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A 2000 year varve-based climate record from the central Brooks Range, Alaska

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Abstract Varved minerogenic sediments from glacial-fed Blue Lake, northern Alaska, are used to investigate late Holocene climate variability. Varve-thickness measurements track summer temperature recorded at Atigun Pass, located 41 km east at a similar elevation ($r^2 = 0.31$, $P = 0.08$). Results indicate that climate in the Brooks Range from 10 to 730 AD (varve year) was warm with precipitation inferred to be higher than during the twentieth century. The varve-temperature relationship for this period was likely compromised and not used in our temperature reconstruction because the glacier was greatly reduced, or absent, exposing sub-glacial sediments to erosion from enhanced precipitation. Varve-inferred summer temperatures and precipitation decreased after 730 AD, averaging 0.4°C above the last millennial average (LMA = 4.2°C) from 730 to 850 AD, and 0.1°C above the LMA from 850 to 980 AD. Cooling culminated between 980 and 1030 AD with temperatures 0.7°C below the LMA. Varve-inferred summer temperatures increased between 1030 and 1620 AD to the LMA, though the period between 1260 and 1350 AD was 0.2°C below the LMA. Although there is no equivalent to the European Medieval Warm Period in the Blue Lake record, two warm intervals occurred from 1350 to 1450 AD and 1500 to 1620 AD (0.4 and 0.3°C above the LMA, respectively). During the Little Ice Age (LIA; 1620 to 1880 AD), inferred summer temperature averaged 0.2°C below the LMA. After 1880 AD, inferred summer temperature increased to 0.8°C above the LMA, glaciers retreated, but aridity persisted based on a number of regional paleoclimate records. Despite warming and glacial retreat, varve thicknesses have not achieved pre-730 AD levels. This reflects limited sediment availability and transport due to a less extensive retreat compared to the first millennium, and continued relative aridity. Overall, the Blue Lake record is similar to varve records from the eastern Canadian Arctic that document a cool LIA and twentieth century warming. However, the occurrence and timing of events, such as the LIA and Medieval Warm Period, varies considerably among records, suggesting heterogeneous climatic patterns across the North American Arctic.

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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Introduction

Late twentieth century and early twenty first century Northern Hemisphere warming is unprecedented within the context of instrumental records (Rigor et al. 2000; IPCC 2007). This is particularly true in the Arctic where temperatures have increased more rapidly than the hemispheric average (Stafford et al. 2000; IPCC 2007). Glaciers across the Brooks Range have retreated dramatically (Ellis and Calkin 1984; Evison et al. 1996; Rabus and Echelmeyer 1998), while Arctic sea ice reached a record low in September of 2007 (Stroeve et al. 2008). These changes amplify climate change through cryosphere–atmosphere-ocean dynamics (Maslanik et al. 1996; Mysak and Venegas 1998). Improving our knowledge of climate variability in the Arctic over the past several thousand years is essential to place the observed twentieth century warming in a longer context. To this end we present an annually resolved 2000-year-long varve record from a small glacial-fed lake located in the central Brooks Range of arctic Alaska.

Study area

Blue Lake (68.0869° N, 150.4650° W, 1275 m asl) is a small (0.04 km^2), shallow (4 m) glacial-fed lake located in the Oolah Valley of the central Brooks Range near Atigun Pass, just north of the Continental Divide (Fig. 1a, b). The watershed is small (4.1 km^2) and has a simple morphology. The drainage basin encompasses a 3.2-km-long valley with a single small glacier (0.07 km^2) in the north-facing cirque at the valley's head. The talus-covered cirque walls rise to a maximum headwall elevation of 1880 m asl. Summer meltwater from the glacier carries a substantial sediment load, as observed during July 2006, and flows unimpeded into Blue Lake at its north end (Fig. 1b, c).

The watershed lithology consists of sandstones and conglomerates of the Upper and Lower Kanayut (lower Mississippian and upper Devonian) interbedded with the red Kayak Shale (lower Mississippian) in the upper, glaciated part of the catchment (lower Mississippian; Kelly 1990). The friable Kayak Shale is extremely susceptible to glacial erosion and is the primary sediment source for Blue Lake, unlike the more resistant sandstones and conglomerates. This is reflected in the striking reddish hue of the Blue Lake sediments (Fig. 2). The glacially eroded Kayak Shale effectively provides an inexhaustible supply of sediment to Blue Lake.

Sediment accumulation rates in Blue Lake are an order of magnitude higher than in three nearby lakes that are not glacially fed that we cored recently (data not presented in this paper). Unlike Blue Lake, the stratigraphy in the nearby lakes is massive with occasional centimeter-scale bands. The millimeter-scale couplets in the Blue Lake sediments are preserved due to rapid accumulation, despite an oxygenated water column. In addition, because the Kayak Shale is restricted to the upper most, glacier-covered part of the watershed, surfacial processes in this area strongly influence varve thickness.

Blue Lake is surrounded by moderately steep talus slopes ($\sim$35°) with a relatively flat area around the lake that shields it from direct rock fall and other mass wasting (Fig. 1b, c). The lake is divided into a shallower northern basin ($\sim$3 m) and a deeper southern basin ($\sim$4 m) by an east–west trending sill, likely a late-glacial moraine (Fig. 1c). This sill isolates the southern basin from turbidity currents and turbulent flow, minimizing disturbances in the varves. Other moraines are located upvalley, including a Little Ice Age moraine proximal to the present glacier margin (Sikorski et al. 2009). No other moraine-dammed lakes are present in the watershed, and there is no evidence of temporary ponding or paleolakes that could have influenced sediment delivery to Blue Lake in the past. Vegetation surrounding the lake is comprised of tundra tussock grasses, mosses, and lichens.

Climatic setting

The Brooks Range forms a physical boundary between the warmer, wetter Alaskan interior (mean annual temperature; MAT = 3.7°C, mean annual precipitation; MAP = 320 mm) and the cold, dry

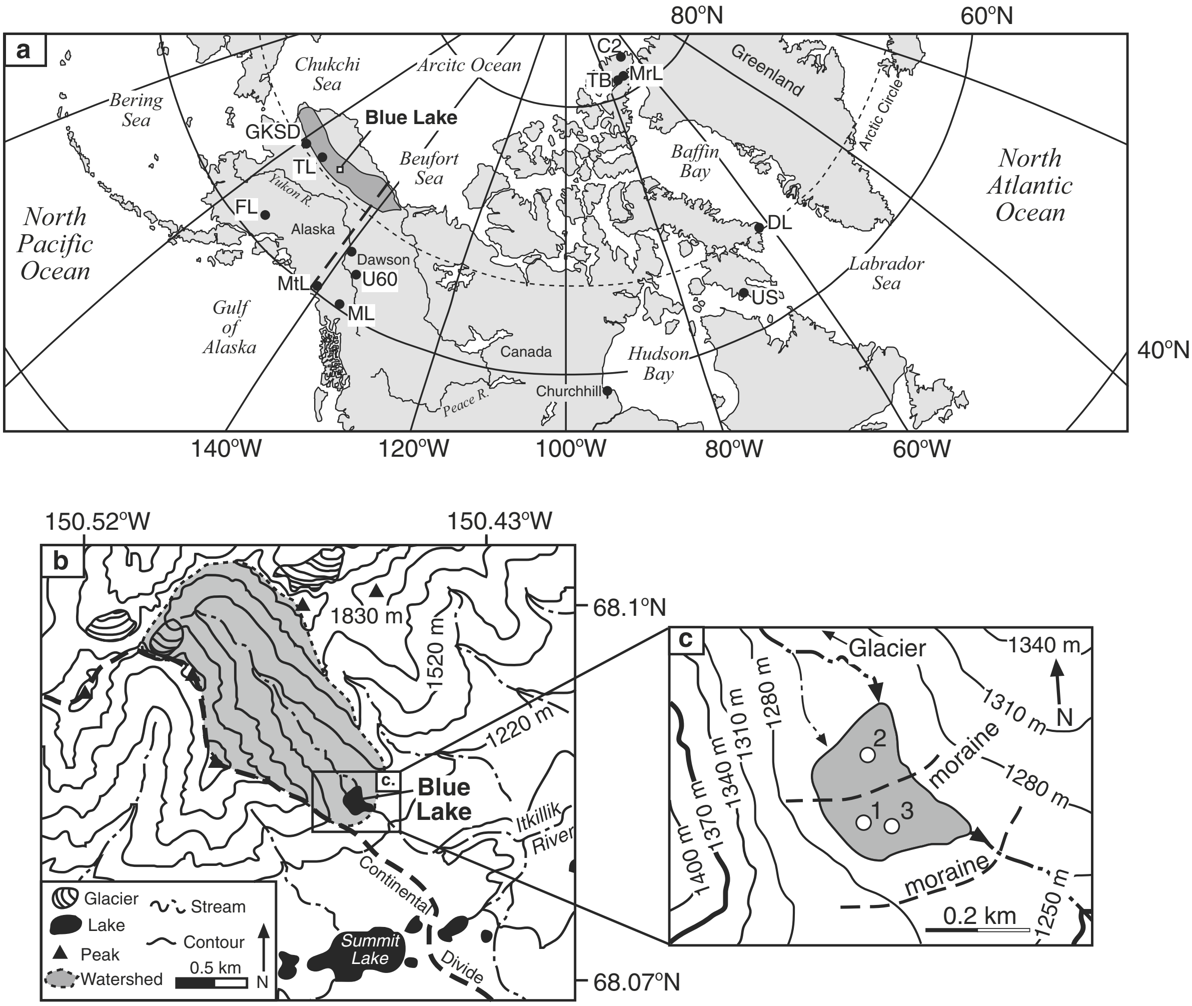

Fig. 1 **a** Map of the North American Arctic showing Blue Lake (*white box*) in the Brooks Range (*dark grey shaded area*) and other records discussed in the text (GKSD = Great Kobuk Sand Dunes, TL = Takahula Lake, FL = Farewell Lake, MtL = Mt. Logan, U60 = Lake U60, ML = Marcella Lake, US = Upper Sopper Lake, DL = Donnard Lake, TB = Tuborg Lake, MrL = Murry Lake, and lake C2). **b** Topographic map of the Blue Lake drainage basin (*shaded grey with a dashed outline*), and the Blue Lake glacier in the upper part of the watershed. **c** Blue Lake with core locations (Table 1)

Arctic (MAT = −12°C, MAP = 150 mm; Stafford et al. 2000). No climate data are available from the Blue Lake watershed. Temperature and precipitation trends for the lake, therefore, are inferred from the Natural Resources Conservation Service (NRCS) Snowpack Telemetry (SNOTEL) weather station at Atigun Pass (~41 km east of Blue at 1460 m asl; Abramovich and Pattee 1999). Temperature and precipitation data are available since 1993 and 1983 AD, respectively. Since 1993, summer temperatures (June–July–August; JJA) have averaged 3.7°C, and winters (December–January–February; DJF) have averaged −14.8°C, with below-freezing temperatures September through May. The melt season, and therefore sediment input to the lake, is generally restricted to JJA when the lake is ice-free and above-freezing temperatures melt snow and glacial ice. Precipitation at Atigun Pass has averaged ~600 mm $year^{-1}$ since 1983 and is highly seasonal. Maxima occur from June through August (322 mm, 51% of MAP), with minima from November to April (150 mm, 24% of MAP).

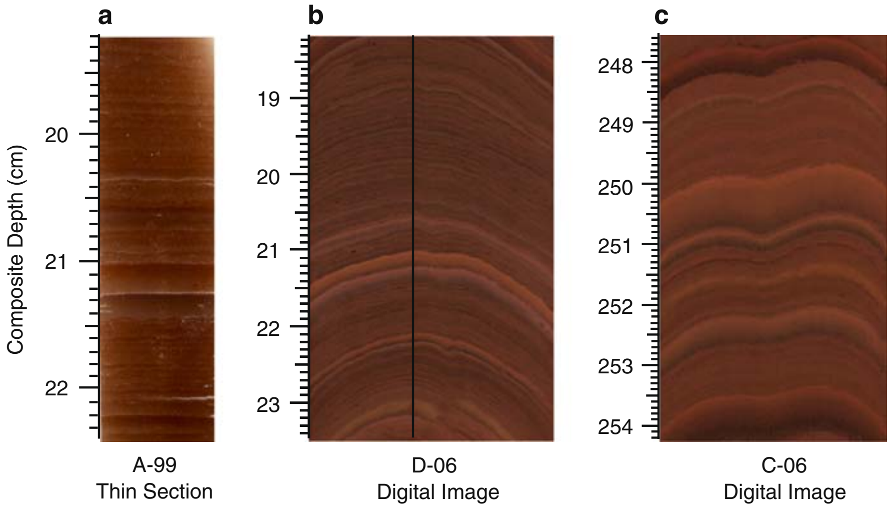

Fig. 2 **a** Thin section photomicrograph from core A-99 showing the fine laminations characteristic of the varved sediments during the Little Ice Age. The lighter layers are the clay caps that overlie the darker silty portion of the varves. **b** High-resolution digital photograph of surface core D-06 showing the same interval represented by the thin section in part (**a**). The black line designates where the couplets were measured. **c** Image of core C-06 from the lower portion of the core (below 100 cm) where varve thickness increases. Note that the color and structure of the varves are the same as in (**a**) and (**b**), only thicker

Methods

Core collection

A 1.8-m-long core (A-99) composed of two drives with 20 cm of overlap was collected in 1999 from the deepest part of Blue Lake (4 m) using a Livingstone square rod corer (Fig. 1c; Table 1; Wright et al. 1984). The sediment-water interface was captured in core B-99, which was collected using an Aquatic Research Universal corer. Twelve additional cores, six long and six surface cores, were collected in July 2006 using a modified percussion piston corer with a 22.5 kg weight and an Aquatic Research percussion corer, respectively (Fig. 1c; Table 1; Nesje 1992).

Table 1 Names, coring device, and length of the cores from Blue Lake, Alaska

Site (Fig. 1c)	Core ID	Core type	Length (cm)	Sediment interface
1	A-99	Livingstone	180	Yes
	B-99	Surface	19	Yes
	A-06	Surface	40	Yes
	B-06	Percussion	254	No
	C-06	Percussion	325	No
	D-06	Surface	57	Yes
2	E-06	Surface	59	Yes
	F-06	Percussion	180	No
	G-06	Percussion	159	No
	H-06	Surface	75	Yes
3	I-06	Percussion	373	No
	J-06	Surface	78	Yes

Radiometric age control

Independent age control was established using ^{137}Cs, ^{210}Pb, and ^{14}C. Samples for ^{137}Cs and ^{210}Pb assays were collected at 0.5 cm intervals from core B-99 to a depth of 14 cm (Table 2). ^{137}Cs and ^{210}Pb activities were determined by gamma counting.

Terrestrial macrofossils were isolated by sieving samples from five depth intervals for AMS ^{14}C dating (Table 3). Samples were cleaned and pretreated at the University of Pittsburgh Radiocarbon Laboratory following standard acid/alkaline/acid pretreatment protocols (Abbott and Stafford 1996) and measured at the University of California Irvine Keck AMS Radiocarbon Laboratory. All ages are reported as the 2-σ median probability age with uncertainties of one-half of the 2-σ calibrated age range. Ages were calibrated to years AD/BC using the online software CALIB 5.0, unless otherwise stated (Stuiver and

Table 2 Results of ^{210}Pb and ^{137}Cs assays from core B-98

Depth (cm)	^{210}Pb excess activity (Bq/g)	^{210}Pb Bq/g (±) 1-σ error	^{137}Cs activity (Bq/g)	^{137}Cs Bq/g (±) 1-σ error
0.25	9.79E−02	6.96E−03	1.46E−02	1.88E−03
0.75	8.16E−02	6.10E−03	1.40E−02	5.11E−04
1.25	5.67E−02	4.76E−03	1.66E−02	1.43E−03
1.75	2.40E−02	3.01E−03	1.61E−02	1.80E−03
2.25	2.48E−02	2.91E−03	1.70E−02	1.18E−03
2.75	2.72E−02	3.07E−03	1.64E−02	1.70E−03
3.25	2.92E−02	3.21E−03	2.12E−02	1.11E−03
3.75	3.25E−02	3.36E−03	2.98E−02	6.95E−04
4.25	2.08E−02	2.80E−03	3.32E−02	1.32E−03
4.75	2.07E−02	2.80E−03	5.21E−02	1.91E−03
5.25	2.18E−02	3.10E−03	1.05E−01	2.68E−03
5.75	2.10E−02	3.01E−03	6.36E−02	1.74E−03
6.25	2.52E−02	3.24E−03	3.19E−02	1.15E−03
6.75	1.65E−02	3.21E−03	4.37E−03	9.92E−04
7.25	1.63E−02	2.73E−03	0.00E+00	0.00E+00
7.75	1.13E−02	2.42E−03		
8.25	7.00E−03	2.01E−03		

Table 3 Radiocarbon ages and related data for samples from Blue Lake, Alaska

UCI no.	Core	Material	Fraction modern	^{14}C age (year BP)	2-σ error (±)	2-σ Calibrated age (AD/BC)	2-σ Median calibrated age (AD/BC)	One-half 2-σ range (years) (±)
37556	B-06	Terrestrial macrophyte	0.9634	300	25	1511–1601 AD	1561 AD	45
37557	B-06	Terrestrial macrophyte	0.6948	2925	20	1213–1045 BC	1130 BC	85
37635	C-06	Terrestrial macrophyte	0.8478	1325	30	650–722 AD	680 AD	35
37636	C-06	Terrestrial macrophyte	0.6172	3875	45	2470–2270 BC	2360 BC	100
37558	I-06	Terrestrial macrophyte	0.6242	3785	25	2288–2140 BC	2220 BC	75

Note: All samples were composed of terresterial vegetation and analyzed at the University of California, Irvine (UCI)

Reimer 1993; Reimer et al. 2004). Ages determined from ^{137}Cs and ^{210}Pb profiles, and ^{14}C were stratigraphically correlated between cores based on the stratigraphic patterns of varves.

Thin-section preparation

Thin sections for detailed sediment fabric analysis were prepared using a resin-impregnation method (Lamoureux 1994; Hughen et al. 1996; Francus and Asikainen 2001). Undisturbed sediment was collected continuously down core with ~1 cm of overlap between sample sections to ensure that all couplets were represented. The sediment was flash-frozen in liquid nitrogen and immediately freeze-dried under high vacuum. Four-component Spurr low-viscosity epoxy resin was used to impregnate the sediment under low vacuum for 2 h. After curing 48 additional hours at 50°C, the samples were cut into sub-sections at a 45° angle to ensure that no couplets were lost due to the thickness of the cutting blade. The final thin sections were prepared by Texas Petrographic Services, Inc.

Core imaging and couplet measurements

Couplet measurements were made from scanned thin-section images and high-resolution (20–30 pixles mm^{-2}) digital images of core surfaces. Thin sections were scanned using a standard desktop flatbed scanner with a resolution of 2400 dots per inch. Digital images were acquired using a line-scanning system with polarized full-spectrum fluorescent lights in a fixed position with respect to the cameras for consistent lighting of the core surface. The final color-calibrated images and scanned thin sections were imported into Adobe Photoshop 7.0 where the couplets were measured following Francus et al. (2002). Some sediment disturbance in the form of bowed couplets occurred as a result of the coring process (Fig. 2b, c). To maximize accuracy and consistency, the couplets were measured at the apex of the bowed sediments (Fig. 2b).

Scanning electron microscope (SEM) images of the thin sections were made at the University of Pittsburgh SEM Laboratory using a Philips XL-30 field emission SEM equipped with detectors for imaging in secondary electron (SE) and backscatter electron (BSE) modes.

Results[1]

Sedimentology

The sediments in Blue Lake are finely laminated to bedded couplets of inorganic glacially derived siliciclastics. Throughout the core, the couplets are made up of dark reddish-brown silt (5YR 4/3) capped by lighter tan clay (5YR 5/4), and range from 0.17 to 10.78 mm (Figs. 2 and 3). Couplets are present throughout the core, indicating continuous rhythmic deposition. SEM images of thin sections show that the transition between the coarse basal layer and fine cap is abrupt, not graded, indicating these they were formed by discrete depositional events without sublayers within the lower couplet that typically mark varves impacted by precipitation events (e.g. Lamoureux et al. 2001).

A sustained decrease in the mean couplet thickness occurs above ~100 cm depth (Figs. 4d and 5). The physical features of the couplets (i.e. grain size, texture, color) do not change, however, suggesting that the couplets below ~100 cm are formed by similar sedimentological processes as those above 100 cm (Fig. 2b, c). These couplets are therefore considered varves and included in the varve chronology.

Twenty-one anomalously thick layers, ranging from 1.1 to 18.14 cm thick were also identified in the cores (Fig. 4). Based on sedimentological characteristics (i.e. presence of graded bedding) the layers were identified as turbidites and excluded from the thickness record and varve chronology.

Radiometric age control

^{137}Cs and ^{210}Pb

^{137}Cs and ^{210}Pb results are in agreement with ages determined from couplet counting (Fig. 4a, b; Table 2). The 1963 AD ^{137}Cs peak occurs between 5.0 and 5.5 cm, the same depth interval that contains the 1963 AD couplet as determined by couplet counting. ^{210}Pb shows a general exponential decrease with depth, although with much variability, suggesting varying sedimentation rates. The linear ^{210}Pb age model estimates the age of the ^{137}Cs peak within 4 years of the expected date of 1963 AD.

^{14}C

One ^{14}C age (UCI 37556; 1560 ± 45 AD) agrees well with those from couplet counting (Table 3; Fig. 4c, d). This age was measured on terrestrial vegetation collected from an interval of typical and undisturbed couplets. The age of the couplet is 1543 AD based on couplet counts, well within the ^{14}C age range (Fig. 4c). The other four ages are older than expected from couplet counting and not in stratigraphic order (Table 3). These samples were collected from layers that were later identified as turbidites. We suspect that these ages were measured on reworked vegetation fragments that were washed into the lake during flood events. The ages were therefore discarded.

^{137}Cs, ^{210}Pb, and ^{14}C results support the interpretation that the sediment couplets in Blue Lake are varves (Fig. 4b–d). We therefore use ages determined

[1] The Blue Lake varve data reported in this study are available online at the World Data Center for Paleoclimatology (ftp://ftp.ncdc.noaa.gov/pub/data/paleo/paleolimnology/northamerica/usa/alaska/blue2008.txt).

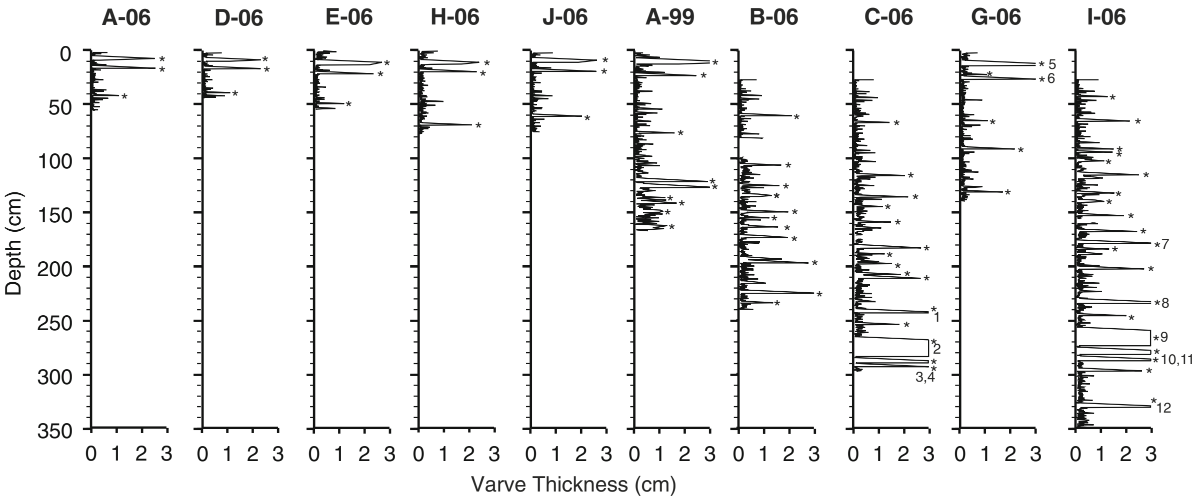

Fig. 3 Varve thickness measurements from the network of cores from Blue Lake plotted by depth. Despite subtle differences, the varves have similar thicknesses and downcore thickness patterns across the lake. Layers identified as turbidites are designated with an asterisk (*). The values are truncated in order to show the finer varves. Thicknesses of the clipped varves are reported in Table 4

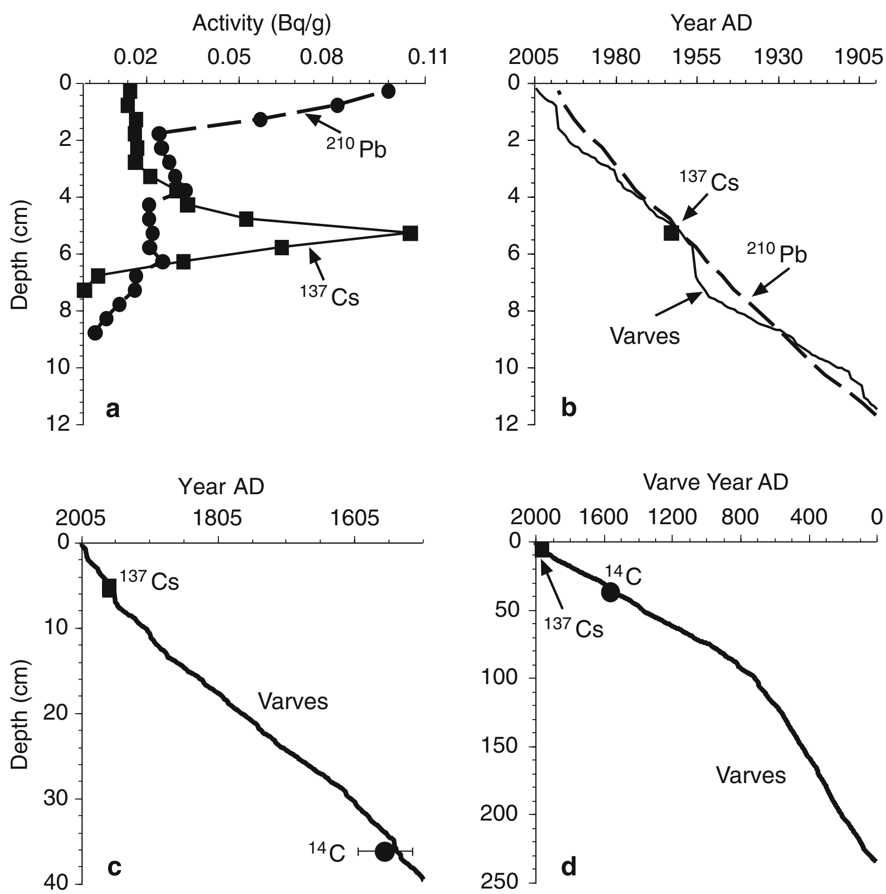

Fig. 4 **a** ^{210}Pb (*circles*) and ^{137}Cs (*squares*) activity profiles in core B-99 (Table 2). **b** Geochronology results from ^{137}Cs (*square*) and ^{210}Pb (*dashed line*) analyses plotted with the age-depth model derived from varve counting (*solid line*). **c** ^{137}Cs assays (*black square*) are plotted with the AMS ^{14}C age (*black circle*; Table 3) and the age-depth model determined from varve counting. The strong agreement between the ages based on varve counting and those from radiometric dating techniques support the conclusion that the couplets in the Blue Lake cores are deposited annually. **d** The complete varve derived age-depth model with ^{137}Cs (*square*) and ^{14}C (*circle*) measurements. Note the change in sedimentation rate at 730 AD

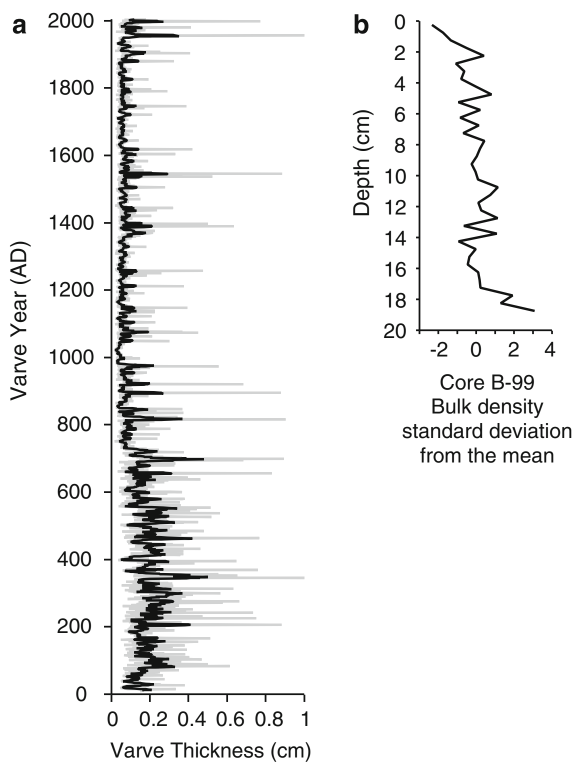

Fig. 5 **a** Composite varve-thickness measurements from Blue Lake. The black line is a 5-point moving average; *grey line* is the annual values. **b** Bulk density from core B-99 shown as the standard deviation from the mean. Bulk density values are within 1σ from the mean at 1.5 cm, indicating that increasing varve thickness at the top of the core are not an artifact of uncompacted sediments

by varve counting (one couplet = one year) for our age model (Fig 4d).

Varve chronology

Varves were measured at least three times on cores used in the chronology to ensure data quality and consistency. We estimate an approximate 1% error based on replicate counts; however, couplets incorrectly identified as varves or indistinguishable varves have an unquantifiable impact on the chronology. We used four cores to develop the chronology; additional cores could help refine the age model and reduce potential chronological errors.

Analyses of multiple surface and long cores from different parts of the lake show consistent depositional patterns (Fig. 3). Slight variations in couplet thicknesses among cores may reflect subtle differences in accumulation due to sediment focusing or disturbances during the coring process. Overall, the entire lake responds coherently to the seasonal influx of sediment as indicated by the consistency of individual varve thicknesses among cores.

We created a composite varve chronology using cores with the least-disturbed sediments and easily identifiable couplets (Fig. 5a). Surface cores D-06 and H-06 were used for the upper section, core C-06 was used for the main body, and a ~10 cm section from core I-06 was used to bridge a 3.5 cm gap in core C-06, where it was cut in the field for transport.

Varve thickness trends

Varves in Blue Lake are thickest between 10 and 730 AD, averaging 1.89 mm with a maximum of 10.26 mm and a minimum of 0.33 mm (Fig. 5a). After 730 AD, varve thicknesses and sedimentation rates decrease abruptly (Figs. 4d and 5). Two shifts from 730 to 850 AD (average = 0.99 mm) and from 850 to 980 AD (average = 0.84 mm) mark the transition to a 50 year period of very thin varves between 980 and 1030 AD (average thickness = 0.41 mm). From 1030 to 1620 AD, varves average 0.76 mm, reach a maximum of 8.84 mm, and a minimum of 0.20 mm in thickness. Another period of thin varves occurs between 1620 and 1880 AD, where they average 0.62 mm and have a maximum and minimum of 3.89 and 0.21 mm, respectively. Varve thickness increases from 1880 AD to the present, averaging 1.05 mm with a maximum of 10.78 mm and a minimum of 0.19 mm. Increased varve thickness after 1880 AD is not due to reduced compaction. The bulk density of sediment from core B-99 reaches average values by 1.5 cm depth (Fig. 5b). Furthermore, the surface cores collected in 2006 were allowed to dewater in the field over several days to ensure that the uppermost sediments were not disturbed during transport. Therefore, the uppermost sediments settled and had low water content when varve thicknesses were measured.

Discussion

Varve thickness and the instrumental climate record

Varve-thickness records from glacial-fed lakes in the Arctic are often interpreted in terms of summer temperature because warmer summers result in higher discharge of sediment-laden melt-water from glaciers and snow melt (e.g. Hardy 1996; Moore et al. 2001). However, several studies demonstrate that other factors, such as extreme precipitation events, can play an important role in varve formation for certain climatic and geomorphic settings (Lamoureux 2000; Lamoureux et al. 2001; Cockburn and Lamoureux 2007). This typically results in varves with multiple summer sub-layers representing major rain events and large numbers of thick turbidites, neither of which are observed in the Blue Lake sediment. Additional factors, including glacial, fluvial, geomorphic, terrestrial-biologic, and inter-basin processes, have also been shown to influence varve formation (e.g. Hodder et al. 2007). We believe that the oligotrophic status of Blue Lake combined with the simple basin morphology and high accumulation rate greatly limits the influence these additional factors.

At Blue Lake our ability to discern the relative contributions of climatic and internal processes is limited by the availability of modern observations and instrumental meteorological data. We therefore restrict our analysis to comparison with data from the NRCS SNOTEL station at Atigun Pass, the nearest available instrumental record. The statistical relationship between varve thicknesses and meteorological data was assessed using linear regression (Fig. 6a, b; Table 4).

Average JJA temperature and varve thicknesses between 1993 and 2005 AD show a weak positive relationship when all the data are considered ($r^2 = 0.02$, $P = 0.65$; Fig. 6a; Table 4). With one anomalous year, 1998 AD, removed from the varve series, the correlation improves ($r^2 = 0.28$, $P = 0.10$; Fig. 6a; Table 4). Anomalous deposition during 1998 AD may reflect an isolated extreme precipitation event or some other intra-basin, non-climate-related event. A log transformation of the varve-thickness and temperature data further improves the varve-temperature relationship ($r^2 = 0.31$, $P = 0.08$; Fig. 6a; Table 4). This suggests a nonlinear relationship between spring/summer melt, sediment transport, and temperature, in which small changes in temperature are amplified within the sedimentary system. Similar logarithmic relationships have been observed in other glacial-fed Arctic and alpine lakes (Leonard 1985; Leemann and Neissen 1994; Hardy 1996).

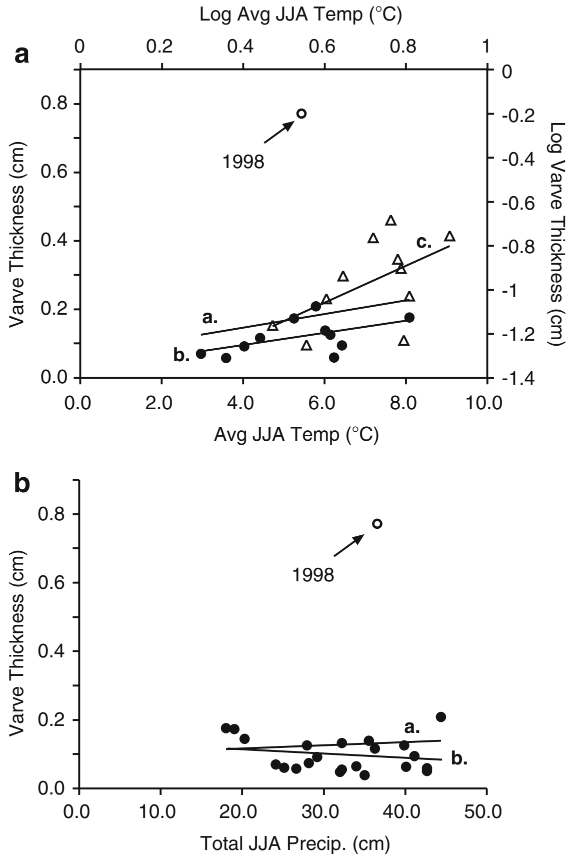

Fig. 6 **a** Varve thickness plotted against average JJA temperatures from Atigun Pass (1993–2005 AD; *black circles*). The correlation between varve thickness and temperature is poor when all the data are considered (line a; $r^2 = 0.02$; $P = 0.65$). With 1998 AD removed, the correlation between varve thickness and temperature is significant at the 90% confidence interval (CI; line b; $r^2 = 0.28$; $P = 0.1$). Also plotted are the log-transformed varve-thickness data and average JJA Atigun Pass temperatures (*open triangles*) with 1998 AD excluded. The log-transformed data show a better correlation ($r^2 = 0.31$; $P = 0.08$; 92% CI; line c). **b** Varve thickness plotted against total JJA precipitation at Atigun Pass (1983–2005 AD). The correlation between varve thickness and precipitation is statistically insignificant (line a; $r^2 < 0.01$; $P = 0.82$), even with 1998 AD removed (line b; $r^2 = 0.04$; $P = 0.38$). The linear regression equations and statistics are in Table 5

Summer precipitation and varve thickness show no statistically significant relationship, regardless of whether the 1998 AD varve is removed from the time series (Fig. 6b; Table 4). This suggests that summer precipitation is not a significant factor in varve formation during the period represented by the instrumental record.

Table 4 Values of truncated varve thicknesses in Fig. 3

Core	Varve no.	Thickness (cm)
C-06	1	4.0
	2	18.2
	3	4.7
	4	3.1
G-06	5	4.4
	6	3.2
I-06	7	3.3
	8	4.6
	9	16.8
	10	6.7
	11	4.5
	12	4.2

Although not significant at the conventional 95% confidence interval (CI; $P = 0.05$), the log-transformed varve-temperature relationship is significant at the 92% CI. The results indicate that 31% of varve thickness in Blue Lake is explained by temperature at Atigun Pass since 1993 AD. The remaining component of varve thickness not related to Atigun Pass temperature may be attributable to differences in temperature between the two sites or additional factors, such as variable winter precipitation, the intensity of snowmelt, or other intra-basin processes.

The limited duration of the instrumental record is the greatest source of uncertainty in our varve-temperature calibration. Temperatures inferred from varve thicknesses that are beyond the range of those in the calibration period are subject to greater error. A longer calibration period that incorporates the full range of observed varve thicknesses would help improve the varve-temperature relationship and the model's predictive ability. Monitoring intra-basin and glacial processes, including glacier discharge and sedimentation dynamics, would further help to quantify the relative contributions of various influences on varve formation at Blue Lake, and thus improve the varve-climate model.

Given the limited process data from Blue Lake, and the significant correlation between varve thickness and average JJA temperatures, we propose a simple interpretive model of varve thickness in which increased (decreased) sediment transport and subsequent deposition in Blue Lake is the result of enhanced (diminished) glacier-ice and snowmelt during warmer (cooler) summers. We recognize that the extent to which summer temperature controls varve thickness may have changed through time, especially during different climate states (Blass et al. 2007). Therefore, we strongly advocate caution when extrapolating this relationship downcore. Given the high quality and temporal resolution of the Blue Lake sedimentary sequence, however, we seek to interpret its climatic implications.

Temperature reconstruction

Keeping in mind the limitations of the varve-temperature relationship, we used least-squares regression of the log-transformed data to estimate JJA temperatures from 730 to 2005 AD (Fig. 7; Table 5). The period from 10 to 730 AD is excluded from the reconstruction because varve thicknesses during this interval are well beyond the range of the calibration data, and because previously published paleoclimate studies from elsewhere in the region suggest that temperature may not have been the dominant control on varve thickness prior to 730 AD (discussed below). The temperature reconstruction was smoothed with a 51-year moving average to reduce the 'noise' from non-climate-related events and to highlight long-term summer temperature trends (Fig. 7). An odd numbered moving average was used so that temperature values would be plotted on a whole year, instead of between years.

Despite the sparse calibration data, the Blue Lake JJA temperature reconstruction shows similarities with other paleo-temperature estimates from the Brooks Range (Ellis and Calkin 1984; Jacoby et al. 1999). Our reconstruction indicates that the Little Ice Age (LIA) was 0.2°C below the last millennium average (1000–2000 AD; LMA = 4.2°C). This is equivalent to 0.6–1.0°C cooler than modern, depending on the reference period used (1880–2005 AD average = 4.7°C or 1950–2005 AD average = 5.1°C, respectively). Similar estimates were derived from tree-ring studies by Jacoby et al. (1999) and lake-based studies by Clegg et al. (2005), which suggest a 0.6°C and 1.5–2°C LIA cooling, respectively. Ellis and Calkin (1984) suggested a 1°C or 3–4°C LIA cooling based on environmental lapse rate calculations and glaciologic-meteorologic measurements in the Brooks Range between 1977 and 1988 AD. However, this reference period was unusually

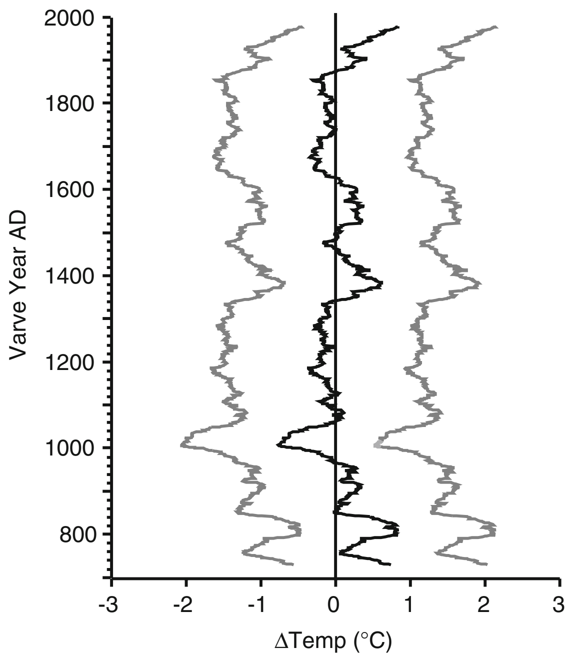

Fig. 7 Blue Lake temperature reconstruction (*black solid line*) with the upper and lower 95% confidence intervals (*grey lines*) shown as the deviation from the last millennium average (4.2°C). The temperature reconstruction is derived for the period 730–2005 AD. Temperatures prior to 730 AD are not reconstructed because varve thicknesses during this time are well beyond the range of the calibration period, reducing confidence in the results. We also suspect that increased varve thickness during this period reflects the role of enhanced precipitation on varve formation (see text for discussion)

warm, so the upper end of these estimates is likely too high. While we recognize the uncertainty in our reconstruction, the similarity with independent temperature estimates is encouraging, suggesting that changes in varve thickness at Blue Lake capture general summer temperature trends.

The temperature reconstruction presented in the discussion uses the LMA as the reference period. All JJA temperature estimates are inferred from varve thicknesses, unless otherwise stated, and shown as the difference from the LMA (ΔT). Temperatures above the LMA are denoted with a positive sign (+), while temperatures below the LMA are denoted with a negative sign (−).

Regional paleoenvironmental records

To aid in the interpretation of the Blue Lake varve-thickness and inferred-temperature trends, comparisons were made with previously published paleoenvironmental records from the region (Fig. 8a–d). The chronology of glacier fluctuations in the central Brooks Range is based on the number of moraines of particular ages as determined by lichenometric and radiocarbon dating (Fig. 8c; Calkin and Ellis 1980; Ellis and Calkin 1984). Hydrologic variability in the Yukon is inferred from several $\delta^{18}O$ isotope records (Anderson et al. 2007; Blotzer et al. 2008). Marcella Lake (Anderson et al. 2007) is presented as a representative record of hydrologic change in the Yukon since trends in this lake are similar to those observed in other Yukon lakes, suggesting a regionally coherent hydrological response (Fig. 8d; Blotzer et al. 2008). Marcella Lake is a closed-basin lake with authigenic carbonate sediments located in the southern Yukon near the British Columbia border. The lake is evaporatively enriched with respect to meteoric $\delta^{18}O$ so that isotopic shifts reflect changes in precipitation and evaporation (P/E balance). Accordingly, positive (negative) values reflect drier (wetter) conditions.

Table 5 Regression statistics for the relation between varve thickness at Blue Lake and annual climate data from Atigun Pass

Variable	Time period AD	Years excluded	Line[a]	Regression equations	r^a	P
JJA avg.	1993–2005	1996[b]	a.	Temp = 5.185 + 1.065(thickness)	0.02	0.65
Temp (°C)	1993–2005	1998	b.	Temp = 3.528 + 15.49(thickness)	0.28	0.10
Log JJA avg. temp (°C)	1993–2005	1998	c.	Log[temp] = 1.0676 + 0.3677(Log[thickness])	0.31	0.08
JJA total	1983–2005	None	a.	Precip = 31.987 + 2.67(thickness)	<0.01	0.82
Precip (cm)	1983–2005	1998	b.	Precip = 35.295 − 32.322(thickness)	0.04	0.38

[a] See Fig. 6 for regression lines

[b] JJA temperature data are incomplete for 1996 AD and so are not included in any of the temperature correlations

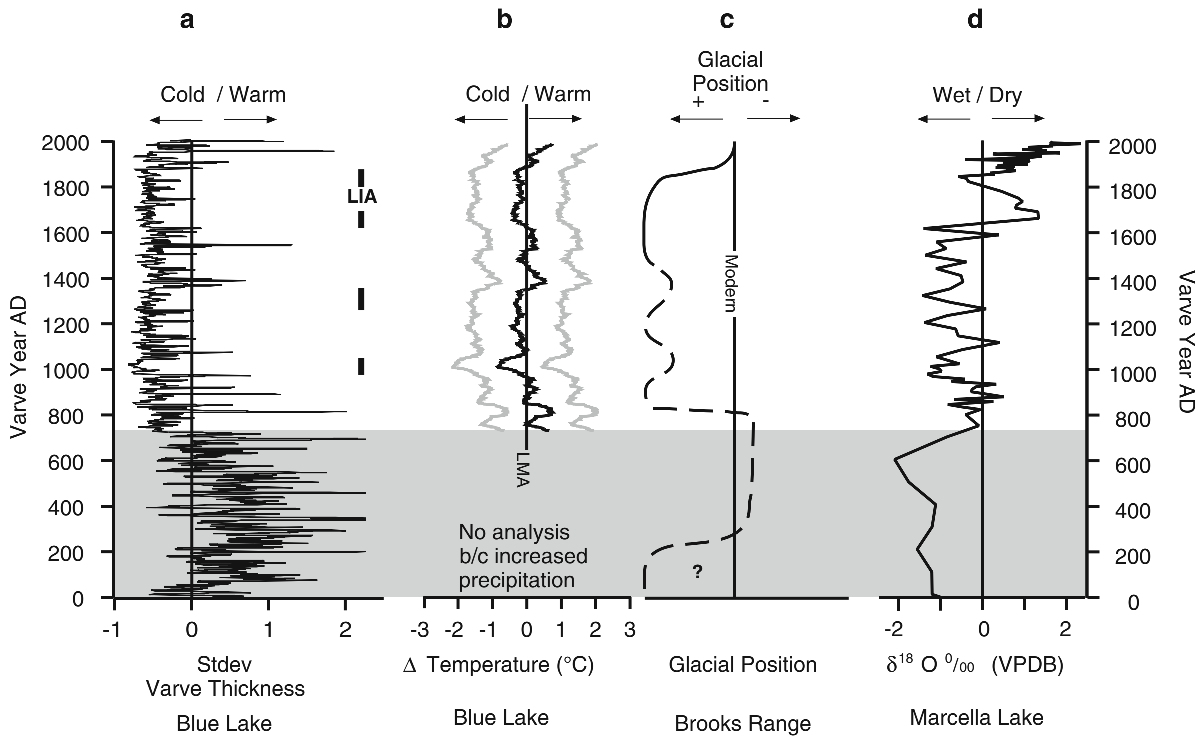

Fig. 8 **a** Blue Lake varve thicknesses plotted as the standard deviation from the mean thickness (5-point moving average). *Black vertical bars* indicate inferred cool intervals in the Brooks Range. **b** Blue Lake temperature reconstruction shown as the difference from the last millennium average (51-point moving average) with the grey lines denoting the upper and lower 95% CI. **c** Glacier fluctuations in the Brooks Range (Ellis and Calkin 1984). **d** Greater Yukon aridity as represented by the Marcella Lake $\delta^{18}O$ record (Anderson et al. 2007). The *grey area* highlights the period during which precipitation, rather than summer temperature, is believed to have dominated varve formation in Blue Lake

10 to 730 AD: first millennium wet period

Varves are thickest in Blue Lake between 10 and 730 AD (Fig. 8a), implying that this was the warmest period of the last 2000 years, assuming that varve thickness is predominantly related to temperature. During the same interval, Ellis and Calkin (1984) identified the most sustained glacial retreat in the Brooks Range since the onset of Neoglaciation at ~5000 year BP (Fig. 8c). Although recessed, many cirque glaciers remained in the Brooks Range (Ellis and Calkin 1984). Together, these records support the occurrence of a warm interval between 10 and 730 AD.

Isotopic evidence from the Yukon strongly indicates that this same period was the wettest in the last 2000 years. $\delta^{18}O$ values from Marcella Lake are persistently −1‰ to −2‰, the lowest values during the late Holocene, indicating wet conditions (Fig. 8d). Lake-level reconstructions from Marcella Lake also support a first millennium wet phase, showing contemporaneous high lake levels (Anderson et al. 2005).

We suspect that increased precipitation during this period of glacier recession influenced varve thicknesses at Blue Lake. With the Blue Lake glacier recessed, large amounts of unconsolidated sub-glacial sediment would have been exposed in the upper reaches of the catchment and subsequently available for transport. We suggest that enhanced sediment availability, in combination with increased precipitation, amplified sediment delivery to Blue Lake, resulting in thicker varves that were not directly related to temperature-controlled summer melt. This inference is supported in part by higher sedimentation rates between 10 and 730 AD (Fig. 4d).

730 to 1620 AD: late Neoglacial cooling

Varve thickness and sedimentation rates in Blue Lake decrease abruptly after 730 AD (Fig. 8a).

Contemporaneously, glaciers in the Brooks Range advanced (Ellis and Calkin 1984) and Marcella Lake $\delta^{18}O$ values increased (Fig. 8c, d; Anderson et al. 2007). These data indicate an abrupt regional shift to colder and drier conditions. With an expanded Blue Lake glacier, previously exposed unconsolidated sediment would no longer be available to summer hillslope runoff, reducing sediment delivery to the lake. We propose that glacial processes and snowmelt influenced by summer temperature became the dominant influence on Blue Lake varve thickness at this time, establishing the varve-temperature relationship.

After 730 AD, varve thicknesses declined in two steps, between 730 and 850 AD, and 850 and 980 AD. Estimated JJA temperatures averaged +0.4 and +0.1°C for these periods, respectively (Fig. 8a, b). Varve thicknesses abruptly decreased again after 980 AD, and remained low for a 50 year period until 1030 AD, indicating an abrupt and severe cold event with estimated JJA temperatures averaging −0.7°C (Fig. 8a, b).

Between 1030 and 1620 AD, JJA temperatures averaged the LMA, except between ~1260 and ~1350 AD when JJA temperatures averaged −0.2°C. Although there is no distinct interval at Blue Lake that corresponds with the European Medieval Warm Period (MWP; 1000 and 1300 AD; Crowley and Lowery 2000), two periods of relative warmth occurred from 1350 to 1450 AD, and 1500 to 1620 AD with average temperatures of +0.4 and +0.3°C, respectively (Fig. 8b).

1620 to 1880 AD: the Little Ice Age

Although cold overall (average −0.2°C from the LMA), inferred temperatures during the LIA were variable (Fig. 8a, b). The coldest phase of the LIA occurred between 1620 and 1720 AD, with average JJA temperatures of −0.3°C (Fig. 8b). Warming between 1720 and ~1800 AD, with temperatures averaging the LMA, was followed by a 0.2°C cooling from 1800 to 1850 AD. After 1850 AD, JJA temperatures increased to the LMA between 1850 and 1950 AD and rose to +0.8°C by 1950 to 2005 AD (Fig. 8b). As previously discussed, LIA temperature estimates appear reasonable as they are consistent with other independent temperature reconstructions (Ellis and Calkin 1984; Jacoby et al. 1999; Clegg et al. 2005).

During the LIA, the number of moraines formed in the Brooks Range reached a maximum, indicating a cool period when glaciers stabilized in advanced positions (Fig. 8c; Ellis and Calkin 1984). The lowering of equilibrium-line altitudes during the LIA (ΔELA) across the Brooks Range was minimal, suggesting that decreased winter precipitation limited extensive glacier growth (Sikorski et al. 2009). However, LIA aridity is also suggested for the Yukon by highly enriched $\delta^{18}O$ values from Marcella Lake (Fig. 8d) and other lakes in the region, as well as by increased salinity in Lake U60 (Fig. 8d; Pienitz et al. 2000; Anderson et al. 2007; Blotzer et al. 2008).

Despite some evidence for aridity in Alaska during the LIA, other studies suggest the LIA experienced enhanced precipitation. In the Brooks Range, Clegg et al. (2005) suggested that winter precipitation increased during the LIA based on $\delta^{18}O$ measurements of carbonate-rich sediment from Takahula Lake. Similarly, Hu et al. (2001), for example, concluded that the LIA was a period of increased effective moisture at Farewell Lake in the northwestern Alaska Range. However, arid conditions appear to characterize the early LIA at Farewell Lake, compared to more humid conditions at ~1700 AD toward the end of the LIA. This pattern of early LIA aridity followed by decreasing, but still arid, conditions is similar to that observed in the Marcella Lake $\delta^{18}O$ record (Fig. 8d; Anderson et al. 2007). Mann et al. (2002) also concluded that conditions were wetter during the LIA based on an inferred reduction of dune activity at the Great Kobuk Sand Dunes. The dune field is ~375 km southwest of Blue Lake (~115 km east of the Chukchi Sea) on the southern foot hills of the Brooks Range between 60 and 80 m asl. Climatic conditions at this location may be influenced by its proximity to the Chukchi Sea and low elevation, and therefore may not reflect high-elevation conditions in the Brooks Range.

Together, these data show a regionally consistent trend in cooler temperatures during the LIA, but a complex hydrological response. Additional records of LIA hydrologic variability from the greater Alaska and Yukon regions are needed to address the spatial expression of LIA precipitation for this region.

1880 to 2005 AD: post-Little Ice Age warming

Increasing varve thicknesses after 1880 AD is consistent with post-LIA warming (Fig. 8a). This period is marked by glacier retreats in the central Brooks Range approaching the extent of the first millennium retreat (Fig. 8c; Ellis and Calkin 1984). Despite a ~1.0°C (+0.8°C from the LMA) temperature increase and widespread glacier retreat, varve thicknesses have not achieved pre-730 AD levels (Fig. 8a, b). At first glance, this suggests that the twentieth century may not be as warm as prior to 730 AD; however, we suggest that varve thickness did not increase dramatically following the LIA because effective moisture did not increase to its pre-730 AD level. As well, the retreat of the Blue Lake glacier may not yet be as extensive as the first millennium retreat, thereby limiting the sediment available to Blue Lake.

Aridity in the Yukon after 1880 AD is evidenced by increasing $\delta^{18}O$ values from Marcella Lake (Fig. 8d; Anderson et al. 2007). A major post-LIA shift is also noted in the $\delta^{18}O$ values from the Mt. Logan Prospector Col ice-core from the southwestern Yukon at ~1850 AD (Fisher et al. 2004). This shift is interpreted as an increase in meridional atmospheric circulation and a strengthened/eastward Aleutian low that is a response to warmer sea-surface temperatures in the tropical Pacific and along the western coast of North America (Fisher et al. 2004). Such circulation results in increased precipitation over the coastal mountain ranges of Alaska, and decreased precipitation in interior regions because of the rain shadow effect from the coastal Alaskan ranges (Stafford et al. 2000). The effects of this circulation change have been observed in the instrumental record of precipitation in northern Alaska, where precipitation has steadily decreased during the last 50 years (Stafford et al. 2000). These results support the idea that the increase in varve thickness at Blue Lake after 1880 AD is the result of increased temperature in the absence of increased precipitation.

Comparisons with Arctic basin records

Comparison of the Blue Lake varve record with varve records from the eastern Canadian Arctic show variable relationships (Figs. 1 and 9). As with the

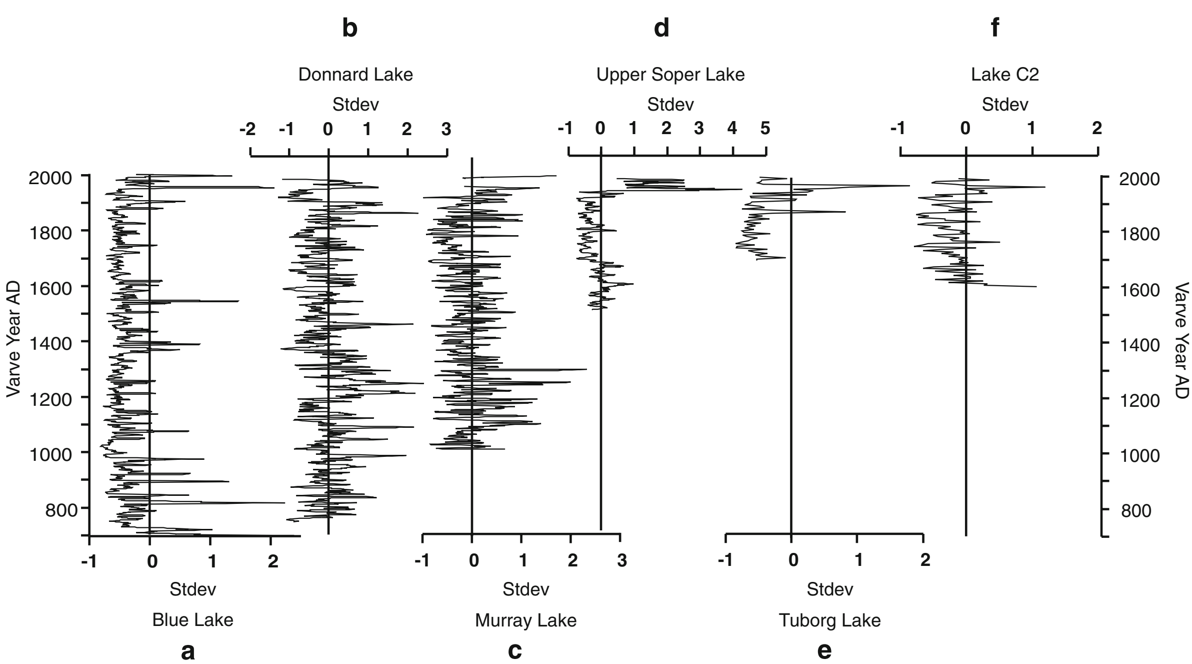

Fig. 9 The 5-point moving average of normalized Blue Lake varve thicknesses compared with normalized 5-point moving average varve records from the eastern Canadian Arctic. **a** Blue Lake, **b** Donnard Lake, **c** Murray Lake, **d** Upper Soper Lake, **e** Tuborg Lake, and **f** Lake C2. The Blue Lake record is similar to Upper Soper Lake, Tuborg Lake, and Lake C2, showing a distinct and similarly phased Little Ice Age (LIA) and post-LIA warming. The timing and magnitude of events at Blue Lake do not match Donnard Lake and Murray Lake as clearly. The locations of the Canadian lakes is shown in Fig. 1a

Blue Lake record, varve records from the eastern Canadian Arctic are interpreted in terms of melt-season temperatures, with thicker varves corresponding to warmer melt season temperatures. Varve-thickness trends between Blue Lake, Donnard Lake (Baffin Island; Moore et al. 2001) and Murray Lake (Ellesmere Island; Besonen et al. 2008) do not show a consistent phase relationship (Fig. 9a–c). For instance, the LIA at Donnard Lake began ~1375 AD, much earlier than the inferred 1620 AD onset at Blue Lake, although there is evidence for glaciation at Blue Lake during this time, and in Murray Lake, the onset of the LIA was later (~1700 AD) compared to Blue Lake. Prior to the LIA, Murray Lake and Donnard Lake show a pronounced interval of thicker varves that is contemporaneous with the European MWP (~1100–1375 AD). An equivalent period is not observed at Blue Lake (Fig. 9). Despite these differences, Blue Lake compares well with the shorter records from Lake C2 (Ellesmere Island; Hardy 1996), Tuborg Lake (Ellesmere Island; Smith et al. 2004), and Upper Soper Lake (Baffin Island; Fig. 9a, d–f; Hughen et al. 2000), which all show a cool LIA followed by twentieth century warming. These relationships illustrate that the North American Arctic may not respond uniformly to climate change during the late Holocene. However, post-LIA warming appears to be consistent in these two regions.

Summary

The Blue Lake varve-thickness record is the first annually resolved reconstruction of summer climate from northern Alaska spanning the last 2000 years. The Blue Lake watershed and depositional system are relatively simple, adding confidence to varve-based paleoenvironmental investigations. Although modern instrumental climate data are temporally limited, Blue Lake varve thicknesses correlates well with temperature data from the nearest weather station at Atigun Pass. With the limitations imposed by a short calibration data set in mind, we used this correlation to infer summer (JJA) temperatures at Blue Lake from 730 AD to the present. Together with regional paleoenvironmental records, the Blue Lake varve-thickness record shows that the Brooks Range was warm and wet between 10 and 730 AD. Glacial recession during this time likely exposed unconsolidated sub-glacial sediments that were subsequently mobilized by enhanced summer precipitation. Because influences other than temperature appear to have affected varve formation, temperatures were not estimated for this period.

The abrupt decrease in varve thickness at 730 AD was accompanied by advancing glaciers in the Brooks Range and aridity in the Yukon, suggesting a shift to cooler temperatures and drier conditions (0.3°C above the last millennium average, LMA = 4.2°C). Cooling culminated in an extreme-cold event between 980 and 1030 AD when estimated JJA temperatures averaged 0.7°C below the LMA. Between 1030 and 1620 AD, JJA temperatures varied around the LMA. One exception is a 90-year-long cold event (~1260 to ~1350 AD) when JJA temperatures fell to 0.2°C below the LMA. There is no clear evidence for a warm event at Blue Lake coincident with the European MWP (1000–1300 AD). Two warm periods, however, occurred from 1350 to 1450 AD, and 1500 to 1620 AD (0.4 and 0.3°C above the LMA, respectively).

Summer temperatures at Blue Lake during the LIA (1620–1880 AD) averaged 0.2°C below the LMA (1.0°C below the 1950–2005 AD average). This estimate agrees with independent regional temperature estimates that suggest the LIA was most likely between 0.6 and 2.0°C cooler. Other published evidence, but not all, suggests the LIA was arid in northern Alaska and the Yukon. After 1880 AD, JJA temperatures increased to 0.8°C above the LMA by 2005 AD, and glaciers retreated in the Brooks Range. Relative aridity, however, has persisted. Notably, post-LIA varve thicknesses do not achieve pre-730 AD levels. We suggest that this reflects the relatively recent glacier retreat that is still occurring, and not yet as extensive as the prolonged first millennium retreat. Abundant unconsolidated sub-glacial sediment, therefore, remain protected by the glacier and are not available for transport to the lake. In subsequent decades as the glacier retreats further, we project that sediment influx to the lake will increase.

Climate trends inferred from Blue Lake varve thicknesses, in comparison with records from the eastern Canadian Arctic, suggest differences in the existence, timing and magnitude of events such as the MWP and LIA between the eastern and western North American Arctic. However, the Blue Lake varve-thickness record compares well with some varve records from the eastern Canadian Arctic (i.e. Lake C2, Upper Soper Lake, and Tuborg Lake) with respect to the timing and magnitude of LIA cooling and post-LIA warming.

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