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Long-term relationships between reconstructed seasonal mass balance at Peyto Glacier, Canada, and Pacific sea surface temperatures

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Abstract: Tree-ring based mass balance reconstructions developed for Peyto Glacier, Alberta, Canada are compared with measured conditions in the Pacific Ocean over the last century and, using reconstructions of Pacific climate indices, over the past ~300 years, at interannual and decadal–interdecadal timescales. Tree-ring reconstructed winter balance totals at Peyto Glacier in La Niña, negative Pacific Decadal Oscillation (PDO) and La Niña/negative PDO years significantly exceed those in El Niño, positive PDO and El Niño/positive PDO years, respectively. The same phase pairings of reconstructed summer mass balance do not differ significantly. These findings confirm those seen in the measured mass balance records and shorter (100 years) tree-ring and instrumental climate record-based reconstructions, suggesting similar relationships have existed over the past ~300 years. Maps showing the regression of Pacific sea surface temperatures (SSTs) on the seasonal mass balance series indicates that both winter and, albeit more weakly, summer mass balance series are related to ENSO-like patterns of SST variability in the Pacific Ocean at both interannual and interdecadal timescales.

Key words: Dendrochronology, Peyto Glacier, glacier mass balance, Pacific Ocean, seasonality, sea surface temperatures, Canada.

Introduction

In many mountain watersheds, glacial meltwater provides an important contribution to total streamflow, particularly in late summer months and during periods of drought (eg, Fountain and Tangborn, 1985). Understanding the large-scale climatic causes and timescales of changes in glacier mass balance is therefore important for effective management and allocation of downstream water resources. This is particularly relevant as warmer global temperatures will lead to further reductions in glacier size in this region (eg, Hall and Fagre, 2003, predict that all glaciers in Glacier National Park, Montana will be gone by 2030) and at other small glaciers (eg, Oerlemans *et al.*, 1998). The primary climatic controls of glacier mass balance in mid-latitude sites are winter precipitation (accumulation) and summer temperatures, which control ablation (see Hodge *et al.*, 1998; Bitz and Battisti, 1999). Variation in these factors may be related to large-scale patterns of circulation and an understanding of the links between these patterns and mass balance will help evaluate the causes of past glacier fluctuations and help to predict how glaciers may respond to future climate changes.

Recent studies have identified relationships between glacier mass balance and conditions in the Pacific Ocean. In particular, the documented shift in North Pacific sea surface temperatures after 1976 has been linked with decreased net mass balance for several glaciers in western Canada and the northwestern USA and increased net balance at some Alaskan glaciers (eg, Walters and Meier, 1989; Ebbesmayer *et al.*, 1991; Hodge *et al.*, 1998; McCabe *et al.*, 2000). These opposite effects are related to changes in storm tracks and atmospheric pressure patterns that primarily influence winter balance and may have additionally accelerated the recession of glacier tongues in response to higher temperatures in the southern Canadian Cordillera.

Exploration of the relationships between glacier mass balance and conditions over the Pacific Ocean are limited by short mass balance records (generally the last 30 yr) that

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contain only one documented phase shift of the Pacific Decadal Oscillation (PDO, Mantua *et al.*, 1997; Zhang *et al.*, 1997). Winter precipitation amounts over the southern Canadian Cordillera (and therefore winter balances) are also influenced by El Niño–Southern Oscillation (ENSO) with lower precipitation during El Niño winters and higher precipitation in La Niña years (Shabbar *et al.*, 1997). The development of a ~300-yr long mass balance reconstruction for Peyto Glacier (51°41′N, 116°32′W) from tree-ring data (Watson and Luckman, 2004a) correlated with winter precipitation and summer temperatures allows proxy mass balance/Pacific sea surface temperatures (SST) relationships to be examined over at least 100 years with instrumental data and over 300 years using reconstructed indices (Stahle *et al.*, 1998; Gedalof and Smith, 2001; Biondi *et al.*, 2001; D'Arrigo *et al.*, 2001). Furthermore, seasonal mass balance reconstructions allow for an exploration of the relationships with oceanic conditions on a seasonal basis.

In general, summer conditions (primarily local temperatures) are thought to have a greater impact on the mass balance of continental glaciers (including Peyto) and exhibit higher variability than winter conditions (Letréguilly, 1988; Walters and Meier, 1989; Bitz and Battisti, 1999). Examination of periods of glacier advance and reconstructed positive balances at Peyto Glacier suggests that advances may be associated with changes in both summer and winter balances (Watson and Luckman, 2004a; Watson *et al.*, 2007). The consistently lower net balances after 1976 at Peyto Glacier and elsewhere are primarily attributable to changes in winter mass balance (McCabe and Fountain, 1995; Luckman, 1998; Moore and Demuth, 2001; Demuth and Keller, 2006) although the greatest annual losses occur in occasional exceptional melt years.

Data and methods

Watson and Luckman (2004a) used tree-ring chronologies from the southern Canadian Cordillera and Alaska to reconstruct winter, summer and net mass balances for Peyto Glacier in the southern Canadian Rocky Mountains. These reconstructions extend back to at least 1673 and were calibrated against measured seasonal mass balance records for the glacier over the period 1966–1995 (see Table 1 for details). The reconstructions pass conventional verification tests applied in dendroclimatological studies using data from outside the period of model calibration. The main reconstructed intervals of positive mass balance generally coincide with periods of glacier advance inferred from independently dated moraine sequences for the Canadian Rockies (Luckman, 2000). Independent seasonal and net mass balance reconstructions for Peyto Glacier are also derived using instrumental precipitation and temperature records from Banff and Jasper, Alberta (Table 1).

Gridded sea surface temperature records were obtained from the Global Sea-Ice and Sea Surface Temperature (GISST) data set and extend from 1870 to 2000 (1° × 1° grid; Parker *et al.*, 1995). El Niño and La Niña years were identified from the Bivariate ENSO index time series (based on Nino 3.4 SSTs and the Southern Oscillation Index (SOI), Smith and Sardeshmukh, 2000). Positive and negative PDO years were defined from the time series by Mantua *et al.* (1997). To take full advantage of the length of the mass balance reconstructions, tree-ring based reconstructions of the SOI (Stahle *et al.*, 1998) and the PDO (Gedalof and Smith, 2001; Biondi *et al.*, 2001; D'Arrigo *et al.*, 2001) were used to identify pre-instrumental ENSO events and the phase of the PDO. The common variability in the PDO reconstructions was represented by the leading principal component (PC; 52% original variance explained; 1700–1979) of the three PDO reconstructions (see Table 1 notes).

Two sets of analyses were used to evaluate relationships between glacier mass balance and Pacific SSTs. Differences in the means of measured and reconstructed (from instrumental records and tree-ring data, Table 1) seasonal mass balance values for different phase pairings of ENSO and the PDO were evaluated using the student's *t*-test or the non-parametric Mann-Whitney U test (eg, von Storch and Zweirs, 1999) where the assumptions of the *t*-test are violated. Second, the tree-ring based mass balance estimates were converted to standardized anomalies from the full period mean (1870–1994) and secular trends were removed. These standardized mass balance reconstructions (winter and summer) were then filtered to yield time series of high (< 8 yr, interannual) and low (> 8 yr, decadal–interdecadal) frequency variability (Koopmans, 1974). November–March SSTs were regressed on these filtered series over the period 1870–1994 and the resulting coefficients mapped.

Results

Relationships between seasonal mass balance and conditions in the Pacific Ocean

Using the above data sets, we examined the relationships between seasonal mass balances and Pacific conditions (PDO and ENSO events) over three different time intervals. A number of studies (eg, Gershunov and Barnett, 1998) have found that relationships between ENSO, PDO and North American surface climate are enhanced when they are in phase (ie, positive PDO and El Niño years, negative PDO and La Niña years). Therefore, we also examined the effects of ENSO/PDO pairings on mass balance.

Events identified in the measured mass balance record, 1966–1999

The short record of measured mass balance shows winter accumulation for negative PDO, La Niña and La Niña/negative PDO years is greater than for El Niño, positive PDO and El Niño/positive PDO years (Table 2; see, eg, Demuth and Keller, 2006) but the mean accumulation values for El Niño versus La Niña years are not significantly different ($p > 0.05$; Table 2). Despite the low degrees of freedom the large differences between the two in-phase pairings (545 mm water equivalent (w.e.)) are statistically significant using both parametric and non-parametric tests (Table 2). The El Niño/positive PDO mean (835 mm w.e.) is far below the mean of the period of record (1966–1999: 1181 mm w.e.) suggesting that this phase pairing of Pacific variability has a strong impact on the climate and mass balance of the region. The mean for the La Niña/negative PDO pairing is slightly less (17% above the mean) than the mean for negative PDO years alone (21% above).

Summer mass balance values are lower for El Niño, positive PDO and El Niño/positive PDO years indicating that, on average, greater melting occurred in these years than La Niña, negative PDO and La Niña/negative PDO years. Instrumental June–August temperatures from Jasper, Alberta correlate significantly, but weakly with the PDO ($r = 0.34$, $n = 79$). However, the high variability in the summer balance series and low number of observations result in non-significant differences between all paired means (Table 2). The summer balance record is dominated by two exceptional years (1970

Table 1 Sources and types of data used in this study

Name	Data type	Start	End	Reference
Peyto Bw[a]	tree-ring based proxy	1468	1995	Watson and Luckman (2004a)
Peyto Bs[a]	tree-ring based proxy	1673	1994	Watson and Luckman (2004a)
SOI[b]	tree-ring based proxy	1706	1977	Stahle *et al.* (1998)
PDO index[c]	tree-ring based proxy	1599	1983	Gedalof and Smith (2001)
PDO index[c]	tree-ring based proxy	1700	1979	D'Arrigo *et al.* (2001)
PDO index[c]	tree-ring based proxy	1661	1991	Biondi *et al.* (2001)
Peyto Bw[d]	reconstruction from measured climate data	1896	1994	unpublished
Peyto Bs[d]	reconstruction from measured climate data	1916	1994	unpublished
Peyto Bw[e]	conventional mass balance from stake network	1966	1999	Demuth and Keller (2006)
Peyto Bs[e]	conventional mass balance from stake network	1966	1999	Demuth and Keller (2006)
Bivariate ENSO Index	based on measured SST and atmospheric pressure data	1871	2004	Smith and Sardeshmukh (2000)
PDO index	based on measured SST data	1900	2005	Mantua *et al.* (1997)
GISST	measured gridded SST data	1870	2000	Parker *et al.* (1995)

[a] Winter mass balance is reconstructing using a *Tsuga mertensiana* ring-width chronology from Alaska (Miners Well available in the International Tree Ring Data Bank; collected by G. Wiles, P.E. Calkin and D. Frank) and a precipitation reconstruction from British Columbia (Lytton; Watson and Luckman, 2004b). The summer mass-balance reconstruction is developed using a maximum summer temperature reconstruction for the central Canadian Rockies (Luckman and Wilson, 2005) and a precipitation reconstruction for Waterton Lakes (Watson and Luckman, 2004b). Adjusted R^2 and the standard error of the estimate for the winter and summer reconstructions are 0.41 and 0.46 and 269 and 303 mm w.e./yr respectively.

[b] The correlation between the Stahle *et al.* (1998) December–February (DJF) SOI reconstruction and instrumental DJF SOI (last accessed 8 June 2006 from http://www.cru.uea.ac.uk/cru/data/soi.htm) is 0.71 over the years 1866–1977. The predictors used in these reconstructions are independent of those used in the mass-balance reconstructions.

[c] The correlation between the leading PC of the three PDO reconstructions and the instrumental PDO record (Mantua *et al.*, 1997) is 0.57 over the period 1901–1979. The predictors used in these reconstructions are independent of those used in the mass-balance reconstructions.

[d] The models were calibrated against the measured mass balance records using the following predictors: winter balance = Banff October–April precipitation (positive coefficient) and April–May temperatures (negative coefficient), calibration $R = 0.83$, reconstruction length 1896–1994; summer balance = Jasper June–August temperatures (positive coefficient), calibration $R = 0.78$, reconstruction length 1916–1994). The instrumental records are from the Adjusted Historical Canadian Climate Data set, last accessed 8 June 2006 from http://www.cccma.bc.ec.gc.ca/hccd/).

[e] Measurements are not available for 1991 and 1992. Demuth and Keller (2006) report that the standard error for the mass-balance measurements is 150–200 mm w.e.

and 1998) with extreme losses of 2770 mm w.e. and 3100 mm w.e. when low accumulation winters were followed by the two hottest June–August periods recorded at Banff and Jasper between 1966 and 1999.

Events in proxy mass balance records (instrumental and tree-ring based) defined using instrumental records of Pacific variability, 1901–1994

Table 3A summarizes seasonal mass balance totals reconstructed from instrumental climate records (1900–1994 winter, 1916–1994 summer) grouped according to conditions in the Pacific. Winter mass balance estimates are, in ascending order, higher for La Niña, negative PDO and La Nina/negative PDO years than for El Niño, positive PDO and El Niño/positive PDO years (Table 3A). *T*-tests reveal differences between mean winter balance means are statistically significant ($p < 0.05$; Table 3A) for all pairings. The significant difference between the in-phase ENSO/PDO pairing confirms that conditions operating on the two timescales in the Pacific influence winter mass balance over this period.

There is more summer melt (a more negative balance) in El Niño, positive PDO and El Niño/positive PDO years but the means are only significantly different for positive and negative PDO years (Table 3A). The in-phase relationships are not significantly different in the summer mass balance estimates as a result of the lower number of observations (Table 3A) even

Table 2 Differences in measured seasonal mass balance means at Peyto Glacier (1966–1999) based on instrumental records of PDO and ENSO

Group a	Mean a	SD a	Group b	Mean b	SD b	*t*	df	*p*
Winter balance								
El Niño (9)	1074	322	La Niña (5)	1380	247	−1.79	12	0.09
+PDO (17)	**971**	**204**	**−PDO (15)**	**1420**	**289**	**−5.12**	**30**	**0.00**
El Niño and +PDO (5)[a]	**835**	**78**	**La Niña and −PDO (5)**	**1380**	**247**	**−4.71**	**8**	**0.00**
Summer balance								
El Niño (9)	−1691	607	La Niña (5)	−1470	290	−0.76	12	0.46
+ PDO (17)	−1823	548	−PDO (15)	−1592	336	−1.42	30	0.17
El Niño and +PDO (5)	−1920	718	La Niña and −PDO (5)	−1470	290	−1.30	8	0.23

SD, standard deviation; *t*, *t* statistic; df, degrees of freedom; *N* for each variable is in brackets, pairings with signficant *t* values are boldfaced, mean and SD are given in mm w.e.

[a] Violates homogeneity of variances assumption but the two means are significantly different ($p < 0.05$) when Mann-Whitney U test applied.

Table 3 Differences in reconstructed seasonal mass balance means at Peyto Glacier (derived from (A) instrumental climate records and (B) tree-ring data) grouped using instrumental records of PDO and ENSO (1901–1994)

(A) Mass balance estimates (mm w.e.) based on instrumental climate records

Group a	Mean a	SD a	Group b	Mean b	SD b	*t*	df	*p*
Winter balance								
El Niño (20)	**964**	**263**	**La Niña (14)**	**1288**	**258**	**−3.57**	**32**	**0.00**
+PDO (51)	**1052**	**233**	**−PDO (43)**	**1301**	**282**	**−4.71**	**92**	**0.00**
El Niño and +PDO (13)	**863**	**179**	**La Niña and −PDO (11)**	**1337**	**216**	**−5.89**	**22**	**0.00**
Summer balance								
El Niño (15)	−1733	375	La Niña (11)	−1572	352	−1.11	24	0.28
+PDO (42)[a]	**−1760**	**331**	**−PDO (37)**	**−1523**	**313**	**−3.25**	**77**	**0.00**
El Niño and +PDO (11)	−1828	385	La Niña and −PDO (9)	−1533	379	−1.72	18	0.10

(B) Mass balance estimates (mm w.e.) based on tree-ring records

Group a	Mean a	SD a	Group b	Mean b	SD b	*t*	df	*p*
Winter balance								
El Niño (21)	1208	252	La Niña (14)	1362	261	−1.74	33	0.09
+PDO (52)	**1213**	**203**	**−PDO (44)**	**1307**	**245**	**−2.07**	**94**	**0.04**
El Niño and +PDO (13)[b]	**1200**	**205**	**La Niña and −PDO (11)**	**1386**	**239**	**−2.05**	**22**	**0.05**
Summer balance								
El Niño (20)	−1629	185	La Niña (14)	−1532	330	−1.10	32	0.28
+PDO (52)	−1619	251	−PDO (43)	−1608	288	−0.21	93	0.84
El Niño and +PDO (13)	−1655	194	La Niña and −PDO (11)	−1566	357	−0.77	22	0.45

Notes: see Table 2.

[a] and [b] not normally distributed; when non-parametric Mann-Whitney U test is applied paired means [a]are significantly different ($p < 0.05$) and [b]are not signficantly different ($p > 0.05$). Note n values are smaller for the summer reconstruction based on the instrumental climate record because it begins in 1916. When all analyses are computed over this period the only notable difference is that mean tree-ring estimated winter balance for the El Niño +PDO: La Niña −PDO pairing is not significant.

though the absolute difference in estimated balance is larger than that between the means of the positive and negative PDO years (295: 236 mm w.e.).

The mean winter tree-ring based mass balance estimates are also higher for La Niña and negative PDO years than for El Niño and positive PDO years (Table 3B) and the means for the positive and negative phase of the PDO and the in-phase ENSO/PDO pairing are significantly different ($p < 0.05$, Table 3B). None of the differences between mean summer balance estimates are significantly different ($p > 0.05$).

The tree-ring based reconstructions of mass balance variation (Table 3B) show similar patterns to the shorter mass balance record (1966–1999; Table 2) and reconstructions based on the instrumental climate records over the 1901–1994 period (Table 3A). However, they exhibit generally lower variability as a consequence of the regression-based reconstruction procedure and the higher uncertainty in the tree-ring estimates (ie, more variance is lost in the tree-ring than instrumental-based reconstructions). As seen in the short measured mass balance records (Table 2), only the differences between the winter balance means for the different phases of the PDO and the in-phase PDO/ENSO pairing are statistically significant. Therefore, although they underestimate the differences between means, the tree-ring reconstructions can be used to examine longer-term relationships with ENSO and PDO variations in the Pacific Ocean.

The differences between the instrumental climate-record based and tree-ring based mass balance estimates are greater for the warm Pacific groupings (El Niño, positive PDO; variable a, Table 3A and B) than the cold Pacific groupings (La Niña, negative PDO; variable b, Table 3A and B). Means for the tree-ring based balance estimates average 193 mm w.e. (winter 248 mm w.e; summer 139 mm w.e.) higher than those based on the instrumental climate records for warm events (ie, they are not picking up the low winter balances and enhanced summer melting linked with a warm Pacific) whereas the estimated net balances for cold events average only 9 mm w.e. above those based on the instrumental records (note that results over the shorter common period (1916–1994) are very similar). If we assume that the instrumental-based reconstructions are closer to the 'true' seasonal mass balance values over this period, this result suggests that the tree-ring reconstructions underestimate the magnitude of below-normal balance years, particularly for the winter season.

Relationships identified using proxy records from the Pacific, 1706–1977

The analysis described above was extended by calculating mean seasonal balances for the same ENSO/PDO pairings over the period 1706–1977 where ENSO and PDO years are identified from proxy records. These analyses reveal statistically significant differences between winter balance for El Niño and La Niña years, positive and negative PDO years and the in-phase ENSO/PDO pairing (Table 4). Summer conditions are not significantly different for any of these comparisons. These results for winter balance are similar to the twentieth-century conditions described above (Table 3A) and suggest that the relationships identified have held over the past 272 years. However, the significant difference in summer balances between positive and negative PDO years seen in the estimates derived from instrumental climate records (Table 3A) is not seen in either of the reconstructions based on tree rings (Tables 3B and 4). This may indicate that this relationship is strongest over the twentieth century or reflect problem(s) (eg, loss of variance) with the mass balance reconstructions.

Relationships between the proxy mass balances, PDO and SOI series were also examined directly. Statistically

Table 4 Differences in tree-ring reconstructed seasonal mass balance means at Peyto Glacier (1706–1977) based on proxy records of the PDO and SOI

Group a	Mean a	SD a	Group b	Mean b	SD b	*t*	df	*p*
Winter balance								
El Niño (43)	**1210**	**248**	**La Niña (47)**	**1351**	**261**	**– 2.62**	**88**	**0.01**
+PDO (152)	**1263**	**252**	**– PDO (128)**	**1457**	**242**	**– 6.52**	**278**	**0.00**
El Niño and +PDO (32)	**1146**	**237**	**La Niña and – PDO (26)**	**1427**	**272**	**– 4.21**	**56**	**0.00**
Summer balance								
El Niño (43)	– 1434	292	La Niña (47)	– 1396	300	– 0.60	88	0.55
+PDO (152)	– 1404	286	– PDO (128)	– 1371	324	– 0.90	278	0.37
El Niño and +PDO (32)	– 1460	278	La Niña and – PDO (26)	– 1354	309	– 1.37	56	0.18

Notes: see Table 2.

significant negative correlations exist between the first principal component of the three PDO reconstructions and reconstructed winter and net balances ($r = -0.53$ and $r = -0.40$, respectively; $p < 0.05$, 1706–1977). The winter and net balance series also correlate significantly with the SOI reconstruction but these correlations are weaker ($r = 0.17$ and 0.14, respectively). The summer balance reconstruction does not correlate significantly ($p > 0.05$) with either the PDO or SOI reconstructions.

The strength of the relationships between winter mass balance at Peyto Glacier and Pacific climate indices vary through time (Figure 1). The relationship between winter balance and the PDO was highest from the late eighteenth century through the mid–late nineteenth century (correlations < -0.70 for the 30-yr periods centred from 1798–1810, 1817–1827, 1871–1875), which is generally a period of positive net balance when many glaciers in the area advanced. The correlation is also high (< -0.70) for the 30-yr periods centred on the years 1957–1962 (ie, the periods 1942–1972 through to 1947–1977), corresponding with a series of positive mass balances in the early measured record (1965–1975) from Peyto and glacier advances elsewhere in the Rockies (Luckman *et al.*, 1987). Correlations between the winter balance estimates and proxy SOI are highest (ie, 0.4–0.5, $p < 0.05$) over the intervals centred on 1874–1879 (ie, the 30-yr periods 1859–1889 to 1864–1894).

SST regression maps

At interannual timescales, the regression maps of November–March Pacific SSTs against the tree-ring based winter and summer mass balance reconstructions (1870–1994; Figure 2a) show an El Niño-like pattern with a band of negative coefficients concentrated along the equator extending from west of the date line to the west coast of the Americas. Centres of opposite sign are located in the central North Pacific and near New Zealand in the south Pacific. Overall, as one would expect, the regression coefficients are stronger with winter (Bw) than summer balance (Bs) and larger areas are better correlated (eg, the positive centre in the South Pacific extends further eastward and the negative coefficients in the equatorial Pacific extend up the coast of North America). Nevertheless the regression patterns against both seasonal series are ENSO-like and, like the *t*-test results, indicate that warm winter (November–March) conditions in the equatorial Pacific (El Niño events) are associated with lower than average Bw (lower accumulation) and lower than normal Bs (summer balance is more negative, ie, greater summer melting).

The regression maps produced using the low pass filtered summer and winter mass balance reconstructions (Figure 2b) show broader centres of significant coefficients than those for the high-pass filtered data. In particular, the wide longitudinal band of negative coefficients in the central-eastern Pacific shows greater meridional extent than the interannual patterns. The coefficients of opposite sign in the northern and southern Pacific are also stronger and more extensive. This pattern resembles the pattern of decadal–interdecadal variability identified previously (eg, Zhang *et al.*, 1997).

Aspects of the relationships demonstrated between Peyto winter balance and Pacific SSTs have been documented from the observational record (eg, Walters and Meier, 1989; Hodge

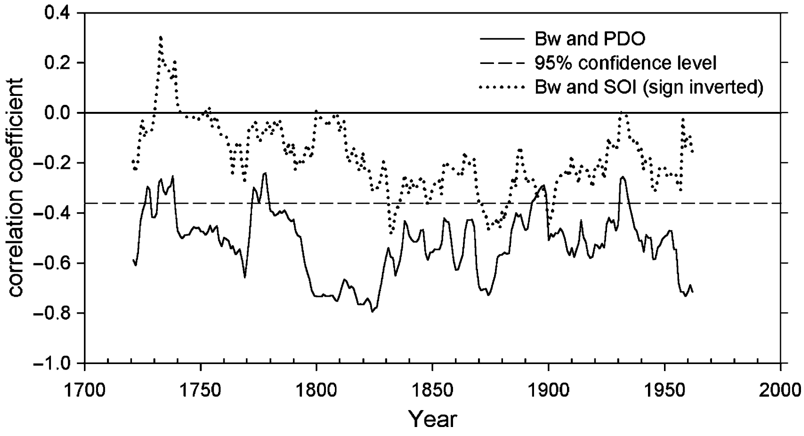

Figure 1 Moving correlations calculated between the tree-ring based winter mass balance reconstruction (Bw) for Peyto Glacier and reconstructed PDO and SOI (see text for sources). Correlation coefficients are calculated over 31-yr periods and plotted on the central year. The unadjusted 95% confidence level is displayed. When the effective sample size is adjusted for first-order autocorrelation (coefficients calculated 1706–1977) the 95% confidence interval for the correlations between winter balance and the PDO series is ±0.51 and ±0.36 with the SOI reconstruction

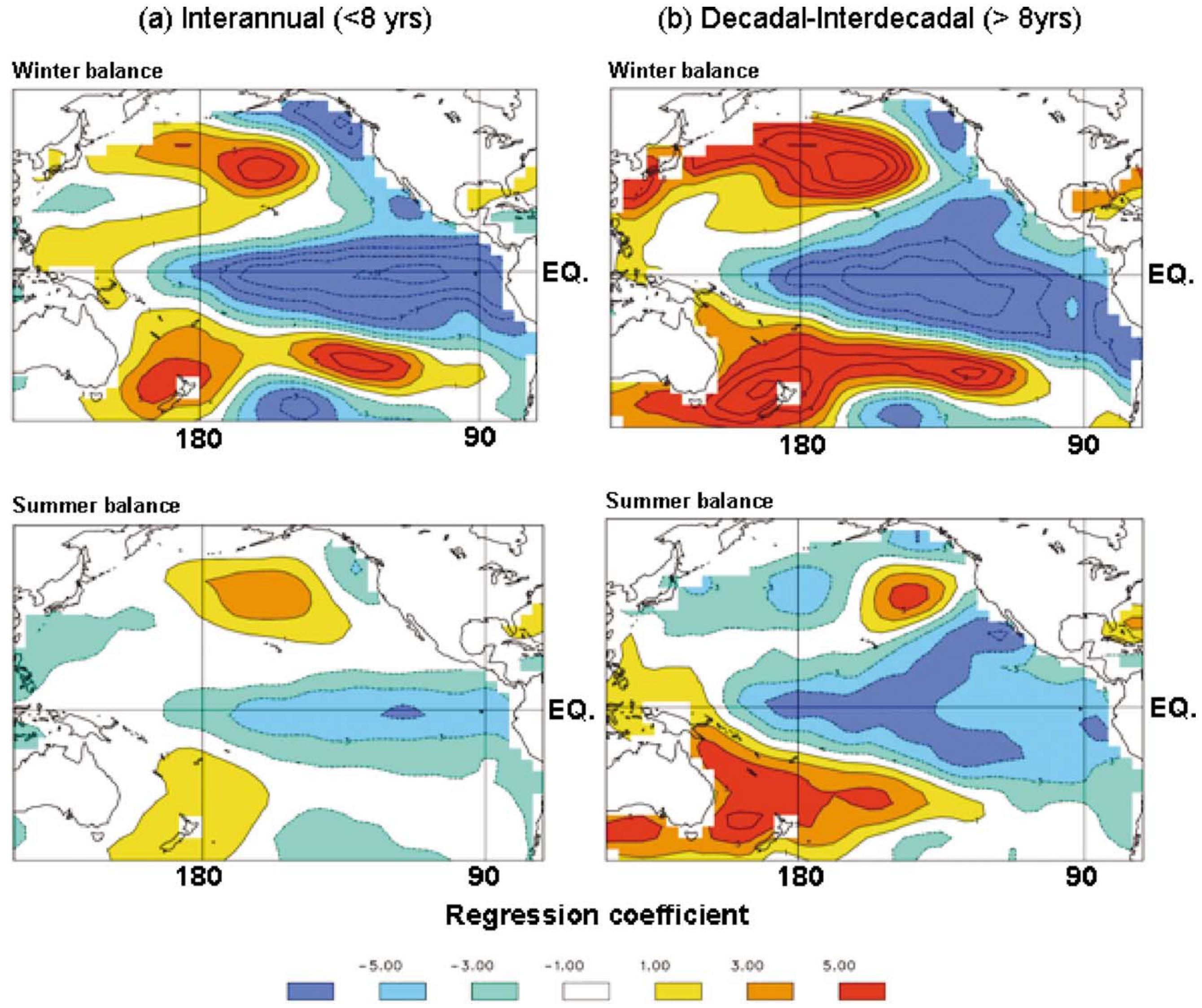

Figure 2 November–March Pacific sea surface temperatures regressed on tree-ring based winter and summer mass balance reconstructions for Peyto Glacier over the period 1870–1994 at (a) interannual and (b) decadal–interdecadal timescales. Units: 1.0e-4°C per standard deviation of Bw (Bs). Correlation coefficients for the winter balance patterns and the decadal–interdecadal summer balance pattern are generally significant at the 95% level in the centres of action

et al., 1998; Bitz and Battisti, 1999; McCabe *et al*., 2000; Demuth and Keller, 2006). Yarnal (1984) noted that Peyto Bs appears to be controlled by mid-tropospheric flow coming off the Pacific but did not explore relationships with Pacific SSTs. The relationship demonstrated here with summer balance suggests that winter SSTs in the Pacific can influence summer balance, and possibly summer climate (see discussion of Bw:Bs relationships below), at Peyto Glacier. Hodge *et al*. (1998) found significant correlations between summer balance at the South Cascade Glacier in Washington State and equatorial SSTs from the prior winter. Winter SST anomalies in the Pacific have also been shown to influence summer drought in western Canada (eg, Bonsal *et al*., 1993). In particular, Shabbar and Skinner (2004) found that an ENSO-like pattern of Pacific variability (a leading mode of DJF SSTs) correlates negatively with Palmer Drought Severity Index values extending from southern British Columbia across the Canadian Rockies, ie, warm, dry conditions that enhance summer melting may correspond with a warm equatorial Pacific. A summer temperature reconstruction for the southern Canadian Rockies (Luckman and Wilson, 2005) – used as one of the predictors in the Peyto Glacier Bs reconstruction (see Table 1 notes) – shows similar relationships with Pacific SSTs.

Summary and conclusions

Previous studies (eg, Bitz and Battisti, 1999) have identified links between conditions in the Pacific Ocean and mass balance of Peyto and other North American glaciers using measured records of mass balance that are generally < 30 yr in length. In this paper we extend these analyses using reconstructions of seasonal mass balance for Peyto Glacier derived from both instrumental climate data and tree-ring records. Despite uncertainties in the measured and estimated mass balance records, the tree-ring reconstructions replicate the differences in seasonal mass balances between different phase pairings of ENSO and PDO events identified over the period 1901–1994 from the instrumental record. La Niña and negative PDO years have greater net balances than El Niño and positive PDO years. Differences were more significant for winter mass balance, which is more sensitive to these wintertime phenomena, and the greatest absolute differences were found between means from the in-phase ENSO/PDO pairings. Yu *et al*. (submitted) suggest that during these periods atmospheric energy propagates towards North America from the north Pacific as well as from the equatorial Pacific, producing a more robust Pacific North American mode-like stationary wave. Mass balance means (winter and summer) for out-of-phase ENSO/PDO pairings do not differ significantly over any of the time periods studied.

Similar relationships were found over the 1706–1977 period using tree-ring based mass balance reconstructions and proxy records of Pacific Ocean variability (PDO and SOI reconstructions), although there are changes in strength of the relationship between Bw and the PDO. Maps displaying interannual relationships between Pacific SSTs and mass balance over the period 1870–1994 resemble an ENSO pattern for both seasons. Maps of decadally filtered data resemble the ENSO-like pattern of decadal–interdecadal variability identified previously (eg, Mantua *et al.*, 1997; Zhang *et al.*, 1997). The mapped patterns are stronger for winter than summer balance (as seen by Bitz and Battisti, 1999) and more extensive at the decadal timescale than the interannual timescale, consistent with previous studies.

Although previous literature has focused on relationships between Pacific SSTs and winter mass balance, we also identify a coherent but weaker relationship between winter SSTs and tree-ring reconstructed summer mass balance (Figure 2). This does not appear to be related to an overall warming of the global oceans as the secular trend has been removed from the mass balance series. Some authors (eg, Bitz and Battisti, 1999; Moore and Demuth, 2001) have noted that Bw for glaciers in this area can correlate with Bs because positive winter balance (ie, greater snow accumulation) can increase the surface albedo, enhancing shortwave reflectivity thereby decreasing summer melt. In the results presented here, the tree-ring (or instrumental) based mass balance proxies cannot directly identify any such physical link between Bw and Bs. Although the tree-ring records used to develop the Bs reconstruction are sensitive primarily to summer temperatures, a similar lagged relationship with winter SSTs may exist: higher winter snowfall (which can be related to SST patterns) can affect spring growth either through a change in the length of the growing season or through changes in spring soil moisture availability. However, the fact that a coherent relationship is identified between the winter SSTs and the tree-ring generated summer balance estimates suggests that, as mentioned earlier, patterns of wintertime Pacific SST anomalies may persist to impact summer climate and subsequently summer balance. Possible relationships between winter SSTs and summer climate require further investigation but are beyond the scope of this paper.

The measured mass balance series for Peyto Glacier are considered to be regionally representative (eg, Watson and Luckman, 2004a) and correlate positively with other glaciers from the US Pacific Northwest (McCabe and Fountain, 1995; McCabe *et al.*, 2000). Therefore, these findings can be applied to glaciers over a much wider region. They confirm that mass balance is strongly related to conditions in the Pacific Ocean where changes in large-scale patterns of SSTs affect the delivery of moisture from winter storms. The results also show a response to Pacific variability on both interannual and decadal–interdecadal timescales. Peyto Glacier mass balance is adversely influenced by warm conditions in the equatorial Pacific (eg, El Niño events and the positive phases of the PDO) that occur on interannual and decadal–interdecadal timescales because they foster atmospheric circulation patterns that lead to lower accumulation during winter months and appear to persist to enhance melt (hot, droughty conditions) during summer months. Persistent positive or negative ENSO-like regime changes in response to increased atmospheric greenhouse gas concentrations would have a substantial impact on winter precipitation at glaciers across the southern Cordillera. Decreases in winter precipitation would exacerbate impacts of increasing summer temperatures on melt rates and recession, whereas increased winter balance may offset future glacier loss.

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