Long-Term Response of Torrey Pine to Coastal Climate: Precipitation, Temperature, and Fog

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Abstract. Torrey pine (*Pinus torreyana* Parry ex Carr.) has one of the most limited geographical ranges and population size in the *Pinus* genus; it is present only on Santa Rosa Island and on the coast between San Diego and Del Mar, where our research was conducted. A 168-year chronology (1827-1994) was developed using 28 increment cores extracted from 15 living and 2 dead standing trees at Torrey Pines State Reserve, San Diego, California. Crossdating was possible but not easy, mostly because of faint latewood boundaries in certain years and specimens. Annual tree growth was highly and directly related to precipitation falling between the previous November and the current April. Temperature was not a significant predictor of tree growth. At seasonal scale, tree growth was highly and directly related to winter and spring precipitation, and was also significantly correlated to summer fog. However, when combined with winter and spring precipitation in multiple regression models, summer fog was not a significant predictor of tree growth. Total November-April precipitation explained a larger amount of variance after 1900 (64% in 1900-1949, 70% in 1950-1994) than before 1900 (48% in 1850-1899). The spatial correlation with western North America winter and spring precipitation, as well as with published tree-ring chronologies, indicates a connection with the American Southwest. Global correlation maps with winter sea level pressure and sea surface temperature are consistent with the hypothesis that San Diego precipitation is affected by a southerly displaced North Pacific storm track and by warmer water farther south, both leading to higher transport of lower latitude moisture.

Introduction

Dendroclimatological studies at coastal sites have been relatively rare in the past because of the widespread belief that trees from such sites are (a) not sensitive to climate variability, (b) not easily datable using dendrochronological techniques, (c) short lived. Recently, Buckley *et al* (1992) and Wiles *et al* (1995) have shown that temperature-sensitive tree-ring records from coastal species can be effectively used to reconstruct climate variability over the last few centuries in the Gulf of Alaska and along the northeastern Pacific Coast.

Farther south along the California borderland, drought-sensitive tree-ring chronologies from near-coastal and interior mountain ranges have been used to reconstruct precipitation (Meko *et al* 1995; Haston and Michaelsen 1994; Michaelsen *et al* 1987; Meko *et al* 1980; Schulman 1947), sea surface temperature (Douglas 1980), fire history (Brown and Swetnam 1994), and El Niño events (Michaelsen 1989). With the exception of Brown and Swetnam (1994), the above-mentioned studies did not incorporate tree-ring records from endemic conifer species (Torrey pine, Monterey pine, bishop pine, Santa Lucia fir, coast redwood, *etc*) growing along the Southern and Central California coast (Barbour and Major

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1977). Because the survival of such species within their limited natural distribution is intimately linked to the health and climatic sensitivity of California coastal environments, dendroclimatological studies are useful to quantify the long-term response of coastal ecosystems to climate change.

A typical feature of the U.S. West Coast is the marine fog layer, which can occur throughout the year. Coastal fog is generated offshore, then spread inland by sea breezes, and usually reaches land areas below 250-400 m elevation (Leipper 1994; Filonczuk *et al* 1995). Despite its widespread and frequent occurrence, the relationship between fog and tree growth is not well understood, especially on interannual and longer time scales. We have recently begun investigating the climatic response of endemic conifer species living along the California coast, which in recent decades has experienced rapid urban development. Our objective is to provide information on long-term climate/tree-growth relationships in coastal areas under changing environmental conditions. In this paper we present the dendroclimatology of Torrey pine (*Pinus torreyana* Parry ex Carr.) where it occurs naturally, between La Jolla and Del Mar. We address the following questions:

- Is it possible to crossdate Torrey pine tree rings?
- What is the maximum age of currently living trees?
- What are the most prominent seasonal climatic features that affect Torrey pine growth?
- Is fog beneficial to tree growth?
- Have climate/tree-growth relationships changed over time?

Torrey pine is a five-needle species characterized by long (up to 30 cm) needle-leaves and massive (up to 15-cm long) female cones that can remain attached to the tree for several years (Haller 1986). It has one of the most limited geographical ranges (a few square kilometers) and population size (about 10,000 individuals) in the *Pinus* genus. Its natural distribution is limited to a mainland population on the Pacific Coast between La Jolla and Del Mar, and to a disjunct population 280 km to the northwest on Santa Rosa Island, about 50 km offshore from Santa Barbara (Haller 1986). Torrey pine has persisted in those areas throughout the Holocene (Cole and Liu 1994) and was much more widespread in ancient times (Kellogg *et al* 1927). The two populations have been isolated from each other for several thousand years, but they do not seem to differ genetically (Waters and Schaal 1991), even though morphological and environmental differences do exist (Haller 1986).

Tree-Ring Records

Field collections took place within Torrey Pines State Reserve and Extension, next to Los Peñasquitos Marsh Natural Preserve between Interstate 5 and Torrey Pines State Beach (Figure 1). The mainland native population of Torrey pines was first protected in 1899 as a city park; it became a reserve in 1921 and has belonged to the California State Park system since 1959 (Hubbs *et al* 1991). Torrey pine is the only overstory species at the study area, usually 10-15 meters in height and open grown, occupying ridgetops, slopes and gullies on eroded marine terraces and sandstone bluffs. The understory varies widely in terms of abundance and species composition, mostly resembling coastal chaparral communities, sometimes with few herbaceous species (Vogl *et al* 1977). The area is characterized by maritime climate with small temperature excursions, limited winter rainfall, and frequent coastal fog. Trees on the most exposed ridges are wind-pruned, and exposure to salt spray varies depending on topography and distance from the shoreline. Despite its ease of access and high biodiversity value, little is known on the life history and ecological relationships of Torrey pine in its natural range.

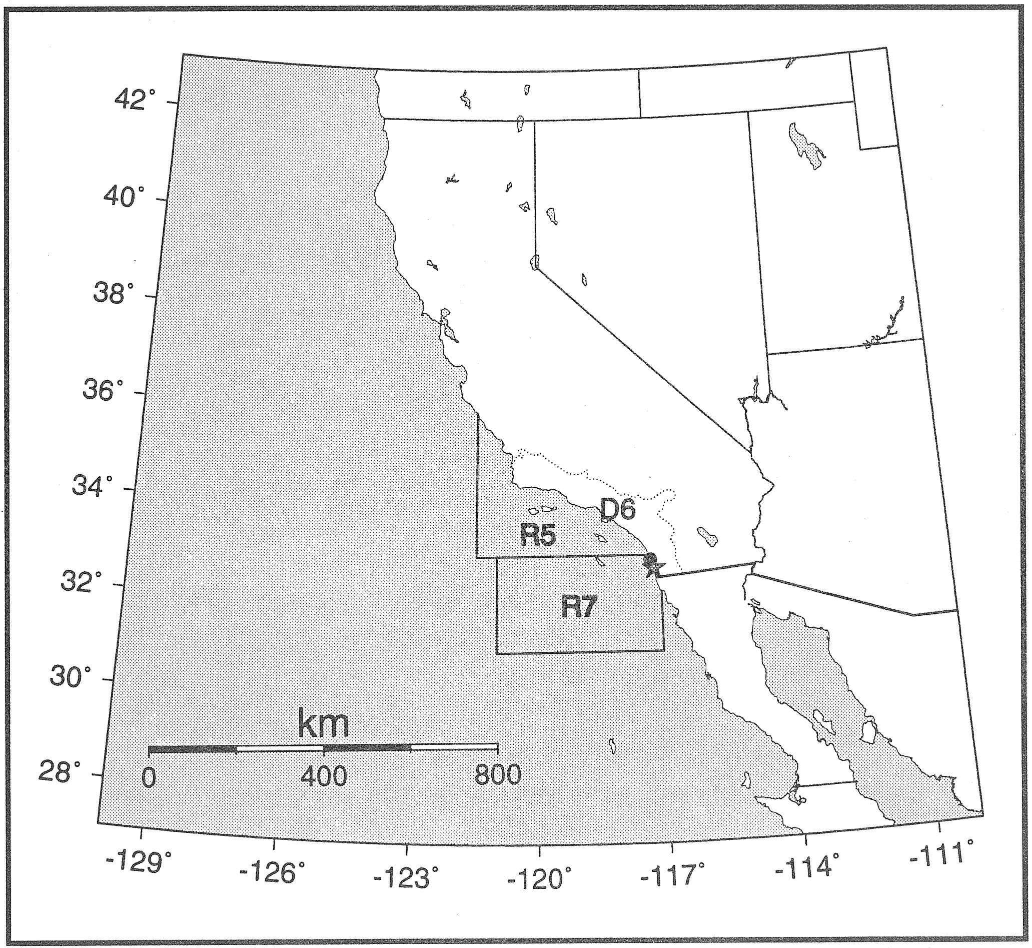

Figure 1. Location of dendroclimatic records. ● = Torrey pine tree-ring chronology; ★ = San Diego precipitation, temperature, and fog; D6 = California Climate Division 6 precipitation and temperature; R5, R7 = fog observations over marine region 5 and 7, respectively.

Dominant trees were sampled by taking two increment cores from the lower stem at about 1 meter above ground level, in a direction parallel to the topographic contour and at about 180 degrees from each other. Wood cores were 4.3 mm wide and less than 50 cm long; all holes were closed and sanitized. Standing trees were selected across the area according to dendrochronological criteria, as first outlined by Douglass (1919). These criteria favor steep, open sites occupied by trees with large branches and flat crown top. Every effort was made to avoid trees affected by non-climatic factors; *eg,* human disturbance, grazing, fire, insect outbreaks, fungi, mistletoe. Information on location, size, and health status of sampled trees was recorded in the field and entered into a computer database for future reference.

All wood samples were transported to the Scripps laboratory, air dried, and glued to wooden mounts after vertically aligning the xylem tracheids. Mounted cores were mechanically sanded, then polished by hand with progressively finer sandpaper until the smallest rings were clearly visible at 10x magnification. Ring patterns were visually crossdated (Douglass 1941; Stokes and Smiley 1968) using a binocular microscope, then ring widths were measured to the nearest 0.001 mm by means of a sliding stage interfaced with an image analysis system. Dating accuracy was numerically verified using the computer program COFECHA (Holmes 1983; Grissino-Mayer *et al* 1996).

Climatic Records

Local climatic data came from different sources. Monthly precipitation (1850-1990) and temperature (1852-1990) records for San Diego were obtained from the Global Historical Climatology Network (Vose *et al* 1993). The most recent years of San Diego records (up to December 1994) were taken from the National Climatic Data Center on-line dataset of U.S. Cooperative and National Weather Service stations. Regional averages of monthly precipitation and temperature were provided by California Climate Division 6 time series (1895-1993) distributed by the National Climatic Data Center. Seasonal fog records for San Diego (1948-1990) as well as averaged over two marine regions (1949-1991), one south and one north of San Diego along the Southern California coast (Figure 1), were derived from the dataset compiled by Filonczuk *et al* (1995). Global datasets of sea surface temperature and sea level pressure compiled by Scripps Climate Research Division were used to map correlation fields with the Torrey pine tree-ring chronology.

Statistical Methods

Ring-width measurements were standardized to remove individual trends as well as age- and size-related differences in growth rates (Cook and Kairiukstis 1990). The Torrey pine tree-ring chronology was produced by means of a statistical model that incorporates both deterministic and stochastic components (Biondi 1992, 1993). The computer program ARSTAN (Grissino-Mayer *et al* 1996) was used for data processing, and the final chronology could be written as follows:

$$\overline{I}_t = (1-\oplus B)\{\oplus_{i=1}^{n_t}[\log(w+k)-y]_{it}+\alpha\}$$

with: I_t = chronology value at year t
w = crossdated ring width
k = constant added to avoid taking the logarithm of 0
y = modified negative exponential or straight line
n_t = number of measured specimens that include year t (in this study, $4 \leq n_t \leq 25$)
$\oplus_i$ = biweight robust mean (Mosteller and Tukey 1977) of the i-values, $i = 1, \ldots, n_t$
α = difference between 1.000 and the arithmetic mean of the robust-mean chronology
$1-\oplus B$ = first-order autoregressive operator (Box and Jenkins 1976)

The relationship between climate and tree growth was investigated by means of correlation analysis and response-function analysis. Correlation of tree-ring chronologies with annual or seasonal climatic variables is straightforward (Douglass 1914, 1919). Correlation with monthly climatic variables requires more advanced statistical techniques to account for possible collinearity of predictors (Fritts 1991). These techniques are based on multiple regression between the pre-whitened tree-ring index and the principal components of the monthly climatic predictors, as well as on bootstrapped confidence intervals to test significance of each monthly variable (Fritts *et al* 1971; Guiot 1990, 1991). To account for numerical and biological persistence in the tree response to climate, we defined a 14-month dendroclimatic window, going backwards from October of the current growth year to the previous September.

The spatial coherency between Torrey pine and other tree-ring chronologies for western North America was analyzed using the International Tree-Ring Data Bank (NOAA 1992; Figure 2). The data bank is a collection of accurately dated tree-ring records developed by dendrochronologists over many years, and is continuously expanding as new datasets become available. In addition, unpublished chronologies for Southern California were provided by Dave Meko, Laboratory of Tree-Ring Research, University of Arizona, and by Laura Haston, formerly at Geography Department, California State University-Northridge. All tree-ring chronologies began prior to 1800 and ended between 1960 and 1993.

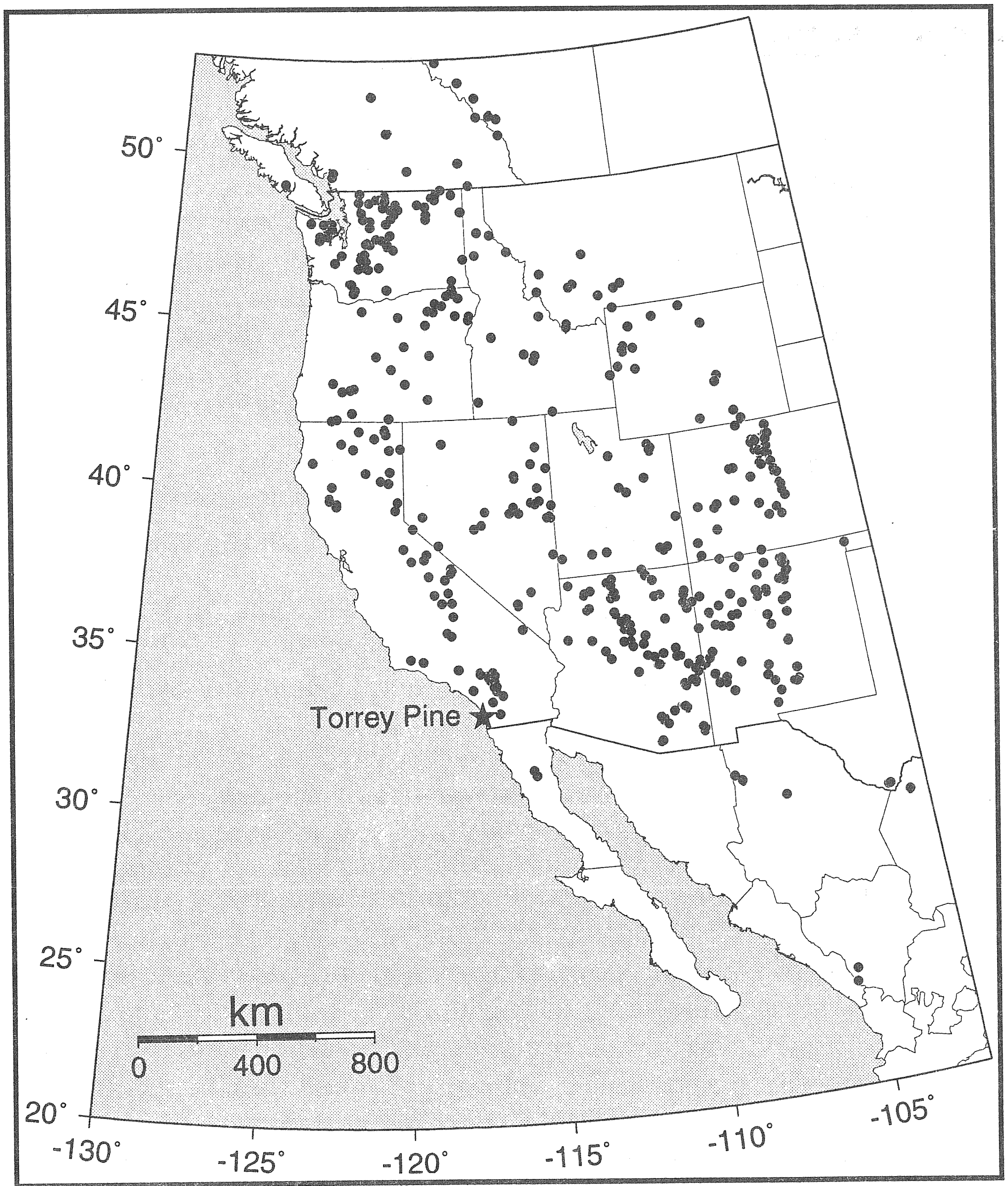

Figure 2. Tree-ring sites in western North America (source: International Tree-Ring Data Bank; NOAA 1992). The period in common between the 585 tree-ring chronologies (●) and the Torrey pine chronology (★) varies from 1827-1960 to 1827-1993.

Results and Discussion

Torrey pine tree rings could be crossdated, even though faint latewood boundaries in certain years and specimens required careful specimen preparation and long hours of microscope work for correct identification. Based on crossdated series, sampled trees reached a maximum age of 170 years at coring height; *ie,* about 1 meter above ground level. Considering an estimated time of 10-30 years to reach coring height, sampled trees were no older than 200 years, which is almost three times the maximum age reported by Vogl *et al* (1977). The possibility that older trees still exist, albeit unlikely, cannot be ruled out. From the collected samples, we developed a continuous chronology spanning the 1827-1994 period using overlapping segments of well-defined annual rings (Figure 3). Chronology sample depth is maximum in 1917-1978, when the mean index is averaged over 20-25 samples. The early years are based on at least four samples (1827-1838); sample depth rises to ten or more after 1867, and the most recent years are based on at least eighteen samples.

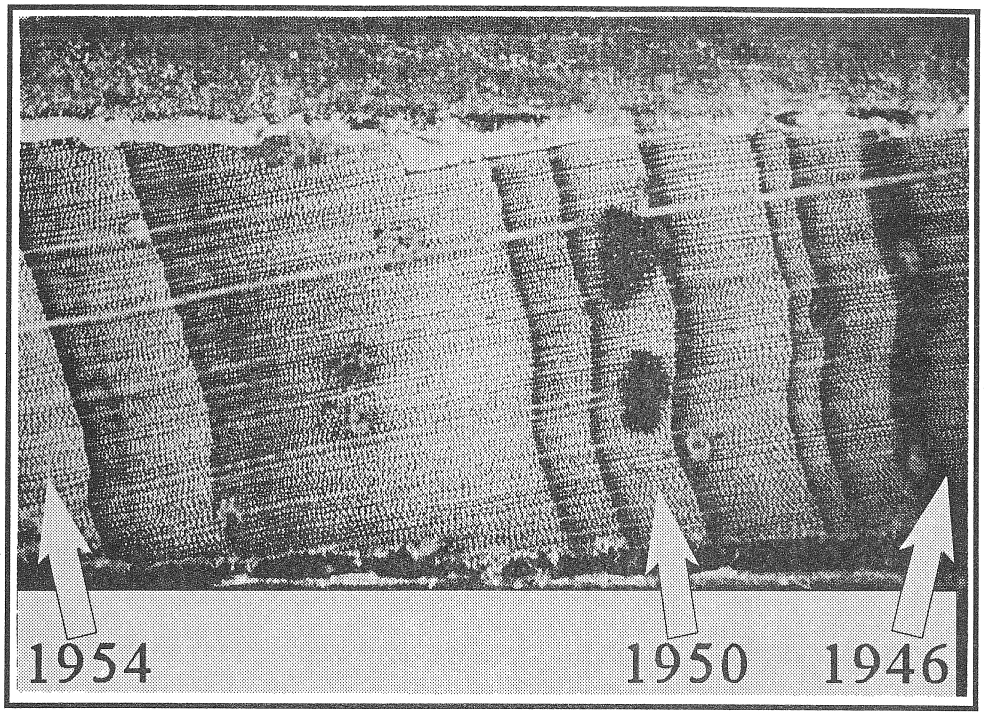

Figure 3. Annual xylem rings of Torrey pine as seen under a binocular microscope after specimen preparation and surfacing.

Response functions based on 28 monthly predictors (14 for precipitation and 14 for temperature) were consistent using either San Diego station data or Climate Division 6 average data. Similarly, response functions based on 12 seasonal predictors (4 each for precipitation, temperature, and fog) were consistent using station data or regional averages. In both cases, however, regression statistics were better using San Diego station data; hence those results are reported in the following paragraphs. The major climatic signal in Torrey pine tree rings consists of winter and spring rainfall, as shown by the significant coefficients for November-April precipitation (Figure 4). Temperature is not a significant predictor of Torrey pine annual growth, and summer fog has a weak, positive association with Torrey pine annual growth (Figure 4). These results were confirmed by linear correlation coefficients between the Torrey pine chronology and climatic time series (Figure 5). From 1850 to 1994, total rainfall from November through April had the highest correlation (0.77, n=145) with the Torrey pine tree-ring chronology. Among seasonal variables, winter and spring precipitation had, respectively, the second (0.63, n=145) and third (0.43, n=145) highest correlation with the tree-ring chronology. The only other seasonal variable significantly correlated (0.37, n=43) to Torrey pine annual growth was summer fog. Most likely, summer fog benefits Torrey pine growth by reducing the evapotranspiration stress during the warmest and driest season of the year. However, when combined with winter and spring precipitation in a multiple regression model, summer fog was not a significant predictor of Torrey pine tree growth.

According to Mallows' *Cp* criterion (Mallows 1973; SAS Institute 1990), from 1850 to 1994 November-April precipitation is the best predictor of Torrey pine tree growth among all possible combinations of seasonal variables. The consistency of climate/tree-growth relationships through time was then investigated by comparing correlation results between November-April precipitation and Torrey pine annual growth during three non-overlapping periods, 1850-1899, 1900-1949, and 1950-1994

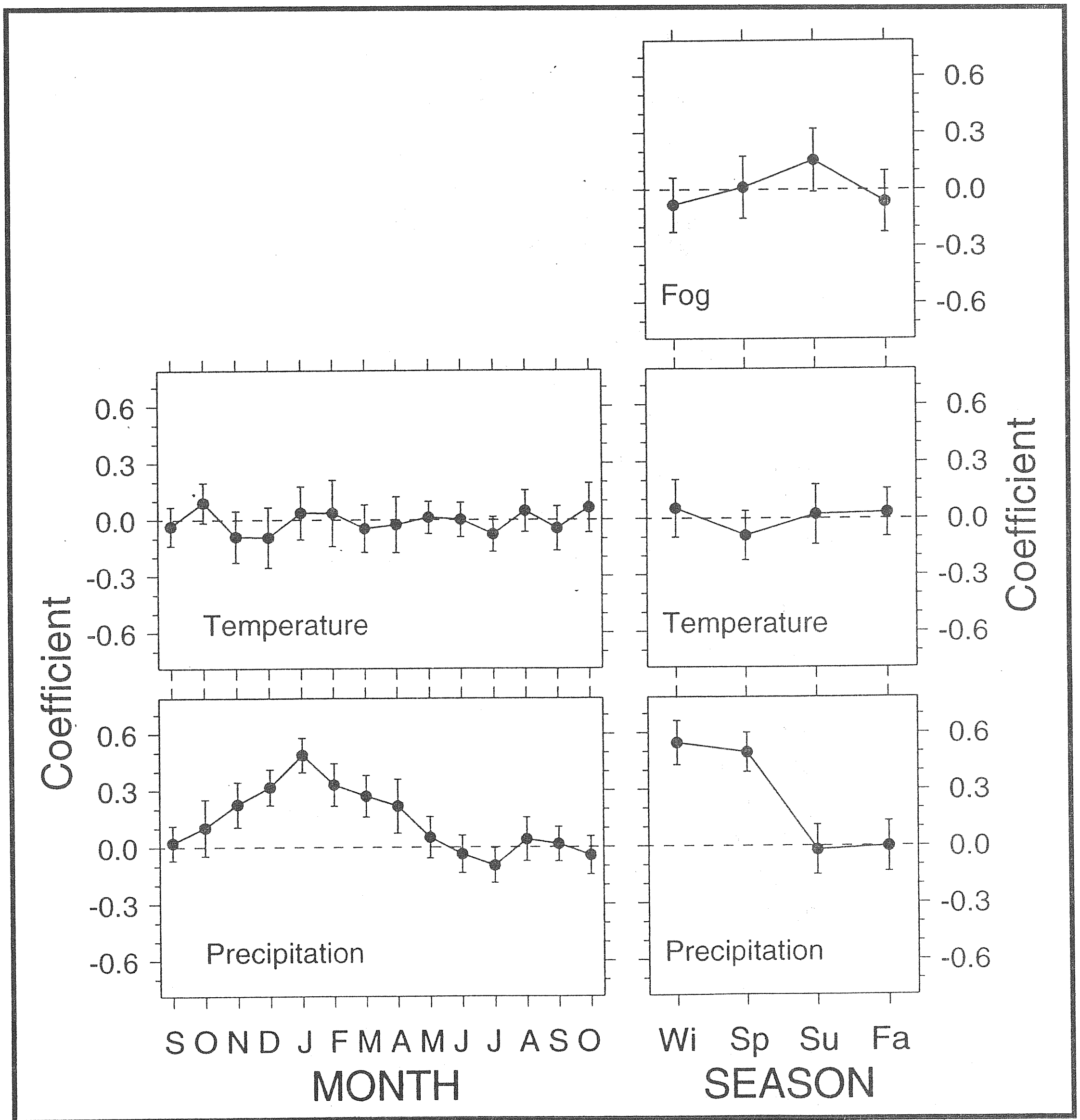

Figure 4. Response functions between Torrey pine tree-ring chronology and San Diego climatic variables. A total of 28 monthly predictors (1892-1990) and 12 seasonal predictors (1950-1990) were decomposed into principal components and randomly selected with replacement to compute bootstrapped confidence intervals.

(Figure 6). The amount of explained variance was higher in the 20th century (64% in 1900-1949, 70% in 1950-1994) than in previous decades (48% in 1850-1899). This difference could be attributed to different factors. Assuming that the tree-ring standardization effectively removed age- and size-related effects on annual growth and that the number of samples used to develop the Torrey pine chronology was large enough throughout the entire period of interest to obscure the effect of time-varying sample depth, temporal differences in climate-tree growth relationships could still be generated by changes in the quality of rainfall data. As an example, the largest value in the whole Torrey pine

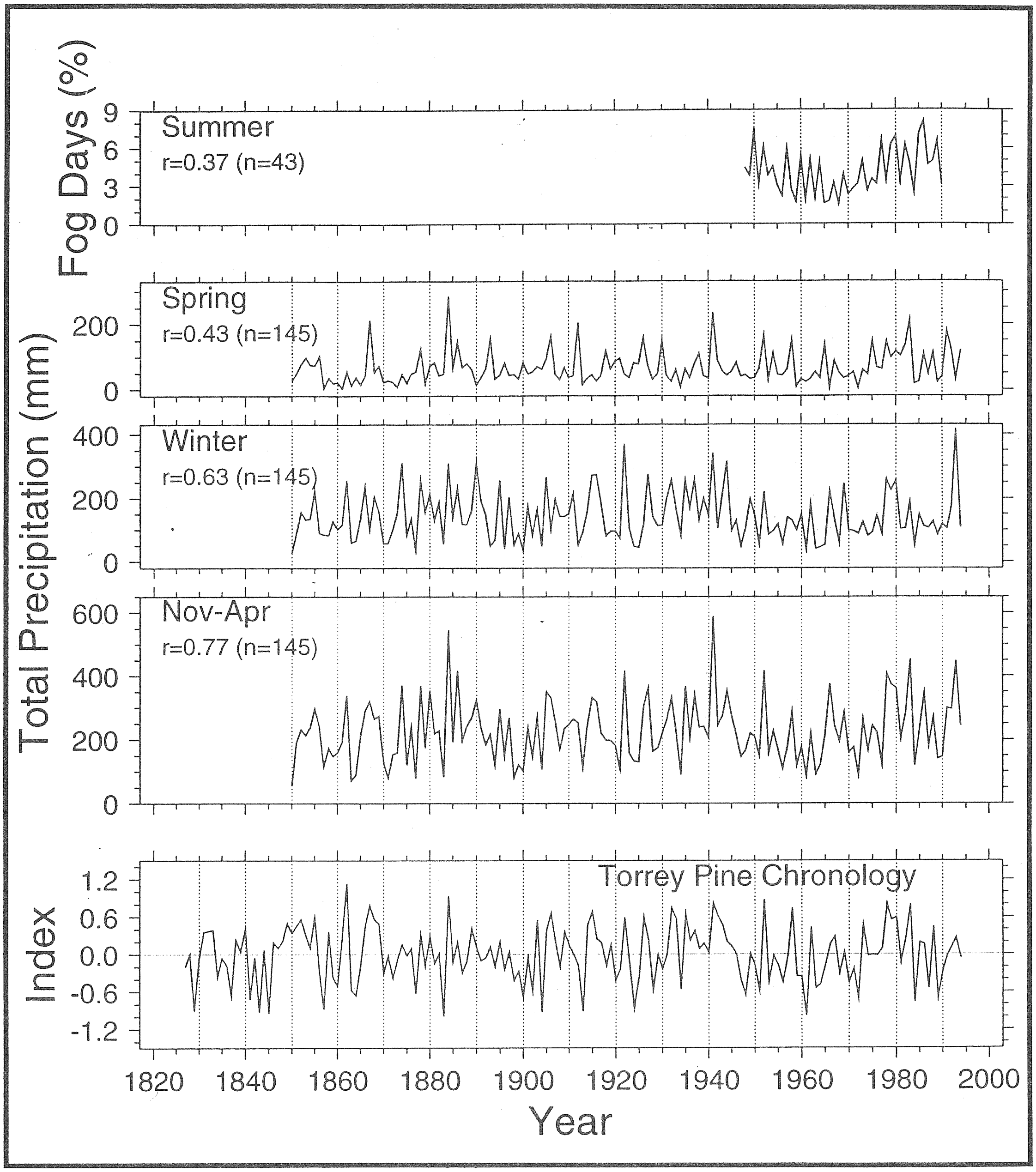

Figure 5. Time-series plots of San Diego dendroclimatic records. The linear correlation (*r*) with the Torrey pine chronology is maximum for total November through April precipitation.

chronology occurs in 1862, which may be one of the wettest winters in recent Southern California history (Engstrom 1996), but is not a very large value in the San Diego precipitation record (Figure 5). The Torrey pine chronology can then provide an estimate of precipitation during the early and pre-instrumental period. As such, it reveals a very dry period in the early and mid-1840s, followed by a wet spell until the early 1850s and by another wet period in the late 1860s (Figure 5).

Spatial correlation between the Torrey pine chronology and seasonal precipitation (1895-1994) over the Climate Divisions identified by NOAA (1983) revealed a connection with the lower half of the West Coast and

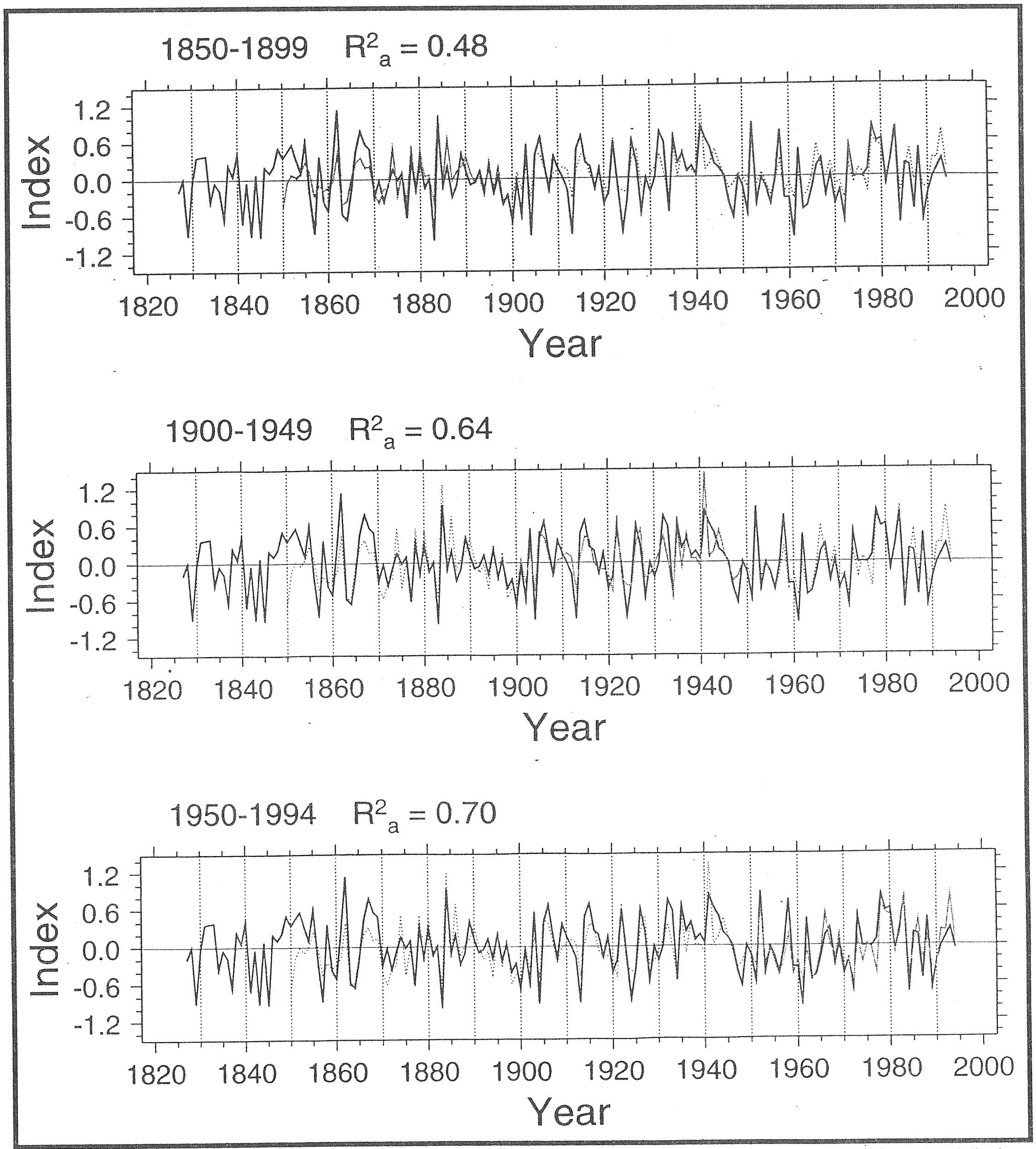

Figure 6. Linear estimates (solid gray line) and predictions (dotted line) of the Torrey pine tree-ring chronology (solid black line) obtained using total November-April precipitation during three adjacent time intervals. The amount of explained variance (R^2_a) is lower before 1900 than after 1900.

the American Southwest in winter and with the American Southwest in spring (Figure 7).

Correlation maps with gridded winter sea surface temperature and sea level pressure were consistent using different near-global datasets. Prominent features were a strong positive association with sea surface temperature south of San Diego and in the eastern tropical Pacific, and an equally strong negative association with sea level pressure directly above the California Current, in an area centered approximately over

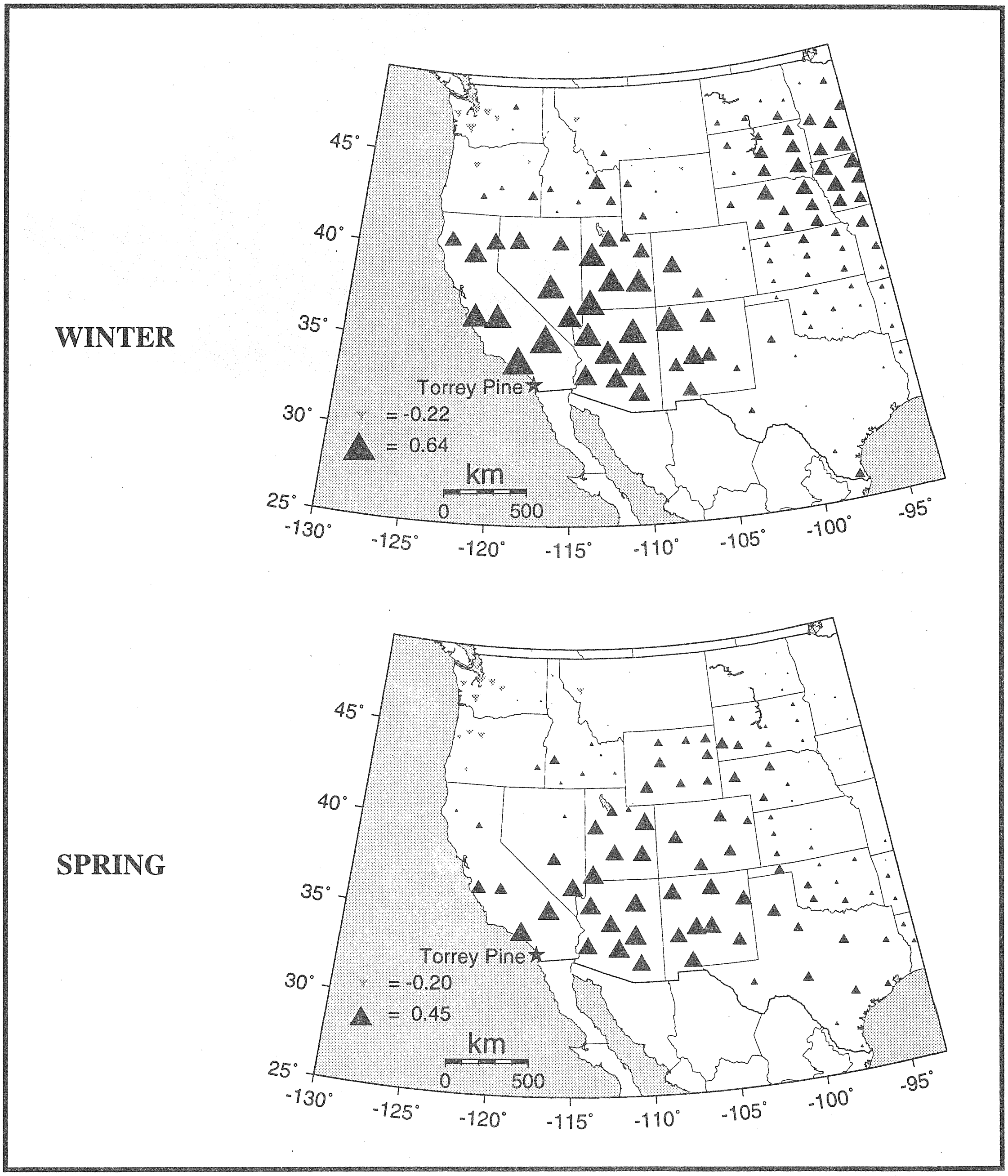

Figure 7. Linear correlation (*r*) between the Torrey pine tree-ring chronology and seasonal precipitation (WINTER and SPRING, 1895-1994) over NOAA/NCDC Climate Divisions for the western U.S. Symbol size for positive (solid, upward triangles) and negative (shaded, downward triangles) correlations is directly proportional to the absolute value of *r*.

30-40°N and 120-130°W, just off the Patton Escarpment (Figure 8). These correlation fields indicate that Torrey pine annual growth is favored, on average, by a weakening or a displacement of the high pressure cell that normally develops off Southern California in winter (Duxbury and Duxbury 1991), hence by a southerly displaced winter storm track. Annual tree

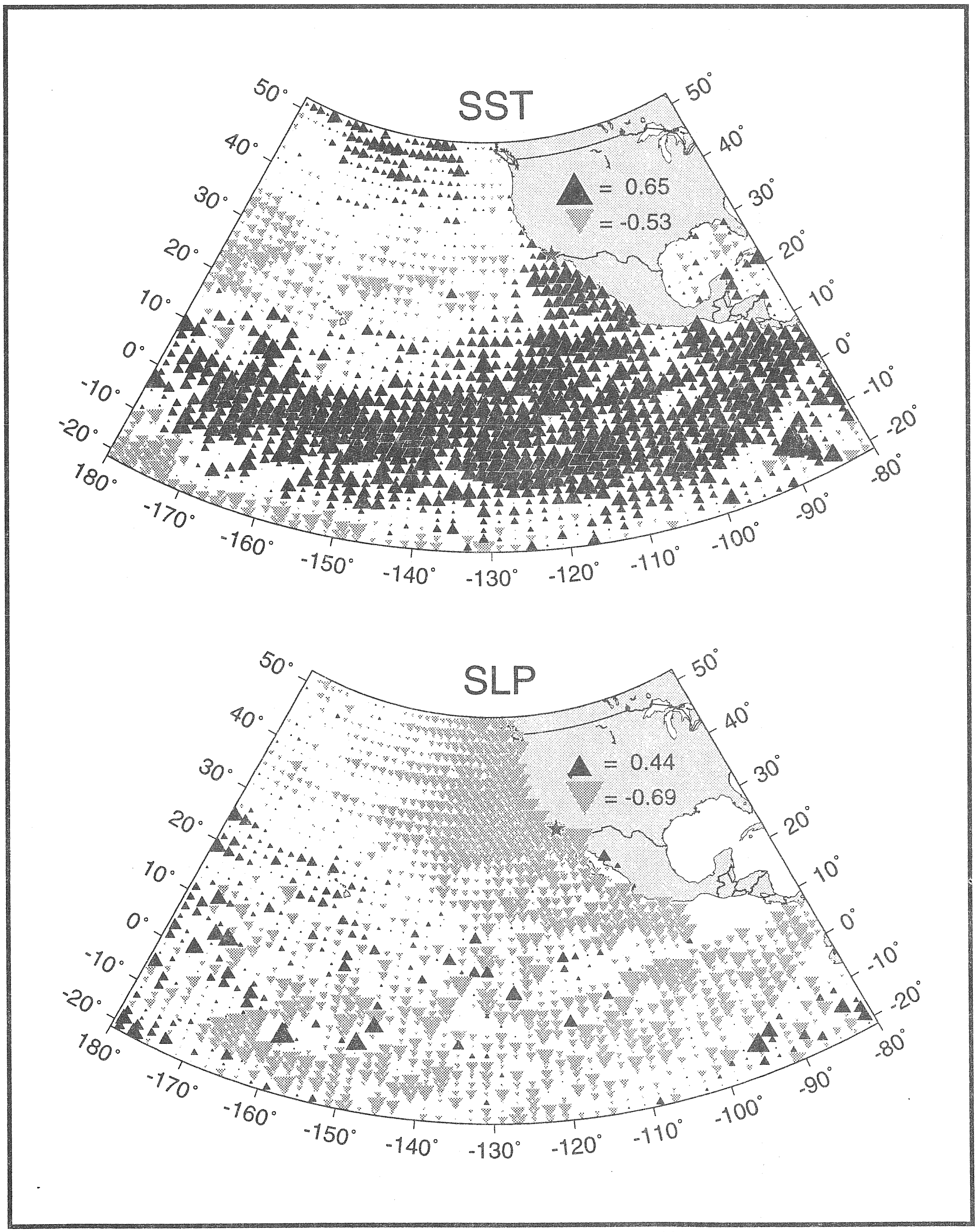

Figure 8. Linear correlation (*r*) between the Torrey pine tree-ring chronology (★) and gridded December to February mean sea surface temperature (SST) and sea level pressure (SLP) in the eastern tropical and subtropical Pacific during 1948-1992. Climate data were obtained from the Comprehensive Ocean-Atmosphere Data Set (COADS). Symbol size for positive (solid, upward triangles) and negative (shaded, downward triangles) correlations is directly proportional to the absolute value of *r*.

growth is also favored by the development of warm anomalies in the southern portion of the California Current region and in the eastern tropical Pacific. Both of these patterns indicate that Torrey pine growth is sensitive to moisture transport from the eastern tropical Pacific driven by a southerly extension of the westerlies caused by the lower-than-average pressures off Southern California. Such a mechanism is enhanced by the El Niño-Southern Oscillation (ENSO) phenomenon: during warm events, surface winds and upper-level jets move from the eastern tropical Pacific into the American Southwest, whereas during cold events that airflow is blocked or reversed (Murphree and Reynolds 1995).

The Torrey pine chronology is highly correlated to tree-ring chronologies developed for Southern California and the Colorado Plateau (Figure 9, top). The contoured correlation field shows a pronounced, V-shaped, southwest-to-northeast gradient extending into a large portion of the American Southwest (Figure 9, bottom). Interestingly, the correlation with other regions of the western United States is consistently near zero (Figure 9).

Torrey pine and Southern California are linked to the Colorado Plateau mostly via winter precipitation patterns, as revealed by the spatial correlation between San Diego winter precipitation and tree-ring chronologies (Figure 10, top). On one hand, the high coherency between Torrey pine and tree-ring chronologies much farther inland is remarkable, considering that coastal species are often scarcely sensitive to climate. On the other hand, the extremely good agreement between the correlation maps shown in Figures 9 and 10 (top) is not surprising, considering the previously discussed relationship between winter precipitation and Torrey pine annual growth. In winter, El Niño events are associated with increased rainfall in a region longitudinally stretched from Southern and Baja California to Western Texas and the Southeastern United States (Schonher and Nicholson 1989; Diaz and Kiladis 1992; Stahle and Cleaveland 1993). However, the linkage between Torrey pine and the American Southwest can only partly be attributed to ENSO, as revealed by the correlation maps between the Southern Oscillation Index (SOI, Ropelewski and Jones 1987) and the western North America tree-ring chronologies (Figure 10, bottom). The Colorado Plateau tends to have greater correlations with SOI than Southern California, and some large correlations are also found in the northern portion of the U.S. West Coast. Persistence effects in tree-ring response to climate, as well as other ocean/atmosphere interactions, may play a role in shaping the Southern California/Colorado Plateau connection, as suggested by correlation maps between tree-ring chronologies and previous summer sea surface temperature at coastal stations (Biondi *et al*, this volume).

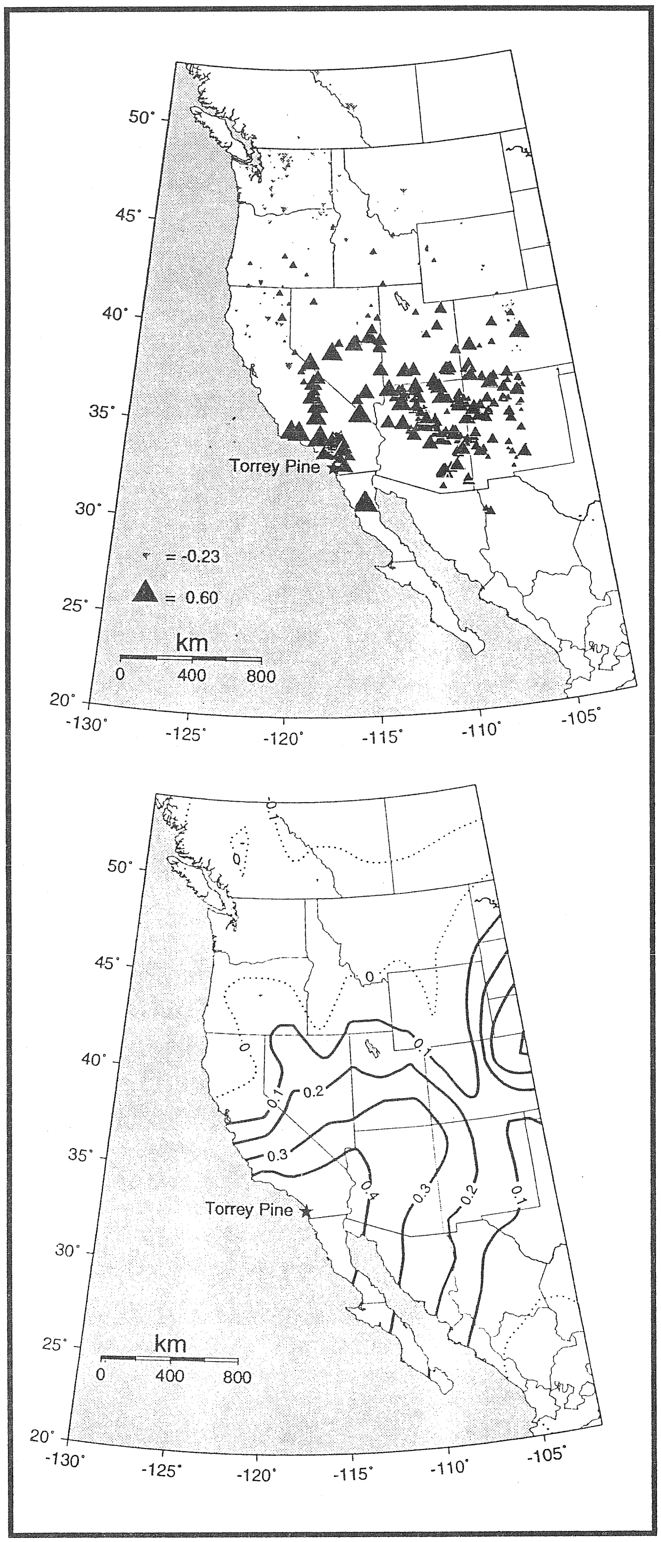

Figure 9. Linear correlation (*r*) between Torrey pine and tree-ring chronologies shown in Figure 3.
Top: Point correlations; symbol size for positive (solid, upward triangles) and negative (shaded, downward triangles) correlations is directly proportional to the absolute value of *r*.
Bottom: Contoured correlation field; contour interval is 0.1 for positive (solid lines) and negative (dotted lines) correlations.

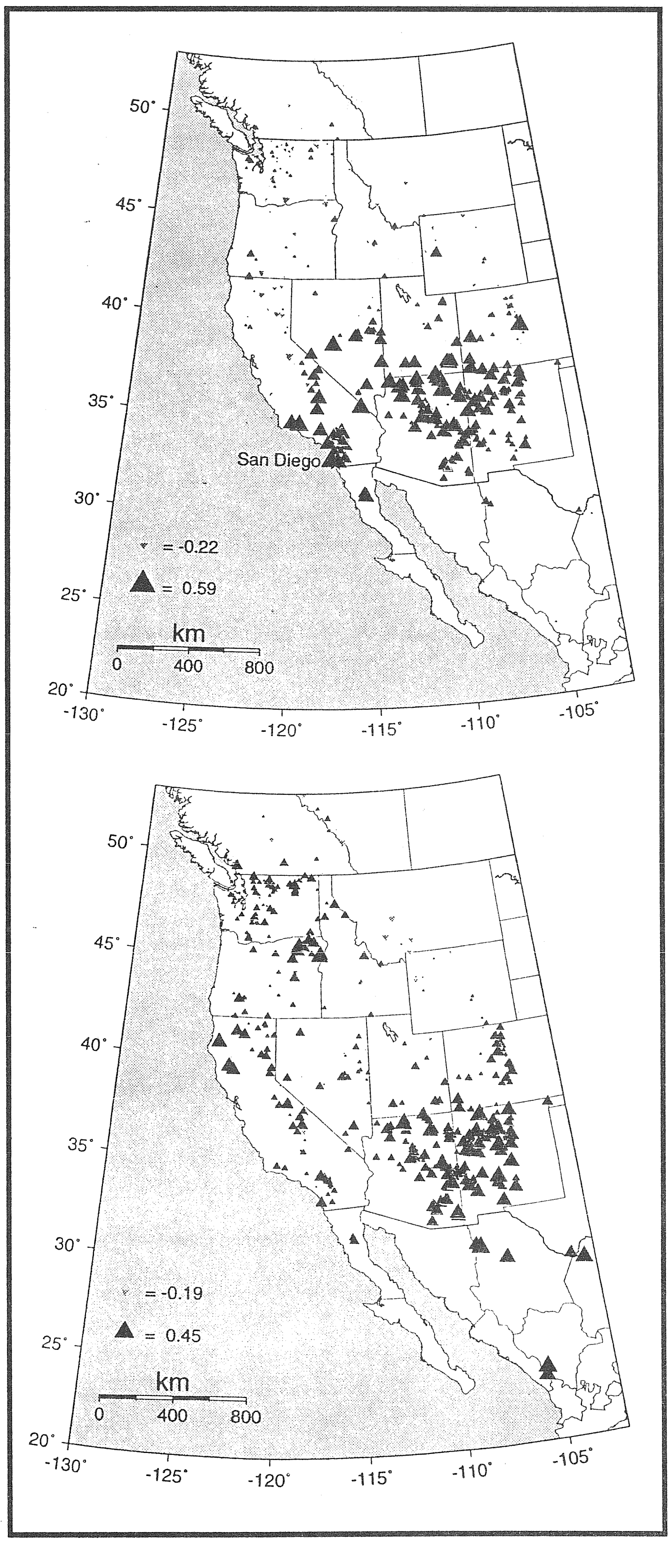

Figure 10. Linear correlation (*r*) between tree-ring chronologies and winter climatic variables. Symbol size for positive (solid, upward triangles) and negative (shaded, downward triangles) correlations is directly proportional to the absolute value of *r*.
Top: Total DJF precipitation in San Diego (1850-1994).
Bottom: Southern Oscillation Index (SOI, 1882-1993; the sign was reversed to make El Niño years positive).

Conclusion

Our study provided evidence that Torrey pine tree rings are datable using dendrochronological techniques, that maximum tree age does not exceed 150-200 years, and that annual growth is highly sensitive to winter and spring precipitation. Summer fog was positively correlated with Torrey pine annual growth, but its predictive ability was minimal when compared with winter and spring rainfall. Large-scale climatic signals in Torrey pine tree rings extend to the California Current region off Southern California and to the eastern tropical Pacific, and show a pronounced gradient from the southern California Coast into the Colorado Plateau. There is little evidence that climate-tree growth relationships have changed over the 20th century. The lower association between tree growth and November-April precipitation in 1850-1899 than in more recent decades may have different causes, including lower quality of rainfall records. The Torrey pine chronology is, then, well suited to provide an estimate of early and pre-instrumental climate records for San Diego.

To complement our results, it would now be desirable to conduct field experiments on the short-term (daily or weekly) response of Torrey pine stem growth to weather variability. Such a study, for instance, could explain why Torrey pine tree rings occasionally show faint latewood boundaries as if, depending on factors internal and external to the tree, xylem growth could slow down but still continue from one growing season to the next. We are also planning to extend this initial dendroclimatic study to other conifer species and sites along the California Coast, and we have already completed the necessary field work (Figure 11).

Resource managers, the public, and the scientific community could benefit from our results. Torrey Pine State Reserve receives an average of one million visitors per year (Mike Wells, *pers comm*). The recreational value alone of conifer species endemic to the California Coast would justify detailed studies on the possible impact of future local and regional climate change on the growth and survival of those species within their natural habitat. Additional results generated by dendrochronological studies of this sort could include age/size equations, which are beneficial to resource managers in assessing the performance of individual trees and stands and in uncovering stand age structure and development.

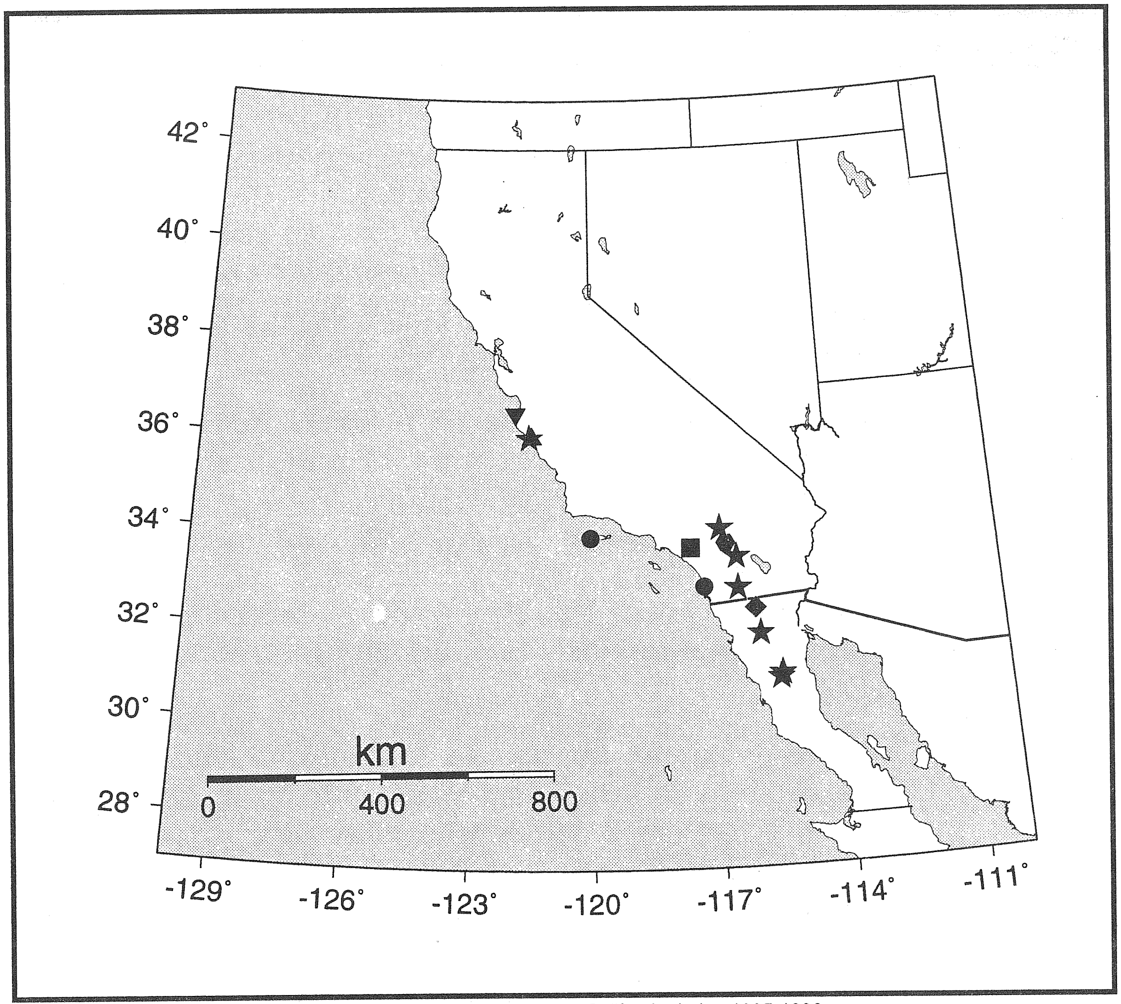

Figure 11. Location of tree-ring sites sampled in Southern and Baja California during 1995-1996.
★ = Jeffrey and ponderosa pine; ● = Torrey pine; ✷ = limber pine; ◆ = piñon pine;
▲ = sugar pine; ▼ = Monterey pine; ■ = Big-cone Douglas-fir.

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