# El Niño-Southern Oscillation and precipitation history in Baja California: reconstruction using tree ring records

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## RESUMEN

Cinco series de anillos de crecimiento de árboles del norte de Baja California fueron evaluadas como fuente de información substituta en la reconstrucción de la precipitación y del fenómeno El Niño-la Oscilación del Sur. Las reconstrucciones fueron comparadas con los registros instrumentales e histórico para su verificación. Cinco cronologías basadas en el ancho de los anillos fueron desarrolladas usando técnicas dendrocronológicas y estadísticas estándares: una de *Pinus coulteri*, dos de *Pinus quadrifolia* y dos de *Pinus jeffreyi*. Una de éstas últimas actualizó una cronología ya existente, logrando doblar su período de calibración con los datos climáticos registrados por instrumentos. La duración de las cronologías fue de 101 a 551 años. Todas la cronologías presentaron correlaciones significativas con los registros de precipitación de Baja California (Ensenada), de California (San Diego) y con un índice ENSO basado en registros por instrumentos. La precipitación explicó entre un 6 a un 57% de la variación en el crecimiento de los árboles. Si bien ambos registros de precipitación estuvieron relacionados con el SOI ($R^2_{ajustado}$ : 48 y 16% respectivamente), las cronologías capturaron una señal más variable y débil ($R^2_{ajustado}$ : 3 a 24%). La concordancia entre el registro documental histórico y el SOI, reconstruído por la serie de anillos de árboles que presentó la mayor habilidad predictiva, fue 82%. Claramente, es necesario guiar la investigación hacia dos áreas. Primero, es necesario extender la cronología corta, que muestra las señales más fuertes de precipitación y ENSO. Segundo, las diferencias entre los sitios y las especies en relación con la señal climática, fuertemente justifica el estudio futuro de otros sitios y especies de Baja California para desarrollar una red de cronologías sensibles de anillos de árboles.

**PALABRAS CLAVES:** Anillos de árboles, clima, El Niño, Oscillación del Sur, precipitación, Baja California

## ABSTRACT

Tree ring records from northern Baja California were used for reconstructing annual series of precipitation and El Niño-Southern Oscillation. Reconstructions were compared to instrumental and historical records for verification. Five tree ring width chronologies were developed using standard dendrochronological and statistical techniques: one of *Pinus coulteri*, two of *Pinus quadrifolia* and two of *Pinus jeffreyi*. One of the latter updated an existing chronology and doubled its period of calibration with instrumental climatic data. The length of the chronologies was 101 to 551 years. All the chronologies had significant correlations with precipitation records from Ensenada, Baja California and San Diego, California and with an ENSO-related index based on instrumental records. Precipitation explained 8 to 57% of the variation in tree growth. Precipitation records were related to SOI ($R^2_{adj}$: 48 and 16% respectively), but tree ring chronologies captured weaker and more variable signals ($R^2_{adj}$ : 3 to 24%). Agreement between historical documentary records and the tree ring reconstructed SOI with the highest predictive ability was 82%. Further research to extend the shorter reconstructed chronologies, which now show the strongest precipitation and ENSO signals, and further study of other sites and species from Baja California, is suggested.

**KEY WORDS:** Tree rings, climate, El Niño, Southern Oscillation, precipitation, Baja California

## INTRODUCTION

It is well-known and well-documented that El Niño/ Southern Oscillation (ENSO) is a large source of interannual variability of rainfall in the tropical Pacific region and in some areas of extratropical latitudes of both the Northern and Southern Hemispheres (Díaz and Markgraf, 1992; Lau and Sheu, 1991). Spatial patterns of anomalies of winter precipitation in the southwestern USA have varied greatly from one El Niño episode to another (Namias and Cayan, 1984). Nonetheless, El Niño events are associated with increased rainfall in a region stretching from Southern and Baja California to western Texas and the southeastern USA (Schonher and Nicholson, 1989; Diaz and Kiladis, 1992; Stahle and Cleaveland, 1993). During the 1982-83 ENSO event, Douglas and Englehart (1984) noted that precipitation was unusually heavy in the southwestern USA and northwestern Mexico. Ropelewski and Halpert (1986) showed that winter precipitation in northern Mexico (mostly east of the Sierra Madre Occidental) was high in the year following ENSO peaks. In Baja California, studies of precipitation variability revealed a strong link to the Southern Oscillation Index (SOI) (Reyes and Rojo, 1985; Reyes-Coca *et al.*, 1990; Reyes and Mejía-Trejo, 1991; Pavía and Badan, 1998; Minnich *et al.*, 2000). Variations of the SOI and associated El Niño events result in above normal precipitation during El Niño events and subnormal precipitation amounts during La Niña events, through mechanisms briefly described by Reyes and Mejía Trejo (1991) and by Minnich *et al.* (2000).

Droughts and floods in Baja California have a great economic and social impact. A need exists to understand the past natural variability of precipitation if we are to estimate the probability of future events using modern records, or to predict climatic from conditions in the present or very recent past. However, few meteorological records in Baja California extend further back than 1953 and the records at most stations are incomplete; they are inadequate to assess the history of past precipitation variability, or its relationships with the El Niño-Southern Oscillation (ENSO) events. For this purpose, proxy and extended historical records are needed.

As proxy records of past climate, the study of annual tree rings has been established and reviewed by Fritts (1976), Hughes *et al.* (1982) and Cook and Kairiukstis (1990). The advantage of tree rings as paleoclimatic records lies in their constant annual resolution and the absolute dating they produce. Trees from the semiarid region of the western USA and northern Mexico grow wider rings in response to greater precipitation primarily during the winter or cooler season, and narrower rings in response to drought. When the precipitation is correlated with the SOI variability, as it is the case of Baja California (Minnich *et al.*, 2000), tree rings may contain information related to variations of the SOI.

The southwestern and western USA and northern Mexico have provided tree ring chronologies that have been particularly useful as proxy records of precipitation, streamflow and other water-related variables (Stockton and Meko, 1975; Meko *et al.*, 1980; Meko and Stockton, 1984). Some chronologies with a sufficiently strong ENSO signal have been of value in climatological studies (Lough and Fritts, 1985; Michaelsen, 1989; Lough, 1992; Stahle *et al.*, 1998). One long chronology from Baja California has been used in combination with more northern chronologies in some of these studies.

Thus, it seems possible that tree ring chronologies from the northern part of the Baja California peninsula may be capable of estimating past precipitation variability and high frequency climatic signals associated with ENSO events. The goal of this study is to examine the sensitivity to precipitation of different species of pines from Baja California and evaluate their potential in the development of regional climatic reconstructions.

## DATA AND METHODS

The five tree ring chronologies constructed in this study were based on measurements of annual ring widths from three species of pine (*Pinus jeffreyi* Grev. and Balf. [Jeffrey pine], *Pinus coulteri* D.Don [Coulter pine] and *Pinus quadrifolia* Parl. [Parry pinyon pine]) growing on Sierra de Juárez, Sierra Blanca and Sierra de San Pedro Mártir in Baja California (Table 1, Figure 1). Stands of pine were sampled in 1998 by taking cores with an increment borer from each of 8 to 50 trees per site, usually with two cores per tree. Within the stands, individual trees were selected on the basis of microsite evidence of moisture stress, apparent tree age, and absence of major natural or human-related disturbance.

Chronologies were prepared using standard procedures (Stokes and Smiley, 1968; Fritts, 1976) in the Laboratory of

**Table 1**

Sites and species sampled to develop the tree ring chronologies

| No. | Species | Latitude (N) | Longitude (W) | Elevation (m) | Site |
|---|---|---|---|---|---|
| 1 | *Pinus jeffreyi* | 31°53.5' | 115°56.2' | 1580 | Las Cuevitas (S. Juárez) |
| 2 | *Pinus coulteri* | 32°02.8' | 116°29.2' | 1230 | Sierra Blanca |
| 3 | *Pinus quadrifolia* | 30°58.8' | 115°39.2' | 1200 | Piedemonte (S. San Pedro Mártir) |
| 4 | *Pinus quadrifolia* | 30°57.8' | 115°36.5' | 1600 | Campamento (S. San Pedro Mártir) |
| 5 | *Pinus jeffreyi* | 30°57.2' | 115°30.8' | 2300 | La Tasajera (S. San Pedro Mártir) |

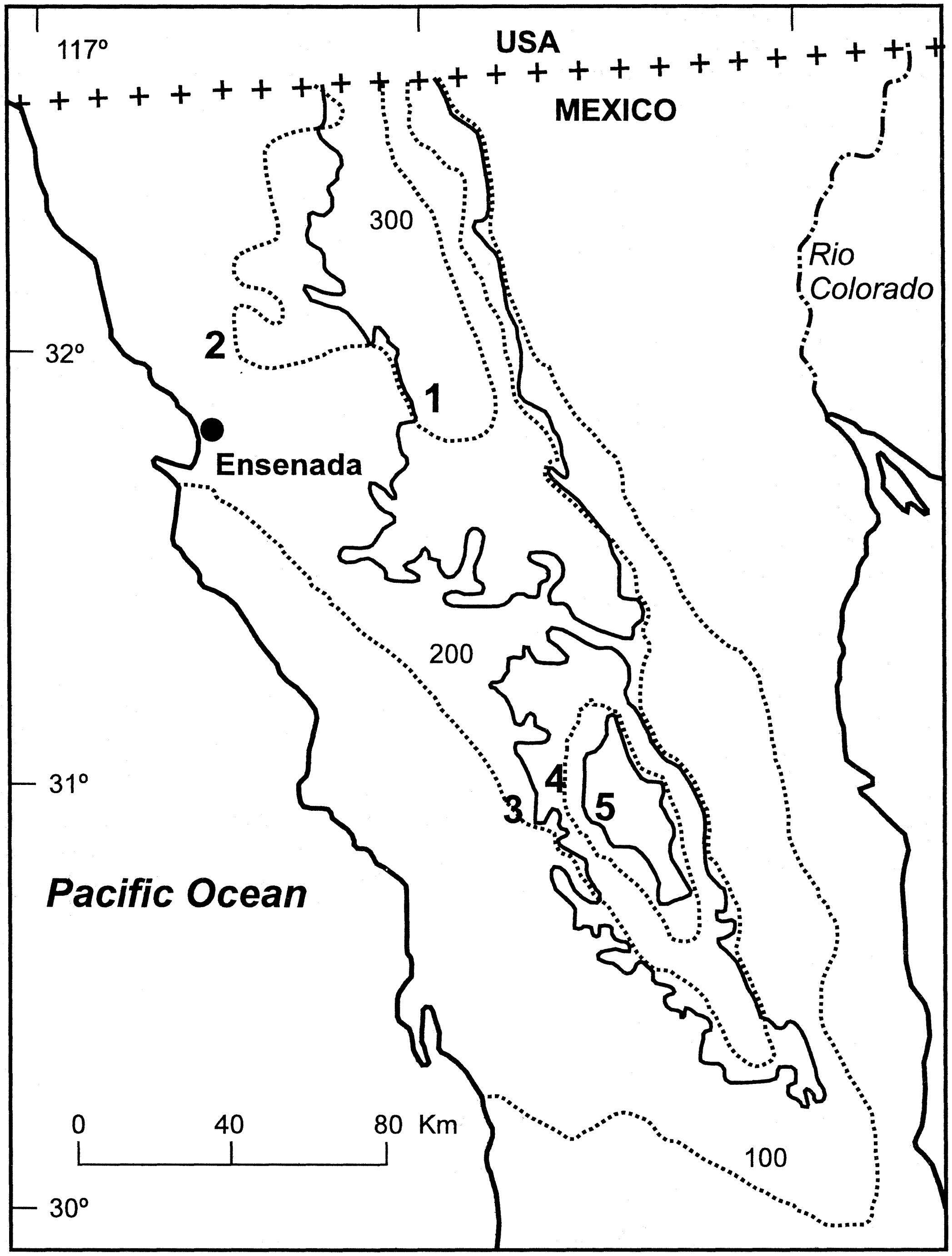


Fig. 1. General locations of the tree ring sites sampled. 1, Las Cuevitas in Sierra de Juárez; 2, Sierra Blanca; 3 and 4, "Piedemonte" and "Campamento" respectively, both in the lower part of Sierra de San Pedro Mártir; 5, La Tasajera in Sierra de San Pedro Mártir. Isohyets (dotted) and contours (1000 and 2000 m) are shown.

Ecology of Arid and Semiarid Zones at CICESE. They represent the mean value of all standardized ring-width measurement series available for each year, and were developed using the computer program ARSTAN (Cook, 1985; Cook and Holmes, n.d.; see Appendix) with a cubic spline to remove growth-trend or age effects and differences in absolute growth rate, while preserving climatic variation (Fritts, 1976).

The climate in the northwestern part of the peninsula is mediterranean characterized by winter precipitation and summer drought (Hastings and Turner, 1965). Monthly precipitation data were obtained for San Diego, California (1851-1998) and for Ensenada, Baja California. The Ensenada record begins in 1894 but is incomplete; a reliable and complete record is available between 1948-1998. The data were further seasonalized by summing three to twelve monthly values, starting with January in the year previous to the growing season (May August).

Because there is not just one index of ENSO, three different reasonable approximations were examined as potential predictands, with the tree ring chronologies as the predictors. The Southern Oscillation Index (SOI) calculated by the Climate Prediction Center (1951-1998, NOAA); a non-smoothed version of the Troup SOI (1866-2000, CSIRO Division of Atmospheric Research; Allan *et al.*, 1996); and finally, El Niño Region 3.4 SST Index (1951 1998; Trenberth, 1997). All three ENSO-related indices were seasonalized into two to four month periods starting with the winter previous to the prior growing season until the current growing season.To determine which of the ENSO indices would be used as a measure of ENSO phenomena and reconstructed, a common calibration period (~1951-1998) was defined for all of them. The ENSO index that showed the strongest and most consistent relationships with the chronologies in that period was chosen; the relationship of this index to both precipitation series was also established.

Simple correlation analyses were used to determine the strongest and most consistent relationships between each chronology and the instrumental data (ENSO and precipitation), and to select the most appopiate season to be calibrated and reconstructed in regression analysis (Cook and Kairiukstis, 1990). Also, the same analyses were performed to relate the ENSO index and the precipitation records. Prior to all these analyses, the time series which exhibited serial correlation were prewhitened using low-order autoregressive models (Box *et al.*, 1994) selected with the minimum Akaike information criterion (Akaike, 1974). After an autoregressive model was fitted, the persistence structure was removed and the residuals were fed into the regression model. Prewhitening the predictor and predictand variables is very important because the low-order persistence in tree ring data can be quite strong, largely biological in origin, and unrelated to climate (Meko, 1981). Nonetheless, the persistence of climate was duly accounted for in the final reconstruction.

For the regression models, three potential predictors were derived for each tree ring series by leading ($t$-1), synchronizing ($t$), and lagging ($t$+1) the series with respect to the instrumental ENSO indices and precipitation. This procedure seeks to accommodate known differences in the seasonal climate response of the trees and in the seasonal timing and persistence of ENSO teleconnections to regional climate (Stahle *et al.*, 1998). Each time, the best subset of the n-independent variables was selected for the final regression equation using the Mallows Cp criterion (Mallows, 1973).

The statistical accuracy of all the reconstructions was evaluated using cross-validation (Mosteller and Tukey, 1977; Michaelsen, 1987). Cross-validation involves deleting each case in turn from the data set, recalculating the regression equation, and testing it on the deleted year such that the full data set is used to develop independent estimates of reconstruction skill. Cross-validation generally provides more reliable estimates of true reconstruction skill than more common approaches to this problem such as reserving a single group of years from model development for model verification (Michaelsen, 1987).

The original autoregression (AR) persistence structure observed in the ENSO indices were subsequently restored by adjusting the tree ring estimates of this variable with the respective AR coefficients. Thus, the persistence of climate was added back into the reconstructions.

Finally, the reconstructed ENSO index with the best cross-validation was compared to a proxy ENSO record developed by Quinn *et al.* (1987) from documentary records, to evaluate their agreement. Their ENSO record covers the period 1524-1983. Only ENSO events meeting three criteria were examined: categorized in strength between Avery strong@ and Aweak moderate@ by Quinn *et al.*(1987); categorized as high confidence (rating 5 or 4) by Quinn *et al.* (1987); and years in which the chosen instrumental ENSO index was negative.

## RESULTS AND DISCUSSION

Five tree ring chronologies were developed. The chronology from Las Cuevitas extends from 1855 to 1998 (143 years), Sierra Blanca from 1897 to 1998 (101 years), Piedemonte from 1905 to 1998 (93 years), Campamento from 1863 to 1998 (135 years) and La Tasajera from 1774 to 1998 (224 years). Hereafter, these chronologies will be referred to as LC, SB, Pd, Cp, and LT, respectively. For the calibration-reconstruction analysis, the Pd and Cp chronologies were joined into one chronology (PdCp, 1863-1998). Regarding LT, an existing chronology (1447-1971) from the same site, collected by M. A. Stokes, T. Harlan and S. Clemans (1971), was extended to 1998 and this updated chronology (1447-1998, 551 years) was used in the calibration and reconstruction.

All the chronologies were sensitive to precipitation (Table 2). Correlations between the tree ring chronologies and the Ensenada precipitation data revealed that the growth of the pines in the Sierra de Juárez, Sierra Blanca and Sierra de San Pedro Mártir, was favored by precipitation from autumn to spring (September-May). While all the other chronologies correlated better with the precipitation record from Ensenada, the LT chronology correlated better with the record from San Diego (r:0.38; p<0.001). The correlations with the San Diego record indicated that the January-April period was the most appropriate predictand for reconstruction with all the chronologies ($R^2_{adj}$:14-29%). For both precipitation records, the SB chronology was the best predictor; it accounted for the highest percent of the variance in Ensenada and San Diego precipitation ($R^2_{adj}$: 57.4 and 29.4 % respec-

**Table 2**

Calibration and verification statistics for the estimates of the precipitation series from the tree ring chronologies and from the Southern Oscillation Index (SOI, CSIRO). The chronologies are: LC, Las Cuevitas; SB, Sierra Blanca; PdCp, Piedemonte-Campamento; LT, La Tasajera. The lead-lag relationships of the predictors with the precipitation season are also listed: predictor is concurrent with the precipitation (t), follows it by 1 yr (t+1) or leads precipitation (t-1). The SOI as predictor of precipitation at Ensenada and San Diego is the Index from September-February (autumn-winter) of the previous year. r is the Pearson correlation coefficient. $R^2_{adj}$ is the variance explained adjusted for loss of degrees of freedom; $R^2_{cv}$ is the variance explained after cross-validation

| | Precipitation at Ensenada | | | | | Precipitation at San Diego | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Predictor** | **Season** | **r** | **Lead-Lag** | **$R^2_{adj}$ (%)** | **$R^2_{cv}$ (%)** | **Season** | **r** | **Lead-Lag** | **$R^2_{adj}$ (%)** | **$R^2_{cv}$ (%)** |
| LC | Sep-May | 0.54 | $LC_{(t)}$ | 27.3 | 20.8 | Jan-Apr | 0.46 | $LC_{(t)}$ | 20.9 | 19.0 |
| SB | Sep-May | 0.76 | $SB_{(t)}$ | 57.4 | 54.4 | Jan-Apr | 0.55 | $SB_{(t)}$ | 29.4 | 27.2 |
| PdCp | Sep-May | 0.57 | $PdCp_{(t)}$ | 31.3 | 26.5 | Jan-Apr | 0.44 | $PdCp_{(t)}$ | 19.0 | 17.6 |
| LT | Sep-May | 0.31 | $LT_{(t)}$ | 7.7 | 3.5 | Jan-Apr | 0.38 | $LT_{(t)}$ | 13.9 | 12.6 |
| SOI | Sep-May | -0.7 | $SOI_{(t)}$ | 47.5 | 44 | Jan-Apr | -0.41 | $SOI_{(t)}$ | 16.2 | 14.1 |

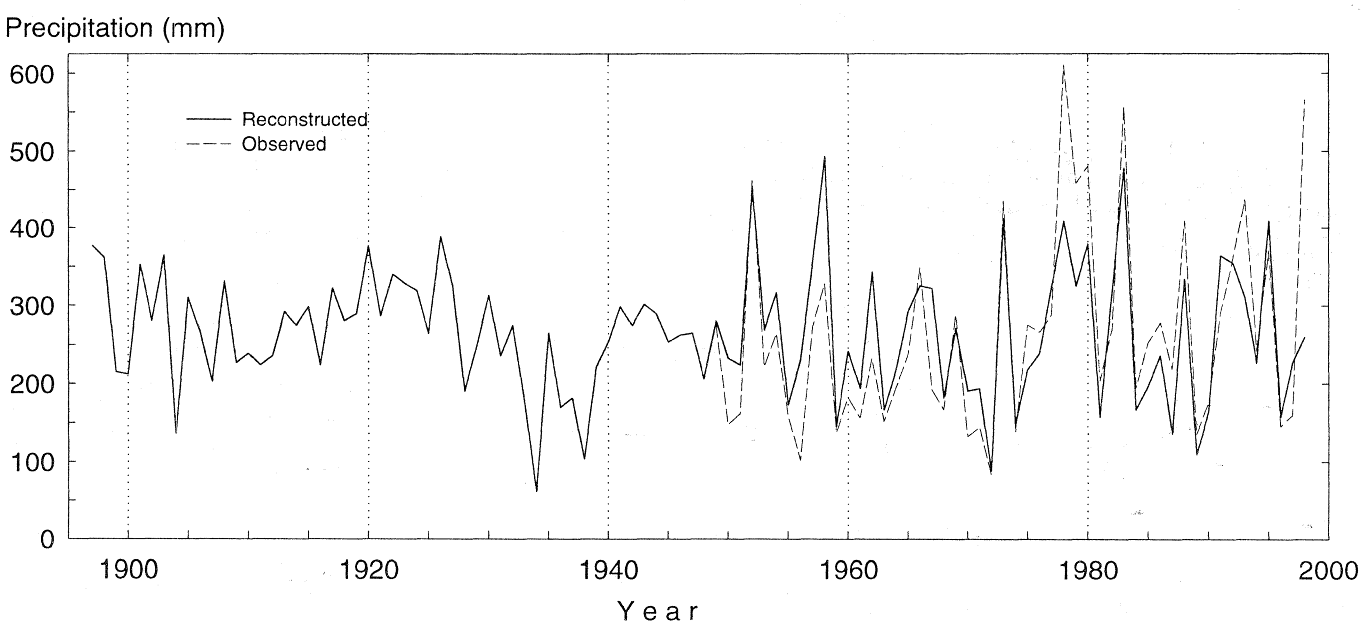


Fig. 2. September-May instrumental precipitation record at Ensenada (observed, dashed line, 1949-1998) and its tree ring reconstruction (solid line, 1898-1998). The good correspondence between them is evident. The reconstruction was built by regression analysis between SB chronology and the precipitation; only the chronology was prewhitened. In 1998, the tree ring sampling was made before the growing season had finished; this account for the smaller value of reconstructed precipitation compared to the observed value.

tively) and was well correlated with independent precipitation values not used to specify the calibration model in the cross-validation process ($R^2_{cv}$: 54.4 and 27.2 % respectively). The similarity between the $R^2$ and the cross-validated $R^2_{cv}$ indicates that the regression models were stable and reconstruction skill was good (Michaelsen, 1987) (Figure 2).

The SOI from CSIRO had a good correspondence with almost all the chronologies (Table 3). Because it was the longest record (1866-1998), it was selected as an index of ENSO phenomena. This index is based on anomalies from the normalized mean differences series in standard deviation units and multiplied by 10 (see Allan *et al.*, 1996). In this index, negative values are associated with warmer El Niño events.

Significant correlations between the SOI and the precipitation records (Table 2) indicated the influence of the ENSO events on the variability of the precipitation, particularly in the case of Ensenada, where 48 % of variability of the autumn-winter-spring (September-May) precipitation was explained by the SOIs of autumn-winter (September-February) in the current year (t). In the case of San Diego, the SOI values from the current autumn-winter (t) account for 16% of the annual precipitation variability.

The chronologies themselves contained information associated with the SOI (Table 4, $R^2_{adj}$: 3-24%, Figure 3). The negative coefficients were physically consistent with the nature of the ENSO teleconnection in this region. Warm events (negative SOI indices) favor cool-wet conditions and good tree growth. Also, differences in the seasonality of the ENSO signal in the tree ring data were identified. The LT chronology from the higher elevation forest in the Sierra de San Pedro Mártir presented ring width anomalies associated with extreme conditions of the SOI in autumn-winter-spring (September-May). The LC and PdCp chronologies from intermediate elevation forests were correlated with the autumn-winter (September-February) SOI. However, the SB chronology from the lower elevation forests, and also the closest to the Pacific coast, was most strongly correlated with the autumn (September-November) SOI, which may reflect an ENSO influence on winter precipitation and its subsequent effect on tree growth in spring-summer through the soil moisture reservoir. Moreover, the relation with the SOI was expressed not only in the next growing season (t) of the Sierra Blanca trees but also in the growing season of the following year (t+1). This may be related to the well-known persistence of tree growth. Again, the SB chronology accounted for the highest percent of the variance in the ENSO index ($R^2_{adj}$: 24%). This value is in the range of values found in other ENSO-tree ring studies (18 to 53% of variance explained; Lough and Fritts, 1885; Michaelsen, 1989; D=Arrigo and Jacoby, 1991; Lough, 1992; Stahle and Cleaveland, 1993; Stahle *et al.*, 1998). However, each of these reconstructions was based on chronologies from a network of sites, in contrast to the present study in which the values were determined for single sites and species. Cross-validation showed that the SB chronology could explain 21% of the variance in the autumn SOI. Because the tree ring data accounted for only 24% of the variance ($R^2_{adj}$), it is clear that factors other

**Table 3**

Calibration statistics for regression models for three seasonalized ENSO-related indices: "NOAA" is the Southern Oscillation Index (SOI) from the Climate Prediction Center (NOAA); "CSIRO" is the revised SOI from the Division of Atmospheric Research (CSIRO); "SST" is the El Niño Region 3.4 SST Index (Trenberth, 1997). The respective calibration periods were 1952-1998, 1951-1996 and 1951-1998. Pr indicates months from the previous year. $R^2_{adj}$ is the variance explained adjusted for degrees of freedom

| | **ENSO (NOAA)** | | **ENSO (CSIRO)** | | **ENSO (SST)** | |
|---|---|---|---|---|---|---|
| **Chronology** | **$R^2_{adj}$** (%) | **Season** | **$R^2_{adj}$** (%) | **Season** | **$R^2_{adj}$** (%) | **Season** |
| LC | 17.4 | Pr.Sep-Nov | 15.1 | Pr.Sep-Nov | 19.2 | Mar-Feb |
| SB | 34.2 | Pr.Ago-Nov | 34.8 | Pr.Sep-Nov | 31 | Pr.Sep-Nov |
| PdCp | 14.4 | Pr.Sep-Nov | 9.3 | Pr.Sep-Nov | 18 | Pr.Sep-Nov |
| LT | 12.7 | Mar-May | 15.2 | Mar-May | 14.2 | Mar-Feb |

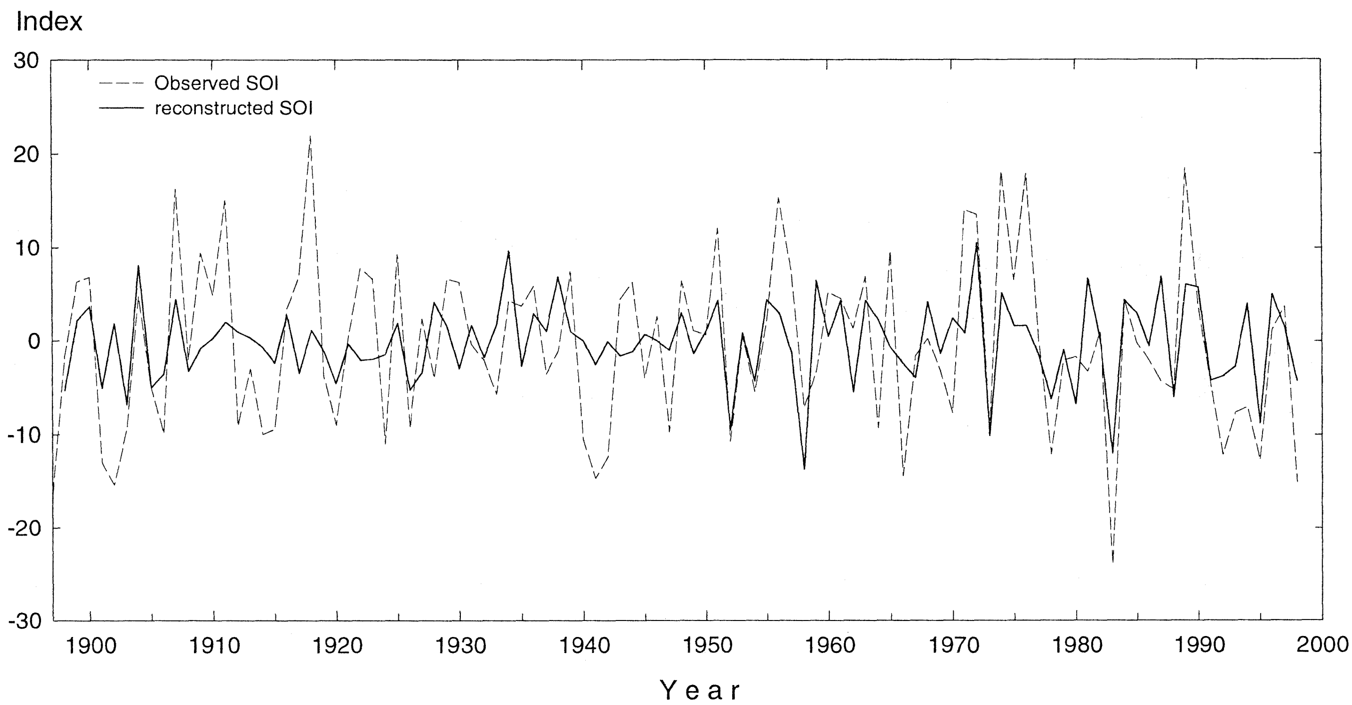


Fig. 3. Observed and reconstructed SOI for autumn prior to the growing season, 1897 to 1996 (dashed and solid lines, respectively). The reconstruction was calibrated using regression analysis between the prewhitened SB chronology and the previous autumn SOI, and it was well correlated with independent SO indices in the cross-validation. Note the higher agreement between the two series from the late 1940s to the present.

**Table 4**

Summary of calibration and verification statistics for the estimates of the Southern Oscillation Index (CSIRO) from the tree ring chronologies. The chronologies are as in Table 2: LC, Las Cuevitas; SB, Sierra Blanca; PdCp, Piedemonte-Campamento together; LT, La Tasajera. Pr indicates months from the previous year. r is the Pearson correlation coefficient. Predictors (chronologies) are concurrent with precipitation (t), follow it by 1 yr (t+1), or lead it (t-1). $R^2_{adj}$ is the variance explained adjusted for degrees of freedom; $R^2_{cv}$ variance explained after cross-validation

| | Southern Oscillation Index | | | | |
|---|---|---|---|---|---|
| **Chronology** | **r** | **Season** | **Predictor** | **$R^2_{adj}$ (%)** | **$R^2_{cv}$ (%)** |
| LC | -0.29 | Pr.Sep-Feb | $LC_{(t)}$ | 7.9 | 5.5 |
| SB | -0.48 | Pr.Sep-Nov | $SB_{(to, t+1)}$ | 24.2 | 21.3 |
| PdCp | -0.32 | Pr.Sep-Feb | $PdCp_{(t)}$ | 9.6 | 7.3 |
| LT | -0.2 | Pr.Sep-May | $LT_{(t)}$ | 3.4 | 1.3 |

than ENSO events are responsible for a large fraction of the climate and tree growth variance in this case.

Nonetheless, the validity of the reconstruction was tested by comparing it to ENSO events that were documented by Quinn *et al.* (1987) from historical records and also recorded instrumentally. Because the SOI used were the index values during September-November (autumn) of the previous year, the ENSO events were plotted (in Figure 4) one year later. Therefore, the conditions of the autumn SOI dur-

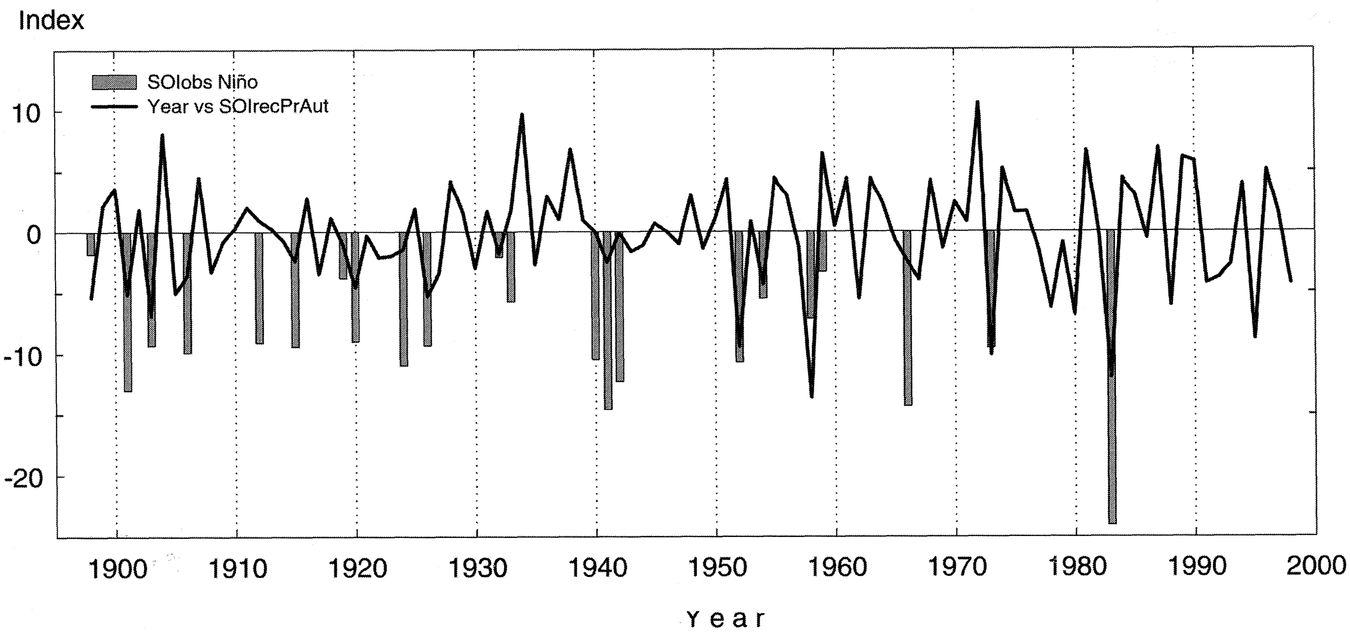


Fig. 4. Comparison between the time series of the reconstructed SOI (solid line) and the occurrences of near-moderate to very-strong ENSO events (vertical bars, after Quinn *et al.*, 1987) from 1897 to 1996. A reasonable correspondence is notable. The reconstruction was built by the correlation between the prior autumn SOI and the prewhitened SB chronology. Size of the bars indicates the actual value of the prior autumn SOI in El Niño years. Notice that both the SOI shown, reconstructed and observed, are the index values during September-November of the year previous to the growing season of the trees. Because of that each El Niño year, according Quinn *et al.* (1987), is plotted 1 yr later.

ing the 1982 event were expressed as the 1983 event. According to this criterion, the onset of 22 El Niño events were identified between 1897 and 1987 (Figure 4). Many of these events were matched by negative SOI estimates in the reconstruction, for example the events of 1925, 1940, 1941, 1957, 1972 and 1982 which fell into the strong and very strong category. However, four historical events were not evident in the reconstructed SOI (1911, 1932, 1939 and 1958 ) although three of them were classified as strong events (1911, 1932 and 1958). There are several possible reasons for these discrepancies, as mentioned by Lough (1992), including (1) the variability between ENSO events of the strength of the extra-tropical signal (e.g. Yarnal and Diaz, 1986; Hamilton, 1988); (2) the non-uniqueness of the ENSO signal in North American climate (Douglas *et al.*,1982; Namias and Cayan, 1984) and tree ring data (Lough, 1992); and (3) other sources of climatic and non-climatic variability in the tree ring chronologies. Despite these limitations, there is a good correspondence between the Sierra Blanca reconstruction and the documentary history; only 4 of the 22 events were not reconstructed (82% agreement).

## CONCLUSIONS

All the species and sites provided climate-sensitive tree ring records. The chronologies and the reconstruction showed significant correspondence with the instrumental records of precipitation and ENSO-related indices. The SB tree ring estimate of prior autumn SOI reproduced the timing of warm events with reasonable fidelity but did not reproduce the full dynamic range of instrumental autumn SOI (Figure 3). Despite these limitations, there was evidence of some degree of ENSO signal in all the tree ring chronologies, which is encouraging for their use in reconstruction.

Examination of the precipitation and ENSO signals in the tree ring chronology data showed that the strongest signals were in *Pinus coulteri* located in Sierra Blanca. More collections are needed to extend this particular chronology and lengthen the reconstruction. Also, the differences among sites and species in strength of the climatic signal strongly justifies further study of other sites and species to develop a network of sensitive tree ring chronologies. Proxy data from different sites are needed to distinguish local from regional-scale variability in climatic signals.

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## APPENDIX

## THE DEVELOPMENT OF TREE-RING CHRONOLOGIES AND PROGRAM ARSTAN

Adapted from Users Manual for Program ARSTAN by E.R. Cook and R.L. Holmes, 1999, Laboratory of Tree-Ring Research, University of Arizona, Tucson, 12 pp.

The information contained in annual tree rings is a valuable resource for studying environmental change. The concept of chronology development is concerned with the problem of extraction of the desired information (signal), relevant to the study of a particular problem, from the unwanted information (noise) that is irrelevant to the problem being studied. According to this, a tree-ring series can be thought of as the aggregation of signals that become signal or noise only within the context of specific application (Cook, 1987; Cook *et al.*, 1990):

$$R_t = A_t + C_t + D1_t + D2_t + E_t\ ,$$

where

$R_t$ = the observed ring-width series;

$A_t$ = the age-size-related trend in ring width; it is a nonstationary process that reflects, in part, the geometrical constraint of adding a volume of wood to a stem of increasing radius.

$C_t$ = the climatic signal which can vary at both low and high frequency and is a signal in common to all trees in a stand.

$D_t$= the tree disturbance signal, often divided into local ($D1_t$) and standwide ($D2_t$) disturbances.

$E_t$ = the unexplained year-to-year variability not related to the other signals; represents the random signal unique for each tree that it is assumed to be serially uncorrelated within and spatially uncorrelated between trees in the stand.

For dendroclimatic studies, the common climatic component $C_t$ is the signal of interest, while $A_t$, $D1_t$, and $D2_t$ are considered collectively as non-climatic variance or noise.

## COMMENTS ON PROGRAM ARSTAN

The main purpose of Program ARSTAN, a computer routine, is the production of tree-ring chronologies from tree-ring measurement series. The concept and methodology were developed by Dr. Edward R. Cook (1985) at the Tree-Ring Laboratory, Lamont-Doherty Earth Observatory of Columbia University in Palisades, New York. In 1983 Dr. Cook provided the source code for ARSTAN to the Laboratory of Tree-Ring Research at the University of Arizona, where Richard L. Holmes updated the program to ANSI standard FORTRAN-77 and in collaboration with Dr. Cook developed several enhancements. Copies of the most recent version of ARSTAN can be down loaded, free of charge, from ftp://ftp.cricryt.ar/users/dendro/edu.

ARSTAN produces chronologies with statistical analysis. This is accomplished by detrending and indexing (standardizing) the tree-ring measurement series to reduce the low frequency noise (particularly the aging effect $A_t$) not associated with the signal of interest. Autoregressive modeling of index series often enhances the common signal. Then, the chronology is produced when the index series from individual trees are combined into a mean value function of all series that represents the departure of growth for a given year vs the series mean. Applying a robust estimation of the mean value function removes effects of local disturbances ($D1_t$). Three versions of the chronology (Standard, Residual, Arstan) are obtained, intended to contain a maximum common signal and a minimum amount of noise. Principal component analysis separates different signals contained in the tree rings and further characterizes the data set. The options allow the data processing to be tailored to a wide variety of situations and purposes.

The Program provides several choices of how a chronology is computed: single or two-stage detrending of measurement series to remove a large part of the variance due to causes other than climate may be done with a variety of options (spline, least-square regression line, negative exponential curve or horizontal line); measurement series may be normalized prior to or after detrending; the process of indexing each series may be computed by subtraction or division of each ring measurement by its expected value; variance may be stabilized. The mean value function may be computed as either the biweight robust estimate or the arithmetic mean (Cook, 1985) and autoregressive modeling may be performed specifying the method to use and thus, obtaining versions of the chronology with and without persistence.

Statistics on the chronology are printed, including the distribution of values, autocorrelation structure and the gain or loss in efficiency of robust estimation of the mean. The statistical quality of the chronology can be measured by empirically estimating the strength of the chronology common signal and quantifying the degree to which the chronology signal is expressed when series are averaged.

The biweight mean estimation is strongly recommended to remove effects of endogenous stand disturbances and to enhance the common signal contained in the data, in comparison with the arithmetic mean which is especialy sensitive to outliers (Cook, 1985).

There is often a high correlation between adjacent tree-rings, so that the autocorrelation in a series is high. Thus, a more statistically efficient estimate of the mean-value function is possible through the use of Autoregressive-Moving Average Model (ARMA). Before the development of ARSTAN with an option that automatically produces AR-modeled ring width residuals, application of the ARMA models was limited due to the time and experience required to fit these models to data series (Yamaguchi and Allen, 1992).

The "double detrending" method (Holmes *et al.*, 1986), which uses decay curves and cubic splines in sequence to remove nonstationary growth trends is the best available way to detrend tree-ring series with a high autocorrelation structure (Yamaguchi and Allen, 1992).

Also, ARSTAN detrending and AR modeling are ideal for the situation in which one is simultaneously developing a chronology from living trees and trying to date samples of wood ("floating series") from other sources by comparison to the chronology.

A limitation of the program is its failure to estimate residuals of the series' initial years by back-forecasting (Box and Jenkins, 1994). Thus, ARSTAN residual series are 1-3 years shorter than the original measurement series.

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