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Recent and dramatic changes in Pacific storm trajectories recorded in δ^{18}O from Bristlecone Pine tree ring cellulose

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[1] A 300-year stratigraphy of annual cellulosic $\delta^{18}O_{VSMOW}$ is presented for the long-lived Bristlecone Pine (*Pinus longaeva)* from the White Mountains of California. The $\delta^{18}O_{VSMOW}$ stratigraphy exhibits two distinctive characteristics: a bidecadal oscillation during the 20th century with peak excursions of 4‰ and a dramatic 9‰ shift in mean δ^{18}O values in the mid-19th century. The bidecadal δ^{18}O variability during the 20th century does not correlate well with the bidecadal pattern of drought recurrence as reflected in the Palmer Drought Severity Index. Geochemical modeling of the cellulose $\delta^{18}O_{VSMOW}$ indicates local climate conditions, particularly humidity and rainfall amount, should have been important influences on the cellulose δ^{18}O variability, but these influences cannot explain the larger bidecadal excursions or the shift in values during the mid-19th century. The large isotope variations must reflect sustained shifts in the frequency of subtropical versus polar storms that affect the isotopic composition of rainfall at the site. The mid-19th century isotopic shift correlates with the major climate shift across the northern hemisphere as documented in a wide range of proxy records. We hypothesize that the large isotopic shift in the 19th century represents the hydrologic response to a regime shift in mean wintertime atmospheric circulation that changed storm trajectories brought about by a more southerly position of the midlatitude jet, increased trade wind strength, and a change in the frequency of the Pacific Decadal Oscillation. The extent to which the hydrologic changes influenced the growth behavior of the high-altitude Bristlecone Pine in the White Mountains remains an important unanswered question.

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1. Introduction

[2] It is well documented that on subcentennial timescales, the societal and environmental impacts associated with anthropogenic climate change will largely be the result of changes in regional hydrologic patterns [*Baettig et al.*, 2007]. This is particularly the case for semiarid regions such as the southwestern United States where precipitation is sparse, highly seasonal, and can exhibit great interannual variability. Considerable effort has been put forth to understand the secular variability of precipitation in southwestern United States in

order to develop prediction capabilities that can be utilized by water managers and local governments. In the face of a rapidly growing populous and an increasingly early snowmelt season [*Stewart et al.*, 2004], the area is precipitously approaching an enhanced state of vulnerability and thus an understanding of the forces that control hydrologic variability becomes more urgent.

[3] The majority of precipitation delivered to coastal southwestern United States is from winter storms that originate in the North Pacific. The dominant influence of winter storms erodes eastwardly across the Great Basin into a bimodal-like distribution, with the prevailing impact of the winter North Pacific storms being superseded by late summer North American Monsoonal storms [*Ingraham and Taylor*, 1991]. On interannual timescales the most well known source of climatic variability within the southwestern United States is associated with El Niño−Southern Oscillation (ENSO), which involves changes in the trade wind strength across the tropical Pacific and subsequent impacts of this on the tropical ocean-atmosphere system. Instrumental and proxy records suggest that in recent times there has been an approximate 4−7 year recurrence frequency of ENSO though it is likely that there are lower frequency cycles generating protracted ENSO-like conditions as well [*Cook et al.*, 2007; *McCabe and Dettinger*, 1999; *Stott*, 2002]. The impact of ENSO on climate conditions in the western United States is not readily predictable because of the varying interactions of other hemispheric modes of climate variability including, but not limited to, the Pacific Decadal Oscillation and North Pacific Index, the Atlantic Multidecadal Oscillation and related factors such as the mean location of the midlatitude jet stream [*Biondi et al.*, 2001; *McCabe et al.*, 2004].

[4] It has been noted in numerous analyses of both instrumental and proxy records that precipitation in the southwestern United States has a persistent bidecadal rhythm [*Cook et al.*, 1997; *Currie*, 1981, 1984; *Mitchell et al.*, 1977; *Stockton et al.*, 1977]. The factors responsible for this recurring variability is not known although it has been suggested that it could be externally driven via solar (Hale) or tidal (18.6-year Lunar Nodal) [*Mitchell et al.*, 1977; *Stockton et al.*, 1977] cycles. Some authors have suggested that this climate variability is driven internally by unstable ocean-atmosphere interactions in the North Pacific, as reflected in modeling studies [*Latif and Barnett*, 1994, 1996]. The bidecadal frequency is overlain onto longer multidecadal cycles that share a common frequency with variations in surface temperatures and pressures over the North Pacific described by a suite of North Pacific climate indices.

[5] Over the most recent millennium, the so-called Pacific Decadal Oscillation (PDO) has been a persistent pattern of ocean/climate variability despite having a transient spectra with frequencies that shift between decadal and multidecadal [*Benson et al.*, 2003; *Biondi et al.*, 2001; *D'Arrigo et al.*, 2001; *Gedalof and Smith*, 2001; *Mantua and Hare*, 2002]. The PDO is recognized as a warm-cold oscillation of ocean surface temperatures, north of 20°N in the Pacific. The oscillatory nature of the PDO over the past several centuries may have been driven by interplay between the subtropical gyre and the Aleutian Low. The depth (strength) of the low-pressure system in the North Pacific responds to changes in the strength of the westerly winds, affecting the latitude of Pacific storm tracks. The positive (negative) state is associated with a southerly (northerly) shift in the storm tracks, resembling a sustained El Niño-like (La Niña-like) state [*Liu and Alexander*, 2007]. The PDO thus affects not only the amount of precipitation being delivered to the southwestern United States but the pathway in which the storm tracks approach from. Indeed on a multidecadal and century-scale the influence of the PDO on precipitation throughout the southwestern United States has been recognized in tree ring chronologies [*Biondi et al.*, 2001; *Gedalof and Smith*, 2001; *MacDonald and Case*, 2005]. During the instrumental period variations in the North Pacific Index appear to have a distinct timescale from the PDO, though it generates a similar effect on the pathway of the midlatitude jet stream by way of the development of a high-pressure blocking cell in the North Pacific, which modifies the course of storms approaching western North America.

[6] It has been observed in tree ring width and lake level reconstructions of the PDO that prior to the terminus of the Little Ice Age in the middle of the 19th century the PDO seemed to have both a smaller amplitude and higher frequency [*Biondi et al.*, 2001; *Gray et al.*, 2007; *Hidalgo*, 2004; *MacDonald and Case*, 2005]. Reconstruction showing that the system toggles between higher and lower frequencies is an observation that is consistent with studies of the Pacific ocean-atmosphere dynamics using coupled global climate models [*Latif*, 2001]. Hydrologic changes across

the western United States may also be influenced by ocean and atmospheric changes within the Atlantic. The Atlantic Multidecadal Oscillation (AMO) may impose an atmospheric response in the North Pacific that resembles that which accompanies the ENSO and PDO shifts [*McCabe et al.*, 2004]. Thus, on decadal to multidecadal timescales the frequency of hydroclimatic variability in the southwestern United States can be thought of as a sum of constructive and destructive interactions between ENSO, PDO (and related Pacific decadal variability) and AMO. It should be noted that while there are indeed strong correlations between the aforementioned atmospheric modes and distribution of rainfall across the western United States, the atmospheric dynamics that are responsible for these shifts remains enigmatic. An alternative dynamically based perspective generated from recent modeling work would suggest that the leading cause for precipitation variability, both rainfall amounts and storm trajectories, is primarily sea surface temperatures in the Tropical Pacific [*Cook et al.*, 2007; *Seager et al.*, 2005]. The factors responsible for this SST variability are not well resolved at present although external (volcanism and solar [*Mann et al.*, 2005]) and internal [*Latif and Barnett*, 1994] have been called upon. Ultimately, well-resolved climate reconstructions that can extend the short instrumental record will help determine how the climate responds to a particular forcing, either internal or external. To this end, we attempt to develop a new high-resolution record of winter storm type variability for the southwestern United States using the oxygen isotope composition of tree ring cellulose.

2. Background Isotopes in Tree Cellulose

[7] The use of δ^{18}O from tree ring α-cellulose (subsequently referred to as simply ‘‘cellulose’’ or ‘‘cellulosic’’) as a means for paleoenvironmental reconstruction was first suggested in the mid-1970s. Observations have shown that δ^{18}O in the cellulose component of wood varies as a function of both changes in temperature and precipitation [*Burk and Stuiver*, 1981; *Masson-Delmotte et al.*, 2005; *McCarroll and Loader*, 2004; *Raffalli-Delerce et al.*, 2004]. Mechanistic models of δ^{18}O in cellulose assume that water entering the tree via the root system is representative of local precipitation, which becomes isotopically enriched in the leaf as a result of a slower diffusion rate of ‘‘heavy’’ water molecules passing through the leaf boundary layer. The vapor pressure gradient between the substomatal cavity and the atmosphere (i.e., relative humidity) varies with meteorological conditions, which helps to explain the negative relationship between water deficits and δ^{18}O values [*McCarroll and Loader*, 2004]. The isotopically enriched leaf water provides the source for hydrogen and oxygen atoms in the photosynthates, and in doing so, captures the magnitude of leaf-water enrichment in the resulting carbohydrates [*Barbour et al.*, 2004; *Deniro and Cooper*, 1989; *Roden et al.*, 2000]. The isotopic ratio of the carbohydrates, which has been substantially enriched relative to the source water (i.e., precipitation), becomes washed out by a partial isotopic exchange that occurs between the source water and photosynthates during the synthesis of cellulose [*Deniro and Cooper*, 1989]. The magnitude of the exchange between the carbohydrates and source water during the synthesis of cellulose is approximately 40% [*Sternberg*, 1989]. Thus, the cellulose records a signal that integrates both the conditions at the leaf-atmosphere interface (~60% of the oxygen atoms) and the source water isotopic ratio (~40% of the oxygen atoms) that varies as a function of temperature, storm trajectory/source region and the amount/type of precipitation that falls.

[8] The extent to which source water variability or ecophysiological interaction control the cellulosic δ^{18}O signal depends on the specific environment where the growth takes place. In locations where, either as a function of meteorology or soil hydrology, the tree’s source water remains relatively constant; the dominant source of year to year isotopic variability will result from changes in humidity. Temperature changes should impart a lower frequency signal as a result of the positive relationship between the δ^{18}O in precipitation and air temperature. These local climate-isotopic relationships have been well documented at temperate latitudes [*McCarroll and Loader*, 2004; *Anderson et al.*, 2002; *Burk and Stuiver*, 1981]. At sites where the local meteorology is more complex, varying storm types (e.g., high-latitude versus low-latitude storms) will impose a greater isotopic influence on tree cellulose than local humidity and temperature. This is indeed the case for southern California where a confluence of North Pacific, subtropical and monsoonal storms generate precipitation with a wide range of isotopic compositions [*Friedman et al.*, 2002a]. It has been shown that tree ring cellulose can capture the impact of isolated storm events such as hurricanes [*Miller et al.*, 2006] or longer-term shifts in precipitation type (snowfall

versus rainfall) as was observed by *Treydte et al.* [2006] in a study on hydrologic variability in Pakistan. In these instances changes in the local climate are superseded by the larger influence of source water heterogeneities. While trees cannot simply be viewed as precipitation "buckets," in regions that have a complex meteorology and where varying storm types bring with them a distinct isotopic signature, the $\delta^{18}O$ in tree cellulose may be cautiously viewed as a proxy for history of change in source water isotopic composition.

3. Bristlecone Pine Trees

[9] A number of previous paleoclimate studies have utilized the long Bristlecone Pine chronology to reconstruct atmospheric temperatures and drought severity [*Lamarche*, 1974; *Mann et al.*, 1998b]. However, no previous study has investigated the secular variability of $\delta^{18}O$ in the tree ring cellulose. An annually resolved chronology of Bristlecone Pine $\delta^{18}O$ thus provides a unique opportunity to look at how changes in the $\delta^{18}O$ values of precipitation in the American west have varied throughout the length of Bristlecone Pine chronology, which can now be extended back over 8,000 years. Both modeling and instrumental measurements indicate that the $\delta^{18}O$ in precipitation is homogenous on a regional (i.e., southwestern United States) scale [*Bowen and Wilkinson*, 2002]. Thus, if changes in source waters can be reconstructed from tree ring cellulose, even a record from a single site can serve as an adequate approximation for a wider region. The present study investigates how the oxygen isotopic ratio of cellulose from two Bristlecone Pine trees in the White Mountains of California has varied over the past three centuries in an attempt to document secular variations in storm types that have influenced the hydrologic balance across the region. The isotopic analysis of the cellulose is coupled with analysis of meteoric water samples and a simple geochemical model to constrain possible mechanisms that have influenced the isotopic variability.

4. Methods

4.1. Cellulosic $\delta^{18}O$

[10] The cellulose samples used in this study were collected from two trees (37°23′11.24″N, 118°10′45.62″W and 37°23′06.57″N, 118°10′40.86″W at 3,075 amsl) in the White Mountains of California just east of the National Forest Service's Shulman Grove Visitor Center along the Methuselah Walk Trail (Figure 1). This site is largely undisturbed with limited evidence for anthropogenic land-use or hydrologic changes. Samples were collected using a 5 mm increment borer in April and July of 2006 from living trees that appeared to be of similar age. The cores were sanded to reveal their annual rings and cores from the first tree were dated with the assistance of Tom Harlan using the "Methuselah Walk" ring width chronology available from the International Tree Ring Database. The master chronology was developed with 285 wood segments with an average width of 0.23 mm and a standard deviation of 0.14 mm [*Graybill and Funkhouser*, 1995]. The dating was done using the "Cross Date" program developed by Greg Lazear and Tom Harlan. The cores chosen for this study were from trees that had a greater than 80% correlation with the master chronology for this grove (see Figure 5) and had no missing rings back through the last three centuries. Working under a microscope, each core was sliced into annual samples using a scalpel or a rotary microtome.

[11] For isotopic measurements it is necessary to remove components of the wood that are mobile and/or the isotopic composition is not stable. It is typical to use a component of the wood referred to as α-cellulose, which describes the portion of the structural component of the wood that is insoluble in 17.5% NaOH [*Boettger et al.*, 2007]. In this study we chose to work with wood from the entire ring as opposed to individual early or late wood components because the diminutive size of the rings made such separations very difficult. This adds a certain amount of year to year autocorrelation owing to the fact that trees often use stored photosynthates from the previous year in the beginning of the growing season [*Hill et al.*, 1995]. Between 0.5 and 1 mg of α-cellulose was extracted from raw wood samples (between 30–40% yield) using a modified version of the "Brendel method" in which the wood samples were cut into thin slices and soaked at room temperature in an acetic (80%) and nitric (70%) acid solution (10:1) for a few hours before being heated to 120°C for 30 minutes to remove lignins and resins from the wood. The samples were then cleansed with a series of water and ethanol washes and soaked in acetone to be dried [*Brendel et al.*, 2000]. The inclusion of an acid presoak preceding the heated acid soak was done to accommodate the fact that the wood samples were often too small to be milled, which resulted in incomplete extractions following the

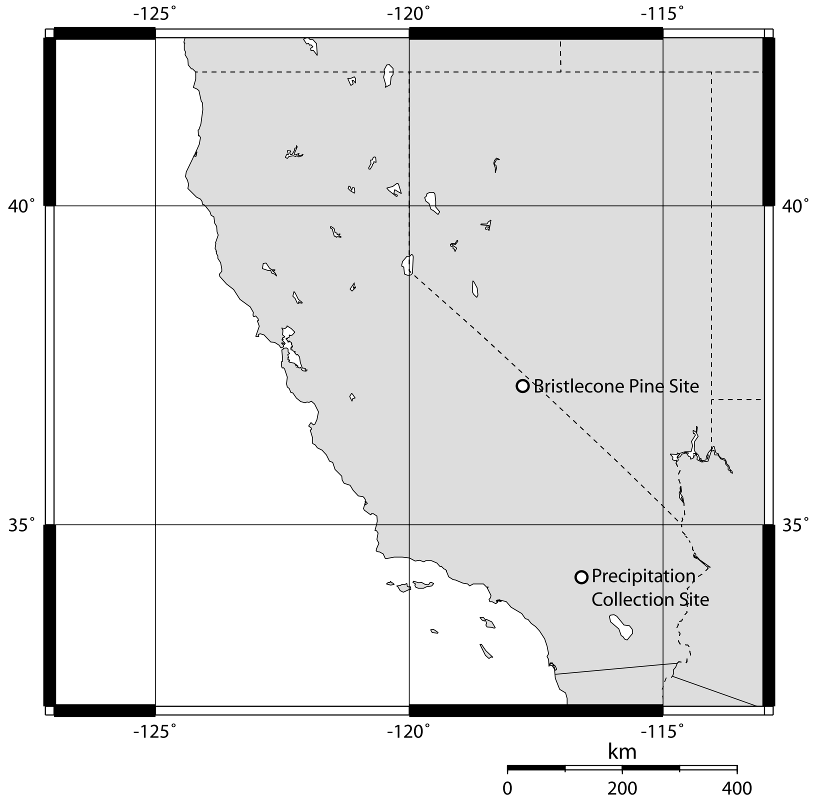


Figure 1. Map of California showing sampling locations.

original method of *Brendel et al.* [2000]. This was based on visual inspection whereby α-cellulose has a distinct white cotton-like appearance, which is starkly distinct from raw wood. We found that by allowing the thin wood slices to be soaked prior to extraction, the method consistently produced a more pure cellulosic product. Wood and cellulose samples of known isotopic compositions were treated with the additional presoak and showed no impact on the resulting isotopic composition.

[12] Some recent studies have found that the Brendel method may produce inconsistent isotopic results owing to either incomplete removal of hemicelluloses or because it fails to remove some of the acid solution used during the extraction procedure [*Gaudinski et al.*, 2005]. We chose to use this method because it readily accommodates very small samples and it is rapid. *Anchukaitis et al.* [2008] compared cellulose extracted using the Brendel method and the more traditional Leavitt-Danzer method using both Mass Spectrometry and Fourier Infrared Thermal Spectroscopy. Their results indicate that the questionable peaks in the NMR spectra as recognized by *Gaudinski et al.* [2005] are the result not of residual solvent but rather a low-order acetylation that occurs when the cellulose is heated in the acid solution. They also report that the acetylation that may occur during the Brendel method has no distinguishable impact on the oxygen isotopic ratio of the residual cellulose compared with the more traditional Soxhlet method.

[13] Approximately 0.25 mg of purified cellulose was loaded into silver capsules and pyrolyzed online with a Carlo Erba Elemental Analyzer maintained at 1054°C. The carbon monoxide produced by pyrolysis was isotopically analyzed on a Micromass Isoprime continuous flow mass spectrometer. The oxygen isotopic ratios are reported in "δ" notation relative to VSMOW via analysis of a reference CO that is calibrated to VSMOW via three organic standards of known isotopic composition: the Baker cellulose standard (28.6‰ VSMOW), the IAEA C3 cellulose standard (32.2‰ VSMOW) and the IAEA sucrose standard (36.4‰ VSMOW) [*Saurer et al.*, 1998]. The analytical precision of cellulose standards analyzed intermittently with the Bristlecone Pine samples (approximately 3 cellulose standards following every 8 samples) is ±0.3‰. We systematically

ran duplicates when samples were sufficiently large, this was done on 25% of the samples and with an average difference between duplicate samples of 0.35‰.

4.2. Meteoric Water Samples

[14] Precipitation was collected from a site just north of Mt. Baldy in the San Gabriel Mountains of southern California (34.27 N, −117.62 W) (Figure 1) approximately 400 km from the tree site. The water was collected in a simple funnel type collector with a small amount of mineral oil on the base of the collector to avoid evaporation from the storage vessel [*Friedman et al.*, 1992]. A series of three 1 L precipitation collectors were deployed during the fall of 2005 and emptied following each precipitation event until April 2006 in order to generate a series of discreet storm samples. The precipitation samples ranged in size from 0.1 L (1 March 2006) to 0.3 L (21 February 2006). The water was removed from each vessel using a syringe that was plunged below the mineral oil directly into the meteoric water sample. The vessel was then cleaned, dried and redeployed in the field. With the exception of one collector being destroyed by a bear, the collectors were undisturbed and faithfully captured each major storm event of the season. 0.2 mL of each of the water samples was equilibrated at 40°C overnight with CO_2 of a known isotopic composition. The equilibrated CO_2 was dried on gas extraction lines and the isotopic composition of the pure CO_2 was measured on a dual-inlet mass spectrometer. The procedure was calibrated using IAEA water samples (GISP (−24.78‰), SLAP (−55.5‰) and VSMOW (0‰)). The procedure had an analytical uncertainty of ±0.15‰.

4.3. Geochemical Model

[15] To assess the extent to which variations in the isotopic composition of precipitation influenced the cellulosic δ^{18}O values, we used the mechanistic model of ^{18}O fractionation and cellulose synthesis developed by *Roden et al.* [2000] and *Barbour et al.* [2004] available for download at http://ecophys.biology.utah.edu/public/Tree_Ring/. The model has been shown to closely approximate the observed response to natural climatic variability over a wide range of environmental conditions. The model requires inputs for a range of climatic, isotopic and physiological parameters in order to determine the degree to which the tree's source water will be modified as it becomes bound in cellulose. We made no alterations to the equations used in the model, which are fully developed by *Roden et al.* [2000, and references therein]. All climatic inputs into the model were taken from instrumental records from the White Mountain region made available by the White Mountain Research Station (http://www.wmrs.edu). We used humidity, wind speed and temperature data integrated over the growing season, which we defined as July through September [*Fritts*, 1969]. We assumed a leaf temperature which would closely follow the ambient temperature over an entire growing season, though deviations from this would clearly arise during periods of increased windiness [*Drake et al.*, 1970]. Given an absence of regular measurements of stomatal conductance we used the data from [*Monson and Grant*, 1989] for mature pine trees growing under an array of climates. Estimates for the isotopic composition of the source water were taken from [*Benson and Klieforth*, 1989; *Friedman et al.*, 1992, 2002a, 2002b] and our own measurements. These data were employed to estimate the isotopic composition of water vapor given a temperature-dependent fractionation factor between falling water and the resulting vapor [*Gat*, 1980; *Majoube*, 1971]. There is a wide range of uncertainty associated with this parameter, which is difficult to constrain in the absence of any measurements for this region. *Roden et al.* [2000] suggest there are potentially large impacts associated with variability in water vapor isotopic composition, which is an issue to be addressed with future monitoring. We assumed a constant barometric pressure derived purely as a function of elevation [*Pearcy et al.*, 1989].

[16] Using these data we tested the sensitivity of the model by perturbing it across the full range of estimated humidity, temperature, source water and stomatal conductance values. Unlike more rigorous approaches to modeling cellulosic δ^{18}O such as *Evans* [2007] or *Anderson et al.* [2002] we used the model to assess how various environmental factors can affect the magnitude isotopic variability at the study site and how such factors may have influenced the BcP cellulosic δ^{18}O over time.

5. Results

5.1. Cellulosic δ^{18}O

[17] Figure 2a shows an annually resolved continuous time series of δ^{18}O for the Bristlecone Pine back to 1700 A.D. A 3-point smoothing has been applied to the δ^{18}O time series to accentuate the

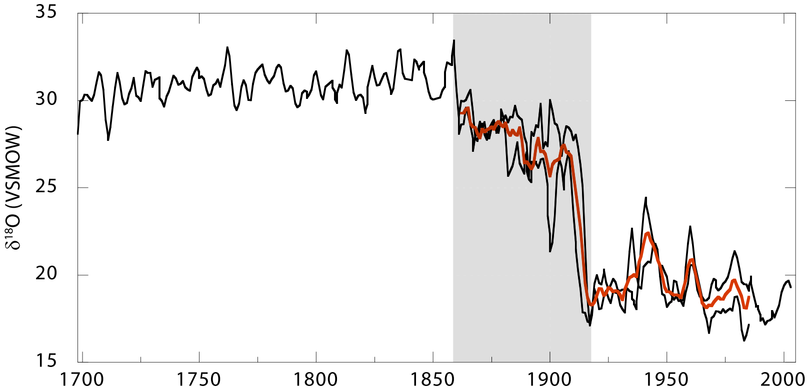


Figure 2a. Measured δ^{18}O values of Bristlecone Pine cellulose. Shown in black are annual values for two cores taken from trees in the same grove; the red line is the mean of the two cores. The cores are well correlated during the period of overlap (1857–2005) (Figure 2b). The shaded region (1855–1910) is used to highlight the major transition that separates the pre-1850 values from the rest of the 20th century. The data have an analytical uncertainty of 0.3‰ (VSMOW).

lower frequency signals. Figure 2b shows the correlation between the mean values of the two trees in 20-year increments (bottom) and throughout the whole record (top). As a whole, the correlation between the two series approaches 0.8, a value which is partially an artifact of the large magnitude transition in the mid-19th century. The correlations during the 20-year intervals ranges from 0.68 (1960–1980) to 0.48 (1920–1940). The high degree of correlation between the two isotopic records validates our use of smaller sample sizes than is typically used in such studies.

[18] Our Bristlecone Pine δ^{18}O record can be split into three discrete regimes: 1700–1860, 1860–1910 and 1910–2004. Between 1910–2004 the record exhibits a distinctive bidecadal oscillation that is punctuated by peaks in δ^{18}O centered around 1920, 1940, 1960 and 1980. With the exception of the 1920 peak, the peaks appear to have become progressively smaller in magnitude toward the present day. The most pronounced feature of the 300-year-long record is a major isotopic enrichment between 1910 and 1857. The oxygen isotope values prior to 1857 are on average 10‰ higher than values during the 20th century (Figure 2a). This shift in isotopic values occurred in a series of step-like events with the majority of change occurring as part of a rapid excursion in the beginning of the twentieth century. These steps also occurred in roughly 20-year intervals and could be identified as a continued, albeit subdued, manifestation of the bidecadal oscillation observable during the rest of the twentieth century. The δ^{18}O values are more stabile prior to the middle of the 19th century, averaging 31‰ through the latter part of the 17th century. Spectral analysis of the entire data set using a Fast Fourier Transform confirms (>90% confidence limit against a white noise background spectrum) that the dominant period is approximately 20 years (Figure 3a). A similar analysis for the period between 1860–1700 indicates that there were 8 and 12-year-long excursional periods during this portion of the chronology (Figure 3b), and this suggests that the predominant

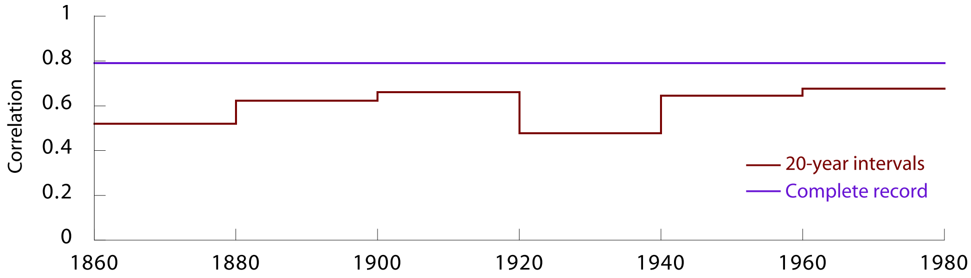


Figure 2b. Correlation of isotopic data from separate cores over the period of overlap. The correlation across the entire record is 0.79, which is slightly higher than the correlation during any single 20-year interval.

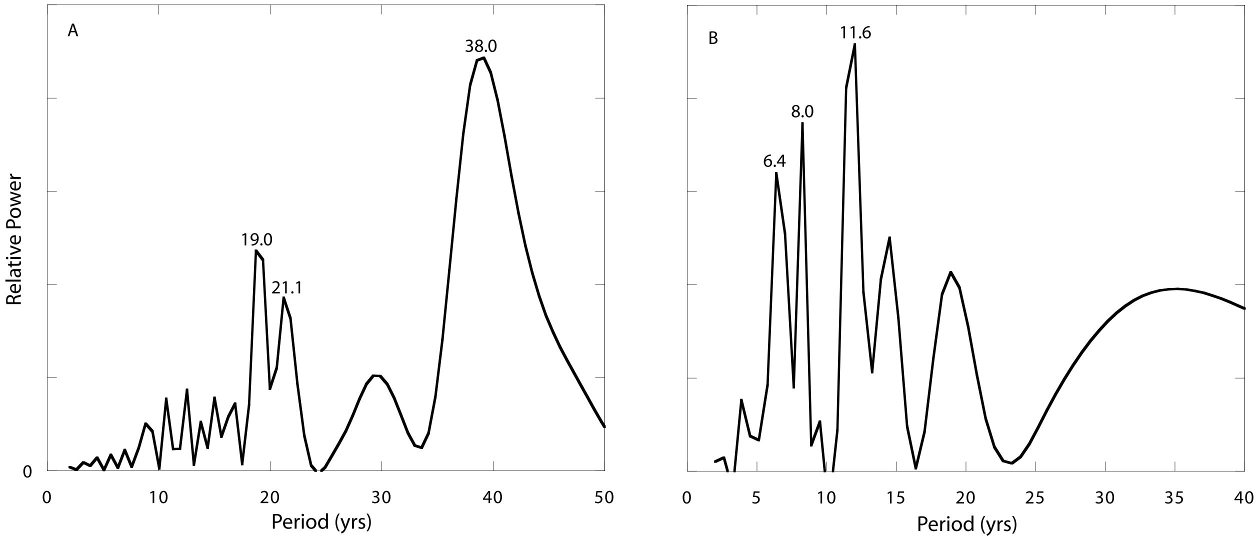


Figure 3. Periodogram showing the relative spectral power using a Fast Fourier Transform. (a) Spectrum for the entire chronology with significant peaks identified for 19-, 21-, and 38-year cycles. (b) Spectrum for 1700–1861 with significant peaks identified for 6.4-, 8-, and 11.6-year cycles. Labeled peaks are those that exceed a 90% confidence interval against a white noise background spectrum.

temporal pattern of variability changed during the middle of the 19th century to a longer timescale.

5.2. Meteoric Water Samples

[19] The meteoric water $\delta^{18}O$ values are shown in Table 1 for six storms that struck southern California during the winter of 2006. The values range from a maximum value of −2.2 ± 0.23‰ for the 4 January storm to a minimum value of −11.50 ± 0.35‰ during the 22 March storm. The storms on 4 January, 22 January and 4 March were subtropical storms and all have similarly enriched values relative to the January storms that originated from the North Pacific. The 1 March and 22 March storms were both North Pacific storms and had oxygen isotopic values similar to the January storms. One of the storms (12 April storm) originated in the North Pacific and had an isotopic value intermediate between the January (northern) and March (subtropical) storms.

5.3. Geochemical Modeling

[20] The isotopic model indicates that the environmental conditions within the White Mountains impose a small influence on the $\delta^{18}O$ of Bristlecone Pine cellulose relative to the magnitude of variability observed in our record. Figure 4a illustrates the sensitivity estimates for cellulosic $\delta^{18}O$ values as a function of interannual growing season relative humidity (RH) change with other environmental parameters held constant. There is approximately a 0.2‰ decrease in cellulosic $\delta^{18}O$ for each percentage change in RH. Daily humidity was collected at the Mount Barcroft Weather Station in the White Mountains between 1981–1999 and made available to us by the White Mountain Research Station FTP site (ftp://www.wmrs.edu/). These values are integrated over the entire growing season in Figure 4b. Although the record is short, there is no evidence that during this instrumental period there was a growing season humidity effect on the BcP $\delta^{18}O$ values (Figure 2a). Nonetheless, these data do provide a constraint on the isotopic variability that would be expected for a range of humidity values, and thus provide an upper limit on the extent to which humidity could have influenced the $\delta^{18}O$ variability in the BcP. The maximum RH of slightly over 60% occurs in 1984 and the minimum value of approximately 46% occurs in 1989, indicating that a range of 14% RH values

Table 1. Winter 2006 Storms Whose Isotopic Compositions Were Measured

Storm Date	$\delta^{18}O_{(VSMOW)}$	Trajectory
4 Jan 2006	−2.90‰	S, SW
22 Feb 2006	−2.25‰	S, SW
1 Mar 2006	−11.07‰	N, NW
4 Mar 2006	−3.33‰	S, SW
22 Mar 2006	−11.50‰	N, NW
12 Apr 2006	−6.25‰	N, NW

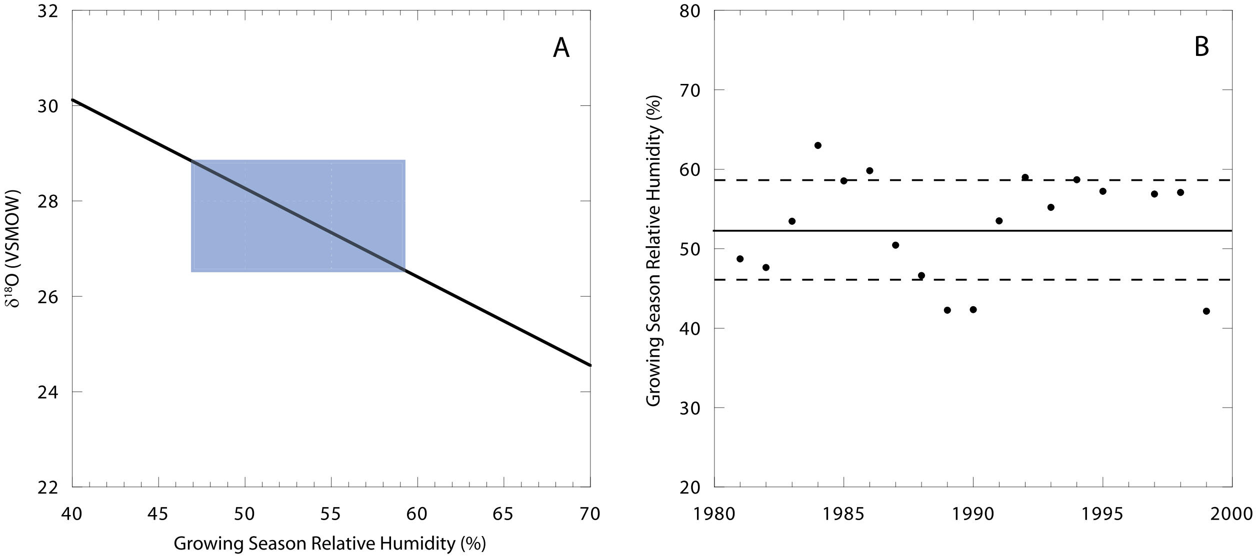


Figure 4. Instrumental growing season relative humidity and modeled impacts on δ^{18}O values. (a) Modeling results showing the negative relationship between growing season relative humidity and cellulosic δ^{18}O using climatic parameters similar to what is observable in the White Mountains of California. The model, which is available for download at http://ecophys.biology.utah.edu/public/Tree_Ring/, is based on equations laid out by *Roden et al.* [2000]. The light blue box encompasses the range of expected humidity values for this site and their impact on the resulting δ^{18}O values, which is approximately 1.75‰. A similar sensitivity analysis was done with both stomatal conductance and temperature, resulting in a far narrower impact on δ^{18}O values. (b) Instrumental average growing season relative humidity values taken from daily values recorded at the Mount Barcroft weather station. The dashed lines envelop one standard deviation (5.9%) from the mean value of 53% over the entire period of record (1981–1999).

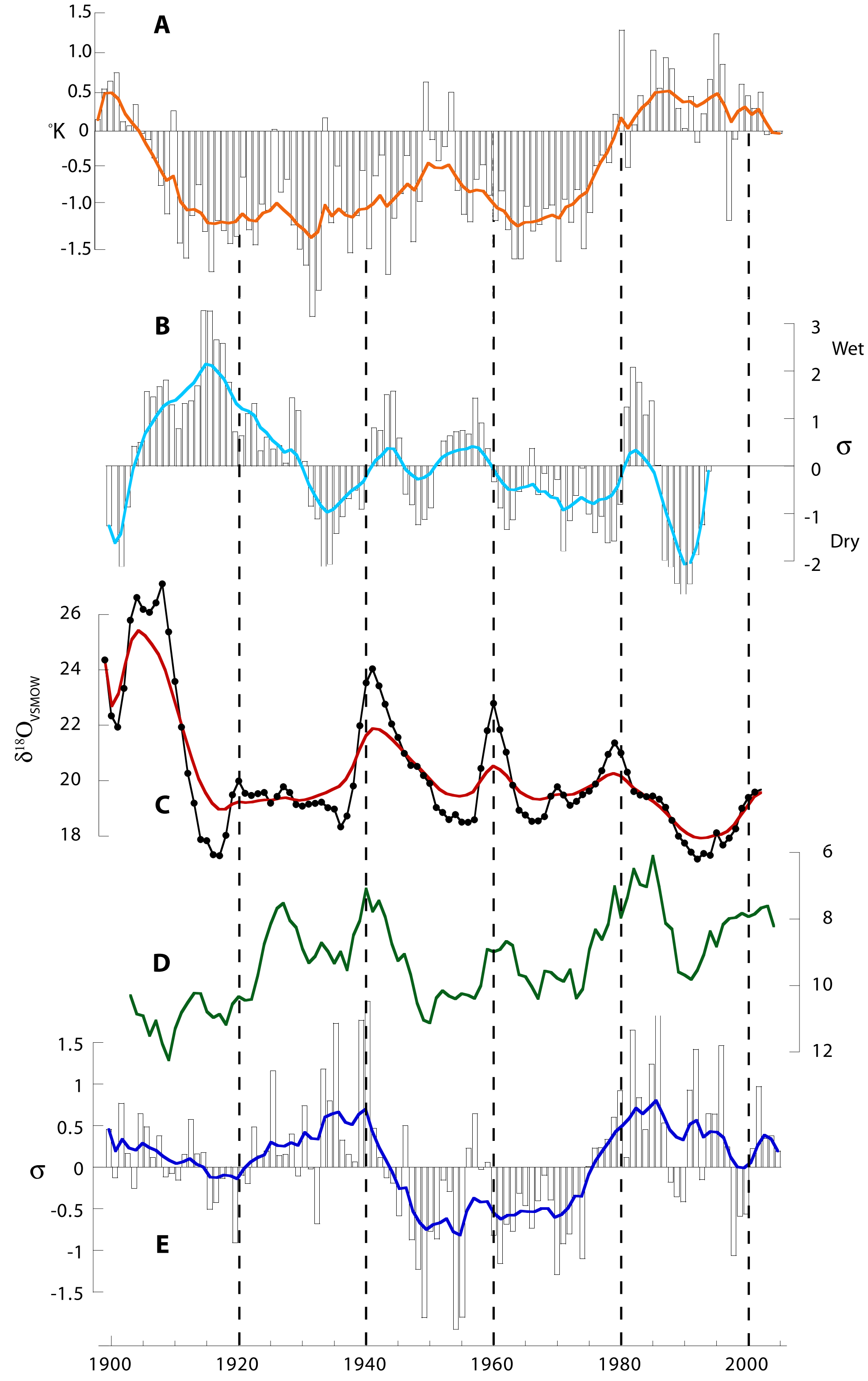
encompasses a first-order estimate for interannual humidity variability. A change of 14% RH would thus generate a change of slightly over 2‰ in the resultant cellulose (Figure 4b).

[21] Although not shown, similar approaches were taken to model the impact of stomatal conductance and temperature on the resulting cellulose. We chose a wide range of potential stomatal conductance estimates (between 20–80 mmol m^{-2} s^{-1}) and a growing season temperature range of 20–26°C as derived from instrumental data. The sensitivity between cellulosic δ^{18}O values and ambient temperature (as it effects the temperature-dependent fractionation factors) is less than a 0.1‰ decrease in cellulosic δ^{18}O for each degree change in growing season temperature, which is negligible relative to the magnitude of variability seen in the data. Over the entire range of stomatal conductance values, the δ^{18}O of the resulting BcP cellulose changed by less than 0.5‰. While a more rigorous modeling approach would elucidate the impact of the parameters on interannual δ^{18}O variability, their impact is far too small to account for the full range of δ^{18}O values observed throughout the 300-year Bristlecone Pine record. Therefore, an ecophysiological response to changes in humidity and related stomatal conductance and temperature parameters alone cannot be called upon to explain the large shift in isotopic values during the middle of the 19th century, implying there must have been a major change in source waters.

6. Discussion

6.1. Instrumental Record

[22] We have used instrumental Palmer Drought Severity Index data (Figure 5b, Series “B”) from Grid Point 59 of the North American Drought Atlas to evaluate the extent to which BcP δ^{18}O responded to changing water availability. The PDSI is a regional index that includes an autocorrelation factor to account for the cumulative impact that accrues during sustained periods of water stress (or abundance) [*Hayes*, 2006]. Previous studies suggest that cellulosic δ^{18}O typically responds positively to water stress as a function of both increased evaporative enrichment and an “Amount Effect,” which produces isotopically enriched precipitation during periods of lesser rainfall [*Shu et al.*, 2005; *Treydte et al.*, 2006]. With the exception of the anticipated negative


A
1.5
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Dry
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$\delta^{18}O_{VSMOW}$
C
6
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1.5
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1900
1920
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1960
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2000

Figure 5

correlation (wet conditions and low δ^{18}O values) observable in the years prior to 1920, there is little coherence between these two records. Despite sharing a preferred bidecadal frequency, the two records seem to be out of phase in a way that is irreconcilable given that the two chronologies have no dating uncertainty. The surprising lack of a correlation between these two records suggests either (1) the δ^{18}O values for Bristlecone Pine trees in this environment simply do not respond to water stress and it is an alternative forcing responsible for the variability or (2) regional PDSI values are not representative of the conditions in the White Mountains. While the latter point could be argued on the grounds that PDSI does not account for the impact of snowpack [*Hayes*, 2006], it is discordant with tree ring climatologies from this site (Figure 6), which have been argued respond to changes in regional PDSI [*Cook et al.*, 1999].

[23] Given that the correlation between BcP δ^{18}O and PDSI is unclear, we suggest that the isotopic values may be more sensitive to shifts in storm type (northerly versus subtropical) and would thus respond to changes in north Pacific climate indices. Shown in Figure 5 are annually averaged measurements of the PDO and NPI taken from http://jisao.washington.edu/pdo/PDO.latest and http://www.cgd.ucar.edu/cas/jhurrell/indices.info.html#np, respectively. There are a number of distinctive similarities and dissimilarities in the temporal patterns of change reflected in each of the records, including the BcP δ^{18}O. The 1940s peak in δ^{18}O observed in the BcP record is a striking example of correspondence between all of the climate indices. The subsequent peak in δ^{18}O in the 1960s is of a smaller magnitude and corresponds to a period of positive NPI but neutral PDO. The 1980 peak in δ^{18}O is of a smaller magnitude than what might be expected given the strongly positive NPI and PDO values. While at first glance the δ^{18}O values show sustained periods that more closely resemble Pacific decadal variability, it is possible that some of this correspondence is the result of nonclimatic autocorrelation, which would be caused by mixing of soil waters over several seasons [*Evans*, 2007]. While further work is necessary to determine residence times of soil waters at this site, the combination of thin well-drained soils (*cyroborrol* type) and a shallow root system that is predominately resigned to the upper 30 cm challenges the notion that the trees are relying substantially on water from previous years [*Fritts*, 1969]. Nonetheless, conditions in the north Pacific as integrated by both the PDO, NPI and related indices are known to influence the tendency of subtropical storms to strike western North America during winters [*Dettinger*, 2004] and thus the sustained changes in BcP δ^{18}O during the instrumental period may be indicative of changes in storm type to this region.

6.2. Proxy Record

[24] The mid-19th century, which predates instrumental monitoring in the White Mountain region, is noted primarily as a time period of major glacial retreat and northern hemisphere warming. Ring width chronologies from high-elevation Bristlecone Pine trees have been recognized as faithful recorders of this long-term warming trend [*Lamarche*, 1978; *Mann et al.*, 1998a]. The temperature changes apparent in the ring width studies are coincident with dramatic change we observe in the BcP δ^{18}O record. However, despite the fact that the warming was concurrent with changes in BcP δ^{18}O, there is no mechanistic reason to assume that the negative relationship is causal. Ambient temperature directly affects cellulosic isotope values in two primary ways: (1) the temperature-dependent fractionation associated with the condensation of precipitation and (2) the temperature-dependent fractionation associated with the evaporation of water from the leaf surface [*Roden et al.*, 2000]. The magnitude of temperature change required to produce the observed excursions in BcP δ^{18}O would suggest that the middle of the 19th century was marked by a colossal cooling and indicates that whatever temperature signal may be imbedded in the δ^{18}O values is masked by a more significant

Figure 5. Comparison of δ^{18}O values of Bristlecone Pine cellulose with instrumental climate records. (a) Mean annual temperature (°F) averaged and concatenated from a series of NCDC COOP climate stations in and around California Climate Division 7. The data are shown as an anomaly to the 1971–2000 mean. (b) Regionally averaged Palmer Drought Severity Index from Grid Point 59 of *Cook et al.* [1999]. The *y* axis is shown in standard PDSI units with positive being nondrought conditions and negative being drought conditions. (c) Twentieth century component of Bristlecone Pine cellulose δ^{18}O values modified from Figure 2a. (d) Annually average North Pacific Index values shown with a unitless index from http://www.cgd.ucar.edu/cas/jhurrell/indices.info.html#np. (e) Annually averaged Pacific Decadal Oscillation Index from http://jisao.washington.edu/pdo/PDO.latest shown as standard deviation units. (The solid line in all records except Figure 5c (cellulose δ^{18}O data) was generated using a decadal smoothing filter to accentuate multiyear trends, and the dashed vertical lines are spaced in 20 year intervals starting with 1920.)

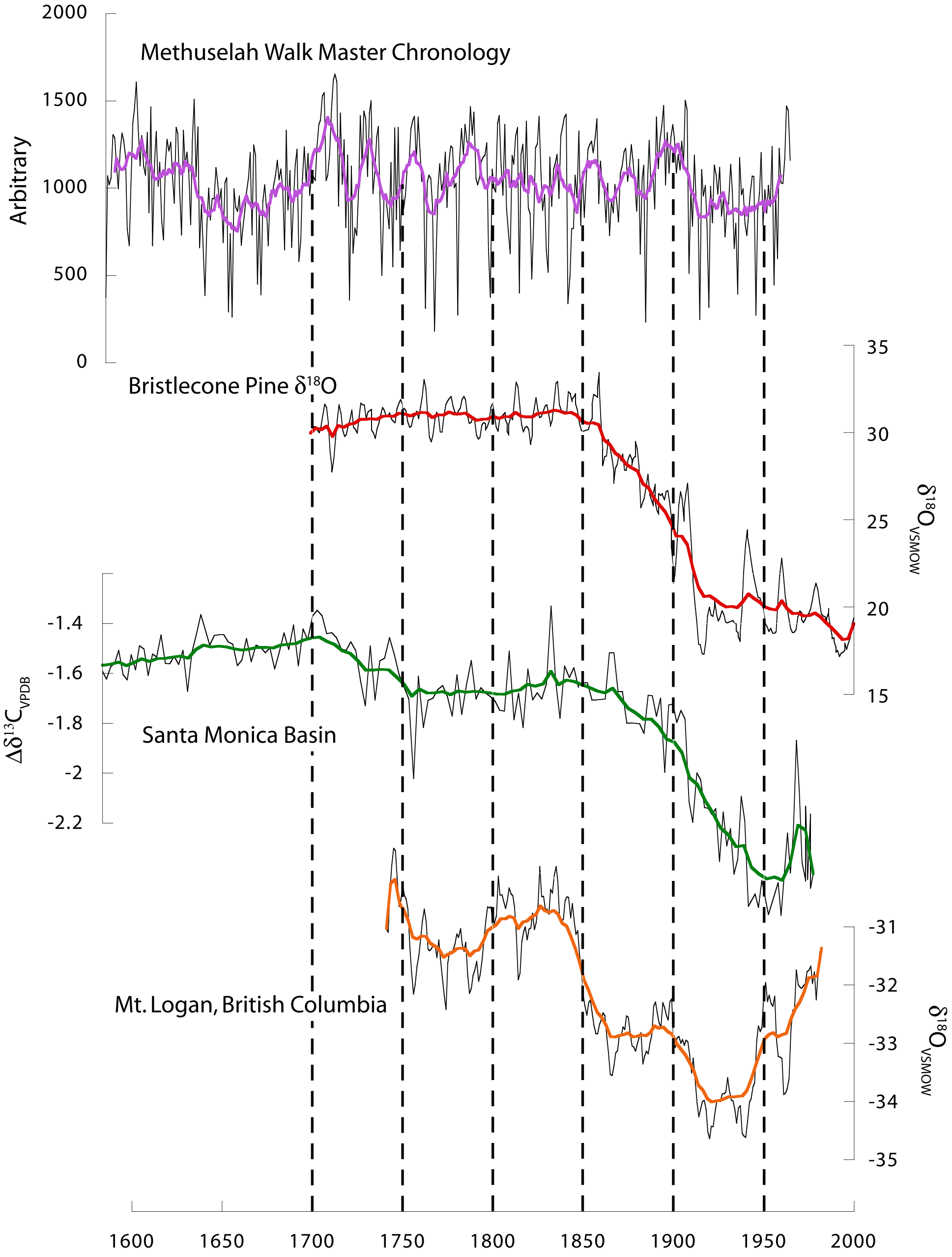

Figure 6. Comparison between δ^{18}O values of Bristlecone Pine cellulose with regional proxy records. Ring width master chronology from the Methuselah Walk chronology available from the International Tree Ring Database [*Graybill and Funkhouser*, 1995]. The values have been standardized to remove nonclimatic trends. Santa Monica Basin $\Delta\delta^{13}$C record from *Holsten et al.* [2004], with $\Delta\delta^{13}$C being the difference in δ^{13}C between *Bolivina argentea* and *Buliminella tenuata*, which was interpreted by the authors as a proxy for upwelling in the basin indicating a major mid-19th century change in wind fields. The δ^{18}O values from Mount Logan Ice Core indicate a change in precipitation source to the region in the middle of the 19th century from one dominated by local North Pacific systems to an increasing prevalence of tropical and subtropical moisture sources [*Fisher et al.*, 2004]. The colored line in all records was generated using a decadal smoothing filter, and the dashed vertical lines are spaced 50 years apart beginning with 1700.

forcing. It is worth noting that the trees used for this study were selected from a lower elevation Bristlecone Pine site than those utilized for the aforementioned temperature reconstructions. The ring widths for our site have been shown to respond largely to water stress because temperature is not a limiting factor for growth at these lower elevation whereas temperature is a limiting factor at higher elevations [*Lamarche*, 1974]. The ring widths at our sample site (Figure 6) do not show a major transition that corresponds with the changes in cellulosic δ^{18}O. Nonetheless, the BcP growing at higher elevation would be exposed to similar hydrologic conditions as those at lower elevations since they derive their water from the same storms. Hence, hydrologic changes, whether it be precipitation amounts or storm types, reflected in the δ^{18}O changes we document would have been influential on the higher elevation trees. We believe there is reason to assess how water stress may have varied within the Bristlecone Pine forest over past centuries since these tree ring climatologies have played such an important role in establishing the long, preinstrumental temperature history for the northern hemisphere.

[25] *Feng and Epstein* [1994] generated a low-resolution (50-year) 8,000 year record of δD from trees near this site. Their record was interpreted as being a proxy for ambient temperature and it exhibits relative stable values throughout the 18th and 19th centuries with an increase in values in the early 20th century. Their chronology shares few similarities with the record shown in our study, though a comparison is relatively difficult to make given the low resolution (50-year) of their D/H record. Our goal is to develop a high-resolution D/H record for the Bristlecone Pine to compliment the δ^{18}O record presented here and to extend this reconstruction back beyond the 17th century in order to investigate how temperature and hydrologic changes have varied.

[26] Variations in rainfall that have been reconstructed previously from a wide network of ring width chronologies from the southwestern United States have documented a recurring pattern of decadal and bidecadal-scale variability during the past three centuries. There has been a sustained decrease in PDSI values identified in these records between 1850 and 1915 A.D. [*Cook et al.*, 2004, 2007]. A similar, though less protracted change, is captured in a δ^{13}C chronology from tree ring cellulose in the southwestern United States as described by *Leavitt and Long* [1989]. The change is most pronounced from 1900 to 1905, which represents the single largest drought pentad since 1790. In another study using trees sensitive to cool season precipitation variability in southern California, *Biondi et al.* [2001] generated a reconstruction of Pacific Decadal variability over the last 3 centuries. They recognized this same period following the turn of the 20th century as an interval of major changes in precipitation that was interpreted as being the result of simultaneous reversals of both ENSO and the PDO. The authors identified an analog to the early 20th century event in the mid-1940s, both of which are periods that coincide with eras of marked isotopic excursions in our record (Figure 2a). Other efforts to look at pacific decadal variability by *Gedalof and Smith* [2001], *Gray et al.* [2007], *Hidalgo* [2004], *MacDonald and Case* [2005], and *Mann et al.* [1995] have identified the middle of the nineteenth century as a period of significant change in the frequency and amplitude of leading temperature and precipitation modes indicating that the multidecadal-scale climate modes of the twentieth and late nineteenth centuries were supplanted by higher frequency lower amplitude modes prior to the 1850s.

[27] Another dramatic example of this mid-19th century climate shift is reflected in the marine proxy records from the Santa Monica and Santa Barbara Basins off the western coast of southern California. Here the sediments that are deposited on the seafloor are laminated, reflecting the absence of bottom burrowing organisms that would otherwise disturb the laminated sedimentation. In the Santa Barbara Basin the laminations are deposited annually as a light (low-density) and dark (higher-density) couplet [*Lange et al.*, 1997]. In the Santa Monica Basin the high- to lower-density layers are deposited interannually [*Christensen et al.*, 1994]. In both basins the extent of laminated sediments has varied over time. Prior to about 300 years ago the sediments within these basins were bioturbated and the laminated sediments were not preserved as they are today. At the end of the LIA the centers of these basins began to undergo a transition to laminated sedimentation and the extent of laminated sediments has expanded progressively outward from the center of the basins [*Christensen et al.*, 1994; *Hagadorn et al.*, 1995]. Similar transitions have also be recognized in the longer Pleistocene sections recovered from the Santa Barbara Basin by the Ocean Drilling Program [*Kennett and Ingram*, 1995]. During the Pleistocene the basin underwent transitions from bioturbated sedimentation during cold stadial periods to laminated sediments deposited in the basin during warmer interstadials [*Kennett and Ingram*, 1995]. Hence, it appears that the pattern of laminated sedimentation along the California margin has been sensitive to climatic changes in the North Pacific on a variety of timescales. In the most recent phase of sedimentation change the transition from bioturbated to laminated sedimentation began

in the middle of the 19th century in close correspondence with the other climatic changes discussed above. A marked shift in the distribution of laminated sediments in the Santa Barbara and Santa Monica Basins occurred in the mid-1970s in association with a transition in the phase of the PDO [*Holsten et al.*, 2004; *Stott et al.*, 2000] (Figure 6). This recent expansion of laminated sediments is attributed to a progressive increase in carbon flux to the seafloor and enhanced carbon oxidation rates that depleted bottom waters of oxygen resulting from enhanced northerly winds that drive upwelling along the continental margin. Historical records from the Santa Barbara Basin provide further evidence for this transition in the winds as sailors noted changes in the extent of kelp forests and storm trajectories during this period [*Schimmelmann and Tegner*, 1992].

[28] Ice core records from the Dasuopu Glacier in China [*Thompson et al.*, 2003; *Zhao and Moore*, 2006], Mount Logan and adjacent ice core and lake records from northwestern Canada [*Fisher et al.*, 2004; *Moore et al.*, 2002] and the Fremont Glacier in Wyoming [*Naftz et al.*, 1996] (not shown) all show major inflection points occurring during the middle of the 19th century (Figure 6). Accumulation totals from the former records show a decrease in snow accumulation since the end of the Little Ice Age, which has been interpreted as evidence of a long-term weakening of the trade winds since the middle of the 19th century as a result of weaker Hadley Cell circulation [*Zhao and Moore*, 2006]. δ^{18}O and *d-excess* measured from the North Pacific ice core records also indicate dramatic shifts at the end of the Little Ice age, which suggest that this region experienced a major change in source water accompanying this shift in accumulation rates. The authors interpreted this to be the result of an ‘‘isolation’’ of the North Pacific during the Little Ice Age, which prevented the intrusion of tropical and subtropical moisture sources from reaching northwestern Canada [*Fisher et al.*, 2004]. The influence of sea ice retreat on this regional climatic transition is not explicitly addressed in the analysis of Mt. Logan record though modeling studies suggest that the sea ice retreat at the end of the Little Ice Age would have influenced atmospheric circulation across the Pacific [*Sewall and Sloan*, 2004]. The Fremont Glacier record shows a dramatic decrease in variance of δ^{18}O in precipitation over Wyoming during this time, which possibly suggests a change in regional seasonality [*Naftz et al.*, 1996; *Schuster et al.*, 2000]. Broadly speaking, the middle of the 19th century was a time of significant environmental change across the Pacific Basin, with not only a rise in global temperatures, glaciers and sea ice retreat, but also on atmospheric circulation patterns as manifest in changes in precipitation patterns and storm trajectories as reflected in the mid-19th century isotopic excursion seen in our BcP record.

6.3. Storm Trajectories

[29] The White Mountains of California are influenced by four distinctive storm types: winter storms that originate in the North Pacific, Subtropical Pacific storms associated with the North American Monsoon, subtropical Pacific storms in the winter or so-called ‘‘Pineapple Express’’ storms that occur as a result of a southward wandering of midlatitude cyclones that funnel moisture-laden warm fronts onto the California coasts [*Dettinger*, 2004], and localized summer thunderstorms associated with intense convection. The North Pacific winter storms represent the dominant source of water to the region and thus a cumulatively large impact on the *hydroisotopic* budget. Each of these storm types has a distinctive isotopic signature, with the North Pacific storms having relatively depleted values and the subtropical summer and winter storms having relatively enriched values [*Benson and Klieforth*, 1989]. Although isotopic compositions of the different storm types reported in this study (Table 1) are based on data from a single winter, the findings suggest that the difference between the two types can be quite dramatic, on the order of 8–9‰ in some instances, which is in line with the findings presented by *Benson and Klieforth* [1989], who measured storm to storm variability in Great Basin precipitation. Because the bulk of precipitation is delivered in the winter and the growing season for these trees is restricted to the summer, the source water represents an integrated mixture of snowmelt and precipitation events that have accumulated in the soil horizon during the winter months. While the occurrence of a single event might be washed out by mixing, a change in the overall contribution of storms that struck the region would result in a change in the isotopic composition of the cellulose.

[30] Currently, Pineapple Express storms, which occur between 0–4 times in a winter over the last 50 years [*Dettinger*, 2004], represent a small part of the overall water budget (approximately 10% for the Crooked Creek Weather station in the White Mountains) and thus, impart a relatively small influence on the isotopic ratio of the BcP cellulose.

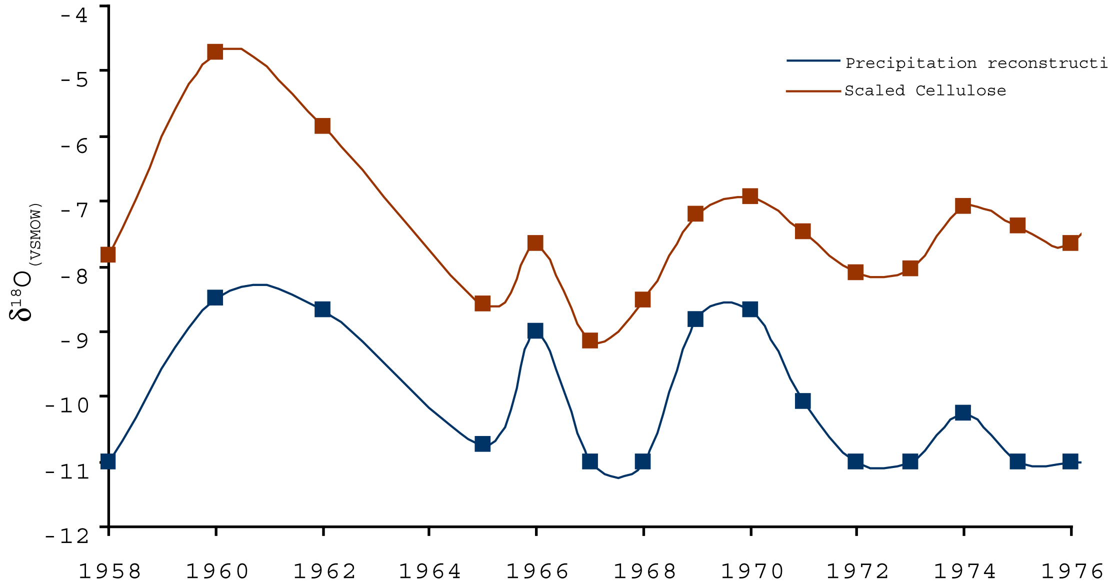

Figure 7. Comparison of cellulosic δ^{18}O with isotopic composition of local precipitation. The source water labeled “Pineapple Express” was calculated assuming that storms were either Pineapple Express events with an isotopic composition of −2‰ or North Pacific storms with an isotopic composition of −11‰. The cellulosic δ^{18}O values are taken from Figure 2a but have been scaled relative to the precipitation by adding 27‰ to each point.

We suggest that the major isotopic change shown in Figure 2a is that prior to the middle of the nineteenth century the Pineapple Express storms were more frequent and these brought isotopically enriched rains to the White Mountains. In a survey of 50 years of Pineapple Express storms [*Dettinger*, 2004] found that these storms occur most frequently in late winter when the midlatitude jet has reached its southern most position. While there is only a short instrumental record of these storms, the available data do suggest that these storms are also more common during positive phases of the PDO when ENSO is effectively neutral, thus presenting a possible explanation for the intermittent relationship between BcP δ^{18}O and PDO shown in Figure 5e. In addition, though not investigated in any previous study, other modes of Pacific decadal variability that influence the behavior of the jet stream such as the NPI may also have had an impact on the occurrence of Pineapple Express storms. Prior to the middle of the 19th century the PDO appears to have oscillated in a different manner than it has since [*Gray et al.*, 2007; *Hidalgo*, 2004; *MacDonald and Case*, 2005]. This observation, combined with the fact that the Northern Hemisphere was cooler prior to the 20th century and there was more extensive sea ice would favor a more southerly flow pattern of the midlatitude jet stream [*Dettinger and Cayan*, 1995]. Each of these factors lends additional support to our interpretation that Pacific meteorological conditions favored more frequent subtropical storms. Consequently, the hydroisotopic budget for the region was weighted toward the subtropical rainwater values and this is reflected in cellulosic δ^{18}O values. This interpretation of the BcP δ^{18}O record supports the interpretation of ice core records from the North Pacific, which capture a dramatic change in source water relating to the subtropical-North Pacific interplay [*Fisher et al.*, 2004].

[31] To further verify our assertion we also calculate a predicted percentage of the annual precipitation that has come from Pineapple Express events in recent years. This was done by comparing the catalog of Pineapple Express events from *Dettinger* [2004] with daily precipitation totals from the White Mountain Research Station’s Crooked Creek weather station. To verify that precipitation in the White Mountains came from known Pineapple Express events we used NCEP Reanalysis data to visually confirm that the precipitation was indeed part of the same system. We then calculate a simple mass balance wherein we assume winter precipitation is either a Pineapple Express event with an enriched isotopic signature of −2‰ or of North Pacific origin with a depleted value of −11‰ (Figure 7). The isotopic values are based on findings from our meteoric water collection. In Figure 7 we show a time series of predicted δ^{18}O for winter

precipitation that is based on our simple two-member mixing model of Pineapple Express and North Pacific precipitation alongside our cellulosic δ^{18}O values that have been scaled by simply adding 27‰, the magnitude of biochemical fractionation [*Sternberg and Deniro*, 1983], to each value. The two values seem to track each other over the short period shown. A more elongate comparison would be valuable but is unfortunately difficult because an unbroken daily precipitation record is not available.

7. Conclusions

[32] There are two dominant features apparent in the BcP δ^{18}O chronology of the past three centuries: a distinctive bidecadal oscillation during the twentieth century and a dramatic 9‰ shift in isotopic values between 1860 and 1910 A.D. Prior to the mid-19th century, the isotopic composition of the Bristlecone cellulose was not only 9‰ higher it also exhibits higher frequency variability at a decadal timescale. In this way the 19th century isotopic shift marked a fundamental change in the pattern of hydrologic variability in the White Mountains region. The local climate conditions, particularly humidity and rainfall amount would have been important influences on the cellulose δ^{18}O variability, but the larger bidecadal and longer isotopic excursions were likely caused by sustained changes in the frequency of different storm types. We suggest that changes in the strength of the PDO, and on shorter timescales the North Pacific Index, altered storm trajectories over the White Mountains and in doing so changed the isotopic composition of rainwater incorporated into the cellulose of the Bristlecone Pine trees. The BcP δ^{18}O appears therefore to be a sensitive recorder of the atmospheric changes associated with the dynamic North Pacific-subtropical relationship, which is particularly evident in its relationship to the North Pacific Index.

[33] The most pronounced feature of the Bristlecone δ^{18}O record is the marked shift in values during the mid-19th century. We suggest that this shift in values can only be explained by a change in the dominant source of rainwater from a low-latitude source region during the Little Ice Age to a dominantly higher latitude source region during the 20th century. The mid-19th century shift in isotopic values corresponds with changes in regional climate patterns that are expressed in a sustained decrease in PDSI over western North America [*Cook et al.*, 2007], global changes in the strength of the trade winds [*Moore et al.*, 2002; *Zhao and Moore*, 2006], regional wind fields over the Santa Monica and Santa Barbara Basins [*Holsten et al.*, 2004; *Schimmelmann and Tegner*, 1992], storm trajectories over the North Pacific [*Fisher et al.*, 2004], decreased Arctic Sea Ice and the spectral features of the oscillatory systems that control precipitation patterns in the United States [*Gray et al.*, 2007; *Hidalgo*, 2004; *MacDonald and Case*, 2005]. We suggest that the 9‰ shift in isotopic values during the mid-19th century was caused by a shift in frequency of Pineapple Express-like subtropical storms. The frequency of these low-latitude storms has been much lower during the 20th century and consequently the primary source of rainwater to the Bristlecone Pines has been the wintertime high-latitude storms that bring isotopically depleted water to the White Mountains. This interpretation of the Bristlecone Pine δ^{18}O record would be consistent with the shift in the amplitude and frequency of the PDO, a more mean southerly state of the midlatitude jet stream, stronger trade winds and a more insulated North Pacific.

[34] Bristlecone Pine trees have played an important role in multiproxy hemispheric temperature reconstructions [*Mann et al.*, 1998a]. The results presented here indicate the presence of significant and coeval hydrologic changes in the White Mountains. It is not yet clear how a shift in storm trajectories affected the overall amount of rain that fell on the White Mountains though regional PDSI reconstructions indicate this was a period of sustained change. Additional empirical work is also needed in order to assess how regionally extensive the hydrologic changes were during the mid-19th century. Ongoing efforts will include the incorporation of isotopic reconstructions from higher elevation sites in the White Mountains and other Bristlecone sites in Colorado where similarly long-lived trees can be sampled to not only increase the spatial coverage but provide a different environmental backdrop. In addition to other oxygen isotopic studies, the measurement of Deuterium in cellulose could allow for both temperature as well as hydrologic information to be inferred from the tree cellulose. In the only other study of D/H from Bristlecone Pine trees it was inferred that this was an adequate proxy for low-frequency temperature changes [*Feng and Epstein*, 1994], which would thus provide a means to look at local temperatures spanning the Little Ice Age and provide further evidence of the large climate change during the mid-19th century. There is the prospect of extending this isotopic work on the

Bristlecone back several millennial and thereby provide a precise, high-resolution record of hydrologic variability that would add to the impressive network of tree ring climatologies.

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