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Extending the Place Glacier mass-balance record to AD 1585, using tree rings and wood density

Lisa J. Wood [a], Dan J. Smith [a,*], Michael N. Demuth [b]

[a] University of Victoria Tree-Ring Laboratory, Department of Geography, University of Victoria, Victoria, British Columbia V8W 3R4, Canada
[b] Glaciology Section, Geological Survey of Canada, Natural Resources Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8, Canada

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ABSTRACT

Recognizing that climate influences both annual tree-ring growth and glacier mass balance, changes in the mass balance of Place Glacier, British Columbia, were documented from increment core records. Annually resolved ring-width (RW), maximum (MXD), and mean density (MD) chronologies were developed from Engelmann spruce and Douglas-fir trees sampled at sites within the surrounding region. A snowpack record dating to AD 1730 was reconstructed using a multivariate regression of spruce MD and fir RW chronologies. Spruce MXD and RW chronologies were used to reconstruct winter mass balance (Bw) for Place Glacier to AD 1585. Summer mass balance (Bs) was reconstructed using the RW chronology from spruce, and net balance was calculated from Bw and Bs. The reconstructions provide insight into the changes that snowpack and mass balance have undergone in the last 400 years, as well as identifying relationships to air temperature and circulation indices in southern British Columbia. These changes are consistent with other regional mass-balance reconstructions and indicate that the persistent weather systems characterizing large scale climate-forcing mechanisms play a significant glaciological role in this region. A comparison to dated moraine surfaces in the surrounding region substantiates that the mass-balance shifts recorded in the proxy data are evident in the response of glaciers throughout the region.

Introduction

Over the last century the majority of glaciers within the southern British Columbia (BC) Coast Mountains have receded and downwasted (Koch, 2009; Moore et al., 2009). Increased temperatures and decreased snowfall in the last two and half decades have accelerated glacier melting in this region since ca. AD 1980 (Schiefer et al., 2007; VanLooy and Forster, 2008; Arendt et al., 2009; Shea et al., 2009). Direct understanding of the response of these glaciers to changing climates is, however, largely limited to mass-balance investigations initiated in AD 1965 during the International Hydrological Decade (IHD) at Place Glacier (Østrem, 1966; Mokievsky-Zubok et al., 1985; Demuth et al., 2009).

Recognizing that annual and seasonal climates influence both annual tree ring growth and glacier mass balance (Nicolussi and Patzelt, 1996; Watson and Luckman, 2004), a preliminary understanding of the long-term glaciological response of Place Glacier and nearby glaciers to changing climates was presented by Lewis and Smith (2004) and Larocque and Smith (2005a). Lewis and Smith (2004) report that individual glaciers within this region experienced sustained intervals of positive mass balance in the AD 1690s, the mid-1850s to the mid-1880s, and during the early 1900s to 1920s. In a broader regional reconstruction that included the mass-balance records from Blue, South Cascade and Place glaciers, Larocque and Smith (2005a) report that glaciers in the central Coast Mountains experienced periods of positive mass balance in the AD 1750s, 1820s to 1830s and 1970s.

The tree ring-width (RW) data used in mass-balance reconstructions such as those aforementioned provide useful proxy insights into the long-term glaciological response of glaciers to changing climates (Watson et al., 2008). Limitations inherent to deciphering the annual climate response of tree-ring widths, due to variables such as lag effects, restrict the precision of RW-derived proxy records (Fritts, 1976). In most applications RW measurements provide only a growing season representation of climate data (D'Arrigo et al., 1992; Larocque and Smith, 2005b). This limitation has encouraged examination of other wood parameters to identify better indicators of climate-year environmental change (Briffa et al., 1988, 1992; D'Arrigo et al., 1992; Wimmer and Grabner, 2000).

Wood density chronologies commonly show higher correlations to climatic factors than do RW chronologies (Polge, 1970; Parker, 1976; Conkey, 1986; Schweingruber, 1990; D'Arrigo et al., 1992; Wimmer and Grabner, 2000; Davi et al., 2002). Maximum ring density (MXD) characteristically displays more variability in time (Davi et al., 2002) and is known to provide significantly better proxy records of growing season conditions (Polge, 1970; D'Arrigo et al., 1992). These strong density–climate correlations are attributed to a greater similarity between changes in amplitude of wood density from year to year, when compared to the variation in RW to climate. Given the demonstrated glaciological connection between climate and mass balance, it is reasonable to assume that changes in density also provide a useful proxy for mass-balance changes.

* Corresponding author. Tel.: +1 250 721 7328.
E-mail address: smith@uvic.ca (D.J. Smith).

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Although researchers have previously employed densitometric relationships to develop robust proxy climatic records in the western Canadian cordillera (Schweingruber et al., 1991, 1993; Luckman et al., 1997; Briffa et al., 2002), only preliminary investigations of their potential application to mass-balance reconstruction have been explored. At Peyto Glacier in Banff National Park, Alberta, Watson and Luckman (2004) constructed a proxy mass-balance record developed from existing temperature and precipitation records that included a multivariate reconstruction incorporating both RW and MXD variables (Luckman et al., 1997). In their reconstruction, climate-derived models of winter and summer balance were combined into a predictive model of net balance, with a small portion of the mass-balance reconstruction based on wood density data (Watson and Luckman, 2004).

To obtain firm conclusions regarding the benefits and drawbacks to using density data to derive proxy mass-balance records, research needed to be carried out to differentiate the climate response variations reported by previous researchers (e.g., Luckman et al., 1997). In this study we sought to use the climate-driven radial growth response of selectively sampled tree species to represent the long-term glaciological response of Place Glacier to changing climates. We specifically focus on reconstructing net (Bn), winter (Bw), and summer (Bs) mass-balance records by exploiting the links between densitometric properties and seasonal climate variables.

Study location

Place Glacier is located at the western extent of the Cayoosh Range in the southern Coast Mountains (Lat 50°25′16.90″N, Long 122°36′05.6″ W; Fig. 1). Positioned at between 2600 and 1800 m asl, northwest-facing Place Glacier is identified as a cirque glacier characteristic of those found in this region (Østrem, 1966). The glacier is divided into two sections: an upper section that is relatively small in area and a lower section that is considerably larger. Munro and Marosz-Wantuch (2009) estimate that the accumulation zone accounts for approximately one-third of the total glacial area. The accumulation zone faces eastward in a westerly wind regime, creating an ideal situation for seasonal snow capture and thick ice accumulation (Østrem, 1973). It is believed that this relatively deep accumulation zone ice compensates for the relatively small accumulation area; however, no ice-thickness data exists to test this assertion (Munro, personal communication, 2010).

Place Glacier decreased in volume by over 20% since AD 1980 (Demuth et al., 2009). The historical mass-balance records show that the glacier is sensitive to seasonal climate variations and regime-scale shifts of regional climate forcing mechanisms (Mokievsky-Zubok and Stanley, 1976; Bitz and Battisti, 1999; Shea et al., 2009). The glacier is influenced by both coastal and continental climate systems, including seasonal impacts associated with generally warm summer temperatures and significant winter snowfall totals (Moore and Demuth, 2001).

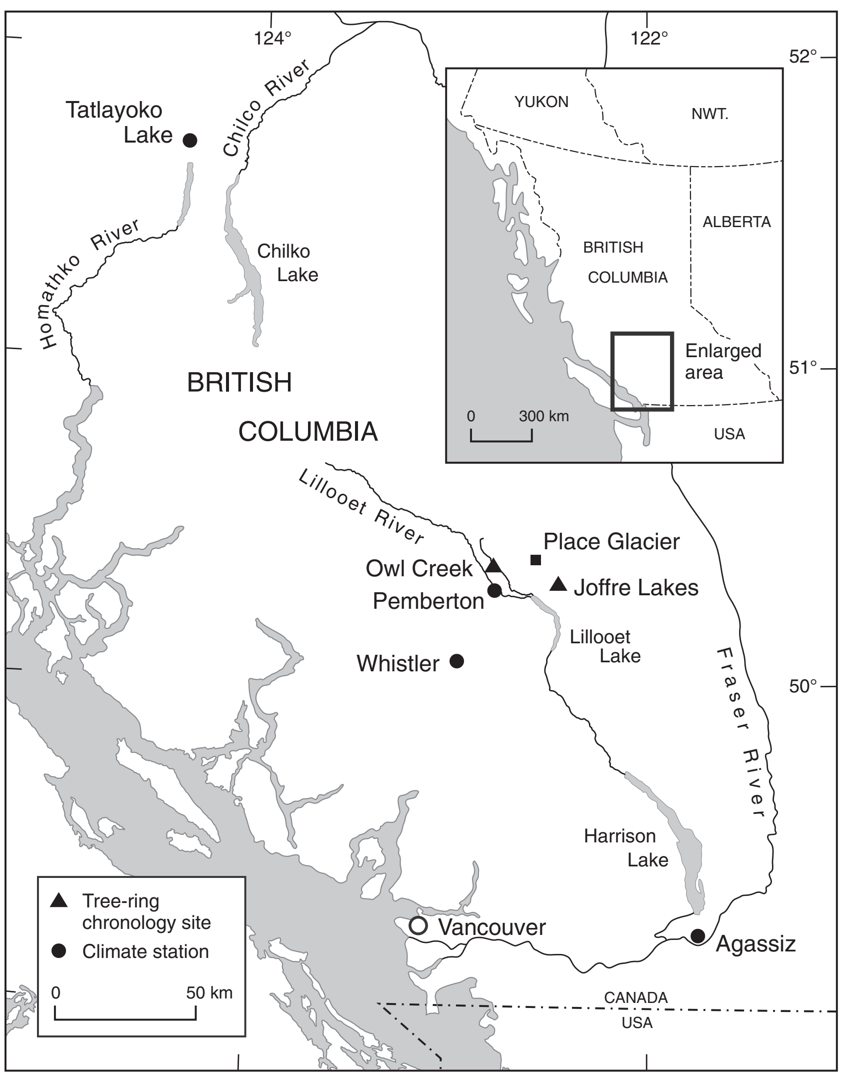

Fig. 1. Location of Place Glacier (white star), climate stations in close proximity (black and gray circles), and location of sampling sites (gray triangles).

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Place Glacier was selected for this investigation because of its relatively long historical mass-balance record, and because of the existence of a previous mass-balance reconstruction to which our density-derived results could be compared. Employing existing mass-balance records Moore and Demuth (2001) reconstructed Place Glaciers' mass-balance history to AD 1890 using a climate model. They report that significant firn depletion occurred prior to AD 1965, precipitating a large reduction in ice area and decreased meltwater production in the following decades.

Munro and Marosz-Wantuch (2009) indicate that the size and shape of Place Glacier increases its susceptibility to changes in regional air-flow patterns. Causal links between climate and Place Glacier mass balance have previously been investigated with reference to the Pacific Decadal Oscillation (PDO), the Southern Oscillation Index (SOI), the Cold Tongue Index (CT), and the Pacific North American index (PNA). Bitz and Battisti (1999) and Moore and Demuth (2001) show that significant relationships exist between the historical mass-balance behavior of Place Glacier, these circulation indices, and decadal fluctuations in temperature and precipitation.

Methods

Tree-ring samples were collected for standard dendrochronological and densitometric analysis. These samples were used to develop tree-ring chronologies for comparison to climate station records and to construct proxy mass-balance indices.

Climate data

Climate data was obtained from the Adjusted Historical Canadian Climate Data website (http://www.cccma.ec.gc.ca/hccd/) and from Climate BC (http://genetics.forestry.ubc.ca/cfgc/ClimateBC/). Station data was obtained for the Tatlayoko Lake (51.67°N, 124.4°W, 870 m asl) and Agassiz climate stations (49.25°N, 121.77°W, 15 m asl) (Fig. 1), 187 and 142 km respectively from Place Glacier. Climate data from the Tatlayoko Lake station provides a regionally consistent glaciological signal (Larocque and Smith, 2005b) and data from the Agassiz station was previously correlated to glacier climates at Place Glacier by Moore and Demuth (2001).

Climate BC provides site-specific climate predictions based on existing station data and global circulation model regional predictions from AD 1900 to 2002 (see http://genetics.forestry.ubc.ca/cfgc/climate-models.html). Monthly temperature and precipitation climate records for Place Glacier were obtained with respect to the glacier's geographical coordinates and elevation.

Snowpack records were derived from Tatlayoko Lake, the snow survey station located closest to Place Glacier (Fig. 1). The winter snowpack data (October through March) extends from AD 1947 to 1982 and illustrates substantial decadal variability. Deep seasonal snow packs characterize the mid-1950s and mid-1970s. Lower than normal snowpacks occurred in the early 1960s, late 1970s, and early 1980s. A slight decrease in total winter snowpack can be observed over the period of record.

Place Glacier mass-balance data were obtained from Dyurgerov (2002, 2005) and from records held by the Glaciology Section, Geological Survey of Canada (see Demuth et al., 2009). The mass-balance record extends over 44 years (AD 1965 to 2009) and exhibits a trend of mostly negative Bn until AD 1996, when years of positive Bn highlight changing glaciological conditions. The impact of the 1976/77 PDO regime shift on winter precipitation and Bn is well-represented in the record (Moore and Demuth, 2001; Demuth et al., 2008).

Tree-ring data

High-elevation forests containing old growth stands were selected for sampling to ensure that climate was a limiting factor (Fritts, 1976). Well-drained, nutrient-rich sites with open canopy structures were targeted to avoid signal noise caused by site conditions or inter-tree competition. Trees were sampled at two sites during the summer of AD 2007 (Table 1). Targeted species included Douglas-fir (*Pseudotsuga menziesii*) collected from Owl Creek and Engelmann spruce (*Picea engelmannii*) collected from Joffre Lakes (Table 1, Fig. 1).

The Owl Creek site was located 11 km west of Place Glacier and consisted of a well-drained south-facing mixed age stand at 993 m asl. Old growth stems of Douglas-fir and western red cedar (*Thuja plicata*) were found scattered among a younger cohort of Douglas-fir and western hemlock (*Tsuga heterophylla*). Sample trees were selected distant from the edge of a recent cutblock. The Joffre Lakes site was located 11.2 km southeast of Place Glacier at 1516 m asl. This west-facing mid-slope stand was dominated by large-diameter Engelmann spruce, with a minor component of mature subalpine fir *(Abies lasiocarpa)*, mountain hemlock *(Tsuga mertensiana)*, and western hemlock trees.

Samples were collected at breast height from individual trees using 5- and 12-mm increment borers. Two 5-mm cores were collected from opposite sides of the tree stem, and a single 12-mm core was collected beneath one 5-mm core position.

The 5-mm cores were allowed to air dry and then glued to a grooved mounting board (Stokes and Smiley, 1968). The cores were sanded to a fine polish until the annual ring boundaries were clearly visible. Digital images were created by scanning the cores with a high resolution Epson XL1000 flat bed scanner. The width of each annual ring was measured to 0.001 mm using Windendro® digital measurement software (Version 2006). Annual rings that were exceptionally narrow or unclear were measured to 0.001 mm using a Velmex® tree ring measurement system equipped with a trinocular boom-mounted microscope and CCD video display.

Following air drying each 12-mm core was prepared for densitometric analysis by gluing it flush to the surface of a 2.5-cm-wide fiberboard block. Once dry, a 2-mm-thick wood lath was cut (pith to bark) with a Waltech high precision twin-bladed saw to reveal the radial surface of the core (Haygreen and Bowyer, 1996).

Table 1
Sample collection information, individual chronology characteristics, and reconstruction verification statistics, chronology length reported to EPS cut-off of >0.80. RW = ring width, MD = mean ring density, MXD = maximum ring density, Se = Engelmann spruce, Fd = Douglas-fir.

Chronology type	Species	Site name	Latitude	Longitude	Number of cores dated (trees dated)	Reconstruction	RE value (calibration period)	RE value (verification period)
RW	Se	Joffre Lakes	50° 21′ 02″	122° 28′ 45″	24 (18)	Bw, Bs, and calculated Bn	Bw = 0.497* Bs = −0.211	Bw = 0.439* Bs = 0.411*
MXD	Se	Joffre Lakes	50° 21′ 02″	122° 28′ 45″	18 (14)	Bw and calculated Bn	Bn = −0.312	Bn = 0.289*
MD	Se	Joffre Lakes	50° 21′ 02″	122° 28′ 45″	16 (14)	Total winter snowpack (TL)	0.144	0.458*
RW	Fd	Owl Creek	50° 23′ 12″	122° 46′ 51″	16 (15)	Total winter snowpack (TL)		

* = significant at 95%.

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Wood resins add to the structural mass of tree rings and must be removed chemically prior to wood density measurement (Lenz et al., 1976; Schweingruber et al., 1978; Grabner et al., 2005). In this instance the resins were extracted from the laths using an acetone Soxhlet apparatus (Jensen, 2007). Following this, each sample was X-rayed using the University of Victoria Tree-Ring Laboratory ITRAX scanning densitometer. The samples were oriented perpendicular to the X-ray beam, allowing for exact measurement of light attenuation by a laser scanner. Measurements were made at 50-micron increments for 20 µs, with the densitometer maintained at 30 kv and 55 mA. The digital X-ray images were analyzed using ITRAX Windendro® version (2008) to provide maximum density (MXD) and mean density (MD) measurements.

The RW, MXD and MD series were cross-dated by identifying characteristic annual ring patterns. The series cross-dating was verified using COFECHA (Holmes, 1983) and annually resolved chronologies produced. The resultant time series were transformed to ARSTAN master chronologies to eliminate non-climatic variation (Cook and Holmes, 1986). A negative exponential curve was applied to series showing age-related radial growth trends (Fritts, 1976). Following this a smoothing spline was applied to the RW chronologies, with a frequency-response cut-off set to 67% to remove non-climate impacts (Cook and Kairiukstis, 1990). As previous research has shown growth trends due to factors such as inter-tree competition are not pronounced in densitometric tree-ring chronologies (Conkey, 1986), only a first-order detrending was completed with negative exponential or straight line fits. To eliminate autocorrelation issues, only the pre-whitened residual ARSTAN chronologies were used.

The standardized and detrended master chronologies were compared to the Agassiz and ClimateBC data. Initial climate–tree growth relationships were established with a response function in PRECON version 5.17B (Fritts, 1999). Using the relationships identified, verification of significant correlations was performed using simple Pearson's correlation or partial correlation analyses in SPSS.

The chronologies were compared to the historical mass-balance records collected at Place Glacier using Pearson's correlation. To ensure that the observed correlations were not autocorrelation artifacts, a Durbin–Watson statistic was employed. Values of 2.0 were considered to have no autocorrelation, and values equal or less than 1.0 deemed negatively autocorrelated.

Final proxy reconstructions were developed with simple or multiple linear regressions using the climate–tree growth and mass balance–tree growth relationships identified through response function and correlation analyses. Where strong correlations were identified, a regression was carried out and the strongest relationships used to construct predictive models. The models were verified using split-period verification, with the most recent 50% of the observed record set as the calibration period. Split-verification models are widely used in tree-ring studies as a basis for developing proxy records (Fritts, 1976; Blasing et al., 1981; Gordon, 1982; Luckman et al., 1997). While split-verification models consistently underestimate extreme events (Youngblut and Luckman, 2008), the increased accuracy of climate measurements in recent decades provides robust data for calibration (Flower and Smith, 2011).

Reconstructed models of climate and mass-balance variables were compared to climate circulation indices, including the SOI, CT, PDO, and PNA. Annual values for these indices were obtained at: for SOI, www.cru.uea.ac.uk/cru/data/soi.htm; for CT, http://jisao.washington.edu/data/cti/; For PDO, ftp.atmos.washington.edu/mantua/pnw_impacts/INDICES/PDO.latest; and for PNA, http://jisao.washington.edu/data/pna/

Observations

Ring-width chronologies

Two RW chronologies were created (Table 1). Cross-dating of 16 Douglas-fir (Fd) series from the Owl Creek site resulted in a master chronology extending from AD 1672 to 2006. The residual EPS cut-off point was 1780, yielding a RW record of 226 years with an interseries correlation of 0.555 and mean sensitivity of 0.216.

The Joffre Lakes Englemann spruce (Se) master chronology extends from AD 1504 to 2006 (Table 1). The chronology has a residual EPS cut-off at AD 1560 and yields a record that is 446 years long. The 24 series included in the chronology have an inter-series correlation of 0.537 and a mean sensitivity of 0.190.

Density chronologies

MXD and MD chronologies were developed for 18 Engelmann spruce sampled at Joffre Lakes. Extending from AD 1503 to 2006 with an EPS cut-off point at AD 1585, the MXD chronology has an inter-series correlation of 0.507 and a sensitivity of 0.057 (Table 1). Sixteen series were cross-dated to form a master MD chronology extending from AD 1503 to 2007 (Table 1). Similar to the MXD chronology, the MD chronology had a residual EPS cut-off of at AD 1585, yielding a 422-yr-long record.

Reconstructions

Linear regression analyses were completed on the residual and standardized ARSTAN chronologies with SPSS to obtain reconstructed values. The ring-width and density parameters were selected as independent variables, and the specific climate–mass balance data as the dependent variable. Se RW was used for reconstruction of Bs, Se RW and Se MXD were used for reconstruction of Bw, and Se MD and Fd RW chronologies were used to reconstruct a Tatlayoko Lake winter snowpack record.

The multivariate regression models showed multicollinearity; however, long-term trends were maintained even with inflated standard errors, so the models were deemed acceptable (see Fig. 2, Table 2). Transforming variables by data centering to reduce multicollinearity was considered, but was deemed inappropriate due to the ineffectual impact on actual data—only the statistical appearance of the model would have been improved (Brambor et al., 2006). Regression analysis was performed on untransformed data, and the autocorrelation was checked to ensure model reliability (Table 2). Standardized reconstructed values were saved and tested against the observed values of the climate or mass-balance variable to verify the reconstruction using DPL version 2.11P.

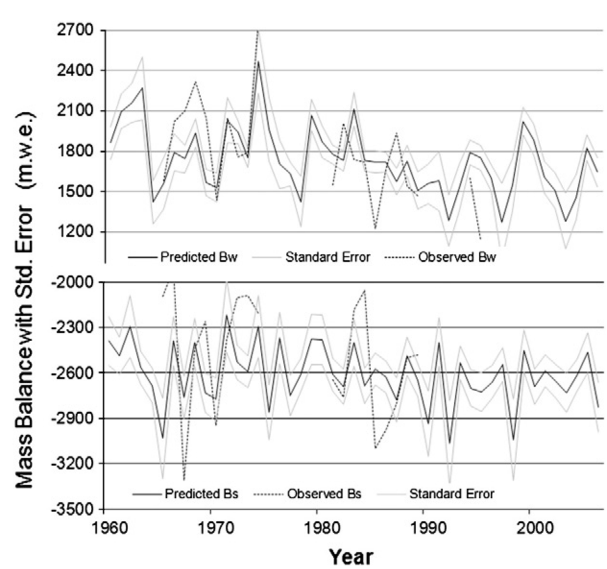

Fig. 2. Observed and reconstructed winter and summer mass balance for the period of the available observed record with standard errors.

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Table 2
Regression model statistics. Adj r2 = adjusted r-squared value for regression, Sig (p) = p-value significance, T sig. = significance of t-test.

	Predicted Bs	Predicted Bw	Predicted winter snowpack
r	0.373	0.597	0.564
r^2	0.139	0.357	0.318
Adj r2	0.094	0.286	0.276
DW	1.253	1.56	1.682
Sig (p)	0.096	0.019	0.002
Beta Var 1	−0.373	−0.389 (mxd)	−0.396 (md)
Beta Var 2	na	−0.393 (rw)	−0.356 (rw)
T sig. Var 1	−0.096	0.057 (mxd)	0.011 (md)
T sig. Var 2	na	0.055 (rw)	0.021 (rw)
Tolerance	na	0.972	0.985
VIF	na	1.028	1.016
Eigenvalue 1	na	2.989	2.981
Eigenvalue 2	na	0.01	0.017
Eigenvalue 3	na	0.001	0.002
Condition index 1	na	1	1
Condition index 2	na	17.288	13.279
Condition index 3	na	50.239	41.912
Max std. residual	1.658	1.523	2.102
Max leverage	0.257	0.54	0.304

Climate station analysis

Moore and Demuth (2001) report that the Agassiz station data has strong climate–mass balance correlations to Place Glacier. To test whether the site-specific climate data generated by ClimateBC were likely to share the same relationship, the modeled monthly temperature and precipitation climate records were compared to the Agassiz station data. Correlation analyses showed that mean summer and winter temperature values from the two data sets were significantly correlated ($r = 0.841$, $p < 0.01$; and $r = 0.905$, $p < 0.01$, respectively). Only a moderate correlation ($r = 0.490$, $p < 0.01$) was detected between the annual precipitation totals recorded at Agassiz (1736 mm, SD 302 mm) and modeled at Place Glacier by ClimateBC (1540 mm, SD 236 mm).

Based on these findings, it was assumed that the temperature data generated by ClimateBC (AD 1900 to 2002) realistically represented conditions and trends at the glacier. ClimateBC indicates that mean summer temperatures (June–August) at Place Glacier range from 12.3 to 8.1°C, whereas winter temperatures (December–February) range from −13.8 to −3.6°C. A weaker correlation to precipitation data recorded at Agassiz suggests that annual trends at the glacier may not follow those recorded at that station.

Results

Place Glacier ClimateBC record

Climate conditions at Place Glacier were shown to have changed over the last century (Fig. 6). The ClimateBC record suggests mean annual temperatures have warmed by 1°C, with corresponding increases in both mean summer (~0.6°C) and winter (~1°C) temperatures. Warmer than average temperatures characterized the early 1940s and from 1985 to present. Cooler than average temperatures occurred from AD 1908 to 1923, in the late 1940s, in the mid-1950s, and the mid-1970s.

Climate BC indicates that annual precipitation totals at Place Glacier have ranged from 1091 (AD 1985) to 2143 (AD 1950) mm. Overall precipitation totals show an increase of 225 mm from AD 1900 to 2002, with average increases of ~30 mm in spring (March–May) and ~20 mm in the summer (June–August) and winter (December–February) months.

Snowpack proxy record

Significant relationships were found between the winter snowpack totals (October–March) recorded at Tatlayoko Lake and the Se MD and Fd RW chronologies (Table 3). Deep snowpacks resulted in narrow tree rings in the Fd RW chronology and low MD values in the Se chronology. Years with shallow snowpacks resulted in wider than normal tree rings in the Fd RW chronology and high MD values in the Se chronology. A multivariate model incorporating these relationships was constructed and explains 32% of the variation in total winter snowpack at Tatlayoko Lake ($p < 0.01$).

The Se MD and Fd RW chronologies were used to construct a proxy record of Place Glacier winter snowpack conditions extending to AD 1730 (Table 1, Fig. 3). The predicted values correlate significantly to the original dataset (Table 4). Split-model verification showed a significant RE value for the verification period, but insignificant RE value for the calibration period (Table 1).

Significant annual and extended variations in snowpack totals are recorded in the 277 year long proxy record. The record reveals years of notable snowpacks in the mid- and late 1700s, 1830s, 1920s and 1930s, and the 1960s and in the late 1970s. Extended intervals of below-normal snowpack totals occurred in the 1840s to 1860s and the 1890s to 1910s (Fig. 3).

The proxy snowpack record negatively correlates with Place Glacier winter temperatures (Table 4), indicating that over the historical period winters with above-average snowpack correspond with years when temperatures were cooler. The proxy winter snowpack record also negatively correlates with winter PDO ($r = -0.359$, $p < 0.01$) and PNA ($r = -0.481$, $p < 0.01$) (Fig. 3). It is evident that, although the general correlation over the whole period of observed PDO and PNA records is negatively correlated with predicted winter snowpack, some variation in the direction of correlation exists when the records are examined in detail (Fig. 3). Prior to AD 1950, winter PDO (averaged values October through March) was positively correlated to the proxy winter snowpack record. Similarly, the observed record for winter PNA (October through March) reveals a positive correlation for the period prior to ca. 1973. These shifts in the relationship between PDO/PNA and snowpack accumulation are presumably associated with phase shifts in the

Table 3
Pearson's correlation matrix for chronologies, observed total winter snowpack (October through March) at Tatlayoko Lake (TL), and observed net (Bn), winter (Bw), and summer balance (Bs) records. RW = ring width, MD = mean ring density, MXD = maximum ring density, Se = Engelmann spruce, Fd = Douglas-fir.

	Se RW	Se MXD	Se MD	Fd RW	Bn	Bw	Bs
Se MXD	0.063						
Se MD	0.092	0.594†					
Fd RW	0.165	−0.034	0.027				
Bn	−0.28	−0.019	0.007	0.081			
Bw	−0.458**	−0.455**	−0.413	0.153	0.644†		
Bs	−0.373*	−0.018	−0.068	0.257	0.914†	0.419	
Total winter snowpack (TL)	−0.084	−0.286	−0.440†	-.405**	0.047	0.703**	0.128

* = significant at 90%, ** = significant at 95%, † = significant at 99%.

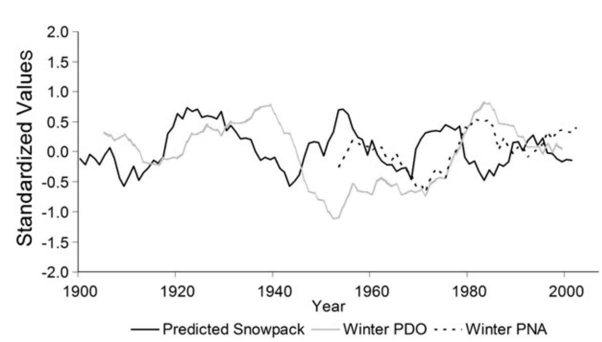

Fig. 3. Average winter PDO (gray) and PNA (dotted), both sharing a negative relationship with predicted Tatlayoko Lake winter snowpack (black). All series are represented by 10-year running means to highlight the decadal periodicity.

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Table 4
Pearson's correlation matrix for winter snowpack records for Tatlayoko Lake (TL), precipitation, temperature, and mass-balance records for Place Glacier (PG), and winter circulation indices (October–March).

	Observed total winter snowpack (TL)	Average winter temperature (PG)	Total winter precipitation (PG)	Average June–July temperature (PG)	Winter PDO	Winter SOI	Winter PNA
Pred. total winter Snowpack	0.564†	−0.241**	0.011	0.149	−0.359†	0.277†	−0.481†
Observed Bs	0.128	−0.326	0.005	−0.459**	−0.286	0.042	−0.114
Observed Bw	0.703**	−0.046	0.625†	−0.162	−0.379*	0.331	−0.385*
Observed Bn	0.047	−0.039	0.327**	−0.349**	−0.438†	0.368**	−0.256
Pred. Bs	0.084	−0.165*	0.016	−0.402†	−0.248**	0.243†	−0.330**
Pred. Bw	0.273	0.02	0.154	−0.168	−0.249**	0.212**	−0.143
Calculated Bn	0.430*	−0.115	0.290*	−0.565†	−0.271†	0.246†	−0.241*

* = significant at 90%, ** = significant at 95%, † = significant at 99%.

circulation indices such as characterize the cool PDO phase from AD 1947 to 1976.

Glacier mass-balance proxy record

Bw was reconstructed from a multivariate analysis of the Se MXD and RW chronologies. The standard error of the original Bw reconstruction in Fig. 2 shows that even though multicollinearity was present in the model, the overall long-term trends are maintained and correspond to the observed Bw data. Split verification indicates the Bw model was significant at 95% (Table 1). Significant relationships were also found between winter PDO (October through March), as well as the observed and predicted model of Bw. This finding suggests that the winter balance of Place Glacier is affected by winter Pacific air circulation patterns.

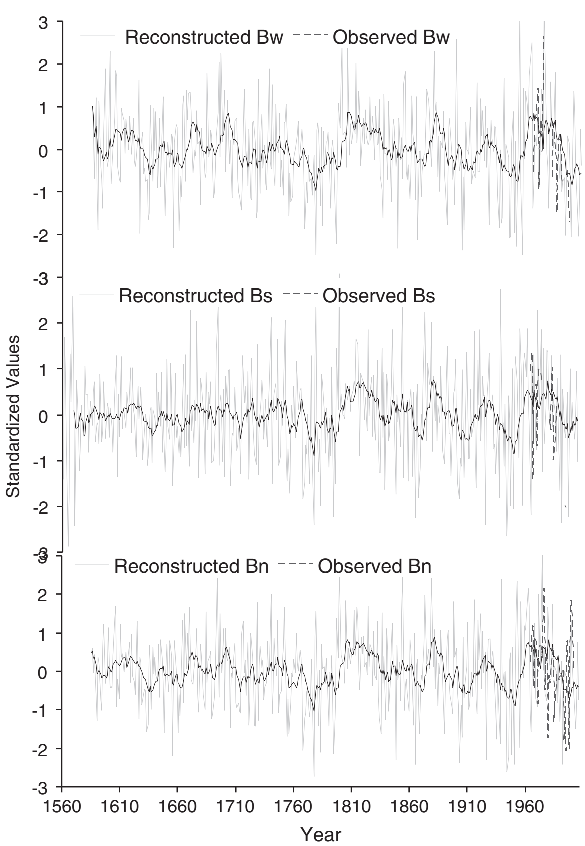

Fig. 4. Mass balance reconstructed from Engelmann spruce MXD and RW (Bw), RW (Bs), and the calculated difference between Bw and Bs (Bn). The thick black trend lines indicates a 10-year running mean for predicted values, and dotted black lines indicate the observed records.

Bs was significantly correlated to the Se RW chronology, although the Pearson's correlation coefficient is low (Table 3). The Bs reconstruction was compared to observed summer air temperature data in order to interpret the influence of air temperature on the record. Bs was shown to be negatively correlated to average June–July temperature ($r = -0.402$, $p < 0.01$) (Table 4). Split-model verification showed a significant RE value for the verification period, but insignificant RE value for the calibration period (Table 1).

A long-term proxy record of Place Glacier Bn was established by subtracting the annual proxy Bs values from the Bw established for the preceding winter. The resulting Bn values were standardized for comparison to Bw and Bs (see Fig. 4). Uncertainty in the proxy Bw ($r^2 = 0.36$) and Bs ($r^2 = 0.14$) records derived from the ring-width and density data weakens the strength of the Bn reconstruction (Fig. 2). A significant source of noise contributing to this uncertainty is assumed to be related to varied site-specific conditions influencing radial tree growth (Cook, 1985).

The Bn proxy record dates to AD 1585 (Table 1) but only moderately correlates with the observed Bn record from AD 1965–2001 at Place Glacier ($r = 0.271$, $p < 0.1$). Fig. 5 presents the correspondence between the observed and reconstructed Bn records showing that the low-frequency oscillations in the two records are actually quite similar. This finding substantiates the usefulness of the proxy for describing historic trends, albeit while recognizing that the values reported for individual years are oftentimes poorly modeled.

The reconstructed Bn record is compared to average June–July temperatures at Place Glacier (Fig. 6). As expected, the mass-balance reconstruction shows a negative relationship to summer temperature. The proxy reconstruction shows periods of positive mass balance in the late 1600s to early 1700s, between 1800 to 1830, in the 1880s, and in the 1960s to early 1980s. Negative mass-balance conditions

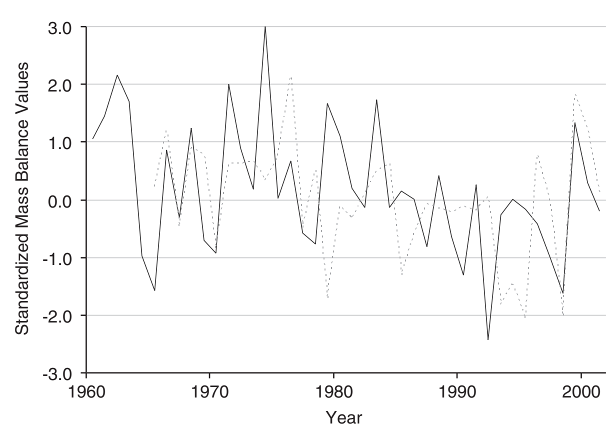

Fig. 5. Reconstructed net mass balance plotted against the observed net mass balance for Place Glacier for the period of the observed record.

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characterize the mid-1600s, the late 1700s, between 1850 and 1865, and the 1940s to 1950s.

Fig. 7 compares the standardized proxy Bn record developed in this study to those previously reported. Common intervals of positive mass balance (AD 1700–1710, 1810–1825, 1860–1880, and 1960–1980) are evident, as are common periods of negative mass-balance conditions (AD 1790–1800 and 1930–1950).

Discussion

Mass-balance models

The observed winter mass-balance record from Place Glacier shows a significant positive correlation with winter precipitation ($r = 0.625$, $p < 0.01$). A comparable relationship was not evident when winter precipitation data was compared to the proxy Bw record modeled from the Se MXD and RW chronologies. This finding was not unexpected, as the radial growth of those chronologies showed little sensitivity to precipitation.

Both the predicted and the observed Bs at Place Glacier were shown to be significantly negatively correlated to average June–July temperatures (Table 4). This finding suggests that during warm summers, ablation rates correspondingly increase thereby significantly reducing the Bn (i.e., Munro and Marosz-Wantuch, 2009). While this characteristic is common to glaciers in the Canadian Rocky Mountains (i.e., Watson and Luckman, 2004), the Bn of glaciers in coastal settings has usually been assumed to be most significantly influenced by yearly Bw fluctuations (Walters and Meier, 1989; Bitz and Battisti, 1999). Nonetheless, a comparison of Place Glacier Bn does show that the yearly balance is negatively correlated, albeit weakly, to average June–July temperatures (Fig. 6).

Large-scale climate forcing mechanisms influence both hydroclimates and glacier mass balance in this region (Stahl et al., 2006; Fleming et al., 2007; Déry et al., 2009). At Place Glacier, Bitz and Battisti (1999) and Moore and Demuth (2001) demonstrated that the PDO and the PNA were associated with glacial mass-balance anomalies. This study also shows that significant correlations exist between the proxy Bw, Bs, and Bn reconstructions and the winter portion of the PDO (October through March) (Table 4, Fig. 8).

Significant correlations also exist with SOI in all three mass-balance reconstructions. Visual correspondence between winter SOI and calculated Bn is shown in Fig. 8, where a significant positive relationship is illustrated. It is likely that SOI and PDO are both influencing climate variables that are in turn influencing the ring width development of Engelmann spruce.

Significant relationships exist between the winter PNA and predicted Bs reconstructed by the Se RW chronology. The relationship

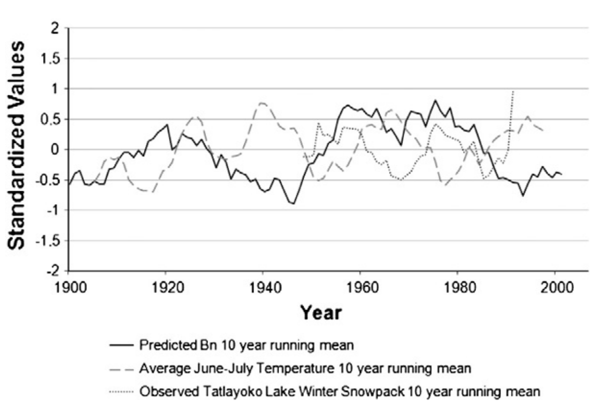

Fig. 6. Reconstructed net mass balance plotted against observed CBC average temperature for June–July and Tatlayoko Lake winter snowpack for the period of the observed temperature record.

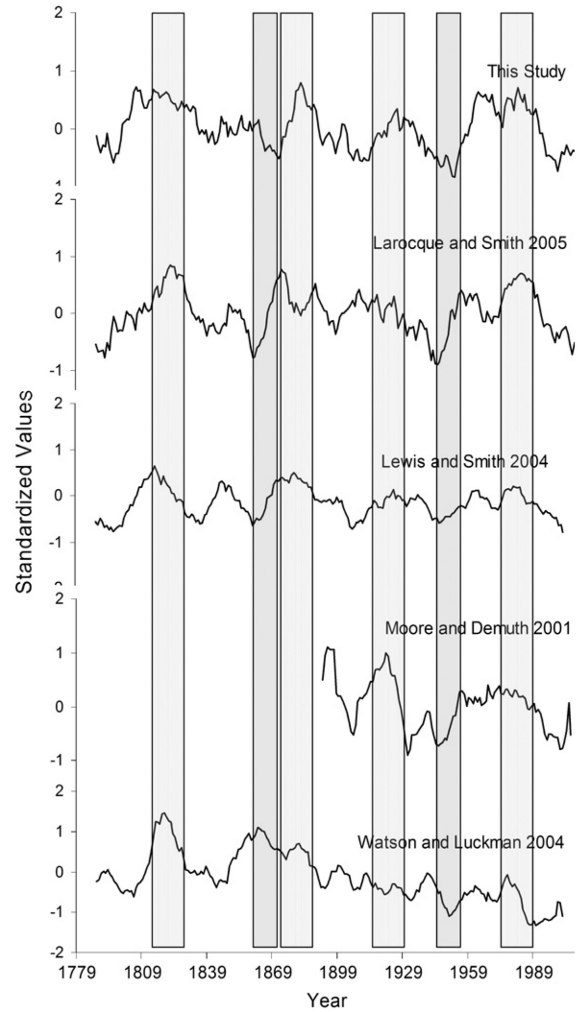

Fig. 7. Net mass-balance reconstructions for various glaciers in Southern BC. Dotted areas (light gray) indicate periods of time when the reconstructed mass balance of these glaciers is increasing or in positive balance. Cross-hatched regions of the figure (dark gray) indicate time periods when mass balance is decreasing in most cases. All reconstructions derived from tree rings with exception of Moore and Demuth, derived from climate variables.

between the reconstructed Bs and the PNA changes through time. While the periods from AD 1960 to 1970 and 1985 to 2001 are positively correlated to the PNA, the period from AD 1970 to 1985 is negatively correlated. Because the PNA is affecting the climate and mass balance for this area in a transient way, it is difficult to make a general assumption about its influence.

Glacial history records from the southern and central Coast Mountains suggest that many glacier fronts have consistently fluctuated in correspondence to the mass-balance models developed in this study. Larocque and Smith (2003) describe intervals of moraine formation in the Mount Waddington area in AD 1767 to 1784, 1821 to 1837, and 1942 to 1946, all periods corresponding to shifts from positive to negative mass-balance states in the Place Glacier reconstruction (Fig. 4). At Bridge Glacier in the Lillooet Icefield area, Allen and Smith (2007) dated episodes of terminal moraine stabilization following ice-front retreat to AD 1649, 1756, 1831, 1856, 1912 and 1946. The majority of these moraines date to intervals when shifts in mass balance from positive to negative states are recorded in the proxy Bn model.

In Upper Lillooet Provincial Park, Koehler and Smith (2011) describe the formation of extensive lateral moraines after AD 1736, 1830, and 1880, time periods that broadly correspond to persistent intervals of negative mass-balance conditions at Place Glacier. Finally,

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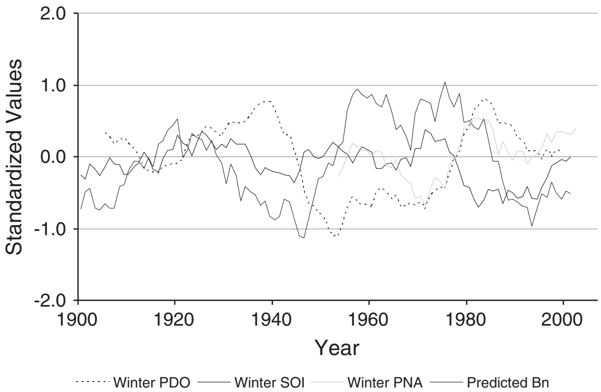

Fig. 8. Predicted net mass balance plotted against the winter PDO, winter SOI, and winter PNA over the period of the available observed record. Variables displayed as 10-year running means.

Koch et al. (2007) note that most glaciers within Garibaldi Provincial Park attained their greatest downvalley extent between AD 1690 and 1720, an interval of time that corresponds to a significant period of positive mass balance in our proxy Bn record (Fig. 4).

While these glacier histories are broadly in agreement with the Place Glacier mass-balance reconstruction, there remain instances where the records do not correspond. This behavior is attributed to errors in moraine dating and/or to the individualistic influence of glacier hypsometry. Clearly not all glaciers in this region respond similarly to changing mass states. It is more likely that that there are variable lag periods between persistent positive mass-balance episodes and moraine building, as well as between periods of negative mass balance, glacier terminus retreat, and moraine stabilization.

Conclusion

The glacier mass-balance reconstructions developed in this study indicate that Place Glacier is affected by continental temperature regimes as well as coastal precipitation systems. The ablation and accumulation records associated with Place Glacier, as represented by mass-balance measurements, are positively correlated with average spring and summer temperatures and total winter snowpack for this region of BC.

Using mean ring density of Engelmann spruce and ring width of Douglas-fir from wood samples collected in the Place Glacier region, a proxy record was developed for total winter snowpack at Tatlayoko Lake. Maximum ring density and ring width from Engelmann spruce were used to reconstruct winter balance, and ring width alone was used to reconstruct summer balance. Net balance was calculated as the difference between the winter and summer balance predictions.

The reconstructions provide insight into the changes that snowpack and mass balance have undergone in the last 400 years, and their relationships to air temperature and circulation indices in southern BC. These changes are consistent with other regional mass-balance reconstructions and indicate that the persistent weather systems characterizing large scale climate-forcing mechanisms play a significant glaciological role in this region. A comparison to dated moraines located in the Mount Waddington area, at Bridge Glacier, and found within Garibaldi and Upper Lillooet Provincial Parks substantiate that the long-term shifts in mass-balance state illustrated in our models is recorded at glacier sites throughout the central and southern BC Coast Mountains region.

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