Vol. 22: 237–244, 2002

CLIMATE RESEARCH
Clim Res

Published November 4

Chihuahua (Mexico) winter-spring precipitation reconstructed from tree-rings, 1647–1992

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ABSTRACT: The state of Chihuahua lies in an arid to semiarid zone in the NW central plain of Mexico. Its agricultural economy is highly vulnerable to frequent droughts. In this study, we reconstruct winter-spring precipitation from 1647–1992 using 6 earlywood width chronologies of Douglas fir from around Chihuahua. The tree-ring data explain 56% of the winter-spring precipitation variance in a linear regression for 1949–1992, and there is strong correlation between the tree-ring reconstructed precipitation data and the observed precipitation data not used for calibration ($r = 0.74$, $p < 0.01$). The 5 driest years in the reconstructed precipitation record were 1974, 1954, 1742, 1980, and 1820 in order of severity, and the longest dry period in the 346 yr record lasted about 17 yr (1948–1964) during the severe 1950s drought that also affected the SW United States. The reconstructed precipitation record has a statistically significant 4 yr spectral peak in the El Niño/Southern Oscillation (ENSO) frequency band and is significantly correlated with indices of ENSO (tropical rainfall index; $r = 0.58$, $p = 0.001$). The correlation between the ENSO and Chihuahuan reconstructed precipitation varied in strength when computed for non-overlapping 18 yr sub-periods (ranging from $r = 0.43$ to $r = 0.68$), which may reflect changes in the ENSO teleconnection to climate in northern Mexico.

KEY WORDS: Chihuahua · Mexico · Reconstructed precipitation · Tree-ring chronologies · Earlywood · Douglas fir · ENSO · Tropical rainfall index

1. INTRODUCTION

Severe droughts occur frequently in the Chihuahua region, which lies in an arid to semiarid zone in the NW central plain of Mexico, bordered by the Sierra Madre Occidental to the west (A. V. Garcia 2000). The Chihuahuan climatic area is part of an arid zone that includes the SW United States (Schmidt 1983). The state of Chihuahua has considerable economic importance to Mexico as the nation's leader in raising cattle and sheep and is an important producer of apples, nuts, and timber (INEGI 1996). The agricultural economy of Chihuahua is highly vulnerable to drought (S. J. Garcia 2000), and it is important to identify past droughts and estimate the frequency of severe droughts in order to develop plans to deal with future water shortages.

Tree-ring research was first conducted in Mexico by Schulman (1944). Since Schulman's work, there have been several publications on tree-ring work in Mexico, mainly from the border lands with the USA, and from the subtropical forests of NW Mexico. For example, Villanueva-Diaz (1995) and Villanueva-Diaz & McPherson (1995, 1996) developed climatically sensitive ring-width chronologies and estimated winter-spring precipitation and the Palmer drought severity index (PDSI) for the SW USA and NW Mexico using ponderosa pine *Pinus ponderosa* and Douglas fir *Pseudotsuga menziesii*.

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Stahle et al. (1999) reconstructed winter and early summer precipitation in Durango, Mexico, using earlywood (EW) and latewood (LW) chronologies from ancient Douglas fir, and also reported on the development of tree-ring chronologies from tropical Mexico (Stahle et al. 2000a). Biondi (2001) reported the development of a chronology of *Pinus hartwegii* from the tree-line in Colima, Mexico, and Díaz et al. (2001) developed a reconstruction of precipitation variability over the past 2 centuries in Baja California Sur, Mexico.

According to several reports, the El Niño/Southern Oscillation (ENSO) can have a strong influence on Mexican climate (e.g. Cavazos & Hastenrath 1990, Kiladis & Diaz 1993, Flores 1998, Tiscareño et al. 1998), and several studies have used tree-ring chronologies from Mexico to reconstruct indices of the ENSO. For example, Lough & Fritts (1985) and Stahle et al. (1998) have developed reconstructions of the Southern Oscillation Index (SOI). Tree-ring chronologies from northern Mexico are well correlated with indices of ENSO primarily because winter precipitation and tree growth tend to be abnormally low during cold (La Niña) ENSO events (Stahle et al. 2000a, Díaz et al. 2001). This study presents further information about the history of drought in Chihuahua, and its relationship with ENSO events for 346 yr. There are no previous reports using tree-rings to reconstruct the climate of Chihuahua.

2. DATA

2.1. Climatic data

The observed precipitation data used for this study are based on monthly gridded precipitation developed by the Climatic Research Unit at the University of East Anglia (gu23wld0098.dat; Hulme 1992, Hulme et al. 1998). The Hulme precipitation data have a 2.5° latitude × 3.75° longitude resolution and extend from 1900 to 1998. Data from 4 grid boxes covering most of Chihuahua (grid-points 4436, 4437, 4532, and 4533) were combined to create a regional average to which the tree-ring data could be compared (Fig. 1). The gridded data are based on single station data, many of which can be found in the Global Historical Climatology Network (GHCN).

Thiessen polygon weights were used to average gauge data within each grid box. Stations could only contribute to these gridded data if they possessed 75% or more valid monthly measurements in the reference period. When a monthly station value was missing, an estimate was obtained by calculating the mean anomaly for that location derived from a maximum of the 50 nearest stations (Hulme et al. 1998). Monthly precipitation is well correlated between the 4 boxes (r ranges from 0.68 to 0.92).

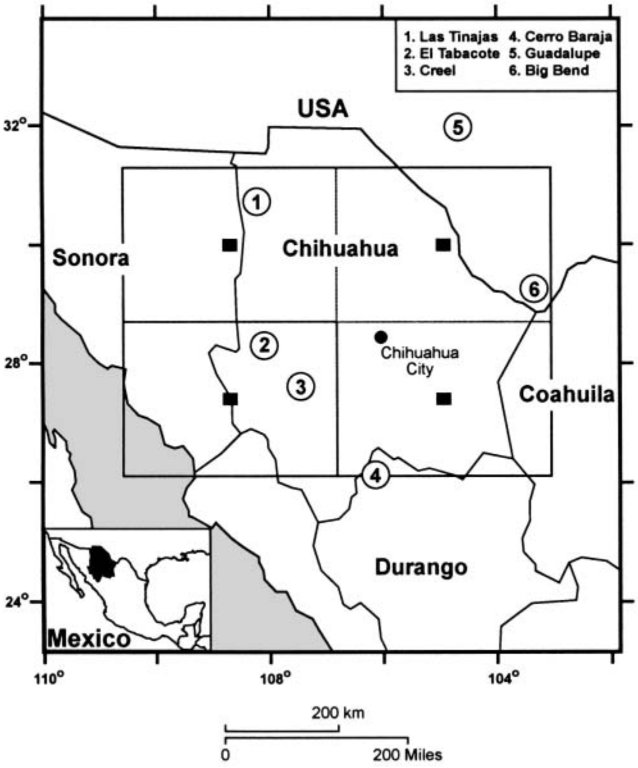

Fig. 1. Chihuahuan climatic study area. Tree-ring chronologies used for the reconstruction are indicated with numbered circles. The 4 Hulme (1992) precipitation data set grid boxes and their centerpoints used to develop the regional precipitation average are also shown

These gridded precipitation data were used rather than single station data because of the difficulty involved in creating a regional precipitation average from the available data. Mexican station data are often short and discontinuous, especially in the early 20th century and after the financial crisis of the 1980s. The Hulme data set does smooth out the dramatic spatial gradients that can occur in some years across the complex topography of Chihuahua, but the regional average of the 4 grid points provides a very reasonable history of the sequence of drought years and wet years for the state of Chihuahua. This is borne out by comparison with climate data from Chihuahua and surrounding regions (e.g. Stahle & Cleaveland 1988, Stahle et al. 1999, S. J. Garcia 2000), and by comparison with the 6 exactly dated tree-ring chronologies from the region (see next subsection).

2.2. Tree-ring data

Six long EW width chronologies of Douglas fir from Chihuahua and Durango were used for this study

(Fig. 1). These EW chronologies range from 347 to 603 yr in length and are well correlated with winter and spring precipitation (Cleaveland & Stahle 1996, Stahle et al. 1998, 1999). Douglas fir in NW Mexico typically produce a well-defined boundary between the light-colored EW laid down in spring and the darker, more dense LW that grows in the early to mid-summer. These 2 seasonal components of the annual ring can be measured with precision and repeatability using methods described by Stahle et al. (2000a).

Tree-ring samples used to develop the chronologies were collected by the University of Arizona Laboratory of Tree-Ring Research and by the University of Arkansas Tree-Ring Laboratory (e.g. Stahle et al. 2000a). The Douglass method of cross-dating was used to exactly date the growth rings on core samples extracted from over 300 trees at the 6 Douglas fir collection sites. In this method the samples are examined under a binocular zoom microscope and compared with other samples to identify a common pattern among the sample tree-ring series. The skeleton plot, an aid to cross-dating, is a graphic representation of the tree-ring data. It can be used to identify missing rings and false rings, and in this way synchronizes the ring series and gives an exact date to each tree-ring (e.g. Stokes & Smiley 1996).

Cross-dating was checked using the computer program COFECHA, which utilizes cross-correlation analysis to identify potential dating and/or measuring mistakes (Holmes 1983). The individual chronologies were created using the computer program ARSTAN, which uses curve fitting to remove age-related growth trends and stand dynamic effects (Cook 1985). The resulting standardized ring-width indices all have a mean of approximately 1.0, and are averaged together into a single site chronology using a robust mean value function that discounts statistical outliers. All 6 EW chronologies exhibit excellent chronology statistics (Fritts 1976), including high mean sensitivity and mean inter-series correlation. They can be obtained from the National Geophysical Data Center Website (www.ngdc.noaa.gov/paleo).

3. METHODS

We used principal component analysis (PCA) to identify orthogonal modes of tree growth that represent most of the variance in the array of the 6 tree-ring chronologies in and near Chihuahua. The first principal component (PC1) explains 65% of the variance in EW tree growth and is significantly correlated with winter-spring precipitation (November–May; Fig. 2). Experimentation indicated that a seasonalization of the precipitation data from November through April was optimal to maximize correlation with the factor scores on the first PC of EW growth.

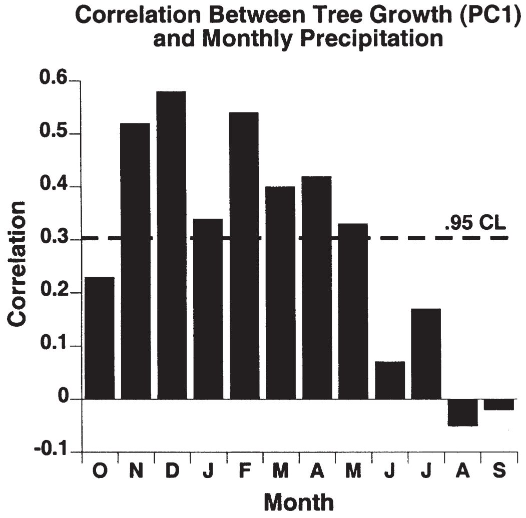

Fig. 2. The first principal component of the earlywood chronologies is significantly correlated with regional precipitation for Chihuahua from November though May (confidence level = 0.95). Although precipitation during this period only accounts for about a third of the annual total, correspondingly low potential evaporation rates during this season make it important for soil moisture recharge and plant growth

While winter-spring precipitation only accounts for a small portion of the annual precipitation (one-third), it can be an important source of water for agricultural activities and native vegetation because evaporation rates during this cool season are low and soil moisture recharge can be high. This is also the season when ENSO influences Chihuahuan precipitation and tree growth most strongly (Cavazos & Hastenrath 1990, Stahle & Cleaveland 1993).

Autoregressive (AR) modeling was used to identify any significant time series persistence in the EW PC1 factor scores and precipitation data prior to calibration. Both predictor and predictand proved to be white-noise processes (AR-0) using Schwarz's Bayesian Criterion (Schwarz 1978, SAS Institute 1993). Furthermore, neither the regional average of winter-spring precipitation nor the EW PC1 factor scores depart significantly from a normal distribution.

Precipitation data were divided into 2 parts (1901–1948 and 1949–1992). The latter half was used to develop a bivariate regression model to calibrate the EW PC1 time series with November–April precipitation, and the first-half was used for independent verification of tree-ring estimates of precipitation. We also performed spectral and cross-spectral analysis on the series to test the relationship between the observed and reconstructed series in the frequency domain (Jenkins & Watts 1968). The spectral power

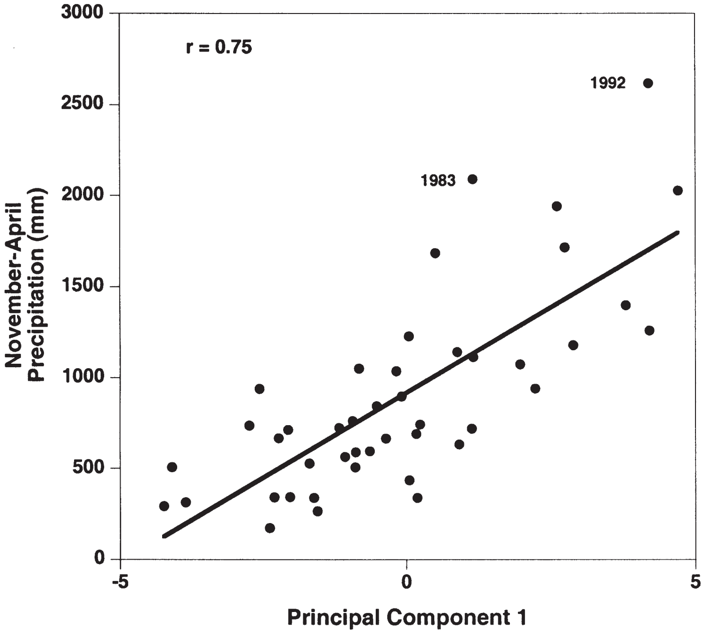

Fig. 3. Linear regression was used to calibrate the tree-ring chronology and winter-spring precipitation (November–April) between 1949 and 1992. The 2 largest errors coincide with the El Niño events of 1983 and 1992. Tree-ring records sometimes fail to register abnormally wet episodes with the same fidelity as they record drought (Fritts 1976)

estimates were smoothed with a Hamming window (IMSL Inc. 1982).

4. RESULTS

PCA revealed a strong region-wide growth signal in the EW chronologies, which is clearly due to common climatic forcing. All 6 chronologies load strongly on PC1, which explains 65 % of the variance in the covariance matrix computed between the 6 chronologies. The annual time series of PC1 factor scores extends from 1647 to 1992, and was used as the predictor in the equation to reconstruct precipitation in Chihuahua. The regional tree-ring chronology (PC1 of EW width) was regressed against the Chihuahua winter-spring precipitation data (November–April) for the period 1949–1992 (Fig. 3). Linear regression using the precipitation data and PC1 shows that the tree-ring data explain 56 % of the variance in winter-spring precipitation (R^2 adjusted for loss of 2 degrees of freedom; Draper & Smith 1981). The calibration equation for 1949–1992 was

$$Y_t = 91.611 + 18.721 X_t \quad (1)$$

where Y_t is the estimated winter-spring precipitation (mm) and X_t is the tree-ring factor score (PC1), both for the year *t*. No significant autocorrelation was detected in the residuals from the regression model, using the Durbin-Watson statistic (Draper & Smith 1981), which indicates that the calibration model has no large and systematic unexplained error.

To validate the regression model, the estimated values for 1901–1948 were compared against independent precipitation data (1901–1948) that were not used in the calibration (Fig. 4). The verification statistics include the Pearson correlation coefficient ($r = 0.74$, $p <$ 0 .01) and the Pearson correlation coefficient after first-difference transformation of series ($r = 0.79$, $p < 0.01$). The latter procedure tests the strength of the relationship between the observed and reconstructed series when low-frequency variance has been removed by the first differencing transformation (Fritts et al. 1990).

The paired Student's *t*-test between the instrumental and reconstructed means indicate that the means do not differ significantly for 1901–1948 (Steel & Torrie 1980). The sign test indicates general agreement in sign for the reconstructed and observed deviations from the instrumental means (36 same/12 different, $p < 0.01$; Fritts et al. 1990). The reduction of error test (RE = 0.57) indicates high skill in the reconstruction, and suggests that approximately equal fractions of instrumental precipitation variance are reproduced by the tree-ring data during the calibration and verification sub-periods of the 20th century. These results indicate that the tree-ring data accurately reproduce the mean and variance of independent winter-spring precipitation during the validation period.

Close examination of Figs. 3 & 4 reveals that the biggest difference between reconstructed and observed values occurred in 1983 and 1992. During these 2 years, tree growth responded poorly to abnormal wetness. The poor estimate of 1983 precipitation stands out because 1982–1983 was one of the strongest ENSO events of the 20th century. This difference may be the result of a skewed distribution of 1982–1983 precipitation over the November–March season in Chihuahua. Precipitation during March 1983 was 46 mm, which is more than 200 % of the historical average for that month (1901–1992). This incredible event is not well reflected in the EW growth of Douglas fir in the region, perhaps because of the uneven distribution of heavy rain during the winter-spring period.

Using the model derived in the calibration (Eq. 1), winter-spring precipitation was reconstructed for the Chihuahuan region back to 1647 (346 yr; Fig. 5). The tree-ring estimates suggest that the 5 driest years in the 346 yr winter-spring reconstruction were 1974, 1954, 1742, 1980, and 1820, in order of severity. Three of the 5 worst winter-spring drought years in the past three-and-a-half centuries are estimated to have occurred during the 20th century.

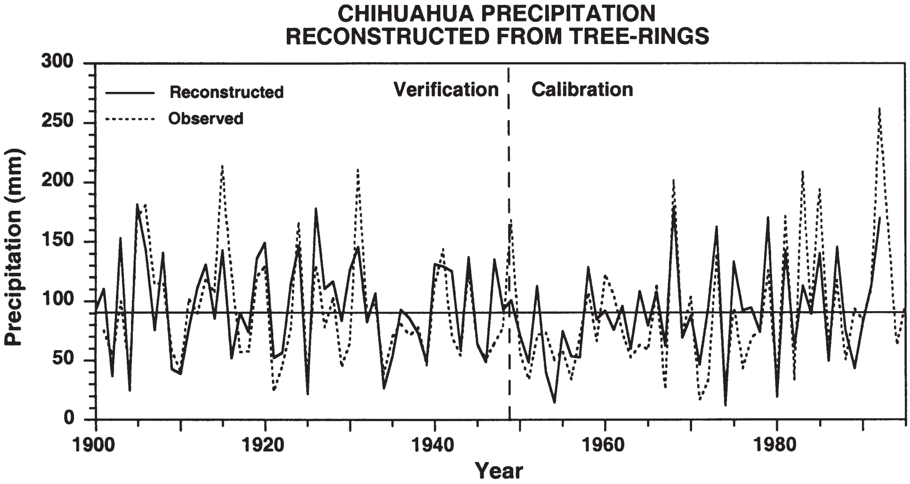

Fig. 4. Reconstructed (solid line) and observed precipitation (dashed line) for the calibration and verification periods. Observed and reconstructed precipitation are generally well correlated during the 20th century, but note that several wet years such as 1983 and 1992 are poorly replicated by the tree-ring record

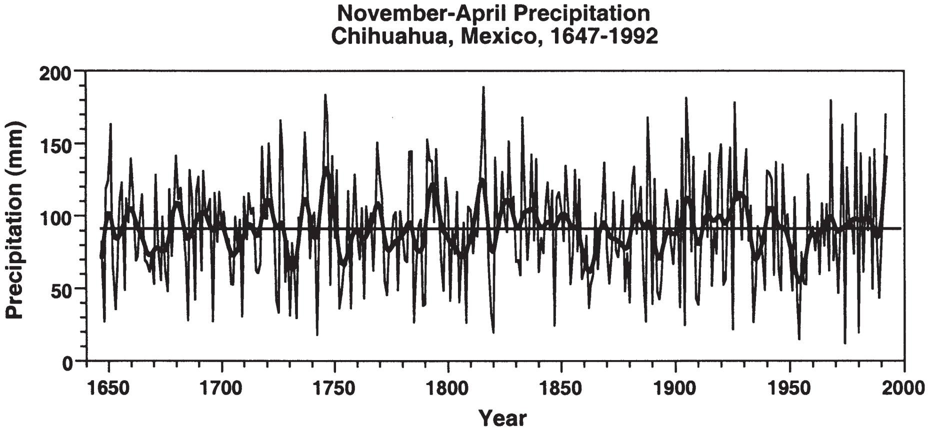

Fig. 5. Reconstructed winter-spring precipitation from 1647 to 1992. A smoothing spline was applied to emphasize the decadal variance in the reconstruction (Cook & Peters 1981), and it clearly shows the severe 1950s drought that impacted much of Mexico and the SW USA. The long drought at the turn of the 19th century has been implicated in the unrest that led to the Mexican War of Independence (e.g. Florescano 1986, Florescano & Swan 1995)

We fit a 10 yr smoothing cubic spline (Cook & Peters 1981) to the reconstruction and observed long periods of below-mean precipitation. The longest drought indicated by the smoothed reconstruction lasted 17 yr (1948–1964). Observed precipitation was also below the mean for most years from 1943 to 1966 (Fig. 5). This result is in accordance with work by S. J. García (2000), who reported that the drought of 1952–1957 was the most severe of the 20th century in the Chihuahua area. In addition, a tree-ring reconstruction for Durango, Mexico, by Stahle et al. (1999) indicates that the worst drought of the 20th century occurred from 1950 to 1965, when 14 out of 16 yr had below-average winter precipitation. Stahle & Cleaveland (1993) also found that the most severe prolonged drought during the past 300 yr in south-central Texas occurred during the 1950s, and work by Díaz et al. (2001) indicates that a drought from 1939 to 1958 occurred in Baja California Sur.

The second-longest drought in the smoothed Chihuahua reconstruction lasted for 15 yr from 1751 to 1765. This drought is also apparent in the winter precipitation reconstruction from Durango (Stahle et al. 1999), and to some extent in tree growth and reconstructed PDSI in south Texas (Stahle & Cleaveland 1988, Therrell 2000). In addition, Molina (2000) notes

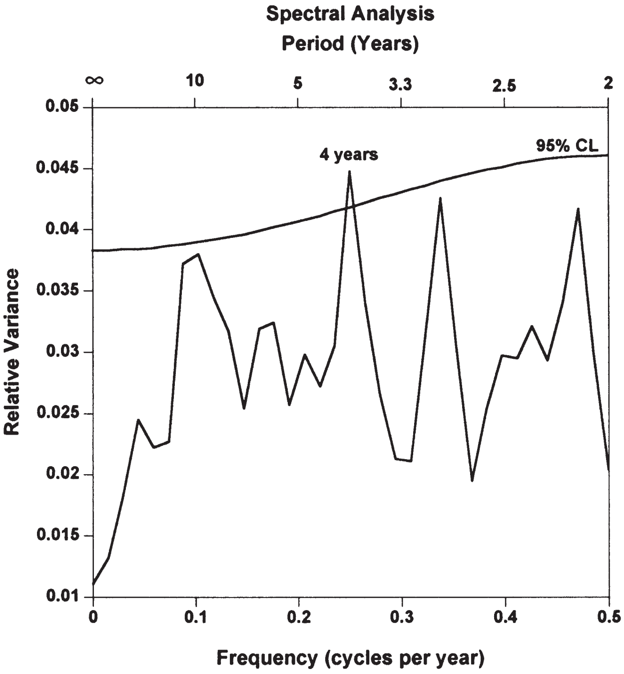

Fig. 6. Spectral analysis of the reconstructed precipitation for the period 1647–1992 shows a significant peak at 4 yr, suggesting that El Niño influences earlywood tree growth in this region

that drought-induced famine occurred at the beginning of this period in central Mexico.

Florescano & Swan (1995) note that just prior to the Mexican War of Independence in 1810 there was increased social discontent in northern and central Mexico due to high corn prices, drought, and famine. The Chihuahua reconstruction indicates that a 13 yr drought occurred from 1798 to 1810. This important event is also reflected in climate reconstructions from Durango (Stahle et al. 1999) and Texas (Stahle & Cleaveland 1988) and in tree-ring chronologies from central Mexico (Therrell et al. 2002). A 14 yr drought from 1664 to 1677 is apparent in the Chihuahua reconstruction, but this event may have been more localized because it does not appear to have strongly impacted Durango (Stahle et al. 1999).

Long periods with high winter-spring precipitation were reconstructed during the late 18th and early 19th centuries, and from 1905 to 1932 (Fig. 5). The early 20th century wet period is particularly interesting as this 'pluvial' is apparent in tree-ring chronologies in northwestern Mexico and across the western United States (Stahle et al. 1999, Fye et al. 2002).

Analyzing the Chihuahua series using spectral analysis (Jenkins & Watts 1968) indicates that the reconstructed winter-spring precipitation (1647–1992) has a significant concentration of variance (4.5%) at 4 yr ($p < 0.05$), which appears to be the principal frequency at which the ENSO phenomenon influences winter-spring precipitation over northern Mexico (Fig. 6; Cleaveland et al. 1992).

The plot of the coherency-squared coefficient from a cross-spectral analysis shows that the instrumental and reconstructed precipitation data are coherent at most frequencies during the instrumental period (1901–1992, Fig. 7). This is equivalent to the squared correlation coefficient in the frequency domain. In addition, both time series are in phase at all frequencies.

To study the ENSO teleconnection to Chihuahua precipitation, we calculated the correlation between the tropical Pacific rainfall index (TRI; Wright 1982) and reconstructed precipitation from 1895 to 1992. The 2 series are significantly correlated for the entire time period ($r = 0.58$, $p < 0.001$; Fig. 8). However, the stability of the teleconnection appears to have varied over time, as has been demonstrated for the United States by Cole & Cook (1998). During 5 non-overlapping sub-periods of 18 yr from 1901 to 1992, the correlation between the TRI and Chihuahua reconstructed precipitation varies from $r = 0.50$ to 0.66. The relationship between the TRI and observed November–April precipitation also varies over time, ranging from $r = 0.32$ to 0.67 (Fig. 9). The correlations between the TRI and both the reconstructed and observed data generally diminish over the 20th century, particularly for the instrumental precipitation data (Fig. 9).

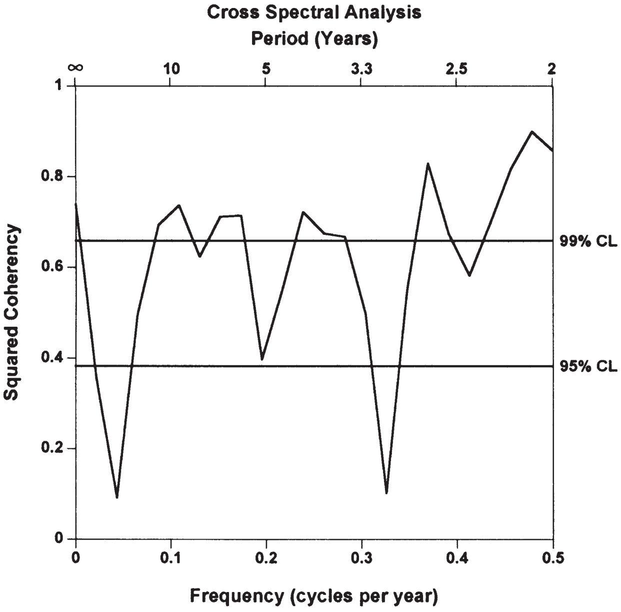

Fig. 7. Squared coherency between observed and reconstructed precipitation, 1901–1992. The 2 series are significantly coherent across most frequencies ($p < 0.05$)

5. CONCLUSIONS

Research using 6 Douglas fir earlywood width chronologies has provided the first high-resolution precipitation reconstruction reported for the region centered on Chihuahua. The reconstruction strongly replicates the instrumental precipitation data during the 20th century, and provides reliable estimates of November–April total precipitation from 1647 to 1992.

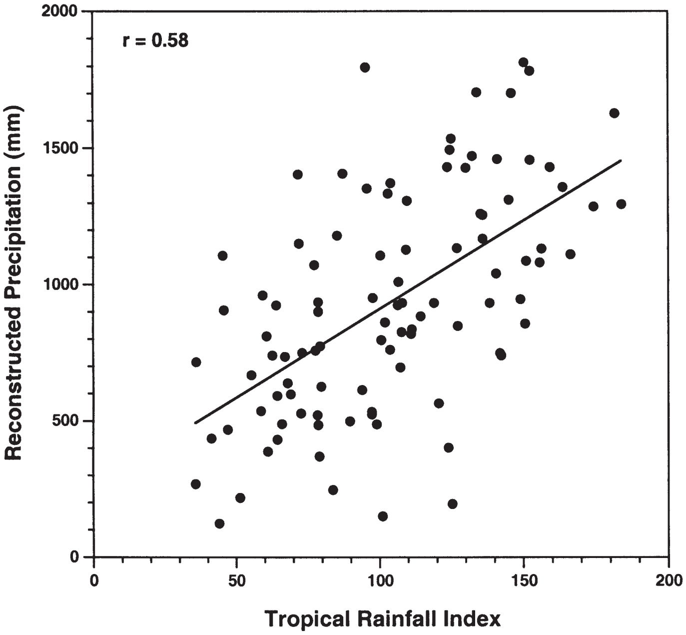

Fig. 8. Scatter plot showing the correlation between the tropical rainfall index (TRI, an ENSO index; Wright 1982) and tree-ring reconstructed precipitation over Chihuahua, 1895–1992. Other ENSO indices show a similar though weaker relationship to the reconstruction

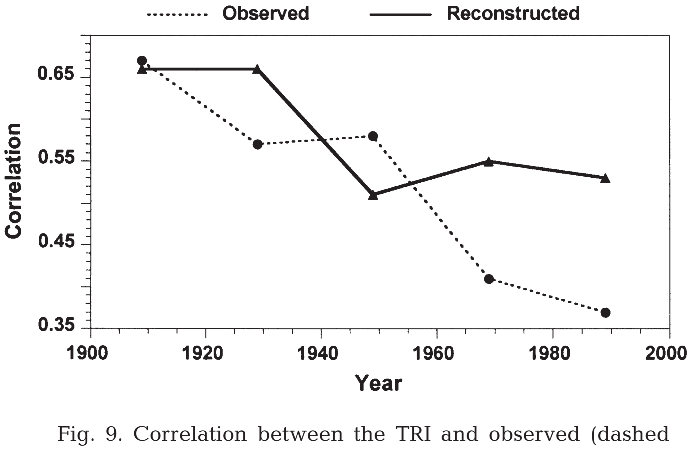

Fig. 9. Correlation between the TRI and observed (dashed line) and reconstructed (solid line) precipitation in non-overlapping 18 yr periods during the 20th century (1901–1992; the last period is 20 yr long)

The winter-spring precipitation reconstruction is coherent with the instrumental precipitation data at most frequencies, and it has a statistically significant 4 yr spectral peak in the ENSO frequency band. The instrumental and reconstructed precipitation data are both significantly correlated with ENSO indices during the 20th century, but the strength of the teleconnection varies on decadal timescales.

The reconstruction suggests that the prolonged drought of the 1950s was the most severe sustained drought over Chihuahua during the past 346 yr. These results are in general agreement with other tree-ring research in Mexico and the SW USA, which suggests that the 1950s drought was among the worst to afflict northern Mexico and the SW USA in the past 350 yr (e.g. Stahle et al. 2000b). However, the reconstruction clearly indicates that droughts of 5 to 10 yr duration are part of the natural variability of winter-spring precipitation over Chihuahua. Historical research by Florescano (1986) and others suggests that some of these past drought episodes were not confined to Chihuahua, and may have had an important influence on Mexican history.

Acknowledgements. This research was supported in part by CIBNOR and the US National Science Foundation, Paleoclimatology Program (grant no. ATM-9986074). We thank the Tarahumara People, Guadalupe Mountains National Park, and Big Bend National Park for permission to sample ancient Douglas fir trees. We also thank B. T. Burns, Ira Fogal, David Meko, Jose Villanueva-Diaz, and Fred Armstrong for assistance and advice.

LITERATURE CITED

Biondi F (2001) A 400-year tree-ring chronology from the tropical treeline of North America. Ambio 30:162–166

Cavazos T, Hastenrath S (1990) Convection and rainfall over Mexico and their modulation by the Southern Oscillation. Int J Climatol 10:377–386

Cleaveland MK, Stahle DW (1996) Tree-ring reconstruction of climate extremes using discriminant function analysis. In: 13th Conf Probability Statistics Atmospheric Sciences. American Meteorological Society, San Francisco, p 33–36

Cleaveland MK, Cook ER, Stahle DW (1992) Secular variability of the Southern Oscillation detected in tree-ring data from Mexico and Southern United States. In: Diaz H, Markgraf V (eds) El Niño: the historical and paleoclimatic record of the Southern Oscillation. Cambridge University Press, Cambridge, p 271–291

Cole JE, Cook ER (1998) The changing relationship between ENSO variability and moisture balance in the Continental United States. Geophys Res Lett 25:1529–4532

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

Cook ER, Peters K (1981) The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. Tree-Ring Bull 41:45–53

Díaz SC, Touchan R, Swetnam TW (2001) A tree-ring reconstruction of past precipitation for Baja California Sur, Mexico. Int J Climatol 21(8):1009–1021

Draper NR, Smith H (1981) Applied regression analysis, 2nd edn. John Wiley, New York

Flores LE (1998) Geosudcalifornia. Geografía, agua y ciclones. Universidad Autónoma de Baja California, La Paz, Baja California Sur

Florescano E (1986) Precios del maiz y crises agricolas en Mexico 1708–1810. Ediciones Era, Mexico City

Florescano E, Swan S (1995) Breve historia de la sequía en México. Universidad Veracruzana, Veracruz

Fritts HC (1976) Tree rings and climate. Academic Press, San Diego

Fritts HC, Guiot J, Gordon GA (1990) Verification: methods of dendrochronology. In: Cook ER, Kariukstis LA (eds) Applications on the environmental sciences. Kluwer, Dordrecht, p 178–185

Fye F, Stahle DW, Cook ER (2002) Paleoclimatic analogs to 20th century moisture regimes. Bull Am Meteorol Soc (in press)

Garcia AV (ed) (2000) Estudios históricos sobre desastres naturales en México. Centro de Investigaciones y Estudios Superiores de Antropología Social (CIESAS), Mexico DF

Garcia SJ (2000) Analisis de vulnerabilidad agropecuaria por sequia en el estado de Chihuahua. Instituto de Ecología, Jalapa, Veracruz; available at www.sequia.edu.mx/proyectos/vulnera.html

Holmes RL (1983) Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bull 43:69–78

Hulme M (1992) A 1951–1980 global land precipitation climatology for the evaluation of general circulation models. Clim Dyn 7:57–72

Hulme M, Osborn TJ, Johns TC (1998) Precipitation sensitivity to global warming: comparison of observations with HadCM2 simulation. Geophys Res Lett 25:3379–3382

IMSL Inc (1982) IMSL library manual. IMSL, Houston, p FTFREQ-1–FTFREQ-5

INEGI (1996) Anuario estadístico del estado de Chihuahua. INEGI-Gobierno de Estado de Chihuahua, Chihuahua City

Jenkins GM, Watts DG (1968) Spectral analysis and its applications. Holden-Day, San Francisco

Kiladis GN, Diaz HF (1993) ENSO and precipitation variability over Mexico during the last 90 years. In: Proc North Annual Paclim Climate (PACLIM) Workshop, April 21–24, 1992. Calif Dept Water Resour Interagency Ecol Stud Prog Tech Rep 34:63–70

Lough JM, Fritts HC (1985) The Southern Oscillation and tree rings: 1600–1961. J Clim Appl Meteorol 24:952–966

Molina VA (2000) Aproximación histórica al estudio de los desastres naturales: siglos XVIII y XIX. In: Garcia AV (ed) Estudios históricos sobre desastres naturales en México. CIESAS, Mexico, p 45–52

SAS Institute (1993) SAS/ETS user's guide, version 6.2d. SAS Institute, Cary, NC

Schmidt RH (1983) Climate and the Chihuahuan desert. In: Campos-Lopez E, Anderson RJ (eds) Natural resources and development in arid regions. Westview Press, Boulder, CO, p 37–52

Schulman E (1944) Dendrochronology in Mexico. Tree-Ring Bull 10:18–24

Schwarz G (1978) Estimating the dimension of a model. Ann Stat 6:461–464

Stahle DW, Cleaveland MK (1988) Texas drought history reconstructed and analyzed from 1698–1980. J Clim 1:59–74

Stahle DW, Cleaveland MK (1993) Southern Oscillation extremes reconstructed from tree rings of the Sierra Madre Occidental and southern Great Plains. J Clim 6(1): 129–140

Stahle DW, D'Arrigo RD, Krusic PJ, Cleveland MK and 11 others (1998) Experimental dendroclimatic reconstruction of the Southern Oscillation. Bull Am Meteorol Soc 79: 2137–2152

Stahle DW, Cleveland MK, Therrell MD, Villanueva-Diaz J (1999) Tree-ring reconstruction of winter and summer precipitation in Durango, Mexico, for the past 600 years. In: 10th Symp Global Change Studies, 10–15 January 1999. American Meteorological Society, Dallas, p 205–211

Stahle DW, Villanueva J, Cleaveland MK, Therrell MD and 5 others (2000a) Recent tree-ring research in Mexico. In: Roig FA (ed) Dendrocronologia en América Latina. Editorial de la Universidad Nacional de Cuyo (EDIUNC), Mendoza, Argentina, p 285–306

Stahle DW, Cook ER, Cleaveland MK, Therrell MD, Meko DM, Grissino-Mayer H, Watson E, Luckman BH (2000b) Tree-ring data document 16th century megadrought over North America. EOS Trans 81:121–125

Steel RGD, Torrie JH (1980) Principles and procedures of statistics, 2nd edn. McGraw-Hill, New York

Stokes MA, Smiley TL (1996) An introduction to tree-ring dating. The University of Arizona Press, Tucson

Therrell MD (2000) The historic and paleoclimatic significance of log buildings in southcentral Texas. Hist Archaeol 34(2):25–37

Therrell MD, Stahle DW, Cleaveland MK, Villanueva-Diaz J (2002) Warm season tree growth and precipitation over Mexico. J Geophys Res 107 (in press)

Tiscareño LM, Rosenberg NJ, Legler DM, Ruiz A and 5 others (1998) Algunos efectos del fenómeno climático El Niño en la agricultura Mexicana. Cienc Desarrollo 139:5–13

Villanueva-Diaz J (1995) Influence of land-use and climate on soils and forest structure in mountains of the southwestern United States and northern Mexico. PhD thesis, University of Arizona, Tucson

Villanueva-Diaz J, McPherson GR (1995) Forest stand structure in mountains of Sonora, Mexico and New Mexico, USA. In*:* DeBano LF, Ffolliott PF, Ortega-Rubio A, Gottfried GJ, Hamre RH, Edminster CB (tech. coord.) Biodiversity and management of the Madrean Archipelago: the Sky Islands of the southwestern United States and northern Mexico: 416–123. General Technical Report RM-GTR-264, USDA Forest Service, Fort Collins, CO

Villanueva-Diaz J, McPherson GR (1996) Reconstruction of precipitation and PDSI from tree-ring chronologies developed in mountains of New Mexico, USA and Sonora, Mexico. Ariz-Nev Acad Sci Hydrol Sect 26:45–54

Wright PB (1982) Homogenized long-period Southern Oscillation indices. Int J Climatol 9:33–54

Editorial responsibility: Andrew Comrie,
Tucson, Arizona, USA

Submitted: May 23, 2001; Accepted: April 22, 2002
Proofs received from author(s): September 6, 2002