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A COOL SEASON PRECIPITATION RECONSTRUCTION FOR SALTILLO, MEXICO

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ABSTRACT

Old Douglas-fir (*Pseudotsuga menziesii*) trees were sampled in the Sierra Madre Oriental of northeastern Mexico and used to develop a 219-year chronology of earlywood width. This chronology is correlated with monthly precipitation totals from January to June recorded at Saltillo some 55 km northwest of the collection site. The chronology was used to reconstruct winter-spring precipitation (January–June total) from 1782–2000. The reconstruction indicates large interannual, decadal, and multidecadal variability in winter-spring precipitation over Saltillo. This variability is vaguely apparent in the short and discontinuous instrumental record from 1950–1998, with January–June totals ranging from 15 to 310 mm, multiyear droughts, and a negative trend in January–June precipitation over the last 50 years. The reconstruction indicates that severe dryness was prevalent over a 24-year period from 1857–1880. This mid-19th century drought exceeds the duration of any droughts witnessed during the 20th century. However, three episodes of winter-spring dryness have prevailed in the Saltillo region after 1950, a much higher frequency of decadal drought than estimated over the past 219 years and aggravating the regional water supply problems associated with this booming manufacturing and ranching center.

Keywords: Sierra Madre Oriental, *Pseudotsuga menziesii,* Douglas-fir, earlywood width, January–June precipitation.

INTRODUCTION

Drought is the most costly natural disaster, both in terms of human mortality and economic impact (*e.g.* Riebsame *et al.* 1991; Ross and Lott 2002). The tree-ring records of old climate-sensitive conifers provide a high-resolution proxy and can be used to extend precipitation records beyond historical documentation (Fritts 1976). These dendroclimatic reconstructions can help define the range of climatic variability for a region and help estimate the probability of extreme drought in the future.

Several dendroclimatic reconstructions have been produced for the southern United States (*e.g.* Stahle and Cleaveland 1988; Swetnam and Betancourt 1990; Cleaveland *et al.* 1992; Meko *et al.* 1996), and dendrochronology is increasingly being applied to climate reconstruction problems in Mexico (Villanueva-Diaz and MacPherson 1996; Stahle *et al.* 1999; Diaz *et al.* 2001). Some species in northern Mexico such as white pine (*Pinus ayacahuite*) are challenging for dendroclimatic analysis because their radial growth appears to respond strongly to multiple wet and dry episodes during the spring-summer growing season, reflected by the formation of multiple intra-annual growth bands (false rings). Other native species, such as Douglas-fir (*Pseudotsuga menziesii*), have more reliable climate-sensitive annual rings and are less prone to false ring formation, but Douglas-fir is only found in restricted microenvironments at higher elevations in Mexico. A few tree-ring chronologies are now available for the Sierra Madre Oriental (Stahle *et al.* 2000a), but they have yet to be used for paleoclimate reconstruction in northeast Mexico.

Douglas-fir radial growth includes an annual couplet of earlywood (EW) and latewood (LW), which can be easily identified and optically measured (Stahle *et al.* 2000a). Douglas-fir EW formation in northern Mexico is well correlated with winter precipitation, which, in turn, is modulated by the El Niño/Southern Oscillation (ENSO; Stahle *et al.* 2000a). Subtropical North America registers one of the strongest extratropical ENSO signals worldwide (Diaz and Kiladis 1992; Stahle *et al.* 2000), where wet winters are typically associated with warm El Niño events and dry winters tend to occur during cold La Niña periods (Diaz and Kiladis 1992; Magaña *et al.* 1999). Douglas-fir LW formation in this region is correlated with summer precipitation (Therrell *et al.* 2002).

This study was part of the 11th North American Dendroecological Fieldweek held at the Universidad Autonoma Agraria "Antonio Narro" in Saltillo, Mexico, during August 2001. This paper describes a precipitation reconstruction based on the EW width of old Douglas-fir found in the Sierra de las Alazanas, near Saltillo in the Sierra Madre Oriental of Coahuila, Mexico. The objectives were to 1) develop an accurately dated master chronology of Douglas-fir EW width in the Sierra de las Alazanas, 2) define the monthly precipitation response of the derived EW width chronology, 3) develop a seasonal precipitation reconstruction for Saltillo, the largest nearby city with a reasonably long monthly precipitation record, 4) document the history of extended drought and wetness episodes for this portion of northeastern Mexico, and 5) determine the strength of the ENSO signal in the reconstructed precipitation series.

STUDY SITE

The study site is located in the Sierra de las Alazanas (25°17′N, 100°30′W, 3,200 m) in the state of Coahuila, Mexico, about 55 km southeast of Saltillo, and only some 10 km south of the Cumbres de Monterrey National Park in Nuevo Leon (Figure 1). The climate of eastern Coahuila is temperate and subhumid with a late summer rainfall regime and low winter precipitation (Garcia 1981). The Las Alazanas range is near the northern limit of the Sierra Madre Oriental, a geologic province that was formed by the folding and uplifting of Cretaceous sedimentary rocks. In eastern Coahuila the Sierra Madre Oriental, including the Sierra de las Alazanas, consist of several parallel east-west ranges of Cretaceous limestone. Limestone outcrops often show dissolution features and it is common to observe karstic depressions (dolines) between the ridges of the Sierra. The soils of the area are dominated by lithosols and scattered patches of rendzinas on gently sloping microsites. Soils found in dolines are typically alfisols. Soil depth is shallow and generally less than 10 cm.

Vegetation is dominated by conifer forests consisting of pines (*Pinus rudis, Pinus ayacahuite*), Douglas-fir (*Pseudotsuga menziesii*), and true fir (*Abies vejarii*). The Sierra de las Alazanas Douglas-fir stands are part of a relatively large area in the northern Sierra Madre Oriental where Douglas-fir are native on protected north-facing exposures at higher elevations. In fact, this is one of the largest populations of indigenous Douglas-fir in Mexico outside of the Sierra Madre Occidental in Chihuahua and Durango (Martinez 1963). Portions of the study site have been selectively logged and are subject to frequent fires and cattle grazing. Yet, Douglas-fir have not been harvested in great numbers because the species is uncommon in Mexico, and pine is the overwhelmingly preferred material for saw timber. Some cutting of Douglas-fir has occurred, however, despite the threatened status of the species in Mexico where logging is prohibited by law (E. Cornejo-Oviedo, personal communication).

Figure 1. Location of the Las Alazanas Douglas-fir tree-ring collection site in the northern portion of the Sierra Madre Oriental of Coahuila. The precipitation gage used to calibrate the winter-spring precipitation reconstruction is located in Saltillo some 55 km northwest of the collection site.

Saltillo is a large commercial, industrial, and ranching center with a population of 550,000. It was founded in 1577 and in the early 19th Century was the capital of the Mexican states of Coahuila and Texas. The Battle of Buena Vista took place just south of Saltillo in 1847 when General Santa Ana was defeated in the war between Mexico and the United States.

Saltillo has recently experienced rapid industrial and population growth. It is Mexico's top coal producer, and a major textile, steel, and manufacturing center (with several "maquiladoras"). Saltillo "supports its entire population and sizeable industrial population through groundwater resources alone" (Allanach and Johnson-Richards 1995). The population is projected to surpass 700,000 by 2010, and the city plans to double its water supply from 1.5 to 3.0 m^3/second to meet the expected growth and industrial expansion (Allanach and Johnson-Richards 1995). The city is trying to increase water supply by developing new groundwater supplies from the region, modernizing the water distribution system, and developing surface water reservoirs. Information on the long term variability of precipitation and the persistence of past drought could be useful for water resource planning in the region.

METHODS

To facilitate crossdating, Douglas-fir trees were sampled both at a dry cliff site, where radial growth is slow and likely moisture-limited, and at a more level and mesic site where radial growth was more rapid. Two increment cores were taken at breast height from each of 25 selected trees. We selected older Douglas-firs by choosing trees with flattened crowns, large-diameter branches, spiral grain, exposed root collar, and other old-growth characteristics. Some subfossil wood was present at the site, and further field sampling of this relic wood might help extend the chronology derived from living trees.

The Douglas-fir increment cores were mounted on prefabricated wooden mounts and polished using progressively finer grits of sandpaper (Stokes and Smiley 1976). Cores were visually crossdated using the skeleton plot method (Stokes and Smiley 1976). Earlywood and latewood ring widths were measured. Where boundaries between earlywood and latewood were diffuse, the difference between pure earlywood and pure latewood was identified, and this transition zone was split in half for measurement (after Stahle *et al.* 2000; Therrell *et al.* 2002). Crossdating and measurement accuracy were verified with the computer program COFECHA (Holmes 1983) using 50-year segments lagged 25 years.

Each tree-ring series was detrended and indexed using the program ARSTAN (Cook and Holmes 1985). Detrending is designed to remove long-term biological growth trends caused by changing size and age, and indexing to remove differences in mean growth rate among trees. All series were first detrended with a curve of best fit (either a negative exponential curve or straight lines of any slope) and were secondly de[illegible]d with a smoothing spline (Cook and Pete[illegible]). The autoregressive modelling option in ARSTAN was used to remove the low-order autocorrelation found in the individual ring width indices. The robust mean value function was used to compute the white noise residual chronology, which corresponds to the time series structure of the instrumental precipitation data for the January–June season (see below). Thirty cores from 20 trees were included in the final EW residual chronology for Las Alazanas.

Instrumental precipitation data were obtained from the meteorological station at Saltillo, Coahuila (25°25′N, 101°0′W; 1,589 m) approximately 55 km northwest of the study site. These monthly data were discontinuous and extended from 1950–1959, 1970–1981, and 1983–1998 (38 total years). A few records from other nearby climate stations were examined, but they were very short, discontinuous, and too weakly related with the derived chronology to contribute to this analysis.

To determine the seasonal precipitation response of the EW chronology, the monthly precipitation data for Saltillo were first correlated with the standardized EW chronology. Consecutive months with the highest correlation were seasonalized and then used to develop the subsequent transfer function. The EW chronology was entered into a bivariate regression analysis with the seasonal precipitation data. The resulting model was used to predict precipitation from EW tree growth, both during and preceding the period of instrumental precipitation measurement. We attempted to verify the model by splitting the instrumental precipitation record in half, performing experimental calibrations on the shorter subperiods, and then comparing the predicted to observed precipitation in the alternate subperiod not used in the calibration. To test the relationship between ENSO and reconstructed winter precipitation, we correlated the observed and tree-ring reconstructed precipitation data for Saltillo with the Tropical Rainfall Index (TRI), a standardized measure of precipitation

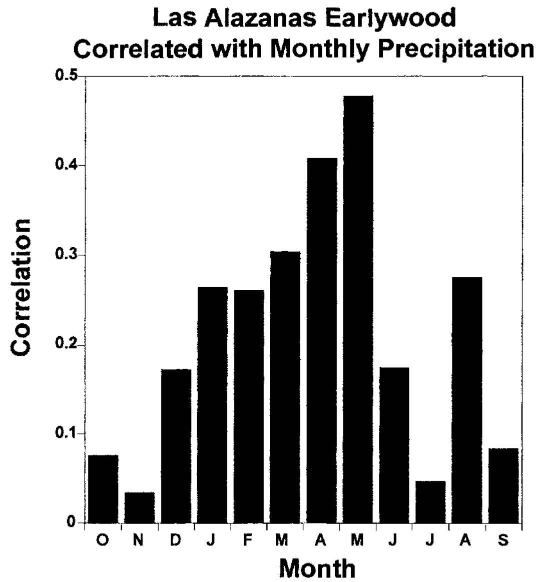

Figure 2. A plot of the correlation coefficients (r) computed between the Las Alazanas EW chronology and monthly precipitation totals for Saltillo from 1950–1998 (minus 11 missing values).

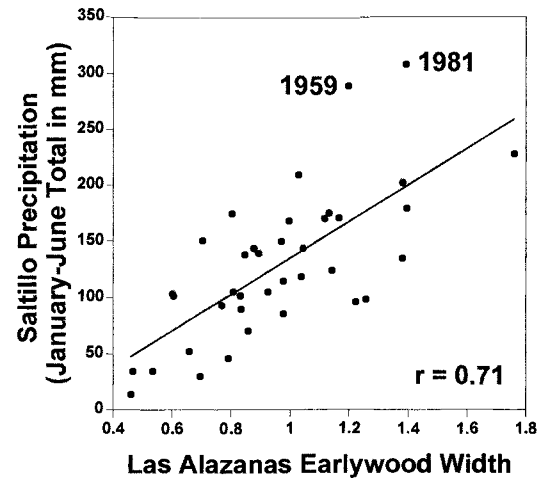

Figure 3. A scatter plot of the bivariate regression model relating the Las Alazanas EW chronology with January–June total precipitation for 1950–1998 (with 11 missing years of precipitation data). Note the underestimation of the two wettest years, 1959 and 1981.

anomalies over the central equatorial Pacific available from 1900 to 2000.

RESULTS

A 219-year EW-width chronology was developed, dating from 1782 to 2000. The earlywood chronology crossdated extremely well and had a high inter-series correlation (r = 0.70 among all radii). The EW chronology is most highly correlated with March, April, and May precipitation at Saltillo (Figure 2), but it is also weakly correlated with the Saltillo data in January, February, and August (although August is likely by chance). Correlation experiments indicated that January through June (winter-spring) was the optimal seasonalization period to maximize the precipitation correlation with the EW chronology.

We regressed the EW chronology against observed winter-spring precipitation to develop a calibration model for reconstruction (Figure 3). This regression model explains 49% of the variance in Saltillo January–June precipitation for the period 1950–1998 (Table 1, after downward adjustment for the loss of two degrees of freedom):

$$Y_t = -27.29 + 162.52x_t \quad (1)$$

where Y_t is the estimate of January–June precipitation in year t, and x_t is the standard EW width chronology also in year t. The observed and reconstructed precipitation series have similar time series structure (both are white noise, with first order autocorrelation coefficients of −0.023 and −0.082, respectively, for 1950–1998). Note that there are 11 missing values in the Saltillo seasonal precipitation series (Figure 4), so this calibration is based on 38 observations from 1950 to 1998.

The time series comparison of observed and reconstructed precipitation indicates that the strongest agreement between the two series is observed after about 1980 (Figure 4). We split the 38 observed Saltillo precipitation values in half and performed calibration and verification experiments on the two subperiods (1950–1976, n = 18, and 1977–1998, n = 20). The calibration and verification statistics computed for the full 38-year time interval and the two experimental subperiods are presented in Table 1.

The EW chronology explains 27% of the variance in January–June precipitation during the early subperiod (1950–1976), and the predicted values during the later verification period agree strongly with the independent observed precipitation data

Table 1. Calibration and verification statistics computed for the full calibration period (1950–1998), and two experimental subperiods (1950–1976 and 1977–1998; CORR. = correlation coefficient, ns = not significant; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$). The variance explained (R^2a) has been adjusted for loss of degrees of freedom associated with the two parameters in the calibration equations. The intercept (B_0) and the slope (B_1) are listed for each model. The Durban-Watson (D-W) statistic tests for autocorrelation in the regression residuals (lack of significant autocorrelation is the desired result, Draper and Smith 1981). The paired t-test compares the observed and reconstructed means, and no statistical difference is the desired result (Steel and Torrie 1980). The sign test compares departures above or below the mean for the observed and reconstructed series (hits/misses, many hits and few misses is the desired result, Fritts 1976). The positive reduction of error statistic (RE) calculated for both models indicates that the predicted rainfall data are more accurate than estimates based only on the observed mean during each calibration period (approximate 95% confidence limits for $n > 10$ is RE > 0.0; Fritts 1976).

Calibration					Verification			
Period	R^2a	B_0	B_1	D-W	Corr.	t-test	Sign Test	RE
1950–1976	0.27	−17.04	167.40	0.03ns	0.56**	2.52*	11/7ns	0.05
1977–1998	0.70	−56.92	178.55	0.18ns	0.84***	−3.29**	17/3**	0.54
1950–1998	0.49	−27.29	162.52	0.16ns				

on most statistical measures (r = 0.84, RE = 0.54, Table 1), except for the paired t-test on the observed and reconstructed means, which are different (Table 1). Also, the calibration based on the late subperiod does not verify exceptionally well against the independent precipitation data in the early 1950–1976 time period (r = 0.56, RE = 0.05, the sign test does not achieve significance, and again failing the paired t-test, Table 1).

These weak validation statistics for the experimental calibration during the 1950–1976 period might reflect problems with the precipitation data, the tree-ring chronology, or both. The tree-ring chronology is certainly located at some distance from the Saltillo gage, and at a significantly higher elevation (3200 *vs.* 1589 m a.s.l.). Therefore, coherence of the climate regimes at Saltillo and in the Sierra de las Alazanas could indeed be subject to significant changes over time. The surest way to improve the tree-ring reconstruction of regional precipitation will involve the further collection and quality control of instrumental precipitation data, and the development of additional tree-ring chronologies in the area. In the meantime, we argue that the full 38-year period common to the instrumental and tree-ring data provides a reasonable calibration model (Equation 1 and Table 1) sufficient for this initial reconstruction of Saltillo winter-spring precipitation in the pre-instrumental period. We do concede, however, that additional research into both the instrumental climate record and regional old-growth forests is needed to improve and extend this reconstruction.

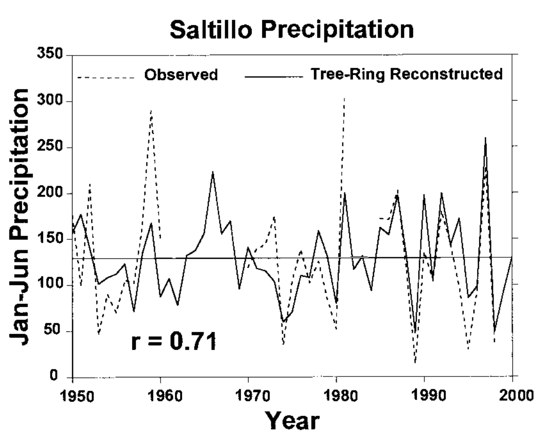

Figure 4. Time series comparison of observed and tree-ring (EW) reconstructed January–June total precipitation for Saltillo, 1950–1998. Note the observed and reconstructed dry conditions during the 1950s and 1970s, the poor agreement between the two series in the early 1950s, the underestimation of observed wetness in 1959 and 1981, and the more accurate tree-ring estimation of the driest years (*e.g.* 1974, 1980, 1989, 1998).

DISCUSSION

The EW reconstruction of winter-spring precipitation from 1782–2000 is illustrated in Figure 5, with a spline curve highlighting decadal variability in past precipitation. The calibration results for the 1950–1998 period suggest that the reconstruction represents about half of the variance in actual winter-spring precipitation, but that is based on the fully replicated chronology of 30 radii. Sample size declines to 14 radii by 1850, and to only 8 radii by 1800, so the uncertainty of this rainfall estimate for northeast Mexico is large before 1850. Nevertheless, comparisons with PDSI reconstructions in Texas (Stahle and Cleaveland 1988), and a winter precipitation reconstruction for Durango to the west in the Sierra Madre Occidental (Stahle *et al.* 1999) tend to support the large decadal excursions in Saltillo precipitation over the past 219 years.

Extended droughts are reconstructed for Saltillo in the early 1800s, 1860–1870s, 1950s, 1970s and in the late 1990s (Figure 5). However, the worst drought in this 219-year reconstruction occurred in the mid-19th Century (1857–1880) when 17 of 24 years are estimated to have been well below the average for winter-spring precipitation. Severe mid-19th century drought has been reconstructed for Texas, Chihuahua, and Durango (Stahle and Cleaveland 1988; Diaz *et al.* 2002; Cleaveland *et al.* 2003), but dry conditions appear to have persisted longer in the Saltillo precipitation estimate.

The latter half of the 20th Century also stands out as a period of repeated decade-long droughts in the observed and reconstructed precipitation records for Saltillo. The 1950's drought lasted five consecutive years from 1953–1957 (Figure 4), followed by dry conditions in the 1970s and several very dry years in the 1990s (Figure 4). In fact, the winter-spring precipitation reconstruction (Figure 5) has noticeable multi-decadal trends of precipitation, with declining precipitation from *ca.* 1830 to 1870, increasing precipitation from 1870 to 1940, and then a decreasing trend after 1940.

The extraordinary wetness reconstructed for 1997, the wettest year in the entire 219-year reconstruction, raises the question of possible ENSO influences on winter-spring precipitation in the Saltillo region. The El Niño event of 1997–1998 was perhaps the strongest warm event in recorded history, but the wet conditions measured and reconstructed at Saltillo in 1997 occurred from January–June, while the massive warming of sea surface temperatures in the central and eastern equatorial Pacific did not begin until May or June of 1997 and peaked during the boreal cool season of

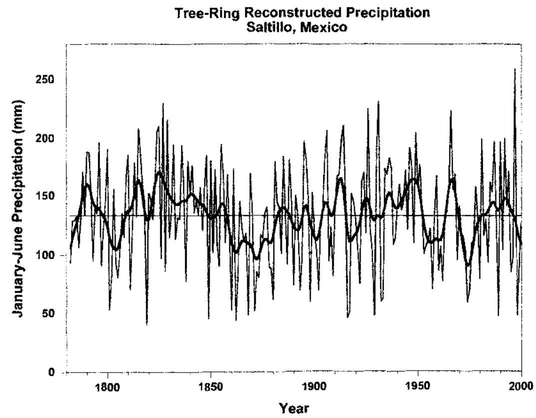

Figure 5. Tree-ring reconstructed winter-spring precipitation (January–June) for Saltillo, Mexico, 1782–2000. A 10-year smoothing spline has been fit to the annual estimates (Cook and Peters 1981). Note the prolonged drought episodes in the 1800s, 1860–1870s, 1950s, 1970s, and 1990s. Sample size includes 2 radii at 1782, 8 at 1800, 14 at 1850, 22 at 1900, and 30 at 1950.

1997–1998 (see K. Wolter's Multivariate ENSO Index at http://www.cdc.noaa.gov/~kew/MEI/mei.html). Consequently, the incredible wetness of 1997 in Saltillo was not linked in any obvious way to the extreme warm ENSO conditions of 1997–1998.

To measure the strength of the ENSO influence on Saltillo precipitation, we correlated the winter-spring reconstruction with the Tropical Rainfall Index from 1900 to 2000 [the TRI is a composite index for rainfall over the central equatorial Pacific (in the Niño 4 region) and was created by Wright (1982)]. Using a seasonalization of the TRI for the boreal cool season (DJF), the correlation with reconstructed Saltillo precipitation is $r = 0.33$ ($p < 0.05$). This preliminary result suggests that approximately 10% of the interannual variability in winter-spring precipitation for the Saltillo area may be linked to large-scale climate dynamics associated with ENSO. However, Cole *et al.* (2002) use coral data from the equatorial Pacific to argue that prolonged La Niña conditions during the mid-19th Century may have been involved in protracted drought over the USA in the 1860s. If correct, Figure 5 indicates that the impact of this cold ENSO event may have included intense drought over northeastern Mexico.

Finally, the first half of the 19th Century (*ca.*

1810–1840) is reconstructed as a period of recurrent winter-spring wetness (Figure 5). The sample size in the EW chronology is low during this time period, but this wet episode is probably real. Fye *et al.* (2003) reconstruct widespread wetness over the western USA during the early 19th Century, one of four or five decade-long pluvials estimated for the West since A.D. 1500.

CONCLUSIONS

The EW width series developed by this project in the Sierra de las Alazanas of Coahuila crossdate extremely well. The high correlation between trees and radii is indicative of a strong external environmental influence on radial growth, which we show to be predominantly precipitation during and preceding the early growing season. We were able to calibrate the derived EW width chronology with January–June seasonalized precipitation measured at Saltillo since 1950. However, attempts to independently verify this reconstruction have been hampered by the short and discontinuous nature of the available monthly precipitation data from Saltillo and nearby stations. The experimental verification performed on two short subperiods after 1950 passes on some statistics, but fails on others. We do see considerable agreement between the decadal moisture anomalies estimated for Saltillo and other tree-ring reconstructions of precipitation and drought indices over the western USA and northwestern Mexico. Additional tree-ring data from the Sierra Madre Oriental and further development of the instrumental precipitation data will help improve precipitation reconstruction for northeastern Mexico. Old-growth Douglas-fir can be found locally at higher elevations on the northern ranges of the Sierra Madre Oriental and promise to provide an excellent network of climate-sensitive chronologies for the region.

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