Anomalous early 20th century sedimentation in proglacial Green Lake, British Columbia, Canada

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Abstract: Annually laminated sediments were recovered from Green Lake, a proglacial lake in the southern Coast Mountains in British Columbia, to examine their potential as a temperature proxy. Varve thickness is moderately correlated with temperature anomalies (A.D. 1900–1994) and annual maximum mean daily discharge of Lillooet River (A.D. 1930–1999), but these relations are not stable through time. Following A.D. 1977, the relation between varve thickness and annual maximum mean daily discharge is stronger. Prior to A.D. 1977, varve thickness is correlated with March to October air temperature, which controls the intensity and duration of glacier runoff. Varve thickness is weakly correlated with reconstructed air temperature records for North America and the Northern Hemisphere for the period A.D. 1600–1976. Less extensive glacier cover may explain the lack of a clear temperature signal in the varved sediment record prior to A.D. 1600 and following A.D. 1977. The period of highest lake sedimentation, from A.D. 1920 to 1945, coincides with rapid retreat of glaciers in the watershed. The lack of a similar level of sedimentation in the varve chronology suggests that glacier recession during the period 1920–1945 was higher than at any time in the past 600 years.

Résumé : Des sédiments à varves annuelles ont été recueillis du lac Green, un lac proglaciaire du sud de la chaîne Côtière en Colombie-Britannique, afin d'examiner leur potentiel en tant qu'indicateur de la température. L'épaisseur des varves concorde en général avec des températures anormales (1900-1994) et la décharge maximale quotidienne moyenne annuelle de la rivière Lillooet (1930-1999), mais ces relations varient dans le temps. Après 1977, la relation entre l'épaisseur des varves et la décharge maximale quotidienne moyenne annuelle est plus forte. Avant 1977, l'épaisseur des varves correspondait bien à la température de l'air entre mars et octobre, ce qui représente la température qui contrôle la durée et l'intensité du ruissellement provenant des glaciers. L'épaisseur des varves correspond légèrement aux enregistrements de la température de l'air reconstitués pour l'Amérique du Nord et l'hémisphère Nord pour les années 1600-1976. Une couverture glaciaire moins étendue pourrait expliquer le manque d'un signal de température clair dans les sédiments varvés enregistrés avant 1600 et après 1976. La période de sédimentation lacustre la plus élevée, de 1920 à 1945, coïncide avec le retrait rapide des glaciers dans le bassin versant. L'absence d'un niveau semblable de sédimentation dans la chronologie des varves suggère un retrait glaciaire plus prononcé au cours de la période 1920-1945 qu'à tout autre moment dans les derniers 600 ans.

[Traduit par la Rédaction]

Introduction

Warming of the North American and Northern Hemisphere land surface occurred during the periods 1924–1944 and 1978–1998 (Jones et al. 1999) and mainly during winter and spring. The later phase of warming affected both North America and Eurasia whereas warming during the 1924–1944 period was primarily limited to high latitudes and western North America (Jones et al. 1999; Jones and Moberg 2003). Warm tropical sea surface temperatures coincided with anomalous circulation patterns over western North America between 1924 and 1944 and created widespread drought conditions in the U.S. and Canada (Fu et al. 1999; Schubert et al. 2004). The severity of this drought in the western U.S. was unprecedented during the last 300 years (Cook et al. 1999). Glaciers in western Canada and the Pacific Northwest retreated rapidly during the early 20th century (Osborn and Luckman 1988; Spicer 1989), presumably in response to unusual warm and dry conditions.

Documenting temperature anomalies prior to the instrumental record requires the use of temperature proxies. In western Canada, North America, and the Northern Hemisphere, annually resolved temperature proxies prior to the period of instrumentation are based largely on tree rings (Mann et al. 1998; Briffa et al. 2002; Luckman and Wilson 2004). Other temperature proxies could supplement tree-based temperature reconstructions in regions where trees are absent, short-lived, or are not sensitive to temperature variability. The primary objective of this paper is to examine whether annually laminated (varved) lake sediments from southwest British Columbia can be used as an air temperature proxy. Western Canada is of interest for climate change studies both because there are relatively few long-term temperature reconstructions from this region, and because the region is strongly influenced by major ocean-atmospheric modes of climate variability that influence temperature fields in North America and the Northern Hemisphere (Shabbar and Khandekar 1996; Mann et al. 1998; Mantua and Hare 2002). This influence, and the degree of spatial correlation in North American temperature, is well expressed in the recent temperature field (Fig. 1). Consequently, western Canadian temperature

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reconstructions should improve regional and hemispherically averaged temperature estimates prior to the instrumental period.

Study area and methods

Oligotrophic Green Lake (50°10′N; 122°55′W) drains a medium-scale (178 km^2) watershed in the southern Coast Mountains of British Columbia, Canada (Fig. 1). The lake has a principal inflow (Fitzsimmons Creek) that delivers the majority of the water and sediment to the lake. The Spearhead and Fitzsimmons ranges (Fig. 1) are underlain by Cretaceous quartz diorite and granodiorite, and by intruded metamorphic rocks of the Gambier Group (Monger 1994). Important sediment sources to Green Lake include contemporary glaciers (7% of catchment area), glacier forefields, and steep hillslopes adjacent to Fitzsimmons Creek. Maximum ice cover during the latter half of the Little Ice Age (1700–1850) is estimated to have been 12% (Menounos 2002).

Green lake (1.99 km^2) comprises several individual basins and a wide, shallow sill in proximity to the contemporary delta (Fig. 1). The lake is dimictic, and it develops a weak to moderate thermal structure during summer. The lake is generally ice covered between December and early April. Detailed limnological surveys of the lake are discussed elsewhere (Schiefer 2004; Schiefer 2006).

Sediments were recovered from Green Lake during winter using a percussion coring system (Reasoner 1993), and by vibra-coring (Smith 1998). The cores were collected from the sill at 15 m water depth (Fig. 1). This coring location was chosen to enhance the proportion of sediments delivered by overflow and interflow events that are common in proglacial lakes during the glacier melt season (Smith 1978). Sedimentation in deep basins in proximity to major inflow is heavily influenced by underflow events that are typical during floods (Gilbert 1975; Schiefer 2004; Best et al. 2005). The deep, proximal basins of Green Lake may also record localized patterns in sedimentation (e.g., Lamoureux 1999) as both the location of the Fitzsimmons delta and its distributaries have varied through time (Pelpola and Hickin 2004).

Recovered sediment cores were split, photographed, and sampled for bulk physical properties including water content, density, particle size, and organic matter. The loss on ignition (LOI) method (Dean 1974) was used to estimate organic carbon content (2 h at 550 °C). Representative samples were treated with 35% H_2O_2 and dispersed in a solution of sodium hexametaphosphate prior to particle size analysis by laser diffraction.

Overlapping sediment slabs (15 cm × 2.5 cm × 1 cm) were collected from the cores using a metal tray and impregnated with low viscosity resin (Lamoureux 1999). Water was removed from the slabs both by the flash-freeze freeze-dry method and by chemically dehydrating the sediments with successive acetone replacements. The quality of embedded slabs that were dehydrated with acetone was superior to that of the flash-freeze freeze-dry method (e.g., sub-millimetre stratigraphy was preserved), but hardening of acetone-treated slabs was difficult in dense, clay-rich sediments. It is suspected that interstitial water remained in the sediments and softened the epoxy, despite completing over 20 acetone exchanges. Polished sediment slabs and thin sections were prepared for measurement of laminae thickness (±0.05 mm) under a dissecting microscope (Lamoureux 2001). Laminae were also identified and measured from images of freshly split and partially dried sediment cores (Gilbert 1975).

Sediment monitoring in the Green Lake basin included the collection of depth-integrated suspended sediment samples from Fitzsimmons Creek during the 1999–2002 season. Sampling during snow melt and glacier runoff seasons was approximately weekly with additional sampling during high flows. Results of the sediment monitoring on Fitzsimmons Creek and within Green Lake are discussed in detail elsewhere (Schiefer 2004; Menounos et al. in press; Schiefer 2006).

Sediment record

Sediment cores range from 0.5 to 11 m in length. The uppermost 6 m of sediment is well laminated, inorganic (1.5%–3.0% LOI), clayey silt to silty clay (median grain size = 7.5 μm). A 5 cm interval of bioturbated sediment occurs 150 cm below the lake floor and it was not possible to measure or identify lamina boundaries in this interval. Thus, the current analysis is limited to the well-laminated sediments above 150 cm.

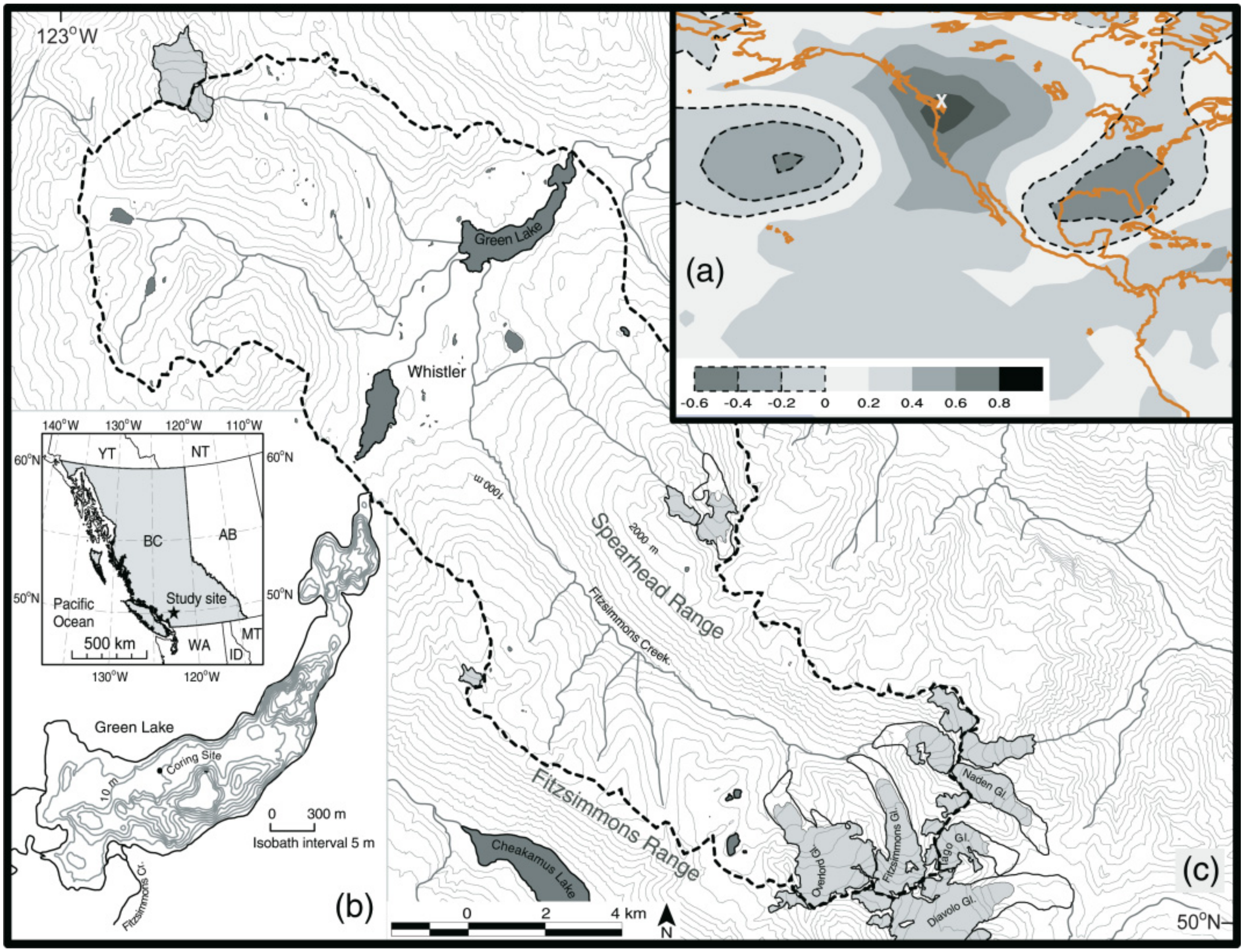
Dry sediment density varies slightly (1.19 ± 0.012 g cm^{-3}; $n = 150$) but surprisingly, it shows little increase downcore. Natural consolidation of the sediments at depth is probably compensated by coring-induced compression of the uppermost sediments (e.g., Desloges and Gilbert 1994). Organic matter, like dry sediment density, shows only negligible changes for sediments above 150 cm depth. Smear slide analysis reveals that the sediments above 150 cm are primarily comprised of mineral matter. Most of the coarse silts and fine sands are quartz and feldspars.

Laminae range from 0.5 to 20 mm thick and most laminae consist of simple couplets: a lower ungraded unit of coarse silt grading into an upper, darker clay-rich unit (Fig. 2). Thick (>5 mm) couplets generally consist of either a thick-graded lamina between the underlying silt and overlying clay unit (e.g., Desloges and Gilbert 1994) or silts that are micro-laminated (e.g., Gilbert 1975) (Fig. 2). Thick-graded laminae are typically brown, whereas the micro-laminated silts are white to pale green.

Based on sediment monitoring in the Green Lake basin (Schiefer 2004; Menounos et al. in press; Schiefer 2006), most of the sediments are delivered to Green Lake during floods and during the summer melt season. Consequently, the thick, normally graded couplets and micro-laminated silts (Fig. 2) were probably formed in years where inflow was dominated by major flooding or prolonged glacier runoff, respectively.

The presence of new couplets in surface sediment cores obtained over a period of a year or more and the ^{137}Cs activity of the upper sediments are consistent with a varve interpretation (Menounos et al. 2005). Cores were cross-dated using varves that were distinctive in colour, thickness, or the number of sub-annual laminae (e.g., Lamoureux 2001). Uncertainty in varve counts was determined both by repeat counting and by calculating the number of missing and extra varves between marker varves. Prior to the 20th century, uncertainty is ±1.7% or approximately two varves per century. A varve chronology was produced by averaging varve thickness across the contributing

Fig. 1. (*a*) Spatial correlation of monthly temperature anomalies (1900–2003) of grid point 50°N 120°W with neighbors (5° × 5° grid) for land and oceans (Jones and Moberg 2003). The correlation pattern is similar to temperature field anomalies during years when tropical (El Niño Southern Oscillation) and extra-tropical (Pacific Decadal Oscillation) climate modes are strongest (Shabbar and Khandekar 1996; Mantua and Hare 2002). Dashed contours denote negative correlation. Location of Green Lake labeled with white "X". (*b*) Location of Green Lake, lake bathymetry (5 m isobaths), and location of coring site. Green Lake bathymetry provided by E. Schiefer. (*c*) Green Lake watershed. Dashed line is watershed boundary. Black lines downvalley from contemporary glaciers (light gray) denote outermost limits of glaciers during the Little Ice Age. Contour interval is 100 m.



cores. Standardization for differences in average sedimentation rates for the cores was not required because varve thickness for a given year did not vary significantly among cores, most likely because the coring sites were in close proximity to one another.

Coring-induced disturbance of couplets, losses introduced by splitting cores into 1–2 m sections in the field, and incomplete dehydration of sediments prior to resin impregnation result in differences in the number of contributing cores through time to approximately two cores from 1400–1650, four cores from 1650–1800, and five cores following 1800. Mean inter-series correlation of varve thickness among the sediment cores is 0.73.

The ability of the recovered sediment cores to represent lake-wide sedimentation over the past 600 years is uncertain. However, patterns of recent lake sedimentation provide some confidence that the sediment cores are a suitable proxy for lake-wide sedimentation: varve thickness explains 80% of the variance in the averaged sedimentation rate extracted from a dense ($n = 120$) network of surface cores over the period 1930–1998 (Menounos et al. 2005).

Varve thickness trends and comparison to the instrumental and proxy records of air temperature

Lake sedimentation over the last 100 years is characterized by uncommonly thick varves and a secular trend in varve thickness through time (Fig. 3). Sedimentation increases abruptly at about 1920, peaks at 1940 and declines thereafter (Fig. 3). Varve thickness at the sill is characterized by high inter-annual variability following 1970, and the thickest varves consist of normally graded silts overlain by a thick clay lamina. The 1931–1945 varves are noticeably inorganic, micro-laminated, and slightly denser than varves formed between 1946 and 1990 which consist of simple couplets. Post 1991 varves are tan,

Fig. 2. Green Lake varves from 57.5–64 cm depth (A.D. 1723–1739). Horizontal black lines delimit varve boundaries. The section shows simple couplets (e.g., A.D. 1723–1726), varves containing micro-laminated (MS) silts (e.g., A.D. 1736–1737), and varves where white, micro-laminated silts are overlain by a graded brown lamina (L) capped by clay (e.g., A.D. 1733). These couplets are interpreted to reflect years where inflow to Green Lake is dominated by snowmelt runoff, prolonged glacier melt, and prolonged glacier melt followed by a late-season inflow event (autumn). The image was acquired from a polished sediment slabs scanned on a flatbed scanner at 1200 DPI with reflected light. Small white features are areas of incomplete resin impregnation.

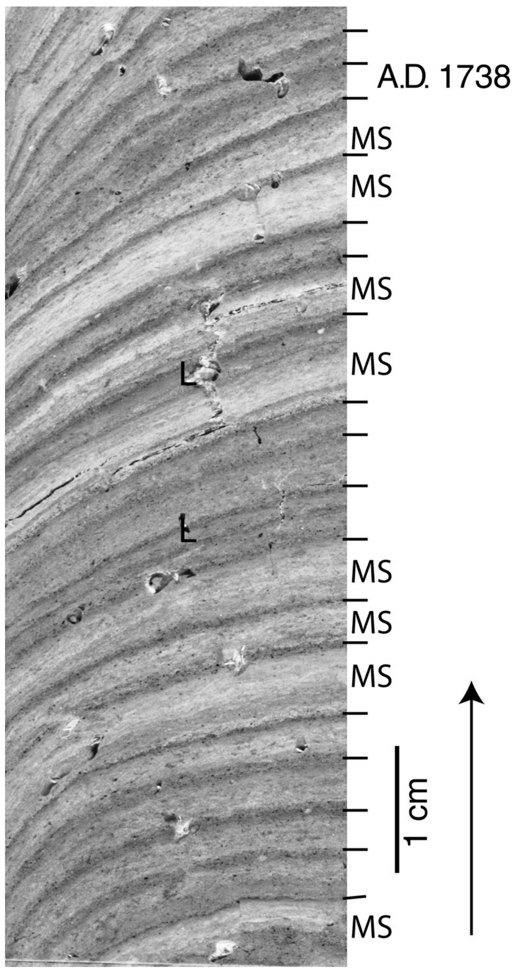
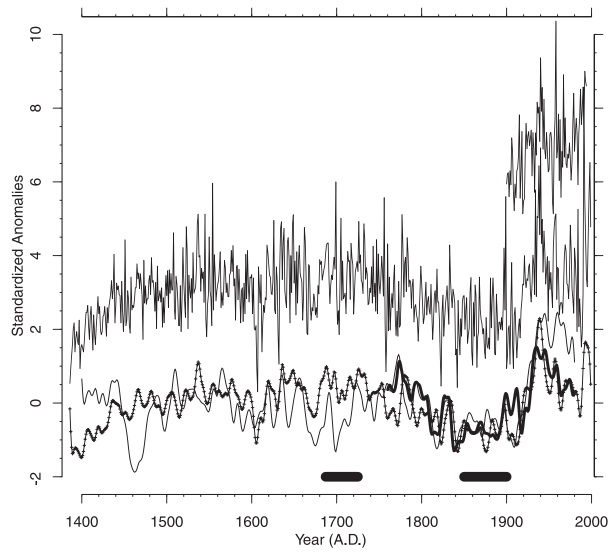


Fig. 3. Comparison of varve thickness and air temperature records. All time series are standardized (zero mean and unit variance). Upper series denotes leading mode of May–October air temperature variability (offset by six units) for the North Pacific region (PC1 of Table 1). Second uppermost series is the log-transformed Green Lake varve chronology (A.D. 1400–1999) offset by three units. The three lower series are the North American (thick line, A.D. 1650–1980) (Mann et al. 2000), the Northern Hemispheric (Mann et al. 1998) reconstructed temperature record (A.D. 1400–1980), and the Green Lake varve record (dotted line). All series are decadally smoothed with a 13-year Gaussian filter. The horizontal bars denote major intervals of moraine construction in the Canadian Cordillera (Osborn and Luckman 1988; Luckman 2000).



slightly coarser, and frequently contain sub-annual laminae between the lowermost silts of the varve and the upper clay cap.

As glacigenic sedimentation is governed both by meteorological conditions during inflow and changes in sediment availability, the Green Lake varve chronology was compared to environmental time series known to influence sediment transport and production. The time series include local, regional, and hemispheric air temperature records, and monthly precipitation records from stations near the study area. In addition, the correspondence between varve thickness and other hydro-climatic factors including April 1 snow water equivalence, glacier mass balance (Place Glacier), and streamflow records (annual and seasonal mean and annual maximum mean daily discharge of Lillooet River: 08MG05) were also examined. The Lillooet River discharge series was favoured over closer streamflow stations given the length, the continuity, and the quality of this hydrologic record. Time series characterizing major modes of North Pacific and global ocean-atmospheric (ENSO) states (e.g., Bitz and Battisti 1999; Mantua and Hare 2002) were also considered.

The most significant predictors of Green Lake varve thickness include flood magnitude and average air temperature during the spring, summer, and autumn. Varve thickness is correlated to the annual maximum mean daily discharge of Lillooet River, but this relationship is not stable through time. For example, the relationship between varve thickness and annual floods is strongest between 1977–1999 ($r = 0.68$) but weakens considerably for the period 1930–1976 ($r = 0.43$).

Varve thickness covaries with regional, North American, and Northern Hemisphere air temperature time series (Table 1, Fig. 3), but in a similar way to flood magnitude, the strength of these relationships is time dependent. Varve thickness and regional air temperature are correlated during the May–October period for eight long-term, meteorological stations in the Pacific Northwest and western Canada (Easterling et al. 1996; Zhang et al. 2000). The principal mode of annual temperatures (PC1), was calculated from standardized monthly mean anomalies for the May–October period to extract the common temperature signal from the records. PC1 explains 73% of the common variance over the period 1900–1994 (Ta-

Table 1. Correlation between varve thickness, local, North American, and Northern Hemisphere air temperature.

	$_{ln}$varve[a]	PC1[b]	NA[c]	NH[d]	NArecon[e]	NHrecon[f]
$_{ln}$varve	—	—	—	—	—	—
PC1	0.41[g]	—	—	—	—	—
NA	0.42	0.36	—	—	—	—
NH	0.49	0.58	0.44	—	—	—
NArecon	0.32	0.47	0.67	0.44	—	—
NHrecon	0.22	0.17	0.44	0.70	0.68	—

Note: Correlations among records are based on period of common overlap.
[a]Log-transformed Green Lake varve thickness.
[b]Leading mode of May–October temperature anomalies (1900–1994) from eight North Pacific climate stations (1) Corvallis Ore.; (2) Blaine, Wash.; (3) Bellingham, Wash., (4) Port Angeles, Wash.; (5) Agassiz, B.C.; (6) Victoria, B.C.; (7) Princeton, B.C.; (8) Bella Coola, B.C.].
[c]North American temperature record (1902–1998) (Mann et al. 2000).
[d]Northern Hemisphere temperature record (1865–1999) (Jones et al. 1999).
[e]North American reconstructed temperature record (1650–1980) (Mann et al. 1998).
[f]Northern Hemisphere reconstructed temperature record (1387–1980) (Mann et al. 1998).
[g]All correlations significant at $p < 0.05$ when corrected for autocorrelation.

Table 2. Calibration, verification, and full-model statistics.

Calibration	r^2	SE[a]	RE[b]	*Verification*	r^2	RE[b]
1900–1938	0.26	0.71	0.44	1939–1976	0.33	0.25
1939–1976	0.33	0.86	0.34	1900–1938	0.26	0.37
Full Model						
1900–1976	0.35	0.79	0.41			

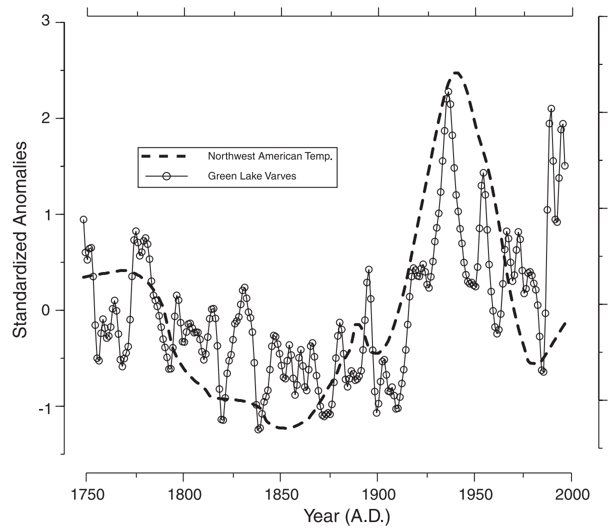
[a]Standard error of the estimate.
[b]Reduction of error (β) statistic (Mann et al. 1998).

ble 1). PC1 is significantly correlated to varve thickness over the period 1900–1994 (Table 1), but there is no similarity between the records following 1977 (Fig. 3). Varve thickness explains 35% of PC1 variance for the period 1900–1976. The stability of this temperature signal prior to 1977 is revealed by backward and forward calibration and verification tests (Table 2). Residuals of the full model lack autocorrelation or trend through time. These results indicate that the relation between air temperature and varve thickness is real and apparently stable for the period 1900–1976.

Varve thickness over the period 1387–1999 shows a secular trend, with increasing sedimentation up to about 1700 followed by a gradual decline (Fig. 3). The most abrupt change in lake sedimentation occurs at about 1920 when varves become thicker and commonly micro-laminated. Thicker varves also occur in the intervals 1620–1665, 1670–1755, and 1770–1785. Simple and micro-laminated varves are most common during these periods of higher than average sedimentation (Fig. 2).

Inter-decadal variations in varve thickness (Fig. 3) are correlated with North American and Northern Hemisphere temperature reconstructions (Mann et al. 1998; Mann et al. 2000). The highest correlation ($r = 0.32$; $p < 0.001$) is with the North American temperature reconstruction (Fig. 3, Table 1). The relationship between varve thickness and the longer North-

Fig. 4. Trends in Green Lake varve thickness and the northwest American temperature reconstruction derived from changes in glacier length (Oerlemans 2005). The number of contributing glaciers ranges from 2 to 24. The Green Lake record is smoothed with a 7-year Gaussian filter to facilitate comparison between the records.



ern Hemisphere temperature reconstruction is weaker ($r = 0.22$; $p < 0.001$) and the series covary greatest during the period 1600–1980 (Fig. 3). Thickest varves in the Green Lake chronology coincide with warmer than average (1901–1980) summer temperatures based on temperature reconstructions for the British Columbia interior region (Wilson and Luckman 2003) and the Canadian Rockies (Luckman and Wilson 2004) based on tree growth. In interior British Columbia, reconstructed temperatures for the decade 1931–1940 were the warmest in the last 400 years (Wilson and Luckman 2003).

The low-frequency trend in Green Lake sedimentation is broadly similar to a multi-decadal temperature reconstruction for northwest America (Fig. 4) based on glacier extent (Oerlemans 2005). This reconstruction models the temperatures required to sustain the length of a given glacier based on an assumed climate sensitivity and the response time of the glacier (Oerlemans 2005). Negative anomalies are observed in both of the records for most of the 19th century (Fig. 4). Positive anomalies occur in both series after about 1920, and these anomalies peak at about 1940 and decline thereafter. However, neither proxy captures the late 20th century warmth that is present in the instrumental record (Fig. 4).

Discussion

Air temperature has influenced Green Lake sedimentation over the past 600 years, but the strength of the temperature signal has varied. A positive relation between lake sedimentation and summer air temperature has been observed in other proglacial lake systems (Leonard 1981; Leemann and Niessen 1994; Ohlendorf et al. 1997; Tomkins and Lamoureux 2005). Glacier runoff increases during warm summers and heightens the delivery of glacigenic sediments to proglacial lakes. Warm summers also enhance basal sliding of temperate glaciers which increases the production of glacigenic sediments due to abrasion (Hallet et al. 1996). The results of sediment monitoring in the Green Lake watershed (Schiefer 2004; Menounos et al. in press; Schiefer 2006) and in nearby mountain catchments (Moore and Demuth 2001; Menounos 2002) indicate that warm temperatures during spring and early autumn months can substantially lengthen the glacier runoff season. For example, warm temperatures during spring can expose glacier ice sooner by melting winter snowcover, while warm autumns can extend the duration of glacier runoff.

Wintertime precipitation anomalies have been suggested to be the most important control of the net mass balance of North Pacific glaciers (Bitz and Battisti 1999). Since glacier runoff is governed by ice loss during the ablation season, however, one may expect summer mass balance to be a better predictor of Green Lake varve thickness than either winter or net mass balance. Unfortunately, summer mass balance records from nearby Place and Sentinel glaciers are too short and discontinuous to assess whether true relations exist between varve thickness and summer mass balance.

The temperature signal in the Green Lake sediment record was unexpected since the fraction of ice cover is low, and surface runoff from the Green Lake catchment is predominantly snowmelt driven. Although there are few similarities between the varve chronology and the instrumental record of precipitation, some correspondence is observed between periods of drought and thick varves (Cook et al. 1999; Watson and Luckman 2004). For example, highest sedimentation rates in the Green Lake record occurred during the longest drought (1917–1941) reconstructed for the southern Canadian Cordillera for the period 1700–1990 (Watson and Luckman 2004). This interval also coincides with the most severe drought to affect the western USA in the last 300 years (Cook et al. 1999). Since drought conditions are typically caused by both warm temperatures and low precipitation and the varve record is correlated with reconstructed temperatures, air temperature has probably been more important in controlling glacigenic sedimentation than changes in annual or seasonal precipitation totals.

Similar to Green Lake, high sedimentation rates were recorded in proglacial lakes in the Canadian Rockies between 1931 and 1946 (Leonard 1981). Glaciers there were presumably responding to similar climatic conditions favouring glacier recession. Maximum sedimentation rates in Bow Lake during the last 300 years occurred between 1925 and 1934 (Leonard 1981). Early 20th century glacier recession was apparently caused by warm and dry conditions in western North America (e.g., Mann et al. 1998; Cook et al. 1999; Fu et al. 1999; Schubert et al. 2004). The coincident increase in lake sedimentation and regional, North American and Northern Hemisphere surface air temperature indicates local glaciers responded quickly to warming. This assertion is substantiated by photographic evidence that glaciers in the Green Lake watershed receded between 200–300 m between 1931 and 1946, the highest recession rates in the last 70 years (Menounos et al. 2005). Glacier recession slowed considerably between 1946 and 1980. This observed pattern is generally consistent with glacier fluctuations elsewhere in the Canadian Cordillera (Osborn and Luckman 1988; Luckman 2000). The lack of a similar sedimentation event in the 600-year Green Lake varve record suggests that glaciers experienced their highest rates of recession during the period 1920 to 1945.

The rapidity and amplitude at which glaciers in the Green Lake basin responded to early 20th century warm temperatures is confirmed at the regional level by the northwest America temperature reconstruction (Oerlemans 2005) based on changes in glacier length (Fig. 4). It could be argued, however, that the positive anomalies observed in both the varve and the glacier length record (Fig. 4) were caused by glaciers retreating from extended Little Ice Age positions, and climatic conditions during the early 20th century were not unusual. However, substantial temperature anomalies revealed in the non-glacial temperature reconstructions for North America and the Northern Hemisphere (Mann et al. 1998) indicates that this event was not limited to glacier systems. The amplitude of this signal in all of the temperature proxies considered in this paper indicates that climatic conditions that caused the anomalous sedimentation pattern in Green Lake during the period 1920–1945 were unusual and regional to hemispheric in scope.

A recent update to the land station temperature data base (Jones and Moberg 2003) indicates that that the land-averaged rate of warming for western North America for the period 1920–1944 exceeded that for the period 1977–2001. Consequently, the strength of the earth 20th century temperature signal in all of these proxy records may have been caused both by the absolute temperatures as well as the rate of warming. The importance of the rate of warming, as opposed to absolute temperature, may account for the inability of both the Green Lake varve record and the glacially derived temperature reconstruction for northwest America to record warm conditions of the late 20th century. Reduced sensitivity to late 20th century temperatures is not limited to temperature proxies derived from lake sediments or changes in glacier length. Tree growth at many high latitude sites does not respond to recent warm temperatures observed in the instrumental record (Briffa et al. 2004).

Over long time scales, the fidelity of the temperature signal in clastic varves may be compromised because proglacial lake sedimentation is also controlled by long-term changes in glacier cover (Leonard 1997). An increase in glacier cover enhances sediment production by increasing the area over which glacier erosion occurs (Hallet et al. 1996). Generally high sedimentation between 1650 and 1720 coincides with the construction of the outermost Little Ice Age moraines in the Green Lake and adjacent watersheds (Koch et al. 2003). Conversely, less extensive ice cover prior to 1600 and following 1977 probably accounts for lower than expected sedimentation rates at these times. Apparently the temperature signal contained in the Green Lake varve record depends on an important geomorphic threshold, namely the fraction of ice cover in the watershed.

Changes in flood frequency can also influence proglacial lake sedimentation in western Canada (Desloges and Gilbert 1994; Menounos et al. 2005; Gilbert et al. in press). The correlation between varve thickness and flood magnitude (annual maximum daily discharge for nearby Lillooet River) is strongest after 1945 when glaciers were less extensive. Based on the stream flow record of Lillooet River (1930–1999), the thickest varves occur during years with major autumn floods. The magnitude of these floods in the Lillooet River basin has increased in the last 35 years (Menounos et al. 2005) and broadly coincides with the post-1976 climate regime shift of the North Pacific (Minobe 1997). Increased autumn flooding, in addition to less extensive ice cover, may explain the lack of a post-1976 temperature signal in the Green Lake varve chronology. The importance of floods in influencing Green Lake sedimentation prior to the instrumental record remain uncertain given the lack of suitable flood proxies from western Canada.

The complex relationship between varve thickness and environmental factors influencing lake sedimentation is not unique to Green Lake. For example, snow cover has been reported to be an important, albeit complex control on proglacial lake sedimentation (Menounos et al. 2005; Tomkins and Lamoureux 2005). Reductions in glacigenic sediment supply, rather than complex meteorological conditions, may explain the decreased importance air temperature in explaining recent patterns of Green Lake sedimentation. Following 1977, glaciers probably contribute less sediment to Fitzsimmons Creek than during early periods when ice was more extensive.

In addition to decreased glacigenic sediment supply, the delivery of hillslope-derived sediments to Fitzsimmons Creek has likely increased in recent decades. Fitzsimmons Creek is adjacent to steep, unstable slopes and these sediments are mobilized during exceptional, late autumn precipitation events (Menounos et al. in press). In 1991, for example, a late summer rainstorm produced the second largest flood on Lillooet River. The rainstorm triggered a landslide that temporarily blocked Fitzsimmons Creek and caused widespread channel aggradation. Gullies and landslide scars produced during the 1991 event remain unvegetated and are important sediment sources to Fitzsimmons Creek in recent decades (Menounos et al. in press). Mobility, transport, and delivery of these sediments to Green Lake require high-flow events as opposed to warm temperatures during the glacier runoff season.

Conclusions

Over the past 400 years, inter-decadal patterns of sedimentation in Green Lake have covaried with regional, North America and, to a less degree, Northern Hemisphere temperature reconstructions. Highest sedimentation rates occurred during the early 20th century in response to rapid retreat of glaciers under unusual climatic conditions. The lack of a comparable sedimentation event in the 600-year Green Lake varve record suggests that glaciers achieved their highest rates of glacier recession during the period 1920–1945.

The detection of a temperature signal in proglacial lake sediments from the North Pacific region is important because these records can supplement other temperature-based proxies for detecting and analyzing climate change. However, since many climatic and geomorphic factors influence glacigenic sedimentation, the temperature signal preserved in the sediments of Green Lake is neither strong nor stationary. It is likely that the lack of a temperature signal in the Green Lake varves prior to 1600 and following 1977 originates from climatic and geomorphic factors including glacier extent below a critical threshold, and possibly, a change in the frequency and magnitude of flooding in recent time. One method to amplify the temperature signal contained in glacigenic sediments may include the use of a network of varve records from a region (Menounos et al. 2005) to average out basin-specific controls on lake sedimentation. This approach is currently being tested to examine the relation between temperature change and glacigenic sedimentation in southwest British Columbia over the past 1000 years.

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