Decadal-scale climate drivers for glacial dynamics in Glacier National Park, Montana, USA

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[1] Little Ice Age (14th–19th centuries A.D.) glacial maxima and 20th century retreat have been well documented in Glacier National Park, Montana, USA. However, the influence of regional and Pacific Basin driven climate variability on these events is poorly understood. We use tree-ring reconstructions of North Pacific surface temperature anomalies and summer drought as proxies for winter glacial accumulation and summer ablation, respectively, over the past three centuries. These records show that the 1850's glacial maximum was likely produced by ~70 yrs of cool/wet summers coupled with high snowpack. Post 1850, glacial retreat coincides with an extended period (>50 yr) of summer drought and low snowpack culminating in the exceptional events of 1917 to 1941 when retreat rates for some glaciers exceeded 100 m/yr. This research highlights potential local and ocean-based drivers of glacial dynamics, and difficulties in separating the effects of global climate change from regional expressions of decadal-scale climate variability. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1812 Hydrology: Drought; 1827 Hydrology: Glaciology (1863); 1854 Hydrology: Precipitation (3354); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology. **Citation:** Pederson, G. T., D. B. Fagre, S. T. Gray, and L. J. Graumlich (2004), Decadal-scale climate drivers for glacial dynamics in Glacier National Park, Montana, USA, *Geophys. Res. Lett.*, *31*, L12203, doi:10.1029/2004GL019770.

1. Introduction

[2] As in the majority of the world's temperate, continental regions, alpine glaciers throughout the Rocky Mountains of the northern United States and southern Canada are currently experiencing a substantial decrease in their number and extent [*Luckman*, 2000; *Hall and Fagre*, 2003]. Glacier National Park (GNP), Montana (Figure 1), offers numerous examples of this pattern, with over 110 of 150 glaciers and snow/ice fields disappearing over the last century [*Carrara and McGimsey*, 1981]. To date, the remaining 40 glaciers and snowfields continue to decline. Additionally, evidence from dated moraines and forest trimlines shows that this 20th century retreat follows a significant Little Ice Age (LIA) advance that was otherwise unprecedented in the late Holocene [*Carrara*, 1989].

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[3] Though much is known about the mid- to late-20th century dynamics of glaciers in the Northern Rockies, there has been little exploration of the regional climatic conditions that drove their LIA advance or the late-19th and early-20th century transition to ablation-dominated modes. Here we compare documented advances and retreats for the extensively studied Jackson and Agassiz glaciers in GNP (Figure 1) with tree-ring based reconstructions of climate indices related to summer ablation potential [*Pederson*, 2004]. Fluctuations in snowpack for the U.S. Northern Rockies, the primary driver of glacial accumulation rates, are strongly linked to the Pacific Decadal Oscillation (PDO; see *Mantua and Hare* [2002] for description), with negative modes correlating with increased snow depth and snow water equivalent (SWE) [*McCabe and Dettinger*, 2002]. Therefore, we also examine Pacific Basin drivers of winter precipitation [*D'Arrigo et al.*, 2001] in order to produce a comprehensive picture of long-term glacial accumulation potential. Finally, we utilize the long-duration nature of these accumulation and ablation proxies to explore how decadal-scale variability in both regional and Pacific Basin climate influences glacial dynamics in GNP.

2. Data and Study Area

[4] We used the terminus position chronologies of *Carrara and McGimsey* [1981] to represent post-Little Ice Age and 20th century dynamics for the Jackson and Agassiz glaciers (Figure 1). These chronologies were developed from tree-ring dating (n = 116) of multiple terminus positions (n = 21) for these glaciers during their retreat from LIA forest trimlines. National Park Service observations and repeat photography were also used in the development of the chronologies. Because actual mass balance measurements are not available, these records provide a general representation of glacial extent and retreat rates through time.

[5] In a related study, *Pederson* [2004] used tree-ring data to reconstruct Mean Summer Deficit (MSD [*Newhall and Berdanier*, 1996]) calibrated on Kalispell, Montana, meteorological records (Figure 1). Here we utilized the MSD reconstruction as a proxy for summer (JJA) ablation potential extending back to A.D. 1540. MSD was chosen to represent summer ablation because this index, calculated as precipitation minus potential evapotranspiration, incorporates both temperature and moisture variability into a single metric. Moreover, for the GNP study area, MSD is strongly governed by mean summer maximum temperatures ($r = -0.827$), a primary driver of summer mass balance [*Brathwaite and Olesen*, 1989]. The reconstruction was based upon a subset of the three longest Douglas-fir (*Pseudotsuga menziesii*) and limber pine (*Pinus flexilis*) tree-ring chronologies available

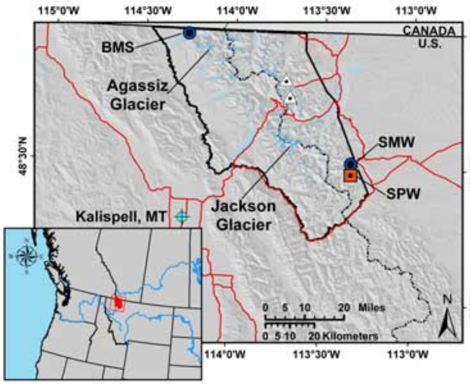

Figure 1. Location of glaciers, tree-ring chronologies (Douglas-fir [blue dotted circle], limber pine [orange dotted square]) and the Kalispell meteorological station (light blue circle w/crosshairs). Three snow courses are shown as white dotted triangles, with the two southern locations overlapping.

for the area (Figure 1). Each chronology was detrended using methods that preserve both low- and high-frequency variation (negative exponential, or mean line [*Cook and Kairiukstis*, 1990]). All three chronologies used in the reconstruction have good sample depth through time (>9 trees per chronology for any year), and we limited the reconstruction to a period where each chronology exceeded a subsample signal strength value of 0.85, or 85% of the common variance retained [see *Wigley et al.*, 1984]. The most parsimonious MSD reconstruction was produced using a transfer function model that explained over 44% of the variance (adjusted for degrees of freedom) in the instrumental record. The reconstruction passes all standard calibration and verification procedures, accurately tracks decadal-scale variability, and provides conservative estimates of interannual variation (see *Pederson* [2004] for details).

[6] Initial investigation of winter snowpack (accumulation) involved establishing the spatial relationships between North Pacific variability and winter precipitation by correlating October–March U.S. climate division data with the PDO index (http://www.cdc.noaa.gov/USclimate/Correlation/). Relationships between standardized May 1st SWE (winter snowpack) and PDO were then assessed using GNP snow course data (Figure 1) over the 1922–2000 common period (methods adapted from *Selkowitz et al.* [2002]). For a pre-instrumental perspective of variations in the PDO we focused on the *D'Arrigo et al.* [2001] A.D. 1700–1979 reconstruction over other available reconstructions [e.g., *Biondi et al.*, 2001] because it utilized the largest spatial network of chronologies, included proxies that integrated temperature and precipitation signals, and produced stronger calibration and verification statistics than previous reconstructions.

3. Multidecadal Variability in Summer Drought

[7] Previous studies using instrumental records have suggested that, in the western U.S., summer moisture variability contains significant decadal and lower-frequency behavior [e.g., *Cayan et al.*, 1998] that may have profound impacts on the long-term forcing of glacial dynamics. Here, the 461 yr reconstruction of MSD (Figure 2a) was analyzed using wavelet analysis to explore the frequency characteristics of drought for the study region in both the instrumental and pre-instrumental periods. Wavelet analysis employed the Morlet wavelet and zero padding, allowing for investigation of localized changes in decadal variability within the time series [*Torrence and Compo*, 1998]. The MSD reconstruction exhibits significant power in a wide band spanning the 16 to >64 yr domain (Figure 2b). Figure 2 shows that over the A.D. 1630–1750 interval significant power is concentrated in the 16–32 yr wavelengths due to rapid shifts from strong summer cool/wet events to sustained droughts. As the end of the LIA approached (∼A.D. 1750–1850), power increased in the >64 yr wavelengths, coinciding with a series of long-duration cool/wet events spanning A.D. 1770–1840. From A.D. 1850 onward the climate shifts to higher intensity droughts of greater length than any experienced in the preceding 310 yrs, which corresponds with a shift to significant variability in the 32–64 yr frequencies.

[8] In the 19th and 20th centuries, persistent shifts in MSD (Figure 2a) from sustained drought to cool/wet periods coincide with key events captured in the *Carrara and McGimsey* [1981] recession chronologies for the Jackson and Agassiz glaciers (Figures 3a and 3b). In particular, the shift from sustained pluvial-like conditions in the early 19th century to a period marked by moderate drought (1850's to early 1900's) coincides with the onset of retreat from the LIA glacial maxima. The switch to extreme drought conditions over the 1917–1941 period is matched by rapid recession (40–100 m/yr) in both glaciers.

4. Linking Summer Drought, Pacific Decadal Variability and Glacial Dynamics

[9] MSD appears to provide a useful representation of summer ablation potential in GNP glaciers. A more com-

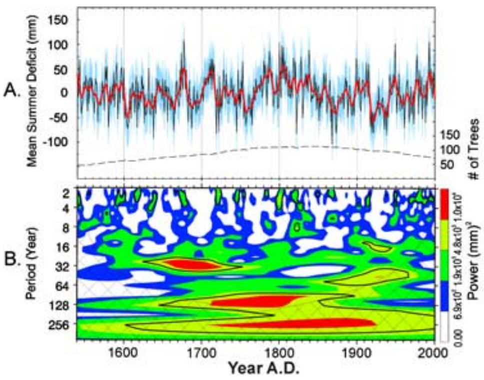

Figure 2. Summer drought reconstruction (Mean Summer Deficit) for GNP. (a) Annual MSD reconstruction (black line) overlain with a 10 yr cubic spline (thick red line), confidence bands representing root mean squared error estimates (light blue), and sample depth (below). (b) The wavelet power spectrum for the summer drought reconstruction. Colored intervals represent 5, 25, 50, and 75% of the wavelet power, respectively. Black contours represent the 95% confidence level (compared to red-noise), and the crosshatched region indicates areas where zero padding has reduced the power. Software provided by C. Torrence and G. Compo (available at; http://paos.colorado.edu/research/wavelets/).

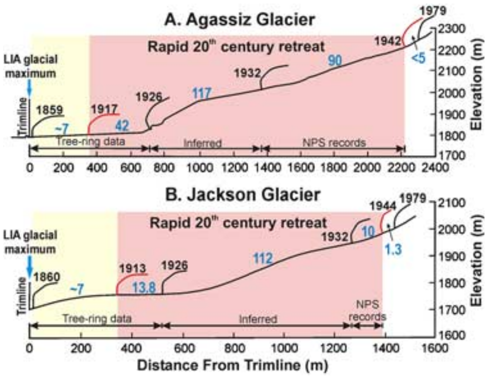

Figure 3. Profiles of the Agassiz (a) and Jackson Glaciers (b) showing the elevation of their terminus positions through time [modified from *Carrara and McGimsey*, 1981]. Key observation dates of glacial margins are displayed as black lines. Yellow shading indicates initiation of glacial recession in the late-19th and early-20th centuries. Red lines and red shading highlight changes in glacial margin position between the onset and termination of the severe 1917–1941 drought. Estimated net retreat rates (m/yr) are shown in blue.

plete understanding of glacial dynamics, however, also requires investigation of winter accumulation potential. Numerous studies have demonstrated that winter mass balance in the Pacific Northwest, Alaska and western Canada is strongly linked to decadal-scale variability in the North Pacific [e.g., *McCabe and Fountain*, 1995; *Hodge et al.*, 1998; *Bitz and Battisti*, 1999]. Likewise, winter snowpack fluctuations in GNP exhibit a significant relationship with the PDO [*Selkowitz et al.*, 2002]. More specifically, PDO and local May 1st SWE (Figure 4a and inset) are negatively correlated ($r = -0.764$; $p < 0.001$). Assuming this connection remained stationary prior to the instrumental record, we can then use reconstructed values of the PDO as a proxy for winter-accumulation potential for the Jackson and Agassiz glaciers.

[10] Comparing both the PDO and MSD reconstructions for GNP indicates that the maximum LIA advances of the Jackson and Agassiz glaciers coincide with an extended period where cool conditions in the North Pacific likely contributed to high winter snowpack (e.g., A.D. 1770–1790 and 1800–1830; Figure 4b). These conditions, which favor positive winter mass balance, were also coupled with little potential for significant summertime ablation (Figure 3c). After A.D. 1850 a long period (1860–1890) of low winter-accumulation potential (warm North Pacific) and high summer ablation potential overlap, producing conditions favorable for negative annual mass-balance and the start of glacial retreat. Having already entered an ablation-dominated mode, over the A.D. 1917–1941 period the Jackson and Agassiz glaciers respond to extremely low snowpack and severe summer drought by retreating at rates of >100 m/yr. From the mid-1940's through the 1970's retreat rates slowed substantially, and several modest advances were documented as the North Pacific transitioned to a cool phase. Relatively mild summer conditions also prevailed during this period. From the late 1970's through the 1990's instrumental records (Figure 4a) indicate a shift in the PDO back to warmer conditions resulting in continuous, moderate retreat of the Jackson and Agassiz glaciers.

[11] To illustrate the interaction between these regional and large-scale drivers of glacial dynamics, we developed an index of mass balance potential (MBP) for the past 300 yrs. Again, summer ablation potential was represented by MSD and winter accumulation potential (snowpack) by the PDO. Values for MSD and the PDO were combined by first converting each series to standard deviation units and then summing the resulting normalized values. Values of the PDO were also inverted so that cool (warm) values correspond with higher (lower) winter snowpack. Indexing was performed on both instrumental records and available PDO and MSD reconstructions.

[12] The maximum glacial advance of the LIA coincides with a sustained period of positive MBP that began in the mid-1770's and was interrupted by only one brief ablation phase (~1790's) prior to the 1830's (Figure 5). The mid-19th century retreat of the Jackson and Agassiz glaciers then coincides with a period marked by strong negative MBP. From ~1850 onward *Carrara and McGimsey* [1981] indicate a modest retreat (~3–14 m/yr) for both glaciers until approximately 1917, when the MBP shifts to an extreme negative phase that persists for ~25 yr. Results obtained

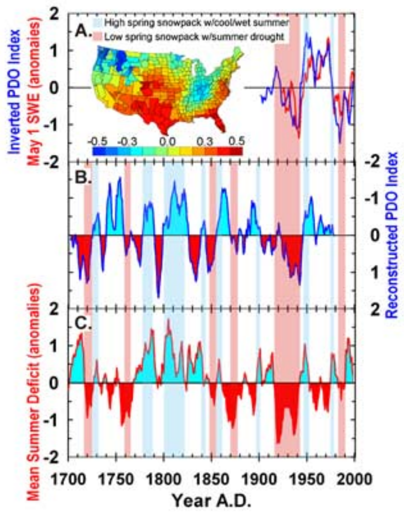

Figure 4. Comparison of GNP summer drought, winter snowpack (May 1 SWE) and the Pacific Decadal Oscillation. All time series have been smoothed using a 5 yr moving average. (a) Relationship between the average annual instrumental PDO index (blue line, inverted for ease of comparison) [*Mantua and Hare*, 2002] and May 1 SWE anomalies (red line) for GNP. (inset) Correlations between winter (October–March) precipitation and the PDO index for all U.S. climate divisions spanning 1949–2003 (http://www.cdc.noaa.gov/USclimate/Correlation/). (b) Reconstructed PDO [*D'Arrigo et al.*, 2001] used as a proxy for snowpack anomalies back to 1700. Positive (negative) values of the reconstructed PDO correspond with low (high) winter snowpack as indicated by the strong relationship with instrumental May 1 SWE anomalies ($r = -0.688$) for the common period of overlap (1922–1979). (c) Summer drought (MSD) reconstruction for GNP.

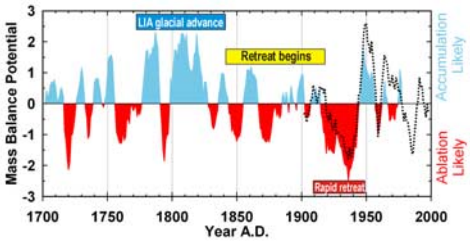

Figure 5. Index of glacial mass balance potential derived by summing PDO (Figure 4b) and MSD (Figure 4c) anomalies for GNP. Mass balance potential based on proxy data (red and blue fill) and instrumental data (dotted black line) are shown. Both series were converted to standard deviation units, and the sign of the PDO reversed to make conditions favoring high (low) snowpack positive (negative). PDO and MSD are equally weighted in the resulting index.

were similar using other available PDO reconstructions [i.e., *Biondi et al.*, 2001].

[13] A recent study from the southern Canadian Rockies suggests that the relative importance of summer and winter forcing in determining annual mass balance varies over time [*Watson and Luckman*, 2004]. In our index of MBP, for example, a period of high ablation potential around 1790 is largely driven by a positive PDO (Figures 4b and 5). On the other hand, near normal to slightly cool/wet summer conditions at this time (Figure 4c) might have ameliorated the effects of low winter-accumulation potential. Because of the absence of mass balance observations for these sites, the exact relationship between PDO, MSD and glacial dynamics must still be determined for GNP. Nevertheless, the MBP index appears to explain the gross features of the *Carrara and McGimsey* [1981] recession chronologies quite well.

5. Conclusions

[14] The evidence presented here suggests that both the late-19th century advance and the rapid early-20th century retreat of GNP glaciers arose from unique (in the context of these proxy records) interactions between summer ablation and winter accumulation. If couplings of high summer ablation and low winter accumulation become more common under doubled CO_2 conditions, physical and biological systems in the U.S. and Canadian Rockies face widespread and profound changes over the coming decades [*Hall and Fagre*, 2003]. This study also highlights the difficulty in detecting regional impacts of global climate change when decadal-scale climatic variations have a strong influence on local processes.

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