Abstract: The intention of this research was to explore whether dendroclimatological relationships could be used to reconstruct long-term proxy records of ‘Little Ice Age’ glacier mass balance changes in the southern Coast Mountains of British Columbia. Tree-ring width chronologies from the Mt Waddington area were used in concert with historical glacier records to construct models spanning the past 450 years. The approach was to build models that were based on derived relationships between tree-ring growth and glacier mass balance: (1) warmer temperatures in the summer positively influence tree growth but are detrimental to glacier health; (2) colder temperatures during the winter and deeper snowpack have a negative impact on tree growth, whereas they are related to greater accumulation on the glacier during the winter season. Stepwise regression analyses were applied to tree-ring chronologies to predict glacier mass balance at local and regional scales. The models of net annual balance for the region (regional data set) show that periods of positive mass balance occurred in the AD 1750s, 1820s to 1830s and 1970s. Peaks of winter balance correspond closely to these periods, showing a sharp drop in winter mass balance towards the end of the nineteenth century. Wavelet analyses suggest that glacial mass balance regimes in the region respond synchronously to Pacific Ocean circulation systems such as the El Niño Southern Oscillation and the Pacific Decadal Oscillation.

Key words: Tree-ring analysis, dendrochronology, dendroglaciology, British Columbia Coast Mountains, glacier mass balance modelling, ‘Little Ice Age’, Canada.

Introduction

The synchronous response of glaciers in coastal northwestern North America to historical climate changes suggests their mass balance regimes are broadly comparable (Luckman and Villalba, 2001). Examined in detail, however, contemporary glacier mass balance data from western North America show that these findings greatly simplify the complex glacier–climate relationships that prevail within this region (Hodge et al., 1998). For example, whereas many glaciers in southern British Columbia and Washington state have experienced a half-century or more of repeated negative net mass balance conditions, Sentinel and Blue glaciers in the same region have experienced generally positive regimes over the same period (Walters and Meier, 1989; Conway et al., 1999; Larocque and Smith, 2003). Furthermore, prior assessment of the mass balance regime of three Alaskan glaciers indicates their behaviour commonly diverges as a result of altered ocean–atmosphere circulation patterns (McCabe and Fountain, 1995; Hodge et al., 1998) or to surging processes independent of climatic change (Barclay et al., 2001).

Glacier response to climate change is commonly benchmarked by dating moraines that are formed as glaciers retreat from advanced positions reached during or after a positive mass balance episode (Johannesson et al., 1989b). Glacier sensitivity to climate is, however, more precisely assessed by changes in ice volume that are transferred to the ice terminus through complex ice flow processes (Meier, 1965). Because ice terminus response to mass balance fluctuations is delayed, building models of glacier mass balance based on available instrumental records allows for a more detailed history of past climate change, providing insights into the evolution of future atmospheric and glacial systems.

Tree-growth patterns have been used to reconstruct glacier behaviour and mass balance with encouraging results (Matthews, 1977; Nicolussi, 1994; Nicolussi and Patzelt, 10.1191/0959683605hl848rp
1996; Lewis, 2001; Watson and Luckman, 2004). Because winter precipitation and summer temperatures have an influence on both tree growth and glacier mass balance, the development of an inductive model of proxy mass balance fluctuations through the ‘Little Ice Age’ (LIA) climatic episode using regression analysis is possible (Karlén, 1984; Raper et al., 1996).

The purpose of this paper is to use dendroclimatological relationships inherent within the radial growth chronologies of living conifers to construct robust proxy records of LIA glacier mass balance changes within the Mt Waddington area of the British Columbia Coast Mountains, Canada. We expect that this research will lead to a better understanding of the magnitude of climatic changes within the last millennium, particularly those recorded by corresponding changes in glacial mass balance. Given that glaciers in this region appear responsive to climatic changes recorded during the twentieth century, a clearer understanding of these changes is critical for forecasting the impacts of future climatic fluctuations.

**Study site**

The Mt Waddington area is located within the central Coast Mountains of British Columbia, Canada (Figure 1). Some of the highest peaks in British Columbia and largest glaciers in the southwestern cordillera are found in this area (Clarke, 2002). Glaciers located along the windward maritime slopes of the Coast Mountains experience annual air temperatures that average 7.9 °C and precipitation totals that annually average greater than 1677 mm at low elevation (normals 1961–90; Bella Coola, 52°22’N–126°41’W, 18 m a.s.l.). The climate of glaciers located adjacent to the Interior Plateau is more continental in character, with average annual air temperatures ranging from 2.2 °C (normals 1961–90; Big Creek; 51°43’N–123°02’W, 1128 m a.s.l.) to 4.1 °C (normals 1961–90; Williams Lake; 52°11’N–122°03’W, 940 m a.s.l.) and average annual total precipitation falling within the 400–450 mm/yr range at 1000 m elevation (Meteorological Service of Canada, 2002).

![Figure 1: Location of study site and glacier mass balance measurement sites used in our analyses](image)

The LIA behaviour of glaciers within the Mt Waddington area corresponds closely with the emerging chronology of events in the Pacific Northwest (PNW) (Larocque and Smith, 2003; Lewis and Smith, 2004). Whereas maximum LIA glacier terminus positions were dated to AD 1200s, 1400s and 1500s, moraine-building episodes were found to have occurred by AD 620, and in AD 925–933, 1203–26, 1260–75, 1344–62, 1443–58, 1506–24, 1562–75, 1597–21, 1657–60, 1767–84, 1821–37, 1871–1900, 1915–28, and 1942–46. Although synchronicity between periods of glacial activity was common, local factors such as aspect and size were shown to play an important role in individual glacial response.

During the twentieth century, most glaciers in the Mt Waddington area have undergone an extended period of general retreat and downwasting. Whereas a few glaciers continue to maintain terminal positions close to those they held 50 years ago, the majority retreated up valley from 550 m to 2177 m (Tiedemann Glacier). Historical aerial photographs and dated moraines show that immediately prior to 1954 glacier ice fronts were retreating at an average rate of 10.7 m/yr (range 2.7–21.9 m/yr). This rate doubled over the next decade to 21.5 m/yr (range 0–64.6 m/yr), before slowing (0–11.3 m/yr) or advancing between 1965 and 1977. Over the next three years, the pace of ice-front glacier recession increased to average 14.2 m/yr (range 0–40.3 m/yr), subsequently slowing to an average rate of 8.6 (6.3–24.8 m/yr) between 1980 and 1994.

The historical behaviour of glaciers within the study area suggests that the climate of this region has led to mostly negative mass balance conditions over the last 50 years. Mass balance data from Tiedemann (Lat. 51°20’; Long. 125°03’; 1981–85 and 1989–90) and Bench (Lat. 51°26’; Long. 124°55’; 1981–85 and 1988–90) glaciers located within the Mt Waddington area, although limited in length, support this contention. Reduced rates of ice front retreat and glacier advance between 1965–77 and 1980–94 correspond to similar short-lived positive mass balance conditions at other glaciers in Pacific North America.

**Glacier mass balance in Pacific North America**

In this paper, net mass balance (Bn) is defined as the change in glacier mass balance at the end of two consecutive summers, the hydrological year ending on 30 September, in units of water equivalent (mm w.e.; Dyurgerov, 2002). Bn corresponds to the difference between winter (Bw) and summer (Bs) mass balance. Winter mass balance describes the net snow accumulation at the end of the winter season above the previous summer surface. Summer mass balance refers to the sum of the net and the winter mass balance, and corresponds to the total ablation occurring during the summer season.

Glacier mass balance records are, in general, sparse and short term in Pacific North America. Eight glaciers have mass balance measurements that extend back to the 1950s and 1970s (Figure 1; see Dyurgerov, 2002, for more details): three of these are located in Alaska (Wolverine, Gulkana and Lemon glaciers); three are located in the British Columbia Coast Mountains (Sentinel, Helm and Place glaciers); and two are located in Washington State (South Cascade and Blue glaciers). Wolverine Glacier is a low-elevation (400–1700 m asl) south-facing maritime glacier located in the southern-coastal region of Alaska. Gulkana Glacier (1165–2460 m a.s.l.) is located in interior Alaska, where the continental character is distinct from the more maritime Lemon Creek Glacier (470–1512 m a.s.l.) located along the coastal border between the
USA and Canada (Miller and Pelto, 1999). Sentinel Glacier is located on a north-facing slope within the southern Coast Mountains of British Columbia (1660–2105 m a.s.l.; Mokievsyk-Zubok, 1973; Yarnal, 1984). Mass balance measurements at Sentinel Glacier ended in 1989 because of the proximity and high correlation with Helm Glacier (1770–2150 m a.s.l.) located on a nearby northwest-facing slope. Place Glacier (1860–2610 m a.s.l.) is located on the eastern side of the coastal range and is more continental in character than either Sentinel or Helm (Moore and Demuth, 2001). In Washington State, mass balance measurements at north-facing South Cascade Glacier (1630–2140 m a.s.l.) in the North Cascades began in 1957 (Meier, 1965; Tangborn, 1980; Krimmel, 1989, 1999; Hodge et al., 1998). Blue Glacier (1280–2320 m a.s.l.) is a distinctly maritime glacier located on the northeastern slope of the Olympic Mountains (Armstrong, 1989; Spicer, 1989; Conway et al., 1999).

Mass balance data collected at these glaciers show regional synchronicity (Walters and Meier, 1989; Bitz and Battisti, 1999; McCabe et al., 2000), with six of the eight glaciers having experienced generally negative Bn conditions over the period of record (Dyurgerov, 2002). The greatest cumulative volumetric losses occurred within the southern group sites at Helm (−1199 mm w.e.), Place (−867 mm w.e.) and South Cascade (−588 mm w.e.) glaciers. Bn losses at the three Alaskan glaciers are comparatively less (−362 to −221 mm w.e.). By contrast, Sentinel and Blue glaciers both record comparable positive Bn regimes and declining rates of frontal retreat over the measurement period (245 and 313 mm w.e.).

Examination of the historical mass balance regimes shows that significant correlations exist between the southern glaciers, with the strongest relationships existing between Helm and Sentinel glaciers ($r = 0.822$). On the other hand, Gulkana and Wolverine glaciers are characterized by a negative relationship with the southern glaciers, supporting the differential behaviour discussed by McCabe et al. (2000). Lemon Creek Glacier does not correlate significantly with any of the glaciers, suggesting either an individualistic behaviour related to local factors or problems with measurement data.

A principal component analysis of the Bn, Bw and Bs data from this group of glaciers reinforces the findings of previous researchers who noted the behavioural contrasts between the northern and southern glaciers (Walters and Meier, 1989; McCabe and Fountain, 1995; Hodge et al., 1998; McCabe et al., 2000). Our analyses show that the first and most important component of variance is explained at 48.5% mostly by the annual mass balance of southern glaciers. Glaciers from Alaska form the second and third components, the latter being explained mainly by continentality (Gulkana). Both explain, respectively, 19.5 and 12.6% of the variance. Similar results were found for the winter and summer mass balance, with summer ablation on the southern glaciers being strongly negatively correlated to that at the Alaskan glaciers.

**Methodology**

Tree-ring width chronologies of climatically sensitive conifer trees from the Mt Waddington area were used to reconstruct robust proxy mass balance records applicable to the southern British Columbia Coast Mountains. Previous research has shown that the radial growth of high-elevation trees is sensitive to climate and that dendroclimatological analyses have the potential to serve as glacier mass balance proxies (e.g., Bhattacharyya and Yadav, 1996; Nicolussi and Patzelt, 1996).

**Dendrochronological analysis**

Field investigations were undertaken during the summers of 2000 and 2001 in the Mt Waddington area. Fifteen tree-ring chronologies were sampled in adjacent mountain ranges at sites occupying valley slopes close to the ice terminus of glaciers at elevations ranging from 760 to 1860 m a.s.l. (Larocque, 2003). The tree-ring sites were mostly south- and west-facing, representing relatively drier sites and accentuated temperature extremes. Increment core samples were collected from *Pinus albicaulis* Engelmann (white bark pine), *Abies lasiocarpa* [Hoo-ker] Nutall (subalpine fir), *Tsuga mertensiana* (Bongard) Carriere (mountain hemlock), *Pseudotsuga menziesii* (Mirbel) Franco (Douglas-fir) and *Chamaecyparis nootkatensis* (D. Don in Lambert) Spach (yellow-cedar). Two increment cores extracted at breast height (at c. 90°) were collected from at least 20 trees per site.

Samples were returned to the University of Victoria Tree-Ring Laboratory (UVTWL) where they were air dried, glued to slotted wood mounting boards and sanded with progressively finer sand paper to enhance the boundaries between the annual rings. A WinDENDRO™ (Version 6.1b) digital tree-ring image processing and measuring system (Guay et al., 1992) and a Velmelex-type stage were used to measure the annual ring increments (precision: ±0.01 mm).

The tree-ring measurements were visually cross-dated using narrow marker years and were quality checked using the International Tree-Ring Data Bank Library (ITRDBL) software program COFECHA (Holmes, 1999). Verification was based on 50-year dated segments with 25-year lags, significant at a 99% critical level of correlation of 0.320 (Fritts, 1976). Low-frequency variance was removed by filtering with a cubic smoothing spline having a 50% cut-off of 32 years. An autoregressive model was fit to the data to remove any persistence within the smoothed series and a log-transformation was performed in order to produce more equal ring measurements. Segments that were not significantly correlated were remeasured, corrected and/or deleted to account for radial growth anomalies arising from the inclusion of missing or false rings or operator error.

Standardized chronologies were constructed with the ITRDBL program ARSTAN (version 6.04P, 2000) and incorporated a double-detrending approach. First, a negative exponential curve, a linear regression or a horizontal line passing through the mean was used to remove any age-growth trends (Fritts, 1976). Following this, the series were detrended a second time to reduce the impact of abiotic factors on radial growth (e.g., competition and defoliation) with a smoothing spline having a 67% frequency-response cut-off. Both detrending methods are believed to preserve low-frequency climate variability (Fritts, 1976). Both standard (detrended index) and residual (index derived from autoregressive modelling) series were included in further analyses. Standardization is essential in comparative analyses of tree-ring series, as it removes non-climatic trends related to tree growth and stand disturbance (Fritts, 1976; Cook et al., 1995).

**Dendroclimatological analysis**

To examine the contribution of climatic parameters to tree-ring width variance, correlation analyses were undertaken between annual radial growth and historical climate (Environment Canada, 2002) and snow (River Forecast Centre, 2003) data. Standardized tree-ring indices were correlated to monthly climate data and the significant variables ($p \leq 0.05$) were then used to verify any dendroclimatological relationships (Larocque, 2003). The sub-sample signal strength (SSS) values (program ARSTAN) provide a statistical tool useful for
determining the size of a sample needed to capture the theoretical population signal of tree-ring variation. SSS values above 0.80 were used to identify a cut-off year in the chronologies, above which there was sufficient sample robustness to reconstruct a reliable time series (Wigley et al., 1984).

**Glacier mass balance reconstruction**

Our reconstructions rely upon the historical glacier mass balance data presented by Dyurgerov (2002) and two derived regional glacier mass balance indices (principal components and average of mass balance records from southern glaciers). Most of the data used were originally obtained using the stake and snowpit method described by Østrem and Brugman (1991). An exception are the data from Blue Glacier, where the annual mass balance has been estimated by probing the residual snow (1956–86) and using late-season Equilibrium Line Altitude (ELA) (1987–99) in a regression that was developed over the years of direct measurement (Conway et al., 1999).

Correlations between the data series were established, and significant variables were entered into a stepwise multiple regression analysis. Goodness-of-fit of the models was determined using coefficients of correlation and determination, $r$- and $F$-values ($p \leq 0.05$), and analysing the residuals for normality, variance and autocorrelation. Because the entire historical data sets were used for calibration purposes, independent data sets of reconstructed glacier mass balance in the southern Coast Mountains were used for validation from Tangborn (1980), Burbank (1982), Lewis (2001), Moore and Demuth (2001) and Watson and Luckman (2004). Dated LIA moraine-building episodes in the Mt Waddington area (Larocque and Smith, 2003) and wet-cool periods determined from dendroclimatic reconstructions (Larocque, 2003) were compared with our models to provide an additional source of verification.

A wavelet analysis was completed to determine the dominant modes of variability in time within the glacier mass balance reconstructions (Torrence and Compo, 1998; Larocque, 2002; Gray et al., 2003). The analyses were undertaken at the interactive website developed by Torrence and Compo (1998). A Morlet wavelet function with a significance level of 5% was applied using a red-noise process of lag-1 autoregression, as this orthogonal approach allows for increased precision on the periodic scale (Torrence and Compo, 1998). To overcome any time-related errors at the beginning and the end of the series, the extremities were padded with zeros to limit the edge effects.

**Observations**

The dendroclimatological behaviour of the 15 tree-ring chronologies was established by compiling them into species-specific master tree-ring chronologies. In general, the correlation analyses indicate that radial growth within this region is negatively impacted by summer air temperature of the previous growth year, positively influenced by air temperature of the current growing season and negatively related to the seasonal snowpack (Larocque, 2003). The climate variables are essentially the same as those that govern glacier mass balance fluctuations in this region (Tangborn, 1980; Burbank, 1982; Letréguilly and Reynaud, 1989; Brugman, 1992; McClung and Armstrong, 1993; Moore and McKidney, 1996; Bitz and Battisti, 1999). Warm summer air temperatures enhance radial growth but lead to accelerated glacier ablation and negative $B_s$ conditions. Cold winters and deep seasonal snowpack have a negative impact on tree growth (Gedalof and Smith, 2001a) but positively enhance $B_w$ conditions. Discovery of the influence of climate on tree-ring growth in this setting and recognition of the corollary impact on glacier mass balance provides a rationale for constructing proxy mass balance records using a tree-ring based climate-response model.

**Glacier mass balance modelling using tree-ring width series**

Table 1 presents the findings of correlation analyses between the five regional ring-width chronologies and the existent historical mass balance records. Whitebark pine presents the greater number of significant correlations with the different glacier mass balance records, mostly as a consequence of the influence of summer temperature. Mountain hemlock also represents a good predictor-species, likely related to the significant influence of January temperature and spring snowpack on annual growth (Larocque, 2003). Despite the short series included in the PC scores, the highest values of correlation are recorded with the PC1 ($B_n = -0.556$) and 2 ($B_s = -0.811$). Significant inverse relationships exist between radial growth of some tree species and the mass balance

<table>
<thead>
<tr>
<th>Glaciers</th>
<th>Bn</th>
<th>Bw</th>
<th>Bs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>df</td>
<td>wbp</td>
<td>mh</td>
</tr>
<tr>
<td>Helm (n = 23)</td>
<td>–0.660</td>
<td>0.641</td>
<td>0.582</td>
</tr>
<tr>
<td>Place (n = 35)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sentinel (n = 23)</td>
<td>–0.502</td>
<td>0.440</td>
<td></td>
</tr>
<tr>
<td>Blue (n = 41)</td>
<td>–0.522</td>
<td>0.492</td>
<td>0.466</td>
</tr>
<tr>
<td>S.Casc. (n = 43)</td>
<td>–0.527</td>
<td>0.508</td>
<td>0.409</td>
</tr>
<tr>
<td>Galkana (n = 34)</td>
<td>–0.491</td>
<td>0.403</td>
<td>0.436</td>
</tr>
<tr>
<td>Lemon (n = 46)</td>
<td>0.372</td>
<td>0.417</td>
<td>0.445</td>
</tr>
<tr>
<td>Wolve (n = 34)</td>
<td>0.367</td>
<td>0.509</td>
<td>0.358</td>
</tr>
<tr>
<td>Reg. (n = 33)</td>
<td>0.533</td>
<td>0.556</td>
<td></td>
</tr>
<tr>
<td>PC1 (n = 13)</td>
<td>0.811</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC2 (n = 13)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC3 (n = 13)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tree species: df, Douglas-fir; wbp, whitebark pine; mh, mountain hemlock; ye, yellow-cedar; sf, subalpine fir. All correlations are significant at the 95% significance level.
The significant relationships to the 15 local tree-ring chronologies were included within a stepwise regression function that included only the first or second most highly correlated variables for each mass balance series. Analysis of model statistics and evaluation of the residuals indicate that seven have significant predictive power (Table 2). These reconstructions (SSS ≥ 0.80) are shown in Figure 2. Whereas tree rings explain from 78% to 82% of the variance in the proxy records constructed from the principal component models, overall the models explain from 27% (Bw, South Cascade) to 51% (Bn, Regional) of the variance in glacier mass balance recorded at the various sites (Table 2). These findings are similar to those of Lewis (2001) who reconstructed the glacier mass balance regime of glaciers on Vancouver Island using tree-ring width series with explained variances of 50%. Table 3 shows that the models correlate significantly, with correlation coefficients ranging from 0.137 (PC1 Bn and Place Glacier Bw) to 0.961 (PC1 Bn and Bs).

Whereas the regional and PC models are believed to better represent glacier behavior in southern British Columbia and Washington state because of the reduction of variance related to local factors (Lewis, 2001), the development of glacier-specific models is justifiable as: (1) a regional climate signal exists along the Pacific Coast (Gedalof and Smith, 2001a), on Vancouver Island (Laroque, 2002) and in the Mt Waddington area (Laroque, 2003); (2) glacier mass balance measurements from southern locations are significantly correlated between sites and with tree-ring chronologies in the Mt Waddington area; (3) the models are supported by significant statistics and are visually similar; (4) the regional glacier mass balances series consist of a mixed signature, which possibly reduces confidence in the regional chronology: glaciers such as Blue and Sentinel show a positive mass balance over the measurement period, although the others have a negative overall net balance; and (5) the PC series are not highly reliable because of the short series used to calibrate the models.

Periods of positive mass balance based on a ten-year moving average were found in the regional model in the 1750s, 1820s–30s and 1970s (Figure 2). Based on the PC1 net balance model, peaks of score values, which correspond to peaks of positive glacier mass balance in southern glaciers, indicate that most glaciers in this region possibly grew in size at around 1480, 1520, 1700, 1820, 1875 and 1985. We suggest that the periods of positive mass balance derived from the regional data sets are underestimated as the calibration was undertaken on a negative period of glacier mass balance and the series were smoothed (e.g., see original series in Figure 2). Peaks of winter balance were found in 1740s–50s, 1780s, 1810s, c. 1850, 1860–70s, 1890s, c. 1920, 1950s and 1975. A distinct characteristic is the sudden and sharp drop in winter mass balance at the end of the nineteenth century. The summer balance is similar to the net annual balance derived from the PC1 model (r = 0.961, Table 3), both using the same tree-ring chronology. The Blue Glacier model presents some distinct characteristics, as the series includes more positive values and greater variability. We suggest that the calibration based on positive glacier mass balance is responsible for this result. The main periods of positive Bn occurred at Blue Glacier in the 1740s to 1770s, 1850s–70s, 1880s–1900s and 1950s–90s.

**Discussion**

Rigorous verification of our reconstructions is problematic owing to the limited duration of the glacier mass balance time series (maximum 46 years). Although correlation analysis does suggest the relationships are robust and significantly correlated with one another (Table 3), there are insufficient historical data to allow us to partition the time series in half for model calibration and verification of the predicted values.

To overcome the limited availability of instrumental data, we compared our reconstructions with those based on tree-rings presented by Lewis (2001) on Vancouver Island and Watson and Luckman (2004) at Peyto Glacier and those based upon temperature and precipitation models developed by Moore and Demuth (2001) at Place Glacier, Tangborn (1980) at South Cascade Glacier, and Burbank (1982) at Mt Rainier. As shown in Figure 3, the existent proxy records overlap positive mass balance conditions in c. 1700, 1740, 1810–20, 1850, 1875, 1895, 1920, 1930, 1955–70. Periods of positive mass balance were generally found in one or all of our annual balance models (Figure 3) and show significant relationships (r range: 0.227–0.469) to the reconstructed glacier mass balance from Place and South Cascade glaciers (Table 3). They correspond to the most important regionally recognized cooler/wetter periods observed from temperature and snowpack models developed in the Mt Waddington area in early to mid-1700s and mid to late 1800s (Table 4, Laroque, 2003).
Corollary research at 14 glacier forefields in the Mt Waddington area provides a record of moraine construction that spans the LIA (Larocque and Smith, 2003). Comparison of this record with our reconstructions shows positive balance conditions precede all but two of the LIA moraine-building events (1657–60) in the Mt Waddington area (Table 4). The most well-represented periods of advanced ice front positions recognized in Pacific North America, such as mid-1700s, early

Table 3 Correlation between glacier mass balance models

<table>
<thead>
<tr>
<th></th>
<th>Reg. Bn</th>
<th>PC1 Bn</th>
<th>Blue Bn</th>
<th>Reg. Bw</th>
<th>S.Casc. Bw</th>
<th>Place Bw</th>
<th>PC1 Bs</th>
<th>Place*</th>
<th>S. Cascade Bs*</th>
<th>S. Cascade Bw*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reg. Bn</td>
<td>0.400</td>
<td>0.612</td>
<td>0.217</td>
<td>0.179</td>
<td>0.307</td>
<td>0.547</td>
<td>0.231</td>
<td>0.269</td>
<td>0.227</td>
<td></td>
</tr>
<tr>
<td>PC1 Bn</td>
<td>0.399</td>
<td>0.304</td>
<td>0.300</td>
<td>0.137</td>
<td>0.961</td>
<td>0.421</td>
<td>0.401</td>
<td>0.317</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blue Bn</td>
<td>0.494</td>
<td>0.558</td>
<td>0.518</td>
<td>0.550</td>
<td>0.297</td>
<td>0.459</td>
<td>0.459</td>
<td>0.275</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reg. Bw</td>
<td>0.861</td>
<td>0.516</td>
<td>0.310</td>
<td>0.424</td>
<td>0.365</td>
<td>0.282</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S.Casc. Bw</td>
<td>0.476</td>
<td>0.321</td>
<td>0.384</td>
<td>0.358</td>
<td>0.358</td>
<td>0.266</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Place Bw</td>
<td>0.187</td>
<td>0.275</td>
<td>0.469</td>
<td>0.469</td>
<td>0.469</td>
<td>0.278</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC1 Bs</td>
<td>0.406</td>
<td>0.401</td>
<td>0.285</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All correlations are significant at $p \leq 0.05$.

*Moore and Demuth (2001); b Tangborn (1980).
and late 1800s and early to mid-1900s, are likely associated with positive glacier mass balance. Notwithstanding this observation, there is an apparent delay between the termination of positive Bn conditions and the dated moraine-building events of up to 48 years (Table 4). This is similar to the estimate of 42 years calculated for Rae Glacier in the southern Canadian Rocky Mountains (Lawby et al., 1995). The response time reflects differential decade- to century-scale glaciological responses (partly determined by glacier geometry and local conditions) to ongoing environmental changes (Oerlemans, 1989; Johannesson et al., 1989; Lawby et al., 1995) and variable moraine stabilization periods (Meier, 1965).

A wavelet analysis of our reconstructed glacier mass balance series indicates that the highest energy is directed towards periods shorter than eight years (two to four years being predominant; Figure 4). This high-frequency cycle is associated with El Niño Southern Oscillation (ENSO), characterized by the Southern Oscillation Index (SOI), which represent the difference in sea-level pressure across the tropical Pacific Ocean. ENSO is known to influence precipitation regimes in Pacific North America and McCabe et al. (2000) described the role positive SOI events play in enhancing winter mass balance events within the PNW. Hodge et al. (1998) estimated a lag of about 3.5 ± 0.5 months between SOI and the effect of ENSO on glacier mass balance.

A shift in glacier mass balance state following the winter of 1976–77 is widely documented and corresponds to changing spring snowpack conditions in British Columbia (Moore and McKendry, 1996) and Washington State (Pelto, 1987). This inherent step-like fluctuation, from primarily positive to negative mass balance regimes (McCabe and Fountian, 1995; Hodge et al., 1998; McCabe et al., 2000), within the southern

Figure 3 Periods of positive glacier mass balance (black boxes) as determined by models reconstructed from the Pacific Northwest and the Canadian Cordillera. Included are the LIA moraine-building events as determined in Larocque and Smith (2003) and the net mass balance models developed in this study. Grey lines represent minor positive glacier mass balance events

<table>
<thead>
<tr>
<th>Moraine-building episodes</th>
<th>Equivalent periods of positive net glacier mass balance (this study)</th>
<th>Cooler than average temperature</th>
<th>Above average 1 April Snowpack</th>
<th>Cool and wet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waddington area Regional</td>
<td>PC1 Blue Glacier Waddington area Waddington area Waddington area</td>
<td>Waddington area</td>
<td>Waddington area</td>
<td>Waddington area</td>
</tr>
<tr>
<td>1506–24</td>
<td>N/A 1475–87 (19–31) 1519–20 (0)? N/A</td>
<td>N/A 1848–02 1848–51 1867–02</td>
<td>N/A 1867–02, 1876–77</td>
<td>N/A 1926</td>
</tr>
<tr>
<td>1562–75</td>
<td>N/A No equivalent N/A 1872–75 (0–28) 1852–76 (19–48)</td>
<td>N/A 1848–02</td>
<td>N/A 1867–02, 1876–77</td>
<td>N/A 1926</td>
</tr>
<tr>
<td>1657–60</td>
<td>N/A No equivalent N/A 1819–28 (2–9) 1814–22 (7–23)</td>
<td>N/A 1848–02</td>
<td>N/A 1867–02, 1876–77</td>
<td>N/A 1926</td>
</tr>
<tr>
<td>1767–84</td>
<td>1749–53 (18–35) No equivalent 1872–75 (0–28)</td>
<td>N/A 1848–02</td>
<td>N/A 1867–02, 1876–77</td>
<td>N/A 1926</td>
</tr>
<tr>
<td>1821–37</td>
<td>1827–32 (6–11) 1819–28 (2–9)</td>
<td>N/A 1848–02</td>
<td>N/A 1867–02, 1876–77</td>
<td>N/A 1926</td>
</tr>
<tr>
<td>1871–00</td>
<td>No equivalent 1827–25 (0–28) 1852–76 (19–48)</td>
<td>N/A 1848–02</td>
<td>N/A 1867–02, 1876–77</td>
<td>N/A 1926</td>
</tr>
<tr>
<td>1915–28</td>
<td>No equivalent N/A 1882–05 (33–46)</td>
<td>N/A 1848–02</td>
<td>N/A 1867–02, 1876–77</td>
<td>N/A 1926</td>
</tr>
<tr>
<td>1942–46</td>
<td>No equivalent N/A 1916–17 (26–30)</td>
<td>N/A 1848–02</td>
<td>N/A 1867–02, 1876–77</td>
<td>N/A 1926</td>
</tr>
</tbody>
</table>

The bracketed numbers correspond to the estimated time between the first year of positive mass balance (based on a 10-year moving average) and moraine stabilization (based on lichenometric and tree-ring dated moraines). Question marks indicate unlikely equivalent positive mass balance episode because of the short estimated time.

As determined in Larocque and Smith (2003).

As determined in Larocque (2003).

N/A: Not covered by the model.
A group of glaciers is attributed to a 20–30 year cycle inherent to the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997; Gedalof and Smith, 2001b). Corresponding to enhanced modes of variability at this frequency within our reconstructions (Figure 4), the attendant changes in mass balance are attributed to the relative strength and position of the Aleutian Low off Pacific North America. Whereas warm phases of the PDO lead to negative mass balance conditions within the southern group of glaciers shown in Figure 1, cold phases result in increased storminess and winter accumulation, a reduction in summer ablation resulting from the displacement of the transient snowline elevation and a tendency toward positive mass balance conditions (Wallace and Gutzler, 1981; Walters and Meier, 1989; McCabe et al., 2000; Moore and Demuth, 2001).

**Conclusion**

Seven tree-ring-based models of reconstructed glacier mass balance were presented in this study. Three annual balance models were developed from the regional series, PC1 scores and Blue Glacier. The regional series, South Cascade and Place glaciers led to the reconstruction of three additional winter mass balance models. Summer balance was also reconstructed from the first principal component. Periods of positive net mass balance in the regional model were found in the 1750s, 1820s–1830s and 1970s. Peaks of winter balance correspond closely to these periods, showing a sharp drop in winter mass balance towards the end of the nineteenth century represented in other models by positive periods of net balance. They are correlated with cool and wet climate episodes in the

---

**Figure 4** Wavelet power spectrum showing the significant modes of variability in the reconstructed net and winter mass balance (SSS ≥ 0.80). The wavelet power spectrum uses a Morlet wavelet function. The left axis corresponds to the Fourier period (in years). The contour levels represent 75, 50, 25 and 5% of the wavelet power. The thick contours indicate significant modes of variance at 95% confidence using red-noise (AR lag-1) background spectrum. The cross-hatched region corresponds to the cone of influence, where zero-padding has reduced the variance.
Mt Waddington area. They precede LIA moraine-building episodes recorded in the Mt Waddington area by as much as 50 years in some cases, which includes the glacial response time and a period of moraine stabilization after the ice terminus retreats. The extension of current glacier mass balance measurements to several centuries enables a more precise assessment of the impact of past climates on glacial systems. Long-term mass balance oscillations of variable duration (8 years, ENSO; 20–30 and 40–80, PDO) indicate that climate-forcing mechanisms in the Pacific Ocean have a pervasive effect of glaciers in southwestern British Columbia and Washington state. The suggested 1998–1999 shift in the PDO state (Mantua and Hare, 2002), introducing the PNW to a ‘cool’ period should increase storminess along the eastern Pacific Coast, which in return may impact positively glacial systems if the natural variability is not perturbed by human-induced climate change.

Acknowledgements

The study was supported by grants from the Natural Sciences and Engineering Research Council of Canada, the Canadian Foundation for Climate and Atmospheric Sciences and the Inter-American Institute for Global Change. We are grateful to Laurel George, Ryan Hourston and Alexis Johnson for their field and laboratory assistance, and Colin Laroque for his dendroclimatological insights. This research would not have been possible without the logistic support of the King family of Bluff Lake, British Columbia.

References


