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Little Ice Age recorded in summer temperature reconstruction from varved sediments of Donard Lake, Baffin Island, Canada

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Abstract

Clastic varved sediments from Donard Lake, in the Cape Dyer region of Baffin Island, provide a 1250 yr record of decadal-to-centennial scale climate variability. Donard Lake experiences strong seasonal fluctuations in runoff and sediment fluxes due to the summer melting of the Caribou Glacier, which presently dominates its catchment. The seasonal variation in sediment supply results in the annual deposition of laminae couplets. A radiocarbon date measured on moss fragments, with a calibrated age of 860 ± 80 yrs before present (BP), is in close agreement with the age based on paired-layer counts. Together with the fabric of the laminae determined from microscope analysis, the age agreement demonstrates that the laminae couplets are annually deposited varves. Comparisons of varve thickness and average summer temperature from nearby Cape Dyer show a significant positive correlation ($r = 0.57$ for annual records, $r = 0.82$ for 3-yr averages), indicating that varve thickness reflects changes in average summer temperature. Varve thickness was used to reconstruct average summer temperatures for the past 1250 yrs, and shows abrupt shifts and large amplitude decadal-to-centennial scale variability throughout the record. The most prominent feature of the record is a period of elevated summer temperatures from 1200–1375 AD, followed by cooler conditions from 1375–1820 AD, coincident with the Little Ice Age.

Introduction

Previous research has shown that Baffin Island, in the eastern Canadian Arctic, is sensitive to climatic fluctuations on regional-to-hemispheric scales (Andrews et al. 1972; Bradley & Miller, 1972; Barry et al., 1977). The location of Baffin Island beneath a major trough in the northern hemisphere upper Westerlies contributes to local climatic sensitivity to global-scale changes in atmospheric circulation (Keen, 1980). Warming or cooling causes shifts in the hemispheric temperature gradient and the east-west position of the trough, directly affecting surface winds and the advection of southerly vs. northerly air masses over the Baffin Island region (Brinkman & Barry, 1972; Keen, 1980). Bradley & Miller (1972) showed that the mass balance of alpine glaciers and perennial snowbanks on Baffin Island responds rapidly to abrupt changes in climate. Varved glacial lakes associated with alpine glaciers are ideal places to investigate high-resolution climate change in the eastern Canadian Arctic.

Climate change takes place on a variety of time scales, but perhaps the least understood of these is the decadal-to-centennial scale (Overpeck, 1991). It is important to gain an understanding of the patterns of natural variability on this time scale in order to measure the human impact on the Earth's climate system, as well as to successfully predict climatic changes in the future.

Most instrumental records are too short for the study of decade-to-century scale climate variability, particularly in the Arctic (Bradley, 1973). Obtaining high-resolution paleoclimate records is therefore necessary to study the record of these rapid fluctuations. Annually laminated (varved) lake sediments record seasonal changes in sediment deposition and are capable of preserving a history of abrupt climatic changes (Overpeck, 1996). Lakes containing varved sediments exist throughout the Arctic, and provide an important paleoclimatic proxy in regions north of treeline (Bradley et al., 1996; Overpeck et al., 1997). Varved records may provide a broad network of sites with which to decipher temporal and spatial patterns of climate change. Here we present a new paleotemperature record from varved sediments of Donard Lake, a glacierized meltwater-dominated lake on Baffin Island in the eastern Canadian Arctic. Calibration of the varve thickness record using instrumental temperature data allowed the reconstruction of average summer temperature variability for the past 1250 yrs.

Background

Cape Dyer, on Cumberland Peninsula, is the easternmost point on Baffin Island (Figure 1). Sharp glacially carved peaks (maximum elevation of 1800 m) dominate the landscape from the Penny Ice Cap, which covers most of Cumberland Peninsula, eastward to Cape Dyer. The combination of rugged topography and a network of deep, fault-controlled valleys may have helped to isolate Cape Dyer from all but local ice for much of its recent Quaternary history (Miller, 1973; Miller & Dyke, 1974; Hawkins, 1980; Dyke et al., 1982; Locke, 1987). Most of the bedrock in the field area consists of Precambrian gneiss, granite, and quartz monzonite (Clarke & Upton, 1971). Carbonate bedrock is entirely absent from eastern Cumberland Peninsula. Donard Lake, a small glacially fed lake at an elevation of approximately 450 m, lies 19 km west of the Distant Early Warning (DEW) Line site at Cape Dyer and 2 km north of Sunneshine Fjord (Figure 2). Donard Lake is 0.9 km long, 0.4 km wide, and 22 m deep at its deepest point (Figure 3), and is surrounded on its elongate sides by steep walls that rise to elevations in excess of 1000 m. The lake completely freezes over beginning in October, with ice usually melting in June. During cold summers, an ice pan surrounded by an ice-free moat will persist throughout the summer.

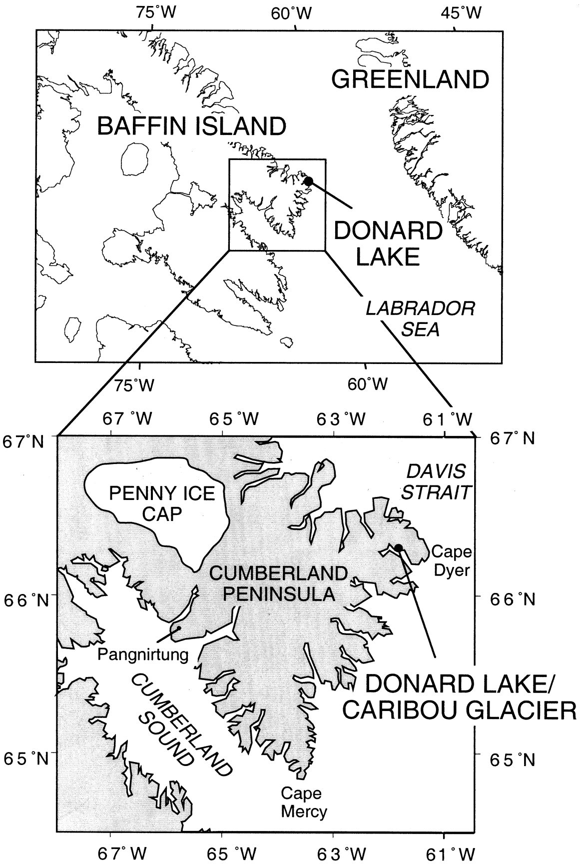

Figure 1. Location of Donard Lake and the Caribou Glacier system on eastern Cumberland Peninsula, Baffin Island.

A bedrock saddle separates the Donard Lake basin from an adjacent, deeply excavated glacial valley containing the Caribou Glacier (Figure 2). The Caribou Glacier is approximately 7.5 km long and 1 km wide at its widest point, and originates from icefields in the mountains 6 km north of Donard Lake. As the glacier leaves these headlands it flows south-southwest past Donard Lake, terminating 1 km north of Sunneshine Fjord. A small sub-lobe of the glacier currently extends over the bedrock saddle and terminates 0.75 km from the west end of Donard Lake (Figure 2). The Neoglacial end moraine for the Caribou Glacier in the Donard Lake drainage lies approximately 0.25 km from the lake. Caribou Glacier input into Donard Lake operates around a threshold ice volume. When the Caribou Glacier possesses enough ice to crest the lip of the bedrock saddle, the drainage along the southern margin of the glacier is diverted from the Caribou valley and flows into Donard Lake. During these periods the drainage basin reaches a maximum of 7.8 km^2 and delivery of glacial sediment facilitates the formation and preservation of organic-poor clastic laminae. When the volume of ice

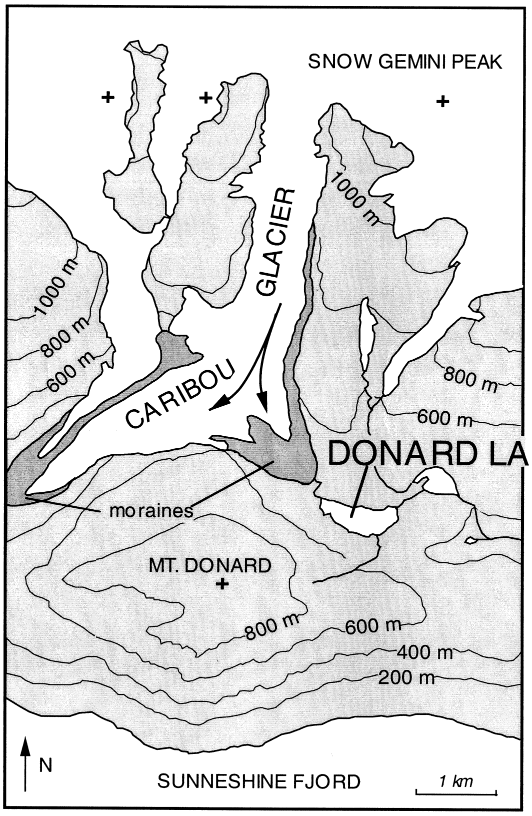

Figure 2. Spatial relationship between Donard Lake and Caribou Glacier. Donard Lake is situated between the steep walls of Mount Donard to the south and Snow Gemini Peak to the north. The main body of the Caribou Glacier flows past Donard Lake to the southwest. At present, a minor splay of the glacier flows over a bedrock saddle and eastward into the Donard Lake catchment.

falls below the threshold, the Caribou Glacier does not bridge the saddle and the drainage basin shrinks to 3.3 km^2. At these times Donard Lake is non-glacial, and sediments consist primarily of organic-rich gyttja. Because of this configuration, Donard Lake is a sensitive recorder of advances and retreats of the Caribou Glacier. In addition to Caribou Glacier meltwater, a small, shallowly incised stream flows down the side of Mt. Donard into the lake from the southeast. Glacial rock flour is evident in surface sediments throughout Donard Lake, indicating that Caribou Glacier meltwater is presently the most significant source of sediment.

Methods

Sediment coring

Field work at Donard Lake was conducted in the summers of 1994 and 1995 to collect sediment cores. Piston cores containing 1–4 m of sediment were retrieved using a modified version of a Nesje (1992) coring system. Cores were taken from proximal to distal locations in the lake to ensure that the sediment record was representative of the entire lake basin and to reduce the impact of local turbidity currents. Although eight piston cores were taken, only those from the flat-bottomed deepest part of the basin (Figure 3) were analysed in this study. One of the objectives of coring Donard Lake was to retrieve an annual-resolution record of climate change, requiring the intact recovery and preservation of the sediment-water interface. Piston

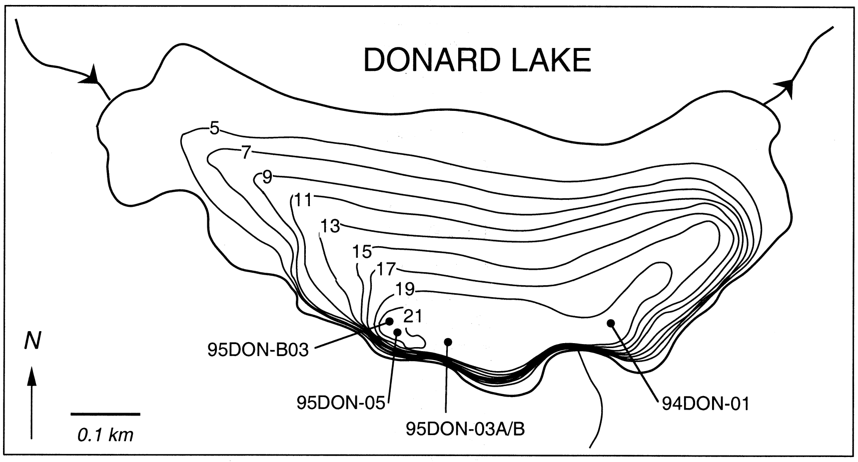

Figure 3. Bathymetry of Donard Lake. The lake bottom is relatively flat and lies close to the steeper southern wall. The cores used to construct the varve chronology, 95DON-B03 and 95DON-05, lie in the deepest part of the lake at the western end of the deep basin. The core used for radiocarbon dating, 94DON-01, lies at a similar depth at the eastern end of the deep basin. The major inlet from the Caribou Glacier is shown at the western end of the lake, and the outlet stream is shown in the east.

coring usually destroys this interface, and therefore we also collected box cores using a small Ekman dredge-type corer, 10 cm × 10 cm in cross section. The box corer typically seized 7–8 cm of sediment, preserving the delicate uppermost structures and sediment-water interface. Box core subsamples were taken in the field using Glew (1988) core barrels and sealed for transportation back to the lab. Unfortunately, only one box core sample, 95DON-B03, survived transportation with the uppermost sediment structures intact. A continuous sediment record extending from regolith to the sediment surface was constructed via the combination of overlapping records from the box core and several long piston cores. Ideally, multiple cores with intact sediment-water interfaces should be taken for cross-correlation to improve accuracy in the chronology and calibrated paleotemperature record, but this was not possible during the 1994 and 1995 field seasons. A recent expedition to Donard Lake resulted in the recovery of a suite of five surface sediment cores, and construction of a multiple-core, cross-correlated chronology and thickness record for the past several centuries is planned for the future.

^{14}C dating

Proglacial arctic lakes typically lack abundant macroscopic organic material suitable for ^{14}C dating, whereas in Baffin Island lakes, soluble organic matter (SOM) often occurs in concentrations adequate for radiocarbon dating 1 cm slices of large diameter (11 cm) piston cores. However, the low primary productivity and slow rate of organic matter decomposition in some Baffin Island lakes have been shown to result in SOM ^{14}C ages up to 600 yrs older than the contemporaneous atmosphere (Miller et al., 1999). This 'reservoir age' can change as a funtion of time (Miller et al., 1999; Sauer et al., 2001), and introduce error into chronologies. We therefore restricted our ^{14}C dating in Donard Lake to aquatic moss macrofossils. Aquatic mosses derive their carbon from dissolved inorganic carbon in the water column which is equilibrated with atmospheric CO_2 (Abbott & Stafford, 1996). Unfortunately, aquatic moss samples are infrequently preserved and only five ^{14}C dates on moss macrofossils were obtained within the Donard Lake sediment record. Three dates were measured from piston core 94DON-01, and two from core 95DON-03.

Magnetic susceptibility

To assist in correlating sediments and constructing a continuous record, the piston cores were analyzed for volume magnetic susceptibility. Whole core volume magnetic susceptibility was measured on each core at 2.5 cm intervals using a Bartington MS2C 12.5 cm loop attached to a Bartington MS2 meter. Higher-resolution measurements of piston core 95DON-03 were made on 3.2 cc cubes sampled every 3 cm using a Sapphire Instruments SI2 magnetic susceptibility meter at 600 Hertz (reported as low-frequency magnetic susceptibility).

Laminae analysis

All of the cores from the 1994 and 1995 field seasons were split and photographed in order to identify the most continuous and undisturbed sediment record. X-ray analysis of 1 cm thick slabs, cut from the surfaces of the split cores, allowed clear imaging of millimeter-scale laminations without the downward deflection of the layers near the core barrel caused by penetration into stiff sediments. Pattern-matching of distinct laminations and individual 'marker beds' showed continuous, traceable centimeter-scale patterns of deposition across the lake basin, with sedimentation rates decreasing from proximal to distal sites. Piston core 95DON-05 was retrieved from the most proximal part of the deep basin, and had the thickest, most distinct laminated sediments. Box core 95DON-B03 contained an intact sediment-water interface and together, the two cores were selected for detailed laminae analysis. Sediment sampling and preparation for petrographic thin section study followed procedures outlined by Hughen et al. (1996). The samples were cut into 6 cm-long blocks, allowing 1 cm overlap with adjacent blocks, freeze-dried, and then embedded in epoxy resin and processed into thin sections for a high-magnification study of the mm-scale laminae. Images for digital analysis were obtained using a light microscope and digitizing video camera attached to a computer (Thetford et al., 1991; Hughen et al., 1996), and NIH Image 1.61 software. The digital analysis was used to note the character of each varve and identify possible slump deposits or turbidites, as well as measure precisely varve thickness.

Results

^{14}C dating

A radiocarbon chronology was constructed from five dates on aquatic moss macrofossils. The sequence of dates contain no reversals (Table 1), and place the beginning of sedimentation in the Donard Lake basin

Table 1. Radiocarbon sample data for Donard Lake piston cores. All ages are conventional dates on aquatic moss macrofossils. Depths have been scaled according to a combined adjusted depth scale for all piston cores (Moore, 1996)

Core	Depth	Material	Weight	^{14}C age
94DON-01	48 cm	moss	1.76 mg	935 ± 60
94DON-01	221 cm	moss	1.57 mg	4210 ± 80
94DON-01	232 cm	moss	1.42 mg	4650 ± 90
95DON-03	320 cm	moss	26.0 mg	8940 ± 80
95DON-03	350 cm	moss	0.51 mg	12600 ± 60

at 12,600 ± 60 ^{14}C yr BP. Organic-rich gyttja was deposited from 12,600–8500 ^{14}C yr BP, followed by clastic laminae from 8500–7800 ^{14}C yr BP. Organic-rich sedimentation returned from 7800 until 5000 ^{14}C yr BP, when clastic deposition began again and continued until the present day. Sedimentation rates for the different regimes were estimated using calibrated calendar ages and a composite, lake-wide depth scale (Figure 4). Sedimentation of the organic sediments was slow, approximately 8 cm/kyr, whereas clastic sedimentation was faster, about 55–65 cm/kyr. The absolute depth of sediment deposition per yr varies between distal and proximal cores in the lake basin, but the ratio of clastic vs. organic sedimentation rates, about 7–8 times higher, is consistent throughout the lake.

Magnetic susceptibility

Whole-core magnetic susceptibility shows a consistent pattern in cores throughout the lake (Figure 4). High values in the upper, clastic sediments indicate that the mineral grains are relatively freshly eroded. Organic content within these sediments, measured as percent readily oxidized organic matter (ROOM), is less than 0.5% (Moore, 1996). Lower magnetic susceptibility occurs in the deeper sediments, in agreement with generally higher organic content, from 1.5–4.5% (Moore, 1996). The pattern of changes in magnetic susceptibility allows for good correlation between cores, particularly in the upper, clastic sediments (Figure 4).

Laminated sediments

Piston core 95DON-05 is 2.0 m in length and contains over 1200 couplets, whereas box core 95DON-B03, the top ~4.5 cm of sediment, contains about 80 couplets. Initial inspections of the freshly split surface of core

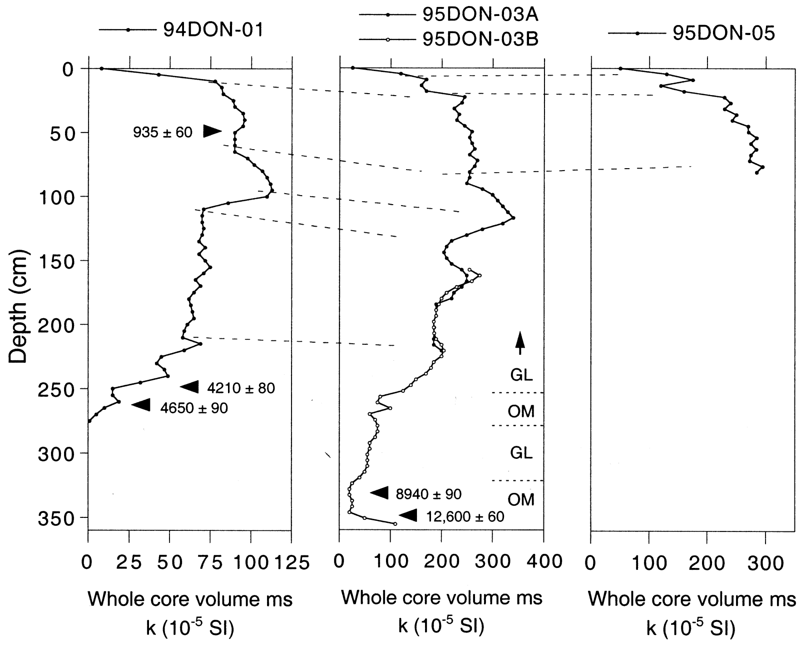

Figure 4. Whole-core volume magnetic susceptibility for Donard Lake piston cores 94DON-01, 95DON-03 and 95DON-05. Magnetic susceptibility for each core is plotted versus a common composite depth in order to show the different sedimentation rate cores on a comparable scale. Locations of samples for ^{14}C dates in cores 95DON-01 and 95DON-03 are indicated. Dashed lines show the tie points used to anchor the correlations between cores.

95DON-05 revealed centimeter-scale, banded sediments comprised mostly of silts and clays with some intermittent micaceous sand lenses. X-ray analysis of slabs cut from the cores, however, showed that millimeter-scale laminations occur throughout the sediments. The laminated sediments are grey, glacially derived couplets classified as clayey silts.

Viewed in thin section, the sediments appear as couplets of light, coarse-grained layers bounded on the top by a thin dark layer (Figure 5). Coarse grains, in some cases as large as fine sand, occur at the bottom of each couplet and grade into silt-sized particles that are typically very well sorted. A dark layer, composed of fine clays, caps the top of each couplet. High-magnification analysis of thin sections reveal the fine details of grain sorting and gradation within individual laminae (Figure 6). Individual grains, including fine sand deposited at the base of each layer, can be clearly identified, as well as the high degree of sorting within the silt grains comprising the majority of each couplet. The mineralogy of the grains is predominantly freshly eroded quartz, feldspars and micas, consistent with the types of bedrock underlying the Caribou Glacier. The silts grade gradually upward into fine clay, whereas the transition from clays into the overlying coarse grains is sharp. Although most of the individual light laminae are normally graded, there are instances of inverse grading usually caused by coarse sand lenses contained within the laminae (Figure 7). These sub-laminae are infrequent and do not represent a significant fraction of the overall sediment column. Total couplet thickness

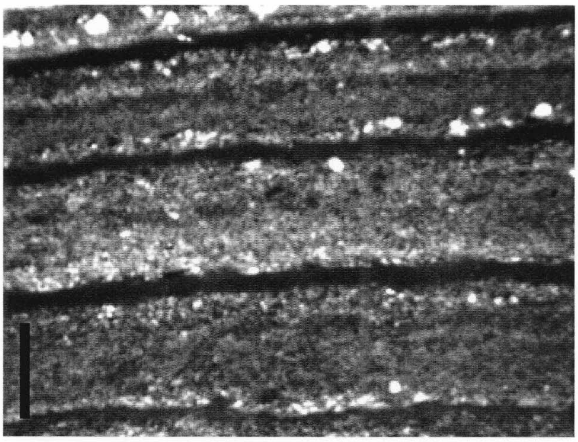

Figure 5. Photomicrograph of Donard Lake laminae from piston core 95DON-05. Individual layers of annual deposition may be identified by the lighter, coarse-grained material at the bottom of each layer and the thin dark layers at the top. Scale bar = 1 mm.

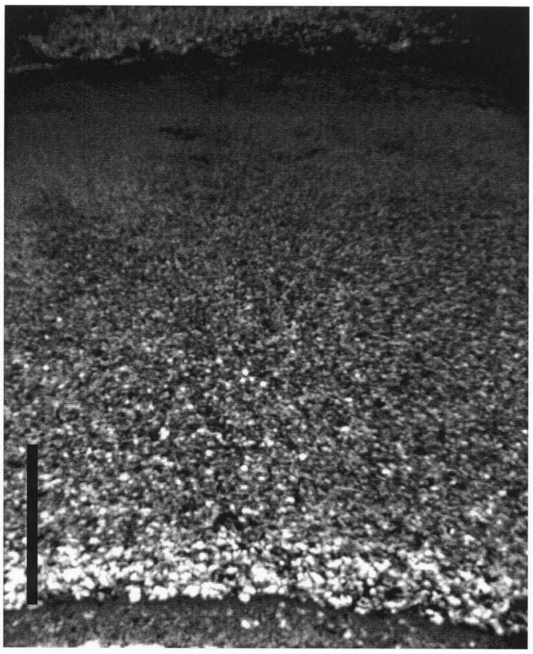

Figure 6. High-magnification photomicrograph of a single varve from piston core 95DON-05. Normal grading from fine sand to clay-sized grains is discernible, as is well-sorted nature of silt grains comprising the main body of the varve. Scale bar = 1 mm.

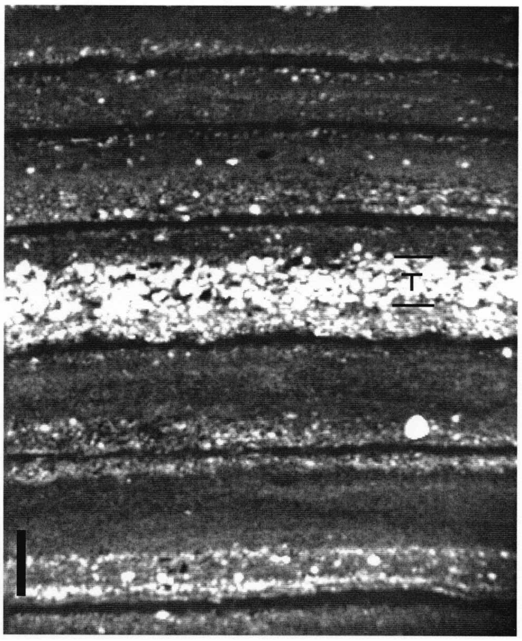

Figure 7. Photomicrograph of varves from piston core 95DON-05 showing anomalously coarse lens of sand grains, indicated by a 'T'. Such lenses probably result from increased runoff due to infrequent extreme rainfall events. Scale bar = 1 mm.

ranges from 0.2–2.5 mm, with a mean thickness for the entire record of 0.8 mm.

Discussion

Dating

The succession of fine sands to silts through the summer months, followed by a winter clay cap, is the classic mode of varve formation in a glacial basin (De Geer, 1912; O'Sullivan, 1983; Leonard, 1985; Saarnisto, 1986; Björck et al., 1992; Leeman & Niessen, 1994; Zolitschka, 1996; Lamoureux & Bradley, 1996; Retelle & Child, 1996; Bradley et al., 1996; Wohlfarth et al., 1998). The upward gradation from relatively coarse to fine grains results from a decrease in the energy of sediment transport throughout the year. During the spring flush, terrigenous fine sands and silts are delivered to the lake as a result of snowmelt and glacier runoff (Hardy, 1996; Retelle & Child, 1996). Glacial melt continues to produce runoff throughout the summer, although with snowcover mostly melted, the flux of runoff and available energy of transport is diminished and the size of grains washed into the lake is reduced. During the winter months, Donard Lake is covered by up to two meters of ice and all sediment transport into the lake ceases. During the winter season, fine clay-sized material suspended in the water column continues to settle out, forming an independent layer which appears in thin section as a dark lamina. Based on their internal structure, composition, and depositional setting, the millimeter-scale laminations contained in Donard Lake sediments appear to be annually deposited varves.

Before the Donard Lake laminae couplets can be used to construct calendar-age chronologies, annual deposition must be demonstrated using independent dating methods. We used radiocarbon dating to estimate Donard Lake sedimentation rates, and then compared the radiocarbon sedimentation rate to rates measured by laminae counting. An AMS ^{14}C date of 935 ± 60 ^{14}C yrs BP (calibrated age of 860 ± 80 cal yrs; Stuiver & Reimer, 1993) was obtained on 1.7 mg of moss macrofossils from piston core 94DON-01 (Figures 4, 8). An overall depth of 55–60 cm for this sample was estimated using magnetic susceptibility correlations between piston cores 94DON-01 and 95DON-05 (Figure 4), and laminae thickness variations between piston core 95DON-05 and box core 95DON-B03 (Figure 9). A ± 2.5 cm uncertainty in the depth estimate is included to account for the imprecision in the correlation based on magnetic susceptibility. More-precise correlations based on laminae thickness could not be used between the piston cores because only one piston core, 95DON-05, was prepared into thin sections and analysed for laminae thickness. A depth of 55– 60 cm for a calibrated age of 860 yrs BP yields a sedimentation rate between 64 and 70 cm/kyr, in agreement with the average sedimentation rate based on varve thickness, 67 cm/kyr (Figure 8).

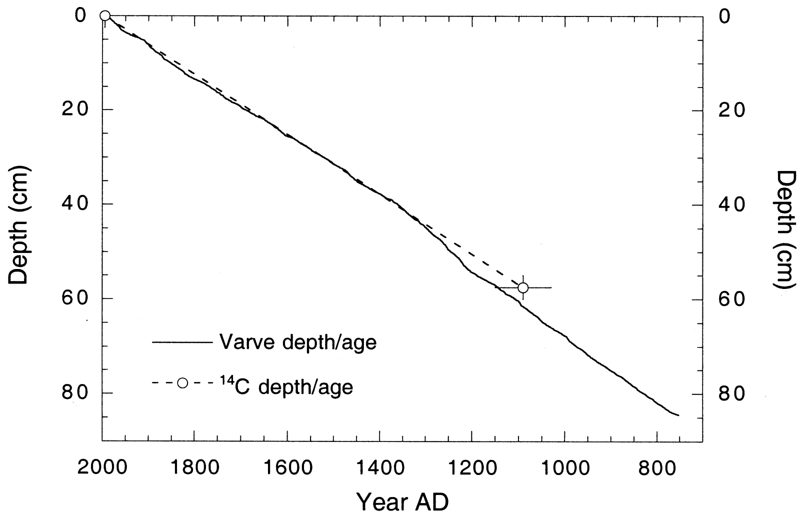

Figure 8. Comparison of age versus depth curves for Donard Lake sediments based on laminae couplet counts and ^{14}C dating. The ^{14}C and laminae-based sedimentation rates agree, indicating that the laminae couplets are annually deposited varves and can be used to construct calendar-age chronologies. ^{14}C errors are 1σ.

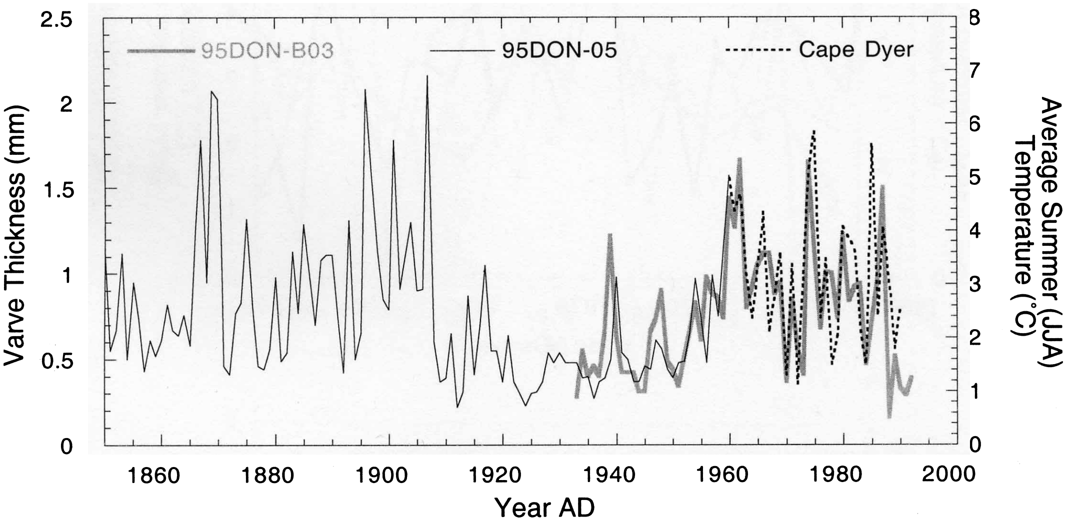

Figure 9. Detail of overlap section used to splice a varve thickness record from the floating deep core chronology of piston core 95DON-05 and the absolute surface chronology of box core 95DON-B03. Thin line is the record from core 95DON-05, thick grey line is the record from 95DON-B03. In order to produce a coherent record, the raw thickness measurements of the deeper record were scaled to a least-squares fit of the corresponding layers in the surface core. The dotted line shows the instrumental average summer (JJA) temperature record from a meteorological station at nearby Cape Dyer.

Unfortunately, the varve chronology is based on a single core, whereas ideally, multiple cores should be used to minimize errors from disturbances, core breaks, misinterpreted laminae and sub-laminae, etc. (Overpeck, 1996; Lamoureux, 1999; Hughen et al., 2000). This Donard Lake chronology likely contains somewhat high errors and will need to be reproduced with multiple cores at a future date. Nevertheless, the good agreement between radiocarbon and varve-based sedimentation rates, together with the internal structure and glacial setting of the laminated sediments, suggests that the laminae couplets are annually deposited varves and can be used to construct a calendar-age chronology.

Calibration of climate signal

In addition to geochronological applications, annually deposited laminated sediments are a potential archive of high-resolution paleoclimate information. Previous workers have used hydrological and sedimentological process studies in glacier-fed lakes to demonstrate that the fluxes of runoff and suspended sediment vary directly as a function of average summer temperature (Leonard, 1985; Leeman & Neissen, 1994; Hardy, 1996). Clastic varve/laminae thickness records from both glacial and non-glacial lakes have been shown to record average summer or snowmelt season temperatures (Leonard, 1985; Leeman & Neissen, 1994; Hardy et al., 1996; Gajewski et al., 1997; Wohlfarth et al., 1998; Hughen et al., 2000). In order to use the Donard Lake varve thickness record to reconstruct past temperature changes, it is necessary to calibrate quantitatively the most recent part of the record using instrumental data.

Monthly mean air temperature was recorded at a meteorological station at the Cape Dyer DEW Line radar site, 19 km east of Donard Lake, from October, 1959–December, 1990. These instrumental data provided an evaluation of the relationship between average monthly and summer temperature and Donard Lake varve thickness. Comparisons of June, July, August and summer (JJA) temperatures to varve thickness all show positive correlations (r = 0.24, 0.49, 0.23 and 0.57, respectively). Correlations for summer averages including May (MJJA) or September (JJAS) showed no improvement over JJA, and those for other months were negative or insignificant. Varve thickness is most strongly influenced by temperature averaged throughout the summer, suggesting that the Donard Lake varve chronology can be used to construct a record of summer paleotemperature (Figure 10). However, there remains a large degree of variance in the varve record not explained by Cape Dyer summer temperature. This unexplained variance may be due to several factors, including environmental variability unrelated to temperature that influences sediment deposition; spatial heterogeneity in patterns of climate variability between Cape Dyer and Donard Lake; and error in the Donard Lake varve chron-

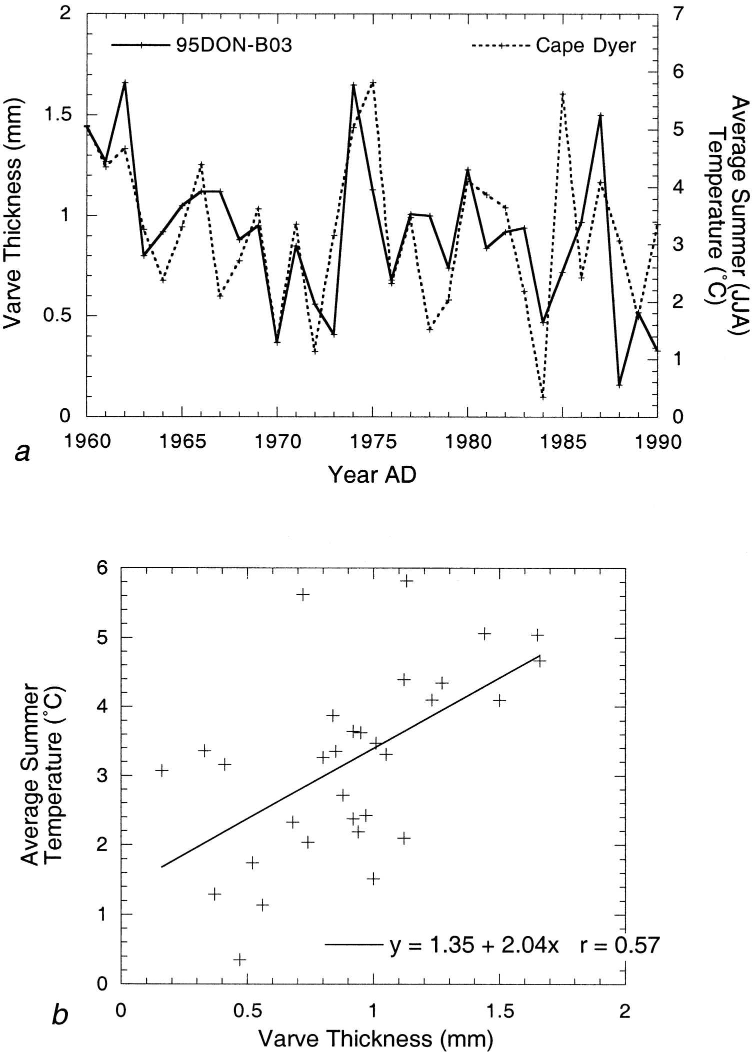

Figure 10. Comparison of annual Donard Lake varve thickness and average summer (JJA) temperature from Cape Dyer. (a) Annual varve thickness (solid line) and temperature data (dotted line) plotted against year. The overall agreement in trends between the two records is good, although differences can be seen for individual years; (b) Scatterplot of varve thickness versus average summer temperature. The data sets show a reasonably strong positive correlation (r = 0.57), indicating that Donard Lake varve thickness records average summer temperatures in the Cape Dyer region.

ology introduced by the lack of averaging between multiple cores.

We used monthly precipitation records from Cape Dyer to test whether the amount or seasonal distribution of precipitation has a significant influence on varve thickness. Intense rainfall events during the ice-free summer months can produce brief periods of anomalously high runoff and increased suspended sediment loads into high arctic lakes (Retelle & Child, 1996; Hardy, 1996). In addition, winter precipitation may possibly influence sediment deposition the following summer. For example, a thick snowpack could help sustain higher runoff long into the summer, augmenting the amount of runoff produced by glacier meltwater alone, while a thin winter snowpack will reduce the amount of available runoff, even during relatively warm summers. Comparing summer precipitation records to Donard Lake varve thickness gives conflicting results (June, July, August and JJA correlations of r = 0.08, –0.18, 0.33 and 0.20, respectively), and correlations for other months and winter average precipitation (DJF) showed even weaker relationships. We also investigated whether precipitation may account for any of the variability in varve thickness left unexplained by summer temperature. We calculated a monthly residual varve thickness record by subtracting the variance explained by JJA temperature. We then compared the residual varve thickness to monthly precipitation with results that were similar to those for total varve thickness. In general, although late summer precipitation may have a discernible influence on varve thickness, the correlation does not explain a significant amount of variability (< 10%). The poor correlation may also be due to the fact that individual major rainfall events can influence sediment deposition, but will not be discernable in a monthly precipitation record. Daily precipitation data from Cape Dyer are unavailable, however, and a field monitoring study would be necessary to test this hypothesis.

The lack of a stronger correlation between annual records of climate and varve thickness may also be due to non-environmental factors. The Cape Dyer meteorological station is 19 km from Donard Lake, and may not be representative of local conditions at Donard Lake. In particular, this may explain the poor correspondence between varve thickness and precipitation, due to the high degree of spatial variability in precipitation. However, this explanation is less satisfactory for the relationship to temperature, which is less susceptible to strong spatial gradients over these distances. More likely, it is possible that there is both error and noise contained in the varve thickness record that is unrelated to climate. The error inherent in a single-core reconstruction has already been discussed, but there is also the potential for local, random noise to obscure the basin-wide signal. For example, turbidites or erosional scour can result in greater thickness or missing varves, respectively, in individual sediment cores. Typically, noise can be reduced by cross-correlating records from multiple cores in order to average out random variability within single sediment cores and construct a record with a regionally significant signal (Zolitschka, 1996; Lamoureux, 1999; Hughen et al., 2000). Unfortunately, this multiple-core approach was not possible due to logistical constraints during the 1994 and 1995 field seasons, and only one core was recovered with a sediment-water interface that was suitable for comparisons with instrumental records.

In order to reduce some of the annual-scale noise potentially obscuring the temperature-varve relationship, we averaged the varve thickness and temperature data into 3-yr averages. The averaged data were then binned into discrete 3-yr intervals (i.e., sampled every 3 yrs) to avoid the problems of using a running average, which induces autocorrelation into each data set and therefore artificially increases the correlation coefficient between smoothed data sets. The 3-yr averaged varve thickness and summer temperature data sets record similar trends at the sub-decade scale (Figure 11), and yield a much stronger correlation than for annual data ($r = 0.82$). Although the varve thickness record from a single core may contain noise that masks the climate signal at the annual scale, the record accurately reflects trends in average summer temperature at the sub-decadal scale. The limitation to using this approach, however, is that the ability to identify single warm or cold years is lost.

Paleoclimate record

The varve thickness records of piston core 95DON-05 and box core 95DON-B03 were spliced together using nearly 30 yrs of overlap (Figure 9), creating a continuous 1250-yr long record of sedimentation from approximately 750–1990 AD, when the meteorological observations from Cape Dyer were discontinued (Figure 12). The equation from the regression of 3-yr averaged varve thickness on summer temperature (Figure 11) was used to calculate paleotemperature from the spliced varve thickness record. Several years contained varve thickness measurements that corresponded to unrealistic summer temperatures (up to 15 °C). This led us to re-examine thin section images of the sediments and to determine that some varve thicknesses were overestimated due to lenses containing anomalously coarse-grained material (e.g., Figure 7). These layers may not relate directly to temperature (Hardy, 1996; Retelle & Child, 1996), but may result from rapid deposition during brief periods of intense rainfall or mass flow events. Thus, coarse-grained lenses were subtracted out of the total varve thickness for individual years which contained those deposits, and paleotemperature was calculated from these revised varve thicknesses (Figure 12). Because of the uncertainties inherent in producing a time series based on a single core, the paleotemperature record is presented with 10-yr smoothing. This is a conservative approach, since the agreement between varve thickness and summer temperature is strong at resolution as high as 3-yr (Figure 11). The majority of the long paleotemperature record falls within the temperature range covered by the period of calibration, thus little extrapolation was needed to produce the record.

Summer temperatures at Donard Lake over the past 1250 yrs averaged 2.9 °C. During the period 750–1200 AD, temperatures averaged 2.9 °C, equal to the long-term mean. Anomalously warm decades (~3.9 °C)

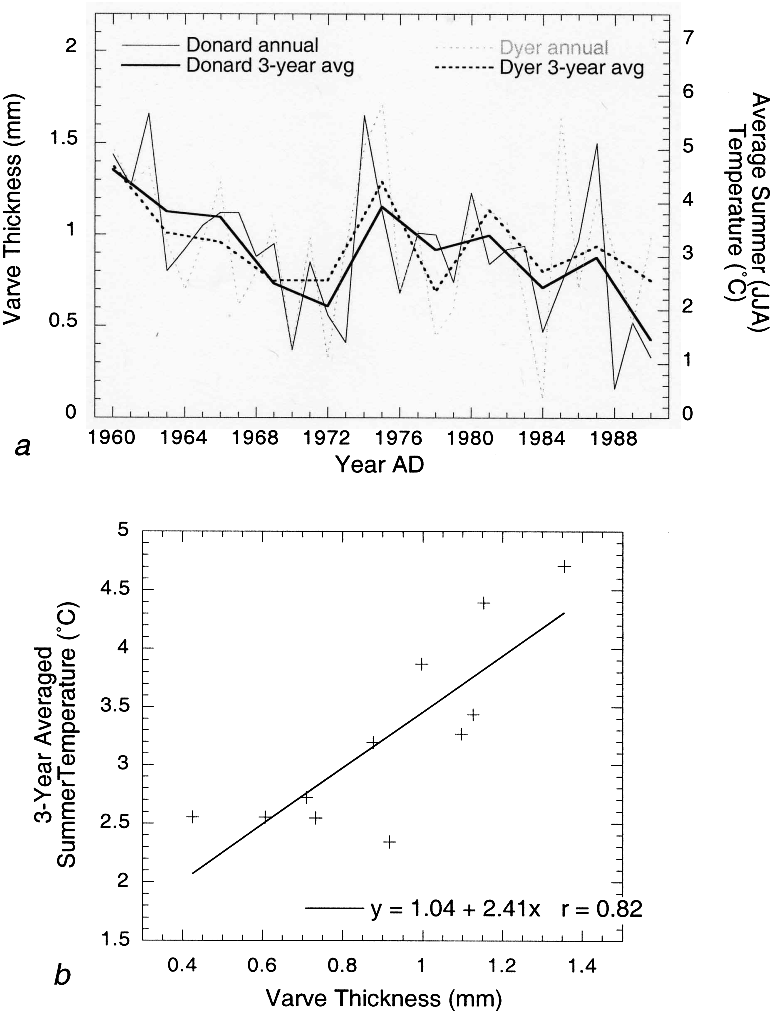

Figure 11. Comparison of annual and averaged Donard Lake varve thickness and summer (JJA) temperature from Cape Dyer. (a) The grey solid and dotted lines are annual data from Donard Lake and Cape Dyer, shown in Figure 10. The black solid and dotted lines are the same data binned into discrete 3-yr averages (see text). The agreement in trends between the 3-yr averaged data sets is much better than for the annual data; (b) Scatterplot of 3-yr binned averages for varve thickness and average summer temperature. The agreement between the data sets is improved over the annual data sets, r = 0.82, indicating that Donard Lake varves record sub-decadal trends in summer temperature, but may be subject to substantial noise during individual years.

occurred around 1000 and 1100 AD. Extended cold periods of about 50 yrs duration occurred from 1000–1050 AD and 1150–1200 AD. The latter cold interval may have resulted in moderate glacial advances in the area (Locke, 1987). At the beginning of the 13th century, Donard Lake experienced one of the largest climatic transitions in over a millennium. Average summer temperatures rose rapidly by nearly 2 °C from 1195–1220 AD, ending in the warmest decade in the record (~4.3 °C). A dramatic warming event is seen around the same time (~1160 AD) in a tree-ring width record from Fennoscandia (Briffa et al., 1990). If these events in fact occurred simultaneously, it would imply an error of ~4% in the Donard Lake chronology, a reasonable value given that the record relies on a single core. The rapid warming at Donard Lake was followed by a period of extended warmth, with average summer temperatures of 3.4 °C (Figure 12). This time of warm summer temperatures corresponds to the period when Thule Inuit moved into the Canadian Arctic from Alaska using open boats and hunting whale. A ~150–200 yr period of increased temperature around the same time is also seen in historical records of mild conditions allowing the expansion of settlements in Greenland (McGovern, 1991), and radiocarbon-dated records of glacial advance and retreat from numerous glaciers throughout the

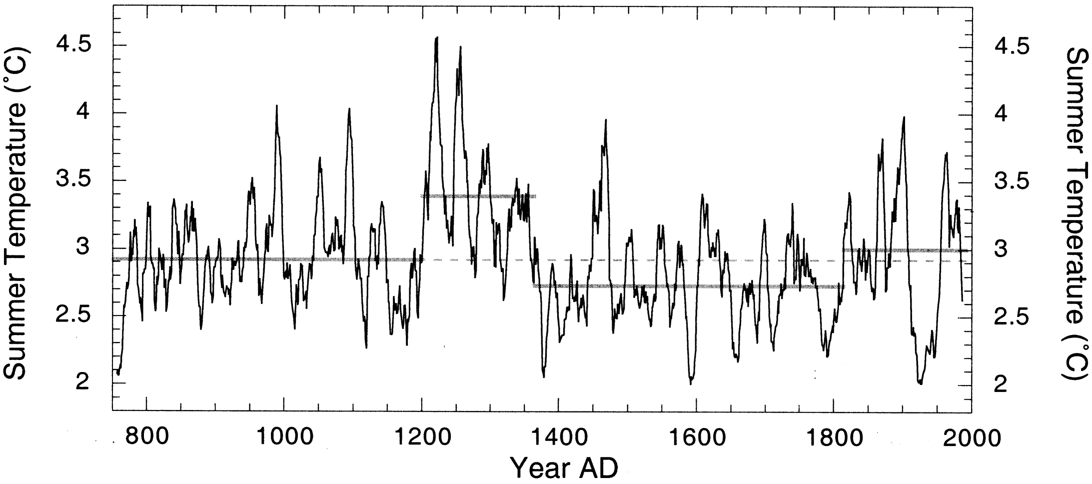

Figure 12. 1250-yr long summer temperature record for Donard Lake calculated from varve thickness using the regression equation from Figure 11. The record is shown with a 10-yr running average to emphasize decadal trends and reduce noise from the annual record. Distinct periods of different mean temperature are identified with thick grey lines, average temperature for the entire 1250-yr record is shown by the thin dashed line.

Kenai peninsula in Alaska (Wiles & Calkin, 1995), as well as humifaction records from Irish peat bogs (Blackford & Chambers, 1995). However, other well-dated sites fail to record warm conditions at this time and recent reviews have demonstrated the absence of a globally coherent 'Medieval Warm Period' at this time (Hughes & Diaz, 1994).

This record lacks a long-term cooling trend over the last 1000 yrs as seen in the Northern Hemisphere paleotemperature reconstruction of Mann et al. (1999). This could result from a threshold limiting the potential response of the glacier-sediment system to temperature increase. For example, it is possible that only a finite amount of fine-grained sediment is available to be entrained by meltwater in a given summer. There is no source of easily eroded sediment in the catchment, such as raised river deltas or dry lake basins, that could supply an effectively limitless supply of suspended sediment into the Donard Lake basin as long as glacier meltwater is available to erode it. The Caribou Glacier catchment area mainly contains scoured gneissic bedrock, and it is probable that the majority of grains deposited each summer are only produced recently – in the preceding few winters. Similarly, it is unlikely that there are significant non-climatic influences on long-term varve thickness trends. Leonard (1985) demonstrated the effect of long-term changes in glacier proximity on varve thickness measurements in lakes downstream. However, the Donard Lake/Caribou Glacier system is not a typical lake far 'downstream' of a large, upvalley glacier. Rather, Donard Lake is perched on the side of the glacier valley. Once the glacier sub-lobe has crested the saddle, it is effectively as close to the lake as it will become without over-running the basin. Glacier growth and extension down the main valley will result in a lesser amount of extension down the Donard Lake valley, and the extended amount of bedrock available to glacial erosion will likely not contribute directly to Donard Lake but rather to runoff down the main Caribou Glacier valley.

The 13–14th century warm period came to a sudden end on Baffin Island when summer temperatures dropped abruptly in 1375 AD and failed to recover for any substantial length of time afterward. The decade following 1375 AD was one of the coldest in the record and represents the onset of a 400-yr Little Ice Age on Baffin Island. Average summer temperatures during the Little Ice Age were 2.7 °C, nearly 1 °C colder than during the preceding period. The date of the abrupt shift to a colder regime recorded at Donard Lake is in agreement (within errors) with the time when dietary reconstructions of Thule Inuit show a shift from whale to seal (indicating increased sea ice), and also with the date of the sudden abandonment of the western Norse settlement in Greenland, just across Davis Strait, at about 1350 AD (McGovern, 1991; Barlow et al., 1997). The timing of the Donard Lake cold shift also agrees with paleotemperature records from Greenland ice cores (Fischer et al., 1998), Irish peat bogs (Blackford & Chambers, 1995), and glacial advances in Alaska (Wiles & Calkin, 1995).

However, well-dated Little Ice Age records from around the globe have shown this event to be highly variable in both time and space (Briffa et al., 1990; Scuderi, 1993; Bradley & Jones, 1993). The Little Ice Age at Donard Lake is marked not only by low average summer temperatures, but by lower minimum temperatures (with the exception of the early 20th century) than during any other period in the last 1250 yrs. Records of glacial advances on eastern Baffin Island also provide evidence of cold summers during the Little Ice Age. Radiocarbon dates on lichen and moss overrun by ice and lichenometric dating of moraines record glacier advances at ~1580, 1650 and 1770 AD (Falconer, 1966; Miller, 1973; Locke, 1987), in agreement with several of the coldest intervals recorded at Donard Lake (Figure 12).

The Little Ice Age lasted more than 400 yrs before terminating in a gradual warming trend from around 1800–1900 AD. During this warming period, minimum temperatures are nearly half a degree warmer than during the Little Ice Age. However, maximum temperatures are relatively moderate and do not exceed those seen during the 13th and 14th centuries or the preceding interval of ‘average’ conditions. The first half of the 20th century at Donard Lake was marked by a dramatic cooling beginning around 1900 AD, followed by ~50 yrs of temperatures as cold as during the Little Ice Age. The cold period was followed by large and rapid warming in the 1950s leading to a maximum around 1960 AD and cooler conditions toward the present. Glacier advances in the Cape Dyer region dated by lichenometry (Locke, 1987) at 1850, 1885 and 1912 AD coincide with two brief cold pulses at Donard Lake that interrupted the century-long warming trend, and the cold interval afterward. Instrumental records of average summer (JJA) temperature from western Greenland, extending from 1866–1990 AD, show some of the same trends as Donard Lake – gradual warming from 1866–1900 AD followed by cooling, and particularly high temperatures around 1960 AD followed by an abrupt drop and low temperatures in the 1970s and 1980s. A major discrepancy between Donard Lake and western Greenland is the presence in Greenland of significant warming in the 1920s leading to high average temperatures in the 1930s, whereas the early 20th century at Donard Lake represents the longest continuous period of extreme cold conditions in the entire record. A 1920s warming is also seen in paleotemperature records from around the circum-Arctic and Northern Hemisphere (Overpeck et al., 1997; Mann et al., 1998), and is particularly well-expressed in Upper Soper Lake on southern Baffin Island (Hughen et al., 2000). Unfortunately, the cold interval at Donard Lake occurs near the splice between box core 95DON-B03 and piston core 95DON-05. Although the interval is almost entirely represented within the continuous core 95DON-05, the disagreement with other regional records suggests that the extreme cold period at Donard Lake might be an artifact of occurring near a core break. A number of longer cores containing the surface-water interface must be analyzed to provide accurate dating and varve thickness measurements through this section in order to confirm or deny this result.

Conclusions

Varved sediments of glacier-fed Donard Lake on eastern Baffin Island record variability in average summer temperatures over the past 1250 yrs. The laminated sediments are clastic laminated couplets typical of glacier meltwater-dominated lake systems, and provide an annual varve chronology back to ~750 AD. Quantitative calibration of varve thickness with instrumental meteorological records shows that varve thickness measurements from the single core used for this study can be used to reconstruct summer temperatures at the sub-decadal scale (3-yr averages), but contain too much noise to be used for temperature reconstructions at annual resolution. The 1250-yr record documents the timing of the Little Ice Age onset in the eastern Canadian Arctic around 1375 AD. This transition involved a drop in long-term (multi-century) average summer temperatures of 0.7 °C, and perhaps more importantly, marked the end of a period (1200–1375 AD) when minimum summer temperatures were significantly warmer than either the preceding or subsequent periods. The Little Ice Age lasted over four centuries before gradually warming during the 19th century. This quantitative record helps determine the timing and magnitude of climatic change that may have forced the abandonment of Norse settlements on western Greenland. Further work using multiple sediment cores will be required in order to refine the accuracy and resolution of both the varve chronology and summer temperature reconstruction from this site.

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