The Holocene 15,8 (2005) pp. 1163–1171

Environmental reconstruction from a varve network in the southern Coast Mountains, British Columbia, Canada

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Received 28 September 2004; revised manuscript accepted 18 March 2005

A HOLOCENE RESEARCH PAPER

Abstract: Cores of annually laminated sediments (varves) from five lakes in the southern Coast Mountains of British Columbia, Canada, document clastic sediment response to climate and geomorphic change over the past 120 years. Interannual varve thickness correlates with annual flood magnitude. Interdecadal trends in varve thickness are influenced by other environmental factors such as glacier recession. Despite major differences in the lakes and their contributing watersheds, substantial concordance is observed among the records. A pronounced change in the nature of lake sedimentation, accompanied by higher interannual variability, occurred in 1980. The change coincides with an increase in the magnitude of autumn flooding and major re-organization of the North Pacific climate system. These results highlight new directions for palaeoenvironmental research using varved sediment records, specifically to study the magnitude and spatial extent of past hydro-climatic events.

Key words: Varves, lake sediments, glacier retreat, floods, environmental change, interannual variability, hydroclimatology, British Columbia, Canada.

Introduction

Varved sediments have long been used as a chronological tool in Quaternary research (e.g. Antevs, 1922). Recent studies have used varves to detail intra-annual sedimentary events (Lamoureux, 2000), pollen flux over millennia (Bartlein and Whitlock, 1993), and interdecadal changes in sedimentation (Tiljander *et al.*, 2002). Most lake and ocean environments lack the combination of factors required to form varves, namely heterogeneous sediment flux, high sedimentation rates and an absence of reworking (Sturm, 1979; Smith and Ashley, 1985; Grimm *et al.*, 1996). Consequently, the use of these records is generally limited to studies of single basins. This paper presents a network of varved sediment records from southwestern British Columbia, Canada, and discusses trends in interlake sedimentation during the period 1880–2000. We document a pronounced change in sediment delivery to the study lakes in 1980, probably triggered by a shift in the North Pacific climate regime. Our analysis indicates that cores of varved sediments from many lakes can facilitate an understanding of regional sediment delivery at the event to interdecadal timescales. The benefits of the approach include isolating a common signal among records and assessing sediment source variability and runoff-generating mechanisms.

Study area and methods

The southern Coast Mountains of British Columbia (Figure 1) comprise northwest-trending mountain ranges with up to 3000 m of relief and extensive snow and ice cover (Ryder, 1981; Muhs *et al.*, 1986). The dominant bedrock is granodiorite and quartz diorite of the Coast Mountains Crystalline Complex, largely of Mesozoic age (Monger and Journeay, 1994). The watersheds and lake basins of this study differ substantially in

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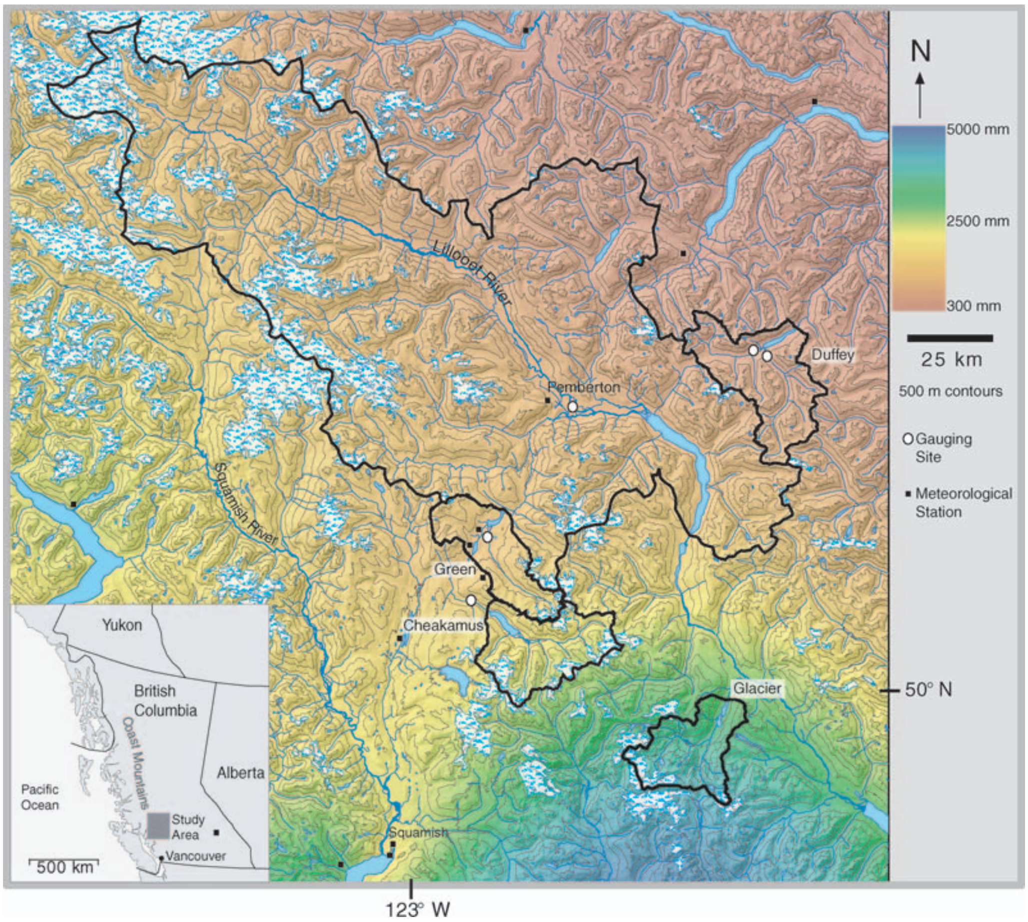

Figure 1 Digital elevation model (DEM) of the study area, mean annual precipitation for the period 1970–1999, watershed boundaries and location of hydro-meteorological series used in this study. DEM data provided by the Government of British Columbia

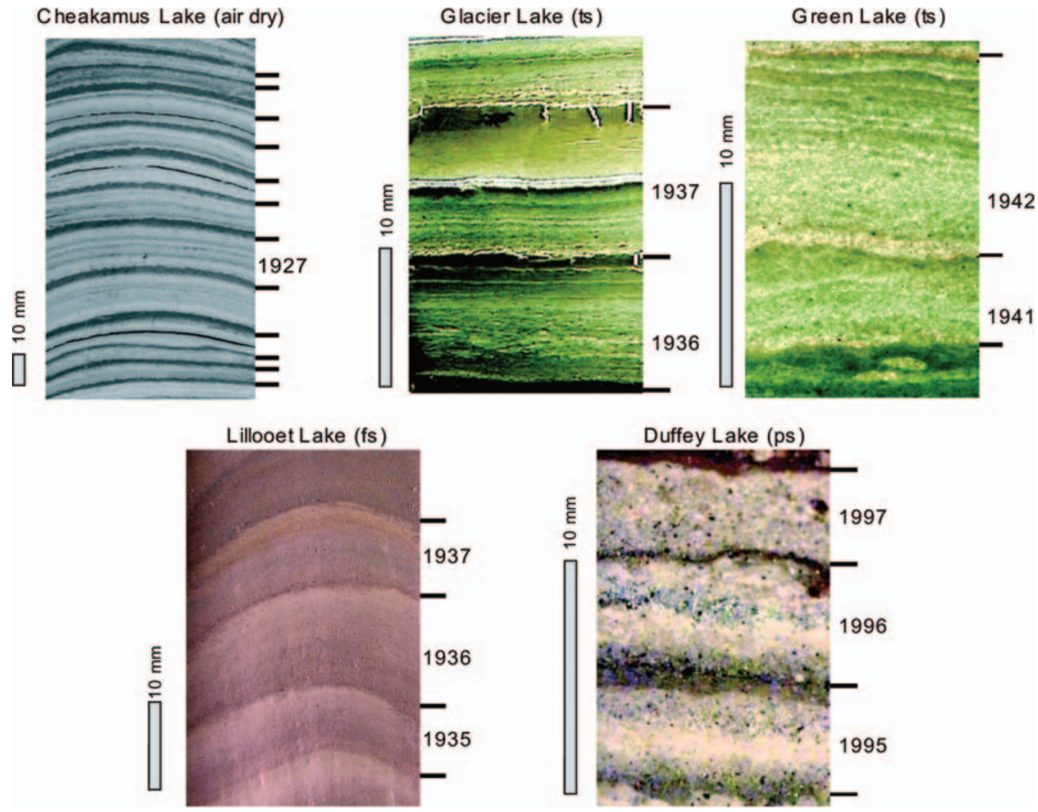

Figure 2 Thin-sections (ts), polished slab (ps), fresh sediments (fs) and air-dried images showing types of varves found in this study. Images from Lillooet and Duffey lakes illustrate simple couplets in distal areas of the lakes. Late-season laminae are present in the Cheakamus and Glacier lake varves. Microlaminated varves like those shown for Green Lake are common in all lakes between 1934 and 1945

Table 1 Morphometric relations of the study lakes and watersheds

	Catchment area (km^2)	Lake area (km^2)	Catchment-lake ratio	Z_{max}[a] (m)	Glacier cover (%)	Relief (m)
Cheakamus Lake	216	4.69	46	119	23	1580
Green Lake	178	1.99	89	40	7	2016
Glacier Lake	205	2.13	96	29	12	2100
Lillooet Lake	3580	30.44	117	137	7	2640
Duffey Lake	255	3.98	64	90	2	1600

[a]Maximum lake depth.

morphology and ice cover (Table 1). Glaciers cover 2–23% of the watersheds (Table 1). Analysis of hydro-meteorological records reveals a notable rain-shadow effect imposed by the Coast Mountains (Figure 1).

Mean annual precipitation declines from 2700 mm/yr near the southwest corner of the study area to approximately 700 mm/yr on the east. Watersheds close to the coast experience rainfall-generated floods, whereas floods in basins east of Lillooet River are caused by snowmelt or rain-on-snow events (Melone, 1985). Aerial photograph analysis and field surveys indicate that the dominant sediment sources are glaciers (subglacial and forefield sources) and landslides. Sediments derived from these sources are temporarily stored in channels and on floodplains (Jordan and Slaymaker, 1991; Desloges and Gilbert, 1994), but ultimately delivered to lakes and the sea. The temperate, oligotrophic lakes of this study are dimictic and develop weak-to-moderate thermal structure during summer. All of the study lakes except Lillooet Lake are generally ice-covered between December and April.

We collected percussion and gravity cores from Cheakamus, Duffey, Glacier, Green and Lillooet lakes between 1997 and 2002 (Figure 1). All of the cores with the exception of those from Green Lake were recovered in the deepest, central basins of the lakes. Sediment cores from Green Lake were collected from a shallow (15–20 m) sill near the contemporary delta (Menounos *et al.*, in press). Sediment cores were analysed for water content, bulk density, organic matter content and particle size. The loss on ignition (LOI) method (Dean, 1974) was used to estimate organic carbon content (2 hours at 550°C). Particle size analysis was performed using a Malvern™ laser diffraction system on samples pre-treated with 35% H_2O_2 to remove organic matter and with sodium metaphosphate added as a dispersant. Interpretations of the sedimentary record from Lillooet Lake have been presented elsewhere (Gilbert, 1975; Desloges and Gilbert, 1994) and are not repeated here.

Varves were identified and measured on photographs, resin-impregnated polished sediment slabs and thin sections under a stereo microscope ($\pm$0.05 mm). Varve thickness was defined as the sediment between two clay (>4 µm) laminae. Photographs of partially dried sediment cores (Figure 2) were valuable for identification of clay laminae in varves consisting of several silty laminae (Gilbert, 1975; Leonard, 1997). A varve chronology was produced by averaging varve thickness for a given year across the suite of sediment cores. In many cases varve thickness for a given core represented the average of measurements made on polished sediment slabs, thin sections and photographs of wet and partially dried sediments. Standardization was not required since varve thickness for a given year did not differ significantly between cores.

Cores were cross-dated based on the presence of marker varves (Lamoureux, 2001). We combined varve measurements from five to seven cores from each lake to create master chronologies. Mean interseries correlation coefficients for individual varve chronologies (Duffey: 0.77 ($n=6$ cores); Glacier: 0.86 ($n=5$); Lillooet: 0.84 ($n=5$); Green: 0.85 ($n=6$); Cheakamus: 0.89 ($n=7$)) are significant at $p=0.05$. Varve identification errors, assessed by recording the number of 'missing' or 'extra' varves observed between cores (Lamoureux, 2001), are 0.5–1.0%, except for Duffey Lake (2–3%).

Results

Sediments recovered from each lake are well laminated, inorganic, silty clay to clayey silt. Dry sediment density ranges from 0.6 to 1.4 g/cm^3, depending on the lake and core location, and does not increase substantially with depth. Most laminae are 0.5–20 mm thick and occur as couplets, consisting of a silt lamina grading upward to a darker, clay-rich lamina (Figure 2). Contacts between the couplets are generally sharp and uniform. Thick, graded laminae occur between some of the lower silt and upper clay laminae (Figure 2). The median grain size (D_{50}) of Glacier and Cheakamus laminae is finer (7.5 µm) than that of Duffey and Green lake laminae (13 µm). Clay-rich units are too thin to obtain reliable particle size data, except in Lillooet Lake where D_{50} of clay-rich laminae is 5.9 µm, compared with 9.0 µm of silt laminae. We do not know whether these differences reflect true differences in particle size among the lake basins because of the small number of cores per lake basin.

Two lines of evidence demonstrate that the couplets in three of the five basins (Duffey, Lillooet and Green lakes) are varves: (a) the onset (1954) and peak (1963) North American ^{137}Cs atmospheric fallout levels coincide with calendar ages of couplets (Figure 3) counted back from the sediment–water interface (Desloges and Gilbert, 1994; Menounos, 2002; Menounos *et al.*, in press); and (b) new couplets are predictably observed in cores taken in subsequent years. Agreement between varve counts and calibrated radiocarbon ages obtained from terrestrial macrofossils in longer sediment cores (unpublished data) confirms a varve interpretation for the sediment records of Cheakamus and Glacier lakes.

Varve thickness trends

Sedimentation in the lakes of this study can be explained in large part by the location of primary water and sediment inflow and by lake bathymetry. Varve thickness generally decreases away from the point of inflow, a common trend observed in proglacial lakes (Smith and Ashley, 1985). In Green Lake, for example, average varve thickness decreases from 33 mm, 300 m from the principal inflowing stream (Fitzsimmons Creek), to 2.4 mm near the lake outlet. In Lillooet Lake, varve thickness increases slightly in the distal regions of the main basins because of turbidity current ponding (Gilbert, 1975).

Decadal-scale variations in sedimentation and rare, high-magnitude sedimentation events are revealed in the master varve chronologies developed for the lakes of this study

(Figure 4). Thick varves commonly consist of one or several distinctive, thick laminae capped by clay (Figure 2). We used principal component analysis (Preisendorfer, 1988) over the period of overlap (1908–1995) of the individual chronologies to extract a common sedimentation signal from the records. The first principal component (PCvarves) explains 46% of the variance in the varve network. Inspection of the common signal reveals high sedimentation between 1920 and 1945, followed by a steady decline until 1980. Interannual variability is notably lower between 1945 and 1980 (Figure 3). Following 1980, there is a pronounced increase in interannual variability in PCvarves (Figure 4). The Duffey Lake chronology contributes an insignificant proportion of variance to PCvarves. Sedimentation rates in Duffey Lake are lower than average during the periods 1912–1920, 1935–1960 and 1977–1985 (Figure 4).

Environmental factors influencing varve thickness

We investigated environmental controls on lake sedimentation by comparing individual varve chronologies and the PCvarve record to hydro-climatic time series that may influence the production and transfer of fine sediment within the study area. The time series included in the analysis are precipitation and temperature records, glacier mass balance records, snow course data and streamflow records. Unfortunately, most of these records are short, contain significant gaps or were discontinued in the last decade, limiting their use in the present study. Inspection of a long-term, re-homogenized, monthly temperature record from Agassiz, British Columbia (Environment Canada Station 1100120) reveals a weak correlation ($r = 0.40$) between Green Lake varve thickness and mean annual temperature over the period 1895–1999. A consistent relation between air temperature and varve thickness for the other catchments was not observed. We also examined indices of climate that explain the dominant modes of winter North American atmospheric (Wallace and Gutzler, 1981) and North Pacific atmospheric–ocean variability known as the Pacific Decadal Oscillation-PDO (Mantua and Hare, 2002).

Annual maximum mean daily discharge (Q_{max}) is the best predictor of varve thickness (Table 2), but its timing during the year differs across the study area. Analysis of streamflow records for Lillooet River (08MG005), the longest and highest quality streamflow record available for the study area, shows an increase in the magnitude of autumn flooding after 1975 (Figure 5). Historically, most of the largest floods in Lillooet valley have occurred during autumn rather than during the nival or glacier runoff season (Figure 5). In lower elevation watersheds Q_{max} occurs during spring, autumn or winter. In contrast, most basins east of Lillooet River experience Q_{max} during the nival runoff season in late spring or early summer (Melone, 1985). Stream monitoring on tributary rivers to Duffey Lake between 1997 and 2001 confirms the nival character of Q_{max} for this continental watershed. To approximate a long-term Q_{max} record for the Duffey Lake basin, we used the maximum mean daily flow of Lillooet River during the May–June period for the period of record (1923–1930) where observations are complete (Figure 1, Table 2). The relation between Duffey Lake varve thickness and Lillooet Q_{max} during spring is low ($r = 0.26$; $p = 0.03$) for the period 1923–1999, although it is higher ($r = 0.42$) for the period 1928–1999 (Table 2).

The largest between-lake differences in varve thickness are for the period 1920–1945 (Figure 4). Sedimentation was high in Cheakamus and Glacier lakes during the early 1920s, but not in Green Lake until about 1934 (Figure 4). Residuals of Q_{max} and varve thickness for all of the lakes except Duffey are strongly autocorrelated and are mostly positive between 1930 and 1945. Persistence in these Q_{max}-varve thickness residuals continues until about 1955 in Lillooet Lake.

Major flood events and lake sedimentation

Micro-stratigraphic analysis of the thickest varves indicates differences in the quantity and nature of lake sedimentation

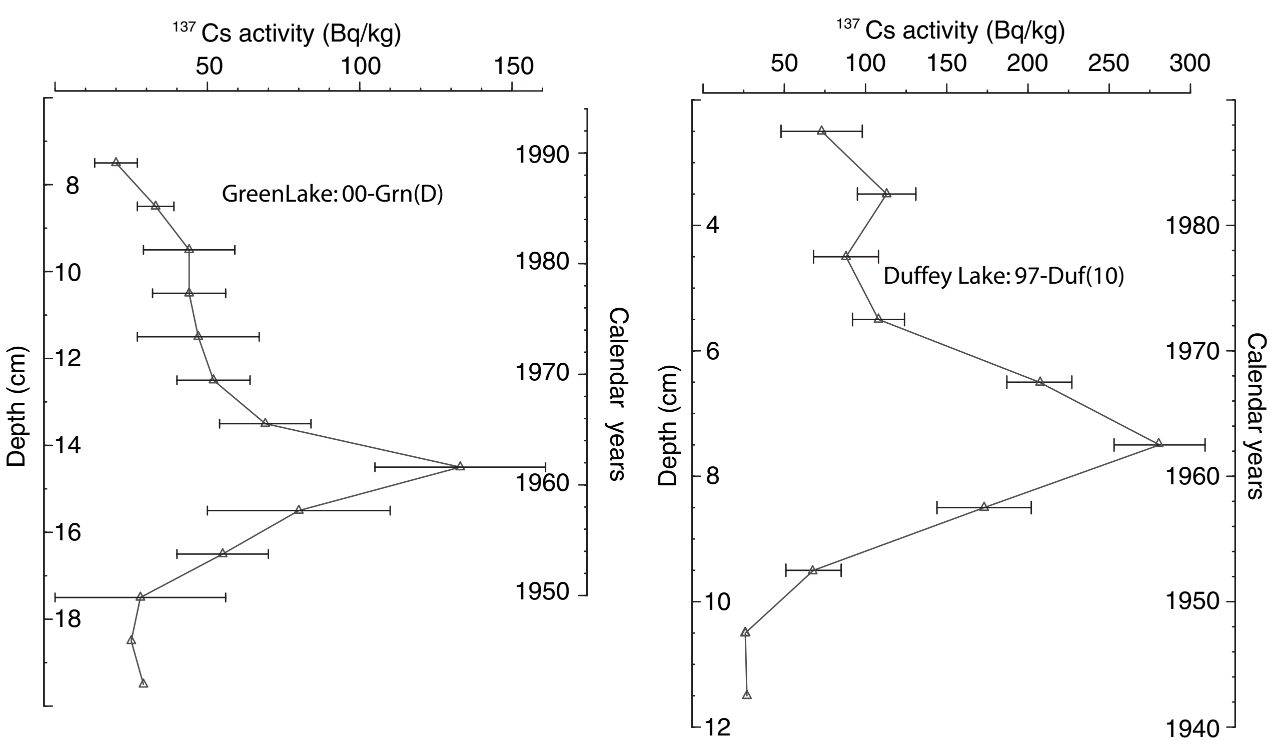

Figure 3 Cesium activity levels of Green and Duffey lake sediments. Horizontal error bars indicate analytical uncertainty ($\pm 1\ \sigma$) in ^{137}Cs activity determination. Peak activity in both sediment cores occurs at *c*. AD 1963 based on varve counting. The profiles are largely consistent with the North American ^{137}Cs fallout record. Calendar age of sediments reflect mid-varve age of 1.0 cm thick samples

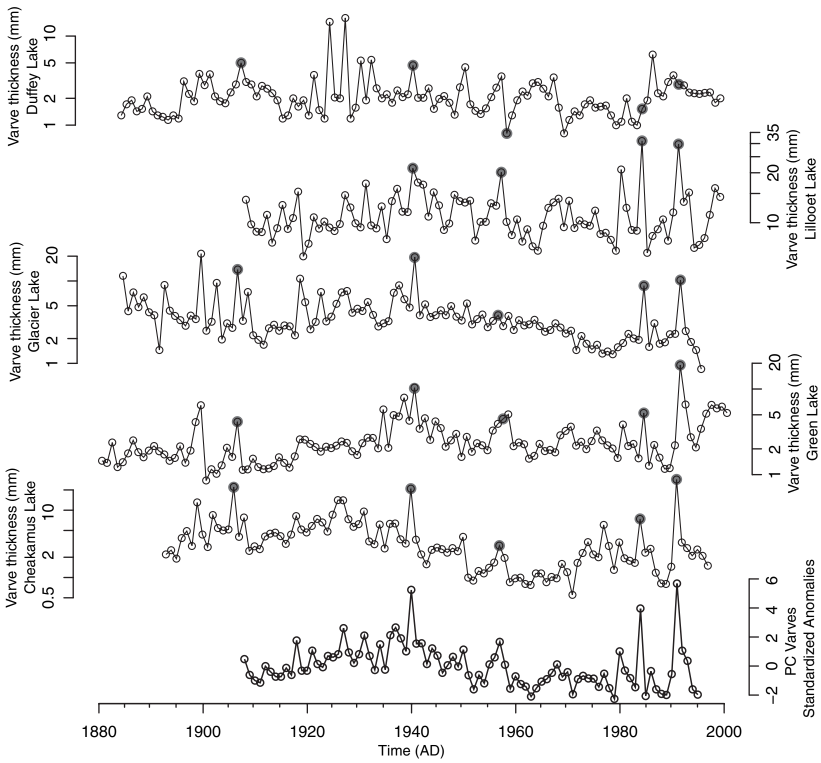

Figure 4 Varve thickness data displayed from continental (Duffey) to more maritime (Cheakamus) environments. Abscissa scale in log units. The Lillooet Lake chronology is a compilation of data from Desloges and Gilbert (1994) and cores collected in 2000. The first principal component (eigenvector) extracted from the network explains 46% of the common variance. Solid symbols denote years of extreme floods (1906, 1940, 1957, 1984, 1991)

during years of large floods. A late summer rainstorm in 1991 produced the second largest flood of record (1260 m^3/s) for Lillooet River (Figure 5). Estimated recurrence intervals for the precipitation event range from 20 years (yearly one-day rainfall) to 100 years (summer only) (Ward and Skermer, 1992). The rainstorm triggered a deep-seated landslide that temporarily dammed the stream flowing into Green Lake and caused aggradation and, later, scour in excess of 5 m (Ward and Skermer, 1992). An estimated 7.8×10^4 t of sediment were deposited in the lake, producing the thickest varve of the last 3000 years (Menounos *et al.*, in press). Major channel changes were also observed along rivers west of Lillooet Lake. The event also produced thick varves in Cheakamus, Glacier and Lillooet lakes (Figure 4). A conspicuous, light brown lamina from the 1991 event is apparent in thin sections of Duffey Lake sediments, but the 1991 varve in that lake is not unusually thick

Table 2 Pearson correlation coefficients for varve records

	Cheakamus Lake	Green Lake	Glacier Lake	Lillooet Lake	Duffey Lake	PC_{varves}	Blue Glacier[a]	PDO[b]	Lillooet River[c] Q_{max}	Cheakamus River[d] Q_{max}
Cheakamus Lake	–	0.28	0.60	0.39	ns	0.75	0.52	0.33	0.43	0.66
Green Lake	–	–	0.35	0.60	ns	0.70	0.23	ns	0.56	0.64
Glacier Lake	–	–	–	0.44	ns	0.79	0.67	ns	0.34	0.60
Lillooet Lake	–	–	–	–	ns	0.81	0.26	ns	0.62	0.74
Duffey Lake	–	–	–	–	–	ns	ns	ns	0.26[e] (0.42)[f]	ns
PC_{varves}	–	–	–	–	–	–	0.56	0.22	0.61	0.78
Blue Glacier	–	–	–	–	–	–	–	0.35	ns	ns
PDO	–	–	–	–	–	–	–	–	ns	ns
Lillooet River Q_{max}	–	–	–	–	–	–	–	–	–	0.81
Cheakamus River Q_{max}	–	–	–	–	–	–	–	–	–	–

Note: All correlations significant at $p < 0.05$ unless specified (ns).
[a] Time series of Blue Glacier terminus fluctuations (m/yr), Olympic Mountains, Washington (Rasmussen *et al.*, 2000). Linear interpolation used to derive annual time series from original data ($n = 55$).
[b] PDO index is the annual average (October–September) of the principal mode of monthly North Pacific sea surface temperature anomalies (Mantua and Hare, 2002).
[c] Annual maximum mean daily discharge (Q_{max}) for Lillooet River (1930–1999).
[d] Q_{max} for Cheakamus River (1921–1948, 1981–1995).
[e] Q_{max} for Lillooet River during the nival (May–June) runoff season (1923–1999).
[f] Q_{max} for Lillooet River during the nival (May–June) runoff season (1928–1999).

(Figure 4). Sediment delivered to all of the studied lakes, except Glacier Lake, was considerably less during extreme autumn runoff events in 1940 and 1984 than during the 1991 event. Sediment deposited during the 1940 event is distinctive – a normally graded lamina (40–60% of the total varve thickness) is underlain by microlaminated sediment. The thickness of the autumn flood deposit is appreciable, but about half of the year's sediment was deposited prior to the flood (Figure 4).

Anomalously thick varves of 1924 and 1927 are unique to the Duffey Lake varve chronology (Figure 4) and appear to reflect basin-specific sedimentation events that may be unrelated to hydro-climatic controls. The 1924 and 1927 varves are sandier than average and contain terrestrial organic detritus suggesting formation by episodic processes. Longer cores from the Duffey Lake basin obtained closer to steep, south-facing slopes adjacent to the lake contain gravel units and many normally graded beds that are attributed to debris-flow and snow avalanching into the lake (Menounos, 2002).

Glacier fluctuations and lake sedimentation

Glacier fluctuations affect sediment delivery and influence decadal to centennial sedimentation patterns in proglacial lakes (Souch, 1994; Leonard, 1997). We documented changes in glacier extent in the study area between 1929 and 1996 from aerial photographs and documentary sources to examine the relation between glacier fluctuations and lake sedimentation (Menounos, 2002). Glaciers for which aerial photographs or maps are available responded more or less similarly over decadal timescales during this interval. The period between 1929 and 1946 was one of rapid glacier retreat, typically, hundreds of metres per year. Recession of glaciers slowed between the late 1940s and 1960s and was negligible between 1969 and 1980, consistent with previous mapping (Ricker, 1978) and mass balance studies (Hodge *et al.*, 1998). Retreat rates increased after 1990 but were lower than during the period 1929–1946. The climatic conditions driving these changes were regional, as glaciers in the middle Coast Mountains, Canadian Rockies and the US Pacific Northwest behaved similarly (Luckman and Osborn, 1979; Spicer, 1989).

We compared the individual varve chronologies and PCvarves against a time series of change in terminus position

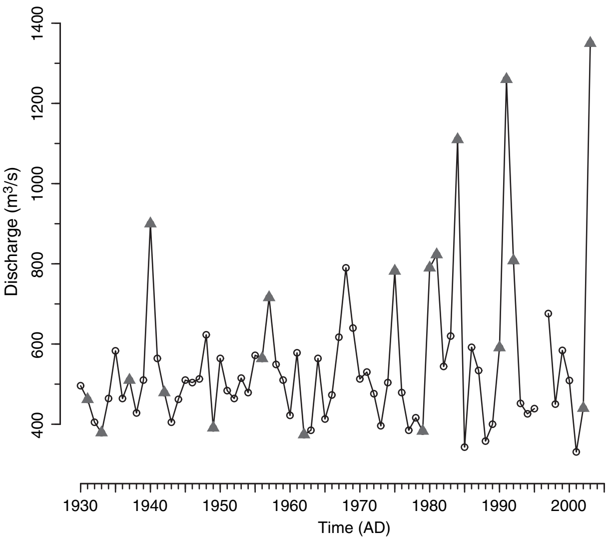

Figure 5 Maximum daily discharge series for Lillooet River (08MG005). Triangles denote floods that occurred during the autumn season (15 August–31 December)

(m/yr) of Blue Glacier, Washington, to investigate the interannual to decadal relation between glacier fluctuations and regional lake sedimentation (Table 2). We chose Blue Glacier for analysis because it is the closest glacier for which detailed terminus positions are available for the twentieth century (Rasmussen *et al.*, 2000). Changes in the position of Blue Glacier are significantly correlated to lake sedimentation except at Duffey Lake (Table 2). The strongest correlations are for basins (Cheakamus and Glacier) that are closest to Blue Glacier; the stronger relation may reflect greater similarities in long-term climate.

We developed a multiple regression model to predict the common sediment signal (PCvarve) based on interdecadal changes in glacier extent and the frequency of flooding. A multiple-regression model explains 60% of the variance in PCvarves using the Lillooet River Q_{max} record and the Blue Glacier time series (Table 2) as independent variables. Randomly distributed residuals that are uncorrelated in time indicate adequacy of the regression model.

Discussion

Our stream and lake monitoring indicates that over half of the annual suspended sediment load is delivered to lakes of this study during large runoff events (Gilbert, 1975; Menounos, 2002, Menounos *et al.*, in press). The relation between large floods and rapid lake sedimentation is also supported by documentary sources prior to the period of instrumentation. Microstratigraphic analysis of the 1906 varve, for example, reveals two normally graded laminae, that are most apparent in cores recovered from Cheakamus Lake. The upper lamina (silt and clay cap) conformably overlies the lower lamina, which lacks a clay cap. This structure is interpreted to record two closely spaced floods with little time for sedimentation of clay after the first event. Newspaper records for 1906 describe regional damage and fatalities caused by two intense rainstorms in September of that year (*Vancouver Daily Province*, 1906).

Lake sedimentation is also influenced by interannual to interdecadal changes in glacier runoff (Desloges and Gilbert, 1994; Leemann and Niessen, 1994; Leonard, 1997). Glacier melt in the US Pacific Northwest and western Canada is favoured by light snowpacks or unusually warm summers (Hodge *et al.*, 1998; Bitz and Battisti, 1999). Warm and dry conditions in the study area between 1934 and 1946 caused rapid retreat of glaciers from extended 'Little Ice Age' positions (Menounos *et al.*, in press). Changes in proglacial sediment availability in the Cheakamus, Glacier, Green and Lillooet lake basins, caused by melting of dirty ice and exposure of fine-grained sediments in glacier forefields, are the most likely factors for the positive residuals between varve thickness and Q_{max} events. Although glacier retreat would be expected to increase late summer runoff, the change in discharge in these drainage basins was relatively minor.

Varves deposited between 1934 and 1946 are easily identifiable in the lakes of this study by their above-average thickness and microlaminated structure (Figure 2). High sediment concentrations in inflowing proglacial streams, together with well-developed thermal lake stratification, would favour microlaminated varves. Episodic underflows are the most likely source of the microlaminae in cores obtained from deep locations subject to turbidity currents. Delivery of sediments in the epi- and metalimnion during sediment-charged inflow events may explain microlaminae at shallow (10–15 m) locations sheltered from turbidity currents. Whatever the exact mode of formation, the microlaminated structure of varves deposited between 1934 and 1946 indicates variable inflow of fine-grained sediments to all of the lakes.

Our approach has elucidated the major hydro-meteorological and geomorphic controls of lake sedimentation in the southern Coast Mountains. Despite major differences in basin and lake morphometry (Table 1), significant concordance is observed in the records. This agreement implies that clastic sedimentation is controlled by environmental factors common to the lake basins. Our analysis indicates that interannual to interdecadal patterns in regional clastic sedimentation in the study area can be explained by the timing and magnitude of large floods and the magnitude of glacier recession, in agreement with previous studies (Gilbert, 1975; Leonard, 1985; Smith and Ashley, 1985; Desloges and Gilbert, 1994; Leemann and Niessen, 1994; Sander *et al.*, 2002). Our findings also highlight the importance of watershed location, elevation and the seasonal timing of floods in controlling sediment yield. Elevation and timing of floods are important because these attributes control precipitation type, as well as snow-cover extent and duration. The steep environmental gradient across this portion of the Coast Mountains has likely amplified the significance of these secondary controls.

In contrast to this study, a recent study of a proglacial lake in Alaska did not document high sedimentation rates following rapid glacier retreat (Loso *et al.*, 2004). Geomorphic factors responsible for the difference may include differences in the efficiency of fine-sediment production by glacier abrasion, sediment routing of fines following ice retreat and reworking of deposits in glacier forefields. Future studies that compare interannual to decadal changes in ice cover and down-valley lake sedimentation over a common time interval may clarify the relation between glacier recession and proglacial lake sedimentation.

Analysis of the common signal from the varve network guarantees that basin-specific trends in lake sedimentation are not erroneously attributed to climate change. Nonclimatic trends may arise from a variety of factors, including colluvial processes, differing glacier response times, catastrophic release of sediment from glaciers during outburst floods (Gilbert and Shaw, 1981), changes in fluvial sediment storage and human-induced land-use change. The anomalously thick varves of 1924 and 1927 in Duffey Lake are examples of basin-specific events.

Our results indicate a coincident change in the nature of flooding and lake sedimentation in the study area after 1980 (Figures 4 and 5). The change occurs just after the well-known regime shift of the North Pacific climate system in 1976 (Ebbesmeyer *et al.*, 1991; Mantua and Hare, 2002). Long-term meteorological records required for detailed analysis of these changes are lacking for the study area. An increase in precipitation intensity and a rise in freezing level during autumn storms are the most likely mechanisms driving the post-1980 changes.

Despite the common signal extracted from the varve network, there remains much unexplained variance in inter- and intralake sedimentation (Table 2). Such complexity is common in proglacial environments (Leemann and Niessen, 1994; Ohlendorf *et al.*, 1997) and likely arises, in part, from seasonal hysteresis effects on fine sediment transfers. For example, snow cover can introduce complexities into the relations between meteorological events and sediment erosion and transport (Caine, 1995). The 1940 and 1984 events occurred in autumn when snow at higher elevations may have blanketed proglacial sediment sources, limiting sediment availability. The Duffey Lake watershed is higher than the watersheds of the other study lakes, thus it may have snowed rather than rained there during the 1991 storm, which would explain the thin varve in Duffey Lake. In addition, the continental location of the watershed would have caused smaller precipitation totals for the 1991 event. Similarly, differing glacier response times, temporary storage of fine-grained sediments on floodplains and basin-specific stochastic events such as landslides may explain differences in early twentieth-century sedimentation rates observed in the varve records (Figure 4).

The lack of long, high-quality streamflow records for watersheds east of Lillooet River makes detailed interpretations of the Duffey Lake varve record difficult. Reasons for the poor relation between varve thickness and nival runoff may include complexities between lake inflow and central lake sedimentation or lack of suitable hydro-meterological records west of Lillooet River (Figure 1). For example, although a strong relation was observed between maximum hourly inflow and sediment flux to the lake floor near the delta, the relation is poorer in the deepest portion of the lake where continuously laminated sediments exist (Menounos, 2002) and where sediment cores were recovered for this study. In addition, steep hillslopes bordering Duffey Lake deliver sediments by debris flows and snow avalanches, and may complicate any catchment-wide hydro-climatic signal. Because only two cores span this interval, it is possible that erosion or varve identification errors have compromised the accuracy of the Duffey Lake varve chronology prior to 1927. This suspicion is supported by the substantial increase in the correlation between varve thickness and Lillooet $Q_{\max}$ during spring for the period 1928–1999 (Table 2).

Duffey Lake is also the most continental basin of this study, consequently climatic events responsible for lake sedimentation are expected to differ from hydro-climatic controls in the more maritime watersheds. Furthermore, the Duffey Lake catchment has the smallest fraction of contemporary ice cover (2%), thus the common signal attributed to changes in ice cover would be lowest for this watershed. Collection of varved sediments from continental basins near Duffey Lake might clarify the relation between lake sedimentation and hydro-climatic events in continental environments of the southern Coast Mountains.

Conclusions

The benefits of regional and hemispheric networks have been demonstrated in both tree-ring (Cook *et al.*, 1999) and multiproxy (Mann *et al.*, 1998) studies of past climate change. A recent study incorporating low-resolution lake sediment records has shown the value of using sediment records from several lakes to infer hydro-climatic events at the regional scale (Noren *et al.*, 2002). The advantages afforded by a lake network become clear in the case of annually resolvable lake sediments. Our approach provides new, fruitful avenues for environmental research including: (a) reconstructing the spatial extent and influence of hydro-climatic events; (b) extracting a common, regional signal to increase the signal-to-noise ratio of lake sediment records; (c) reducing varve counting errors in long chronologies using marker varves produced by floods or years characterized by rapid glacier retreat; and (d) identifying basin-specific stochastic events that may be assigned hydro-climatic significance. Our analysis implicates glaciers and floods as primary environmental controls of lake sedimentation in proglacial lakes of the southern Coast Mountains. An abrupt increase in interannual sedimentation rates after 1980 is recorded in four of the five lakes of this study. The increase coincides with an increase in autumn flooding and a major re-organization of the North Pacific climate system. Analyses of longer records from these lake basins are in progress to improve our understanding of late Holocene environmental change in the southern Coast Mountains.

Acknowledgements

Financial support for this project was provided by the Natural Science Engineering Research Council of Canada and the Geological Society of America. We thank BC Parks for access and logistical support. This study and manuscript benefited substantially from discussions with M. Church, K. Grimm, S. Lamoureux, D. Moore and T. Pedersen. ^{137}Cs activity was determined by Dr S. Sonoc. DEM data were provided by the province of British Columbia. We thank Environment Canada for use of the hydro-meteorological data for this study. L. Clague, J. Koch, K. Menounos, T. Newton, D. Ray, E. Schiefer and J. Venditti helped in the field. E. Leonard, A. Ojala, P. Sanborn and A. Wolfe contributed substantially to the clarity of the manuscript.

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