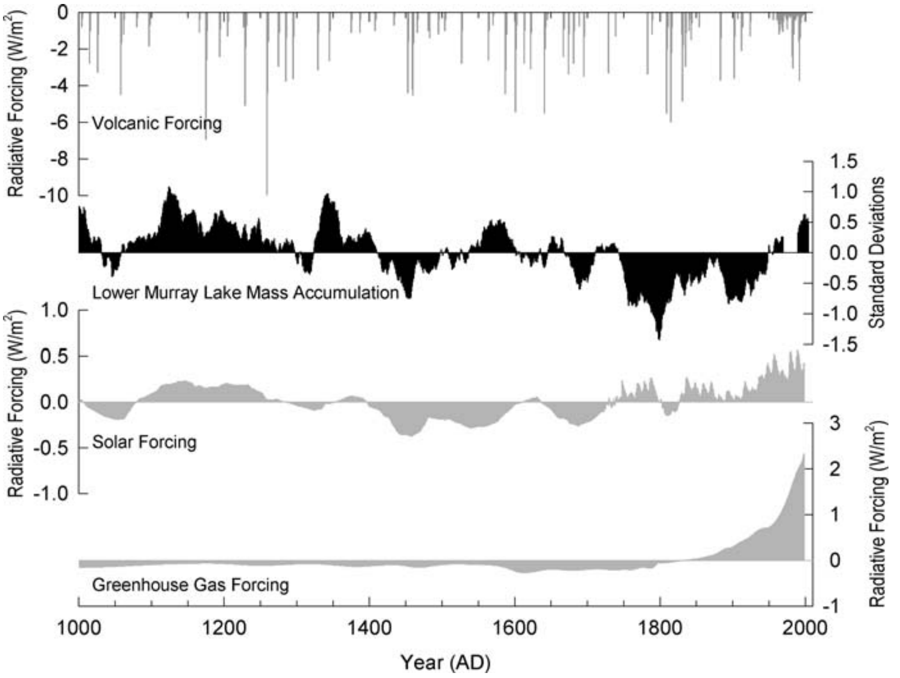

Fig. 10 Lower Murray Lake mass accumulation over the past 1000 varve years (*black*) relative to external forcings of global temperatures (Crowley 2000): volcanic forcing (*top panel*), solar variability (*third from top*), and greenhouse gasses (*bottom panel*). Note the different scales for radiative forcing by the different variables. Lower Murray Lake mass accumulation, radiative forcing from greenhouse gasses, and solar variability are plotted relative to their 1001–2000 AD mean. Periods of increased mass accumulation in the twelfth to fourteenth centuries coincide with episodes of elevated solar activity and reduced volcanic activity, whereas reduced mass accumulation around 1450, 1700, and 1800 AD coincides with periods of enhanced volcanism and reduced solar activity. Increased mass accumulation in the twentieth century coincides with anthropogenic forcing of greenhouse gas concentrations

elevated runoff resulting from a combination of increased precipitation throughout the year and enhanced melt production in the summer. In addition, warmer conditions should have increased sediment availability by increasing the depth of the active layer. Because sediment availability and runoff ultimately limit lake sedimentation, an increase in these variables due to warmer temperatures should have led to increased sediment accumulation in lakes. Indeed, a positive correlation between temperature and sedimentation rate has been observed in several other lakes in the Canadian Arctic (e.g. Hardy et al. 1996; Hughen et al. 2000; Moore et al. 2001).

Is there a consistent regional pattern?

Climatic controls on lake sedimentation were further examined by comparing Lower Murray Lake mass accumulation to other regional records of environmental change (Fig. 11). Lake Tuborg is the nearest location from which another varve record has been produced (~110 km from Lower Murry Lake; Fig. 1), and relative to Lower Murray Lake, likely reflects the most similar climatic setting of the available records. Similar patterns in each record, particularly relating to the timing of reduced sedimentation in each lake are evidence of an external (climatic) forcing mechanism. Process monitoring in the Lake Tuborg watershed by Braun et al. (2000b) demonstrated a relationship between summer temperature and sediment transfer to Lake Tuborg that is consistent with our interpretation of the climatic controls on Lower Murray Lake sedimentation. Although varve deposition in Lake Tuborg has been previously described by Smith et al. (2004), the Tuborg varve series shown here (T. Lewis, *unpublished data*) has not been independently dated. In contrast, comparison of Lower Murray Lake mass accumulation with Lake C2 varve thickness (Lamoureux and Bradley 1996) shows much less consistency.

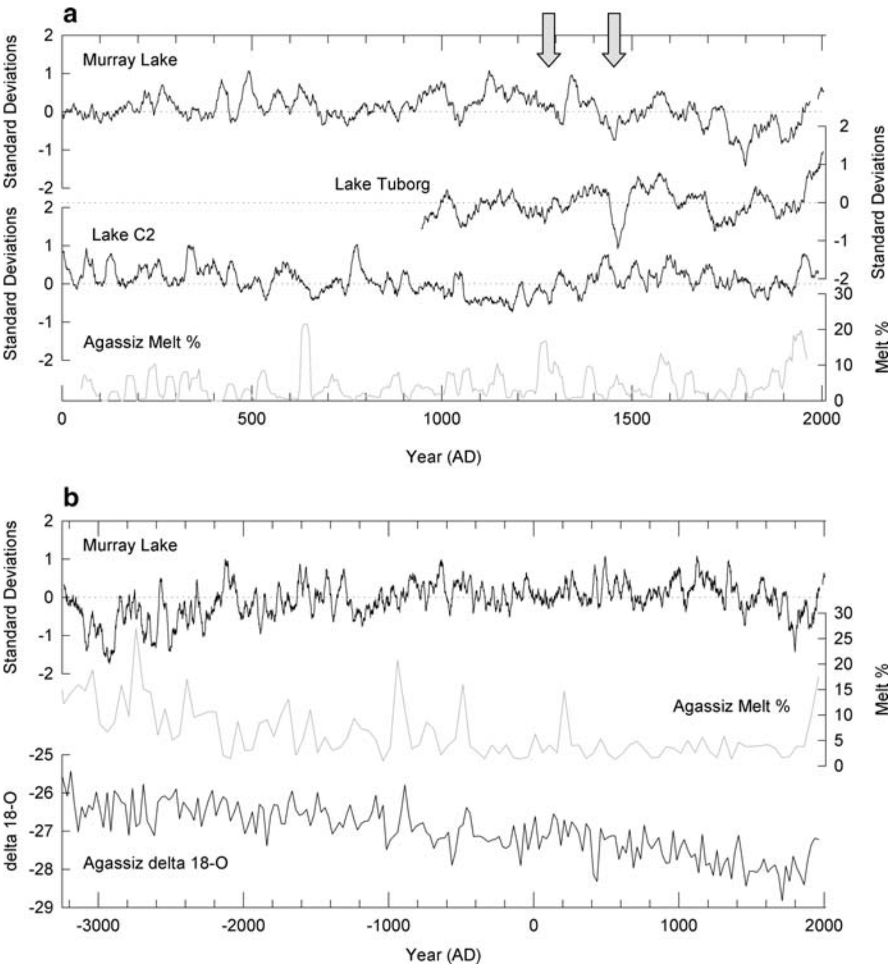

Fig. 11 **a** Comparison of the last 2000 years of Lower Murray Lake mass accumulation with Lake Tuborg (T. Lewis, *unpublished data*) and Lake C2 (Lamoureux and Bradley 1996) varve thickness and Agassiz Ice Cap melt percentage (Fisher et al. 1995; Fisher and Koerner 1994). Running means (25 year) are plotted for each record; varve data are log transformed, normalized departures from 1000 to 2000 AD mean. Arrows indicate periods of widespread ice-cap expansion identified in northern Baffin Island ca. ~1280 and ~1450 AD (Anderson et al. 2008). **b** Long-term, 5,200 year record of Lower Murray Lake mass accumulation compared to Aggasiz Ice Cap melt percentage and δ^{18}O (Fisher et al. 1995; Fisher and Koerner 1994)

Lake C2 is located along the north coast of Ellesmere Island, adjacent to the Arctic Ocean and in a considerably different climatic setting. Thus differences in the two records may reflect either different local climatic conditions or the unique effects of site-specific processes acting within the lakes and surrounding catchment. Lower Murray Lake mass accumulation, Lake Tuborg varve thickness, and Agassiz Ice Cap melt percentages (Fisher and Koerner 1994; Fisher et al. 1995) all show a large increase in the twentieth century. Earlier peaks in Agassiz Ice Cap melt percentage frequently coincide with periods of elevated sedimentation in Lower Murray Lake; however, the relative magnitude and timing of events is not always consistent. These discrepancies may reflect uncertainties in the chronology of both records, or differences in the way individual proxies respond to climate forcing. Anderson et al. (2008) identified two periods of widespread ice-cap expansion on northern Baffin Island around ~1280 and ~1450 AD (indicated by arrows in Fig. 11a). These events coincide with episodes of reduced sediment accumulation in Lower Murray Lake and support the interpretation that cold periods in the past are associated with reduced sedimentation in Lower Murray Lake.

On longer time scales (Fig. 11b) the period of extremely low sediment accumulation in Lower Murray Lake centered around 1800 AD is roughly consistent with the timing of lowest melt percentage and δ^{18}O values observed in the Agassiz Ice Cap (Koerner and Fisher 1990). Although δ^{18}O values in the Agassiz Ice Cap reflect the combined influence of changes in climate, ice-cap thickness, and wind scouring, low δ^{18}O values and melt percentages in the nineteenth century signify the culmination of the

'Little Ice Age' and likely reflect the coldest period of the last several thousand years in the High Arctic (Koerner and Fisher 1990; Fisher et al. 1983). Thus, reduced sediment mass accumulation during this period is consistent with the inferred temperature control on lake sedimentation. Identifying the warmest periods in paleoclimate records from northern Ellesmere is less straightforward. δ^{18}O values and melt percentages in the Agassiz Ice Cap indicate that the warmest conditions were experienced in the early Holocene ~8000–10000 ^{14}C years BP, with temperatures generally decreasing until the end of the 'Little Ice Age' (Koerner and Fisher 1990). In contrast, the earliest portion of the Lower Murray Lake record (~5200–4500 varve years) is characterized by extremely low rates of sedimentation. This difference may reflect regional climatic variability, the local influence of the waning Innuitian Ice Sheet at this time, or both. Indeed, Smith (2002) examined the abundance of diatoms in a series of lakes ~50 km from Murray Lake on the Hazen Plateau and identified evidence of a similarly delayed 'thermal maximum' ~4200–3000 ^{14}C years BP attributed to the effects of locally retreating glaciers. These differences illustrate the level of remaining uncertainty in the climatic history of the High Arctic and underscore the need for additional paleoclimate reconstructions so that local anomalies in individual proxy records can be separated from regional climatic trends.

Stability of the climate-sedimentation system

Quantitative reconstructions of past climatic conditions are strongly dependent on the data selection and calibration methods used (Esper et al. 2005). In the High Arctic, quantitative relationships between climate and varve characteristics have been based on either a few years of process monitoring or correlation of varve measurements with the instrumental record. The general assumption underlying the use of these models is that the relationships observed during the calibration period are stationary through time. In addition, previously published varve calibrations have largely relied on linear statistical models related to a single climate variable (e.g. Hardy et al. 1996; Hughen et al. 2000), whereas the actual climate-varve process network as defined by Hodder et al. (2007) involves numerous variables which often interact in a non-linear fashion. Given these uncertainties, it is worth examining the long-term stability of the Lower Murray Lake system and its reliability as an archive of changing climatic conditions.

Blass et al. (2007) demonstrated that, in a glaciated alpine lake, a calibration model based on twentieth century observations was not valid for longer-term temperature reconstructions because of large-scale changes in the sediment transport system. Failure of the varve-climate calibration was coincident with distinct changes in mean sedimentation and in the amplitude of interannual variability (Blass et al. 2007). In contrast, several lines of evidence from the Lower Murray Lake record suggest that linkages within the climate-varve process network have remained relatively stable throughout the past several thousand years, including : (1) a reasonably consistent response to climate forcing mechanisms and similarities to other regional records during the last 1000+ years indicates that major processes linking the climatic conditions to lake sedimentation have been stable throughout this period; (2) mean sedimentation and the scale of variability in the long-term record of mass accumulation are nearly constant throughout the last 5000 years; (3) apart from the anomalous event deposits characterized by thick laminae and increased grain size and bulk density, median grain size is highly consistent throughout the period of record, suggesting that sediment transport has occurred under steady hydrodynamic conditions.

The apparent stability in the varve-climate process network at Lower Murray Lake has occurred despite considerable climate variability and substantial changes in the expanse of ice caps within the study area. Deglaciation of the Lower Murray Lake area occurred ~6900 ^{14}C years BP (England 1983), with ice retreat continuing until margins close to or behind present conditions were reached by ~5000 ^{14}C years BP (Smith 1999). Plateau ice caps at favorable, high-elevation locations likely persisted through the mid-Holocene (Smith 1999), but may have subsequently disappeared and later reformed following the Holocene thermal maximum (Koerner and Paterson 1974). Similarly, small plateau ice caps on northern Baffin Island are believed to have existed continuously since at least ~350 AD, and experienced significant expansion around 1280 AD and again around 1450 AD (Anderson et al. 2008).

Consistent controls on sedimentation in Lower Murray Lake are likely facilitated by several factors, including: the lake has a simple drainage basin that is characterized by short, high-gradient streams that lead to rapid transport of sediment from the catchment into the lake basin. Upper Murray Lake traps a significant portion of the sediment produced within the watershed and likely acts as a partial buffer to changes in Lower Murray Lake sedimentation. In addition, cold-based ice caps like those adjacent to Lower Murray Lake are minimally erosive (Paterson 1969), and even at maximum extent covered less than ~10–15% of the Lower Murray Lake drainage basin. As a result, changes in ice expanse are not likely to have caused major changes in sediment production.

Conclusions

Lower Murray Lake varves contain an annual record of sediment mass accumulation spanning the past 5000+ years. In general, periods of elevated sediment accumulation coincide with periods of presumed warm conditions in the past. Likewise, suspected cold periods in the past are associated with low rates of sedimentation in Lower Murray Lake. Lower Murray Lake mass accumulation rates were positively correlated with mean July 600 m free air temperatures at the two nearest permanent weather stations at Alert and Eureka. Calibration of the MAR timeseries provided a quantitative estimate of the magnitude of past temperature variability. These results indicate that decadal-scale patterns of sedimentation in Lower Murray Lake are influenced by regional temperatures driven by radiative forcing. The lowest rates of sediment accumulation, and by inference the coldest periods occurred around varve year 1800 AD and prior to ~4200 varve years ago. In contrast, periods of increased sedimentation, and by inference the warmest conditions, occurred in the twelfth, fourteenth, and twentieth centuries, and throughout the middle portion of the record, approximately 1000–4200 varve years ago.

Lower Murray Lake sediments maintain a consistent pattern of deposition throughout the period of record and respond predictably to presumed climatic conditions in the past. Despite the complexity and inherent uncertainty in the varve-climate process network, the stability of the Lower Murray Lake sedimentary system supports the use of annual mass accumulation as a proxy indicator of climatic conditions in the past. Nonetheless, discrepancies between the Lower Murray Lake varve record and other regional paleoclimate records highlight the need to validate varve-based climate reconstructions using multiple lines of evidence from numerous locations. In the High Arctic, comparison of regional records is hindered by the limited number of high-quality paleoclimate reconstructions of any sort. Consequently, the acquisition of additional climate reconstructions from the High Arctic should be a priority.

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