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PART THREE

# Trends in Natural Landscapes

*Climate Change*

10

# Glacier Mass Balance in the Northern U.S. and Canadian Rockies

## PALEO-PERSPECTIVES AND TWENTIETH-CENTURY CHANGE

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Alpine glaciers in the U.S. and Canadian Rocky Mountains reached their maximum Holocene extent during the Little Ice Age (Luckman 2000; Carrara 1989). Subsequently, glaciers throughout the region underwent dynamic and sometimes rapid phases of frontal recession (Carrara 1989; Luckman 2000; Key, Fagre, and Menicke 2002). Recent glacier research has focused on developing detailed histories of glacier fluctuations throughout the Little Ice Age. These data, though sparse, indicate multiple periods of glacier advance and suggest that the timing of maximum advance may not have been synchronous (Luckman 2000). Moraine dates at several of the northernmost glaciers studied (e.g., in Jasper National Park) indicate maximum glacier extent between 1700 and 1750 (Luckman 2000) with a subsequent only slightly less extensive advance between 1800 and 1850. Farther south (e.g., in Kananaskis and Glacier National Park) the Little Ice Age maximum extent occurred between ca. 1800 and 1850 (Carrara 1989; Smith, McCarthy, and Colenutt 1995; Luckman 2000; Key et al. 2002).

Mass balance records for this region are limited to two records from the Canadian Rockies (Peyto Glacier 1965–present and Ram River Glacier 1965–75 [Demuth and Keller 2006; Young and Stanley 1977]). Watson and Luckman (2004*a*) and Pederson et al. (2004) have used tree-ring data to investigate the paleoclimatic drivers of glacier fluctuations for two sites located along the Continental Divide (Figure 10.1). Although these reconstructions used different paleoclimate and glacier data, the results produced some interesting similarities and differences in inferred glacial dynamics over the past 300 years. In this article we use instrumental and proxy climate data to investigate whether the differences between these proxy mass balance series reflect regional differences in mass balance over time or result from differences in the approaches and data used to develop the reconstructions. In doing so, we begin to explore differences in timing of the Little Ice Age maximum glacier advance and

Note: Emma Watson's contribution to this chapter is courtesy Environment Canada.

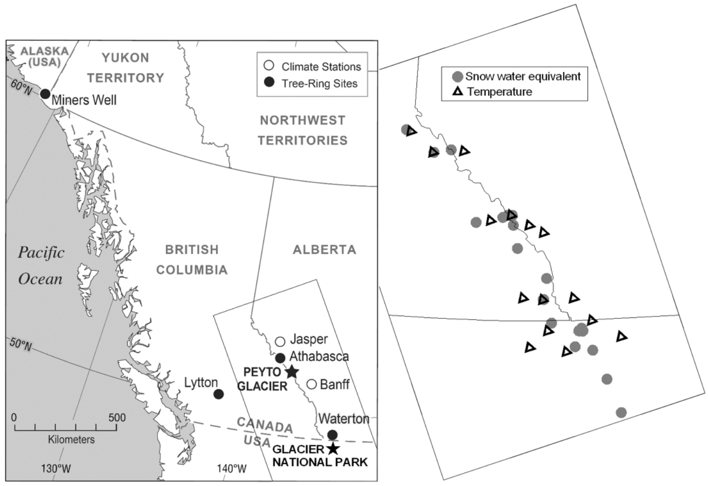


FIGURE 10.1. Location of Peyto Glacier, Alberta, and Glacier National Park, Montana, showing selected meteorological stations and tree-ring chronology sites used to develop the Peyto Glacier mass balance reconstructions. The larger-scale map shows the stations located along the Continental Divide from which snow water equivalent and temperature records were obtained.

their implications for future paleoglaciological research.

## CONSTRUCTION OF GLACIER MASS BALANCE PROXY RECORDS

The variability in width (or density) of annual growth rings in many species of trees has a demonstrated sensitivity to climate variables such as precipitation and temperature (Fritts 1976). Tree-ring chronologies are routinely used as predictor variables in statistical models that provide valuable estimates of climate conditions before the advent of instrumental measurement. The mass balance of continental glaciers is sensitive to many of the same climate factors that influence tree growth. Therefore, tree-ring chronologies can be used to generate useful estimates of past glacier conditions.

In this chapter we compare tree-ring-based mass balance reconstructions for Peyto Glacier in the Canadian Rockies and for the glaciers of Glacier National Park in the northern U.S. Rockies. Approximately 35 years of mass balance data for Peyto Glacier allow direct calibration of mass balance estimates. Watson and Luckman (2004*a*) have developed 322 year-long reconstructions of winter, summer, and net mass balance for Peyto Glacier using temperature and precipitation-sensitive tree-ring chronologies from Canada and Alaska. The winter component was estimated using a *Tsuga mertensiana* (mountain hemlock) ring-width chronology from as Miners Well[1] and a July–June precipitation reconstruction from *Pinus ponderosa* (ponderosa pine) from Lytton, British Columbia. Summer mass balance predictors include the Columbia Icefield maximum temperature reconstruction from *Picea engelmannii* (Engelmann spruce) (Luckman and Wilson 2005) and a July–June precipitation reconstruction from *Pseudotsuga menziesii* (Douglas fir) for Waterton (Watson and Luckman 2004*b*). Both winter and summer models were calibrated against the measured mass balance records (1966–94), and they explain > 40% of the variance in these records and pass conventional verification tests conducted in dendroclimatological studies.

Pederson et al. (2004) used tree-ring-based proxy records to compare and explain measured fluctuations in the Agassiz and Jackson Glaciers (Carrara 1989; Key et al. 2002) over the past 300 years. Winter mass balance was estimated using a reconstruction of the Pacific Decadal Oscillation (PDO; D'Arrigo, Villalba, and Wiles 2001) because of the demonstrated strong linkage between this sea-surface-temperature anomaly, atmospheric circulation, and regional snowpack patterns (e.g., Selkowitz, Fagre, and Reardon 2002; Moore and McKendry 1996). Summer balance estimates were based on a summer drought (June–August; precipitation-potential evapotranspiration) reconstruction for Glacier National Park from mid-elevation *Pseudotsuga menziesii* (Douglas fir) and *Pinus flexilis* (limber pine) chronologies.

## COMPARISON OF MASS BALANCE PROXY RECORDS

The methods and data used to infer and reconstruct glacier mass balance differ between the two studies, resulting in interesting similarities and differences in balance estimates. The seasonal balances in both regions exhibit strong decadal and multidecadal variation (Figure 10.2). The winter balance proxies often share periods of above- and below-average accumulation events, though the magnitude and intensity of individual events may vary. There is general correspondence between records from the 1770s to the 1790s throughout the nineteenth century and a common period of high accumulation from the mid-1940s to the late 1970s. There are fewer similarities between the records of summer balance. The two periods of highest summer balance correspondence are the favorable (cool) summer conditions of the early 1700s and the early to mid-1800s.

The many similarities between the seasonal mass balance records result in common periods of predicted positive and negative net balance, but differences between the net balance records point to some striking and perhaps important disparities between the seasonal proxies. For example, above-average accumulation is reconstructed for the early 1700s for Peyto Glacier, whereas the D'Arrigo, Villalba, and Wiles (2001) PDO reconstruction used to estimate winter balance in Glacier National Park indicates average to below-average accumulation. The proxy records also indicate major differences between snowpack levels for the early twentieth century. There are also significant differences between the proxies for summer balance. Glacier National Park shows average to high summer ablation rates between ca. the 1720s–1770s and the 1850s–1880s, when

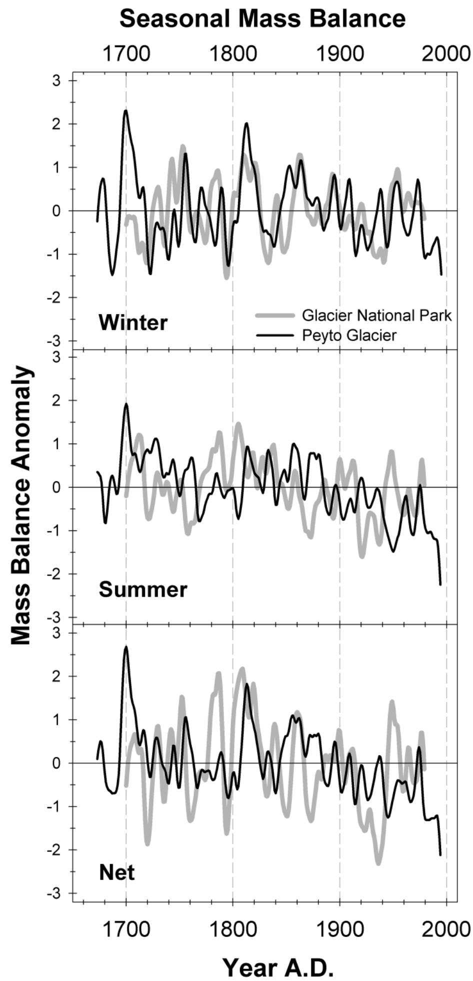


FIGURE 10.2. Smoothed (ten-year spline) seasonal and net mass balance reconstructions for Peyto Glacier (Watson and Luckman 2004*a*) and Glacier National Park (Pederson et al. 2004).

low ablation conditions are reconstructed for Peyto Glacier. The most striking difference, however, is the long-term linear trend toward higher summer ablation rates for Peyto Glacier that critically influence its net balance record. These differences between the components of reconstructed net balance may reflect either actual differences in climate (or glacier) regimes between these two areas or differences in the parameters/techniques used to develop the reconstructions. To address this issue, we first investigate the instrumental climate records.

## INSTRUMENTAL CLIMATE RECORDS

Most scientists agree that the net balance of glaciers in western North America is controlled primarily by summer temperatures and winter snowpack (e.g., Letréguilly 1988; Bitz and Battisti 1999; Pederson et al. 2004; Watson and Luckman 2004*a*). Therefore, to investigate possible differences in contemporary climate drivers of mass balance between these two regions, we examined instrumental records of snow water equivalent (used to evaluate winter snowpack) and minimum and maximum temperature that could be used to assess the magnitude of summer melting and changes in seasonality in the region.

### SNOW WATER EQUIVALENT RECORDS

We assembled the longest, most complete snow water equivalent[2] records from 25 stations located at elevations > 1,000 m along the portion of the Continental Divide located within the study region (Figure 10.1). The majority of these records are from snow courses (Canadian and U.S. data) and snowpack telemetry sensors (most of the U.S. data) located near present-day glaciers, though at lower elevations (mean = 1,570 m, range 1,040–2,030 m). These records probably underestimate actual snowfall amounts at the glaciers, as Peyto Glacier is between 2,140 and 3,180 m and glacier termini in Glacier National Park range from 2,000 to 2,400 m a.s.l. The snow water equivalent data are presented in standardized (i.e., dimensionless) units to permit comparison of records from different elevations and compensate for the considerable spatial variability in snowfall totals even at the same elevation.

The Peyto Glacier winter mass balance reconstruction is positively and significantly ($P < 0.05$) correlated with the record from 22 of the 25 stations over the 1951–87 interval. Moreover, more than 60% of these correlation coefficients exceed 0.50, indicating that these records are suitable for exploring the primary controls of winter mass balance in the instrumental record. They also display coherent decadal-scale variation, with below-normal winter snowpack between 1922 and 1945 and between 1977 and 2003 and above-normal snowpack from 1946 to 1976 except for values slightly below the mean in the early 1960s (Figure 10.3). This pattern and the spatial scale of coherence are consistent with records of snowpack in British Columbia (Moore and McKendry 1996), Glacier National Park (Selkowitz, Fagre, and Reardon 2002), the Pacific Northwest (Mote 2003), and other parts of western North America (Brown and Braaten 1998; Cayan 1996). Similar variation, particularly the sharp decrease in the mid-1970s, has been identified in time series of many other climate-related variables in the western Americas (Ebbesmeyer et al. 1991) and corresponds with interdecadal variations in sea-surface temperatures in the Pacific Ocean (Mantua et al. 1997; McCabe and Dettinger 2002). In the absence of local proxies for winter precipitation totals, these results demonstrate that winter precipitation varies coherently over large areas in the western cordillera, justifying the use of more distant tree-ring-derived proxy records to estimate winter balance in the Canadian Rockies and adjacent Montana.

The mean intercorrelation of each snow water equivalent record with all 24 others over the 1951–87 period exceeds 0.50 except for two of the most northern records, Field and Yellowhead, both in the Rocky Mountain Trench. Interestingly, principal components analysis (with varimax rotation) calculated over the 1951–2003 interval (17 records) identified northern and southern regions (Figure 10.3) that differ primarily in the magnitude rather than the timing of major periods of above- and below-normal snow water equivalent values. In particular, the period of high snowpack centered around 1952 is slightly more pronounced in the southern part of the region. Although snowpack over the past 20 years has been relatively low, mean snow water equivalent values are greater at recording stations in the northern half of the transect. These differences may simply reflect the earlier measurement date of these northern records

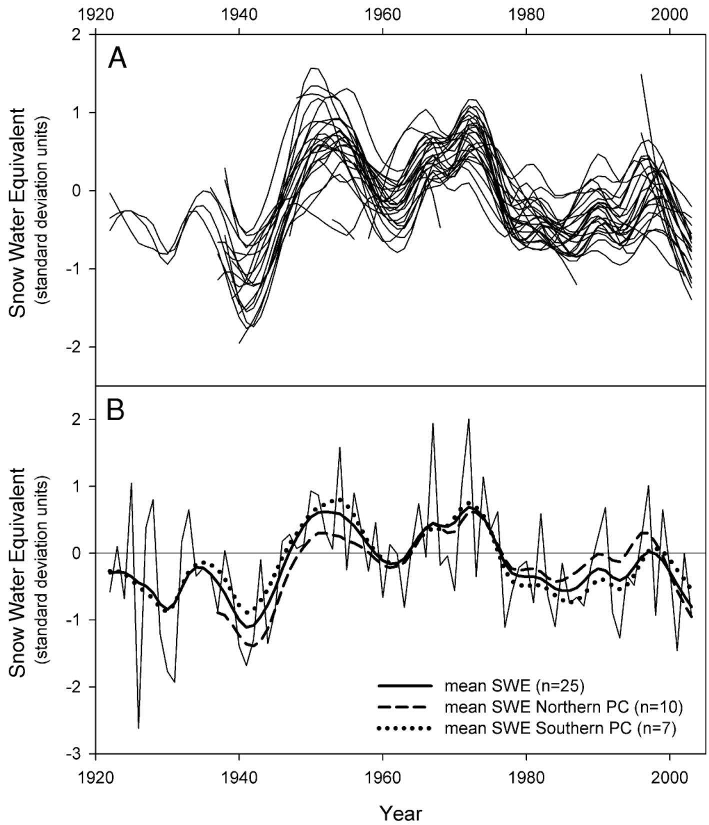


FIGURE 10.3. Standardized snow water equivalent (SWE) records for April 1 (May 1 for the U.S. stations) over the twentieth century. (A) Standardized values at 25 stations. (B) Mean annual values for these stations smoothed with a ten-year spline. The data are presented in standard-deviation units from their 1951–2003 means (several station records end before 2003). Also plotted are smoothed (10-year spline) mean values for the 10 most northerly stations that load on Principal Component 1 (41% variance explained; varimax rotation) and the 7 southern stations that load on Principal Component 2 (35% explained).

(April 1, generally the time of maximum snowpack [Cayan 1996]) compared with the southern records (five of seven are Montana stations that report May 1), but this is unlikely because over the length of the record the northern measurements are not consistently higher than their southern counterparts. The mean elevation of the northern sites (1,611 m) is also slightly higher than that of the southern sites (1,522 m). Mote (2003) and Selkowitz, Fagre, and Reardon (2002) note that the April 1 snow water equivalent is weakly correlated with winter (October–March) temperatures in this part of the Rockies. However, snowpacks are less at the lower-elevation southern stations over the past ~20 years, suggesting that they are perhaps more sensitive to the higher winter (Luckman 1998) and spring (Figure 10.4) temperatures recorded across the region. A more detailed analysis of a larger set of snow water equivalent records and related monthly/seasonal precipitation and temperature records may help identify the cause(s) of these slight north-south differences.

## SUMMER TEMPERATURE RECORDS

Temperature records were assembled from the longest and most complete meteorological station records in the region along the Continental Divide ($n = 15$; Figure 10.1). The highest-quality long-term stations are all located in valley bottom sites ranging from 640 to 1,390 m in elevation. Temperature data from these lower-elevation sites probably underestimate warming at higher elevations near glaciers because of nonlinearities in the scale and pace of temperature change with elevation in mountains (Diaz and Bradley 1997; Beniston, Diaz, and Bradley 1997), but the trends documented at valley floor stations may be considered representative, if conservative, estimates of changes at glacier sites.

Figure 10.4 shows summer (June–August) mean maximum and minimum temperatures

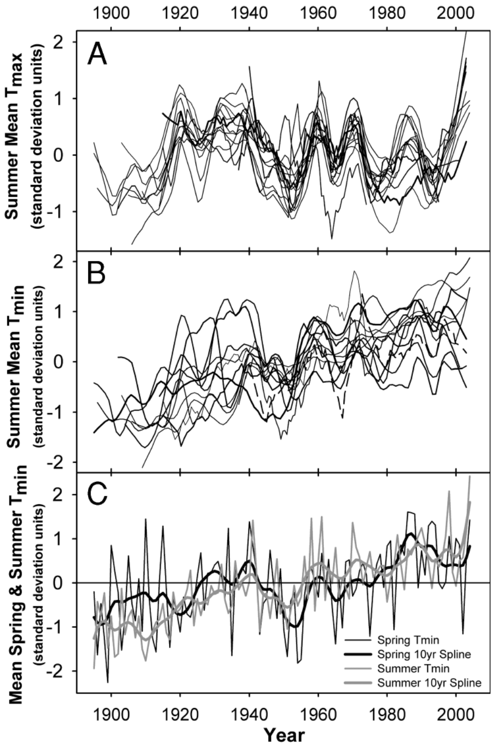


FIGURE 10.4. Standardized seasonal maximum ($T_{max}$) and minimum ($T_{min}$) temperature records over the twentieth century. (A) Mean summer $T_{max}$ anomalies for 15 meteorological stations. (B) Mean summer $T_{min}$ anomalies for these 15 stations, smoothed using a ten-year spline. (C) Mean annual and smoothed (ten-year spline) values for spring (March–May) and summer (June–August) $T_{min}$ anomalies using all stations. The majority of the temperature data was obtained from the Web sites of the U.S. Historic Climatology Network (Easterling et al. 1996; ftp://ftp.ncdc.noaa.gov/pub/data/ushcn/) and the Adjusted Historical Canadian Climate Data (Vincent et al. 2002; Environment Canada 2006). Additional unadjusted Canadian station records were obtained from the Canadian National Archive, Meteorological Service of Canada.

from all 15 stations within the study area over the 1895–2003 interval. The records of mean summer maximum temperature display strong decadal-scale coherence but no long-term trend after ca. 1920.[3] Periods of above-average maximum temperature occur from 1920 to 1940 and in the 1960s, 1970s, and 1980s before increasing to the extreme value in 2003. The Peyto Glacier summer balance reconstruction shows significant ($P < 0.05$) correlations (ranging from $-0.22$ to $-0.53$) with summer maximum temperature for 11 stations, with the strongest relationships occurring with the more northerly ones. The summer mass balance reconstruction for the Glacier National Park region is significantly ($P < 0.05$) correlated with summer maximum temperature for 13 stations (range $-0.36$ to $-0.65$, highest with Kalispell). Thus, the temperature variation exhibited in the instrumental records of summer maximum temperature is representative of a large portion of the variation in summer mass balance for glaciers throughout the region.

Summer minimum temperature records exhibit a different but common mode of variation and change. There is a strong linear increase over the twentieth century, with all stations exhibiting a mean intercorrelation exceeding 0.50. Linear increases in nonstandardized individual station records show changes ranging from 0.5 °C to 4.0 °C (ca. 1895–2003; the length of record varies) that appear to be dependent on elevation and station location in relation to the Continental Divide. Thus the most extreme changes in mean summer minimum temperature exhibited by many of the recording stations ranges from 4–5 °C in the early twentieth century to 7–8 °C in 2003. The strong linear trend in the summer minimum temperature records, combined with the variation in the maximum temperature records, also indicates a decreasing diurnal temperature range that is consistent with studies of other instrumental records (e.g., Skinner and Gullett 1993) and paleoclimatic investigations (Wilson and Luckman 2002). These changes may result in greater summer ablation as temperatures at the glaciers are maintained at higher levels throughout the summer season. Because these trends in minimum temperature tend to be consistent across all seasons, increases in the spring and autumn also extend the period of melting. Averaged spring (March–May) and summer (June–August) minimum temperatures for the standardized records of the 15 stations show strong increases over the twentieth century. Absolute spring minimum temperature values (1895–2003) for these stations ranged from $-2$ °C to $-8$ °C in the early twentieth century. By the 1980s, however, average spring

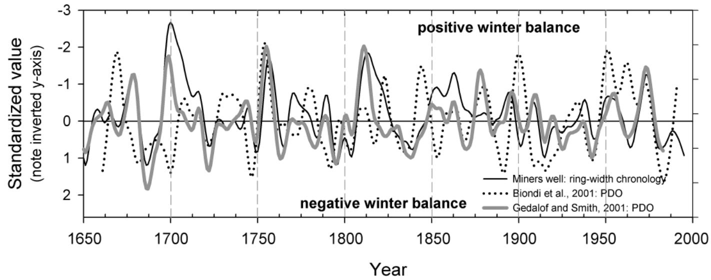


FIGURE 10.5. Tree-ring-derived records related to sea-surface temperatures in the Pacific Ocean and winter mass balance in the study area. The Gedalof and Smith (2001) and Biondi, Gershunov, and Cayan (2001) series are reconstructions of PDO; Miners Well is a *Tsuga mertensiana* (mountain hemlock) tree-ring-width chronology from the Gulf of Alaska developed by G. Wiles, P. E. Calkin, and D. Frank (National Climatic Data Center n.d.). All series have been smoothed with a ten-year spline.

minimum temperature values at the lower or more southerly sites had risen to (or beyond) 0 °C, extending the duration of the annual melt. Similar effects would be expected at higher elevation sites.

Shea, Marshall, and Livingston (2004) find spring, summer, and autumn minimum temperatures to be important predictors for modeling twentieth-century glacier locations in the Canadian Rockies. Summer minimum temperature is not a specific component of the summer balance reconstructions developed for either glacier because of the lack of representative proxy records, though it likely plays an important role in summer ablation rates. Since neither summer balance proxy accounts specifically for the observed increases in minimum temperature, we cannot account for the possible impact on glaciers of changes in the diurnal temperature range. However, estimates of summer ablation for Peyto Glacier show a strong twentieth-century linear increase that is not seen in the instrumental maximum temperature records largely because of the length of the instrumental series. This trend in the summer balance reconstruction results largely from the Athabasca summer maximum temperature reconstruction used as a predictor. Wilson and Luckman (2002) show a strong linear increase in proxy maximum temperature for interior British Columbia beginning ca. 1825 and extending into the early twentieth century, when records begin to exhibit strong decadal variation through the mid-twentieth century. The Athabasca maximum temperature reconstruction exhibits the same behavior (Luckman and Wilson 2005; Figure 10.5). Thus the Peyto Glacier reconstruction mirrors the long-term trend in maximum temperature, but the instrumental records of minimum temperature suggest that estimates of summer ablation rates in both studies might be improved if the long-term trends in minimum temperature could be better quantified back through time.

The regional instrumental temperature records for the twentieth century demonstrate coherence in both pattern and trend, though for certain periods (e.g., 1920s–1930s and 1960s–1990s) the relative magnitude of peaks differs between stations. Given that temperatures are a major control of the magnitude of summer balances, this similarity suggests that the pattern of summer balances should also be similar. A denser network of climate reconstructions will be necessary to explore details of possible differences in summer temperatures and winter snowfall across the region in the preinstrumental period. Nevertheless, given the generally strong regional coherence of the instrumental records of the principal climatic inputs to both summer and winter balances, it seems that significant differences between the reconstructions are unlikely to be related to regional variation in the climatic drivers of mass balance.

## TREE-RING BASED SEASONAL MASS BALANCE PROXIES

### WINTER MASS BALANCE

Previous studies of late-twentieth-century glacier mass balance in the western cordillera (McCabe, Fountain, and Dyurgerov 2000; Bitz and Battisti 1999; Walters and Meier 1989; Demuth and Keller 2006) have identified connections with conditions in the Pacific Ocean and, in particular, with the documented pattern of decadal-interdecadal sea-surface temperature variation (Mantua et al. 1997). Therefore, given the lack of proximal winter-sensitive tree-ring chronologies, both attempts to reconstruct winter balance targeted predictors related to this variation (Figures 10.1 and 10.2). This strategy assumes that the teleconnected relationships seen in the instrumental record are stable through time and across space (e.g., that the Miners Well chronology is strongly correlated with Peyto Glacier winter balance throughout the last several centuries). It also assumes that the PDO operated in a similar manner (with similar variation) prior to the period of instrumental records. Tree-ring-based studies of past interdecadal variation in the Pacific Ocean (MacDonald and Case 2005; D'Arrigo, Villalba, and Wiles 2001; Gedalof and Smith 2001; Biondi, Gershunov, and Cayan 2001; Evans et al. 2000; Minobe 1997) show little agreement as to conditions prior to ca. 1840 (Gedalof, Mantua, and Peterson 2002). Given potential changes in the behavior of the Pacific and the resultant impact on local climates, the choice of potential predictor variables for winter balance has a strong influence on the resultant reconstructions. This source of variation necessitates verification of these reconstructions through comparisons with other proxy data sources.

In evaluating the winter balance results, we look to independently derived records for additional confirmation of reconstructed trends and variation in mass balance. The dated moraine record compiled from 66 glaciers in the central Canadian Rockies by Luckman (2000) is particularly useful. Terminal moraines form at the downvalley limits of glaciers following the change from positive to negative net mass balance. Major periods of moraine formation in the regional record correspond with or follow the periods of strong positive mass balance (i.e., 1700–1725 and 1825–1850 [Figure 10.2]) identified in the Peyto Glacier reconstruction (Watson and Luckman 2004*a*). The mid-nineteenth-century period is also identified as one of positive mass balance in the Glacier National Park series and corresponds with independent assessments for the Little Ice Age maximum for the region (Carrara 1989; Key, Fagre, and Menicke 2002). However, the interval of high winter balances for Peyto Glacier in the early 1700s is neither as prolonged nor as pronounced in the Glacier National Park reconstruction (Figure 10.2).

Both sets of reconstructions indicate that periods of glacier advance were usually associated with a combination of cool summers and wet winters. The summer balance component of the Glacier National Park reconstruction indicates that summers in the early 1700s were cool and wet (i.e., summer melting was below normal) but winters were relatively dry (Figure 10.2). The PDO reconstruction used to derive the winter balance proxy for the park incorporates temperature-sensitive tree-ring chronologies from Alaska and the Pacific Northwest plus reconstructions of the Palmer Drought Severity Index (PDSI) from northern Mexico (Figure 10.2).[4] If the Gedalof and Smith (2001) PDO reconstruction (Figure 10.5) were used to predict winter balance in Glacier National Park, net balance values in the early 1700s would be strongly positive and consistent with the moraine record for the central Canadian Rockies and the Peyto Glacier reconstruction. This similarity is not surprising given that the Gedalof and Smith PDO and Peyto winter balance reconstructions both use chronologies from Alaska and western British Columbia.

Further differences are noted between the reconstructions over the twentieth century. The

Glacier National Park winter balance series shows more consistently positive values in the latter half of the twentieth century than the Peyto series. Peyto winter balance is estimated as above average for parts of the twentieth century, but high summer ablation (related to warm summer temperatures) results in negative net balances. Given the strong similarity of snowpack (Figure 10.3) and temperatures (Figure 10.4) across the region, the striking differences in net balance over the twentieth century are probably related to the Glacier National Park summer balance reconstruction, which may at times reflect variation in precipitation more strongly than the higher temperatures over this period. Both net balance series do, however, show positive values in the 1960s to 1970s that correspond to the formation at several sites of small readvance moraines in the 1970s and 1980s (Luckman, Harding, and Hamilton 1987; Pederson et al. 2004).

These results demonstrate the strong sensitivity of the winter balance reconstructions to the predictor variables used. Even though many of the predictors are considered to represent the same phenomenon (i.e., variations in North Pacific sea-surface temperatures), they are developed using data from different areas. Several studies (e.g., Gedalof, Mantua, and Peterson 2002; Biondi, Gershunov, and Cayan 2001) have suggested that the PDO itself has varied in intensity over time, and this variation would likely impact the strength and pattern of teleconnections to North American climate. Significant predictors in the D'Arrigo, Villalba, and Wiles (2001) and Biondi, Gershunov, and Cayan (2001) PDO reconstructions are from Mexico and California and are therefore strongly related to conditions in the equatorial Pacific. The similarities between the Peyto mass balance reconstruction, the moraine record for the Canadian Rockies, and the Gedalof and Smith (2001) PDO reconstruction suggest that the stronger weighting of data from Alaska and the Pacific Northwest may better reflect the conditions in the North Pacific that control the strength and movement of winter storms (i.e., the strength and location of the Aleutian Low) and ultimately affect winter mass balance at glaciers in this part of the Rockies.

## SUMMER MASS BALANCE

An interesting difference between the Peyto Glacier and Glacier National Park mass balance estimates is the increasingly negative summer and net mass balance values during the twentieth century in the former. The summer balance component for Glacier National Park is estimated from a summer drought reconstruction that is only partially temperature-dependent. Although this drought reconstruction is significantly correlated with 13 of 14 maximum summer temperature records, it is much more strongly correlated with Kalispell precipitation (instrumental drought $r = 0.98$; reconstructed drought $r = 0.60$). This is a significant limitation considering that summer mass balance records collected at Peyto Glacier (1966–present: Demuth and Keller 2006) are not significantly correlated with summer precipitation. Therefore, it would appear that at times the Glacier National Park summer balance estimates contain a mixed temperature and precipitation signal that may not consistently track summer melt.

The instrumental temperature records for this region show a steep positive trend in mean monthly minimum temperatures (Figure 10.4) that is consistent with previous research (e.g., Wilson and Luckman 2002) but not seen in instrumental maximum temperature records. However, estimates of summer balance at Peyto Glacier do not explicitly include or necessarily capture changes in minimum temperature, making it difficult to assess the importance of this temperature variable. The trend toward increasing summer ablation is consistent with independent estimates based on photographic evidence that Peyto Glacier has lost 70% of its volume over the past 100 years (Demuth and Keller 2006; Demuth 1996; Wallace 1995). The Glacier National Park summer balances during the twentieth century are much more variable, and the absence of a trend may be because this drought-driven reconstruction captures little of the long-term trends present in minimum temperature. Although both summer precipitation and temperatures contribute to drought, drought records generally do not exhibit the same amount of low-frequency variability seen in temperature reconstructions. The differences may also be related to the amount of centennial-scale variation that is both preserved and present in the reconstructions. For example, the most heavily weighted predictor in the Peyto summer balance reconstruction (the Athabasca summer maximum temperature reconstruction) was constructed using a standardization procedure (i.e., regional curve standardization [Briffa et al. 1996]) that maximizes the retention of low-frequency climate information. Also, the Athabasca reconstruction spans more than 1,000 years, which is sufficient for preservation of centennial-scale variation, whereas the Glacier National Park summer drought reconstruction extends back only 461 years.

## SUMMARY AND DISCUSSION

In this chapter we have compared the first attempts to provide proxy mass balance information for Peyto Glacier in the Canadian Rockies and the glaciers of Glacier National Park, Montana. Though different data and approaches were used, these studies indicate that, with careful selection, tree-ring data can provide effective proxies for the major components of mass balance and thereby assist in the reconstruction of continuous records of past glacier fluctuations that are not available from more traditional glacier studies. These reconstructions also allow a more direct evaluation of the relative importance of temperature and precipitation controls on mass balance variability in the absence of long-term instrumentally derived records.

Evaluation of the reconstructions and longer instrumental climate records from the region indicate that decadal and longer-term trends in both precipitation and temperature have significant influences on mass balance that are not detectable in relatively short measured mass balance series (generally <40 years in length). Although these sites are approximately 500 km apart, examination of appropriate temperature and winter snowpack records confirms that the low-frequency variation in the temperature and snow water equivalent records is very similar during the twentieth century. Slight north-south differences in snow water equivalent were identified, however, and absolute amounts of precipitation and temperature values vary. If this strong coherence across the region has held over the past 300 years, the comparison of the proxy mass balance records and evaluation of the predictor variables suggests that many of the differences between these reconstructions may result from the choice of predictor variables used. Although the strength and intensity of the PDO appear to have varied over time, the scale and mean location of the Aleutian Low in winter and its control on regional snowpack should not have been dramatically different in the past. Therefore, the coherence seen across the region related to the Aleutian Low, through its influence on storm tracks, likely existed as well. However, the slight differences in snow water equivalent values across the region do suggest that there may have been breakdowns in regional coherence in the past (perhaps related to slight deviations in the location of the mean zonal flow). Further investigations of the instrumental climate record and the development of additional reconstructions of climate parameters for sites across the region would help address this issue.

In the cases discussed here, twentieth-century snowfall variability is driven principally by changes in circulation in the Pacific Ocean. Both reconstructions estimate positive winter and net mass balance for the mid-nineteenth century, confirming the dated moraine records in the two regions. Positive net mass balance is also identified in both series for the 1970s, coincident with minor readvances in both regions. There are, however, striking differences in the magnitude of seasonal and net balance estimates for the early 1700s and the twentieth century. It is difficult to distinguish differences in the winter balance reconstructions that may reflect local climate differences within the Rockies from those that may reflect larger-scale differences in teleconnection patterns influencing the proxies used to estimate winter mass balance. Winter balance proxies should ideally be based on more locally developed tree-ring data. In addition, these results indicate that proxies used to estimate summer balance should maximize the temperature signal and minimize the influence of summer precipitation. The development of a summer temperature reconstruction for Glacier National Park may reduce ambiguities related to the mixed precipitation and temperature signal in its summer balance series.

Although these glaciers experience a continental climate regime and have been assumed to be mainly sensitive to variations in solar radiation and hence temperatures, our results indicate that it is important to consider both precipitation- and temperature-related variables in these cases. Studies of the instrumental record and these reconstructions indicate that winter balance values may vary by as much as 30–40% on decadal time scales in response to circulation changes. Therefore, snowfall variation is an important factor regulating net glacier mass balance. Our analysis of the temperature record also suggests that the increase in minimum temperatures over the twentieth century may be a key variable influencing glacier mass loss, producing changes in the duration of the melt season and related changes in the ratio of rain/snow inputs to these glaciers. Neither proxy summer balance series explicitly includes predictors that are related to minimum summer temperatures, and therefore both may underestimate mass balance changes related to these effects. Discovery of tree-ring series or other proxy records that are sensitive to (*a*) minimum in addition to maximum temperatures and (*b*) winter rather than summer precipitation might lead to significant improvement of these mass balance estimates.

The moraine record suggests slight differences in the history of glacier fluctuations between northern sites in Jasper and sites in Banff and Waterton/Glacier Parks. A slight north-south difference in the magnitude of snow water equivalent anomalies was identified in the instrumental record, and it is possible that this difference was greater in the past and caused differences in winter balance between the two regions. The 1700s advance in the more northerly sites is of similar or only slightly larger extent than the mid-1800 advance, and small differences in snowfall or reduced temperatures along this gradient may be sufficient to account for minor differences in the relative extent of eighteenth- and nineteenth-century glaciers.

Reconstruction of mass balance data using proxy climate records derived from tree rings offers the possibility of examining the drivers of glacier fluctuations directly rather than through the filtered and often censored record seen in conventional reconstructions of glacier history. Assessing the degree of similarity between these proxy mass balance series and known glacier fluctuations can help us identify the scale of the forcing factors and therefore possibly identify their causes (in these cases, large-scale Pacific variation versus local controls). This type of analysis may also help us understand the timing and rate of climate changes. These two preliminary attempts indicate the potential for the development of a more comprehensive picture of how glaciers have fluctuated in the past and how future modeled or actual climate changes may influence glaciers in the future.

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DARKENING PEAKS

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*Glacier Retreat, Science, and Society*

Edited by

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and Brian H. Luckman

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Cover illustration: Piedras Blancas Glacier, Patagonia, Argentina. The glacier has diminished, its lower portion detached and calving into a newly formed lake. Photograph by Mariano Masiokas.

# CONTENTS

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