Long-Duration Drought Variability and Impacts on Ecosystem Services: A Case Study from Glacier National Park, Montana USA

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ABSTRACT: Instrumental climate records suggest that summer precipitation and winter snowpack in Glacier National Park (Glacier NP), Montana, vary significantly over decadal to multidecadal timescales. Because instrumental records for the region are limited to the 20th century, knowledge of the range of variability associated with these moisture anomalies and their impacts on ecosystems and physical processes are limited. We developed a reconstruction of summer (June - August) moisture variability spanning A.D. 1540-2000 from a multi-species network of tree-ring chronologies in Glacier NP. Decadal-scale drought and pluvial regimes were defined as any event lasting 10 yrs or greater, and the significance of each potential regime was assessed using intervention analysis. Intervention analysis prevents single intervening years of average or opposing moisture conditions from ending what was otherwise a sustained moisture regime. The reconstruction shows numerous decadal-scale shifts between persistent drought and wet events prior to the instrumental period (before A.D. 1900). Notable wet events include a series of three long-duration, high-magnitude pluvial regimes spanning the end of the Little Ice Age (A.D. 1770-1840). Though the late-19th century was marked by a series of > 10 yr droughts, the single most severe dry event occurred in the early-20th century (A.D. 1917-1941). These decadal-scale dry and wet events, in conjunction with periods of high and low snowpack, have served as a driver of ecosystem processes such as forest fires and glacial dynamics in the Glacier NP region.

Using a suite of paleo-proxy reconstructions and information from previous studies examining the relationship between climate variability and natural processes, we explore how such persistent moisture anomalies affect the delivery of vital goods and services provided by Glacier NP and surrounding areas. These analyses show that regional water resources and tourism are particularly vulnerable to persistent moisture anomalies in the Glacier NP area. Many of these same decadal-scale wet and dry events were also seen among a wider network of hydroclimatic reconstructions along a north-south transect of the Rocky Mountains. Such natural climate variability can, in turn, have enormous impacts on the sustainable provision of natural resources over wide areas. Overall, these results highlight the susceptibility of goods and services provided by protected areas like Glacier NP to natural climate variability, and show that this susceptibility will likely be compounded by the effects of future human-induced climate change.

1. Introduction

Evidence from an increasingly rich paleo-proxy record demonstrates that over the last millennium decadal to multidecadal precipitation anomalies have been a substantial, if not defining, component of western North America's climates. As in the 20th century, the last 1,000 years has experienced sporadic episodes of both persistent (> 10 yr) droughts and wet regimes, though the magnitude and duration of many paleo-droughts surpasses those captured by the instrumental record (Graumlich, 1993; Cook et al., 2004; Stine, 1994; Woodhouse and Overpeck, 1998). These long-duration droughts and pluvials likely result from a complex set of forcings linked to low-frequency variations and state changes in sea surface temperature and pressure anomalies in both the Atlantic and Pacific Oceans (McCabe et al., 2004; Gray et al., 2003*a*; Cayan et al., 1998). Such mechanisms, based on ocean-atmosphere teleconnections, often produce regional to subcontinental drying or wetness (Cook et al., 2004; Fye et al., 2003; Gray et al., 2003*a*) and may facilitate rapid phase-switching between moisture regimes.

In combination with a severe, ongoing drought and concerns over future climate change in western North America, these findings have invigorated interest concerning the influence of long-duration precipitation anomalies on natural processes, particularly at regional scales. A growing body of work demonstrates that remote large-scale forcing mechanisms associated with persistent droughts and pluvial events in western North America (e.g. Pacific Decadal Oscillation, Atlantic Multidecadal Oscillation, etc.) also entrain ecosystem processes across broad geographic regions. In systems ranging from ocean fisheries, (e.g., Stenseth et al., 2002) to semi-arid woodlands (e.g., Swetnam and Betancourt, 1998) to herds of ungulates in the Arctic (e.g., Post and Stenseth, 1999), decadal to multidecadal climate anomalies serve to synchronize ecosystem processes and may lead to rapid shifts in the structure and function of ecosystem processes. Such rapid shifts in ecosystem structure and function have large implications for management and conservation goals in light of increasing habitat fragmentation and future climate change scenarios.

When considered from the standpoint of human-environment interactions, these persistent climate anomalies can also have dramatic effects on the provision of "ecosystem services," or the benefits people obtain from ecosystems (Daily, 1997), over decadal to multidecadal timescales. As in the case of fisheries and forests (e.g. Stenseth et al., 2002; Swetnam and Betancourt, 1998) these services include the production of goods essential to human societies (i.e. provisioning services). In addition, ecosystem services include the maintenance and regulation of natural processes such as water and nutrient cycling (i.e. regulating services) and provide non-material benefits related to recreational and aesthetic values (i.e. cultural services). In this paper, we first present a case study from a tree-ring reconstruction of summer precipitation variability in Glacier National Park (Glacier NP), Montana, USA over the period 1540-2000 A.D. We then use this and other paleo-proxy records of regional climate and ecosystem dynamics to explore how persistent (> 10 yr) droughts and wet events affect ecosystem services provided by Glacier NP. Finally, we expand this discussion to include other mountainous protected areas in western North America. Our goal is, ultimately, to broaden discussion of the impacts of climatic variability by defining linkages between drought, large-scale climate regimes and the sustainable provision of ecosystem services.

2. Study Area

Glacier NP encompasses an area totaling 4,082 km^2 that is composed primarily of montane, subalpine, and alpine communities in the northern U.S. Rocky Mountains. The climate of this region can be described as Pacific Maritime with continental modifications, and is most similar climatologically, as well as geologically and biologically, to the southern Canadian Rockies (Finklin, 1986). The annual distribution of precipitation is defined by two distinct periods of peak precipitation, with significant amounts received during the early growing season (April-June) and over the winter months (October-March). Here, valley inversions are common, and the orographic effect of the Continental Divide causes the western slopes of the Park to be some of the most mesic areas in Montana (Figure 1). Similarly, given the region's westerly storm tracks, and cold, dry continental air masses, the Continental Divide also causes the eastern foothills and high-plains bordering the Park to receive far less precipitation over the winter months (Figure 1; Cunningham, 1982).

Glacier NP provides a variety of ecological services to the surrounding communities and the regional economy (Table 1). Three major river systems have a portion of their headwaters in Glacier NP: the Missouri/Mississippi, the Columbia, and the Saskatchewan/Nelson. Given the semiarid climate of the eastern slope, Glacier NP functions as a regional "watertower" providing critical water supplies for agricultural uses as well as hydropower. The Park is surrounded by two national forests, the Blackfoot Indian Reservation, Waterton National Park in Canada and, to a lesser extent, private lands. Tourism facilities are embedded within the Park and are a prominent feature of all surrounding gateway communities. The gateway communities thrive, because of their dependence on visitors attracted to one of the nation's premier national parks. The tourism industry located in and near the Park is a strong and growing part of the region's economy. The role of tourism on the regional economy is best illustrated with Montana's state-wide data recently released from the Institute for Tourism and Recreation Research at University of Montana (Wilton, 2004): in 2003 nearly 10 million non-resident travelers visited Montana whose expenditures directly and indirectly contributed to the generation of nearly 6% of all jobs in the state; in 2003, nonresident travel expenditures in Montana totaled \$1.86 billion, which constitutes a steady annual growth of 1%, making tourism one of the fastest growing segments of Montana's economy. Natural amenities associated with the Park are cited as the primary attraction for tourists to the region.

3. Data and Methods

3.1. Paleo-proxy Reconstructions of Climate

Though instrumental climate records are invaluable tools for understanding short-term (years to a few decades) atmospheric variations, such observations are inadequate for capturing decadal to multidecadal phenomena (Cayan et al., 1998). In the case of precipitation, only 3 to 4 significant wet/dry regimes spanning a decade or more were experienced in western North America during the instrumental period (roughly the last 100 yr), and each of these regimes likely resulted from a different combination of forcings (Gedalof and Smith, 2001; Villalba et al., 2001). As a result, long-duration moisture sensitive tree-ring records provide the primary means for examining decadal to multidecadal variability in the hydroclimatic system. In the Rocky Mountains, ring-widths from climatically sensitive trees are especially suited to this purpose because they provide records of moisture variability that encompass several centuries or even millennia (Fritts, 1976; Briffa and Matthews, 2002). Tree rings also yield continuous, precisely-dated proxies that are highly replicable (Fritts, 1976; Cook and Kairiukstis, 1990). With proper sampling and analysis, tree-rings preserve both the high- and low-frequency (decadal to multidecadal) components of precipitation variability (Cook et al., 1995).

3.2. Tree-ring Chronology Development for Glacier NP

We sampled mid-elevation (1600-2040 m) sites in the Livingston, Lewis and southeastern Teton mountain ranges (Figure 1; Table 2) to provide a north-south transect of tree-ring records on both sides of the Continental Divide. Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) were sampled at seven sites. Limber pine (*Pinus flexilis* James) was collected from a single location. All samples were taken from open-grown stands located on well-drained, south-facing slopes with sparse understory vegetation without signs of recent disturbance. Soils were shallow and calcareous, originating from sedimentary rocks of the Appekunny, Prichard and Altyn Formations (Middle Proterozoic).

We collected at least two cores from each suitable live tree, and samples were obtained from remnant wood when available. A total of 243 trees (385 cores) were used in constructing the final chronologies, with records from each site encompassing between 341 to 885 yrs. Numbers of trees sampled at each site ranged from a minimum of 12 to a maximum of 53 (Table 2). Cores and cross-sections were mounted, sanded and crossdated following standard techniques (Stokes and Smiley, 1968; Fritts 1976; Briffa and Jones, 1990). Total ring-widths were measured to a precision of ±0.001 mm, and dating of all series was verified using the COFECHA program (Grissino-Mayer et al., 1997). Age-related growth trends in each ring-width series were removed using methods that preserve both high- and low-frequency variability (negative exponential curve, or linear trend line of negative or zero slope), and the individual series combined into a standardized chronology using the biweight robust mean function in the ARSTAN program (Cook et al., 1990). To constrain error resulting from decreasing sample depth in the early portion of the record, subsample signal strength (SSS; Wigley et al., 1984) was computed for each chronology. An SSS value of 0.85 was selected as the cutoff for including a chronology in the reconstruction, thus limiting the amount of error arising from a decreasing number of trees to 15% (Table 2).

3.3. Exploring Potential Tree-Growth Responses to Climate

To determine the suitability of these tree-ring records for use in climate reconstructions, we used standard and bootstrapped correlation analyses and moving-window correlation coefficients (Biondi, 1997; Biondi and Waikul, 2004) to compare each chronology with local meteorological stations and Montana state climate division records (Figure 1). Correlations were calculated between individual chronologies and monthly, seasonal, and annual combinations of temperature and precipitation. Many western U.S. chronologies integrate temperature and precipitation signals, so relationships between mean summer deficit (MSD), and the Palmer Drought Severity Index (PDSI; Palmer, 1965) were examined. Calculation of MSD (precipitation - potential evapotranspiration [Thornthwaite, 1948] for June-August) and monthly PDSI was performed using the individual station Newhall Soil Moisture model (Newhall and Berdanier, 1996) and PDSI software available from the National Agricultural Decision Support System (http://nadss.unl.edu/). Each chronology was compared against instrumental climate records at *t*, *t-1(2,3)* and *t+1(2,3)* yrs to account for lags in growth response and persistence in the climate system.

Correlation analysis showed a significant relationship between monthly temperatures and precipitation at each of the eight study sites (Figure 2*a*,*b*). The strongest and most temporally-stable monthly correlations were found between ring widths and mean monthly maximum temperature (T_{max}) for the previous July (r = -0.30 - -0.63), with a consistent - but slightly reduced - response to growth-year July T_{max} (r = -0.28 - -0.40). We also observed significant positive correlations (r = 0.23 - 0.49) with previous July total precipitation (PPT), and half of the Douglas-fir chronologies responded to January PPT (r = 0.18 - 0.50). The majority of the chronologies exhibit a consistent response to previous growing season, or summer (June-August), PPT and T_{max} with a reduced response to spring and summer conditions during the year of growth (Figure 2*a,b*). Overall, the strongest and most temporally stable correlations were observed between each chronology and Kalispell MSD (r = 0.33-0.64) and summer PDSI (r = 0.25-0.62, [Table 3]). Summer PDSI calculated for Montana climate division data failed to improve the relationship with all chronologies, especially those east of the Continental Divide, as did the use of station records other than Kalispell. Annualized climatic data and drought indices for 13 different 12-month periods resulted in lower overall correlations and decreased temporal stability (Pederson, 2004).

3.4. Calibration and Verification of the Reconstruction Model

Based on the results of the correlation analyses (Table 3), we initially selected MSD and summer PDSI at Kalispell, Montana for reconstruction. Potential predictor chronologies for use in estimating MSD and PDSI were chosen using a "best subsets" regression procedure. The strongest and most parsimonious models were then identified based on their adjusted r^2 values, Mallow's C-P and root of mean squared error (Draper and Smith, 1998).

The final model was constructed using a combination of the Boundary Mountain Site (BMS), Spot Mountain (SMW) and Scenic Point (SPW) chronologies (Figure 3) to estimate MSD:

$$\text{MSD} = -450 - 72.8\,(\text{BMS})_t + 201\,(\text{BMS})_{t-1} + 54.2\,(\text{SMW})_t + 56.3\,(\text{SPW})_t$$

Lagged chronologies were used in the final model rather than residual chronologies because they accounted for a greater degree of temporal autocorrelation in the climate system. The above equation obtains an r^2 value of 0.466 (p-value < 0.01), the Mallow's C-P value of 4.3 indicates the model is relatively unbiased, and the standard deviation (σ) of the regression error was optimally reduced (S = 40.5). Tests comparing subsets of the instrumental and tree-ring datasets and the PRESS procedure (Draper and Smith, 1998) indicated that estimates of MSD provided by this model were temporally stable (Table 4). Other common metrics of model fit such as the Durbin-Watson (D-W = 1.94), sign test (75/25 [agree/disagree]), and reduction of error statistic (re = +0.53) showed favorable results (Table 4; [Fritts, 1976; Cook and Kairiukstis, 1990]). Thus, we used this model to hindcast MSD estimates back to A.D. 1540, the year at which SSS drops below 0.85 for BMS.

Similar results were obtained for summer PDSI. However, we excluded PDSI from further analysis because of slightly reduced adjusted r^2 (PDSI = 0.395 vs. MSD = 0.443) and Mallow's C-P (PDSI = 5.0 vs. MSD = 4.3), indicating increased lack of fit in a 4-predictor model. Admittedly, reconstruction using either drought metric is justifiable and produces comparable results, but the minor improvement in terms of variance explained and the simple computation and interpretation of MSD values favored our selection of MSD for reconstruction. Other models for both MSD and PDSI using additional site chronologies or predictor variables derived from factor analysis either resulted in significantly shorter reconstructions, or failed to improve various tests of model skill (e.g. adjusted r^2 values, Mallow's C-P and root of mean squared error).

3.5. Identification and Detection of Non-Stationary Behavior in Glacier NP Climate

We subjected the reconstruction to intervention analysis (Box and Tiao, 1975) in order to identify and characterize decadal-scale (>10 yr) and longer moisture regimes for Glacier NP over the 1540 to 2000 period. Identification of sustained moisture regimes using this method prevents single intervening years of average or opposing conditions from ending what would otherwise be a sustained decadal-scale moisture anomaly when compared with the long-term mean. Potential regimes were first identified using an intervention detection algorithm (Gedalof and Smith, 2001). This method uses a moving window where values during one period are compared to values in a successive period via a two-sample t-test. The size of the moving window was set to 20 yr based on previous work showing strong modes of decadal variability in surrounding regions and the Rocky Mountains at large (Gray et al., 2003*a*; Gray et al., 2004*a*). The significance of potential regimes was evaluated by first fitting a univariate autoregressive integrated moving average (ARIMA; *see* Box and Jenkins [1970]) model to the MSD reconstruction. Each potential regime was then incorporated into a new model as a step-change variable. Potential regimes with a p-value ≤ 0.05 were considered significant. Each significant regime was then classified in terms of duration, magnitude and intensity using methods outlined by Biondi et al. (2002).

3.6. Identification and Detection of Non-Stationary Behavior in the Climate of the North American Rockies

Observation of regional and subcontinental anomalies in moisture variability on decadal- and multidecadal-scales was accomplished using drought and precipitation reconstructions arrayed along a north to south transect through the Rockies. These reconstructions include: annual precipitation (pJuly-June) from Banff National Park (NP) and Waterton NP, Alberta, Canada (Watson and Luckman, 2004*a*); summer drought (June-August) for Glacier NP, Montana (this study); annual precipitation (pJune-June) for Yellowstone NP, Wyoming (Gray et al., 2004*b*); Uinta Basin, Utah June PDSI (Gray et al., 2003*b*; Gray et al., 2004*a*); and annual precipitation (pJuly-July) for El Malpias National Monument (NM) in northwestern New Mexico (Grissino-Mayer, 1996*a,b*). Though the choice of season for reconstruction varies among these records, all of the proxies have signals that are strongly related to growing season drought while also integrating precipitation over the winter and spring months (Stahle et al., 2000). The associated authors provided data for the Banff NP, Waterton NP, and Yellowstone NP reconstructions, and all remaining datasets were obtained from the World Data Center for Paleoclimatology (http://www.ngdc.noaa.gov/paleo/recons.html).

For each reconstruction along the Rocky Mountain transect dominant modes of moisture variability were examined using multi-taper method (MTM; Mann and Lees, 1996) spectral analysis. Power in the frequency domain was tested against a red-noise background over an interval common to all of the reconstructions (1540-1992), and only peaks exceeding the 95% confidence limit were considered significant. Based on the MTM analysis, we determined that all of the reconstructions share similar modes of lower-frequency variability in a band from 20-30 yr (and generally > 50 yrs). We then smoothed the reconstructions with a 25 yr spline to highlight this common variability.

3.7. Defining Ecosystem Services in the Context of Glacier NP

We drew on a variety of sources to characterize ecosystem services provided by mountainous parks and protected areas, and to determine the degree to which those services might be vulnerable to lower-frequency climatic variability (Table 1; Bugmann and Huber, 2004; Baron, 2002; Körner and Spehn, 2002). Our overall framework melds the efforts of Messerli and Ives (1997) in defining mountains as the "water towers for the 21st century" and the conceptual taxonomy of the Millennium Ecosystem Assessment (De Groot et al., 2002; MEA, 2003) in classifying services as provisioning, regulating and cultural services.

In seeking to relate the general notion of ecosystem services to the specific context of Glacier NP, we compiled several time-series of key ecosystem drivers that are tightly linked to climate variability. To capture decadal variability in precipitation over winter months, we used historic records of May 1st Snow Water Equivalent (SWE; 1922-present) and instrumental and reconstructed records of the Pacific Decadal Oscillation (PDO; Mantua et al., 1997; D'Arrigo et al., 2001) to infer long-term variability in winter snowpack for Glacier NP. The relationship between PDO and Glacier NP snowpack was first described by Selkowitz et al. (2002), and further utilized by Pederson et al. (2004*b*) to investigate climatic drivers of glacial dynamics. Our drought reconstruction represents moisture variability over the summer months (June-August). A recession chronology for the Sperry Glacier (1850-2003; Key et al., 2002) is utilized to display common patterns of glacial retreat since the LIA maximum, as Sperry is representative of general pattern of glacial retreat throughout the Park. Finally, we characterized the long-term pattern of fire in Glacier NP by compiling records of historic fire extent and frequency from Barrett (1982, 1986, 1988, 1993) and Key (1984) along with the current fire database provided by (and maintained by) Glacier NP. The fire history dataset is most useful for observing the frequency of fires through time. Due to the extent of late-19th and early-20th century fires, estimates of areas burned for previous centuries are confounded, and may be underestimated by an unknown order of magnitude (Barrett, personal communication).

4. Results

4.1. Reconstructed Summer Moisture Availability in Glacier NP, A.D. 1540 to 2000

The reconstruction of summer moisture variability (mean summer deficit; MSD) since 1540 indicates that the 20th century captures the full range of interannual variation of the previous four centuries with the exception of several severe single-year droughts in the 19th and 17th centuries (Figure 4*a*,*b*). The 20th century equals or exceeds the previous four centuries in terms of numbers of single-year severe ($\leq -1\sigma$) and extreme ($\leq -2\sigma$) droughts, though the 17th century is similar (Table 5). In contrast, the 18th and 19th centuries are dominated by many single-year wet events ($n = 17$ and $n = 20$ yrs, respectively) 1σ above the long-term mean for MSD. Over the entire reconstruction, the clustering of extreme single year events suggests strong multi-decadal persistence in Glacier NP moisture variability.

Intervention analysis of decadal-scale MSD variations indicates that long-duration wet and dry regimes were common throughout the proxy record (Figure 4*b*,*c*). Over the latter portion of the 20th century, intervention analysis detected two significant multi-year pluvial events, each lasting nine years (Table 6). However, comparison against previous decadal-scale wet events in the period 1540 through 1916 indicates that these 20th century regimes were unremarkable in terms of duration, magnitude and intensity. In particular, based on both their duration and magnitude, the 1770-1791 and 1818-1840 regimes were extraordinarily wet (Table 6, Figure 4,*bc*). Over the 20th century the only extended long-duration (>10 yr) pluvial event occurred from 1899 to 1916. In relation to other long-duration, pre-instrumental pluvials in the proxy record, the 1899-1916 event had the lowest magnitude and intensity (Table 6, Figure 4*b,c*). Prior to the 20th century, the single most intense decadal-scale wet regime spanned 1800-1810, with the 1672-1680 event attaining a similar intensity. Intensities for all pluvial regimes were >1σ above the reconstructed mean, and the 1800-1810 event included 6 of 11 yrs 1σ above the mean (with 3 of the 6 yrs surpassing 2σ above). Overall, summer pluvial regimes of the 20th century have not been exceptional in the context of the past 461 yrs.

In contrast, decadal-scale droughts of the 20th century were unprecedented when compared to dry events of the previous four centuries. In particular, the drought of 1917-1941 achieves the greatest event score of any drought or wet regime within the reconstruction (Table 6). This dry event encompassed over 25 yrs, and included 12 individual yrs > 1σ below the MSD mean. Four years over this same period had MSD values at >2σ below the long-term average. Only the three pluvial events that occurred over 1770-1840 had similar event scores (Table 6). In terms of intensity (magnitude/duration), the 1917-1941 drought was surpassed only by the drought of 1601-1609. Intensity, however, is a metric that may mask important differences related to a moisture regime's duration and magnitude (e.g., 1917-1941 and 1601-1609), and such differences may have a variety of alternative implications for natural resources. Although several droughts in the instrumental and reconstructed record had durations similar to the 1917-1941 dry event, no other decadal-scale regime equaled its magnitude.

4.2. Decadal-Scale Moisture Variability in the North American Rockies

To place Glacier NP climate within a larger spatial context, we investigated decadal and longer-term moisture variability along a north to south transect spanning the U.S. and Canadian Rockies (Figure 5). Each reconstruction was found to exhibit significant decadal and multidecadal variability in the 20-30 yr and > 50 yr domains (Pederson, 2004), resulting in marked regional coherency of drought and pluvial events. As typified by the period from the 1920s to 1940s, extremely dry conditions in Glacier NP often coincide with severe droughts throughout the Pacific Northwest and Canadian Rockies. The most intense drought in our long-term Glacier NP reconstruction (1917-1941) was accompanied by strong drying in Waterton NP and Banff NP (Figure 5). This was also the most intense dry event in the past 300 yrs for much of Washington, Idaho, and Montana (Cook et al., 1999; Watson and Luckman, 2004*a*). This early 20th century drying was coupled with wet conditions throughout much of the southwestern U.S. and northern Mexico. Conversely, severe drought conditions seen in the Southwest during the late-16th century "megadrought" (Stahle et al., 2000) were only weakly expressed in the Banff NP and Glacier NP reconstructions.

As seen in both the mid-18th century and the current drought (late-1990s to 2004), severe dry events may also span almost all of western North America. Similarly, wet events centered around the 1910s and 1980s through 1990s spanned much of the U.S. and Canadian Rockies (Figure 5). Thus, the paleo-proxy records demonstrate both regional and subcontinental phasing of long-duration moisture anomalies.

5. Discussion

5.1. Linking Decadal-Scale Moisture Regimes and Natural Processes in Western North America

Our reconstruction of summer moisture variability for Glacier NP exhibits strong decadal to multidecadal variability resulting in persistent (> 10 yr) wet and dry regimes over the past five centuries. The period spanning A.D. 1670 to 1850 was characterized by many long-duration, high intensity pluvial events (e.g. Figure 4*b,c*) that correspond with the height of the Little Ice Age (LIA; ~1300-1850 A.D.). This period of generally cool and wet summers was unsurpassed by any other wet regime in the instrumental or proxy record. Since the middle of the 19th century, however, our reconstruction indicates that summer drought regimes have generally been more severe than those in previous centuries. Consistent with the findings of Cook et al. (2004), Glacier NP and much of the West has again shifted to a severe drought phase, though conditions abated somewhat in 2004.

Persistent shifts in moisture regimes related to decadal and multidecadal climate variability are a major driver of landscape changes in Glacier NP. Interactions between snowpack and summer drought over decadal to multidecadal timescales appear to have a particularly strong impact on fire regimes in the Glacier NP region (Figure 6*a,b,c*). On annual and inter-annual time scales, fire within Glacier NP is undoubtedly driven by summer drought and possibly snowpack conditions. For example, the major fires of 1910 resulted from extreme summer drought conditions and average snowpack during the year of the fire events. When viewed in the context of the past three centuries, however, decadal and longer persistence in summer drought and winter snowpack conditions emerge as the major driver of fire regimes (Figure 6*a,b,c*). The periods from the 1780s to the 1840s and the 1940s to the 1980s, for example, had generally cool and wet summers coupled with high winter snowpack resulting in extended (> 20 yr) burn regimes characterized by small, infrequent fires with relatively little area burned. Conversely, decadal and longer couplings of low snowpack and droughty summers resulted in burn regimes characterized by frequent, severe fires and large total area burned (e.g. 1910 to 1940, 1980s to present).

Similarly, long-duration summer and winter moisture anomalies, coupled with summer temperatures (Watson et al., 2005), drive glacial dynamics in Glacier NP. Prior to the height of the LIA (~1850), 70 years of cool wet summers coupled with high snowpack conditions , in part, caused glaciers to reach their greatest extent since the Last Glacial Maximum (Pederson et al., 2004). At the LIA maximum, glaciers and perennial snowfields covered approximately 99 km^2 of Glacier NP (Key et al., 2002). Over subsequent periods when drought and snowpack were generally in opposing phases (e.g. 1850-1910; Figure 6*a,b*) Glacier NP glaciers experienced moderate retreat rates (1-7 m/yr). During the period from 1917 to 1941, however, sustained low-snowpack coupled with extreme summer drought conditions, in part, drove rapid glacial retreat. The Sperry Glacier, for example, retreated at 15-22 m/yr and lost approximately 68% of its area (Figure 6*d*). Other glaciers such as the Jackson and Agassiz Glaciers at times retreated at rates ≥ 100 m/yr (Carrara and McGimsey, 1981; Key et al., 2002; Pederson et al., 2004). Climatic conditions over the middle of the 20th century became generally favorable (i.e. high snowpack w/variable summer drought conditions) for stabilization and even slight re-advance at some glaciers (Figure 6*a,b*). Combined with changes in the glacier retreat rates due to topography (e.g. increased shading), retreat rates decreased after the 1940's (11 m/yr by 1950; 5 m/yr by 1979 for the Sperry Glacier). Since the late 1970's, however, winter snowpack has been low while severe and sustained summer drought conditions have returned, and many Glacier NP glaciers are again shrinking rapidly (Figure 6*a,b,d*). If this pattern of hot and dry summers coupled with extremely low snowpack continues, Hall and Fagre (2003) predict glaciers will be largely gone by 2030.

As in our study of Glacier NP climate, networks of moisture reconstructions from the Rocky Mountains (Figure 5) indicate strong regional expression of long-duration drought and pluvial anomalies. The patterns associated with regional moisture anomalies often exhibit opposing phases between the Northern and Southern Rocky Mountains (Fye et al., 2003; Gray et al., 2003). However, subcontinental-scale droughts spanning large portions of the Rockies from Canada to the southwestern U.S. were also observed.

Regional- to subcontinental-scale synchrony of moisture regimes during strong and persistent drought/wet events, and the consistency of decadal to multidecadal modes throughout the Rockies (Gray et al. 2003; Pederson, 2004), suggest that a common mechanism drives the spatial and temporal expression of precipitation variability in these regions. Because many different tree species were included in the transect, this coherency implies that these low-frequency signals do not result from species-specific biological traits (e.g. needle retention, masting, etc.). Instead, the observed modes of variation most likely extend from complex ocean-atmosphere teleconnections associated with the Pacific Decadal Oscillation (20-30 yr modes of variation; see Mantua and Hare, 2002) and Atlantic Multidecadal Oscillation (60-80 yr modes of variation; Enfield et al., 2001; Gray et al., 2003; McCabe et al., 2004).

Such ocean-atmosphere linkages provide a means for entraining natural processes over regional to subcontinental scales. Swetnam and Betancourt (1998), for example, documented how droughts can synchronize western spruce budworm outbreaks and natality/mortality events in woodlands and conifer forests throughout the West. Decadal-scale shifts in moisture regimes have also been shown to drive the productivity of high-elevation forests of the Pacific Northwest (Peterson and Peterson, 2001) as well as rapid and persistent landscape change (Allen and Breshears, 1998). In addition to its effects on mortality and recruitment, landscape composition and structure might also be affected by plant migration dynamics related to persistent moisture anomalies. Lyford et al. (2003) showed that, over the late Holocene, climate variability at multidecadal and longer time-scales strongly influenced the probability of successful colonization by new plant species. In this case, low-frequency climate variability regulates the distribution and density of suitable habitats at regional scales. Decadal to multidecadal climate variability may also impact the strength of seed sources and dispersal of propagules.

A growing number of studies document the importance of decadal to multidecadal drought variability in controlling the frequency and severity of fires over the entire West. Over the past 20 years, widespread fires in the western U.S. show a strong response to drought regimes, regardless of 20th century management practices (Westerling et al., 2003). The Pacific Decadal Oscillation (PDO), in particular, has been shown to modulate the severity of fire seasons in western North America over longer (> 10 yr) timescales (Norman and Taylor, 2003; Hessl et al., 2004).

Large-scale impacts of decadal to multidecadal moisture regimes are also observed in many physical systems. In the western U.S. and Canada, changes in snow-depth and snow water equivalent (SWE) show strong modes of decadal to multidecadal variability (Brown and Braaten, 1998; Cayan et al., 1998; Dettenger et al., 1998; Selkowitz et al., 2002). Coupled with summer drought and increasing temperatures, these regime-like shifts in wintertime precipitation affect glacial dynamics and runoff from high mountain areas (McCabe and Fountain, 1995; Pelto, 1996; Watson and Luckman, 2004*b*; Pederson et al., 2004; Watson et al., 2005). Persistent changes in precipitation, and in some regions runoff from glaciers, then reinforce strong decadal to multidecadal variations in the availability of water resources in western North America (McCabe and Dettinger, 2002; Jain et al., 2002; Hidalgo, 2004).

5.2. Decadal-Scale Variability in Ecosystem Services

Among the services provided by ecosystems of Glacier NP, spring-summer seasonal water availability, governed by snowpack accumulation, is the most easily quantified. Selkowitz et al. (2002) have demonstrated that Glacier NP snowpack is significantly correlated with indices of ocean-atmosphere interactions, specifically the Pacific Decadal Oscillation (PDO). Taken together with the summer drought reconstruction presented here, it is clear that the drivers of Glacier NP regional water supplies are characterized by persistent episodes above and below the long-term mean.

Research from throughout the West echoes this point. Under the Colorado River Compact of 1922, flows were divided among the upper (Wyoming, Colorado, Utah and New Mexico) and lower-basin states (Nevada, Arizona, and California) based on observations made from 1905 to 1922. When tree-ring based climate reconstructions were used to examine these flows in a longer-term context, this early-20th century reference period was seen to be part of an anomalously wet regime (Meko and Graybill, 1995; Hidalgo et al., 2000; Piechota et al, 2004). Thus, water that will rarely- if ever- return to the river was promised to the lower-basin states. Such case studies consistently demonstrate that the instrumental climate record and, in turn, observations of ecosystem services made during the instrumental period, fail to capture the full range of variability we should expect and plan for (Cook and Evans, 2000; Gray et al., 2004*a*). Moreover, these examples show how expectations for the delivery of a vital resource that were developed during one type of climate regime may not be viable under subsequent regimes.

While the scientific evidence for decadal to multidecadal variability in water supplies continues to accumulate, demands on water resources in the western U.S. have risen with increasing human populations (Gray et al., 2004*a*; Hidalgo, 2004). These findings, coupled with the current severe, multi-year drought in the western U.S. are invigorating a dialogue between researchers and water managers that may result in new concepts and tools for Western water management. To date, most of this attention has focused on the semi-arid Southwest (e.g., Lord et al., 1995). We anticipate that as the demand for water increases in the northern Rocky Mountains, water managers will look to the Colorado and other southwestern basins for lessons learned.

Beyond their role as a regional water tower, the ecosystems of Glacier NP play a regulatory role that is less tangible. First, the diverse habitat and large area contained within Glacier NP not only conserves a high level of biodiversity, but allows the region to function as source of biodiversity. Also, like all of the montane regions in the western U.S., the forests of Glacier NP play a key role in the global carbon cycle (Schimel et al., 2002). The most important role of climate variability at decadal and longer time-scales in the regulatory function of mountain ecosystems is likely to be its influence on the release of carbon through fire. In compiling the fire history results and comparing these results with long-term climate variability (Figure 6*a,b,c*), we see intriguing evidence for long-term drought as a factor governing large, stand-replacing fires in the montane forests of Glacier NP. Multi-millennial records of fire and climate from Yellowstone NP area similarly suggest a relationship between persistent drought and substantial changes in the frequency of stand-replacing fires (Pierce et al., 2004). An intriguing and important result from Pierce et al. (2004) is the role of superposed centennial- to millennial-length climate variability in regulating the large stand replacing fires associated with severe multidecadal droughts of the 'Medieval Warm Period' (MWP; A.D. 900-1300), and the frequent but low-severity fires associated with generally cooler conditions of the LIA. This is of great concern today because Cook et al. (2004) find that since our emergence from the LIA, the 20th century anthropogenic warming has been trending towards conditions similar to the extraordinary droughts of the MWP. These results, taken together with the findings of Swetnam and Betancourt (1998) on the capacity for climate to synchronize fire at regional to subcontinental scales, imply that the regulatory role of montane forests as carbon sinks will vary over decadal and longer time scales as future climate change continues to alter large-scale fire regimes.

Such regime-like behavior may confound efforts to disentangle the effects of management activities and climate impacts on the provisioning of key ecosystem services. Beginning in 1977, salmon harvests in the Pacific Northwest underwent a dramatic decline that lasted for nearly two decades (Mantua et al., 1997). Diminished salmon populations were widely seen as a sign of over-fishing, and numerous reforms were enacted to counteract the "improper exploitation" of a valuable ecosystem service. Careful examination of long-term records of Pacific Northwest salmon and other fisheries, however, revealed that changes in this ecosystem service were related to a major reorganization of Pacific Basin climate (Mantua et al., 1997; Chavez et al., 2003). Likewise shifts in Glacier NP climate may have led to alternating 20th century fire regimes that are often associated with management activities.

Finally, the cultural services provided by ecosystems are inherently difficult to quantify in an economic valuation, in part, because they are not consumed (i.e., non-use values; see Randall, 1991). The loss of glaciers in Glacier NP has an obvious cultural resonance value that has not been lost on politicians and pundits who refer to a scenario by which Glacier NP is the "Park formerly known as Glacier" (Henneberger, 2004). At the same time, a diminished snowpack reduces some Glacier NP operational expenses and potentially provides a boon for local tourism. The sole road across the crest of the Rockies in Glacier NP (the "Going-to-the-Sun Road") is closed in the winter due to snow, and there is a substantial cost to plow and open the road each spring. The Road is the economic lifeline for gateway and regional communities, generating approximately one million dollars per day in revenue when open. Thus, a longer snow-free season may not only provide local economic benefits, but also reduce costs associated with home heating and decrease the number of days of treacherous road travel. However, the degree to which this tradeoff is underpinned by decade and longer shifts in climate has not been clearly articulated. Also, what seems on the surface to carry potential benefits for local communities (i.e. shorter winters and lower snowpack) may be offset by increasingly longer and dryer summers and the resulting fire seasons that are predicted to increase in length by up to two weeks over the 21st century (Brown et al., 2004). In any case, economic strategies that depend heavily on climate-related services are especially vulnerable to natural climate variability and future climate change.

6. Conclusions

As demonstrated in these analyses for Glacier NP and surrounding regions, the provision of a wide range of ecosystem services is strongly influenced by climate variability over decadal and longer timescales. This relationship between provisioning of ecosystem services and the attendant regime-like behavior of climate pose challenges to management and sustainability in three key ways. First, long-duration proxy reconstructions call into question the conventional strategy of defining reference conditions or management targets based solely on short duration (< 100 yr) observational records. For example, the use of 30 yr climatology for allocation of natural resources, and development of resource management goals, is clearly flawed as it is probable that any 30 yr climatic mean might only capture a single mode of climate variability (i.e. an extended regime of wet or dry conditions). Second, step-like changes from one climate regime to the next can have prolonged impacts on ecosystem services. These persistent and frequent shifts in the availability of natural resources and services may be misinterpreted as resulting from management activities. Likewise such climate-related shifts may amplify or dampen the effects of management activities. Lastly, decadal and longer persistence of either deficits or abundances of climate-related services can lead to management policies and economic strategies that, while appropriate during the current regime, may not be robust under subsequent climates. Overall, greater awareness of regime-like behavior must shape our expectations for ecosystem services and, in the face of global change, the institutions that manage these resources.

ACKNOWLEDGEMENTS

We thank Andy Bunn, Chris Caruso, Brian Peters, Karen Holzer, Todd Kipfer, Jeremy Littell, Blase Reardon, Anne Schrag and Lindsey Waggoner for suggestions and technical assistance in the field and lab. The comments from an anonymous reviewer helped improve the quality of the manuscript. We thank Brian Luckman, Emma Watson, and contributers to NOAA's World Data Center for Paleoclimatology for providing their precipitation reconstructions. We also thank Steve Barrett for sharing and discussing his fire history data, and Richard Menicke for technical assistance and distribution of the GIS database. We are grateful for all the support Glacier National Park and the National Park Service provided in allowing us to conduct this research, and also communicating the results to the public and park service staff. This work was funded by the U.S. Geological Survey - Northern Rocky Mountain Science Center and the National Science Foundation (#0082376).

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Table 1. Several critical ecosystem services provided by mountainous protected areas that may be altered by decade and longer shifts in precipitation regimes. For each ecosystem, we list three categories of associated ecosystem services: 1) provisioning services (i.e. production of essential goods); 2) regulating services (i.e. maintenance and regulation of ecosystem processes); and 3) cultural services (i.e. non-material benefits obtained from ecosystems such as recreation and aesthetic experiences). We also suggest key implications of decade and longer variability in climate on these services.

Ecosystem Component	Ecosystem Services	Impacts of Climate Variability	Implications
Alpine Glaciers and Snow Fields	Provides fresh water to downstream ecosystems	• Timing of snowmelt • Summer streamflow	• Irrigation • Hydropower • Habitat
	Moderates stream temperature variations	• Timing and quantity of snow melt alters stream temperature	• Macroinvertebrate assemblages change with implications for fish populations
	Enhances recreation opportunities, aesthetic and cultural values of landscape	• Reduction in winter recreational opportunities • Loss of sense of place associated with glaciers • Loss of cultural and religious icon	• Tourism revenues associated with snow-based recreation may decline • Perceptions of degraded landscape value • Park visitor satisfaction
Montane Forests	Provides habitat for plant and animal species	• Changes in snow alters whitebark pine demography and productivity with consequences for grizzly bear habitat	• Species recovery plans need to address decadal-scale climate variability
	Regulates disturbance	• Fire extent, frequency, and severity • Pathogen outbreaks	• Disturbance regimes may change substantially over decades
	Amenity values	• Recreation sites and roads close due to fire and fire risk; • Drought increases access (e.g., earlier opening of Going to Sun road)	• Tourism revenues decline in fire years but increase with earlier spring access

Table 2. Location and description of tree-ring chronology network used in this study. Light (dark) gray shading indicates sites west (east) of the Continental Divide.

Location	Site Name	Site Code	Species[a]	Lat (ºN)	Long (ºW)	Elevation (m)	No. Trees	No. Radii	Chronology Period (yr)	SSS ≥ 0.85
West	Boundry Mountain	BMS	PSME	48° 59'	114° 15'	1710	33	64	1499 - 2002	1540(9)[b]
	Numa Ridge Falls	NRF	PSME	48° 51'	114° 12'	1695	18	34	1645 - 2001	1710(6)
	Doody Mountain	DOO	PSME	48° 23'	113° 37'	1890	20	37	1660 - 2001	1704(6)
East	Going-To-Sun	GTS	PSME	48° 42'	113° 31'	1860	12	22	1337 - 2002	1610(5)
	Two-Medicine Lake	TML	PSME	48° 29'	113° 22'	1636	34	51	1564 - 2001	1670(7)
	Spot Mountain West	SMW	PSME	48° 31'	113° 22'	1950	42	65	1163 - 2002	1386(8)
	Teton River Valley	TRV	PSME	47° 55'	112° 44'	1678	31	46	1509 - 2001	1618(8)
	Scenic Point	SPW	PIFL	48° 29'	113° 19'	2040	53	66	1115 - 2000	1268(8)
						Total:	243	385		

[a] PSME, Douglas-fir; PIFL, limber pine

[b] Number of trees

Table 3. Seasonal correlations between all chronologies and summer T_{max}, summer PPT, MSD, and summer PDSI for Montana climate division 1(MTdiv1; $n \approx 115$) and Kalispell (Kal.; $n \approx 99$). Correlation coefficients shown are the maximum values obtained from a lag 1 yr relationship and are significant at the $p < 0.05$ level. Light (dark) gray shading indicates chronologies west (east) of the Continental Divide.

Site Code	Kal. Summer Tmax	Kal. Summer PPT	Kal. MSD	Kal. Summer PDSI	MTdiv1 Summer PDSI
BMS	-0.590	0.559	0.640	0.591	0.509
NRF	-0.589	0.569	0.631	0.622	0.491
DOO	-0.531	0.466	0.498	0.512	0.446
GTS	-0.538	0.451	0.502	0.493	0.407
TML	-0.455	0.320	0.368	0.361	0.318
SMW	-0.585	0.390	0.462	0.451	0.378
*TRV	-0.366	0.394	0.400	0.504	0.422
SPW	-0.302	0.306	0.327	0.250	0.199
Mean	-0.495	0.432	0.479	0.473	0.396

*TRV Correlation coefficient for growth year (current year)

Table 4. Regression model verification statistics for the final MSD reconstruction - including the calibration and verification periods.

Model	Period	n	r^2	r^2_{adj}	PRESS	SSE	r	RE[a]	Sign Test[b] (agree/dis.)	D-W[c]	S[d]
MSD	1900-2000	100	0.466*	0.443	176,771	155,897	0.68*	+0.53	75/25	1.94	40.5
Calibration	1931-2000	69	0.504*	0.473	137,743	113,261	0.71*	+0.50	50/19	1.81	42.1
Verification	1900-1930	31	0.397*		52,901	37,580	0.63*	+0.60	24/7		

Verification tests were conducted by splitting the data into calibration and verification periods.

To assess the stability of the of the model when calibrated over subsets and the full instrumental period the PRESS procedure (Draper and Smith, 1981) was used. The PRESS criterion is similar to the 'leave one out' validation method in that successively each observation is left out and SSE is estimated from the remaining n-1 cases. Thus, a PRESS value reasonably close to SSE, as demonstrated here, supports the validity of the regression model.

[a] RE is a highly sensitive measure of reconstruction reliability. Positive (negative) values of the statistic indicate successful (unsuccessful) reconstruction. (Fritts, 1976)

[b] Sign of departures for predicted and instrumental sample mean are significantly associated ($p < 0.01$)

[c] The Durban-Watson statistic indicates no significant serial correlation in the residuals ($p = 0.01$)

[d] The root mean squared error estimate from the regression.

*Significant at $p = 0.01$ level.

Table 5. Number of extreme single year dry and wet events per century equal to or greater than +/- 1 and 2 standard deviations.

Century	Stdev +2	Stdev +1	Stdev -1	Stdev -2	Row Total
16th*	0	10	5	0	*
17th	2	4	19	2	27
18th	2	15	7	3	27
19th	4	16	8	3	31
20th	3	10	19	4	36
Total:	11	55	58	12	

*Record begins A.D. 1540

Table 6. Decadal-scale dry (gray) and wet (white) regimes. Intervention analysis determined the significance of each regime (*p*-value), and duration describes the number of years a positive or negative intervention remains above or below the long-term mean. Magnitude identifies the severity of the mean departure for the entire duration, and intensity = magnitude/duration (Biondi et al., 2002). Hence, intensity is equivalent to the average magnitude of a regime, which corresponds with the step-change value used for significance testing of each regime in intervention analysis. Each regime was given a score by summing the rankings for duration, absolute magnitude, and absolute intensity. The higher an event's overall score indicates the 'stronger' the overall regime, thus allowing for a quantitative comparison between regimes in relation to the three types of descriptors.

Years	Condition	Intervention (*p* -value)	Duration	Magnitude	Intensity	Score
1566-1571	Dry	0.052*	6	-163.1	-27.2	15
1601-1609	Dry	0.006	9	-354.5	-39.4	33
1626-1641	Dry	0.015	16	-420.4	-26.3	36
1672-1680	Wet	0.003	9	379.9	42.2	36
1681-1702	Dry	0.038	22	-377.8	-17.2	29
1703-1717	Wet	0.005	15	523.6	34.9	42
1718-1727	Dry	0.023	10	-222.1	-22.2	20
1754-1769	Dry	0.011	16	-453.9	-28.4	40
1770-1791	Wet	0.008	22	633.7	28.8	49
1800-1810	Wet	0.001	11	549.0	49.9	46
1818-1840	Wet	0.008	23	580.8	25.3	45
1861-1883	Dry	0.014	23	-556.9	-24.2	43
1888-1898	Dry	0.048	11	-197.6	-18.0	16
1899-1916	Wet	0.005	18	330.7	18.4	26
1917-1941	Dry	0.000	25	-978.7	-39.1	57
1942-1950	Wet	0.011	9	241.5	26.8	22
1951-1974	Dry	0.032	24	-352.5	-14.7	29
1975-1983	Wet	0.037	9	198.2	22.0	15

*Decreasing sample depth and borderline *p* -values suggests cautious interpretation.

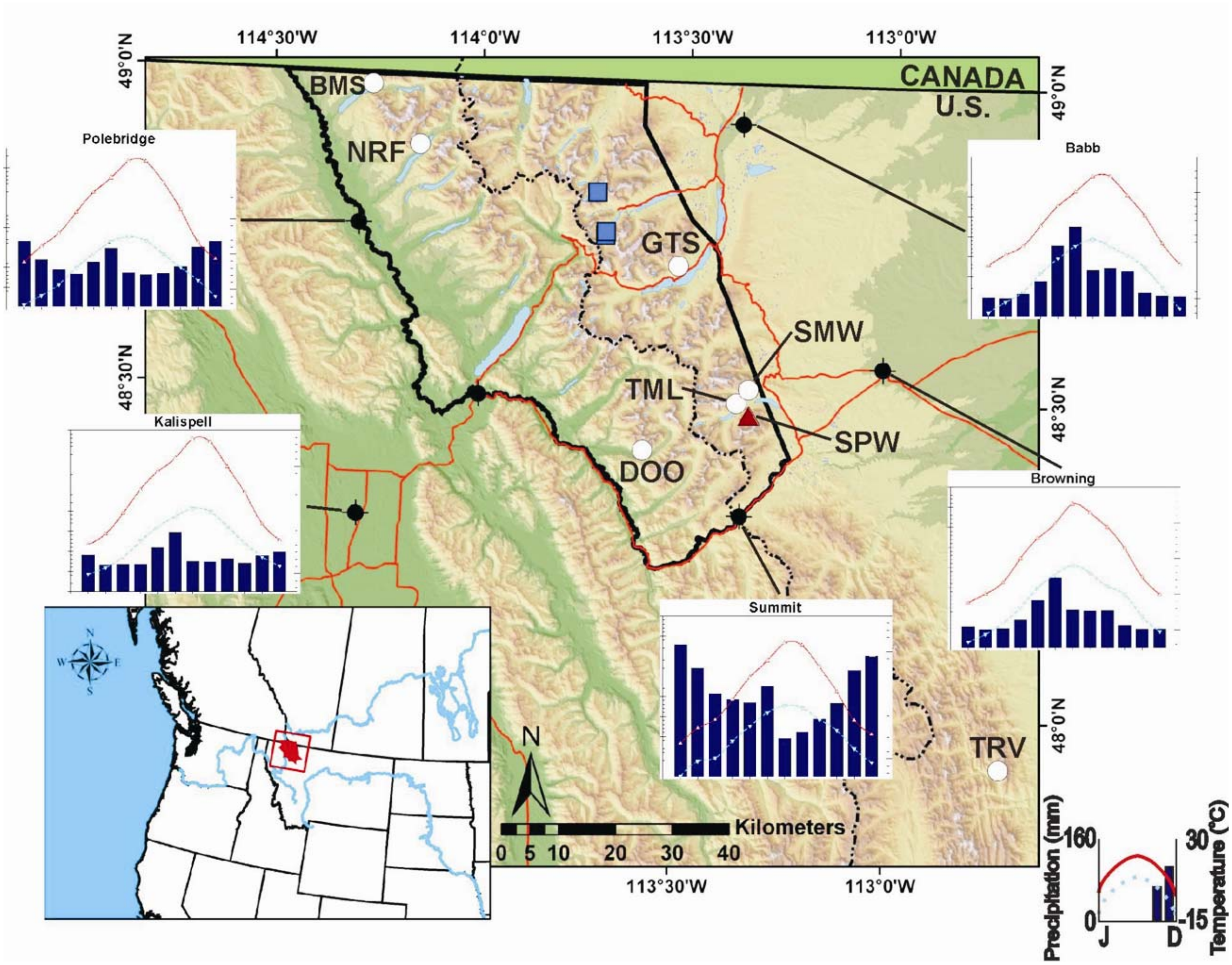

Figure 1. Location of tree-ring chronologies and climate stations in the Glacier National Park region. The heavy black line delineates the park boundary, and the stippled black line bisecting the park displays the path of the Continental Divide. White circles and red triangles represent Douglas-fir and limber pine chronologies respectively. Blue squares identify the location of three snow course sites in the Many Glacier drainage. Meteorological station locations are indicated with a black circle and climatographs for Kalispell, Polebridge, Summit, Babb, and Browning display regional climate differences. Solid red lines indicate monthly mean maximum temperatures, dashed light blue lines display monthly mean minimum temperatures, and monthly average precipitation is graphed using blue vertical bars with error bars plotted as +1 standard error from the mean. Historical weather data used in this study was obtained from the Western Regional Climate Center (WRCC; http://www.wrcc.dri.edu/), and the U.S. Historical Climatology Network (USHCN; *see* Easterling et al., [1996]; http://cdiac.esd.ornl.gov/epubs/ndp019/ndp019.html).

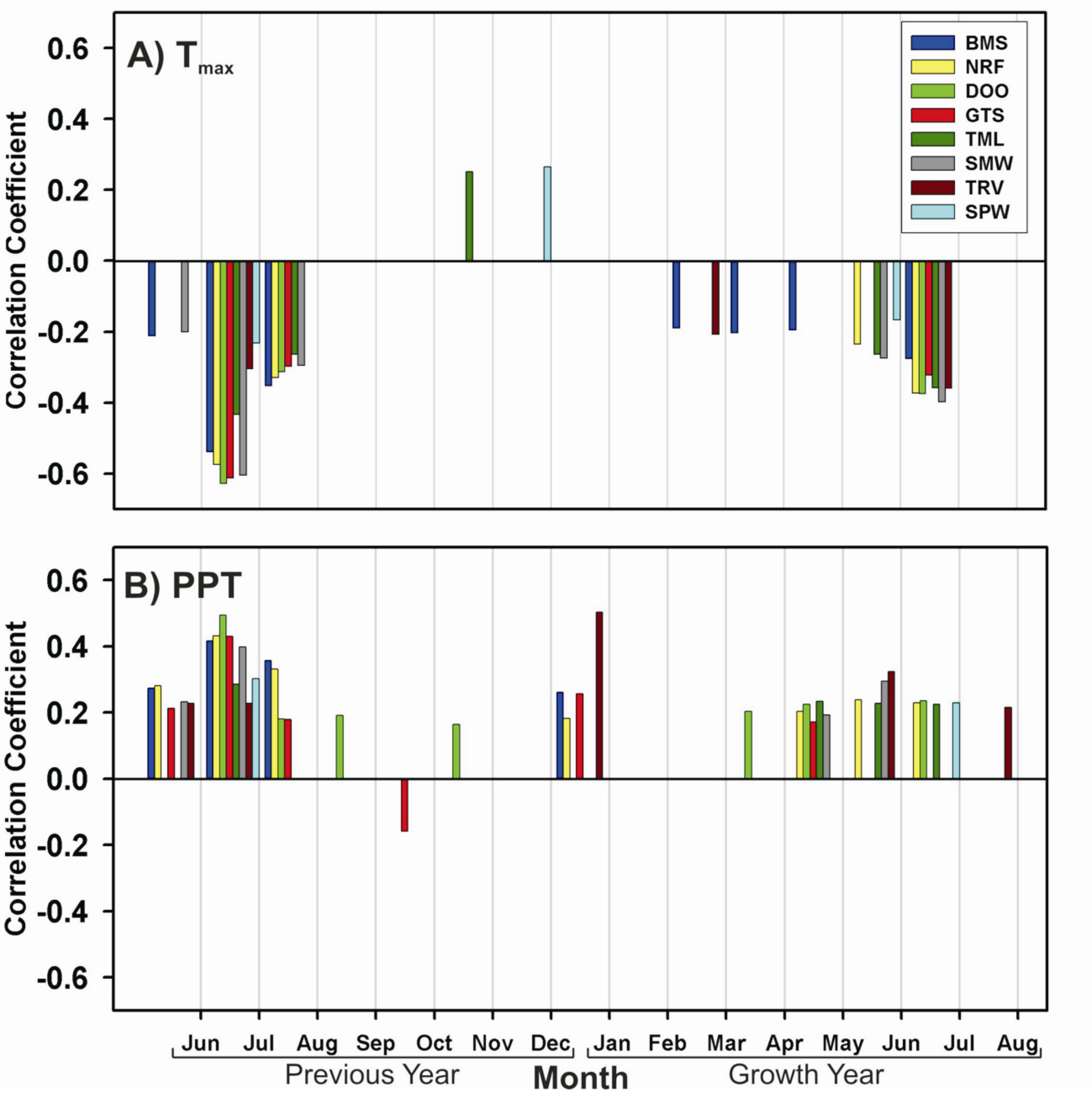

Figure 2. Correlations between all eight standardized ring-width chronologies and monthly temperature and precipitation over the 1900-2001 period. Analysis was carried out for: A) monthly mean maximum temperatures, and B) total monthly precipitation. Only correlations exceeding the 95% confidence limit when bootstrapped 1000 times are displayed.

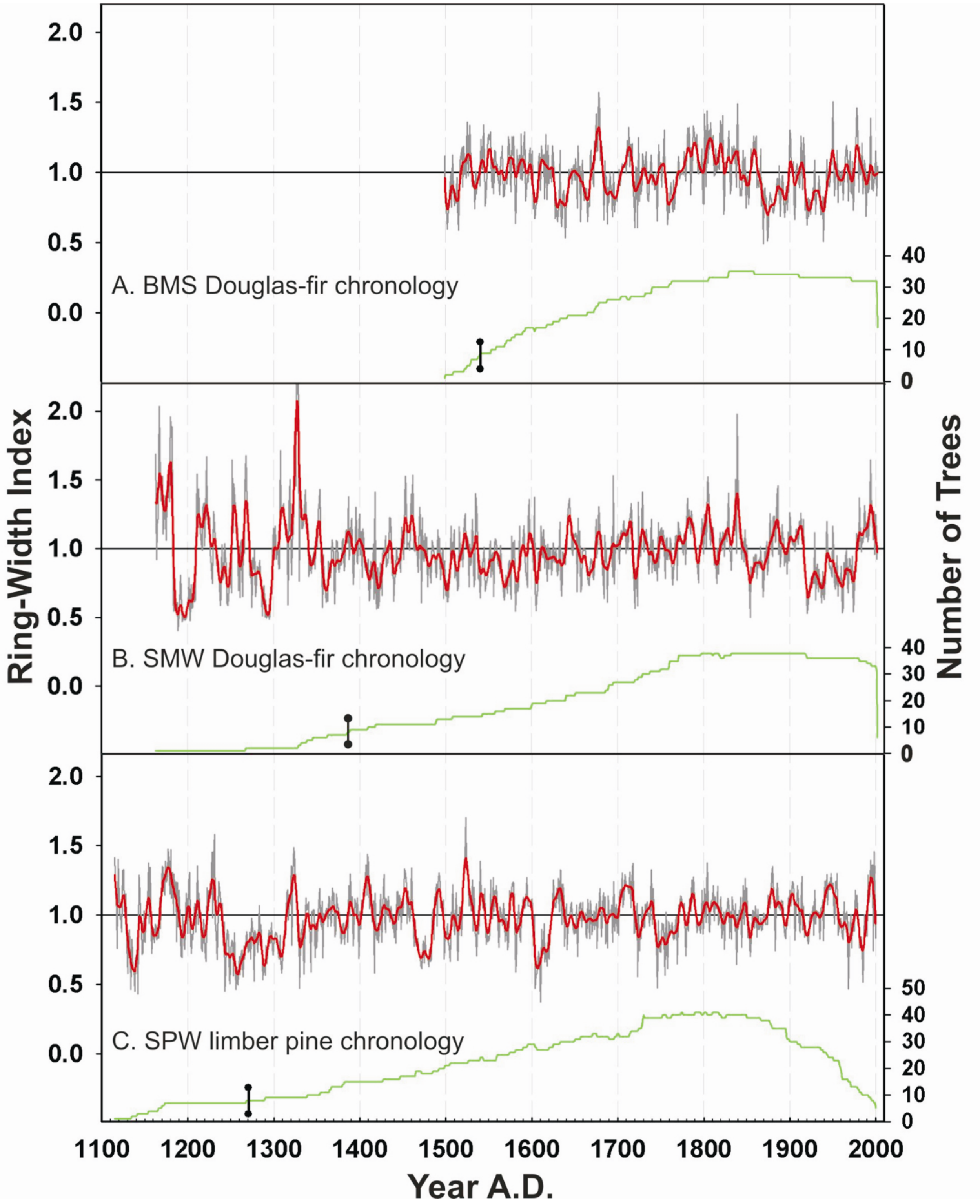

Figure 3. Standardized chronologies (gray line) smoothed with a 10 yr cubic spline (heavy red line) for (A) BMS, (B) SMW, and (C) SPW. Lower green line indicates sample depth (number of trees) through time with subsample signal strength ≥ 0.85 indicated by a heavy, vertical black bar.

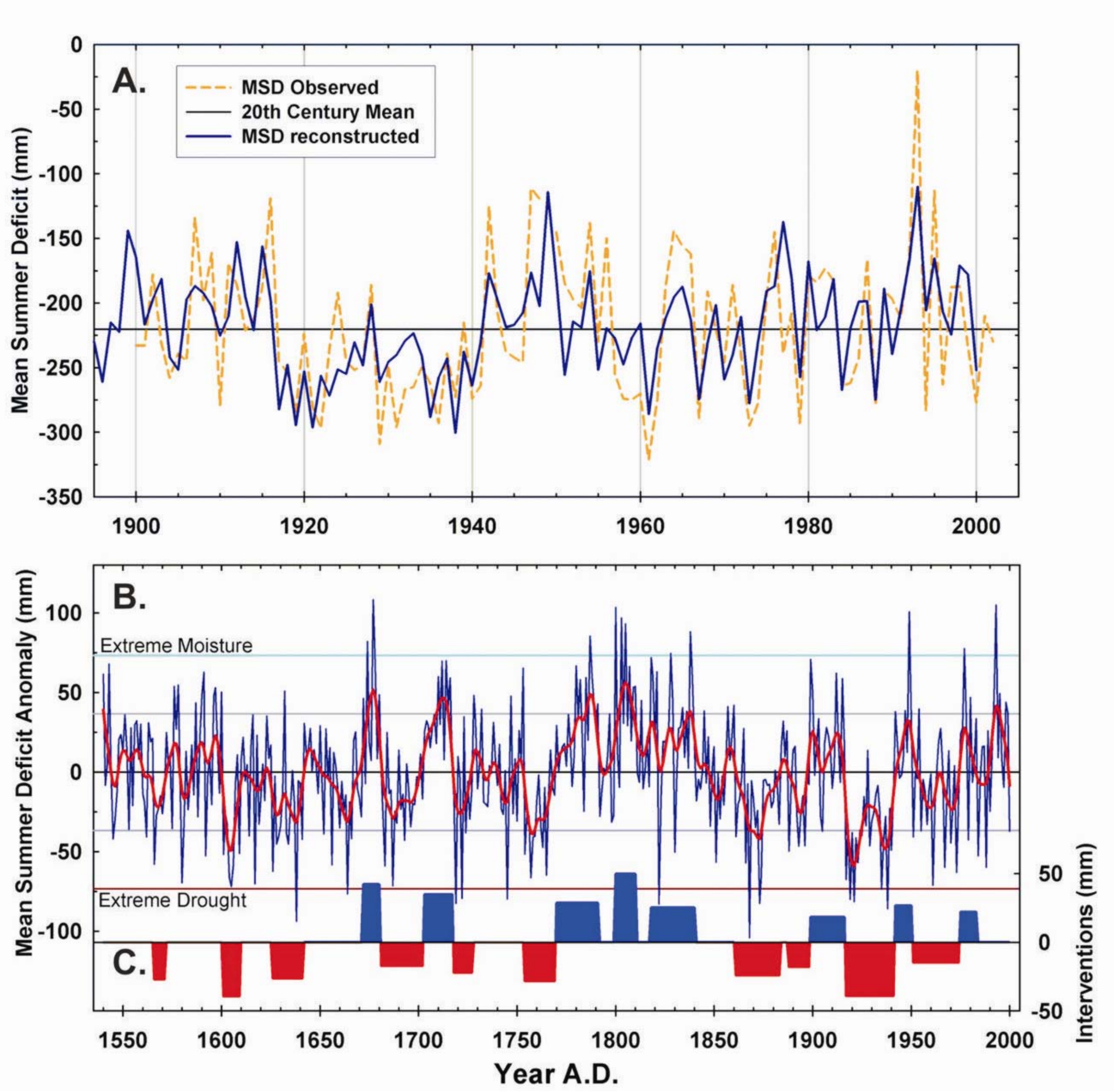

Figure 4. The summer drought reconstruction for Glacier NP. (A) Comparison of the observed and reconstructed MSD records for the 1900-2000 calibration period. (B) Mean centered reconstructed MSD (blue line) smoothed with a 10 yr cubic spline (thick red line) and spanning A.D. 1540-2000. Gray lines represent ± 1σ, and light blue and dark red line represent ± 2σ respectively from the long-term mean. (C) Decadal-scale drought regimes exhibiting the significant step-changes in the mean (event intensity) identified by the intervention model.

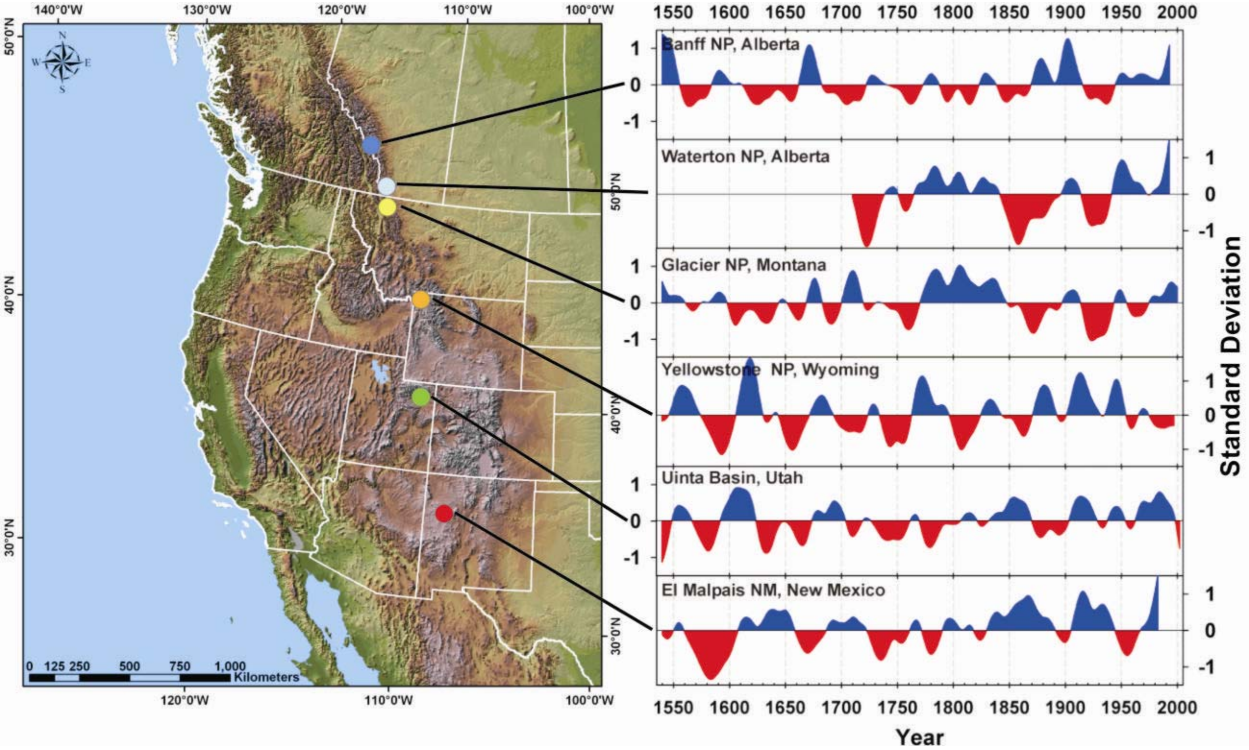

Figure 5. (Left) Location of tree-ring based precipitation and drought reconstructions used in comparison of moisture conditions along a north to south Rocky Mountain transect. (Right) Tree-ring based reconstructions of moisture anomalies. Each series has been normalized and smoothed using a 25 yr cubic spline to highlight the prominent 20 to 30 yr frequencies identified by MTM spectral analysis (Mann and Lees, 1996).

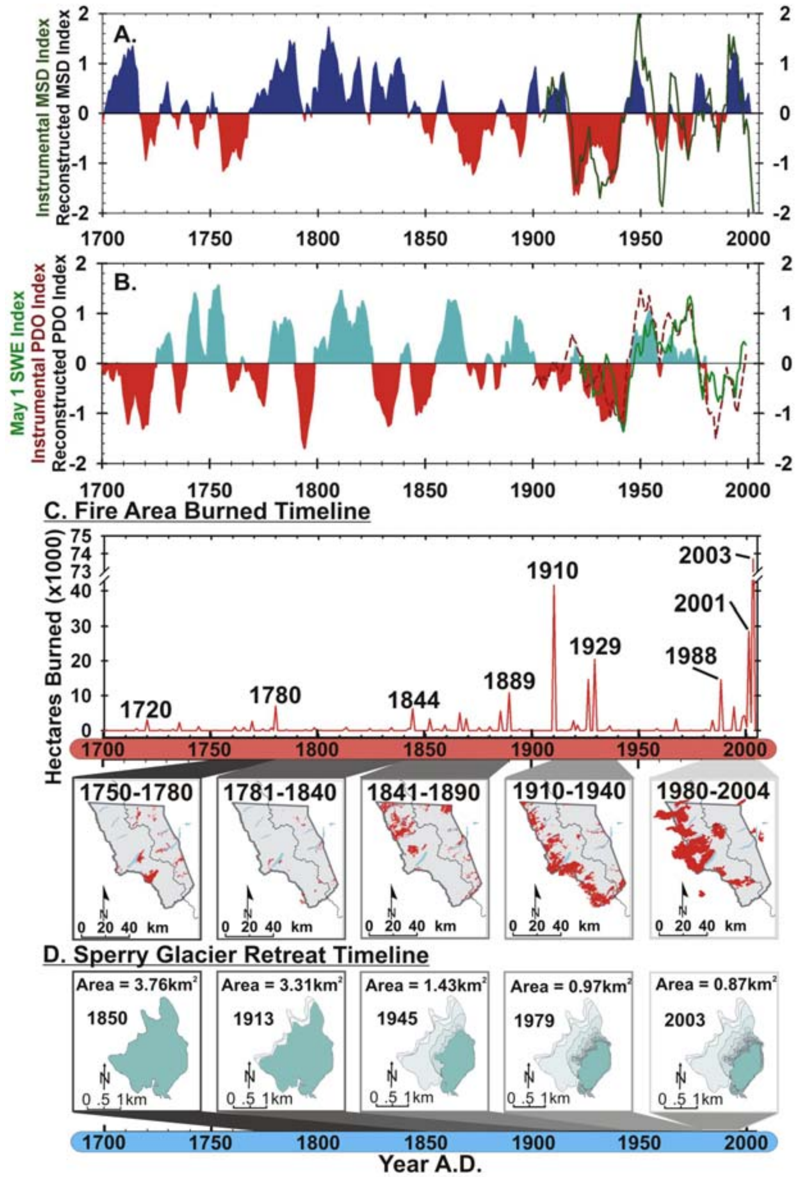

Figure 6. Relationship between Glacier NP historic summer drought, inferred winter snowpack (May 1st SWE), and ecosystem processes (i.e. fire area burned and glacial recession) back to A.D. 1700. (a) Instrumental and reconstructed summer drought (MSD) for Glacier NP normalized by converting to units of standard deviation and smoothed using a 5yr running mean. (b) Measured Spring snowpack (May 1st SWE) anomalies (1922-present) and average annual instrumental and reconstructed PDO anomalies (1700-2000). Each time series was normalized and smoothed using a 5 yr running mean to highlight decadal variability. For ease of comparison the instrumental and reconstructed PDO index was inverted due to the strong negative relationship between PDO anomalies and May 1st snowpack. (c) Fire area burned timeline for the Glacier NP region spanning A.D. 1700-present. Timeline is presented with maps exemplifying fire activity using decadal snapshots in time over periods corresponding to interesting winter and summer precipitation regimes. (d) Maps showing the decrease in area of the Sperry Glacier at critical points in time from 1850 to 1993. The retreat patterns of the Sperry Glacier are representative of other regional patterns of recession for glaciers sensitive to regional climate variability.