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A TREE-RING RECONSTRUCTION OF PAST PRECIPITATION FOR BAJA CALIFORNIA SUR, MEXICO

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ABSTRACT

There is great interest in the climatic variability of Baja California and the Sea of Cortes, but long-term information is limited because instrumental climate records begin in the 1940s or 1960s. The first tree-ring chronology of *Pinus lagunae* was developed from the southern part of the Baja California Peninsula and the chronology is used to reconstruct the history of precipitation variations. A September–July precipitation reconstruction is developed for the period AD 1862–1996 ($R = 0.71$, $p < 0.0001$, $n = 56$, cross-validation = 0.68). This reconstruction is used to assess precipitation variability over the past two centuries, including the relationship with ENSO events. The reconstructed precipitation series indicates a long drought period from 1939 to 1958. It also shows that 1983, one of the strongest El Niño events of the 20th century, is the wettest year. El Niño events during the 20th century are associated with above-normal precipitation, whereas La Niña events are characterized by below-normal precipitation. Four of the most extreme wet years occurred in association with these warm events (1905, 1912, 1919 and 1983). Seventy-one percent of La Niña events are characterized by below-normal precipitation. Sixty-two percent of El Niño events are characterized by above-normal precipitation. Tree-ring growth of *P. lagunae* is most strongly correlated with winter precipitation in Sonora, Sinaloa and southern Baja California Sur. Precipitation data from meteorological stations in northern Baja California do not correlate well with the tree-ring chronology because this zone has a Mediterranean climate, which differs from the rest of northwest Mexico. Copyright © 2001 Royal Meteorological Society.

KEY WORDS: Baja California Sur, Mexico; dendroclimatology; ENSO-precipitation; *Pinus lagunae*; Sierra de La Laguna

1. INTRODUCTION

In many regions meteorological records are too sparse to investigate regional climatic patterns (Anderson, 1990). These data are frequently limited to the most recent decades and come from stations located at lower elevations, thus providing poor temporal and spatial coverage (Metcalfe, 1987). For northwest Mexico, most of the climate data starts in the 1950s and contain little information on variability of climate over decades and longer. Indirect evidence of climatic variability such as long time series of tree-ring growth measurements may serve as proxy records of past conditions (e.g. Schulman, 1956; Fritts, 1976; Stahle *et al.*, 1998). A major reason for investigating past climate variability is because it is a key factor directly and indirectly affecting ecological processes and human economies.

Few dendrochronological and dendroclimatological studies have been done in Mexico and even fewer in tropical regions. The most southerly studies on the North American continent were done in Michoacan in Central Mexico, where the signals of spring precipitation and winter temperature were recorded by *Abies religiosa* (Huante *et al.*, 1991). An examination of tree rings of the same species near Mexico City showed decreases in ring widths over the past 30 years caused by air pollution (Alvarado *et al.*, 1993).

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In northwest Mexico, studies reconstructing fire histories (Villanueva-Diaz and McPherson, 1995; Swetnam and Baisan, 1996; Villanueva-Diaz, 1996) and dating archaeological sites (Scott, 1963, 1966; Buk and Minnin, unpublished) have concentrated on forests near the US border (Sierra San Pedro Mártir and the Sierra Madre Occidental). Elsewhere in northwest Mexico, dendroclimatical studies have been used to evaluate precipitation patterns and trends (Rueda, 1983). Michaelsen (1989) studied the frequency of El Niño events. Other researchers have reconstructed El Niño–Southern Oscillation (ENSO) events and indices (e.g. Lough and Fritts, 1985; Cleaveland *et al.*, 1992; Lough, 1992; Stahle and Cleaveland, 1993; Stahle *et al.*, 1998, 1999). Stahle and Cleaveland (1993) found that the strongest and most consistent ENSO signal in tree rings is in northern Mexico and the southern USA. They used a network of tree-ring chronologies from these regions to reconstruct a winter Southern Oscillation Index from 1699 to 1971. Villanueva-Diaz (1998) found that winter precipitation and chronologies of earlywood widths tend to be enhanced during warm ENSO events in Chihuahua and Durango to the east of the study area. Stahle *et al.* (1999) reconstructed winter precipitation in Durango and found that this season was significantly correlated with indices of ENSO.

O'Hara and Metcalfe (1995), using tree-ring records from Baja California, Sonora and Chihuahua, and historical evidence from the valley of Mexico City, identified Mexican climate fluctuations over the past 600 years, though they did not find a clear climatic relationship between north and central Mexico. Villanueva-Diaz and McPherson (1995) reconstructed Palmer Drought-Severity Indices (PDSI) for the borderlands of Sonora, but comparable reconstructions of PDSI or precipitation from more southerly states are not yet available.

The variability of the climate in Mexico makes it important to determine the palaeoclimate data for each region. Except for a study by Biondi and Fessenden (1999), there are no dendrochronological studies for Baja California Sur and the coastal plain of Sinaloa and Sonora attempting to develop climatic reconstructions or determine climate variations. The broad goals of the current study were to: (i) develop a tree-ring chronology using the endemic pine *Pinus lagunae* from Sierra de La Laguna at the tip of the peninsula of Baja California; (ii) use the chronology to develop a dendroclimatic reconstruction for the southern part of the peninsula; (iii) use the chronology to evaluate broad-scale winter precipitation patterns in the Baja California and Sea of Cortes region; and (iv) use tree-ring reconstructions to evaluate the potential influence of ENSO on winter precipitation and tree-ring patterns in this region.

2. SITE DESCRIPTION

Northwest Mexico comprises four states surrounding the Sea of Cortes, two on the peninsula of Baja California (Baja California and Baja California Sur), and Sonora and Sinaloa on the mainland (Figure 1). The Tropic of Cancer crosses the region near 22°50′N. The peninsula of Baja California begins at the US border near 32°30′N. It is approximately 1400 km long and varies from 45 to 200 km wide (Hastings and Turner, 1965). The topography and climate of the peninsula is dominated in the north and west by the central mountain axis, the Sierra Juárez and the Sierra San Pedro Mártir, and in the south by the Sierra de La Laguna (Shreve, 1942).

The Sierra de La Laguna (22°50′–24°N, 109°45′–110°115′W) is a small mountain range in the extreme southern end of the peninsula (Figure 1). Desert environments and sea surround the middle and high ranges of the Sierra. The flora and fauna of the Sierra have developed unique species because the Sierra de La Laguna, as part of Cape Region, was isolated from the rest of the continent during the Miocene (Arriaga and Ortega, 1988). In its upper portion, the only pine–oak forest of the state covers about 20 000 ha (Villa-Salas, 1968) at an altitude ranging between 1800 and 2000 m above sea level. The soil of the Sierra de La Laguna is granitic and in the highest part the dominant soils are Euthric cambisols. These soils are associated with Haplic phaeozem and Humic cambisol rich in phosphorus, moderate in calcium and potassium, and with low magnesium (Maya, 1988).

Northwest Mexico is in a climatic transition zone (tropical–subtropical). Many factors influence the climate in this area, including the cool waters of the California Current (moving from the polar region

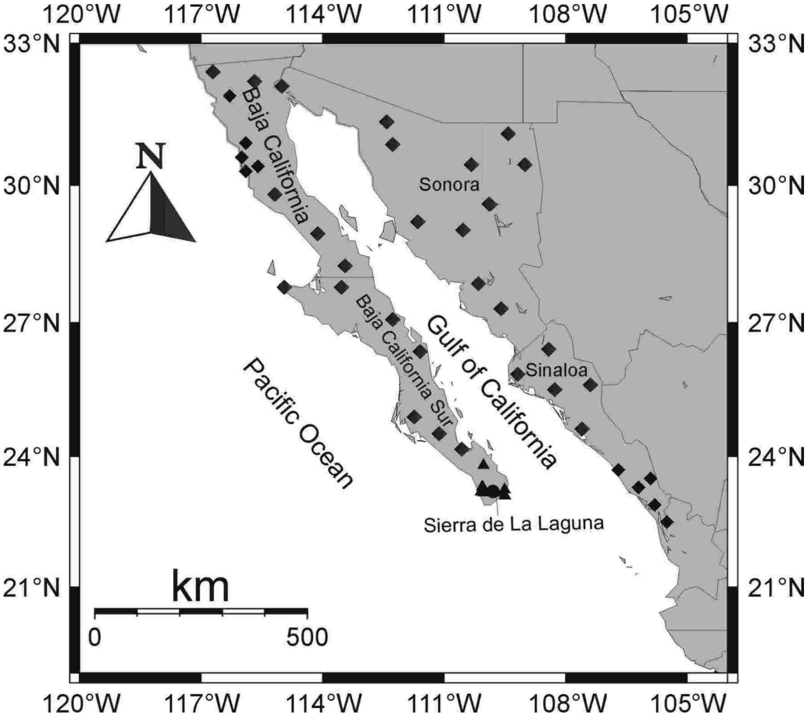

Figure 1. Map of the study area. ▲ represent the seven weather stations closest to the Sierra de La Laguna tree-ring site that were used in the precipitation reconstruction. ◆ represent other regional weather stations used to compare region-wide precipitation patterns to the tree-ring chronology

toward Ecuador), the warm Gulf of California, and the Pacific tropical current. Atmospheric subtropical high pressure and maritime polar air from the Pacific Ocean also influence the region (Hastings and Turner, 1965). The air mass brings fog, drizzle and occasional moderate precipitation over the northern portion of this area during the winter months. The Pacific coast of the state of Baja California is more Mediterranean in nature (Comrie and Glenn, 1998). Tropical cyclones are crucial in determining the total annual precipitation and mainly influence the southern part of the region. They occur mostly in August, September and October (García-Oliva *et al.*, 1991). The dry season extends from November to late June in the southern part, although winter rains occur periodically in small amounts.

The precipitation in the southwestern USA and northwest Mexico is associated with ENSO events (Andrade and Sellers, 1988). The ENSO is correlated with moist-cool conditions over northern Mexico (Kiladis and Díaz, 1993; Stahle and Cleaveland, 1993). Wet winters are typical during warm El Niño events, and dry winters are prevalent during cold La Niña events (Douglas and Englehart, 1981; Andrade and Sellers, 1988).

There are four different dry climate types in northwestern Mexico: (i) steppe with winter rains, (ii) desert with winter rains, (iii) desert with rains during all the year, and (iv) desert with summer rains (García, 1981). A great part of the region is arid, based on characteristics of the vegetation where the predominant vegetation is desert-like xerophilus scrub and thorn forest. At higher altitudes, the prevailing dryness is somewhat mitigated and there are deciduous-tropical and conifer–oak forests (Rzedowski, 1978). There are similar forest stands on Islas Cedros and Guadalupe that have some potential for dendrochronological work. The larger forests are on the mainland in the Sierra Madre Occidental.

The Sierra de La Laguna pine–oak forest overstorey is dominated by the endemic species *P. lagunae* and the oak *Quercus devia*, with *Arbutus peninsularis* and *Nolina beldingii* dominant in a lower tree stratum (Mercado, 1993). *P. lagunae* is the species used in this study. *P. lagunae* was formerly considered a variety of *P. cembroides*, but in 1987 its taxonomic level was upgraded to a species (Passini, 1987). Two other oak species, *Q. rugosa* and *Q. arizonica*, have a restricted distribution within the forest (Arriaga *et al.*, 1992). The common species in the understorey are *Calliandra peninsularis*, *Heterotoma aurita*, *Verbesina pustulata* and *Hypericum peninsularis*, and some short-lived species like *Arracacia brandegeei*, *Desmodium postratum*, *Stachys coccinea* and *Tagetes lacera* (León de La Luz and Domínguez-Cadena, 1989).

3. METHODS

3.1. Chronology development

Two increment cores were taken from each of 80 pine trees in the forest of the Sierra de La Laguna. To minimize non-climatic influences on ring growth, only trees with no obvious injury or disease were sampled. To maximize the ages of sampled trees and the length of the tree-ring chronology, the tallest and largest diameter trees were sampled. Cores were mounted and fine-sanded. All tree rings were cross-dated to their exact year of formation by standard dendrochronological techniques (Stokes and Smiley, 1968). The annual rings of each core were measured to the nearest 0.01 mm. Each ring-width measurement series was detrended by fitting a cubic smoothing spline with a 50% cutoff frequency of 100 years to remove the age trend and the effects of stand dynamics (Cook and Kairiukstis, 1990). The index series were combined into a master chronology using a biweight robust estimate of the mean (Cook, 1985).

3.2. Precipitation reconstruction

As typical with tree-ring chronologies, sample size (number of measured ring-width series included in the chronology) decreases with time before the present. Subsample signal strength (SSS) was used to determine the adequacy of sample replication in the early years of the chronology where the number of the samples is usually smaller than in the more recent period (Wigley *et al.*, 1984). To ensure the reliability of the climate reconstruction, based on the sample size and between tree correlations, the analysis was restricted to the time period with a SSS of at least 0.80, which in these data sets represents a sample size of three trees. The chronology spans the period AD 1862–1996.

Seven meteorological stations close to the sampling site with both monthly total precipitation and monthly mean temperature records were selected. Climate records were obtained from two Mexican Federal agencies, the Biological Research Center (CIB) and National Water Commission (CNA) (Salinas-Zavala, 1995). Missing data were estimated by the method of Paulhus and Kohler (1952), and double-mass analysis (Kohler, 1949) was used to test for inhomogeneity between stations. Averaging the seven meteorological stations developed the regional climate record. There was a significant correlation ($R = 0.79$, $p < 0.05$) between the climate stations for the period AD 1940–1996 (57 years).

Response function analysis (Fritts, 1976) was done using the chronology and monthly and seasonal precipitation and temperature data covering the same period to determine the most appropriate model for reconstruction. A linear regression equation between the predictors (tree-ring indices) and the predictand (climatic data) was computed for the calibration period. To evaluate the goodness-of-fit of the model, cross validation was done by the PRESS procedure (Weisberg, 1985).

Spectral analysis was used to evaluate periodic behaviour of the reconstructed precipitation time series. A spectrum of reconstructed precipitation was estimated by smoothing the periodogram with a succession of Daniel filters (Bloomfield, 1976). Five percent of each end of the series was tapered with a raised-cosine filter (Hamming, 1983), and the series was padded with zero to a length of 256 years. The periodogram of the series (1860–1997) was computed by discrete Fourier transform and smoothed by a 7-weight Daniel filter to produce the estimated spectrum. A null continuum was calculated by smoothing the periodogram successively with broader filters (window length of 33 and 55) than used for the spectral estimates. The 95% confidence intervals for the spectral estimates were computed based on the assumption of Chi-square (Bloomfield, 1976; Meko *et al.*, 1985).

3.3. *ENSO analysis*

Extreme wet and dry years in the standardized reconstructed precipitation series (1862–1996) were compared with the ENSO events. An arbitrary threshold of 0.5 S.D. above or below the mean was used to determine El Niño years (> 0.5 S.D.) and La Niña years (< -0.5 S.D.). The number of events that occurred below or above the mean was also computed. The probability of observing these associations by chance was computed by means of contingency (Chi-square) tests. For comparison with the standardized reconstructed precipitation dates, El Niño and La Niña events were assigned calendar dates of the year following the start of the warm and cold events (Kiladis and Díaz, 1993).

3.4. *Relationship between the tree-ring chronology and regional meteorological station precipitation data*

Monthly and seasonalized precipitation data from 48 stations were correlated with the tree-ring chronology to search for a relationship between tree growth and the climate of northwest Mexico. Those precipitation series correlating with the tree-ring chronology with a coefficient greater than 0.5 were analysed by rotated principal component analysis (PCA) to evaluate the spatial relationships. Two components were retained, explaining 76% of the variance. The first component explained 48% of the variance and the second 28%. The first component grouped 16 stations with a loading greater than 0.7. Nine of these series were in Sinaloa, with two series in Sonora, but very close to Sinaloa, and five from Baja California Sur. The second component grouped eight series, five from Sonora and three from Baja California Sur. The correlation matrix showed strong correlations ($r > 0.7$, $p < 0.01$) between the series within the same group, providing further justification for separating the two groups.

4. RESULTS AND DISCUSSION

4.1. *Chronology*

The cross-dating process with *P. lagunae* was difficult because there was cross-dating success for only 25% of the trees, mainly for the large number of intra-annual ring boundaries (false rings). This is not unusual in dendrochronology. Schulman (1956) found similar problems in studying *P. cembroides*, the Mexican pinyon. Many other species that have produced valid annual tree-ring chronologies also have many individual trees whose growth rings are too complex for dating (e.g. *Juniperous virginiana*, *J. scopulorum*, *P. edulis*, *Taxodium disticum*; D. Stahle, personal communication).

A previous study by Biondi and Fessenden (1999) using ^{14}C indicates that there are indeed missing and false rings in *P. lagunae*, and consequently they could not assign calendar years to the tree-rings. However, their study was based on only three trees. The current study demonstrates that it is possible to cross-date *P. lagunae* (Figure 2). The derived chronology is highly correlated with annual rainfall indicating that *P. lagunae* can be used for dendroclimatic studies.

The chronology spans 165 years (1833–1997). This is short by dendrochronological standards. *P. lagunae* is not as long-lived as many other *Pinus* species. Other researchers have reported that *P. lagunae* lives for only about 150 years (Pinel, 1985; Díaz, 1995), whereas *P. edulis* Engelm., a species similar to *P. cembroides* (Mirov, 1967), lives almost 1000 years in rare instances (Brown, 1996). The inner part of the older trees was difficult to cross-date because the ring boundaries were not clearly visible and they did not exhibit common patterns of wide and narrow rings. Only three trees had datable rings earlier than the 1830s. The mean correlation coefficient between all measured ring width series was 0.41 ($n = 32$, $p < 0.05$), indicating a moderate common growth signal among trees.

4.2. *Precipitation reconstruction*

None of the climate records from meteorological stations exhibited inhomogeneity. The average correlation coefficient for the seven stations of Sierra de La Laguna was 0.7 ($p < 0.05$) (Díaz *et al.*, 1994). The monthly averaged data for 1940–1996 (57 years) were used with the chronology in the response

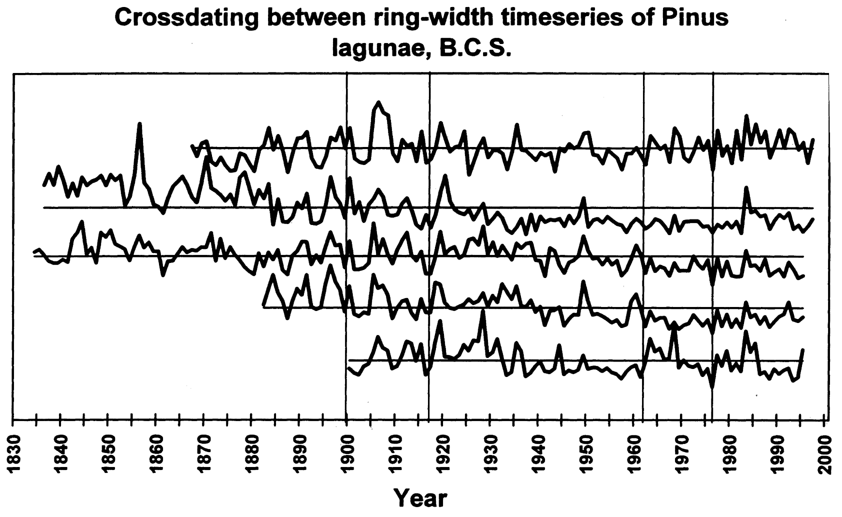

Figure 2. Examples of some annual ring width series of *P. lagunae* showing the coherency of the common annual growth pattern. The vertical lines identify common low tree-ring widths

function analysis (Figure 3). The precipitation data from September of the previous year through to July of the current year was the most appropriate predictand for reconstruction. The precipitation of this 11-month period accounts for 73% of the annual precipitation. Substantial precipitation occurs in the previous autumn, winter and spring before the tree-growth period of May–October (Díaz, 1995), and this moisture is apparently important to *P. lagunae* tree-ring growth. This climate-tree growth pattern involving prior cool season precipitation is commonly found in conifers in temperate zone, semi-arid sites (Fritts, 1976).

The meteorological stations from this region reflect a desert climate with summer (July–October) rains. It appears that the heavy summer rains are not as important for tree-ring growth. This may be because the rain falls so rapidly that a large part of the water runs off to the sea (García, 1978) rather than penetrating the soil and benefiting the trees. Winter (November–February) rain comprises only 5% of the

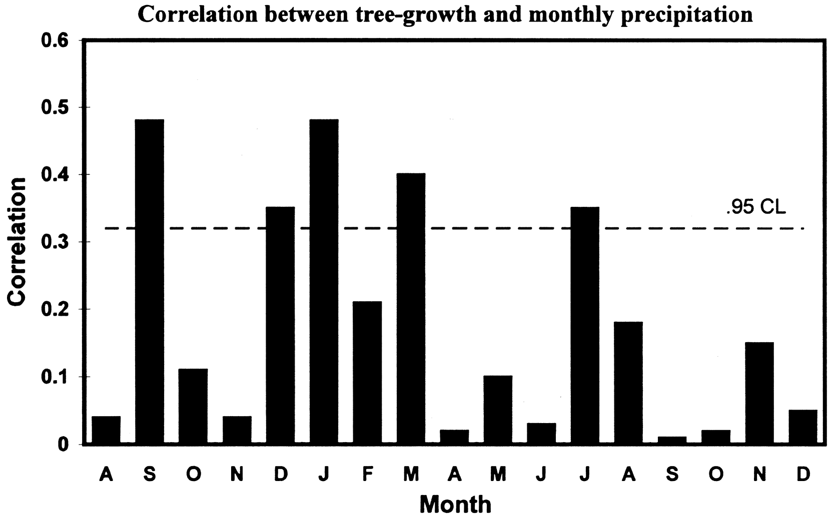

Figure 3. Correlation between tree growth and averaged monthly precipitation data (1939–1996). Dotted line represents 95% confidence level

total annual precipitation (García, 1981); however, it is probably important to tree-ring growth because the lower temperatures reduce evaporation, and the rains also tend to occur over longer periods of days and weeks, allowing the moisture to soak into the soil.

The linear regression model between tree-ring indices and precipitation for the 1940–1996 calibration period was significant ($F = 55.93$, $p < 0.001$). The model obtained was:

$$Y = -32.1 + 338X,$$

where Y is September–July precipitation (in mm) and X is the tree-ring index.

Tree-ring indices explain 50% of the variance in precipitation (Figure 4). Cross-validation using the PRESS test (Weisberg, 1985) indicates the model adequately estimates precipitation data not used in the fitted model ($R^2 = 0.46$). Therefore, the fitted linear model was used to reconstruct September–July precipitation back to 1862. Reconstructed precipitation generally matches both the interannual patterns and decadal-scale trends in the observed precipitation time series (Figure 4). The largest outlier (the difference between values observed and predicted by the model was 436 mm) was in 1950, with the observed precipitation being much higher than that reconstructed. Heavy rains that fell in a few days in September 1949 probably caused this difference. The rain was caused by a single hurricane in 1949 (NOAA, 1999). Tree growth generally responds poorly to such heavy rainfall because most of the water runs off and is not available to the trees.

The reconstructed precipitation series (Figure 5) allows one to extend the climatic information back 79 years for Baja California Sur. The reconstructed series shows the highest precipitation recorded by the trees was in 1983, which corresponds to one of the strongest El Niño events of the past century. Other extremely wet years that occurred in association with El Niño events were 1905, 1912 and 1919.

Tree-ring reconstruction indicates a major and prolonged drought from 1939 to 1958, with only 2 years of above average reconstructed precipitation. The 1950s drought was severe over Mexico and the southwest USA (Swetnam and Betancourt, 1998). The reconstruction suggests that the 1950s drought was a continuation of the event that started in the 1930s in Baja California Sur.

The reconstructed precipitation had a moderately low frequency spectrum, with low variance at 2.5–4 years, and high variance at 4–20 years (Figure 6). The high variance around 5.9–7.4 years could be an ENSO signal. The dive in variance near zero frequency is probably caused by the standardization procedure (detrending). Meko (1992) found that regional tree-ring (southwest USA) spectra are generally dominated by low frequency, with 32–46% of the variance in a 2.8–10.2-year ENSO band. Diaz and Pulwarty (1992) found a significant peak at 7.1 years for ENSO warm events from 1882 to 1935.

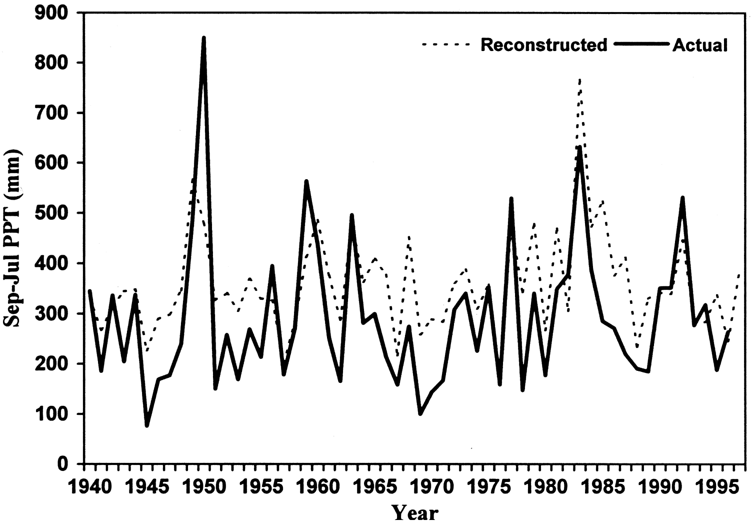

Figure 4. Meteorological stations (solid) and reconstructed (dash) September–July precipitation for Sierra de La Laguna, Southern Baja California, Mexico

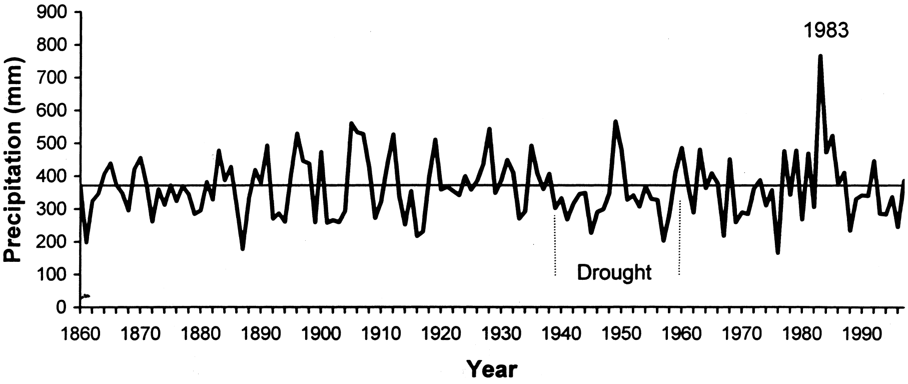

Figure 5. Reconstructed September–July precipitation for Sierra de La Laguna, Southern Baja California, Mexico

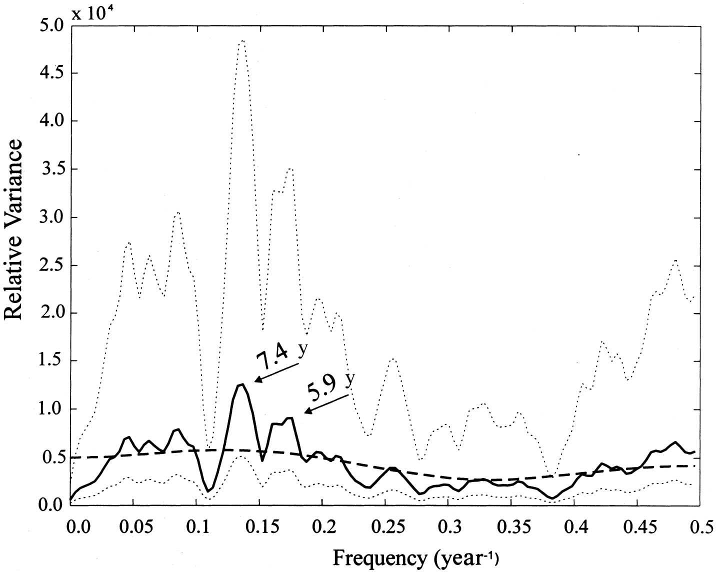

Figure 6. Estimated spectral density of reconstructed September–July precipitation for Baja California Sur, Mexico. The spectrum was estimated by successively smoothing the raw periodogram with a Daniel filter of length seven (solid line). The dotted lines are 95% confidence bands. The dashed line is the null continuum, estimated by smoothing the raw periodogram with Daniel filters of lengths 33 and 55

4.3. ENSO analysis

ENSO is considered to be the most important source of interannual climatic variation (Folland *et al.*, 1990; Stahle and Cleaveland, 1993; Neelin and Latif, 1998). The extreme events of ENSO have significant effects on climate over certain parts of North America, specifically over northern Mexico and the southeastern USA (Cavazos and Hastenrath, 1990). The major reason Baja California is affected by ENSO is that during a warm event (El Niño), the following occur: (i) the warm water source of strong convection in the equatorial Pacific Ocean shifts from the western to the central Pacific (Holton, 1991); (ii) this results in an increase of energy input into the subtropical jet stream and an increase of the strength of westerly flow associated with the subtropical jet during the Northern Hemisphere winter (Rasmusson, 1991; Cayan and Webb, 1992); (iii) the Hadley Circulation intensifies, as the Walker Circulation is disrupted and the 'normal' easterly winds slacken over the eastern Pacific (Trenberth, 1991); and (iv) as eastward travelling Kelvin waves in the equatorial Pacific reach the eastern Pacific, warm water is transported north along the Central American and Mexican coast by northward moving gyres (Cane, 1991). The result of the increased westerly flow and enhanced subtropical jet is an increased transfer of energy, momentum and moisture in the atmosphere in the latitudinal band of Baja California. Warm water in the eastern Pacific transported northward along the Central American–Mexican coast, ensures that warm moist air is available for enhanced precipitation along the coast of Mexico. This water is a source of convective energy for eastern Pacific tropical storms, which increase in number during El Niño events (Cayan and Webb, 1992).

In comparison with the standardized reconstructed precipitation values, it was found that 33% of El Niño events coincided with extreme wet years (>0.5 S.D. above the mean), and 62% of El Niño events coincided with years of above average precipitation. Only 41% of La Niña events coincided with extreme dry years (<0.5 S.D. below the mean), but 71% of La Niña events coincided with years of below average precipitation (Figure 7(A) and (B)). Trees in arid regions are more sensitive to dry than wet years, because the dry years limit the tree-ring growth whereas other factors may limit positive growth response in extremely wet years. Therefore, the reconstruction may estimate dry conditions better than wet conditions.

A contingency analysis with Yates' correction yielded the value $X^2 = 2.78$ ($p = 0.05$). This suggests a non-significant relationship between the El Niño–La Niña events and the reconstructed extreme precipitation events. However, $X^2 = 3.98$ ($p = 0.05$) was significant when the El Niño–La Niña events were compared with reconstructed precipitation values below and above the mean.

As in other studies using tree-ring chronologies and meteorological data from Mexico and the southwestern USA, the climate signal best recorded by conifers is winter precipitation (Michaelsen, 1989; Stahle and Cleaveland, 1993; Stahle *et al.*, 1999). ENSO has the strongest influence on winter climate in the region. This winter precipitation has a strong effect on subsequent tree growth via recharge of soil moisture (Stahle *et al.*, 1998). The influence of ENSO (both warm and cold events) in the region confirms the studies of Kiladis and Díaz (1993) who found in their Sierra Madre division (including a great part of northwest Mexico) that the winter precipitation is significantly modulated by ENSO.

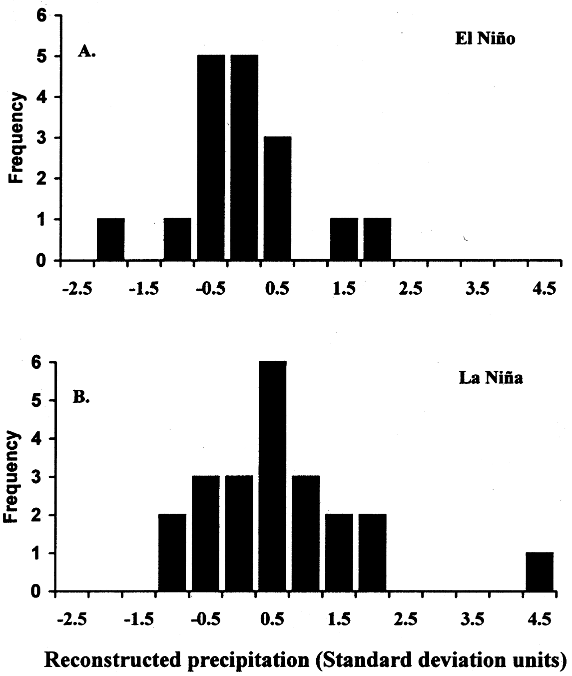

Figure 7. Histograms showing the distribution of: (A) wet and dry years during El Niño (warm) events and (B) wet and dry years during La Niña (cold) events

4.4. Relationship between the tree-ring chronology and regional meteorological station precipitation data

Precipitation of northwest Mexico from November to February had the best correlation with the tree-ring chronology, even in areas where summer precipitation is predominant. This apparently reflects the sensitivity of *P. lagunae* to winter rains. The relatively high correlations with the data of many meteorological stations over this large area is most likely caused by broad-scale atmospheric circulation patterns responsible for winter precipitation in northwest Mexico (Stahle *et al.*, 1998).

There are not enough years of recorded precipitation in Sinaloa (1964–1986), and Sonora (1962–1988) to do a reconstruction. But the local reconstruction has an important large-scale signal of precipitation for Baja California Sur, southern Sea of Cortes, and the coastal plain of Sinaloa and Sonora. The spatial pattern of regional precipitation is different compared with the spatial pattern recorded by trees in Chihuahua and Durango, which belong to the Sierra Madre Occidental and central tableland of northwest Mexico (Cleaveland *et al.*, personal communication).

The winter signal for the northern portion of the peninsula is somewhat different from the rest of the region (Figure 8), because it is characterized by a Mediterranean climate defined by the classic pattern of the dominant north Pacific anticyclone and an associated west-coast ridge in summer (Comrie and Glenn, 1998). In the middle part of the peninsula, 30% of annual precipitation falls during the winter and the percentage increases to the north (Hastings and Turner, 1965). The 0.5 significant correlation line (Figure 8) includes parts of Baja California Sur, Sonora, and Sinaloa. The highest values of correlation coefficients are in Sinaloa. This line is coincident with the Monsoon and Baja California Sur regions defined by Comrie and Glenn (1998) which have the same rainfall pattern with the summer rainfall peak, but with much less precipitation in Baja California. The peak of rainfall is in September for the monsoon region and in August and September for Baja California, possibly because of increased tropical storms. There are lower correlation values in west central Sonora (Figure 8). This area is more arid (Salinas-Zavala *et al.*, 1998) and has floristic (Wiggins, 1980), and faunistic (Alvarez-Castañeda *et al.*, 1995) similarities with the peninsula rather than with the surrounding mainland. Cool upwelling waters that favour desert conditions (Badan-Dangon *et al.*, 1985) may cause this pattern.

Summer and autumn precipitation is most abundant for almost the whole region. However, summer precipitation comes from different sources for the different areas and there is a lower spatial coherence of convective rainfall during this season (Stahle *et al.*, 1999). During the summer, the northern peninsula is considerably drier, with the influence of mid-latitude Pacific storms (Hastings and Turner, 1965; Reyes and Mejía-Trejo, 1991). In a great part of Sonora and Sinaloa, summer rainfall mainly comes from

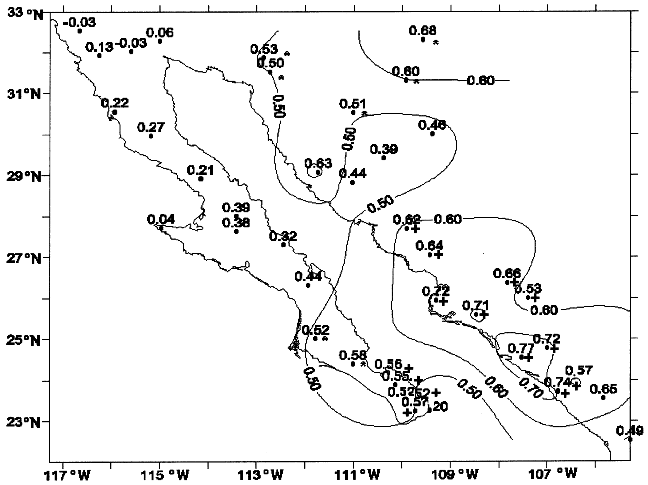

Figure 8. Isoline map of correlation coefficients between winter precipitation and the Sierra de La Laguna tree-ring chronology. Individual meteorological stations are indicated by their correlation with the chronology. The threshold line is the significant correlation of 0.5. + show the series grouped with factor 1, and * show the series grouped with factor 2

monsoon activity (Comrie and Glenn, 1998), whereas tropical perturbations are more important in Baja California Sur and a narrow coastal strip in Sinaloa, with the greatest frequency of rain in September (Rosendal, 1963).

5. CONCLUSIONS

P. lagunae has been successfully cross-dated and dendrochronologically analysed. The chronology is strongly correlated with instrumental climate records and provides accurate estimates of the natural precipitation variability over Baja California Sur and coastal plain of Sinaloa and Sonora. The reconstructed precipitation indicates a prolonged drought from 1939 to 1958. It also shows that 1983, one of the strongest El Niño events of the 20th century, is the wettest. The reconstruction also indicates the persistence of a winter precipitation signal in the region. Summer–autumn precipitation did not show significant correlation with our chronology, probably because the heavy rains result in runoff that is not available for tree growth.

The standardized reconstructed precipitation was sensitive to ENSO events. ENSO has the strongest influence on winter climate in the region. Seventy-one percent of La Niña events coincide with below average precipitation and 62% of El Niño events coincide with above average precipitation.

More tree-ring samples, including other species, such as the oak and dead trees from the Sierra de La Laguna site are needed to increase the length and improve the accuracy of the reconstruction. This may improve the reliability of statistical and spectral analyses. To understand past climate variability in the whole Baja California region, more tree-ring samples are needed from northern Baja California, such as Islas Cedros and Guadalupe, and to reunite other palaeoclimatic data that can extend the climate regional knowledge. Finally, it is important to investigate the relationship between the tree-ring data and the relationship with other teleconnections or simple variables like sea-surface temperature to derive a better knowledge of their effects in the region.

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