INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. (2010)
Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/joc.2117

Royal Meteorological Society

Millennial precipitation reconstruction for the Jemez Mountains, New Mexico, reveals changing drought signal

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ABSTRACT: Drought is a recurring phenomenon in the American Southwest. Since the frequency and severity of hydrologic droughts and other hydroclimatic events are of critical importance to the ecology and rapidly growing human population of this region, knowledge of long-term natural hydroclimatic variability is valuable for resource managers and policy-makers. An October–June precipitation reconstruction for the period AD 824–2007 was developed from multi-century tree-ring records of *Pseudotsuga menziesii* (Douglas-fir), *Pinus strobiformis* (Southwestern white pine) and *Pinus ponderosa* (Ponderosa pine) for the Jemez Mountains in Northern New Mexico. Calibration and verification statistics for the period 1896–2007 show a high level of skill, and account for a significant portion of the observed variance (>50%) irrespective of which period is used to develop or verify the regression model. Split-sample validation supports our use of a reconstruction model based on the full period of reliable observational data (1896–2007). A recent segment of the reconstruction (2000–2006) emerges as the driest 7-year period sensed by the trees in the entire record. That this period was only moderately dry in precipitation anomaly likely indicates accentuated stress from other factors, such as warmer temperatures. Correlation field maps of actual and reconstructed October–June total precipitation, sea surface temperatures and 500-mb geopotential heights show characteristics that are similar to those indicative of El Niño–Southern Oscillation patterns, particularly with regard to ocean and atmospheric conditions in the equatorial and north Pacific. Our 1184-year reconstruction of hydroclimatic variability provides long-term perspective on current and 20th century wet and dry events in Northern New Mexico, is useful to guide expectations of future variability, aids sustainable water management, provides scenarios for drought planning and as inputs for hydrologic models under a broader range of conditions than those provided by historical climate records. Copyright © 2010 Royal Meteorological Society

KEY WORDS drought; dendrohydrology; reconstruction

Received 18 June 2009; Revised 15 January 2010; Accepted 18 January 2010

1. Introduction

Drought is a recurring phenomenon in the American Southwest. The frequency and severity of hydrologic droughts and other hydroclimatic events are of critical importance in ecology and to the rapidly growing human population of the region. Careful and prudent resource management and planning requires detailed and reliable knowledge of hydroclimatic conditions on annual to centennial time-scales. Such planning requires the ability to anticipate climatic variability, especially drought. Tree-ring analysis is the best available method for extending our knowledge of the hydroclimatic variability on annual time-scales beyond the relatively short instrumental records. Such dendrohydrological reconstructions provide us with knowledge of the past frequency and severity of climatic anomalies such as drought and wet periods, and can be used to help anticipate the future probability of such events.

The Jemez Mountains, in Northern New Mexico, offer opportunities for exploiting the dendrohydrologic potential of tree-ring data. This mountain range is a source of runoff to the Jemez and Rio Chama Rivers, two important tributaries to the Rio Grande River. Limited water supplies and an exploding population have increasingly stressed water supplies in the Rio Grande River region. Information from a study in the Jemez Mountains could provide a framework for expanded research in the greater Rio Grande basin. Previous tree-ring studies have identified the Jemez as a rich source of trees with climatically sensitive tree-rings (Rose *et al*., 1982; Touchan and Swetnam, 1995; Allen, 2004).

Groundwork for tree-ring chronology development has been laid in the Jemez Mountains and surrounding parts of Northern New Mexico. Dendroclimatic reconstructions based largely on archaeological tree-ring series were developed by Rose *et al*. (1982) and Dean and

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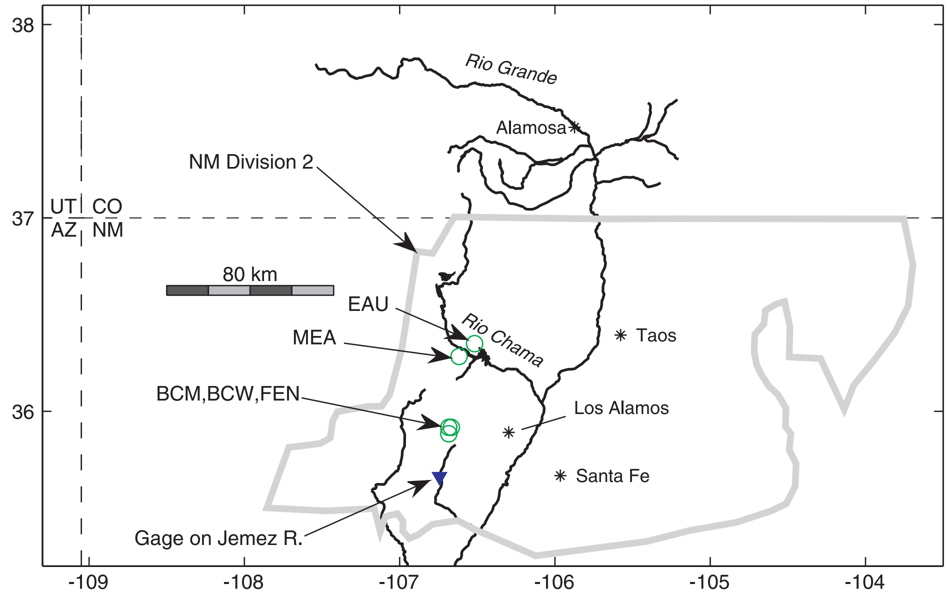

Figure 1. Map showing data locations. Data include five tree-ring chronologies (circles, see Table I), gaged flows for the Jemez River near Jemez, NM, and climate data for Division 2, New Mexico. This figure is available in colour online at www.interscience.wiley.com/ijoc

Funkhouser (1995). Because the individual tree-ring series that go into the archaeological chronologies are usually short (less than 200 years in length), they are poorly suited for providing reliable information on long-term climate trends and fluctuations (Cook *et al*., 1995; Grissino-Mayer, 1996).

Touchan and Swetnam (1995) developed a December–June precipitation reconstruction for the Jemez Mountains from a network of ponderosa pine tree-ring chronologies that were originally developed as climatic controls in a tree-ring reconstruction of western spruce budworm history (Swetnam and Lynch, 1993). The watersheds included in this network were Jemez River, Red River, Rio Pueblo and Rio de Taos (Figure 1). Touchan (not published) developed new precipitation reconstructions based on chronologies greater than 300 years in age to better capture long-term climate trends. On a larger spatial scale, Ni *et al*. (2002) and Cook *et al*. (2004) have reconstructed drought-related variables for climate divisions and a longitude–latitude grid that include Northern New Mexico. A shortcoming of these studies is that they made use of pre-existing chronologies only, and so were based on tree-ring data that end in the 1980s or early 1990s. Subsequent years are of great interest because of the recent Southwest drought. Accordingly, we have conducted new field work and chronology development so that records cover this most recent drought. Our geographic focus on a single hydrologically important mountain range (the Jemez) is also somewhat more restrictive geographically than the broader regional studies by Ni *et al*. (2002) and Cook *et al*. (2004).

The goal of this paper is to increase understanding of the long-term natural hydroclimatic variability in the Northern New Mexico portion of the Rio Grande Basin through tree-ring reconstruction of cool-season (October–June) precipitation. Our reconstruction documents 1181 years of climate and drought variability that can be used to place current and 20th century wet and dry events into a long-term perspective. Records of past hydroclimatic variability can be used to guide expectations of future variability, aid sustainable management, provide scenarios for drought planning and as inputs for hydrologic models to test systems under a broader range of conditions than those provided by the historical climate records. We will also examine the links between large-scale climate and reconstructed climate.

2. Site description

The Jemez Mountains are located in north-central New Mexico (Figure 1) and cover an area of about 543 522 ha, with elevations ranging from 1590 m at the Rio Grande to 3526 m at the summit of Tschicoma Peak (Smith *et al*., 1976). We collected tree-ring samples from new sites on Mesa Alta (MEA), Bear Canyon Middle (BCM) and Bear Canyon West (BCW), and we updated previously existing chronologies from Fenton Lake (FEN) and Echo Amphitheater (EAU) (Figure 1, Table I). The elevation of the sampled areas varies between 2059 and 2597 m (Table I). Soil parent material varies from rhyolites and andesites with some dacites and latites, to tuff and pumice on the plateaus and basalt near the Rio Grande (Nyhan *et al*., 1978).

The length of the frost-free growing season in Los Alamos is 157 days or around five months (Bowen, 1989). July is the warmest month at Los Alamos, with a mean temperature of 28 °C, and January is the coldest month, with a mean temperature of −1.6 °C. Annual precipitation ranges from about 30 cm at the lower elevations to about 90 cm at higher elevations.

The Jemez Mountains lie at the southern fringes of the track of frontal storms that bring cool-season moisture

Table I. Site information for Northern New Mexico.

Site Name	Site code	Species	Elevation (m)	Latitude	Longitude	Time span	No. of trees	No. of radii	Source
Echo Amphitheater	EAU	1	2059	36°21′N	106°31′W	1295–2007	18	19	4 and 5
Mesa Alta	MEA	1 and 2	2525	36°17′N	106°37′W	644–2007	47	82	5
Bear Canyon Middle	BCM	2	2597	35°55′N	106°40′W	1568–2007	24	45	5
Bear Canyon West	BCW	1 and 2	2561	35°55′N	106°41′W	1298–2007	30	56	5
Fenton Lake	FEN	3	2529	35°53′N	106°41′W	1304–2007	37	66	5 and 6

1 = *Pseudotsuga menziesii*. 2 = *Pinus strobiformis*. 3 = *Pinus ponderosa*. 4 = Contributed to the International Tree-Ring Data Bank by Dean, J.S., Burns, B.T., Robinson, W.J. and Bowden, D.O. 5 = This work. 6 = Swetnam and Lynch, 1993

Table II. Summary statistics for the seven chronologies for the ARSTAN program.

Site code	Total chronology				Common interval			
	MSSL[a]	Std[b]	SK[c]	KU[d]	First year EPS[e] >0.85	Time span	MCAR[f]	EV[g] PC1(%)
EAU	294	0.35	0.03	0.01	1367	1713–2002	0.73	77
MEA	243	0.43	0.41	0.27	824	1798–2007	0.74	75
BCM	228	0.23	0.09	1.12	1667	1834–2007	0.56	58
BCW	222	0.24	0.33	2.00	1655	1805–2007	0.56	58
FEN	262	0.31	−0.16	0.33	1535	1764–1980	0.59	61

[a] MSSL is mean sample segment length.
[b] Std is standard deviation.
[c] SK is skewness.
[d] KU is Kurtosis.
[e] EPS is expressed population statistic (Wigely *et al*., 1984).
[f] MCAR is mean correlation among radii.
[g] EV is explained variance.

from the Pacific Ocean. In summer the region is influenced by the North American monsoon (Sheppard *et al*., 2002; Gutzler, 2005). The months of highest precipitation are July and August (Sheppard *et al*., 2002) but a peak runoff in spring for many streams reflects snowmelt-driven hydrology, indicating the hydrologic importance of cool-season precipitation to water resources. Winter precipitation is influenced to some extent by El Niño–Southern Oscillation (ENSO) events, particularly during extremely wet or dry years. During El Niño winters, the jet stream tends to shift to the south, bringing more moisture to the southwestern U.S., while in La Niña winters, storm tracks take a more northerly course (Douglas and Englehart, 1981; Kiladis and Diaz, 1989), resulting in winters that are typically drier than average. Decadal variability in winter precipitation appears to be related to fluctuations in the Pacific Ocean (e.g. Pacific Decadal Oscillation (PDO), Mantua *et al*., 1997), which can amplify or dilute the impacts of ENSO events (Gershunov and Barnett, 1998).

3. Methods and data processing

3.1. Chronology development

This study focussed on developing three new chronologies (MEA, BCM, BCW), extending and enhancing one existing chronology (FEN), and updating another (EAU) from the species *Pseudotsuga menziesii* (Douglas-fir), *Pinus strobiformis* (Southwestern white pine) and *Pinus ponderosa* (Ponderosa pine) (Figure 1 and Table I). Two of the chronologies (MEA and BCW) contain two species, *Pinus strobiformis* and *Pseudotsuga menziesii,* that were merged because visual crossdating and computer-based quality control confirmed a strong common signal. The growth of these species is known to be strongly driven by climate and is significantly correlated with precipitation and streamflow over a broad region in the western U.S.

The tree-ring sites were selected based on past experience of the authors with the region. Sampling was concentrated on the Jemez Mountains based on *a priori* interest by the funding agency (U.S. Geological Survey) in the climate variations there. Increment cores were taken from living trees at all sites and full cross-sections were taken from selected logs and stumps. Samples were fine-sanded and crossdated using standard dendrochronological techniques (Stokes and Smiley, 1968; Swetnam, 1985). The width of each annual ring on the cores and cross-sections was measured to the nearest 0.01 mm. Five chronologies were developed from the region (Table II).

A systematic procedure was applied in chronology development. Each series of tree-ring width measurements was fit with a cubic smoothing spline with a 50% frequency response at 67% of the series length to remove non-climatic trends due to age, size and the effects of stand dynamics (Cook and Briffa, 1990). The detrended series were then prewhitened with low-order autoregressive models to remove persistence. The removed persistence is presumably not related to persistence in the precipitation record being reconstructed, as that record has essentially zero first-order autocorrelation (see Section 4.2). It is of course possible that some portion of the persistence removed is climatic in origin. The individual indices were combined into a single master chronology for each combination of site and species using a bi-weight robust estimate of the mean (Cook, 1985).

3.2. Climate data

We used monthly temperature and precipitation division data from New Mexico Climatic Divison 2, 1895–2007, obtained from the National Climate Data Center (Figure 1) for our dendroclimatic analyses. Tree-ring reconstructions made use of seasonal-total divisional precipitation. Monthly flow data were also downloaded from the U.S. Geological Survey (http://water.usgs.gov/data/) for gage 08324000, the Jemez River near Jemez Springs, New Mexico (Figure 1). These data were used to evaluate the agreement between reconstructed precipitation and runoff from one of the important rivers in the study region. There are no major reservoirs above this gage and the gaged record is considered to be relatively unimpacted by human activities (Slack *et al*., 1988). The basin upstream of the gage has an area of 470 square miles (1217 square kilometers) (USGS, 2009) and the flows represent runoff from the interior of the Jemez Mountains. Monthly flows are available for the period 1953–2007.

3.3. Dendroclimatic reconstructions

The relationships between the tree-ring chronologies and monthly Division 2 temperature and precipitation were investigated with response function analysis (RFA) to determine the seasonal climate variables to which tree growth is responding (Fritts, 1976, 1991). The RFA identified the particular seasonal climate variable to be reconstructed.

The reconstruction model was developed by linear regression of the climate variable on principal components (PCs) of tree-ring chronologies. Regression equations were calibrated on the period 1895–2007. A nested reconstruction was developed to accommodate the varying chronology lengths while exploiting the potential to accurately capture the long-term extreme events history of the region (Touchan *et al*., 2008). This procedure also allows for a maximum length reconstruction, although the earliest part of a record may be reduced in robustness because of thin sample size. To avoid bias in comparison of droughts, the individual nested reconstructions were scaled such that they all have the same standard deviation (that of the most recent model) for their common calibration period. Stepwise regression was used to select predictors for the models. These are PCs of chronologies if two or more chronologies are available, and a chronology itself if only a single chronology is available. The strength of the reconstruction model was examined using regression and correlation statistics, and the PRESS procedure was used for cross-validation (Weisberg, 1985; Fritts *et al*., 1990; Meko, 1997; Touchan *et al*., 1999, 2003, 2005a and b). A split-sample procedure (Snee, 1977; Meko and Graybill, 1995; Touchan *et al*., 2003, 2005a and b) that divides the full period (AD 1895–2007) into two subsets was also used to verify model stability. The reduction of error statistic (RE) was calculated to test for skill of reconstruction compared with that of a simple model that would use the calibration period mean of observed precipitation as the reconstruction. An RE value of greater than zero is considered positive skill (Fritts, 1976). Low-frequency time series variations in reconstructed precipitation were summarized with moving averages (7-year) and a 9-weight Gaussian filter (Mitchell *et al*., 1966).

3.4. Drought and circulation analysis

In order to investigate the correspondence between droughts in Northern New Mexico during the instrumental period and the circulation patterns associated with them, we developed correlation field maps using Division 2 precipitation and October–June global sea surface temperatures (SSTs) and 500-mb geopotential heights for the periods 1949–2006 from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis dataset (Kalnay *et al*., 1996). To further confirm this relationship, particularly during extreme wet and dry years, composite maps of SST for the five wettest and driest years in the October–June New Mexico Division 2 data, 1986–2007, were generated using NOAA Extended SSTs dataset (Xue *et al*., 2003; Smith *et al*., 2008). We analysed the differences between the driest 7-year period in the reconstruction, 2000–2006, and the driest 7-year period in the observed data, 1950–1956, by comparing the sequences of years in both the observed and reconstructed data using monthly New Mexico Division 2 precipitation and temperature data. The New Mexico Division 2 temperature data, 1896–2008, were obtained from the PRISM data set (Daly *et al*., 1997).

4. Results and discussion

4.1. Chronologies

We developed five ring-width chronologies from the Jemez Mountains for a regional analysis (Figure 1). The length of the five chronologies ranges from 439 (BCM) to 1364 years (MEA) (Table I). Statistical analyses of each chronology are summarized in Table II. The mean correlation among individual radii at each site represents the strength of their common signal and ranges from 0.56 to 0.74. The highest correlation is for MEA and the lowest are for the chronologies developed from BCM and BCW. The mean sample segment length (MSSL) of the eight chronologies ranges from 222 to 294 years. All of the chronologies have MSSL greater than 200 years

Table III. Split-sample calibration and validation statistics of two reconstruction models.

Reconstruction Models	Calibration Period	Verification period	Adjusted-R^2 calibration	r^2-Verification	Reduction of error, RE
1305–2007	1896–1951	1952–2007	0.65	0.54	0.53
824–2007			0.60	0.54	0.54
1305–2007	1952–2007	1896–1951	0.53	0.65	0.63
824–2007			0.54	0.60	0.59

Table IV. Calibration and validation statistics for reconstruction models calibrated on period 1896–2007.

Reconstructions	Variable	Coefficient	Adjusted-R^2 calibration	PRESS	No. of chronologies
1305–2007	Constant	23.4	0.59	0.57	4
	PC1	2.61			
824–2007	Constant	11.8	0.57	0.56	1
	MEA	11.8			

and many have several samples exceeding 300 years. Therefore, the chronologies are suitable for investigating low-frequency climate variability on decadal to century time-scales. Principal component analysis (PCA) applied to the four chronologies showed a strong common statistical growth signal for their overlapping years. Principal component 1 accounts for 73% of the tree-ring variance. Scores of this PC were retained for use as predictors in the most recent reconstruction model.

4.2. Dendroclimatic reconstructions

The RFA identified October–June total precipitation as the most appropriate seasonal predictand for reconstruction. Temperature response was non-significant except for the single month of June, which had a negative response. October–June total precipitation (hereafter, 'precipitation') was adopted as the variable for reconstruction. This precipitation variable has no significant (0.05 level) autocorrelation at lags 1–20 years. Precipitation was applied in two different reconstruction models with varying time coverage and chronology makeup. The first reconstruction model covered the common period 1305–2007 and the earliest model extended back to 824. The expressed population signal (Wigley *et al.*, 1984) was used to identify the earliest year for possible reconstruction by the single-chronology model. Stepwise regression with adjusted R^2 and Mallow's Cp (Mallows, 1973) as selection cutoff criteria indicated that only the first principal component (PC1) should be used as predictors for the model with data beginning in 1304. Selection of predictors did not apply to the earliest model (824 start years) as only one predictor was available. Split-sample calibration/validation shows that the models that went into the nested reconstructions are skilful as a function of time and the underlying tree-ring data (Tables III and IV), and account for a significant portion of the observed variance (>50%) irrespective of which period is used to develop or verify the regression model (Table IV). The split-sample validation also supports our use of the reconstructions based on the full period of reliable observational data (1896–2007) in the following discussions (Figure 2). None of the regression models showed any trend or first-order autocorrelation in the residuals. The nested reconstruction utilized the two models to take advantage of the robustness derived from the models that incorporated a greater number of chronologies.

The October–June reconstruction time series is plotted in Figure 3. Dry and wet years are arbitrarily defined as reconstructed precipitation below the 30th or above the 70th percentile based on the 1896–2007 instrumental period (PPT $\leq$19.65 cm and $\geq$26.59 cm, respectively). The long-term reconstruction contained 240 drought events, defined as one or more consecutive years below the threshold. One-hundred-sixty-three events have a duration of one year, Thirty-five events have a duration of two years, one event has a duration of three years (AD 1097–1099) and one event has a duration of four years (AD 951–954). The driest single year over the full length of the reconstruction is 1996 (10.4 cm) while the driest year in the instrumental data is 2002 (10.97 cm). The second driest year is 1748 (10.7 cm), which Towner (2003) reported as the driest year in the entire 1348-year precipitation reconstruction for the Gobernador area in Northern New Mexico. Swetnam *et al.* (1999) documented that the region-wide extent of wildfires was greater in 1748 than any year since 1600 in the southwestern U.S.

The long-term reconstruction contains 293 wet events defined as one or more consecutive years above the threshold. One–hundred-and-fifty-one events have a duration of one year, forty-three events have a duration of two years, nine events have a duration of three years, six events have a duration of four years (AD 1015–1018, 1170–1173, 1512–1515, 1594–1597, 1610–1613 and 1983–1986) and one event of five years (1114–1118).

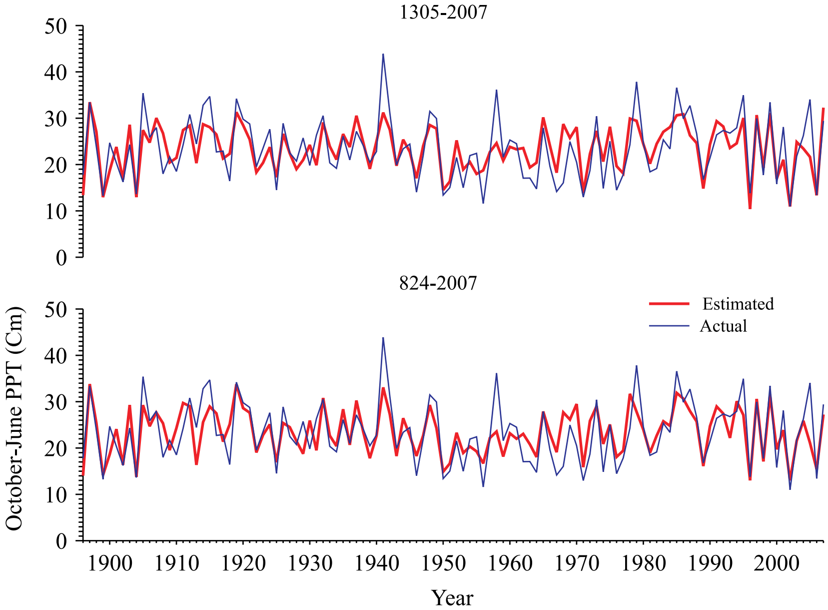

Figure 2. Comparison of actual and estimated October–June precipitation for the 1896–2005 period. This figure is available in colour online at www.interscience.wiley.com/ijoc

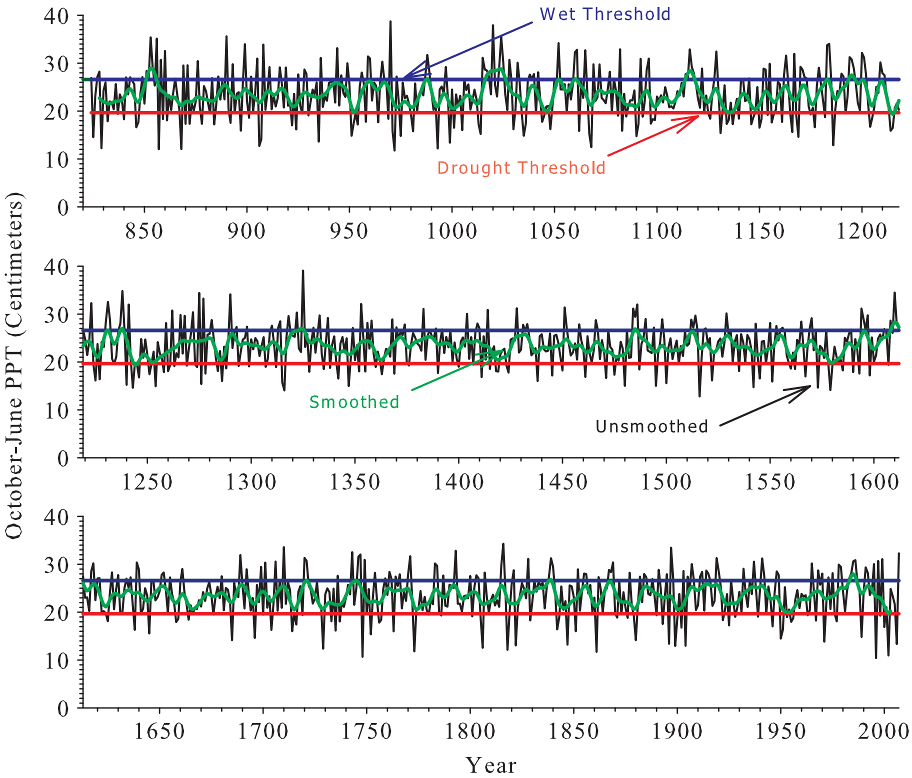

Figure 3. Time series plot of nested reconstructed October–June precipitation, AD 824–2005. Percentile-based thresholds for dry and wet conditions are defined in text (Section 4.2). Gaussian smoothing weights: {0.0204 0.0578 0.1216 0.1900 0.2205 0.1900 0.1216 0.0578 0.0204}. This figure is available in colour online at www.interscience.wiley.com/ijoc

The wettest single year over the full length of the reconstruction is 1325 (39 cm).

The Gaussian-smoothed reconstruction highlights the most recent decade and the 1950s for exceptional dryness (Figure 3). Smoothed precipitation centred on 2002 is at its lowest level since the 1200s. The smoothed series also indicated that this recent drought was immediately preceded by perhaps the wettest period in 400 years, with peak wetness in the late 1980s. The recent drought is especially severe in terms of a 7-year running mean: the record low for the entire reconstruction is AD 2000–2006 (18.87 cm). The second driest seven-year period is AD 1950–1956 (18.88 cm). Thomas (1963) reported that the 1950s drought severely affected the amount of available surface water, and the use of ground water sources increased over normal usage. Manthe (1977) and Tuan *et al*. (1973) report on the impact of this severe extended drought on the region's agriculture and industries.

The precipitation reconstruction is expected to correlate with other hydrologic variables that depend on precipitation, such as runoff and streamflow. The strength of runoff relationship for a particular basin is illustrated by a scatterplot of reconstructed precipitation on log-transformed annual flow of the Jemez River near Jemez, New Mexico, 1954–2007 (Figure 4). For this basin 51% of the variance of transformed flow is explained in a linear regression on the reconstructed precipitation. The need for flow transformation to achieve the reasonably linear and homoskedastic relationship shown in Figure 4 implies that if the tree-ring data in this study were used directly to reconstruct flow the reconstructed flows would have amplified uncertainty in high-flow conditions. This characteristic is shared by several other reconstructions in various parts of the semi-arid western U.S. (e.g. Smith and Stockton, 1981; Meko and Graybill, 1995; Meko *et al*., 2001).

Our precipitation reconstruction is significantly correlated with the multi-millennial July to current July reconstruction developed by Grissino-Mayer (1996) ($r = 0.61$, $n = 1169$, $p \leq 0.0001$) for the El Malpais region in west-central New Mexico. The relatively low correlation between the two reconstructions reflects differences in geographical location and seasonal focus. Another source of difference might be that, unlike the El Malpais reconstruction, our reconstruction is based on multiple site chronologies and multiple species.

Major drought features show similarities and differences. For example, while Grissino-Mayer identified 1579–1585 as the driest 7-year period, our reconstruction indicates the 1950s drought was more severe as a 7-year moving average. The Grissino-Mayer reconstruction ends in 1992, and thus does not cover the most recent 2000s drought that we identify as the driest 7-year period in the full reconstruction.

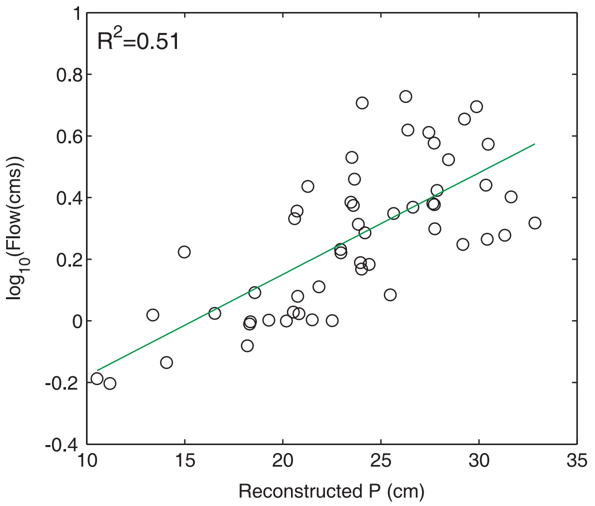

Figure 4. Scatterplot of log-transformed annual flow of Jemez River on reconstructed divisional precipitation. Flow is total for water year at gage 08324, Jemez River near Jemez, New Mexico. Reconstructed precipitation is for New Mexico Division 2, as described in text. Annotated at upper left is regression R^2 for least-squares straight-line fit. Analysis period is 1954–2005. This figure is available in colour online at www.interscience.wiley.com/ijoc

Our precipitation reconstruction is significantly correlated with the Palmer drought severity index (PDSI) reconstructions at four gridded points that were developed by Cook *et al*. (2004) for New Mexico (35 °N 107.5 °W, 32.5 °N 107.5 °W, 35 °N, 105 °W, 32.5 °N 105 °W). The correlation coefficient ranges from 0.71 to 0.76 ($n = 1183$, $p \leq 0.0001$).

4.3. Drought and circulation analysis

Northern New Mexico is on the northern edge of the part of the U.S. that is influenced by the ENS O during the cool season. Correlation field maps of observed October–June total precipitation, SSTs and 500-mb geopotential heights show patterns that are similar to those indicative of ENSO, particularly with regard to ocean and atmospheric conditions in equatorial and north Pacific (Figure 5(a) and (b)). Maps generated from the reconstructed values, instead of the observed precipitation, show similar patterns, further validating the skill of this reconstruction (Figure 5(c) and (d)). Composite maps of the five wettest and driest years show SST patterns that are even more strongly indicative of ENSO as a causal mechanism for wet and dry cool conditions in Northern New Mexico (Figure 6(a) and (b)).

The two driest 7-year periods in the 1184-year reconstruction, 1950–1956, and 2000–2006, are notable in that they both occurred in the last six decades. While the 1950s drought is the driest 7-year period in the instrumental record, the 2000s period ranks 26th driest, in contrast to the severity of this period in the reconstruction. The 1950s drought is characterized by several cold ENSO events (1950–1951, 1954–1956) (Smith and Sardeshmukh, 2000) with cool SSTs in the central and eastern tropical Pacific throughout most of the 7-year period. The period 2000–2006 started during an extended cold ENSO event, which began in 1998 and peaked in 2000, but persisted weakly into 2002 (Hoerling and Kumar, 2003). After 2002, weak warm ENSO conditions developed, and in the winter of 2005–2006 this was augmented by an active Madden Julian Oscillation, with much of the Southwest receiving record or near record rainfall amounts (Lenart, 2005), before returning to cool SSTs in 2006, which plunged the region into severe drought again (Doster, 2006). The wet conditions in 2005 and, to a lesser degree, in 2001 are responsible for this period's ranking of 26th driest, in spite of some extremely dry years (Figure 7(a) and (b)).

Why did the trees not respond with a greater degree of recovery to these wet years? The biological response to the most recent period of drought is more severe than indicated by the precipitation data alone, suggesting that the biological stress was due to more than just

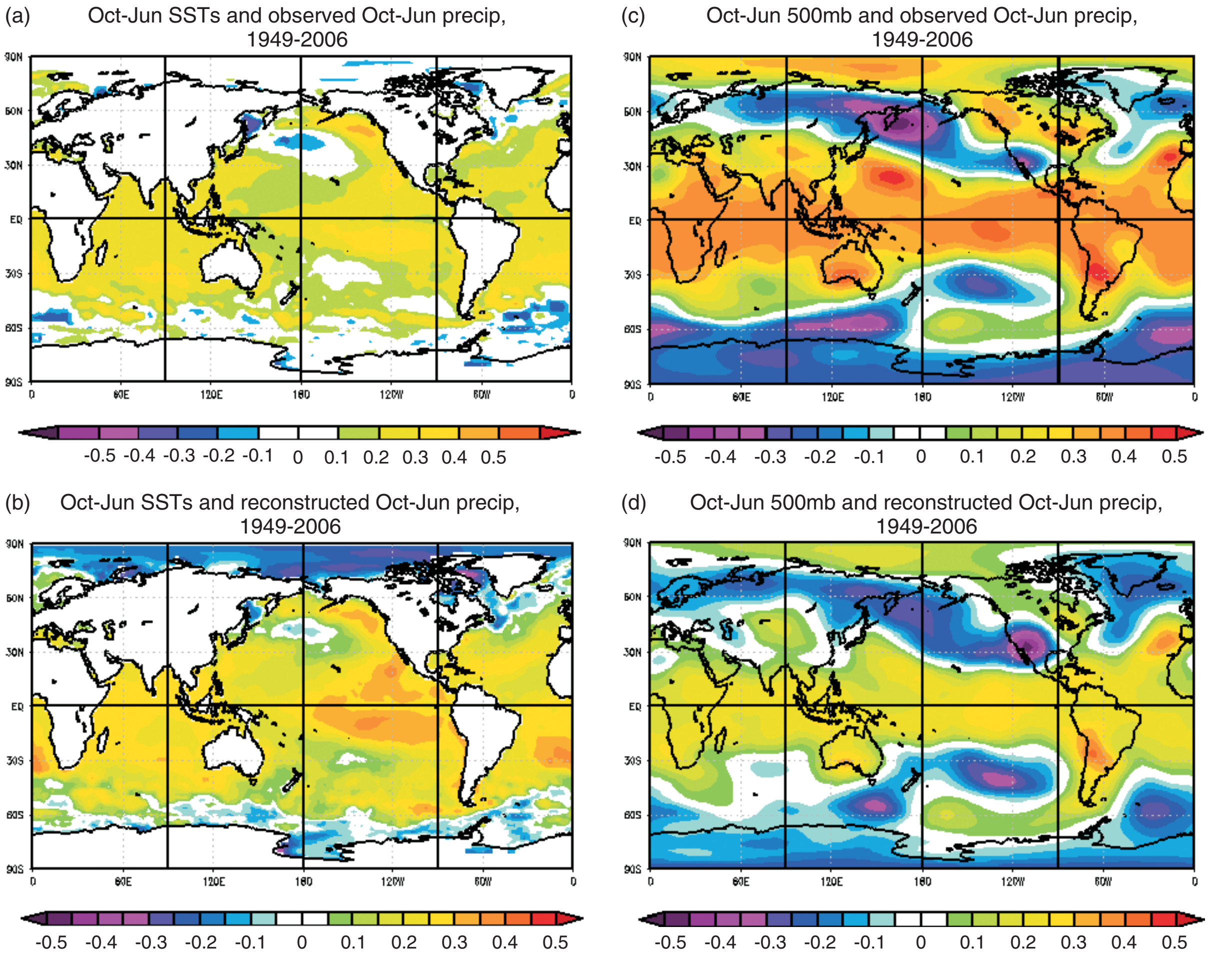

Figure 5. Correlations field maps, 1949–2006. (a) New Mexico Division 2 October–June precipitation and October–June SSTs. (b) New Mexico Division 2 reconstructed October–June precipitation and October–June SSTs. (c) New Mexico Division 2 October–June precipitation and October–June 500-mb geopotential heights. (d) New Mexico Division 2 reconstructed October–June precipitation and October–June 500-mb geopotential heights. Images provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado from their Website at http://www.esrl.noaa.gov/psd/. This figure is available in colour online at www.interscience.wiley.com/ijoc

cool-season precipitation. An examination of the October–June temperatures for 2000–2006 compared with those for 1950–1956 suggests that high temperatures may have exacerbated the trees' ability to recover in the intervening wetter years (Figure 7(c)). Temperatures during 1950–1956 were above the long-term (1896–2007) average in four of the seven years, and more than one standard deviation from average in two of those years. Temperatures during 2000–2006 were above the long-term average in all seven years, more than one standard deviation warmer in six years, and more than two standard deviations warmer in two of those years. Clearly the 2000s drought was warmer than the 1950s drought in this region (average October–June values: 22.5 °C in the 1950s, 23.3 °C in the 2000s, compared to a long-term average of 22.1 °C). This 7-year period encompasses what has been deemed a 'global-change-type drought,' noted to be warmer than the 1950s drought, with widespread tree mortality in woodlands across the southwestern U.S. due to the drought and exacerbated by beetle infestation (Breshears *et al*., 2005). The combination of anomalously warm winter and spring temperatures and several years of severe drought may have compromised the trees' ability to take advantage of the wetter years. Experimental studies of *Pinus edulis* in a controlled environment suggest that warming can affect tree survival through photosynthesis reduction and carbon starvation, independent of any effect on the ecosystem water balance (Adams *et al*., 2009). It is reasonable to expect reduction in growth rate through similar pathways before a threshold for survival is reached. However, warm temperatures may be only part of the story. The role of the summer monsoon in preconditioning the soil moisture for the following growth season has not been investigated, but June–August monthly precipitation in the 1950s period of drought (1949–1955) averaged 16.9 cm while that of the 2000s drought (1999–2005) averaged 14.4 cm (17.4 is the long-term average). By 2007, a wetter year, the reconstructed precipitation closely matched the value for the observed precipitation. Temperatures in 2007 also dipped below one standard deviation from the mean for the first time since 2001, which may have assisted the recovery. But another factor that may have aided recovery was the extremely wet monsoon season in 2006 (130% of

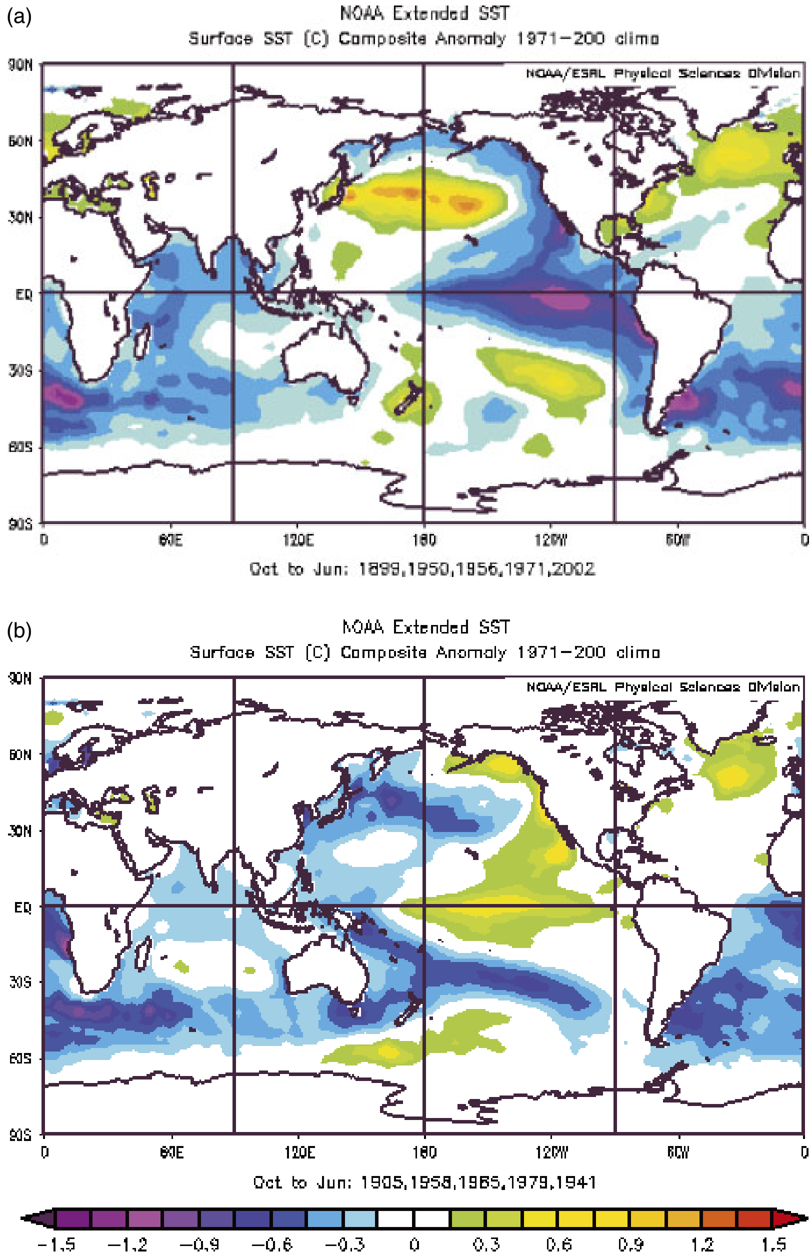

Figure 6. Composite maps of SST for the five wettest and five driest years for New Mexico Division 2 October–June precipitation, 1895–2007. (a) Composite for driest years, 1899, 1950, 1956, 1971, 2002. (b) Composite maps for wettest years, 1905, 1941, 1958, 1979, 1985. Images provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado from their Website at http://www.esrl.noaa.gov/psd/. This figure is available in colour online at www.interscience.wiley.com/ijoc

the long-term average) which could have preconditioned the soil for the growing season.

5. Conclusions

An understanding of natural climate variability is important for water and land management to implement low-risk, long-term plans to achieve conservation and sustainable use of water and other natural resources. This October–June precipitation reconstruction provides a baseline for studying past climate variability in the Jemez Mountains region. Calibration and verification of statistical analyses indicate high accuracy for this tree-ring reconstruction of precipitation. The longest period of reconstructed drought during the last millennium is 4 years, defined in this study as consecutive years below the 30th percentile. The 7-year moving average of the reconstructed precipitation reveals that the worst 7-year drought during the last 1184 years is 2000–2006. Although this study specifically focussed on precipitation, comparison of reconstructed divisional precipitation with annual flows of the Jemez River indicates that the reconstruction has useful information on flows down to a fairly small watershed (less than 2000 km^2). With additional tree-ring data and use of alternative types of reconstruction models it should be possible to improve the flow reconstruction. Interpretation of reconstructions of a specific climate variable (e.g. precipitation) should also consider that multiple climate variables may influence tree-growth departures, at least in some years.

In the period of instrumental record, the main feature that has influenced periods of above–average- and below-average precipitation during the cool season in this area is ENSO. Cold ENSO conditions appear to have been a key factor in the driest 7-year period in the instrumental period, 1950–1956. In the cool-season reconstruction, while the 1950s period is extremely dry, it ranks second to the 7-year period, 2000–2007 period, which is the driest period in the entire reconstruction. Tree responses to the climatic conditions during this latest period, which contained several very dry years interspersed with some wetter years, may reflect anomalously warmer recent temperatures and perhaps a drier monsoon season preceding the growth year. The underestimation of precipitation during some years of this most recent interval of drought suggests the possibility that the tree-ring data may underestimate precipitation during particularly warm droughts in the past. Annually resolved proxy temperature records that extend into the medieval period, noted elsewhere for severe and sustained drought and temperatures warmer than the centuries that followed (at least until the last several decades), do not exist for this region. However, both hemispheric and regional temperature reconstructions (e.g. Salzer and Kipfmueller, 2005; Mann *et al.*, 2008) suggest that the temperatures of the last decade have been anomalously warm in the context of the past two millennia. Warm temperatures exacerbate drought stress in trees, but the recent extreme warm temperatures may now be having a greater effect on trees' ability to respond to wetter years within a period of drought in this region.

The precipitation reconstruction and the tree-ring data used to produce it will be available at the NOAA Paleoclimatology web site (http://www.ncdc.noaa.gov/paleo/treering.html).

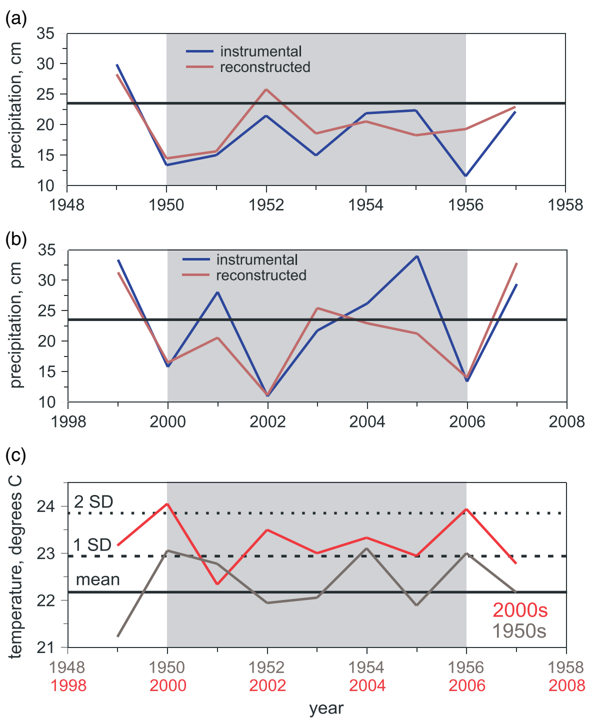

Figure 7. (a) Time series of October–June observed and reconstructed precipitation for 1949–1957 (horizontal line is 1896–2007 mean). (b) Time series of October–June observed and reconstructed precipitation for 1999–2007 (horizontal line is 1896–2007 mean). (c) Time series of October–June observed mean temperature for 1949–1957 and 1999–2007, with mean (horizontal solid line), standard deviation (horizontal dashed line), and two standard deviations (horizontal dotted line) based on 1896–2007. This figure is available in colour online at www.interscience.wiley.com/ijoc

Acknowledgements

We thank Mark Losleben, Irina Panyushkina, Kay Beeley, Rebecca Oertel, Ellis Margolis and Andrew Goumas for their valuable assistance in the field; Julie Wong for her assistance in sample preparation and measurement. Funding was provided by the USGS Biological Resources Discipline, Global Change Research Program, Western Mountain Initiative (Award No. 04HQAG0121).

References

Adams HD, Guardiola-Claramonte M, Barron-Gafford GA, Villegas JC, Breshears DD, Zou CB, Troch PA, Huxman TE. 2009. Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought. *Proceedings of the National Academy of Sciences United States of America* **106**(17): 7063–7066.

Allen CD. 2004. Ecological patterns and environmental change in the Bandelier landscape. Chapter 2. In *Village Formation on the Pajarito Plateau, New Mexico: Archaeology of Bandelier National Monument*, Kohler TA (ed). University of New Mexico Press: Albuquerque; 19–68.

Bowen BM. 1989. *Los Alamos Climatology*. Los Alamos National Laboratory: Los Alamos, New Mexico; 254.

Breshears DD, Cobb NS, Rich PM, Price KP, Allen CD, Balice RG, Romme WH, Kastens JH, Floyd ML, Belnap J, Anderson JJ, Myers OB, Meyer CW. 2005. Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Sciences United States of America* **102**: 15144–15148.

Cook ER. 1985. A time series analysis approach to tree-ring standardization. Unpublished PhD. dissertation, University of Arizona, Tucson.

Cook ER, Briffa KR. 1990. A comparison of some tree-ring standardization methods. In *Methods of Dendrochronology: Applications in the Environmental Sciences*, Cook ER, Kairiukstis LA (eds). Kluwer Academic Publishers: Boston; 153–162.

Cook ER, Briffa KR, Meko DM, Graybill DS, Funkhouser G. 1995. The 'segment length curse' in long tree-ring chronology development for paleoclimatic studies. *The Holocene* **5**(2): 229–237.

Cook ER, Woodhouse C, Eakin CM, Meko DM, Stahle DW. 2004. Long-term aridity changes in the western United States. *Science* **306**: 1015–1018.

Daly C, Taylor G, Gibson W. 1997. The PRISM approach to mapping precipitation and temperature. In *10th Conference on Applied Climatology*, Reno, NV, American Meteorological Society, 10–12.

Dean JS, Funkhouser GS. 1995. Dendroclimatic reconstructions for the southern Colorado Plateau. In *Climate Change in the Four Corners and Adjacent Regions: Implications for Environmental Restoration and Land-Use Planning: Proceedings of the Workshop*, Waugh WJ (ed). Mesa State College: Grand Junction, CO; 85–104.

Doster S. 2006. Southwest drought can pack a hefty punch. Southwest Climate Outlook, May 2006. Climate Assessment for the Southwest, University of Arizona, cited 2008, http://www.climas.arizona.edu/forecasts/articles/drought_may2006.pdf.

Douglas AV, Englehart PJ. 1981. On a statistical relationship between autumn rainfall in the central equatorial Pacific and subsequent winter precipitation in Florida. *Monthly Weather Review* **109**: 2377–2382.

Fritts HC. 1976. *Tree Rings and Climate*. Academic Press: London; 567.

Fritts HC. 1991. *Reconstruction Large-Scale Climatic Patterns from Tree-Ring Data*. The University of Arizona Press: Tucson; 286.

Fritts HC, Guiot J, Gordon GA, Schweingruber F. 1990. Methods of calibration, verification, and reconstruction. In *Methods of Dendrochronology: Applications in the Environmental Sciences*, Cook ER, Kairiukstis LA (eds). Kluwer Academic Publishers: Boston; 163–217.

Gershunov A, Barnett TP. 1998. Interdecadal modulation of ENSO teleconnections. *Bulletin of the American Meteorological Society* **79**: 2715–2725.

Grissino-Mayer HD. 1996. A 2129-year reconstruction of precipitation for northwestern New Mexico, USA. In *Tree Rings, Environment, and Humanity. Radiocarbon* Dean JS, Meko DM, Swetnam TW (eds). Department of Geosciences, The University of Arizona: Tucson, Arizona; 191–204.

Gutzler DS. 2005. New Mexico's changing climate. *Natural Resources Journal* **45**: 277–282.

Hoerling MP, Kumar A. 2003. The perfect ocean for drought. *Science* **299**: 691–694.

Kalnay E, Kanarmitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Leetmaa A, Reynolds R, Jenne R, Joseph D. 1996. The NCEP/NCAR reanalysis 40-year project. *Bulletin of the American Meteorological Society* **77**(3): 437–471.

Kiladis GN, Diaz HF. 1989. Global climatic anomalies associated with extremes in the Southern Oscillation. *Journal of Climate* **2**: 1069–1090.

Lenart M. 2005. Will the drought continue? Southwest Climate Outlook, March 2005. Climate Assessment for the Southwest, University of Arizona, cited 2008, http://www.climas.arizona.edu/forecasts/articles/wetspell_March2005.pdf.

Mallows CL. 1973. Some comments on Cp. *Technometrics* **15**: 661–675.

Manthe GT. 1977. Afloristic analysis of the Sevilleta Wildlife Refuge and the Ladron Mountains. M.A. thesis, University of New Mexico, Albuquerque.

Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* **78**: 1069–1079.

Mann ME, Zhang Z, Hughes MK, Bradley RS, Miller SK, Rutherford S, Ni F. 2008. Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proc Natl Acad Sci* **105**: 13252–13257, DOI:10.1073/pnas.0805721105.

Meko DM. 1997. Dendroclimatic reconstruction with time varying subsets of tree ring indices. *Journal of Climate* **10**: 687–696.

Meko DM, Graybill DA. 1995. Tree-ring reconstruction of Upper Gila River discharge. *Water Resources Bulletin* **31**(4): 605–616.

Meko DM, Therrell MD, Baisan CH, Hughes MK. 2001. Sacramento River flow reconstructed to A.D. 869 from tree rings. *Journal of the American Water Resources Association* **37**(4): 1029–1040.

Mitchell JM Jr., Dzerdzeevskii B, Flohn H, Hofmeyr WL, Lamb HH, Rao KN, Wallen CC. 1966. *Climatic change*, Technical Note 79, World Meteorological Organization: Geneva.

Ni FB, Cavazos T, Hughes MK, Comrie AC, Funkhouser G. 2002. Cool-season precipitation in the southwestern USA since AD 1000: Comparison of linear and nonlinear techniques for reconstruction. *International Journal of Climatology* **22**(13): 1645–1662.

Nyhan JW, Hackerk LW, Calhoun TE, Young DL. 1978. Soil survey of Los Alamos County, New Mexico. Informal Report LA-6779-MS, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 102pp.

Rose MR, Dean JS, Robinson WJ. 1982. *The Past Climate of Arroyo Hondo New Mexico Reconstructed from Tree Rings*. School of American Research Press: Santa Fe.

Salzer MW, Kipfmueller KF. 2005. Reconstructed temperature and precipitation on a millennial timescale from tree-rings in the southern Colorado Plateau. *Climatic Change* **70**: 465–487.

Sheppard PR, Comrie AC, Packin GD, Angersbach K, Hughes MK. 2002. The climate of the US Southwest. *Climate Research* **21**: 219–238.

Slack JR, Lumb AM, Landwehr JM. 1988. Hydro-climatic data network (HCDN): streamflow data set, 1874–1988, USGS Water-Resources Investigations Report 93-4076 (U.S. Government Printing Office).

Smith RL, Bailey RA, Ross CS. 1976. Geological map of the Jemez Mountains, New Mexico. Misc. Geol. Invest. Map I-571, U.S. Geological Survey, Denver, Colorado.

Smith CA, Sardeshmukh P. 2000. The effect of ENSO on the intraseasonal variance of surface temperature in winter. *International Journal of Climatology* **20**: 1543–1557.

Smith LP, Stockton CW. 1981. Reconstructed streamflow for the Salt and Verde Rivers from tree-ring data. *Water Resources Bulletin* **17**(6): 939–947.

Smith TM, Reynolds RW, Peterson TC, Lawrimore J. 2008. Improvements to NOAA's Historical Merged Land-Ocean Surface Temperature Analysis (1880–2006). *Journal of Climate* **21**: 2283–2296.

Snee RD. 1977. Validation of regression models: methods and examples. *Technometrics* **19**: 415–428.

Stokes MA, Smiley TL. 1968. *An Introduction to Tree-Ring Dating*. The university of Arizona: Tucson, Arizona; 73.

Swetnam TW. 1985. Using dendrochronology to measure radial growth of defoliated trees. USDA Forest Service, Cooperative State Research Service. Agriculture Handbook No. 639.

Swetnam TW, Lynch AM. 1993. Multicentury, regional-scale patterns of western spruce budworm outbreaks. *Ecological Monographs* **63**: 399–424.

Swetnam TW, Allen CD, Betancourt JL. 1999. Applied historical ecology: using the past to manage for the future. *Ecological Applications* **9**: 1189–1206.

Thomas HE. 1963. Drought in the Southwest, 1942–1956: general summary of effects of the drought in the Southwest. U.S. Geological Survey Professional Paper-372-H, Washington, D.C.

Touchan R, Swetnam TW. 1995. Fire history in ponderosa pine and mixed-conifer forests of the Jemez Mountains, northern New Mexico: a final report submitted to the USDA Forest Service and, Santa Fe National Forest and USDI National Park Service, Bandelier National Monument.

Touchan R, Meko DM, Hughes MK. 1999. A 396-year reconstruction of precipitation in southern Jordan. *Journal of the American Water resources Association* **35**(1): 45–55.

Touchan R, Garfin GM, Meko DM, Funkhouser G, Erkan N, Hughes MK, Wallin BS. 2003. Preliminary reconstructions of spring precipitation in southwestern Turkey from tree-ring width. *International Journal of Climatology* **23**: 157–171.

Touchan R, Funkhouser G, Hughes MK, Erkan N. 2005a. Standardized precipitation indices reconstructed from Turkish tree-ring widths. *Climatic Change* **72**(3): 339–353.

Touchan R, Xoplaki E, Funkhouser G, Luterbacher J, Hughes MK, Erkan N, Akkemik Ü, Stephan J. 2005b. Dendroclimatology and large-scale circulation influences in the eastern Mediterranean and Near East region. *Climate Dynamics* **25**: 75–98.

Touchan R, Anchukaitis KJ, Meko DM, Attalah S, Baisan C, Aloui A. 2008. The long term context for recent drought in northwestern Africa. *Geophysical Research Letters* **35**: L13705, DOI: 10.1029/2008GL034264.

Towner Ronald H. 2003. *Defending the Dinetah*. University of Utah Press, Salt Lake City, UT.

Tuan Yi-Fu, Everad CE, Widdison JG, Bennett I. 1973. *The Climate of New Mexico*. State Planning Office: Santa Fe.

USGS. Cited2009. Surface Water for the Nation. http://waterdata.usgs.gov/nwis/sw.

Weisberg R. 1985. *Applied Linear Regression*. John Wiley and Sons: New York.

Wigley TML, Briffa KR, Jones PD. 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Climate and Applied Meteorology* **23**: 201–213.

Xue Y, Smith TM, Reynolds RW. 2003. Interdecadal changes of 30-yr SST normals during 1871–2000. *Journal of Climate* **16**: 1601–1612.

