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Climatologic and hydrologic influences on the oxygen isotope ratio of tree cellulose in coastal southern California during the late 20th century

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[1] The oxygen isotope ratio (δ^{18}O) of precipitation in continental, midlatitude regions is a complex measure of atmospheric dynamics and regional climate variability and can be preserved in geologic archives. However, continuous modern observations of precipitation δ^{18}O in many midlatitude regions, particularly in the coastal western United States, are sparse. Here, tree-ring cellulose δ^{18}O from southern California is used to assess the potential of this proxy as an indicator of long-term hydroclimate and atmospheric variability. From 1954 to 2004, we observed that cellulose δ^{18}O was well replicated within a single stand of blue oak (*Quercus douglasii*) on interannual and decadal time scales. By using a forward mechanistic model, we demonstrate that cellulose δ^{18}O is not driven solely by the oxygen isotope composition of precipitation at the site nor any other single hydroclimate variable. Instead, the interannual variability in cellulose δ^{18}O prior to 1979 is positively correlated with growing season soil water δ^{18}O and after 1979 is negatively correlated with relative humidity. In addition, 2 years (1983 and 1998) of anomalously low cellulose δ^{18}O coincided with the wettest years in California and the strongest El Niño events of the late 20th century. For these years, decreased near surface evaporation and/or increased upper-level condensation could account for the more depleted cellulose δ^{18}O values. While blue oak cellulose δ^{18}O is sensitive to atmospheric and hydroclimate variability, the varying temporal correlation between the cellulose δ^{18}O and different environmental variables complicates any attempt to use the cellulose oxygen isotopes for reconstructions of climate variability beyond the calibration period.

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1. Introduction

[2] The stable oxygen and hydrogen isotope ratios of precipitation are often well correlated with one or more climate variables, such as temperature, rainfall amount, or moisture source. These correlations make it possible to use δ^{18}O and δD of geologic materials such as ice cores, speleothems, lacustrine carbonates, and tree rings to study preinstrumental terrestrial climate variability and change. But the δ^{18}O or δD values of precipitation seldom record climate in a simple, straightforward way [e.g., *Noone*, 2008]. There are both spatially and temporally varying influences on the isotopic composition of atmospheric moisture, including rainfall amount effects, both near and distant moisture transport history, condensation temperature, and other postcondensation processes [*Dansgaard*, 1964; *Eltahir and Bras*, 1996; *Risi et al*., 2008; *Rozanski et al*., 1993]. Determining which of these influences is dominant in a particular location is critical to properly interpreting the nature and causes of climate variability. In the tropics, precipitation δ^{18}O decreases with increasing rainfall amount, as there is minimal vapor exchange and re-evaporation, both of which act to enrich precipitation in the heavy isotopologues [*Lee and Fung*, 2008; *Risi et al*., 2008]. On the other hand, proxy reconstructions from high-latitude regions frequently document temperature as the dominant influence on isotopic variations in moisture because of differences in saturation vapor pressures between H_2O, HDO, and $H_2{}^{18}O$. Less common are studies from continental midlatitude regions, where the isotopic signal may not correlate to a single climate variable and may be influenced by precipitation intensity, temperature, and moisture source variability. In the case of moisture source influences, the isotopic composition of tropically derived atmospheric moisture is more enriched in the heavy isotopologues compared to moisture from higher latitudes, which has seen great amounts of rainout [*Buenning et al*., 2012]. Nevertheless, there are valuable climate archives throughout the subtropical to middle latitudes that may provide insight about climate variability, such as shifting storm track behavior.

[3] In the present study, we have focused on the interannual δ^{18}O signal in precipitation that is incorporated into the annual cellulose of blue oak trees, a species native to the Coastal Ranges of California. This is a highly populated region with significant agricultural infrastructure that is dependent upon a sustained supply of moisture. It is also a region that may also be vulnerable to changes in water availability because of rising atmospheric temperatures [*Meehl et al*., 2007]. Southern California, in particular, has experienced repeated decadal to multidecadal periods of reduced rainfall in the past [*Haston and Michaelsen*, 1997; *Meko et al*., 1980, 2011]. The stable isotopic composition of precipitation may provide a way to trace patterns of atmospheric variability that accompany periods of reduced rainfall. To the extent that the δ^{18}O of tree cellulose documents variations in atmospheric oxygen isotopic composition, it may, therefore, be possible to extend a short observational record back several centuries and assess whether there are systematic variations in the isotopic composition of precipitation that accompany drought and specific atmospheric dynamics [*Berkelhammer et al*., 2012; *Buenning et al*., 2012]. Such studies may eventually provide a way to assess the skill of models that attempt to simulate how the hydroclimate of this region is likely to behave in the future.

[4] The modern climate of southern California is characterized by a large seasonal cycle in precipitation, with a large fraction of annual rainfall occurring between October and April. The winter-season precipitation is more depleted in ^{18}O (a decrease in $\delta^{18}O_p$ by as much as 7‰ [*Buenning et al*., 2012]) compared to fall and spring values. This was first observed in the western United States by *Friedman et al*. [1992] who proposed that for southern California and the Great Basin the seasonal isotopic difference between winter and summer precipitation was driven by airflow patterns with winter (summer) storms originating over the Pacific Ocean (Gulf of Mexico). In a follow-up study that extended further north and east to include Oregon, Nevada, and Utah, a similar conclusion was reached where high δ^{18}O values in summer and a drop in winter was linked to the delivery of moisture from different source regions [*Friedman et al*., 2002]. Both of these studies averaged precipitation δ^{18}O over 6 month intervals, which, on the one hand offered broad insights on the seasonality of precipitation δ^{18}O. But on the other hand, at higher resolution, there are likely to be different processes that influence isotopic variability, especially for the months of the most significant rainfall (December to February). Using an isotope-enabled atmospheric general circulation model, *Buenning et al*. [2012] demonstrated that along the western coast of the United States, the seasonal variations in the isotopic composition of precipitation can be

significantly influenced by the steep vertical oxygen isotope gradient within the lower troposphere and variations in the height of condensation. Thus, it appears there are competing influences on the isotopic composition of precipitation and that on the time scale of individual storm events, variations in precipitation δ^{18}O may reflect: (1) closed system convective processes [*Buenning et al*., 2012; *Coplen et al*., 2008] or (2) variations in the contribution of atmospheric moisture from different sources [*Berkelhammer et al*., 2012; *Friedman et al*., 2002, 1992; *Yoshimura et al*., 2010]. In the present study, we have attempted to assess how these atmospheric variables have influenced the isotopic composition of cellulose that forms on an annual basis in long-lived trees.

[5] Across the globe, the oxygen isotope composition of cellulose from tree rings has been used to obtain information about past climate variations and are a valuable resource for annual and seasonal environmental conditions (see reviews by *Barbour* [2007] and *McCarroll and Loader* [2004]). The oxygen isotopic composition of tree cellulose is a composite mixture of the oxygen in xylem water and in leaf water, both of which can vary in response to local environmental conditions, including isotopic exchange with the atmosphere. The oxygen isotopic composition of soil water, which is taken up by the tree roots, is modified within the leaf during evaporation (transpiration) at a rate that depends on the relative humidity [*Flanagan et al*., 1991; *Roden et al*., 2000; *Still et al*., 2009]. In the western United States, cellulose δ^{18}O can also reflect temperature variations if temperature is the primary influence on the δ^{18}O of precipitation and other influences are less significant [*Berkelhammer and Stott*, 2012]. But in some circumstances, the relative humidity may have a significant influence on the isotopic composition of soil moisture and the evaporative exchange of isotopes at the leaf-air boundary [*Roden et al*., 2005; *Shu et al*., 2005]. Therefore, implicit in the use of cellulose δ^{18}O as a paleoclimate indicator is that evaporative influences on the δ^{18}O of soil moisture and, thus xylem water, are not varying significantly enough to overprint the δ^{18}O of precipitation that is transferred to the soil moisture.

[6] In this paper, we have attempted to assess how the environmental parameters outlined above have influenced the oxygen isotopic composition of blue oak (*Quercus douglasii*), which grows in moisture sensitive regions in the Coast Ranges of California. Previous studies of *Q. douglasii* tree ring widths have demonstrated that the growth of this species is particularly sensitive to paleorainfall variability [*Meko et al*., 2011; *Stahle et al*., 2001, 2011]. We focus our analyses on the late 20th century for which there is both instrumental climate data and isotope-enabled climate model simulations [*Daly et al*., 2008; *Kalnay et al*., 1996; *Yoshimura et al*., 2008]. We evaluate how sensitive and how stable the relationship has been between the oxygen isotope composition of tree cellulose and local climate variables using a mechanistic model of cellulose δ^{18}O and statistical correlations.

2. Materials and Methods

2.1. Study Site and Sample Collection

[7] Tree cores were collected in 2004 from a blue oak stand growing at an elevation of 1036 m above sea level on the western slope of Figueroa Mountain, Santa Barbara County, California (34°44.1′N; 119°59.8′W) (Figure 1, top). The site's hydroclimate is Mediterranean-type with cool wet winters and dry warm summers (Figure 1, middle). The majority of precipitation occurs between November and April and is often sourced from storms that originate over the Pacific Ocean. Previous work has demonstrated that the *Q. douglasii* active season is offset from the bulk of the rainy season, indicating that groundwater uptake and evapotranspiration is favored in March [*Miller et al*., 2010; *Raz-Yaseef et al*., 2013] with significant photosynthetic activity occurring in April and May [*Xu and Baldocchi*, 2003]. *Q. douglasii* can grow in regions with a thin surface soil layer where the root biomass is concentrated in the upper 50 cm of the soil column [*Raz-Yaseef et al*., 2013]. Deep (>8 m) groundwater may be important for blue oaks during hot, dry summers; however, due to a lack of significant isotopic differentiation between subsurface (~50 cm depth) water samples and groundwater, confirmation of groundwater uptake could not be confirmed [*Miller et al*., 2010].

[8] All the cores were cross dated at the University of Arkansas Tree Ring Laboratory. The standard ring-width index chronology was compiled from cross sections (16) and cores (82) and used in a previous reconstruction of precipitation gradients in central California over the last 700 years [*Meko et al*., 2011]. In that study, *Meko et al*. [2011] demonstrated that *Q. douglasii*, which have adapted to live in moisture-stressed environments,

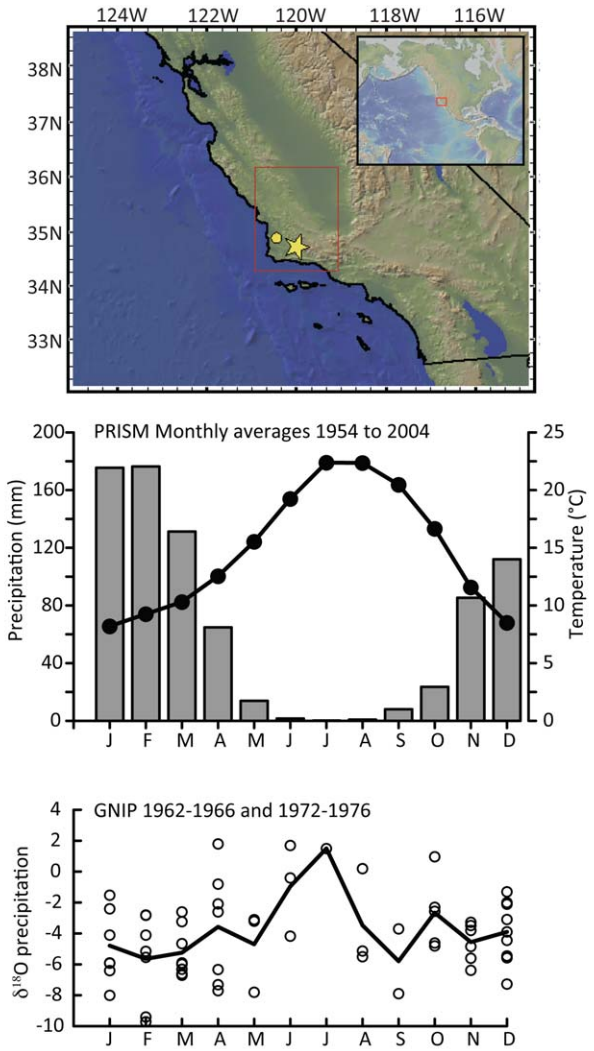

Figure 1. (top) Map of the study site located in southern coastal California. Increment bores were collected from the western slope of Mt. Figueroa in the Los Padres National Forest (yellow star). Meteorological data referenced in the text are from the Santa Maria GNIP station (yellow circle) and the IsoGSM grid (red square). (middle) Monthly precipitation and temperature data from PRISM for the study site. (bottom) Available monthly precipitation δ^{18}O (open circles) and monthly average (solid line) from GNIP for Santa Maria.

have a growth pattern that is highly correlated to cool season (November to April) precipitation of the growth year ($r^2 = 0.8$ in some southwestern regions of California). In this region, an important driver of hydroclimate variability on interannual time scales is the El Niño-Southern Oscillation (ENSO) [*Cook et al.*, 2007; *McCabe and Dettinger*, 1999], and anomalous wet events identified in the master tree ring chronology match known El Niño years during the 20th century [*Meko et al.*, 2011]. Superimposed on ENSO are additional modes of climate variability including the Pacific Decadal Oscillation (PDO), which can be related to the mean position of the jet stream and operates on time scales longer than interannual [*Biondi et al.*, 2001; *McCabe and Dettinger*, 1999; *McCabe et al.*, 2004]. *Meko et al.* [2011] documented a higher frequency of regionally broad wet and dry extremes relative to regional precipitation gradients in California after the 1976 shift of the ocean-atmosphere climate system in the North Pacific [*Miller et al.*, 1994].

[9] We selected five cores for isotopic analysis based on two criteria: (1) trees were at least 200 years old to reduce potential bias from aging [*Young et al.*, 2011] and (2) ring boundaries were clearly visible and straight to allow for discrete sampling for isotope measurements. Individual rings were sliced parallel to ring boundary with a razor blade under a microscope. Similar to other oak trees, *Q. douglasii* have medullary rays that grow perpendicular to ring boundaries. All attempts were made to exclude the rays from the whole wood slices. Oxygen isotopic analyses were conducted on discrete samples from each of the five cores spanning the 51 year period from 1954 to 2004.

[10] Individual wood samples were placed in a 2 mL polypropylene centrifuge tube for cellulose extraction using the method described in *Berkelhammer and Stott* [2012]. Mass spectroscopy was performed at the University of Southern California Climatology Laboratory. Approximately 0.1–0.2 mg of purified cellulose was wrapped into silver capsules and pyrolyzed in a ThermoFinnegan Thermal Combustion Elemental Analyzer (TC/EA) at 1415°C. The CO product was then transferred online to a ThermoFinnegan Delta Advantage isotope ratio mass spectrometer via a purified helium stream. The isotope ratio ($C^{18}O/C^{16}O$) of each sample was measured relative to a reference CO that was calibrated to two cellulose standards of known isotopic composition: the organic International Atomic Energy Agency (IAEA) CH3 cellulose standard (31.9‰) and the synthetic Baker cellulose standard (27.2‰). Oxygen isotope ratios are reported in standard δ notation as per mil deviations relative to Vienna standard mean ocean water. For every 40 tree cellulose samples that were measured, five IAEA standards and four Baker standards were also measured. The analytical precision of the standards with the *Q. douglasii* samples was approximately ± 0.3‰.

2.2. Climate Data

[11] Several types of climatological and hydrological data at monthly resolution were used to characterize

Table 1. Monthly Climate Data and Source Information

Climate Parameter	Data Set	Years	Resolution (Grid Size)	Source (Reference or Website)
Precipitation	RAWS	2002–2012	Single point	http://www.raws.dri.edu
Precipitation	PRISM	1954–2012	4 km × 4 km	http://www.prismclimate.org
Relative humidity	RAWS	2002–2012	Single point	http://www.raws.dri.edu
Relative humidity (calculated from mean temperature and dew point temperature)	PRISM	1954–2012	4 km × 4 km	http://www.prismclimate.org
Precipitation δ^{18}O	IsoGSM	1954–2011	1.85° × 1.85°	*Yoshimura et al*. [2008]
Precipitation δ^{18}O	GNIP	1972–1976	Single point	http://isohis.iaea.org
Soil water δ^{18}O	IsoGSM	1954–2011	1.85° × 1.85°	*Yoshimura et al*. [2008]
Water vapor δ^{18}O	IsoGSM	1954–2011	1.85° × 1.85°	*Yoshimura et al*. [2008]
Soil moisture	IsoGSM	1954–2004	1.85° × 1.85°	*Yoshimura et al*. [2008]
Wind vector fields	NCEP/NCAR	1954–2004	1.85° × 1.85°	http://www.esrl.noaa.gov/psd

the mechanistic causes of isotope variability in atmospheric moisture and the tree cellulose (Table 1). Monthly station data were compiled for Figueroa Mountain from the Western Regional Climate Center using quality-controlled data from Remote Automatic Weather Stations (RAWS) for 2002–2012 (http://www.raws.dri.edu). The Figueroa Mountain station has been in operation since November 2002, and hourly, monthly, and annual means are available online. However, since the *Q. douglasii* tree cores were collected in 2004, there are only two full years (2003 and 2004) where the RAWS climatology overlapped with the tree ring data. Thus, we also incorporated PRISM (Parameter-elevation Regressions on Independent Slopes Model) monthly means, available online (http://www.prismclimate.org) through the 20th century. PRISM is a quality-controlled assimilation of station measurements interpolated onto a high-resolution grid. Climate parameters are weighted based on the physiographic similarity of the station to the grid cell [*Daly et al*., 2002; *Gibson et al*., 2002], and recent climatological studies have demonstrated the success of PRISM relative to other high-resolution global data sets [*Daly et al*., 2008]. PRISM climatology at the study site is well correlated with RAWS station data for the overlapping period between 2002 and 2012; and thus, we have utilized the PRISM data for estimates of local precipitation, temperature, and relative humidity back to 1954 (Figure 2). Composite and anomaly 850 and 200 mb wind vector maps (relative to the 1981–2010 reference period) for the broader western United States were produced from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis version 1 [*Kalnay et al*., 1996] with the online tool provided by the National Oceanic and Atmospheric Administration/Earth System Research Laboratory Physical Sciences Division (http://www. esrl.noaa.gov/psd). Soil moisture content variations (0–50 cm) for the study site were obtained from the Experimental Climate Prediction Center's Global Spectral Model (GSM) which was fit with water isotope tracers (IsoGSM) [*Yoshimura et al*., 2008]. IsoGSM simulations (1.85° grid) were spectrally nudged [*Yoshimura and Kanamitsu*, 2008] at 6 h time intervals to the NCEP/NCAR reanalysis wind and temperature fields [*Kalnay et al*., 1996] and extend from 1954 to 2010 [*Buenning et al*., 2012].

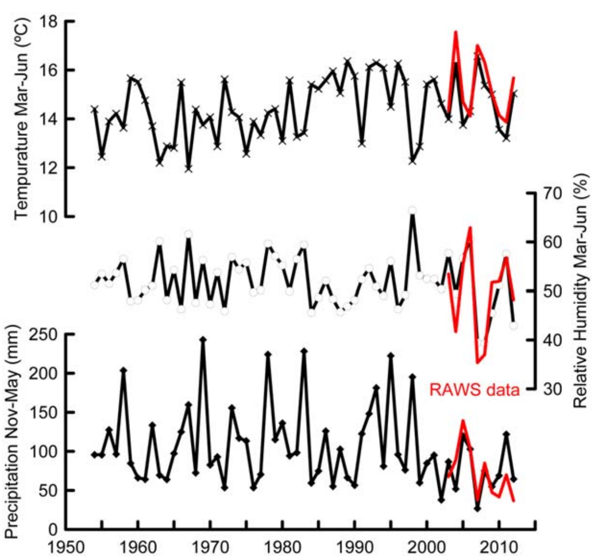

Figure 2. Comparison of RAWS station data (2002–2012) from Mt. Figueroa and PRISM derived climatology for the study site (1954–2012). Interannual precipitation is shown for the November to May wet season and for the March to June blue oak active season for relative humidity and temperature.

[12] Monthly precipitation δ^{18}O values were obtained from the Global Network of Isotopes in Precipitation (GNIP) available for 1962–1966 and 1973–1976 and for the Santa Maria, California station (34.9°N, 120.45°W, 79 m above sea level). The GNIP station data (http://isohis.iaea.org) are maintained by the International Atomic Energy

Association (IAEA) and the World Meteorological Organization (WMO). The Santa Maria station is the closest GNIP station to the study site and is located approximately 50 km northwest of Figueroa Mountain (Figure 1, bottom). Because GNIP station data were discontinuous, it is difficult to use these data for interannual assessments. However, previous work has demonstrated that IsoGSM sufficiently simulated the seasonality of precipitation δ^{18}O at Santa Maria and other station measurements throughout the western United States for the late 20th and early 21st centuries [*Berkelhammer et al.*, 2012; *Buenning et al.*, 2012]. Thus, interannual time series of precipitation δ^{18}O, water vapor δ^{18}O, and soil water δ^{18}O (0–50 cm) for 1954–2004 from IsoGSM simulations are used here.

2.3. Cellulose Oxygen Isotope Model

[13] Cellulose δ^{18}O can be modeled as an integrated system of several environmental parameters and be represented as a mixing function between xylem water with its characteristic δ^{18}O and leaf water with its characteristic δ^{18}O [*Roden et al.*, 2000]. Derived from precipitation, soil water δ^{18}O is modified over time in response to significant rain events and the amount of evaporation at the ground surface. There is no fractionation of oxygen when the roots draw soil water [*Dawson and Ehleringer*, 1991; *Ehleringer and Dawson*, 1992], and thus, xylem water can be represented as a measure of the root-weighted soil water δ^{18}O. For leaf water δ^{18}O, the preferential loss of $H_2{}^{16}O$ from the leaf during transpiration is modeled as a function of local environmental conditions (e.g., relative humidity, temperature, and water vapor δ^{18}O) [*Flanagan et al.*, 1991] and leaf physiology (e.g., transpiration rate, Péclet number) [*Dongmann et al.*, 1974; *Farquhar and Lloyd*, 1993]. With some a priori knowledge of local environmental variables but few constraints on the leaf physiology, we have applied the leaf modified [*Flanagan et al.*, 1991] model of *Craig and Gordon* [1965], defined here in terms of equilibrium fractionation factors for use in δ notation by *Ciais et al.* [1997]:

$$\delta^{18}O_{lw} = \varepsilon_e + \left(1 - \frac{e_a}{e_i}\right)\left(\delta^{18}O_{sw} + e_k\right) + \frac{e_a}{e_i}\left(\delta^{18}O_{wv}\right) \quad (1)$$

where $\delta^{18}O_{lw}$, $\delta^{18}O_{sw}$, and $\delta^{18}O_{wv}$ are the oxygen isotopic compositions of the leaf water, soil water, and water vapor, respectively, ε_e is the temperature sensitive equilibrium fractionation due to the phase change of liquid water to water vapor, e_a/e_i is the ratio of internal to external water vapor pressures, which can be approximated by the relative humidity (assuming that leaf and air temperature are equal), and ε_k is the kinetic fractionation as vapor diffuses through the stomata and the leaf boundary layer into unsaturated air. The temperature sensitivity of ε_e (T, in K) is such that [*Majoube*, 1971]:

$$\varepsilon_e = exp\left(\frac{1137}{T^2} - \frac{0.4156}{T} - 0.0020667\right) - 1 \quad (2)$$

[14] During cellulose synthesis, the enriched leaf water mixes with the nonenriched xylem (soil) water in the plant and the oxygen isotopic composition of cellulose, $\delta^{18}O_c$, can be described [*Roden et al.*, 2000] as a function of these two variables:

$$\delta^{18}O_c = f_o\left(\delta^{18}O_{sw} + \varepsilon_{wc}\right) + (1 - f_o)\left(\delta^{18}O_{lw} + \varepsilon_{wc}\right) \quad (3)$$

where f_o is the fraction of carbon-bound oxygen in sucrose that exchanges with xylem water during cellulose synthesis, and ε_{wc} is the fractionation factor between carbonyl oxygen and water (27‰) [*Sternberg*, 2009].

2.4. Core Reproducibility

[15] Averaging individual measurements of cellulose δ^{18}O from different cores of the same year or pooling samples from different cores of the same year prior to cellulose extraction is often conducted in order to establish common climate variations between trees or between sites. Previous studies have demonstrated that the common signal reflected in cellulose isotope values from different trees can be equal to or more reproducible than that of tree ring-width data, but is highly dependent on the degree of the climate signal in the proxy [*McCarroll and Pawellek*, 1998; *Robertson et al.*, 1997a, 1997b]. Rather than universally defining a required number of trees for each isotope study, *McCarroll and Loader* [2004] suggested that individual studies define an acceptable confidence limit based on the variability within the data and the precision required. The number of trees required to produce a representative isotopic signal for a given location is dependent on the similarity of the year-to-year variations and absolute differences between cores for a single year. One of the

Table 2. Descriptive Statistics of the Cellulose δ^{18}O Time Series

Core ID	Min	Max	Ave	Standard Deviation	Autocorrelation (lag-1)
F87	30.6	33.8	32.0	0.6	0.18
F94	30.3	32.9	31.5	0.6	0.18
F72	29.9	32.3	31.3	0.5	0.43
F73	29.0	33.0	31.0	0.7	0.10
F99	30.1	32.5	31.3	0.5	0.12
5-Core ave	30.1	32.5	31.4	0.5	0.23

most widely used methods to assess the similarity of the year-to-year variations is to determine the expressed population signal (EPS) [*Wigley et al*., 1984]. Calculated using the sample size and the mean interseries correlation:

$$EPS = \frac{N\bar{r}}{1 + N\bar{r} - \bar{r}} \quad (4)$$

where N is the total number of cores and $\bar{r}$ is the mean interseries correlation. Originally designed with an application for tree ring width, an EPS greater than 0.85 denotes an adequate sample size.

3. Results

3.1. Tree Cellulose δ^{18}O

[16] Measured cellulose δ^{18}O of the five individual cores (F72, F73, F87, F94, and F99) were in good agreement about the mean (31.4 ± 0.35‰) over the 51 year interval Table 2 (Figure 3, top). The intracore standard deviation over the length of each time series was highest for core F73 (0.66‰) and lowest for core F99 (0.51‰). The full range of year-to-year variability (maximum minus minimum cellulose value, $\Delta\delta^{18}$O) was between 4.0‰ (F73) and 2.3‰ (F72). For each time series, the interannual variance was always greater in the second half of the record (1980–2004) compared to the first half (1954–1979) by 0.1–0.5‰. Of the five individual cores, F87 exhibited a positive significant trend of 0.013‰/yr and F72 exhibited a significant negative trend of −0.012‰/yr over the length of the time series. The lag-1 autocorrelation was insignificant ($p > 0.05$) for all of the cores except F72. The time series mean and the intercore standard deviation for each year is also shown in Figure 3 (middle). There is no significant trend in mean time series and no significant autocorrelation. The average between core standard deviation for each year was 0.38‰ (1σ), which was slightly larger than the instrumental measurement error of ±0.3‰. The year with the smallest intercore standard deviation was 1977 (0.03‰) and the years with the largest intercore standard deviations were 1973 and 2004 (0.73‰). Years when the individual year standard deviation was equal to or less than 0.1‰ include 1966 and 1977. The standardized ring-width index for the site and for the selection of cores used in the isotope analysis is shown in Figure 3 (bottom).

[17] The degree to which the individual δ^{18}O time series shared common variations with one another was good over interannual time scales. All detrended intercore correlations are statistically significant at the 99% confidence level ($r = 0.40$–0.64, $p < 0.01$, $n = 51$) and the EPS was 0.86 (Table 3). An EPS of 0.85 or greater is generally accepted as a suitable measure of common variance [*Wigley et al*., 1984]. Thus, to a first order, our mean chronology is likely a reasonable representation of the common cellulose signal at the study site.

3.2. Cellulose δ^{18}O and Local Meteorological Data

[18] Starting with November of the previous year and concluding with December of the growth year, PRISM derived precipitation, temperature, and relative humidity at the study site were correlated with tree ring widths available from the selection of cores used in this study and tree cellulose δ^{18}O from 1954 to 2004 (Figure 4). A significant positive correlation was documented previously between tree ring width and cool season precipitation for *Q. douglasii* around California [*Meko et al*., 2011]. For the selection of cores used in this study, tree ring width is also correlated with cool season precipitation (December to April) and relative humidity (January to May) (Figure 4, top). Tree cellulose δ^{18}O exhibits a negative correlation to both precipitation amount and to relative humidity such that lower (higher) δ^{18}O coincides with higher (lesser) precipitation and relative humidity (Figure 4, bottom). Even though the correlations between tree cellulose δ^{18}O, precipitation, and relative humidity were low for individual months of the hydrologic year, the correlations were significant during the rainy and active season for precipitation and during the active season for relative humidity. We note that, individually, August precipitation is significantly correlated with cellulose δ^{18}O, but that the proportion of annual rainfall that occurs in August is small (<1%) and

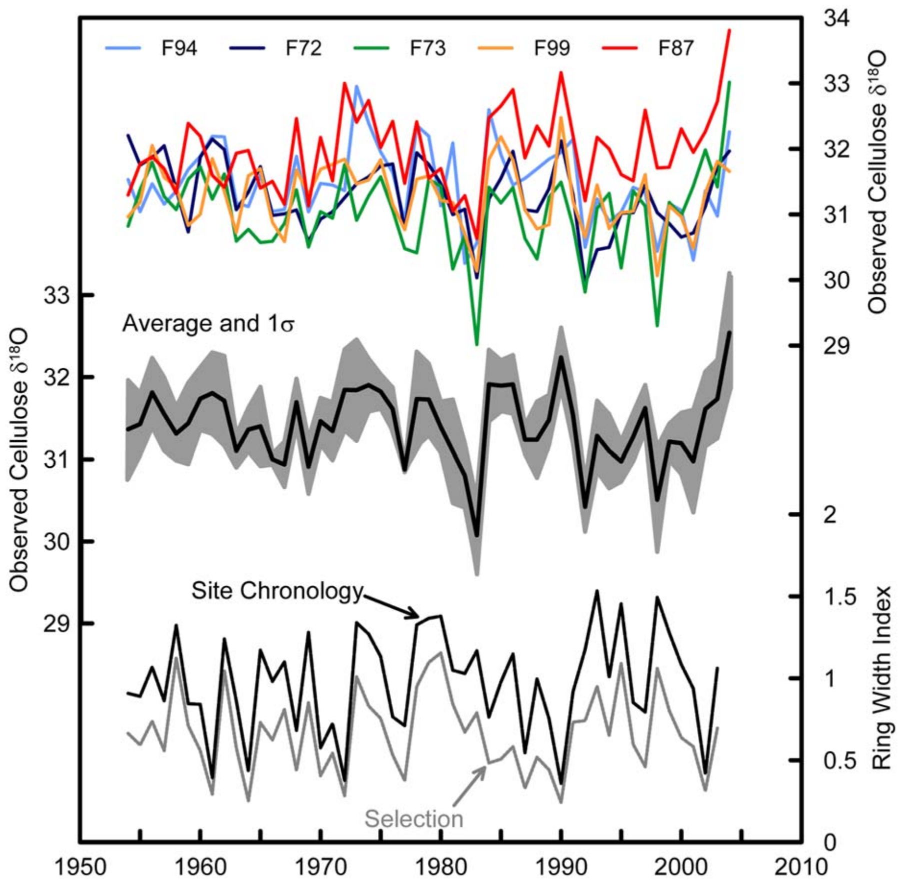

Figure 3. (top) Tree ring cellulose δ^{18}O time series of the five individual cores from Mt. Figueroa. (middle) Mean chronology and intrayear standard deviation calculated from the measured core variance specific to each year. (bottom) Tree ring width from the standardized chronology and the selection of cores used in this analysis.

likely an insignificant driver on cellulose δ^{18}O over the late 20th century. It is also possible that fog, dew, and cloud water inputs, termed "occult precipitation," may have a nonnegligible influence on soil water δ^{18}O, leaf water δ^{18}O, and, thus, cellulose δ^{18}O. However, the specific contribution from occult precipitation is not formally considered in our analysis. Thus, while the amount of radial tree growth as measured by tree ring width was positively related to rainy season, cellulose δ^{18}O was also linked with rainy season precipitation and active season relative humidity.

3.3. Modeled Cellulose δ^{18}O

[19] We modeled cellulose δ^{18}O using equation (1) (Craig-Gordon) and equation (3) (Roden) and monthly isotope data from IsoGSM and monthly hydroclimate data from PRISM. Although at lower spatial resolution than PRISM, IsoGSM provides the longest and highest resolution isotope estimate of precipitation for the region. Based on the previous studies on the timing of the blue oak active season relative to the rainy season [*Miller et al.*, 2010; *Xu and Baldocchi*, 2003] and the monthly correlations shown in Figure 4, we used March to June averages of relative humidity, temperature, and water vapor δ^{18}O and a November to May weighted average for soil water δ^{18}O. To calculate interannual soil water δ^{18}O, we used the top two soil layers from IsoGSM (0–10 cm and 10–50 cm below the surface) in our analysis. Variations for the upper 50 cm were weighted based on the soil water content for each month (and each soil layer) as well as the fractional depth of each soil layer below the surface.

Table 3. Detrended Intercore Correlations ($p < 0.01$)

Core ID	F87	F94	F72	F73
F94	0.52			
F72	0.53	0.52		
F73	0.64	0.40	0.53	
F99	0.60	0.56	0.59	0.56

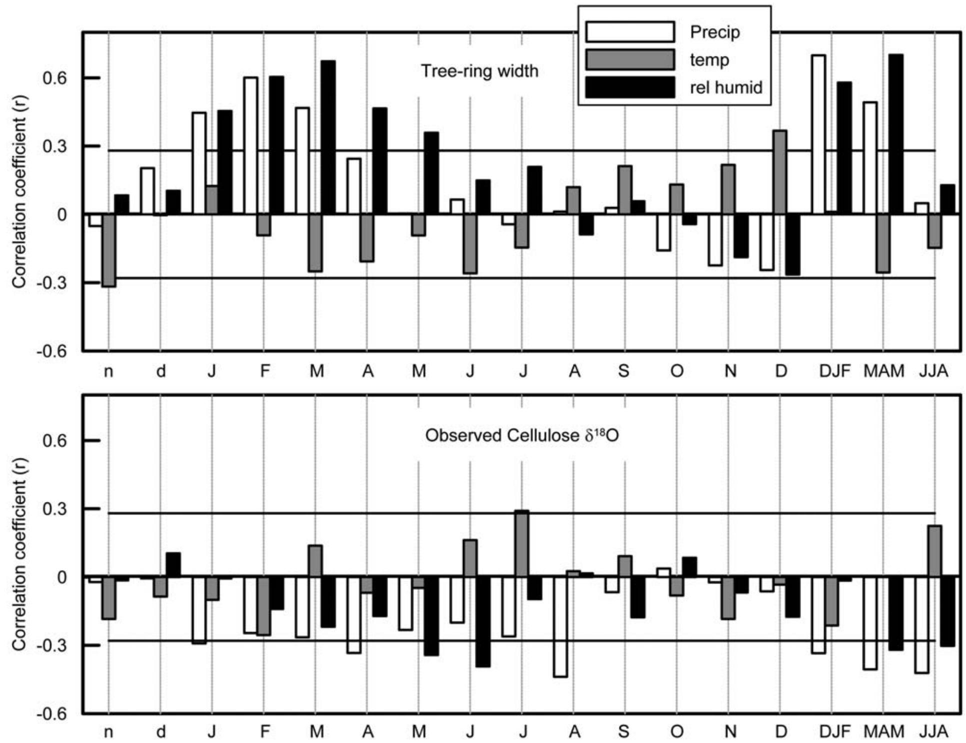

Figure 4. Pearson correlation coefficient (r) between the mean chronology and monthly precipitation (white), temperature (gray), and relative humidity (black) from November of the year prior to growth to December of the growth year for 1954–2004. Levels of significance are given by the horizontal line ($p < 0.05$).

[20] Based on equations (1) and (3), modeled cellulose δ^{18}O is in agreement with the time series mean of cellulose δ^{18}O from 1954 to 2004 ($r = 0.46$, $p < 0.01$) (Figure 5, top). The model explained as much or more interannual variance than simple monthly correlations to the local meteorology (see Figure 4), although much of the variance remained unexplained. In the Roden model, the two primary drivers of cellulose δ^{18}O are soil water δ^{18}O and relative humidity. To isolate the relative influences of these two parameters, we ran the model with relative humidity fixed and then soil water δ^{18}O fixed at their 51 year average values. Comparison of the sensitivity tests to the control simulation demonstrated that relative humidity ($r^2 = 0.62$) (Figure 5, middle), rather than soil water δ^{18}O ($r^2 = 0.25$) (Figure 5, bottom), has the greatest influence on the isotopic variability at interannual time scales in the forward model.

4. Discussion

[21] Our tree ring δ^{18}O reconstruction from five *Q. douglasii* trees at Figueroa Mountain exhibits significant interseries correlation over the late 20th century. Cellulose δ^{18}O was primarily related to rainy season precipitation and active season relative humidity, providing a measure of the hydroclimate variability at this site that is complimentary to the tree ring-width data, which itself was tightly linked with rainy season precipitation amount (Figure 4). The cellulose δ^{18}O model supports a link between soil water δ^{18}O and relatively humidity over interannual time scales (Figure 5). We note that the cellulose model captured the observed interannual hydroclimate variations well after 1979 but the modeled and observed isotopic record prior to 1979 is not as well correlated.

4.1. Cellulose Model-Data Comparison for the Late 20th Century

[22] Our results demonstrate that when the Roden model incorporates realistic values of δ^{18}O of soil water and relative humidity, the predicted values agree well with measured cellulose δ^{18}O. However, the correlation to a single hydrologic variable is not as good over the 51 year study period. Therefore, in order to use this model effectively, relative humidity, soil water δ^{18}O, and f_o must be well constrained. While the observed and modeled cellulose time series captured a common

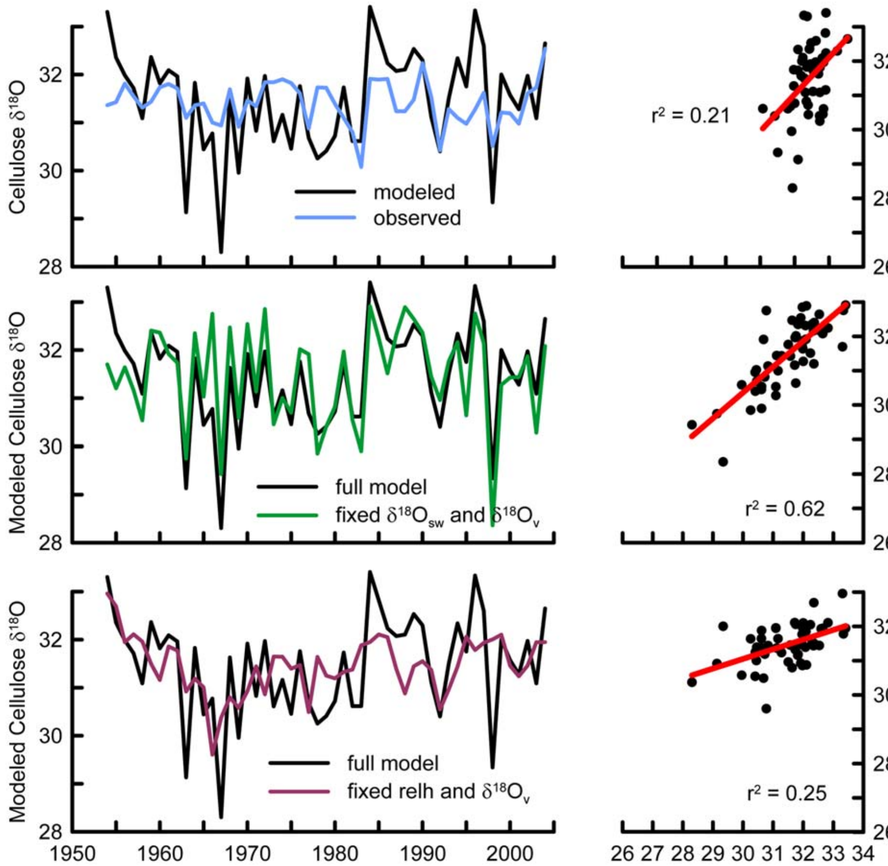

Figure 5. (top) Full forward model of cellulose δ^{18}O (black) compared to the measured mean time series (blue). (middle) Full forward model of cellulose δ^{18}O (black) compared to the forward model of cellulose δ^{18}O when the soil water δ^{18}O and water vapor δ^{18}O is held constant (green). (bottom) Full forward model of cellulose δ^{18}O (black) compared to the forward model of cellulose δ^{18}O when the relative humidity and water vapor δ^{18}O is held constant (purple).

interannual signal, one important feature not revealed by the correlations but observed in Figure 5 (top) was that the magnitude of the variability of the modeled time series ($\sigma = 1.03$, $n = 51$) was larger than that of the mean time series ($\sigma = 0.45$, $n = 51$) or any individual core ($\sigma = 0.51$–0.66, $n = 51$).

[23] We ran two sets of sensitivity experiments with the Roden model and evaluated the strength of the model-data correlation. In the first test, we varied f_o, the fraction of oxygen in sucrose that exchanges with xylem water during cellulose synthesis. Variation of f_o from 0 to 1 caused the mean value of cellulose δ^{18}o to decrease from 40 to 20‰, (Figure 6, top). The value of f_o where mean modeled cellulose δ^{18}O best fit the mean of the measured data was 0.39. In terms of the influence of f_o on the correlation between modeled and measured data, r was at minimum when $f_o = 1$ and reached a maximum of 0.47 when $f_o = 0.5$. Selecting a value for f_o ($f_o = 0.39$) when the average modeled cellulose δ^{18}O best matched measured δ^{18}O yielded an r value of about 0.46, similar to the maximum r value.

[24] This best-fit value of $f_o = 0.39$ was lower than values that have been applied in previous studies [*Li et al.*, 2011; *Roden et al.*, 2000; *Saurer et al.*, 2012]. Recent work suggested that f_o could be species dependent. Using a set of riparian species, *Roden et al.* [2000] applied a value of 0.42. Later studies of oak, pine, larch, and spruce suggested that values of f_o were between 0.25 and 0.36 [*Li et al.*, 2011; *Saurer et al.*, 2012]. In another hypothesis, *Anderson et al.* [2002] proposed that respectively f_o may not be constant for a single species and could vary year-to-year based on specific climatic conditions. Though we did not test an interannual climatic dependence on f_o, our results from these *Q. douglasii* trees favored the interpretation that f_o is not a universal constant but sensitive to species and/or environmental conditions.

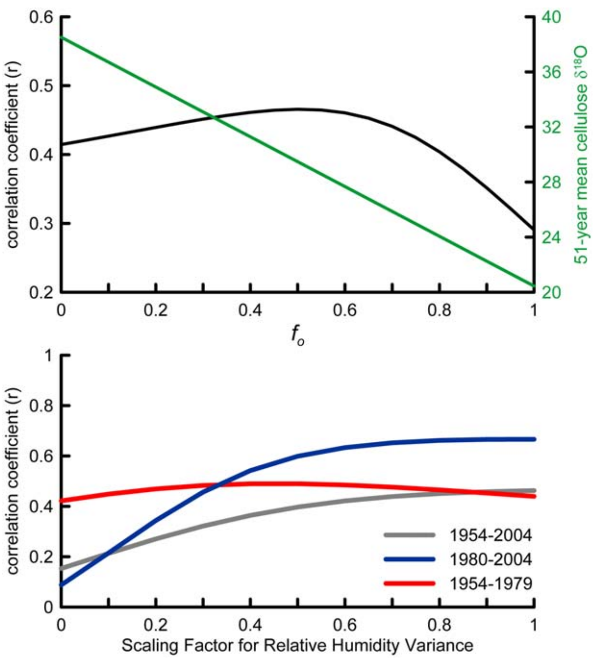

Figure 6. (top) Pearson correlation coefficient (r) for the relationship between the modeled and measured cellulose δ^{18}O (black) as a function of the scaling parameter, f_o. The mean oxygen isotopic composition of the modeled cellulose δ^{18}O is shown on the right axes (green). (bottom) Pearson correlation coefficient (r) for the relationship between modeled and measured cellulose δ^{18}O when the interannual variance of relative humidity is reduced by a scaling factor from zero to one.

4.2. Temporal Stability of Regional Climate Forcing on Cellulose δ^{18}O

[25] In a second sensitivity test, we scaled the variance of relative humidity, the primary driver in the forward model, and assessed whether or not the correlation to the observations improved (Figure 6, bottom). Based on the results of this test, we identified two important characteristics. The first is that the model overestimated the influence of relative humidity for the entire 51 year period and particularly for the early part of the record (1954–1979). A mismatch between modeled and observational data has been identified in previous work both in terms of leaf water enrichment [*Helliker and Ehleringer*, 2000; *Wang and Yakir*, 1995] and observed cellulose δ^{18}O [*Li et al.*, 2011; *Zhu et al.*, 2012]. This discrepancy between the modeled and observed data could be explained as (a) the proxy assimilates aspects of the local environment that causes a reduction in the signal of the cellulose variance compared to the predictive model or (b) that the model requires increased complexity. With respect to (a) signal reduction, oaks may use some sugars stored from the previous year at the start of the growing season [*Reynolds-Henne et al.*, 2007]. However, we note that adding a persistence term did not improve the model-data correlation. With respect to (b) modification of the model, approaches have been taken to parameterize the mechanisms of leaf water evaporative enrichment (see a review by *Barbour* [2007, and references therein]) but such approaches can be difficult to apply in a paleoclimate context where detailed meteorological data are not available.

[26] The second noteworthy characteristic was that the hydroclimate variable with strongest correlation to cellulose δ^{18}O switched from soil water δ^{18}O to relative humidity around 1979 (Figures 5 and 6). Other hydroclimate variables also show a distinct shift in the significance of the interannual correlation before and after 1979 (Figure 7, top). The correlation to precipitation δ^{18}O and soil water δ^{18}O is highest for the first half of the record and the correlation to wetness parameters (precipitation, soil water content, relative humidity, and ring width) is always higher for the second half of the record compared to the first. The isotopic composition of water vapor also falls into this category as predicted by equation (1). We postulate that this is related to overall wetter conditions, and higher relative humidity as seen in the Santa Maria, CA observations for the late 20th century (Figure 7, bottom). As the Craig-Gordon (equation (1)) model predicts, during wetter conditions and when relative humidity is higher, there is less of an influence of soil water δ^{18}O.

4.3. Implications for Reconstructions Prior to the Instrumental Record

[27] The correlation analyses and sensitivity experiments with relative humidity and soil water δ^{18}O demonstrate the potential for using tree cellulose to provide climatic information from the preinstrumental period at interannual and decadal time scales. However, the interpretation of such variability over longer time scales using blue oak is complicated because no single climate influence persists over time. Other studies have also shown that when correlating tree cellulose δ^{18}O to single climate parameters the relationship may hold for some periods of time and break down during other periods [*Reynolds-Henne et al.*, 2007; *Seftigen et al.*, 2011] and that the temporal instability may be related to synoptic weather patterns [*Seftigen et al.*, 2011]. In an attempt to work around this issue of competing influences and avoid

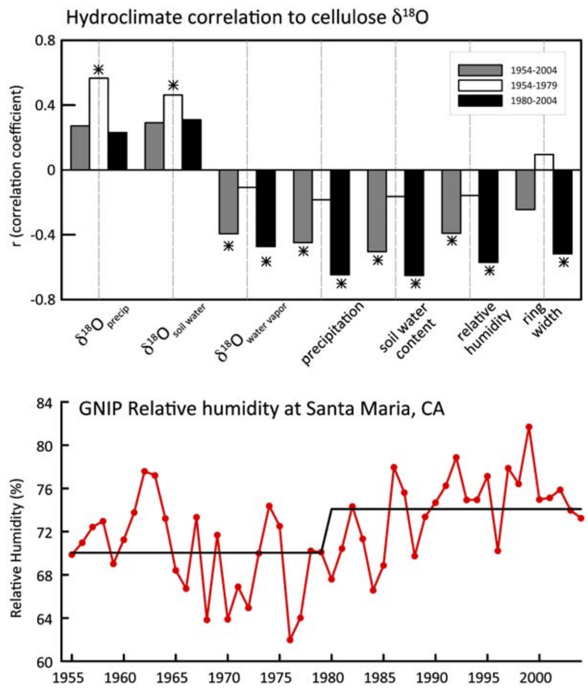

Figure 7. (top) Pearson correlation coefficient (r) between the mean δ^{18}O time series and various climate and isotopic parameters for the full time interval, 1954–2004 (gray), for the first part of the record, 1954–1979 (white), and for the second part of the record, 1980–2004 (black). Levels of significance are indicated by the starred columns ($p < 0.01$). (bottom) time series of March to June relative humidity at Santa Maria, California from station observations (red). Average relative humidity from Santa Maria observations for 1955–1979 and 1980–2004 (black).

correlating to a single climate parameter, *Saurer et al*. [2012] correlated cellulose δ^{18}O from three sites in Switzerland to large-scale pressure patterns over Europe but found that reconstruction of regional circulation may only be possible for large deviations, like the hot-dry summer of 2003.

[28] Climate reconstructions on short time scales that are associated with large isotopic deviations may be possible, especially where the between core standard deviations are low. For example, 1983 and 1998 have the lowest cellulose δ^{18}O of the late 20th century. Hydrologically, 1983 and 1998 are two years with anomalously large tree growth, as indicated by the tree ring width chronology, and are linked with overall wet conditions along the west coast of the United States. Climatologically, these years are also two of the largest El Niño years of the late 20th century. Although these events occurred when cellulose δ^{18}O was more closely related to relative humidity rather than soil moisture δ^{18}O, it may be possible to resolve some aspects of the influences on precipitation oxygen isotope variance for these anomalous events. Wind vector anomalies at the 850 mb level indicate that atmospheric flow was zonal (relative to the 1981–2010 climatological mean) and that moisture was advected from the subtropics (Figure 8, top). Thus, it is unlikely that cellulose δ^{18}O itself contains information about the moisture source for such intervals because moisture that would have been advected to the tree site from the tropics would be relatively more enriched isotopically, whereas the cellulose values during those years are more depleted. However, upper-level divergence (relative to the 1981–2010 climatological mean) was high during those years (Figure 8, bottom left) and this upper-level divergence would have promoted vertical uplift (Figure 8, bottom right). Rising air associated with such upper-level divergence may lead to condensation at higher/colder level in the troposphere where atmospheric vapor δ^{18}O values are lower [*Buenning et al*., 2012; *Coplen et al*., 2008]. This would account for the overall lower isotopic values during these time periods.

[29] Thus, *Q. douglasii* cellulose δ^{18}O values reconstructed from coastal California document changes in past climate variability at single year, interannual, and decadal time scales. However, the potential use of the isotopic composition of cellulose for reconstructions of single parameters may not be practical because of the nonstable nature of the atmospheric variables that influence the isotopic composition of cellulose. Future studies that explore the common variations in cellulose δ^{18}O at different locations throughout the western United States would elucidate the influence of regional weather types on cellulose δ^{18}O. Finally, evaluation of more complex processes, such as evaporation, which is linked with rainfall amount and relative humidity and causes variations in leaf water δ^{18}O and soil water δ^{18}O, may prove useful.

5. Conclusions

[30] A primary goal of this study was to evaluate if tree cellulose δ^{18}O from moisture-stressed trees can be used to interpret the paleoclimatology of southern California. Tree cellulose δ^{18}O values from a *Q. douglasii* stand in the northern Los Padres National Forest reflected climate conditions of the growth year. Spanning the late 20th century, cellulose δ^{18}O correlates well with soil wetness parameters (precipitation, soil water content, relative humidity, and ring width) for the entire period of interest. In particular, this correlation increases

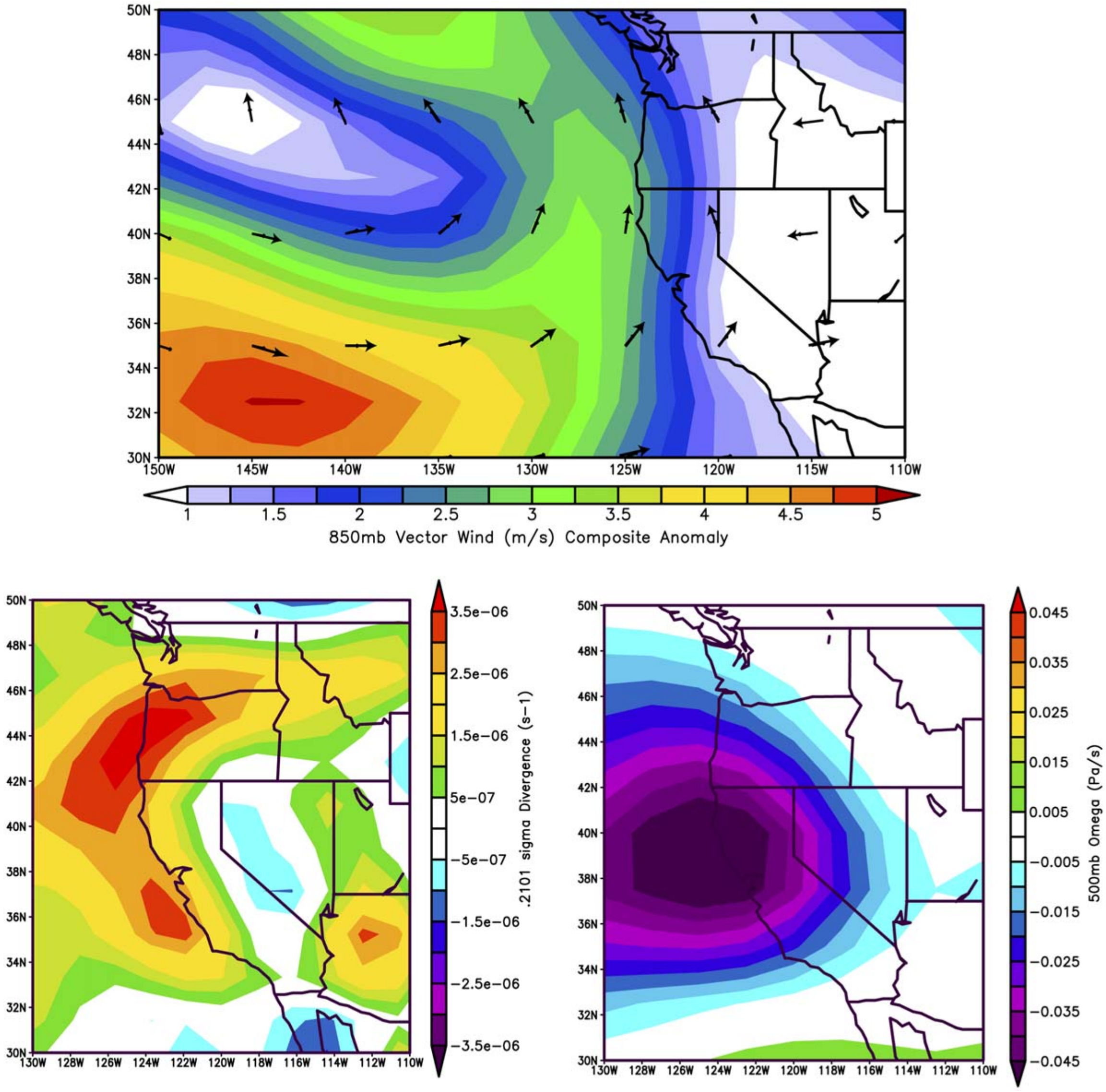

Figure 8. Atmospheric parameter anomalies (reference period 1981–2010) for the western United States for 1983 and 1998. (top) November to April 850 mb wind vector anomalies. (bottom left) November to April upper-level (0.2101 sigma) divergence anomalies, where positive values indicate increased upper-level divergence. (bottom right) November to April 500 mb omega anomalies, where negative values indicate anomalous upward motion in the air column.

for the second half of the record (1980–2004) while the correlation to precipitation δ^{18}O and soil water δ^{18}O (for the upper 50 cm of the soil column) is high for the first half of the record (1954–1979). In the late 20th century, overall wetter conditions persisted and cellulose δ^{18}O more closely resembles relative humidity. The use of a biophysical cellulose δ^{18}O model that incorporates soil water δ^{18}O and relative humidity explained as much or more interannual variance than simple monthly correlations to the local meteorology. This demonstrates the difficulty in using cellulose δ^{18}O in the region to reconstruct a single hydroclimate variable beyond the calibration period. The 1983 and 1998 El Niño events are linked with anomalously low cellulose δ^{18}O, and while primarily influenced by relative humidity at these times, the isotopic signal recorded in the cellulose may reflect moisture condensation from higher altitudes where the isotopic composition of vapor is lower. Even though blue oak cellulose δ^{18}O may not be highly correlated to a single atmospheric variable, different process may be operational over longer time scales or over a broader spatial area.

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References

Anderson, W. T., S. M. Bernasconi, J. A. McKenzie, M. Saurer, and F. Schweingruber (2002), Model evaluation for reconstructing the oxygen isotopic composition in precipitation from tree ring cellulose over the last century, *Chem. Geol.*, *182*(2–4), 121–137, doi:10.1016/S0009-2541(01)00285-6.

Barbour, M. M. (2007), Stable oxygen isotope composition of plant tissue: A review, *Funct. Plant Biol.*, *34*(2), 83–94, doi:10.1071/fp06228.

Berkelhammer, M., and L. D. Stott (2012), Secular temperature trends for the southern Rocky Mountains over the last five centuries, *Geophys. Res. Lett.*, *39*, L17701, doi:10.1029/2012Gl052447.

Berkelhammer, M., L. Stott, K. Yoshimura, K. Johnson, and A. Sinha (2012), Synoptic and mesoscale controls on the isotopic composition of precipitation in the western United States, *Clim. Dyn.*, *38*(3–4), 433–454, doi:10.1007/S00382-011-1262-3.

Biondi, F., A. Gershunov, and D. R. Cayan (2001), North Pacific decadal climate variability since 1661, *J. Clim.*, *14*(1), 5–10, doi:10.1175/1520-0442(2001)014<0005:NPDCVS>2.0.CO;2.

Buenning, N. H., L. Stott, K. Yoshimura, and M. Berkelhammer (2012), The cause of the seasonal variation in the oxygen isotopic composition of precipitation along the western US coast, *J. Geophys. Res.*, *117*, D18114, doi:10.1029/2012JD018050.

Ciais, P., et al. (1997), A three-dimensional synthesis study of delta δ^{18}O in atmospheric CO_2. 1. Surface fluxes, *J. Geophys. Res.*, *102*(D5), 5857–5872, doi:10.1029/96JD02360.

Cook, E. R., R. Seager, M. A. Cane, and D. W. Stahle (2007), North American drought: Reconstructions, causes, and consequences, *Earth Sci. Rev.*, *81*(1–2), 93–134, doi:10.1016/j.earscirev.2006.12.002.

Coplen, T. B., P. J. Neiman, A. B. White, J. M. Landwehr, F. M. Ralph, and M. D. Dettinger (2008), Extreme changes in stable hydrogen isotopes and precipitation characteristics in a landfalling Pacific storm, *Geophys. Res. Lett.*, *35*, L21808, doi:10.1029/2008GL035481.

Craig, H., and A. Gordon (1965), Deuterium and oxygen-18 variations in the ocean and the marine atmosphere, in *Stable Isotopes in Oceanographic Studies and Paleotemperatures*, edited by E. Tongiorgi, Cons. Naz. delle Ric., Lab. di Geol. Nucl., pp. 9–130, Spoleto, Italy.

Daly, C., W. P. Gibson, G. H. Taylor, G. L. Johnson, and P. Pasteris (2002), A knowledge-based approach to the statistical mapping of climate, *Clim. Res.*, *22*(2), 99–113, doi:10.3354/cr022099.

Daly, C., M. Halbleib, J. I. Smith, W. P. Gibson, M. K. Doggett, G. H. Taylor, J. Curtis, and P. P. Pasteris (2008), Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States, *Int. J. Climatol.*, *28*(15), 2031–2064, doi:10.1002/joc.1688.

Dansgaard, W. (1964), Stable isotopes in precipitation, *Tellus*, *16*(4), 436–468, doi:10.1111/j.2153–3490.1964.tb00181.x.

Dawson, T. E., and J. R. Ehleringer (1991), Streamside trees that do not use stream water, *Nature*, *350*(6316), 335–337, doi:10.1038/350335a0.

Dongmann, G., H. W. Nurnberg, H. Forstel, and K. Wagener (1974), Enrichment of $H_2{}^{18}O$ in leaves of transpiring plants, *Radiat. Environ. Biophys.*, *11*(1), 41–52, doi:10.1007/BF01323099.

Ehleringer, J. R., and T. E. Dawson (1992), Water-uptake by plants: Perspectives from stable isotope composition, *Plant Cell Environ.*, *15*(9), 1073–1082, doi:10.1111/J.1365-3040.1992.TB01657.X.

Eltahir, E. A. B., and R. L. Bras (1996), Precipitation recycling, *Rev. Geophys.*, *34*(3), 367–378.

Farquhar, G. D., and J. Lloyd (1993), Carbon and oxygen isotope effects in the exchange of carbon dioxide between terrestrial plants and the atmosphere, in *Stable Isotope and Plant Carbon-Water Relations*, ed. by J.R. Ehleringer, A.E. Hall, G.D. Farquhar, pp. 47–70, Academic, San Diego, Calif.

Flanagan, L. B., J. P. Comstock, and J. R. Ehleringer (1991), Comparison of modeled and observed environmental-influences on the stable oxygen and hydrogen isotope composition of leaf water in *Phaseolus-Vulgaris* L, *Plant Physiol.*, *96*(2), 588–596, doi:10.1104/pp.96.2.588.

Friedman, I., G. I. Smith, J. D. Gleason, A. Warden, and J. M. Harris (1992), Stable isotope composition of waters in Southeastern California. 1. Modern precipitation, *J. Geophys. Res.*, *97*(D5), 5795–5812.

Friedman, I., J. M. Harris, G. I. Smith, and C. A. Johnson (2002), Stable isotope composition of waters in the Great Basin, United States. 1. Air-mass trajectories, *J. Geophys. Res.*, *107*(D19), 4401, doi:10.1029/2001JD000565.

Gibson, W. P., C. Daly, T. Kittel, D. Nychka, C. Johns, N. Rosenbloom, A. McNab, and G. Taylor (2002), Development of a 103-year high-resolution climate dat set for the conterminous United States, paper presented at 13th AMS Conference on Applied Climatology American Meteorological Society, Portland, Oreg, pp. 181–183, May 13-16, AMS (the American Meteorological Society).

Haston, L., and J. Michaelsen (1997), Spatial and temporal variability of southern California precipitation over the last 400 yr and relationships to atmospheric circulation patterns, *J. Clim.*, *10*(8), 1836–1852, doi:10.1175/1520-0442(1997)010<1836:SATVOS>2.0.CO;2.

Helliker, B. R., and J. R. Ehleringer (2000), Establishing a grassland signature in veins: ^{18}O in the leaf water of C_3 and C_4 grasses, *Proc. Natl. Acad. Sci. U. S. A.*, *97*(14), 7894–7898, doi:10.1073/pnas.97.14.7894.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*(3), 437–471, doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

Lee, J. E., and I. Fung (2008), ''Amount effect'' of water isotopes and quantitative analysis of post-condensation processes, *Hydrol. Processes*, *22*(1), 1–8, doi:10.1002/hyp.6637.

Li, Q. A., T. Nakatsuka, K. Kawamura, Y. Liu, and H. M. Song (2011), Regional hydroclimate and precipitation δ^{18}O revealed in tree-ring cellulose δ^{18}O from different tree species in semi-arid Northern China, *Chem. Geol.*, *282*(1–2), 19–28, doi:10.1016/j.chemgeo.2011.01.004.

Majoube, M. (1971), Fractionnement en oxygène-18 et en deutèrium entre l'eau et sa vapeur, *J. Clim. Phys.*, *58*(10), 1423–1436.

McCabe, G. J., and M. D. Dettinger (1999), Decadal variations in the strength of ENSO teleconnections with precipitation in the western United States, *Int. J. Climatol.*, *19*(13), 1399–1410, doi:10.1002/(SICI)1097-0088(19991115)19:13<1399::AID-JOC457>3.0.CO;2-A.

McCabe, G. J., M. A. Palecki, and J. L. Betancourt (2004), Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States, *Proc. Natl. Acad. Sci. U. S. A.*, *101*(12), 4136–4141, doi:10.1073/pnas.0306738101.

McCarroll, D., and N. J. Loader (2004), Stable isotopes in tree rings, *Quat. Sci. Rev.*, *23*(7–8), 771–801, doi:10.1016/j.quascirev.2003.06.017.

McCarroll, D., and F. Pawellek (1998), Stable carbon isotope ratios of latewood cellulose in Pinus sylvestris from northern Finland: Variability and signal-strength, *Holocene*, *8*(6), 675–684, doi:10.1191/095968398675987498.

Meehl, G. A., et al. (2007), Global climate projections, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Planel on Climate Change*, edited by S. Solomon et al., pp. 747–845, Cambridge Univ. Press, Cambridge, U. K.

Meko, D. M., C. W. Stockton, and W. R. Boggess (1980), A tree-ring reconstruction of drought in Southern-California, *Water Resour. Bull.*, *16*(4), 594–600.

Meko, D. M., D. W. Stahle, D. Griffin, and T. A. Knight (2011), Inferring precipitation-anomaly gradients from tree rings, *Quat. Int.*, *235*, 89–100, doi:10.1016/j.quaint.2010.09.006.

Miller, A. J., D. R. Cayan, T. P. Barnett, N. E. Graham, and J. M. Oberhuber (1994), The 1976–1977 climate shift of the Pacific Ocean, *Oceanography*, *7*(1), 21–26, doi:10.5670/oceanog.1994.11.

Miller, G. R., X. Chen, Y. Rubin, S. Ma, and D. D. Baldocchi (2010), Groundwater uptake by woody vegetation in a semi-arid oak savanna, *Water Resour. Res.*, *46*, W10503, doi:10.1029/2009WR008902.

Noone, D. (2008), The influence of midlatitude and tropical overturning circulation on the isotopic composition of atmospheric water vapor and Antarctic precipitation, *J. Geophys. Res.*, *113*, D04102, doi:10.1029/2007JD008892.

Raz-Yaseef, N., L. Koteen, and D. D. Baldocchi (2013), Coarse root distribution of a semi-arid oak savanna estimated with ground penetrating radar, *J. Geophys. Res.*, *118*, 1–13, doi:10.1029/2012JG002160.

Reynolds-Henne, C. E., R. T. W. Siegwolf, K. S. Treydte, J. Esper, S. Henne, and M. Saurer (2007), Temporal stability of climate-isotope relationships in tree rings of oak and pine (Ticino, Switzerland), *Global Biogeochem. Cycles*, *21*, GB4009, doi:10.1029/2007GB002945.

Risi, C., S. Bony, and F. Vimeux (2008), Influence of convective processes on the isotopic composition (δ^{18}O and δD) of precipitation and water vapor in the tropics: 2. Physical interpretation of the amount effect, *J. Geophys. Res.*, *113*, D19306, doi:10.1029/2008JD009943.

Robertson, I., V. R. Switsur, A. H. C. Carter, A. C. Barker, J. S. Waterhouse, K. R. Briffa, and P. D. Jones (1997a), Signal strength and climate relationships in ^{13}C/^{12}C ratios of tree ring cellulose from oak in east England, *J. Geophys. Res.*, *102*(D16), 19,507–19,516, doi:10.1029/97JD01226.

Robertson, I., J. Rolfe, V. R. Switsur, A. H. C. Carter, M. A. Hall, A. C. Barker, and J. S. Waterhouse (1997b), Signal strength and climate relationships in ^{13}C/^{12}C ratios of tree ring cellulose from oak in southwest Finland, *Geophys. Res. Lett.*, *24*(12), 1487–1490, doi:10.1029/97GL01293.

Roden, J. S., G. G. Lin, and J. R. Ehleringer (2000), A mechanistic model for interpretation of hydrogen and oxygen isotope ratios in tree-ring cellulose, *Geochim. Cosmochim. Acta*, *64*(1), 21–35, doi:10.1016/S0016-7037(99)00195-7.

Roden, J. S., D. R. Bowling, N. G. McDowell, B. J. Bond, and J. R. Ehleringer (2005), Carbon and oxygen isotope ratios of tree ring cellulose along a precipitation transect in Oregon, United States, *J. Geophys. Res.*, *110*, G02003, doi:10.1029/2005JG000033.

Rozanski, K., L. Araguas-Araguas, and R. Gonfiantini (1993), Isotopic patterns in modern global precipitation, in *Climate Change in Continental Isotopic Records, Geophys. Monogr. Ser.*, edited by P. K. Swart et al., pp. 1–36, AGU, Washington, D. C.

Saurer, M., A. Kress, M. Leuenberger, K. T. Rinne, K. S. Treydte, and R. T. W. Siegwolf (2012), Influence of atmospheric circulation patterns on the oxygen isotope ratio of tree rings in the Alpine region, *J. Geophys. Res.*, *117*, D05118, doi:10.1029/2011JD016861.

Seftigen, K., H. W. Linderholm, N. J. Loader, Y. Liu, and G. H. F. Young (2011), The influence of climate on ^{13}C/^{12}C and ^{18}O/^{16}O ratios in tree ring cellulose of Pinus sylvestris L. growing in the central Scandinavian Mountains, *Chem. Geol.*, *286*(3–4), 84–93, doi:10.1016/j.chemgeo.2011.04.006.

Shu, Y., X. Feng, C. Gazis, D. Anderson, A. M. Faiia, K. Tang, and G. J. Ettl (2005), Relative humidity recorded in tree rings: A study along a precipitation gradient in the Olympic Mountains, Washington, USA, *Geochim. Cosmochim. Acta*, *69*(4), 791–799, doi:10.1016/j.gca.2004.08.013.

Stahle, D. W., M. D. Therrell, M. K. Cleaveland, D. R. Cayan, M. D. Dettinger, and N. Knowles (2001), Ancient blue oak reveal human impact on San Francisco Bay salinity, *Eos Trans. AGU*, *82*(12), 144–145.

Stahle, D. W., et al. (2011), A tree-ring reconstruction of the salinity gradient in the northern estuary of San Francisco Bay, *San Francisco Estuary Watershed Sci.*, *9*(1), pp. 1–22.

Sternberg, L. D. L. O. (2009), Oxygen stable isotope ratios of tree-ring cellulose: The next phase of understanding, *New Phytol.*, *181*(3), 553–562, doi:10.1111/J.1469–8137.2008.02661.X.

Still, C. J., et al. (2009), Influence of clouds and diffuse radiation on ecosystem-atmosphere CO_2 and $CO^{18}O$ exchanges, *J. Geophys. Res.*, *114*, G01018, doi:10.1029/2007JG00675.

Wang, X. F., and D. Yakir (1995), Temporal and spatial variations in the oxygen-18 content of leaf water in different plant species, *Plant Cell Environ.*, *18*(12), 1377–1385, doi:10.1111/J.1365–3040.1995.TB00198.X.

Wigley, T. M. L., K. R. Briffa, and P. D. Jones (1984), On the average value of correlated time-series, with applications in dendroclimatology and hydrometeorology, *J. Clim. Appl. Meteorol.*, *23*(2), 201–213, doi:10.1175/1520-0450(1984)023<0201:OTAVOC>2.0.CO;2.

Xu, L., and D. D. Baldocchi (2003), Seasonal trends in photosynthetic parameters and stomal conductance of blue oak (*Quercus douglasii*) under prolonged summer drought and high temperature, *Tree Physiol.*, *23*, 865–877.

Yoshimura, K., and M. Kanamitsu (2008), Dynamical global downscaling of global reanalysis, *Mon. Weather Rev.*, *136*(8), 2983–2998, doi:10.1175/2008MWR2281.1.

Yoshimura, K., M. Kanamitsu, D. Noone, and T. Oki (2008), Historical isotope simulation using reanalysis atmospheric data, *J. Geophys. Res.*, *113*, D19108, doi:10.1029/2008JD010074.

Yoshimura, K., M. Kanamitsu, and M. Dettinger (2010), Regional downscaling for stable water isotopes: A case study of an atmospheric river event, *J. Geophys. Res.*, *115*, D18114, doi:10.1029/2010JD014032.

Young, G. H. F., J. C. Demmler, B. E. Gunnarson, A. J. Kirchhefer, N. J. Loader, and D. McCarroll (2011), Age trends in tree ring growth and isotopic archives: A case study of Pinus sylvestris L. from northwestern Norway, *Global Biogeochem. Cycles*, *25*, GB2020, doi:10.1029/2010GB003913.

Zhu, M., L. Stott, B. Buckley, and K. Yoshimura (2012), 20th century seasonal moisture balance in Southeast Asian montane forests from tree cellulose δ^{18}O, *Clim. Change*, *115* (3–4), 505–517, doi:10.1007/s10584-012-0439-z.