RECONSTRUCTED TEMPERATURE AND PRECIPITATION ON A MILLENNIAL TIMESCALE FROM TREE-RINGS IN THE SOUTHERN COLORADO PLATEAU, U.S.A.

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Abstract. Two independent calibrated and verified climate reconstructions from ecologically contrasting tree-ring sites in the southern Colorado Plateau, U.S.A. reveal decadal-scale climatic trends during the past two millennia. Combining precisely dated annual mean-maximum temperature and October through July precipitation reconstructions yields an unparalleled record of climatic variability. The approach allows for the identification of thirty extreme wet periods and thirty-five extreme dry periods in the 1,425-year precipitation reconstruction and 30 extreme cool periods and 26 extreme warm periods in 2,262-year temperature reconstruction. In addition, the reconstructions were integrated to identify intervals when conditions were extreme in both climatic variables (cool/dry, cool/wet, warm/dry, warm/wet). Noteworthy in the reconstructions are the post-1976 warm/wet period, unprecedented in the 1,425-year record both in amplitude and duration, anomalous and prolonged late 20th century warmth, that while never exceeded, was nearly equaled in magnitude for brief intervals in the past, and substantial decadal-scale variability within the Medieval Warm Period and Little Ice Age intervals.

1. Introduction

Conditions in the natural environment, which change over time, establish limits on human societies and other biotic communities. There is increasing evidence that the climate is now changing, and has changed rapidly in the past, and that such abrupt shifts could significantly impact human society. Paleoclimatic proxies with interannual resolution and spanning centuries to millennia are necessary to define natural climate variability and thus help discriminate ongoing anthropogenic effects on climate. This study examines two long proxy records of climate, a precipitation reconstruction and a temperature reconstruction developed from tree rings on the southern Colorado Plateau.

High-resolution millennial-length paleoclimatic reconstructions are relatively rare. Most paleoclimatic research of this nature generates a single reconstructed climatic variable. Reconstructions of both precipitation and temperature from a single region, on the other hand, allow more complete inferences about past and present climate, and so enable a better understanding of recent climatic trends in the context of the late Holocene. We developed two independent time-series of climatic reconstructions from tree-ring chronologies that have distinctive climatic sensitivities.

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We examine changes in both variables on a millennial timescale using these tree-ring-based, annually dated, calibrated, and verified temperature and precipitation reconstructions from the southern Colorado Plateau. In the Sierra Nevada, Graumlich (1993) used a nonlinear response surface technique to reconstruct both temperature and precipitation. Here, we apply an approach similar to that of LaMarche (1974) and Graybill and Funkhouser (1999) that makes use of tree-ring data from different elevations to reconstruct and integrate time series of temperature and precipitation.

Blending of temperature and precipitation histories allows evaluation of their physical interaction on multiple spatiotemporal scales. For example, it is hypothesized from first principles and observed in instrumental data that soil moisture and cloud cover inversely affect local and regional temperatures. However, there may be important and telling cases where this does not hold true. For example, under certain circumstances a warming trend could be associated with wetter, and not drier, conditions. Rather than local sensible heat, the warming could be imbedded in continental, hemispheric, or global-scale processes. In such cases, independent temperature and precipitation reconstructions from the same region might be useful to sort out anomalous warming or cooling events over the last 1,470 years that are not associated with regional precipitation variability; these events might then be linked to extraregional processes. In addition, such anomalous periods of warm-wet and cool-dry could have far-reaching biological effects and interesting consequences for regional ecosystems.

2. Data and Methods

2.1. ECOLOGICAL MODEL

Climatically responsive trees useful in dendroclimatology contain quantifiable variables (e.g., ring-width) that are the result of internal tree processes directly or indirectly limited by climatic factors. It follows that the most responsive trees are found near distributional edges and ecotonal boundaries, where climatic factors are most limiting. Hence, boundary areas, such as the lower forest border and subalpine treeline, are ideal for developing tree-ring chronologies at both the cold and arid limits of trees (Figure 1). On the southern Colorado Plateau, lower elevation pines (*Pinus ponderosa* and *Pinus edulis*) and Douglas-fir (*Pseudotsuga menziesii*) provide information on past precipitation, while high elevation Bristlecone Pine (*Pinus aristata*) renders details about prior temperatures. Through a comparison of these two growth records, paleoclimatic insight unobtainable from either record alone is generated, allowing an integrated view of temperature and precipitation variations.

2.2. TREE-RING AND CLIMATE DATA

Three lower forest border tree-ring chronologies were used in the precipitation reconstruction (Figure 2). Through the process of crossdating, measured ring-width

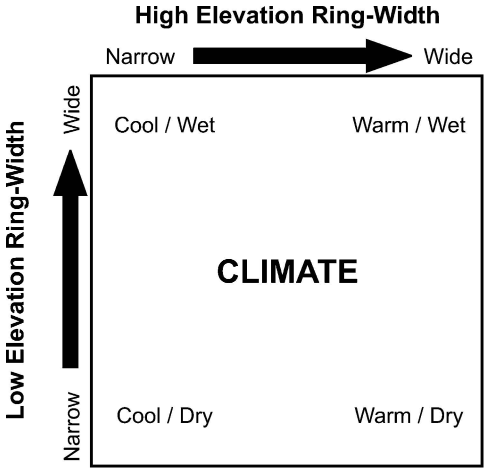

Figure 1. Ecological model of climate and tree-growth emphasizes growth responses to different climatic variables at differing elevations.

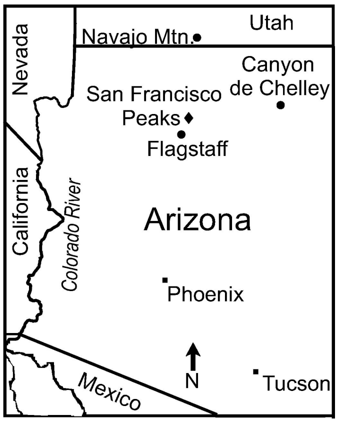

Figure 2. Map of Arizona and adjoining states showing location of the tree-ring site(s) used in the temperature (diamond) and precipitation (circle) reconstructions.

series of construction timbers from archaeological sites are appended to the earlier portions of measured series from living trees at the three sites to substantially lengthen the records. The chronologies are derived from ponderosa pine (*P. ponderosa*), piñon (*P. edulis*), and Douglas-fir (*P. menziesii*) from elevations of approximately 1,890–2,290 m in northern Arizona (Flagstaff and Canyon de Chelly) and southern Utah (Navajo Mountain). They were originally developed as part of the Southwest Paleoclimate Project (Dean and Robinson, 1978) and are on file at the Laboratory of Tree-Ring Research at the University of Arizona. The precipitation reconstruction calibration uses climate data from NOAA Climate Division Two (Northeast) for Arizona over the period 1896–1988.

To build a tree-ring chronology that reflects past temperature variability, upper-treeline Bristlecone Pine (*P. aristata*), whose ring-width variability is a function of temperature, were sampled at timberline in the San Francisco Peaks (~3,536 m), where temperature is most limiting to growth (Figure 2). Increment core and sawed samples were collected from living and dead Bristlecone Pine on both Agassiz Peak and Humphreys Peak. Long chronologies were constructed by crossdating the deadwood samples with the living tree specimens. Prior to AD 659 the chronology is composed entirely from deadwood material. The individual growth rings of each sample were measured to the nearest 0.01 mm. The measured series were converted to standardized tree-ring indices by fitting a modified negative exponential curve, a straight line, or a negatively sloped line to the series. This process removes the age/size related growth trend and transforms the ring-width measurement values into ring-width index values for each individual ring in each series (Fritts, 1976). Several statistics were calculated to gauge the reliability of the tree-ring series (Cook and Kairiukstis, 1990; Wigley et al., 1984) (Table I).

Through conservative standardization techniques and the use of relatively long series, care was taken to preserve low-frequency information in the chronology

TABLE I

Chronology statistics for tree-ring chronologies used in Northern Arizona climate reconstructions

Chronology[a]	Precipitation sensitive chronologies CDC	NAV	FLA	Temp. Sens. SFP
Species[b]	PIED/PIPO/PSME	PIED	PIPO	PIAR
Timespan	1–1990	340–1989	570–1987	−663–1997
Number of trees (radii)	54 (120)	22 (54)	31 (65)	139 (233)
Mean length of series	238	308	238	384
Mean series intercorrelation	0.76	0.83	0.78	0.54
Mean sensitivity	0.46	0.64	0.45	0.22
EPS[c]	0.94	0.95	0.92	0.92
First order autocorrelation	0.33	0.20	0.42	0.71
Signal/noise ratio	15.57	19.65	10.91	10.70
% Variance in 1^{st} PC	48	70	57	38
First year SSS[d] > 0.85 (trees)	465 (7)	402 (2)	769 (4)	167 (13)

[a] Chronologies: CDC: Canyon de Chelly; NAV: Navajo Mtn.; FLA: Flagstaff; SFP: San Francisco Peaks.

[b] Species: PIED: *Pinus edulis*; PIPO: *Pinus ponderosa*; PSME: Pseudotsuga menziesii; PIAR: *Pinus aristata*.

[c] EPS: Expressed population signal.

[d] SSS: Subsample signal strength.

(Cook et al., 1995). A regional curve standardization (RCS) approach (Briffa et al. 1992a), which has been used in some dendroclimatic studies to resolve multidecadal to centennial trends, was considered but rejected. In general, RCS was devised for chronologies built from short series that use heavy detrending. The SFP chronology was built from relatively long segment lengths (Table I) and a conservative standardization process was employed. Additionally, we could not meet the necessary assumptions critical to successfully applying this technique: it was impossible to ascertain pith or near-pith dates from the deadwood material due to the irregular growth form of Bristlecone Pine, and we are not able to demonstrate that the age structure of the samples are evenly distributed.

To create the mean site chronology, the annual standardized indices of tree growth were averaged. A single chronology was developed from samples collected at two sites on Humphreys Peak and one site on Agassiz Peak. The SFP chronology extends from 663 BC–AD 1997. In total, 234 series (130 trees) are used. The period before 266 BC is considered less reliable than the rest of the chronology as six or fewer series cover this interval. The climate data used in the temperature reconstruction calibration are from the Fort Valley Experimental Research Station, which is part of the United States Historical Climatology Network. The station data, from an elevation of 2,239 m and approximately 4.5 km from the high elevation SFP tree-ring sites, span the period 1909–1994.

2.3. BIOLOGICAL MODEL

Correlation and response function analyses were used to investigate the climate–tree growth relationship with the lower elevation tree-ring chronologies and the precipitation data. Growth processes of lower elevation trees in the American Southwest often are limited by climatic conditions during a period before the actual growing season (Fritts, 1976). Ring-width variability can reflect changes in precipitation amounts from the fall/winter seasons prior to the trees' growing season through the growing season of ring formation. The period from the previous October through July of the growing season was determined to be the interval when precipitation had the greatest effect on tree growth. Monthly values for this period were summed for the individual years to create the final climate series used in the reconstruction. Consequently, one variable being reconstructed is prior October through current July precipitation.

Correlation and response function analysis shows that the high elevation SFP tree-ring chronology correlated most significantly with monthly mean-maximum temperatures. The results of several physiological experiments with upper treeline pines (Tranquillini, 1964; Schulze et al., 1967; Mooney et al., 1966) suggest that net photosynthesis at upper treeline is most influenced by the length of the warm season and daily maximum temperatures. While the growth response to temperature of these upper-treeline Bristlecone Pines is complex, two points are clear: first, the most significant and easily understood climate/tree-growth relationship is increased growth with increased daytime (maximum) temperatures, and second, the most important effect of temperature on growth is not immediate. The strongest statistical relationship between mean-maximum temperature and the tree-ring chronology occurred during the year prior to the year of growth. Other Bristlecone Pine studies (Fritts, 1969; LaMarche, 1973; LaMarche and Stockton, 1974) have suggested that growth, especially radial growth of the stem, depends on reserves of stored food produced during earlier periods. On the San Francisco Peaks, the period from January through December prior to the growth year is the interval when mean-maximum temperatures (daytime highs) had the most significant effect upon tree growth. Monthly mean-maximum values for this period were averaged for the years 1909–1994 to create the final climate series used in the reconstruction. Accordingly, the variable being reconstructed is annual mean-maximum temperature. This variable can be considered a general measure of how warm it gets during the daytimes of a given year.

2.4. STATISTICAL MODEL

For the precipitation reconstruction, the October through July precipitation climate series was log-transformed prior to the calibration. This procedure results in the climate data being more normally distributed and more linearly related to the tree-ring data. A stepwise multiple linear regression model was developed using the "standard" (Cook 1985) tree-ring chronologies from Flagstaff, Navajo Mountain, and Canyon de Chelly. The pool of potential predictors includes nine variables: the three chronologies lagged -1, 0, and $+1$ years from the precipitation year (previous October–July). Predictors were allowed to enter the model stepwise in order of importance until R^2 reached a maximum and root-mean-square-error (RMSE) a minimum. Three predictors were used in the final model: The three chronologies at lag 0. The inclusion of additional predictors beyond these three does not increase calibration R^2 or decrease RMSE substantially, indicating that predictors four through nine do not improve the quality of the reconstruction.

Validation was done using the predicted residual sum of squares (PRESS) method (Weisberg, 1985). Crossvalidation statistics indicate a successful reconstruction. The validation reduction of error statistic (RE), which is analogous to calibration R^2, is 0.71. Any positive value of this statistic indicates that the model does a better predictive job than the calibration period mean. Also indicative of a good reconstruction, the validation RMSE remains low and does not differ much from the calibration RMSE in this three-predictor model. Analysis of residuals does not indicate any violations of model assumptions. The residuals are independent of both predictor and predictand values. They are essentially normally distributed and show no apparent trends. The Durbin-Watson statistic demonstrates acceptable autocorrelation in the residuals. The regression model explains 74% of

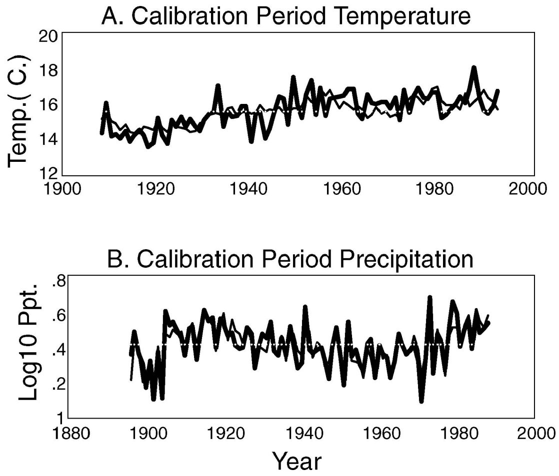

Figure 3. Comparison of observed instrumental climate data (thick line) and regression based values predicted by the tree-ring chronologies (thin line). (A) Calibration between the upper elevation Bristlecone Pine tree-ring chronology (year 1) and maximum annual temperature (year -1) for the period 1909–1994 (calibration $r^2 = 0.46$, validation RE = 0.42). (B) Calibration between low elevation pine tree-ring chronologies (year1) and October (year -1) to July (year 1) log10 precipitation for the period 1896–1988 (calibration $r^2 = 0.74$, validation RE = 0.71).

the variance in the precipitation with a calibration period of 1896–1988 (Table II) (Figure 3B).

A similar approach was taken to create a quantitative temperature reconstruction, but with only one tree-ring chronology as a predictor. The modern part of the SFP tree-ring chronology was compared to the instrumental mean-maximum temperature data, and a linear regression equation was generated from the period of overlap that retrodicts past temperatures for the period corresponding to the length of the tree-ring "standard" (Cook, 1985) chronology. Because these trees respond to climate over a period extending into the previous growing season, the temperature variability was statistically modeled using linear regression and a lagged relationship where mean-maximum annual temperature at *year* $(t - 1)$ can be reconstructed from tree-ring index at *year* (t). A simple linear regression was used with a single predictor and no log-transforms.

The SFP chronology explains 46% of the variance in the temperature data over the 1909–1994-calibration period (Figure 3A). This compares favorably with some other tree-ring based temperature reconstructions (Briffa et al., 1990, 1992b, 1994; Graumlich, 1993; Jacoby and D'Arrigo, 1989; Jacoby et al., 1985; Lara and Villalba, 1993; Luckman et al., 1997; Scuderi, 1993). As with the precipitation reconstruction, validation was done with the PRESS (Weisberg, 1985) method, crossvalidation statistics indicate a successful reconstruction, and residual analysis does not indicate any violations of model assumptions. The validation RE is 0.42 (Table II).

TABLE II
Results of the regression models and calibration/verification statistics

Prior October–July precipitation			Maximum average annual temperature		
Variable	Estimate	99% confidence Interval	Variable	Estimate	Interval
Regression equation parameters					
Constant	1.13	1.06–1.19	Constant	12.96	12.09–13.83
Navajo Mountain	118.63	24.96–212.95	San Francisco Peaks	2.25	1.55–2.96
Flagstaff	83.75	17.91–149.59			
Canyon De Chelly	97.23	41.19–153.27			
Regression statistics					
Model R^2	0.74		Model R^2	0.46	
Std. Error est.	0.07		Std. Error est.	0.75	
F-Statistic	83.7 ($p < 0.000$)		F-Statistic	71.2 ($p < 0.000$)	
RE	0.71		RE	0.42	
Durbin Watson D	1.58		Durbin Watson D	1.64	
Calibration/verification statistics					
$\text{RMSE}_{\text{calibration}}$	0.07		$\text{RMSE}_{\text{calibration}}$	0.75	
$\text{RMSE}_{\text{verification}}$	0.07		$\text{RMSE}_{\text{verification}}$	0.76	
Product means test	6.41 ($p < 0.000$)		Product means test	2.89 ($p < 0.01$)	

From the precipitation reconstruction calibration (Figure 3B), it is apparent that the tree-ring chronologies successfully simulated both high-frequency and low-frequency trends in the precipitation data. The temperature reconstruction calibration (Figure 3A), however, demonstrates that the high elevation bristlecone tree-ring chronology is only able to capture the decadal and multi-decadal scale variability in temperature. This may be partly a result of autocorrelation in high-elevation Bristlecone Pines due to multi-year needle retention. The temperature signal contained in the ring-widths is, in effect, naturally smoothed by needle retention acting like a biologically imposed low-pass filter. The decadal-scale signal from these trees is consistent with the work of others (Graumlich, 1993; LaMarche, 1974; LaMarche and Stockton, 1974; Scuderi, 1993) and suggests that while the total amount of interannual temperature variance explained by the tree-ring chronology is only 46%, the low-frequency decadal scale swings in temperature are sufficiently well mimicked by the tree-ring chronology (Figure 3A). Time-series plots of the climate reconstructions are presented in Figure 4.

2.5. IDENTIFYING EXTREME CLIMATIC INTERVALS

In this study, decadal scale variability is emphasized for two reasons. First, while the SFP temperature reconstruction is an annual estimate, the reconstruction is most

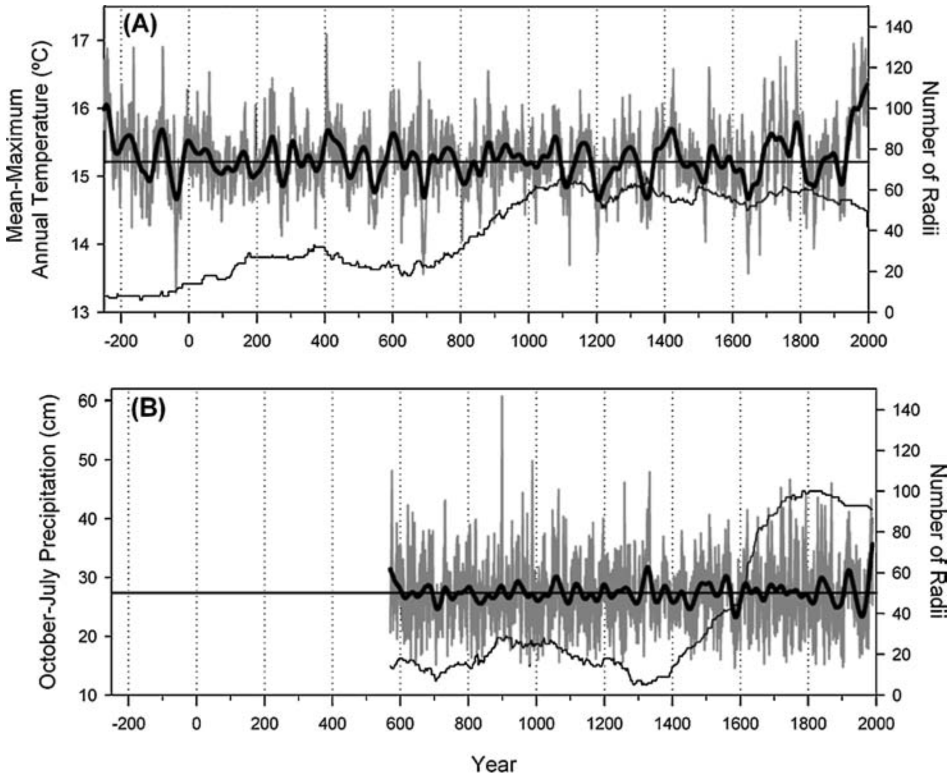

Figure 4. Time-series plots of the southern Colorado Plateau tree-ring based climate reconstructions. (A) Reconstructed mean-maximum annual temperature from 250 BC to 1997. (B) Reconstructed October–July precipitation from AD 570–1994. The gray lines are the annual estimates. The heavy smooth lines are the reconstructions smoothed with a 50-year spline. The thin black lines represent the sample depths of the tree-ring chronologies (number of radii) through time.

reliable in the lower frequencies. It is apparent that much of the temperature variability captured by the SFP tree-ring chronology is approximately at the decadal scale. Analyses and explanations based on year-to-year change are not as well grounded in the data, as are investigations of relatively warm and relatively cool intervals. For this reason, greater emphasis is placed on the lower-frequency component of the temperature reconstruction. Periods, rather than years, that deviate from the mean are more intrinsic within the data set, and interpretations based on such are more accurate and therefore more meaningful. Second, numerous studies have documented that climatic variability on decadal scales in both the instrumental records (Cayan et al., 1998; Dettinger et al.,1998) and tree-ring records (Fritts, 1991; Grissino-Mayer, 1995; Gray et al., 2003) exists in the region. Thus, we are confident that the tree-ring decadal changes are valid.

Changes in mean climate are evident in groups of years when past reconstructed temperatures and reconstructed precipitation differed from their respective long-term means. To identify climatic periods that were well above or below the long-term mean, a 10-year smoothing spline (Cook and Peters, 1981) was fit to the reconstructed temperature and precipitation time series. The original and spline reconstructed values were converted to standard deviation units, or Z scores (Johnson, 1994). This technique quantifies the deviations from the long-term average. Using the spline data, periods were identified that diverged from mean conditions by at least 1.1 SD. This reference point was proposed by Dean (1988) to determine climate episodes potentially significant to the physical environment and to human populations. The beginning and ending years of the extreme climatic periods were defined using the nonsmoothed data because spline values are influenced by preceding (past) and following (future) data. The minimum length for periods was established at five years. The beginning year for an extreme period was determined as that point when the original reconstructed value first substantially deviated from mean conditions (<-0.5 SD or >0.5 SD). The ending year for periods was defined as that point when average conditions (>-0.5 SD and <0.5 SD) returned for more than two consecutive years or when conditions substantially deviated (<-1.0 SD and >1.0 SD) in the other direction for more than a single year. During each extreme period, the smoothed reconstructed values deviate from the long-term average by at least 1.1 SD for at least one year.

3. Deviations from Mean Conditions

Thirty-five extreme-dry periods and 30 extreme-wet periods (Table III) were identified in the 1,425-year precipitation reconstruction. Wet and dry periods range from five to twenty-six years in length. The driest interval was the six-year period from 1818 to 1823; the wettest was the 5-year period from 985 to 989. The longest drought is twenty-six years, from 699 to 724. The 1905–1922 eighteen-year period is the longest wet interval in the precipitation reconstruction. Many of the wet and dry periods in Table III correspond temporally with dry and wet conditions elsewhere in the Southwest. Twenty-two of the 35 dry periods (63%), including 11 of the top 12, and 19 of the 30 wet periods (63%) overlap with similar severe short-term droughts and short-term wet periods described by Grissino-Mayer (1995) for west-central New Mexico. This suggests that these episodes, especially the most severe droughts, are often regional rather than local phenomena.

In the analysis of the temperature data, the 663–267 BC portion was omitted from the examination due to low sample size during this early part of the tree-ring chronology. Thirty extremely cool and 26 extremely warm intervals were identified between 266 BC and AD 1996 (Table IV). The intervals range from five to 49 years. The coldest period identified was an eighteen year interval from AD 683–700. The longest cool period was the 35 years from 1330 to 1364. The late 20th century 49-year period from 1946 to 1996 is the warmest period identified and also the

TABLE III

Short-term ($\geq$5 years and $\leq$50 years) anomalous wet and dry periods in the reconstructed precipitation record

Wet periods	Anomaly	Rank	Dry periods	Anomaly
985–989	+2.15	1	1818–1823	−1.25
1325–1334[a]	+1.79	2	920–924[a]	−1.13
1743–1747	+1.61	3	1751–1757[a]	−1.06
572–577[a]	+1.53	4	1666–1672[a]	−1.04
1865–1869[a]	+1.44	5	660–664[a]	−1.04
1060–1066[a]	+1.42	6	1360–1364[a]	−0.99
1978–1988[a]	+1.26	7	1893–1904[a]	−0.96
1833–1840[a]	+1.23	8	1292–1300[a]	−0.93
1615–1622	+1.14	9	1777–1783[a]	−0.87
1718–1727	+1.05	10	1571–1593[a]	−0.85
1564–1570	+1.05	11	1090–1101[a]	−0.82
798–805[a]	+1.03	12	975–984[a]	−0.80
727–736[a]	+1.00	13	1623–1628	−0.79
1905–1922[a]	+0.99	14	1870–1883	−0.77
940–950	+0.91	15	1943–1947	−0.76
1687–1695[a]	+0.90	16	1857–1861	−0.75
636–642[a]	+0.84	17	823–832	−0.74
1427–1434	+0.83	18	877–884	−0.74
1482–1486	+0.81	19	1215–1221[a]	−0.73
1549–1560[a]	+0.78	20	1542–1548	−0.72
959–965[a]	+0.78	21	611–620	−0.72
1109–1119[a]	+0.74	22	750–757[a]	−0.72
1504–1515	+0.74	23	1953–1972[a]	−0.70
1192–1210[a]	+0.73	24	1389–1393	−0.68
1049–1056[a]	+0.71	25	1455–1464[a]	−0.68
688–695	+0.70	26	847–851	−0.68
1159–1167[a]	+0.68	27	1435–1450[a]	−0.66
1378–1385[a]	+0.66	28	699–724[a]	−0.65
1640–1647[a]	+0.66	29	951–957	−0.65
1760–1771	+0.55	30	991–1005[a]	−0.64
		31	1728–1742[a]	−0.64
		32	900–910[a]	−0.56
		33	1182–1191	−0.52
		34	1033–1046[a]	−0.46
		35	1144–1154[a]	−0.35

[a] Part or all of interval also present in west-central New Mexico (Grissino-Mayer 1995).

Anomalies expressed as average Z score during period. Z values computed by subtracting long-term (AD 570–1994) mean and dividing by standard deviation.

TABLE IV

Short-term (≥5 years and ≤50 years) anomalous cool and warm periods in the reconstructed temperature record

Cool periods	Anomaly	Rank	Warm periods	Anomaly
683–700	−1.96	1	1946–1994	+1.99
1636–1653	−1.83	2	402–410	+1.91
1911–1930	−1.46	3	1529–1534	+1.65
43–22 BC	−1.44	4	1708–1721	+1.49
1195–1219	−1.38	5	1736–1744	+1.48
534–553	−1.34	6	266–228 BC	+1.46
268–279	−1.34	7	1753–1761	+1.34
1330–1364	−1.27	8	238–252	+1.34
122–108 BC	−1.25	9	299–311	+1.29
897–902	−1.25	10	1777–1801	+1.24
1512–1527	−1.22	11	201–194 BC	+1.24
846–859	−1.15	12	89–73 BC	+1.21
1810–1825	−1.13	13	1688–1698	+1.16
1763–1771	−1.12	14	840–845	+1.05
987–991	−1.00	15	673–682	+1.01
1835–1854	−1.00	16	1586–1593	+1.00
1094–1120	−0.98	17	347–352	+0.99
1661–1683	−0.98	18	591–609	+0.98
804–824	−0.96	19	878–893	+0.86
144–134 BC	−0.94	20	190–163 BC	+0.83
663–669	−0.93	21	1146–1155	+0.82
1599–1612	−0.90	22	706–717	+0.82
94–103	−0.88	23	1067–1091	+0.81
230–235	−0.88	24	1390–1443	+0.80
177–194	−0.87	25	16–2 BC	+0.77
729–736	−0.85	26	1367–1380	+0.72
1258–1271	−0.84	27		
1225–1245	−0.75	28		
470–486	−0.75	29		
368–381	−0.66	30		

Anomalies expressed as average Z score during period. Z values computed by subtracting long-term (265 BC – AD 1996) mean and dividing by standard deviation.

TABLE V

Reconstructed cool and warm intervals from three other published millennial-length temperature reconstructions; the associated overlapping extreme periods in the SFP reconstruction are in parentheses

	COOL	(SFP)	WARM	(SFP)
Scuderi (1993)	172–194	(177–194)	408–427	(402–410)
Sierra Nevada	542–561	(534–553)	1439–1458	(1390–1443)
2000 years	800–819	(804–824)	1786–1805	(1777–1801)
	1817–1836	(1810–1825)		
Graumlich (1993)	1604–1623	(1599–1612)	1150–1169	(1146–1155)
Sierra Nevada	1628–1647	(1636–1653)	1354–1373	(1367–1380)
1000 years	1751–1770	(1763–1771)		
Briffa et al. (1990)	795–814	(804–824)		
Fennoscandia	848–867	(846–859)		
1400 Years	1344–1363	(1330–1364)		
	1601–1620	(1599–1612)		

warm interval with the longest duration. While trees at some temperature-sensitive sites in the high northern latitudes are now showing declines in growth (Barber et al., 2000; Kipfmueller, 2003; Vaganov et al., 1999), it is extremely rare in this reconstruction for temperatures to approach 20th century levels. There was a 54-year warm interval from 1390 to 1443, but only during brief intervals in the 200s BC, the early AD 400s, the mid 1500s, and the 1700s did warmth rival 20th century levels.

Although there are no other millennial length temperature reconstructions from the Colorado Plateau to compare to the record of extreme warm and extreme cool intervals, a comparison with two long tree-ring based reconstructions from the Sierra Nevada of California is possible. Scuderi (1993) listed the six coldest and six warmest twenty year periods between AD 1 and 1980; four of the six coldest and three of the six warmest overlap with extreme periods in the SFP reconstruction (Table V). Similarly, Graumlich (1993) identified five extremely cold and five extremely warm twenty year intervals between AD 800 and 1988; three of the five coldest and two of the five warmest overlap with like extreme periods in the SFP reconstruction. Expanding the comparison spatially, Briffa et al. (1990) identified five extreme cold and extreme warm twenty year intervals between AD 500 and 1990 for northern Fennoscandia. Four of the five coldest substantially overlap with contemporaneous extreme cool periods in the SFP reconstruction, suggesting that these events, particularly the coldest intervals, are hemispheric in scale (Table V).

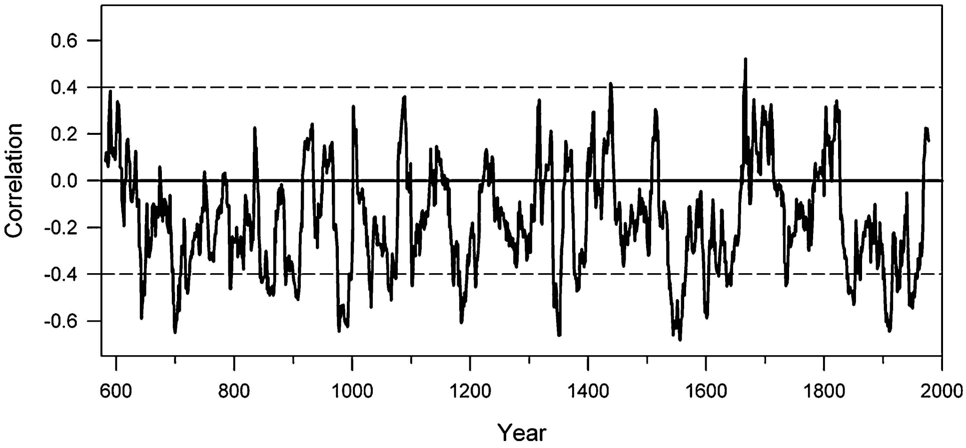

Figure 5. Twenty-five-year running correlation between the southern Colorado Plateau temperature and precipitation reconstructions from AD 570 to 1994. The correlations are for 25-year intervals plotted on the center year and moving in one-year increments. Dashed lines indicate 95% confidence interval.

4. Cool/Dry, Cool/Wet, Warm/Dry, and Warm/Wet Intervals

Temperature and precipitation are usually out-of-phase in the American Southwest. Due to cloud cover and sensible heat effects, when it is dry it is usually warm and when it is wet it is usually cool. In fact, the temperature and precipitation meteorological data used to generate the two reconstructions has a correlation of -0.41 ($p < 0.001$), while the two reconstructions have a correlation of -0.16 ($p < 0.001$) The correlation of the reconstructions, while still significant, is lower than the correlation of the meteorological station data due to the large number of observations in the common interval (570–1989) and to the inherent noise in the tree-ring chronologies. The correlation of the smoothed reconstructions is -0.21 over the 570–1989 period. When integrating the reconstructions however, it became clear that the two reconstructed variables are not always behaving oppositely. A plot of 25-year running correlation coefficients (Figure 5) demonstrates that, while the two time series are predominately out-of-phase at this timescale, with repeated episodes of high negative correlations, departures from this scheme (positive correlations) do occur when it is warm/wet and when it is cool/dry.

We smoothed both reconstructions and superimposed them on each other (Figure 6). We then compared the wet, dry, warm, and cool periods determined above and intervals of overlap were identified, when conditions were extreme in both climate variables: cool/dry, cool/wet, warm/dry, or warm/wet (Table VI). For these analyses only the period during which the chronologies overlap, AD 570–1988, is considered. In total, 40 intervals greater than one year were identified in the 1,425-year period of record, including ten cool/dry, eleven cool/wet, twelve

TABLE VI
Cool/dry, Cool/wet, Warm/dry, and Warm/wet intervals from AD 570 to 1994

Cool/dry	Cool/wet	Warm/dry	Warm/wet
663–664	688–695	706–717	1378–1380
699–700	729–736	878–884	1427–1434
823–824	804–805	1090–1091	1688–1695
847–851	987–989	1146–1154	1718–1721
900–902	1195–1204	1390–1393	1743–1744
1094–1101	1330–1334	1435–1443	1760–1761
1215–1219	1512–1515	1586–1593	1978–1988
1360–1364	1640–1647	1736–1742	
1666–1672	1763–1771	1753–1757	
1818–1823	1835–1840	1777–1783	
	1911–1922	1946–1947	
		1953–1972	

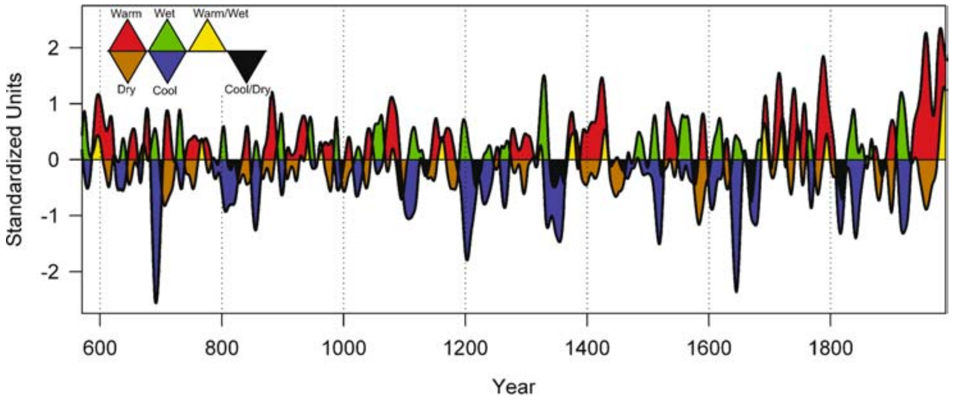

Figure 6. The southern Colorado Plateau annual mean-maximum temperature and July–October precipitation reconstructions. The time period is A.D. 570–1994, inclusive. For comparative purposes, the time series were transformed to standardized units and smoothed using a 20-year cubic smoothing spline to emphasize decadal-scale or greater variability.

warm/dry, and seven warm/wet periods. The intervals range from two to twenty years, with the average duration for cool/dry and warm/wet periods five years, and the duration for cool/wet and warm/dry intervals seven and eight years, respectively.

As there has not been a cool/dry period since the 1818–1823 interval, there is no analog in the modern instrumental climatic record for cool/dry conditions. This makes it impossible to compare reconstructed cool/dry conditions with meteorological measurements and other modern historic records, and thus, more difficult to assess the cultural and ecological impact of this type of climate anomaly. Interestingly, the largest volcanic eruption in modern historic times, Tambora in 1815, occurred shortly before this reconstructed cool/dry period. This is also a cool period in Scuderi's (1993) Sierra Nevada reconstruction. Perhaps this rare and somewhat counterintuitive type of southwestern U.S.A. climatic combination (cool/dry) occurs when strong La Nina events coincide with large volcanic eruptions. The interactions are complex and more work is needed in this area. Preliminary analyses do, however, tend to support the temporal coincidence of large explosive volcanic eruptions and seven of the ten cool/dry intervals listed in Table VI, including 1818–1823, 1666–1672, 1360–1364, 1215–1219, 900–902, 823–824, and 699–700 (see Salzer, 2000a, pp. 112–115).

The 1950s drought in the Southwest provides a modern analog for extreme warm/dry conditions. This drought brought about high levels of plant mortality in shrublands, woodlands, and forests as well as regional scale shifts in species composition (Betancourt et al., 1993; Swetnam and Betancourt, 1998). There is also evidence that the reconstructed warm/dry interval in the late 16th century (1586–1593), also identified by Stahle et al. (2000) across much of North America, may have contributed to widespread coniferous tree mortality (Swetnam and Betancourt, 1998; Swetnam and Brown, 1992).

Cool/wet conditions in the 1910s provide an analog for past cool/wet circumstances. This is a period of extremely high runoff in the Colorado River basin (Stockton, 1975). Additionally, the cool/wet interval beginning in 1911 may have led to a pulse of heavy tree recruitment in Southwestern forests (Allen et al., 1998).

4.1. POST-1976 CLIMATE (WARM/WET 1978–1988)

The warm/wet interval beginning in the late 1970s is the first since the 1760s and corresponds to a post-1976 climate regime shift in the Pacific expressed in the American Southwest as abnormally wet winters and springs (Swetnam and Betancourt, 1998). The long dendroclimatic reconstructions presented here reveal the unusual nature of post-1976 climate in this region. There has been some debate regarding the nature of the relationship between the post-1976 climate regime shift and greenhouse gas induced global warming, as time series modeling suggests post-1976 climatic behavior occurs once every thousand years (Trenberth and Hoar, 1996, 1997). From Figure 6, it is clear the temperature increase in the latter half of the twentieth century is anomalous compared to warm periods of the past, and that warm/wet conditions, extreme until 1988, have actually persisted to some degree to the end of the record. The reconstruction data do not directly address whether the post-1976 climate shift and greenhouse warming are causally linked, and the precipitation reconstruction does exhibit decadal-scale changes in the past 1,425 years, from dry periods to periods with equal or greater amounts of precipitation than the late 20th century, suggesting that such shifts may represent natural variability. However, when both climatic variables are considered, the post-1976 climate history of prolonged, extreme wetness and warmth is unique in the record.

There is some evidence that unusual warm/wet intervals can be important biologically, as they represent ideal conditions for pulses of woody plant establishment in the southwestern U.S.A. The unprecedented nature of post-1976 conditions can be seen in other millennial-length tree-ring chronologies from the American Southwest, where recent growth trends compare favorably with the late twentieth century warm/wet period (Swetnam and Betancourt, 1998). Unequaled post-1976 growth in these higher elevation chronologies has been attributed to CO_2 enrichment (Graybill and Idso, 1983; LaMarche et al., 1984), but may be the result of unusually warm/wet conditions. In particular, a combination of wet springs and longer growing seasons would favor enhanced growth at higher elevations. Both temperature and precipitation influence growth processes with the impact of temperature increasing with elevation (Fritts, 1991). Concomitant with the climate change are a multitude of documented changes in environmental conditions since the mid-1970s (Ebbesmeyer et al., 1991).

5. Medieval Warm Period and Little Ice Age

It has become a popular notion that global climate in the last millennium consisted of a Medieval Warm Period (MWP) followed by a Little Ice Age (LIA). There is some uncertainty regarding the extent and timing of these episodes given the natural spatial variability of climate and the spatial and temporal resolution of the data used to define them (Hughes and Diaz, 1994). We find considerable temperature and precipitation variability on decadal and multi-decadal scales during the MWP and LIA intervals, which further demonstrates the complexity of these intervals.

There are both cold and warm periods within the MWP and LIA in the reconstructions without any clear evidence for sustained warmth or cold as these episodes are traditionally interpreted. When Lamb's (1977) northern European dates for the MWP (1000–1300) and LIA (1550–1850, main phase: 1550–1700) are compared to the climatic reconstructions presented above, the southern Colorado Plateau data show a high degree of decadal and multi-decadal scale variability in both temperature and precipitation during both the MWP and LIA. In the San Francisco Peaks data, the MWP period contains two reconstructed extremely warm periods (1067–1091, 1146–1155) and three reconstructed extremely cool periods (1094–1120, 1195–1219, 1225–1245). The LIA interval contains six cool periods (1599–1612, 1636–1653, 1661–1683, 1763–1771, 1810–1825, 1835–1854) and six warm periods (1586–1593, 1688–1698, 1708–1721, 1736–1744, 1753–1761, 1777–1801), although four of the six warm episodes post-date the main phase of Lamb's LIA.

The lower elevation tree-ring record of extreme wet and dry intervals is not disproportionately affiliated with either of the two northwestern European climate intervals. Five wet and five dry periods occur during the MWP, nine wet and seven dry during the LIA. This is consistent with the findings of Dean (1994) for the Colorado Plateau.

Longer intervals can be identified when, for example, warmer conditions occur more often than cool conditions. This is the case for the period from 870–1090 although this interval is not devoid of cool episodes. Conversely, intervals cooler than they are warm, from 1600–1685 and 1810 to 1930, are separated by a relatively, yet not consistently, warm 18th century. Longer dry and wet intervals are harder to identify as the precipitation reconstruction is characterized by more frequent alternating wet and dry periods.

It has been suggested that the LIA period is marked by high interannual temperature variability (Briffa et al., 1990). The SFP data support this notion for much of the LIA. A running-variance calculation of overlapping 25-year periods shows high variance in temperature from 1630 to 1815. In addition, there is a long period of temperature and precipitation high variance overlap in the 18th century. Interestingly, beginning around 1690 and through the 18th century, the characteristics of both time-series changed; the variance shifted to shorter periods (Figure 6). The cause of this shift remains unclear, but it is undoubtedly linked to natural rather than anthropogenic forcing, and carries with it a myriad of implications for the cultural-ecological landscape.

Spectral analysis of the reconstructions reveals the variance of the temperature reconstruction is primarily concentrated at periods greater than 19 years, with prominent peaks at approximately 41 and 178 years (Figure 7A). The spectra were estimated using the Blackman-Tukey lag window method with a 200-year lag window (bandwidth) (Chatfield, 1996). The temperature reconstruction may also exhibit a pattern of some external forcing associated with volcanic aerosols similar to that reported by Scuderi (1990). Reconstructed temperature minima often coincide with evidence for large explosive volcanic eruptions during the cool interval, including the three consecutive cold periods in the 1200s that have been tentatively linked with 13th century cultural changes on the Colorado Plateau (Salzer, 2000b). Additionally, frost damaged rings (frost-rings) often occur during the year-of or the year-after a known large explosive eruption.

The variance in the precipitation reconstruction resides at shorter periods (higher frequencies) than the variance in the temperature reconstruction. Significant peaks occur at 14, 18, 22, 24, 44, and 68 years (Figure 7B). Forcing mechanisms responsible for the variability in the precipitation reconstruction appear to possibly be related to solar variability and decadal scale oceanic-atmospheric interaction linked to ENSO and the Pacific Decadal Oscillation (PDO). Mantua et al. (1997) found that reversals in the prevailing polarity of the oscillation occurred around 1925, 1947, and 1977. The predominately negative PDO between 1947 and 1976 and positive values since 1977 correspond to dry and wet intervals in the Southwest.

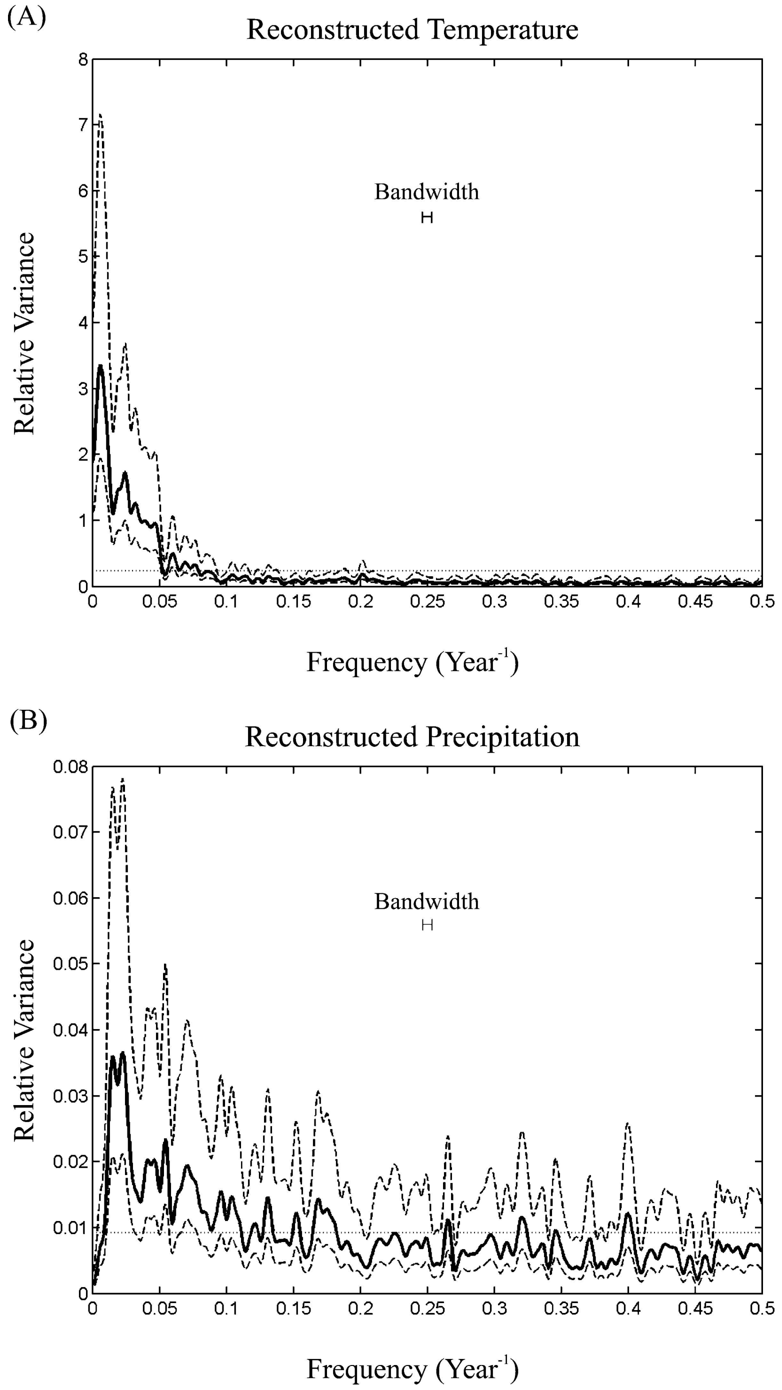

Figure 7. Estimated spectra from reconstructed temperature (A) and precipitation (B) in Northern Arizona. Dashed lines indicate the 95% confidence limit of the estimated spectrum and horizontal dotted line constitutes the null continuum.

6. Summary and Conclusions

Combined temperature and precipitation reconstructions from the same region allow for the determination of past warm, cool, wet, and dry intervals (Figure 6, Tables III–VI). In addition, it is possible to determine periods when the unusual climatic combinations of cool/dry and warm/wet occurred (Figure 6, Table VI). The underlying processes responsible for the onset of such anomalous combinations remain largely untested, although there is some indication of an association between cool/dry intervals and explosive volcanism. There are past cool and warm periods in our temperature reconstruction that overlap with extremely cool and warm periods in the Sierra Nevada and in Fennoscandia (Briffa et al., 1990; Graumlich, 1993; Scuderi, 1993). There are also indications of some correspondence between cool/dry and warm/wet intervals on the southern Colorado Plateau and extreme cool and warm periods reported in the other regions (Tables V and VI). If explosive volcanism acts as a forcing mechanism for cool/dry episodes, these hemispheric-scale linkages would be expected. This also suggests, albeit with a limited comparison, that the anomalous periods of cool/dry and possibly of warm/wet might be used to sort out global from regional cooling and warming events, at least as a first approximation.

The warmth of the 20th century, while never exceeded, was approached for brief intervals in the past when natural forcing mechanisms produced considerable warmth (Table IV, Figures 4 and 6).The second half of the 20th century is the warmest interval in the period of record, which suggests the possibility that warming from human activity has increased temperature outside the range of natural variability. The increase in precipitation following the 1976 climate regime shift in the Pacific is not outside the range of past climatic variability for precipitation. However, when superimposed on anomalous late-twentieth century warming, the ensuing warm/wet climatic conditions are anomalous. The warm/wet climate is unprecedented in the 1,425-year record in both amplitude and duration. Humans and other biotic populations of the southern Colorado Plateau were unacquainted with this association of prolonged extreme wetness and warmth. As the next extreme dry interval occurs, which appears to be the case for the first few years of the 21st century, in all likelihood the drought will be exacerbated by the continued warm conditions. This combination of warm/dry will, no doubt, have profound environmental and cultural consequences on the southern Colorado Plateau and elsewhere in the semi-arid American Southwest.

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