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Dendrochronological Mass Balance Reconstruction, Strathcona Provincial Park, Vancouver Island, British Columbia, Canada

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Abstract

A long-term proxy record of glacier mass balance was developed for Colonel Foster and Septimus glaciers on Vancouver Island, British Columbia, Canada. This was accomplished by analyzing the radial growth characteristics of climatically-sensitive mountain hemlock trees (*Tsuga mertensiana*), and by comparing this response with mass balance records from four glaciers in the Pacific Northwest. A strong (negative) relationship between the two records for the period 1966–1994 provides the basis for a mass balance reconstruction extending back to 1600. The reconstruction is in general agreement with information derived from dated moraine sequences at the two glaciers on Vancouver Island, and it has potential applicability to glaciers in adjacent areas of coastal Pacific North America. Our results highlight the likely influence of the Pacific Decadal Oscillation (PDO) on glacier dynamics during the mid- to late-Little Ice Age (LIA) and provide the groundwork for long-term glaciohydrologic studies.

Introduction

Temperate mountain glaciers are highly sensitive to climatic forcing and conventional mass balance surveys provide a way to directly evaluate their glaciological response to changing climates (Yarnal, 1984; Brugman, 1992; Haeberli and Beniston, 1998; Luckman and Villalba, 2001). In general, larger valley glaciers and icefields respond in a delayed and "smoothed" manner to changing climates, while the mass balance response of the smaller cirque glaciers to changing climates is relatively rapid (Porter, 1981; Burbank, 1982; Luckman, 1986; Lawby et al., 1995; Smith et al., 1995; Haeberli and Beniston, 1998; Oerlemans, 1998, Kovenen, 2003). Provided their mass balance records can be reconstructed (cf. Moore and Demuth, 2001), the relatively rapid response of cirque glaciers has the potential to provide insight into the glaciological impact of decadal- or longer-scale climate variability.

Despite their obvious value, adequate mass balance records are limited to less than 40 glaciers worldwide (Dyurgerov and Meier, 1997). The brevity of these records, and the fact that few surveys have been undertaken at small cirque glaciers, limits their use in studying glacier-climate interactions prior to the mid-1900s in many settings. As a result, other parameters such as changes in glacier volume, area, and length, have been used in place of mass balance measurements to determine the response of cirque glaciers to historical climate change (Oerlemans, 1986, 1994; Stroeven et al., 1989; Zuo and Oerlemans, 1997).

The intent of our research was to develop a long-term proxy mass balance record for two isolated cirque glaciers located on Vancouver Island, Canada. Following LaMarche and Fritts (1971), who reported that annual radial growth variations in high elevation trees in the Austrian Alps were significantly correlated to local glacier activity, we sought to reconstruct the mass balance histories of these glaciers by comparison to the radial growth response of trees found growing in close proximity to the two sites. Related research by Villalba et al. (1990), Bhattacharyya and Yadav (1996), and Nicolussi and Patzelt (1996) provided evidence that this approach could successfully be used to develop proxy insights into such parameters as mass balance, oscillations in glacier length, and periods of glacial advance (cf., Matthews, 1977; Karlén, 1984; Scuderi, 1987; Serebryanny and Solomina, 1989; Kaiser, 1993; Luckman, 1993).

We focussed our investigations on mountain hemlock trees (*Tsuga mertensiana*), because their radial growth is highly sensitive to summer temperature and winter precipitation (Heikkinen, 1985; Graumlich and Brubaker, 1986; Smith and Laroque, 1998; Gedalof and Smith, 2001a; Peterson and Peterson, 2001). Although the relationship between climate and glacier mass balance is more complex, summer temperature and winter precipitation are essentially the same variables that govern glacier mass balance fluctuations in this region (Tangborn, 1980; Burbank, 1982; Letréguilly, 1988; Brugman, 1992; McClung and Armstrong, 1993; Moore and McKendry, 1996; Bitz and Battisti, 1999). Climate conditions that promote above average radial growth (wide rings) in mountain hemlock trees include relatively warm/dry winters and moderately warm summers, the same conditions that favor glacier ablation (negative mass balance) and retreat (see Bray and Struik, 1963). Conversely, climate conditions that result in a shortened growing season and below average radial growth in mountain hemlock trees (narrow rings) on Vancouver Island lead to accumulation, positive mass balance conditions, and glacier advance. We therefore hypothesized that a regional proxy mass balance record could be reconstructed from a dendroclimatological interpretation of the annual ring-width growth characteristics of local mountain hemlock trees.

Research Background

Mass balance is defined as the difference between mass input (accumulation) and mass loss (ablation) on a glacier, measured over a particular time interval and expressed in terms of water equivalence (Paterson, 1995). For most glaciers outside the polar regions, winter accumulation (snowfall) and summer ablation (air temperature) are the primary controls on total annual mass gain and loss, respectively (Tangborn, 1980; Letréguilly, 1988; Walters and Meier, 1989; Harper, 1993; McCabe and Fountain, 1995; Hodge et al., 1998). Given that temporal and spatial variations in weather variables such as precipitation and temperature are controlling factors of glacier mass balance, and given that these variables are functions of synoptic-scale circulation patterns, glacier mass balance can be an effective proxy indicator of regional climate change (McCabe and Fountain, 1995; McCabe et al., 2000).

The degree to which the mass balance of an alpine glacier responds to changes in summer temperature and winter precipitation is a function of its location and continentality (Letréguilly and Reynaud, 1989;

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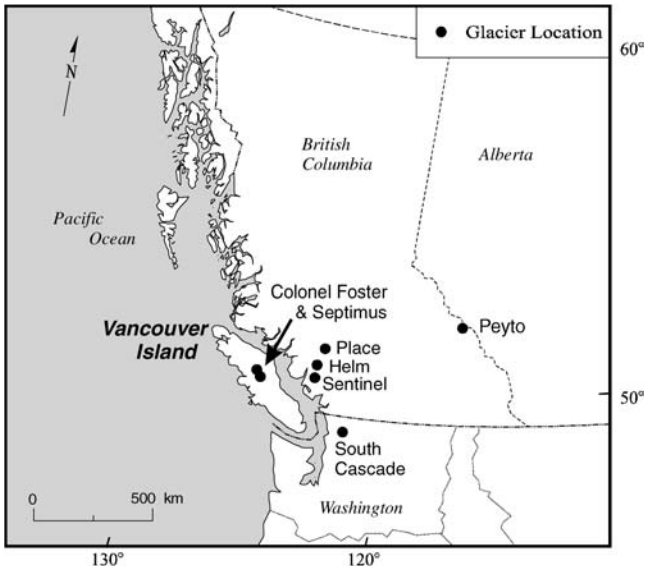

FIGURE 1. Map illustrating maritime and continental glacier locations in Pacific North America.

Oerlemans, 1998). Maritime glaciers in the Pacific Northwest (PNW), such as South Cascade Glacier in Washington State, and Place, Helm, and Sentinel glaciers in the British Columbia Coast Mountains, are highly sensitive to variations in winter precipitation (Fig. 1). However, at more southerly maritime glaciers (i.e., South Cascade) and continental glaciers such as Peyto Glacier in the Canadian Rocky Mountains (Fig. 1), summer temperature plays an increasingly significant role in mass balance (Letréguilly, 1988; Letréguilly and Reynaud, 1989; Walters and Meier, 1989; Brugman, 1992; Demuth and Keller, in press).

Recent glacier-climate studies in the PNW indicate a strong relationship between variations in glacier mass balance and larger scale atmospheric circulation (Yarnal, 1984; Walters and Meier, 1989; McCabe and Fountain, 1995; Moore, 1996; Hodge et al., 1998; Bitz and Battisti, 1999; McCabe et al., 2000). This relationship suggests that a homogeneous glacial response to large-scale climate patterns exists among glaciers in southwestern British Columbia and northwestern Washington State (Letréguilly and Reynaud, 1989; Walters and Meier, 1989; Brugman, 1992; McCabe and Fountain, 1995; Bitz and Battisti, 1999). Mass balance variations have been statistically correlated at distances up to 500 km (Letréguilly, 1988; Letréguilly and Reynaud, 1989, 1990), indicating that a common mass balance signal is applicable to glaciers within this area (Letréguilly and Reynaud, 1989). On the basis of these findings, we assumed that a regional mass balance record would be representative of conditions at Vancouver Island glaciers, for which there are no mass balance records.

Study Site

Field research was conducted in Strathcona Provincial Park (Strathcona PP) on central Vancouver Island, British Columbia, Canada (49°40′N, 125°40′W) (Fig. 1). Strathcona PP straddles the Vancouver Island Ranges and contains the tallest mountains (2134–2228 m a.s.l.) on Vancouver Island. While glaciers are not uncommon at higher elevations in the Park, most are relatively small (Ommaney, 1972) and have experienced significant retreat during the last century. Smith and Laroque (1996) report that Moving Glacier (Fig. 2) has lost more than 95% of its surface area, and retreated almost 1 km since its Little Ice Age (LIA) maximum extent.

Treeline climates in Strathcona PP range from hyper-maritime on the west side of the Vancouver Island Ranges to a drier submaritime climate on the eastern side. The vegetation above 900 m a.s.l. is almost entirely within the Mountain Hemlock (MH) Zone (Kojima and Krajina, 1975; Klinka and Chourmouzis, 2000). The MH Zone is

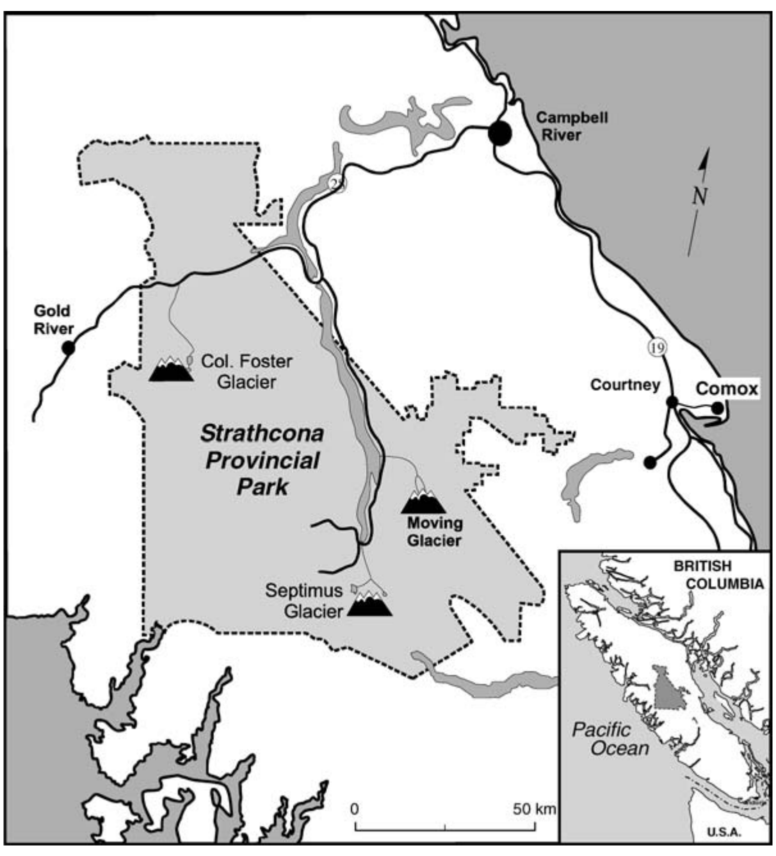

FIGURE 2. Map of Strathcona Provincial Park illustrating locations of study sites and of the Moving Glacier site (Smith and Laroque, 1996).

characterized by short, cool summers and long, cool, and wet winters (Egan, 1997). The growing season is often short, with only 1.7 months of the year having a mean temperature greater than 10.0°C. Mean annual temperature for the MH Zone is 3.0°C, with the coldest month averaging –5.1°C and the warmest month 11.1°C. Annual precipitation can reach up to 5000 mm, with an annual average of 2620 mm (Klinka et al., 1991; Klinka and Chourmouzis, 2000). The majority of winter precipitation (70%) falls as snow, and total accumulations can reach up to 900 cm (Egan, 1997; British Columbia Ministry of Environment Lands and Parks, 2000). Late-lying snow cover is not uncommon in the months of July and August. Soils within the MH Zone remain unfrozen throughout the year (Klinka et al., 1991).

Our fieldwork focussed on two cirque glacier sites where nested moraine complexes place restraints on glacier response to mass balance variations during the LIA (see Burbank, 1982): Colonel Foster Glacier and Septimus Glacier (unofficial names) (Fig. 2). The moraine chronosequences at both sites were derived through the application of lichenometric, dendrochronologic, and dendroglaciological research methodologies; and the results of those investigations are more fully reported in Lewis and Smith (2004). Surface dates are considered to have an error range of ±10 yr given the brevity of the ecesis intervals for both the lichen and the trees used in dating the moraines (Lewis, 2001). All dates presented are in years AD unless specified.

Colonel Foster Glacier is located in a northeast-facing cirque at the base of a steep headwall below the summit of Mount Colonel Foster in northern Strathcona PP (49°46′N, 125°51′W). Colonel Foster Glacier is presently 0.35 km^2 in area and calves into Iceberg Lake (unofficial name) at 980 m a.s l. A nested moraine complex consisting of eight terminal and recessional moraines is located on the north side of the lake, 200 m from the present glacier terminus. Four main intervals of LIA glacier activity were documented: an advance prior to 1396 associated with the deposition of the outer suite of three moraines, which also demarcate the greatest down-valley extent of the glacier; a second episode of terminal and recessional moraine formation following a late 1600s advance; a 19th century re-advance resulting in the deposition of a terminal moraine prior to 1898; and a minor re-advance or stillstand between 1926 and 1935 (Lewis, 2001; Lewis and Smith, 2004).

Septimus Glacier is located on the northern flank of Mount Septimus near the southern boundary of Strathcona PP (49°29′N, 125°32′W). Situated in a northwest-facing cirque at 1350 m, Septimus Glacier has a present area of ca. 0.08 km^2. A suite of four nested moraines is located immediately above a prograding delta on the southeast shore of Cream Lake, at 1261 m a.s.l. Three mid- to late-LIA episodes of glacier activity were documented at Septimus Glacier: a mid-LIA advance that ended prior to the deposition of the terminal moraine dated to 1706; a 19th century re-advance resulting in the deposition of a terminal moraine prior to 1898, and a minor re-advance or stillstand culminating prior to 1934 (Lewis, 2001; Lewis and Smith, 2004).

The moraine records at Colonel Foster and Septimus glaciers indicate that glacier response to climate conditions during the LIA was generally synchronous in Strathcona PP. Both glaciers appear to have responded similarly to three major climatic events: the first in the late 1600s to early 1700s, a second in the late 1800s, and a third event in the mid 1930s.

Methodology

TREE-RING ANALYSIS

For our approach to be robust, we first had to establish a quantitative relationship between standardized climate parameters (average monthly air temperature and monthly precipitation totals) and the ring-width variations of mature mountain hemlock forests located adjacent to each study site. Tree-ring data was collected by extracting two increment core samples from each tree at breast height, approximately 180° apart. Samples were transported in plastic straws to the University of Victoria Tree-Ring Laboratory where they were prepared, counted, and measured. Each core sample was prepared according to standard dendrochronological procedures (Stokes and Smiley, 1996).

After air-drying, each core was glued into a grooved board, labelled, and prepared for analysis by sanding with progressively finer grades of sand paper (100 to 800 grit). Cores were then hand-polished to enhance the definition and contrast of the annual tree-ring boundaries. All samples were counted a minimum of three times using digital and manual measuring systems. First, samples were converted to high-resolution digital images (800 to 2000 dpi) with an AGFA Duoscan scanner, and annual rings were counted and measured to the nearest ±0.01 mm using the WinDENDRO (version 6.4a) digital tree-ring image processing system (Guay et al., 1992). Second, annual ring counts were repeated on a Velmex-type measuring stage using a Wild M3B stereomicroscope, until the total number of rings counted could be replicated a minimum of three times. Any significant anomalies in the annual rings, such as scars or distinctly wide or narrow rings, were recorded, as were the year(s) in which they occurred.

Each time series of measured ring-widths was visually crossdated to a series of narrow marker rings. The crossdated time series were then quality checked using the International Tree-Ring Data Bank (ITRDB) software program COFECHA to create a master ring-width chronology for each site (Holmes, 1983, 1999). Any erroneous segments were then re-measured or deleted from the dataset until a statistically significant master chronology was produced (Holmes, 1983, 1999).

The ITRDB program ARSTAN (Cook and Holmes, 1986, 1988) was used to detrend and standardize each ring-width time series into a stationary dimensionless index. Each series of ring-widths was evaluated individually, and a combination of two user-defined detrending curves was applied to maximize the signal to noise ratio. All cross-dated, detrended indices were averaged into site chronologies using a bi-weight robust mean (Cook and Holmes, 1986, 1988).

The software program PRECON 5.17c (Fritts, 1976, 1998; Fritts and Wu, 1986; Fritts et al., 1991) was used to identify relationships between the standardized growth index (regional master chronology) and records of monthly average temperature and monthly total precipitation. Climate data (1945–1994) used in this analysis is from the Meteorological Service of Canada (MSC) meteorological Station A at Comox, B.C. (49°43′N, 124°54′W, 24 m a.s.l.), ca. 35 km east of Strathcona PP (Fig. 2).

PRECON recalculates matrices of climatic data using principal components analysis (PCA) to create new orthogonalized variables that maximize the variance in the climatic factors influencing tree growth (Fritts et al., 1971; Blasing et al., 1984). The orthogonalized variables were entered into a stepwise multiple regression procedure, where the regression coefficients were multiplied by the principal components of climate to obtain a new set of regression coefficients related to the original monthly precipitation and temperature variables. These new coefficients express the relative importance of each monthly climate variable to the tree-ring chronology (Fritts et al., 1971; Fritts et al., 1991). The output from this analysis is graphically represented as a response function demonstrating the relationship between variations in annual tree growth and the limiting climate variables (Fritts, 1976; Cook and Kairiukstis, 1990).

MASS BALANCE ANALYSIS

Because there are no glacier mass balance records on Vancouver Island, a regional mass balance (RMB) record was constructed from the mass balance records of the four nearest glaciers (Table 1; Fig. 1). Mass balance is no longer recorded at Sentinel Glacier (1966–1990) due to its proximity to, and high correlation ($r = 0.90$) with, Helm

TABLE 1

Mass balance records from PNW glaciers used to construct the standardized Regional Mass Balance anomaly record

Glacier	Period used	Location (lat., long.)
Place	1965–1994[a]	50°26′N, 123°36′W
Helm	1975–1994[a]	49°58′N, 123°00′W
Sentinel	1966–1990[b]	49°53′N, 122°59′W
South Cascade	1959–1994[c]	48°22′N, 121°03′W
Regional	1966–1994	

[a] Provided by M. Demuth, GSC, Glaciology Division.

[b] Provided by M. Brugman, NWRI.

[c] Provided by R. Krimmel, USGS, Water Resources.

Glacier (1975–1997). Therefore, for the PCA analysis, the mass balance records for these two glaciers were combined using regression analysis to create a composite record (1966–1994).

To calculate the regional mass balance anomaly record, each observation was first standardized as follows:

$$\mathrm{SMB}_t = \frac{(\mathrm{MB}_t - m)}{s} \qquad (1)$$

where SMB_t is the standardized mass balance anomaly for year t; MB_t is the observed annual net mass balance at year t (in meters of water equivalence [m w.eq.]); and m and s are the mean and standard deviation of the mass balance time series, respectively (in m w.eq.). The SMB records were then averaged using an arithmetic mean into a single regional time series of mass balance departures relative to 1966–1994 mean. The RMB record is restricted to the 1966–1994 interval in order to incorporate the longest possible mass balance record, as well as to coincide with the last full year of growth in the Septimus Glacier tree-ring chronology.

The standardized RMB anomalies were compared with a second mass balance time series in which PCA was applied to the four mass balance datasets to determine the common signal. The correlation between the two records was very strong ($r = 0.99$) for the common interval (1975–1990), indicating that the standardized RMB anomaly record was representative of the common mass balance signal between the four glaciers.

Observations

TREE-RING RELATIONSHIPS

Three mountain hemlock ring-width chronologies were developed in this study: individual site chronologies from the Colonel Foster Glacier and Septimus Glacier sites, and a regional Strathcona PP master chronology consisting of tree-ring series from both sites (Fig. 3). At Colonel Foster Glacier, 44 increment cores were extracted from 22 mountain hemlock trees in a stand located 10 to 50 m north of the moraine complex. At Septimus Glacier, 62 cores from 31 mountain hemlock trees were sampled above the north side of Cream Lake. A subset of these cores that reflect the greatest common signal was retained for the analysis. Because some of the trees sampled respond to external factors in an individual manner, and do not contain a "common" site signal, they were removed from further analysis. Table 2 summarizes the number of cores used to develop the final chronologies, as well as the ring-width chronology statistics.

The high series intercorrelation and mean sensitivity indicate that: (1) mountain hemlock from Strathcona PP are responding homogeneously to environmental forcing; (2) trees from both sites can be combined into a single, regional Strathcona Master Chronology (MC); and, (3) the trees should have good dendroclimatic utility.

Cores contributing to the Strathcona MC span the interval from 1412 to 1998, with at least 50 cores contributing to each of the last 250 yr of the chronology (Fig. 3c). The number of samples contributing to each

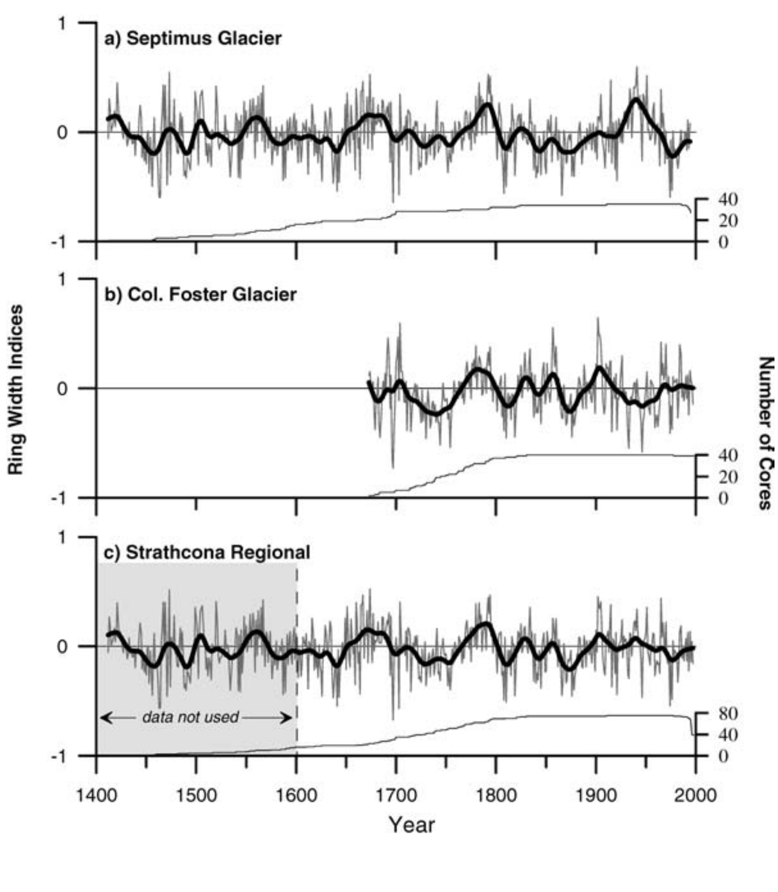

FIGURE 3. Indexed mountain hemlock chronologies for Strathcona PP: A 25-yr smoothing spline (bold line) is fit to the data to emphasize trends. The gray box on the left side of 3c (Strathcona Regional) indicates the cut off date (1600) for usable portion of master ring-width chronology. The sample depth, or number of cores contributing the annual index, is also given for each chronology.

TABLE 2

Summary statistics for Strathcona PP mountain hemlock chronologies

	Colonel foster	Septimus	Strathcona master[a]
Number of trees	20	21	41
Number of cores	40	35	75
Interval (yr)	1673–1998 (326)	1412–1995 (584)	1412–1998 (587)
Mean core length (yrs)	251	359	301
Series Intercorrelation	0.671	0.638	0.618
Mean Sensitivity	0.253	0.268	0.261

[a] Chronology truncated at AD 1600 for MB reconstruction as the common signal among trees prior to this is 1600 is statistically unreliable (Briffa and Jones, 1990).

year decreases progressively to 16 cores at 1600, and to less than 8 cores from 1550 to 1412 (Fig. 3c). Growth trends in the early part of the Strathcona MC (1412 to 1550) are quite variable and likely an artefact of the limited number of samples contributing to the chronology. As a result, this chronology was truncated at 1600, as the subsample signal strength (SSS) values indicated that the common signal between trees prior to 1600 was unreliable (>0.85 acceptable) (Briffa and Jones, 1990).

Significant intervals of reduced growth rates occur from 1600 to 1650, 1690 to 1765, 1800 to 1820, 1835 to 1850s, and 1865 to 1890. Less significant episodes of reduced growth occur in the 20th century: 1915 to 1930 and again in the 1970s. Notable intervals of above average growth occurred in the late 1600s, late 1700s, and early 1900s (Fig. 3c).

The Strathcona MC was examined to determine whether the climate variables responsible for limiting mountain hemlock radial growth were similar to those of other studies in the PNW. Figure 4 shows the growth response of the mountain hemlock chronology to temperature and precipitation data from the MSC Comox A climate station. The figure illustrates the amount of variation in ring-width explained by temperature and precipitation during an 18 month interval, from May of the previous year to October of the growth year. An 18 month growth period was used to capture the annual growth signal, as high-elevation trees are often influenced by growth in the preceding year (Colenutt and Luckman, 1991).

The response function analysis reveals a strong positive response to mean July air temperature of the growing season, and a negative response to November precipitation in the winter preceding growth (Fig. 4). Of the 77% variation in annual radial growth (1945–1994) explained by the climate response function, 51% is attributed to climate in the present year and 26% to growth conditions in the previous year.

Previous studies by Graumlich and Brubaker (1986) and Smith and Laroque (1998) show that the effect of monthly air temperature and precipitation on mountain hemlock radial growth is nonlinear, and

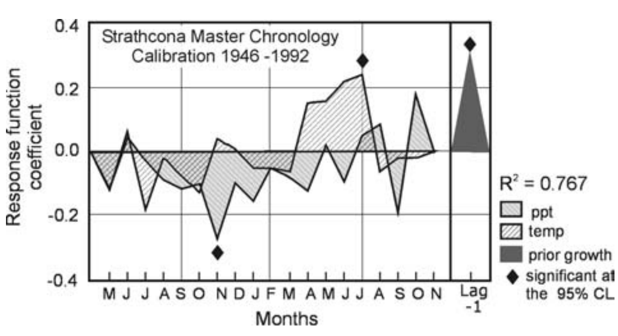

FIGURE 4. Response function analysis output for the Strathcona PP master chronology. 76.7% of the ring-width variation is explained by winter precipitation (November) and summer temperature (July).

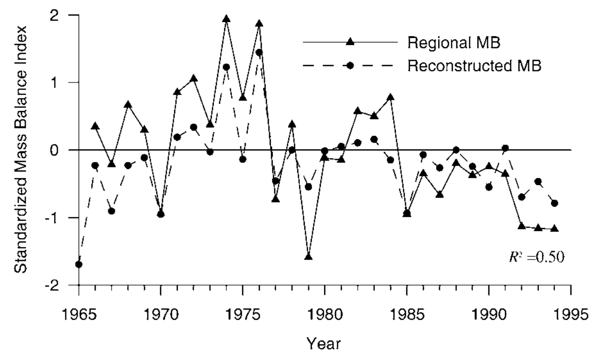

FIGURE 5. Reconstructed and historic standardized RMB anomalies for the period 1966 to 1994. Solid line is the RMB record and dashed line is the reconstructed mass balance record.

that annual spring snowpack depths are significant in governing growth (Brubaker, 1986; Smith and Laroque, 1998; Gedalof and Smith, 2001a; Peterson and Peterson, 2001). This inherent nonlinear relationship indicates that below average radial growth is a response to a combination of both low summer air temperatures and increased winter precipitation (i.e., spring snowpack depth). Conversely, enhanced radial growth is a consequence of higher summer temperatures and drier winter conditions.

RADIAL GROWTH AND GLACIER MASS BALANCE RELATIONSHIPS

Correlation analysis between the Strathcona MC and the standardized RMB anomaly record (1966–1994) shows a moderately strong, negative correlation ($r = -0.71$ at the 99% confidence level). A simple linear regression of these datasets indicates that an acceptable amount of mass balance variation ($r^2 = 0.50$) is explained by variations in mountain hemlock ring-widths (Fig. 5). Based on the reasonable reproduction of the measured mass balance record, the Strathcona MC was used to develop a proxy mass balance record back to 1600 (Fig. 6) using the following equation:

$$\mathrm{MBA} = -4.37(SRW) + 3.74 \qquad (2)$$

where MBA is the standardized mass balance anomaly and *SRW* is the standardized mountain hemlock ring-width index. Due to the brevity of the mass balance record, and the effect of a significant change in the climate regime (1976 Pacific Decadal Oscillation (PDO) step—see Discussion) in the middle of the data, the dataset was not divided into separate calibration and verification subsets. The 20-yr spline fit to the proxy data highlights intervals of positive mass balance anomalies occurring from 1622 to 1668, 1696 to 1702, 1721 to 1762, 1802 to

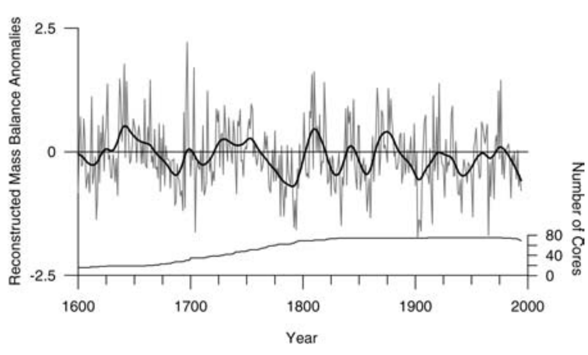

FIGURE 6. Reconstructed mass balance anomalies from 1600 to 1994. Narrow line is annual values and bold line is a 25-yr spline to emphasize trends.

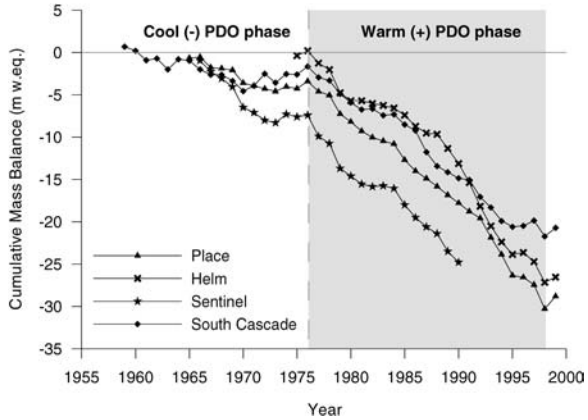

FIGURE 7. Cumulative mass balance for four PNW glaciers (1966–1999), and the effect of the PDO. The gray area on the right side of the graph highlights the 1976 shift to a positive PDO phase.

1820, 1839 to 1847, and 1864 to 1886, including a minor positive anomaly in the mid 1970s (Fig. 6).

Discussion

To assess the accuracy and meaning of our mass balance reconstruction, we compared it with the dated moraine chronologies from Septimus and Colonel Foster glaciers. The deposition of two early 1700s moraines (1706, 1708) follows a short, but strong 12-yr positive trend in mass balance anomalies (1687–1699). Two moraines dated to 1898 follow a 20-yr interval of increasingly positive mass balance anomalies (1856–1875), and a subsequent positive mass balance anomaly interval (1876–1885), by 13 yr. Finally, a pair of recessional moraines constructed in the 1930s (1934, 1935) follow a 20-yr trend of increasingly positive mass-balance anomalies that terminated in the early- to mid-1920s. Although the local LIA moraine chronology is in general agreement with our mass balance reconstruction, the lack of a direct correlation may be attributed to several factors.

First is the systematic error inherent in long time-series of conventional surface mass balance measurements due to surface area changes. Mass balance measurements are often taken at select points and integrated over the surface of the glacier. Unless detailed surface maps are created for each year, the resulting annual errors will be compounded when calculating a cumulative balance series (Elsberg et al., 2001). The second factor is the complex response of glaciers to climatic forcing. Because conventional mass balance measurements incorporate both climatic forcing and surface area change, the relationship between mass balance and climate is not a simple linear one, just as the response of mountain hemlock trees in this region to air temperature and precipitation is also nonlinear.

Despite these inherent errors, our proxy mass balance record does appear to provide a good approximation of glaciological conditions at the study glaciers over the past 400 yr. In addition, given the short response time of these and other glaciers in the PNW (5 to 10 yr; Kovanen, 2003), we believe that they are responding to decadal to quasi-decadal variability in a similar but inverse manner to the local mountain hemlock trees. This relatively short response time suggests that these glaciers may be only mildly impacted by persistent climate forcing at longer time-scales.

Significant differences in large-scale (i.e., synoptic) circulation patterns during the mass balance calibration period and the LIA may also impact the proxy mass balance record. The reconstructed mass balance record shown in Figure 6 was developed relative to the 1966–1994 average net mass balance, an interval that includes 16 of the warmest and 14 of the driest years since nationwide records began in 1948. The distinct climate shift of 1976 that resulted in higher air temperatures, reduced winter precipitation (snow), and an overall reduction in winter storminess, is manifest in a change to strongly negative mass balance conditions at glaciers throughout southern British Columbia and northwestern Washington State (Fig. 7) (Walters and Meier, 1989; McCabe and Fountain, 1995; McCabe and Legates, 1995; Mantua et al., 1997; Cayan et al., 1998; Hodge et al., 1998; Bitz and Battisti, 1999; McCabe et al., 2000; Kovanen, 2003). Similar patterns in climate variability have been recorded at least twice in the last century, and are considered symptomatic of the PDO (Hare, 1996; Mantua et al., 1997; Gedalof and Smith, 2001b; Laroque and Smith, 2001).

TABLE 3

Correlations between reconstructed MB and reconstructed PDO records

	PDO (G&S)	PDO (L)	MB (reconstruction)
PDO (G&S)	1	—	—
PDO (L)	0.52	1	—
MB (reconstruction)	−0.44	−0.65	1

All p-values are 0.00 at the 99% confidence interval.

The PDO is a long-lived El Niño–like pattern of climate variability characterized by alternating regimes of higher and lower sea surface temperatures in the North Pacific (Zhang et al., 1997). The positive phase of the PDO is characterized by an enhanced Aleutian Low and reduced storminess in the PNW. Storm tracks tend to be diverted away from the PNW toward Alaska, resulting in warmer, drier winters with below average snow packs and negative winter glacier mass balances. Conversely, the negative phase of the PDO is associated with a diminished Aleutian Low and increased winter storminess in the PNW, as storm tracks are diverted away from Alaska, resulting in lower air temperatures, increased precipitation, and greater snow pack depths in the PNW.

Recent mass balance climate studies have shown that interdecadal climate variability associated with the PDO is negatively correlated with the net winter balance of maritime glaciers in the PNW, accounting for 56 to 60% of winter mass balance variability (McCabe and Fountain, 1995; Bitz and Battisti, 1999; McCabe et al., 2000). The significant relationship between the PDO and winter mass balance of PNW glaciers is a result of greater variability in winter atmospheric circulation compared to summer circulation patterns, as well as the high sensitivity of maritime glaciers to changes in synoptic-scale atmospheric circulation (i.e., winter storminess). If the majority of the calibration period for our proxy record falls within one phase of the PDO (i.e., positive/warm phase), reconstructed mass balance anomalies associated with the opposite phase (cold phase) will likely be weakened as a result of significantly different climate conditions being used for calibration and (or) verification.

Our proxy mass balance record (1600–1994) correlates well with reconstructed PNW PDO indices of Gedalof and Smith (2001b) and Laroque and Smith (2001) (Table 3). The Gedalof and Smith (2001b) PDO index (PDOI) is derived from mountain hemlock chronologies from Alaska to California, whereas the Laroque and Smith (2001) PDOI is derived from mountain hemlock and yellow-cedar tree-ring chronologies from Vancouver Island (Laroque, 2002). Figure 8 illustrates the comparison of the reconstructed Strathcona PP mass balance record with the reconstructed mean spring (March–May) PDOI of Laroque (2002) for the interval 1600 to 1994. Intervals of negative PDO (cool/wet) phases correspond well with intervals of positive mass balance anomalies, and also precede the three major moraine-depositing episodes in Strathcona PP (ca. 1700, 1898, and 1935). Positive PDO (warm/dry) phases also show a good correspondence with periods of negative mass

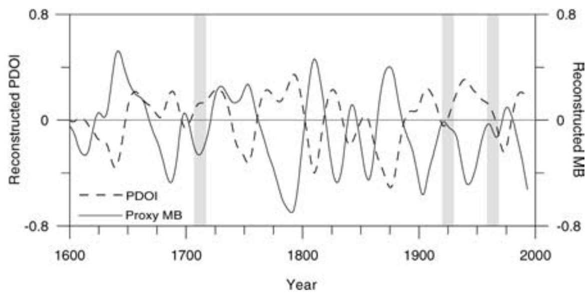

FIGURE 8. Relationship between reconstructed mass balance anomalies (1600–1994), moraine deposition events, and mean spring (March–May) PDO Index. Mass balance anomalies (solid line) and the PDO Index (dashed line: Laroque and Smith, 2001) are represented by a 25-yr cubic spline to emphasize long-term trend. Gray vertical bars represent synchronous 1708, 1898, and 1935 moraine deposition events recorded at Septimus and Colonel Foster glaciers (Lewis, 2001).

balance anomalies. While there are intervals where the connection between the two records weakens (i.e., late 1600s prior to stabilization of the 1700 moraine), overall there is a good relationship between the PDO and our proxy mass balance record.

Conclusions

Our investigations confirm the existence of a marked, but inverse, relationship between the radial growth of mountain hemlock trees and glacier mass balances on Vancouver Island, British Columbia. On the basis of this finding, we developed a proxy record of glacier mass balance anomalies that extends from 1994 back to 1600, and has potential applicability to glaciers in adjacent areas of coastal Pacific North America. Our results highlight the likely influence of the PDO on glacier dynamics during the late-LIA and provide the groundwork for long-term glaciohydrologic studies.

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