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DENDROCHRONOLOGY OF *ABIES RELIGIOSA* IN MICHOACAN, MEXICO

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ABSTRACT

An exploratory investigation of tree growth and climate relationships in *Abies religiosa* from Michoacan, Mexico, produced the first crossdated and standardized tree-ring chronology from the North American tropics. Pearson correlation coefficients and principal components response function analysis were employed. Results indicate that ring-width series from this species have moderately high signal-to-noise ratio (S/N = 13.42). A substantial percentage of the ring-width signal can be explained by instrumented monthly climate data, particularly spring precipitation and winter temperature. Although correlation between climate data and the tree-ring measurements indicate that growth of *Abies religiosa* is highly influenced by year-to-year climate variation, longer climate records and tree-ring chronologies are needed from this tropical region to improve understanding of climate-tree growth relationships, and for dendroclimatic reconstruction.

Eine orientierende Untersuchung über die Klima-Wachstums-Beziehungen von *Abies religiosa* in Michoacan, Mexico, führte zur ersten standardisierten Jahrringchronologie für die nordamerikanischen Tropen. Hierbei wurden der Pearson'sche Korrelationkoeffizient sowie eine auf einer Hauptkomponentenzerlegung beruhende 'response function' berechnet. Die Jahrringfolgen dieser Baumart zeigen einen mäßig hohen 'Signal-Rauschen-Quotienten' von 13,42. Ein erheblicher Anteil des Jahrringsignals kann durch monatliche Klimadaten erklärt werden, vor allem durch Frühjahreniederschlag und Wintertemperatur. Obwohl der Zusammenhang zwischen Klima und Wachstum anzeigt, daß *Abies religiosa* von der jährlichen Witterungsschwankungen stark beeinflußt wird, sind längere Klimazeitreihen und Jahrring-Chronologien für diese tropische Region erforderlich, um die Klima-Wachstums-Beziehungen besser zu verstehen und dendroklimatologische Rekonstruktionen durchzuführen.

Une étude préliminaire des relations cerne-climat portant sur *Abies religiosa* provenant de Michoacan au Mexique a fourni la premiére chronologie datée et standardisée obtenue dans les régions tropicales du continent nord-américain. Les méthodes utilisées ont mis en oeuvre le coéfficient de corrélation de Pearson et la fonction de réponse basée sur une analyse en composante principale. Les résultats obtenus indiquent que les séries dendrochronologiques de cette espéce montrent un rapport signal-bruit modérement élevé (S/N = 13,42). Un pourcentage important du signal dendrochronologique peut être expliqué par des données climatiques mensuelles, en particulier les précipitations printaniéres et les températures hivernales. Bien que les corrélations existant entre les données climatiques et les mesures de cernes montrent que la croissance d'*Abies religiosa* est fortement influencée par les variations climatiques interannuelles, il faudra obtenir dans ces régions tropicales de plus longues séries climatiques et dendrochronologiques pour améliorer la compréhension des relations cerne-climat et pour réaliser des reconstitutions dendroclimatiques.

INTRODUCTION

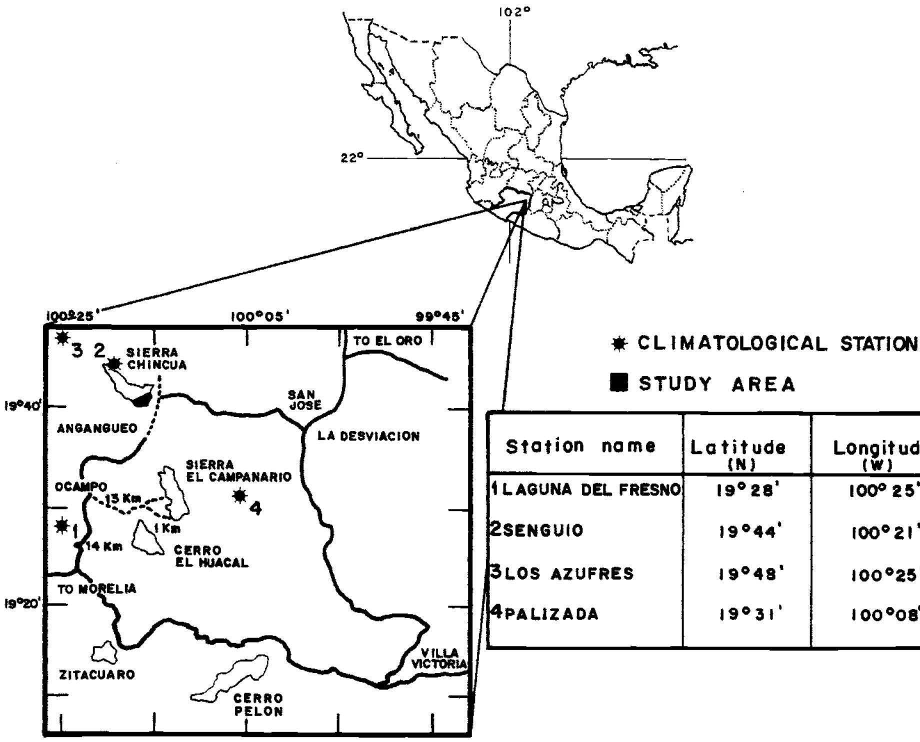
This work is intended as a contribution to the ecological knowledge of *Abies religiosa* (H.B.K.) Schlecht. & Cham., whose forest habitat is part of the winter refuge of the migratory Monarch Butterfly (*Danaus plexippus* L.). The importance of maintaining the forest integrity and cover in this area for the butterfly has been documented by Calvert and Brower (1981). In all but the most inclement weather, the moderating effect of the forest canopy protects the butterflies from temperature extremes. Ground conditions are generally colder and wetter than those prevailing in the canopy layer above, and butterflies trapped on the ground for one or more nights, or in forest clearings, suffered flight incapacitation or died.

Development of tree-ring chronologies from Central Mexico is important because of the potential for tracing long-term climatic changes in a tropical region. There is a lack of tropical tree-ring records world wide. To the best of our knowledge, the tree-ring data reported here represent the most southerly collection on the North American continent that has been successfully crossdated and dendrochronologically analyzed. Both the climate and tree-ring records compiled so far are too short for dendroclimatic reconstruction; however, we believe that with concerted effort longer time series can be obtained. Despite the brevity of records obtained so far, these data are useful for identifying relationships between temperature and precipitation variables and tree-ring growth.

STUDY AREA

The study area is located in Sierra Chincua at 2800 meters above sea level. This range is part of the Transvolcanic Belt in Michoacan, Mexico (Figure 1). The climate is temperate with rainfall occurring primarily during the summer. Mean total annual precipitation is 1228 mm (range: ± 72 mm)(Figure 2), mean minimum annual temperature is 0.13 ºC (± 0.30 ºC), mean temperature is 10.73 ºC (± 0.35 ºC), and mean maximum annual temperature is 21.9 ºC (± 0.19 ºC)(Figure 3).

The main tree components of the coniferous forest in this region are *Abies religiosa*, *Pinus pseudostrobus*, and species of *Cupressus* (Rzedowski 1978). The dominant tree within stands is generally *Abies religiosa*. Herbaceous plants include different species of the genera *Senecio, Eupathorium, Salvia* and the species *Alchemilla procumbens*, *Baccharis conferta, Cestrum anagyris*, and *Acaena elongata*. A variety of moss and lichen species is also present.



Station name	Latitude (N)	Longitude (W)
1 LAGUNA DEL FRESNO	19° 28'	100° 25'
2 SENGUIO	19°44'	100°21'
3 LOS AZUFRES	19°48'	100°25'
4 PALIZADA	19°31'	100°08'

Figure 1. Location of study areas. Heavy lines on detailed map are major roads.

METHODS

Tree-Ring Data

A total of 25 cores from 17 trees was collected with an increment borer from opposite sides of each tree. Preparation and dating of the cores was carried out in the usual manner; skeleton plots were made from each sample and were crossdated in order to obtain the correct dating (Stokes and Smiley 1968, Swetnam et al. 1985). The ring widths were then measured on a sliding-stage micrometer interfaced with microcomputer (Robinson and Evans 1980).

The program COFECHA (Holmes 1986) was applied to the ring-width data set as a statistical verification and test of the dating and measurement. This program uses the ensemble of all dated series to form a master chronology (less the individual tree-ring series to be tested) against which each individual series is then compared. The program ARSTAN (Cook 1985, Cook and Holmes 1986) was used to detrend the ring-width series and perform autoregressive modeling. ARSTAN produces a set of mean index chronologies from all detrended core series that includes a standard chronology (arithmetic mean in this case), a residual chronology, and an "ARSTAN" chronology (Cook 1985). The standard and residual chronologies were used in this analysis. The residual chronology was derived by averaging the residuals of autoregressive models fit to individual core series. ARSTAN also produces a set of descriptive statistics for the entire length of each index chronology, and for a "common period", which in this case was the period when 85% of the cores were included in the chronology.

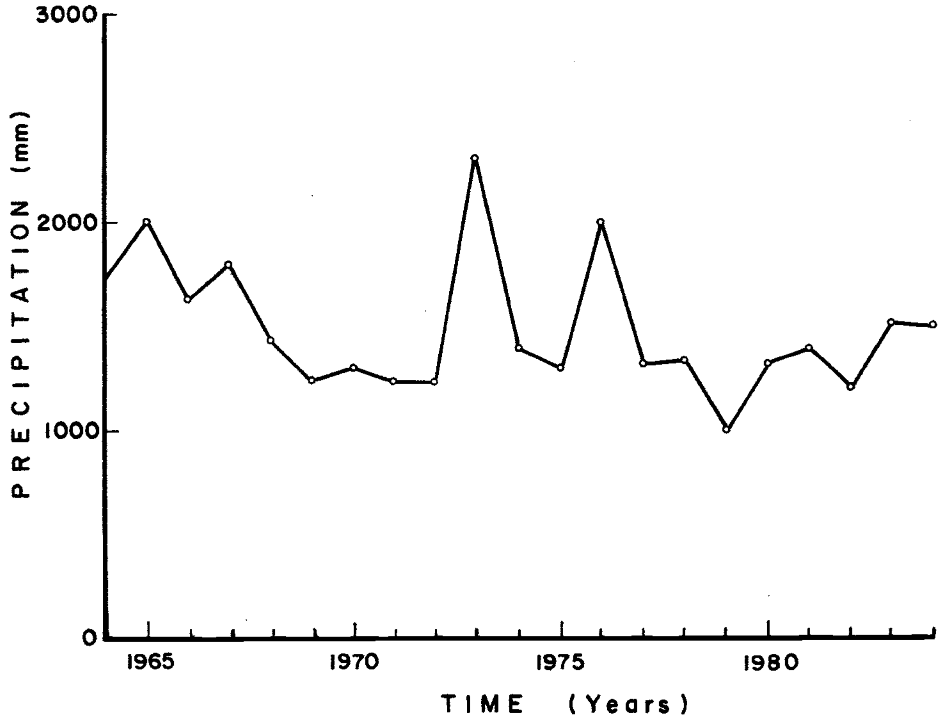


Figure 2. Total annual precipitation at the Los Azufres meteorological station (1967-1984).

The detrending procedure initially involved fitting a variety of curve types to the ring-width series with the primary objective of removing age-related trends and growth variation that appeared to be unique to specific trees or cores. Ring-width indices are formed by dividing each ring-width value by the value of the fitted curve at that year. Curve fitting options included negative exponential curves, straight lines of horizontal or negative slope, and cubic splines of 50% frequency response and variable lengths (stiffness). The double detrending option provided in ARSTAN was also used in some cases. Graphical and statistical comparison of chronologies produced using these different options revealed that they were generally quite similar. For the sake of simplicity, and with the intention of preserving maximum climatic information where possible, the index chronologies developed by fitting negative exponential and straight lines (single detrending) were used in all subsequent analysis.

Climatic Data

Weather data were compiled from six stations in the region (Figure 1) and include the mean, maximum, and minimum monthly temperature, and total monthly precipitation. These data were collected by the National Observatory of Mexico. The characteristics for each station are as follows:

Station Name	Elevation	Length of Records
Laguna del Fresno	2070	1961-1984
Senguio	2511	1968-1984
Los Azufres	2800	1967-1984
Palizada	2660	1961-1984
Jungapeo	1430	1961-1984
Morelia	1923	1951-1973

The climatic records are characterized by a problem common to meteorological series; rainfall and temperature measurements are missing for a few individual months scattered throughout the series. Therefore, it was necessary to estimate the missing values to produce complete time series suitable for analysis. Homogeneity tests were also applied to determine if particular station series are nonstationary, and would therefore be unreliable for use in dendroclimatic analysis (Fritts 1976, Rose et al., 1981)

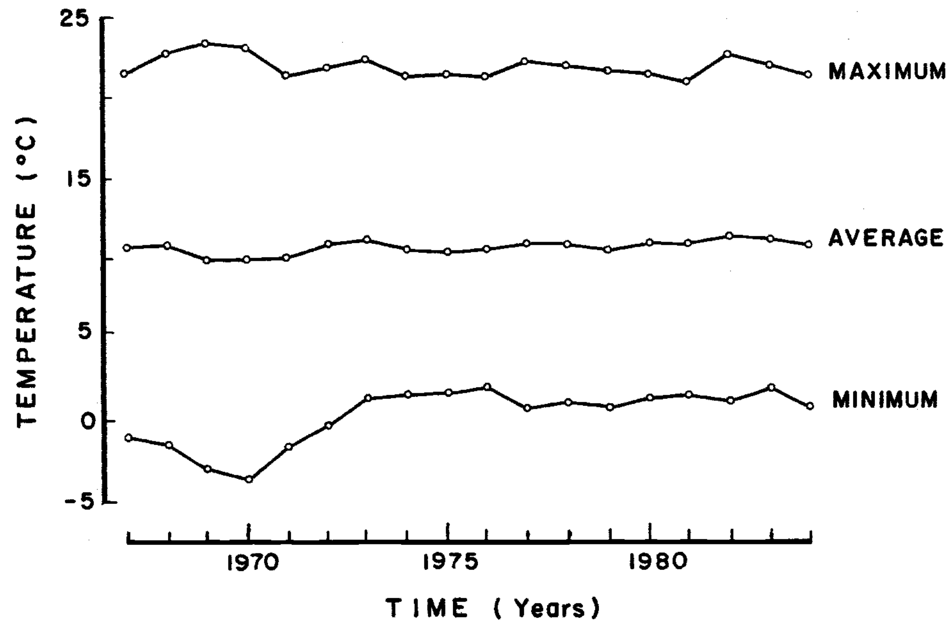


Figure 3. Annual minimum, maximum, and average temperature at the Los Azufres meteorological station (1967 - 1984).

Tree Ring and Climate Analysis

Pearson correlation coefficients (Sokal and Rohlf 1969) were computed for the prewhitened chronology and nonprewhitened climate data. Monthly and seasonal combinations of the climate data were tested. Three month seasons included fall (September to November, prior year), winter (December to February), spring (March to May), and summer (June to August). Six month seasons included winter-spring (December to May) and summer-fall (June to

November). Response functions (Fritts 1976) were computed using maximum, mean, and minimum temperature, and precipitation of the Los Azufres station.

RESULTS

Tree-Ring Series

Figures 4 and 5 illustrate the index series from 25 cores and the mean standard and residual chronologies from these cores, respectively. Table 1 lists descriptive statistics for the common period (1940-1984). Mean sensitivity is low and first-order autocorrelation is some-

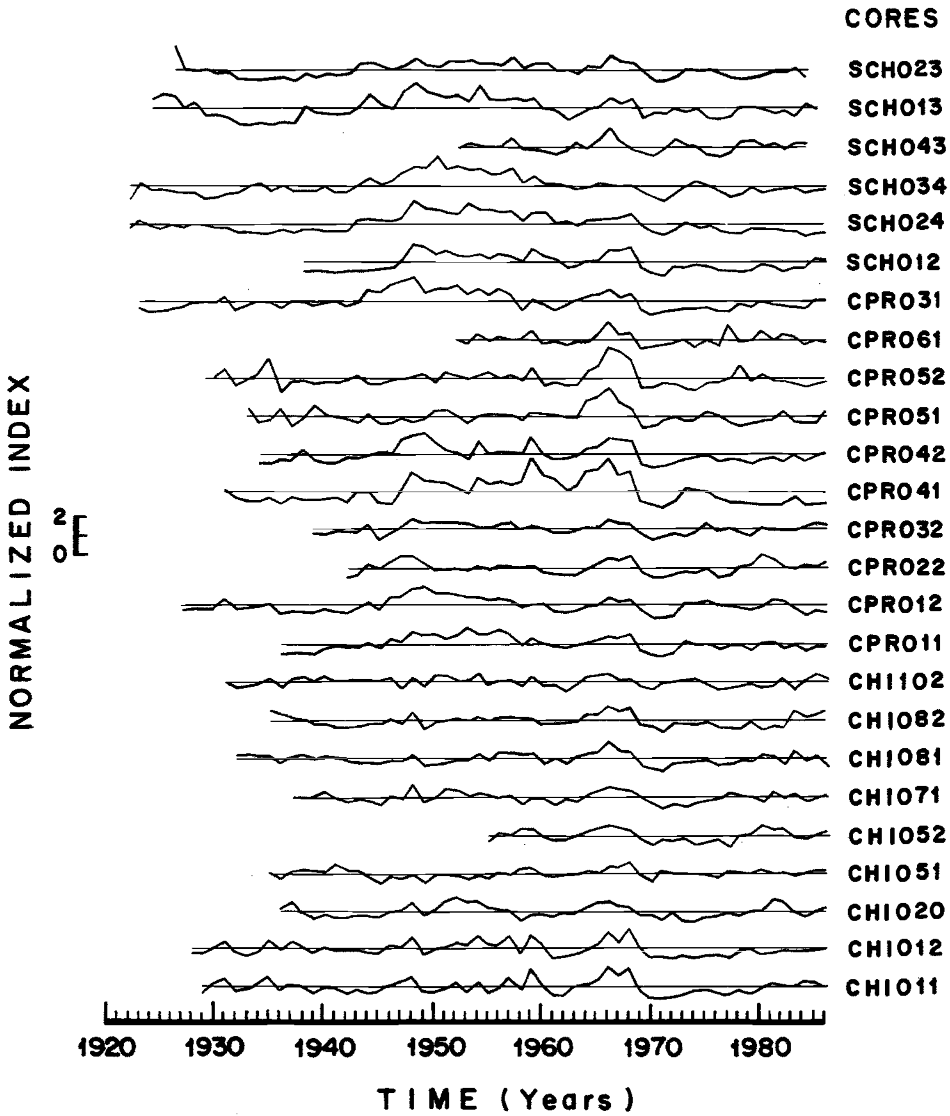


Figure 4. Index series of individual core samples from Michoacan, Mexico.

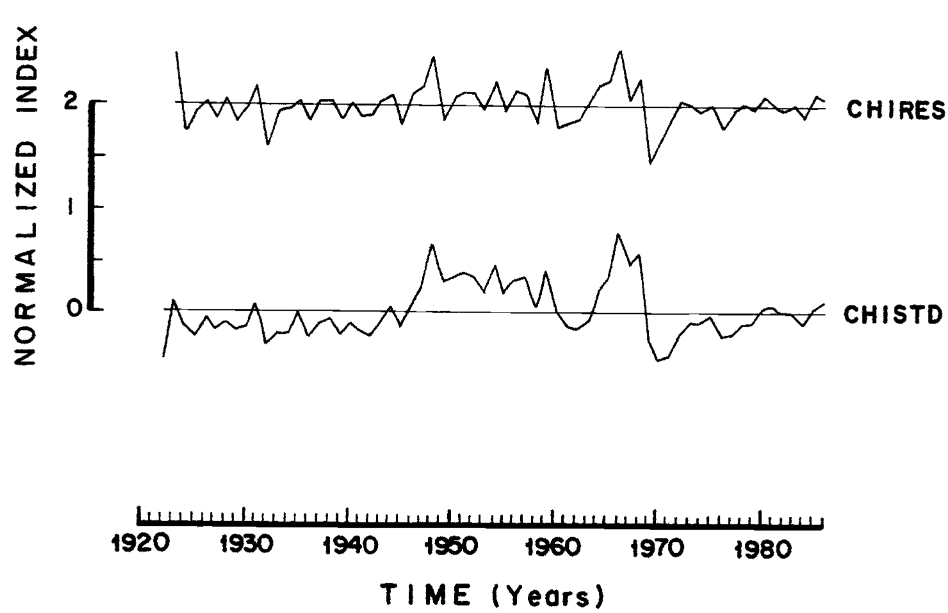


Figure 5. Master chronologies of residual (CHIRES) and standard series (CHISTD) from 1922 to 1986.

what high relative to most other tree-ring chronologies from western North America (Fritts and Shatz 1975; Holmes et al. 1986). The residual series has a higher mean sensitivity than the standard chronology.

In general, the *Abies religiosa* tree-ring series are complacent relative to more dendroclimatically revealing tree-ring collections from, for example, the Southwestern United States. However, crossdating is observable in visual comparison of skeleton plots and ring-width plots (Figure 4), indicating that a common signal is present in these series. Cross correlation statistics computed by the COFECHA and ARSTAN programs support this observation (Table 1). Correlations within trees are quite good (as expected and strictly necessary for further dendrochronological study), and correlations among radii and between trees are moderately high relative to other North American chronologies. Signal-to-noise (S/N) ratios are moderately high. The lower mean correlations and S/N ratios for the residual series than for the detrended series are somewhat unexpected. Generally, the individual (cores) residual series have greater correlations and higher S/N ratios. In this case, the autocorrelation in the standard series apparently inflates the interseries correlation.

Climatic Series

Tests of the precipitation series demonstrated that the records are homogeneous, and therefore could be used in further analysis. Different combinations of the temperature data from the six stations revealed that some inhomogeneities may be present in some of these series. The Los Azufres station was selected for all subsequent analysis because it is closest to the tree-ring site, is located at a similar elevation, and has few indications of inhomogeneity.

Table 2 lists results of the correlation analysis. Pearson correlation coefficients for tree growth versus annual mean and minimum temperature are moderately high (0.589 and 0.481

Table 1. Statistics for standard and prewhitened chronologies for the period 1922-1986 (a) and for common interval 1940-1984 (b).

Chronology Type	Standard	Prewhitened
a.	1.00	1.00
mean	0.93	0.99
mean sensitivity	0.15	0.20
standard deviation	0.25	0.19
skewness	0.88	0.34
kurtosis	0.57	1.81
autocorrelation order 1	0.629	-0.003
partial autocorr order 2	-0.155	-0.079
partial autocorr order 3	0.140	0.107
variance due to autoregression	45.40 %	
error variance	0.007	

b.	Mean Correlations	
	Standard	Prewhitened
among all radii	0.55	0.47
between trees	0.54	0.45
within trees	0.92	0.90
signal-to-noise ratio	18.84	13.42
agreement with population chron	0.95	0.93
variance in the first eigenvector	56.87 %	46.63 %
chron. common interval mean	1.05	1.00
chron. common interval std. dev.	0.27	0.19

respectively). A high inverse correlation was observed for maximum temperature during the fall (-0.719), while tree growth was generally positively correlated with minimum temperatures (particularly January and February), and with mean temperatures in previous October (Table 2).

The cambial growing season of *Abies religiosa* is unknown, but we assume that minimum temperatures and precipitation are important in limiting this process at the beginning and end of the growing season. In accordance with Figures 6 and 7, the period from April to September would seem to be a reasonable growing season window. For purposes of exploration, Pearson correlations were computed for three months of temperature and precipitation for prior years (October to December) and for all 12 months of the current year. Although there may be no biological reason to expect that late fall or winter variables of the current growing season could influence current year tree-ring widths (assuming that cambial growth has ceased by this time), some significant correlations were observed with temperature

Table 2. Pearson correlation coefficients for *Abies religiosa* tree-ring index (prewhitened) and monthly temperature and precipitation at Los Azufres. TMAX is average maximum daily temperature, TMEN is average daily temperature, TMIN is average daily minimum temperature, and precipitation is total monthly precipitation.

	TMAX	TMEN	TMIN	Precipitation
OCT(Y-1)	-0.208	0.466*	0.388	0.440*
NOV(Y-1)	-0.388	0.210	0.203	0.173
DEC(Y-1)	0.092	0.034	0.109	-0.170
JAN	0.120	0.667*	0.520*	0.330
FEB	-0.065	0.652*	0.473*	0.384
MAR	0.311	0.081	0.396	0.516*
APR	-0.173	0.106	0.300	0.325
MAY	-0.197	-0.023	0.564*	0.610*
JUN	0.357	-0.156	-0.090	0.122
JUL	-0.349	-0.075	0.173	0.172
AUG	0.338	0.170	0.270	0.227
SEP	-0.453*	-0.035	0.083	0.135
OCT	-0.658*	0.148	0.289	0.101
NOV	0.703**	0.337	0.166	0.086
DEC	0.097	0.207	0.155	0.006
ANNUAL	-0.098	0.589*	0.481*	0.404
SUMMER/FALL	-0.101	0.007	0.423	0.202
WINTER/SPRING	-0.081	0.540*	0.418	0.419
FALL	-0.719**	0.175	0.204	0.079
WINTER	-0.016	0.562*	0.406	0.316
SPRING	-0.050	0.126	0.537*	0.659*
SUMMER	0.225	-0.035	0.285	0.088

* $p < 0.05$ ** $p < 0.01$

variables (Table 2). This effect could be due to intercorrelation of these late season (and presumably postcambial growth) months with previous months' temperatures that are important to tree growth. Because of the low variability and shortness of the temperature records only limited confidence can be placed in these results.

The correlation coefficients for tree growth and precipitation variables reveal that all months of rainfall are positively correlated with tree growth. The spring months are most important, especially March and May.

The principal components response functions using Los Azufres precipitation, minimum temperature, mean, and maximum temperature are illustrated in Figure 8. The normalized response coefficients generally confirm the monthly associations identified in the simple corre-

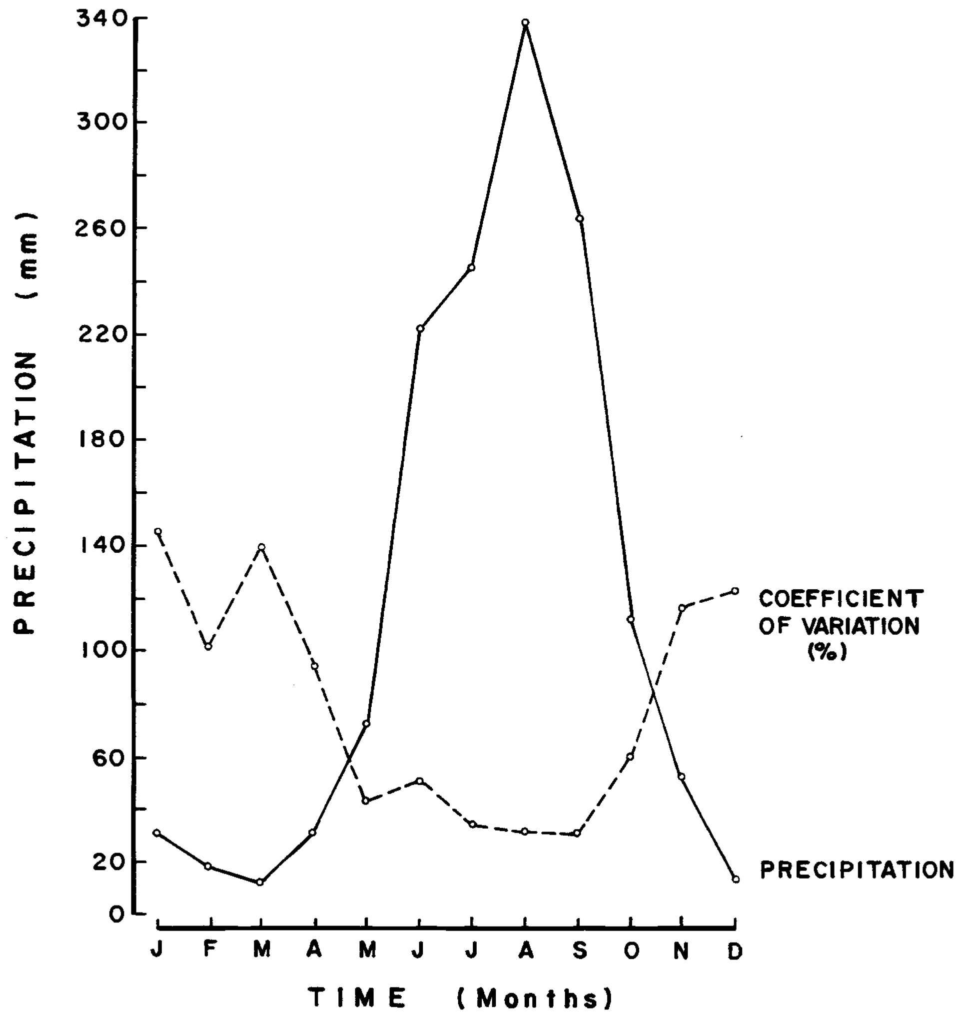


Figure 6. Monthly distribution of precipitation at Los Azufres meteorological station (1967-1984).

lation analysis. Precipitation is positively associated with tree growth (one month, July, appears to be nonsignificantly negative)(Figure 8a), and January and February mean temperatures have strong positive associations with tree growth (Figure 8c).

DISCUSSION AND CONCLUSIONS

A tree-ring chronology from crossdated *Abies religiosa* increment cores was developed extending from 1922 to 1986. Generally good correlation is observed between trees, and this is reflected in a fairly good signal/noise ratio. Relatively low variation in the chronology is revealed by low mean sensitivity. However, variation is sufficient for crossdating, which indi-

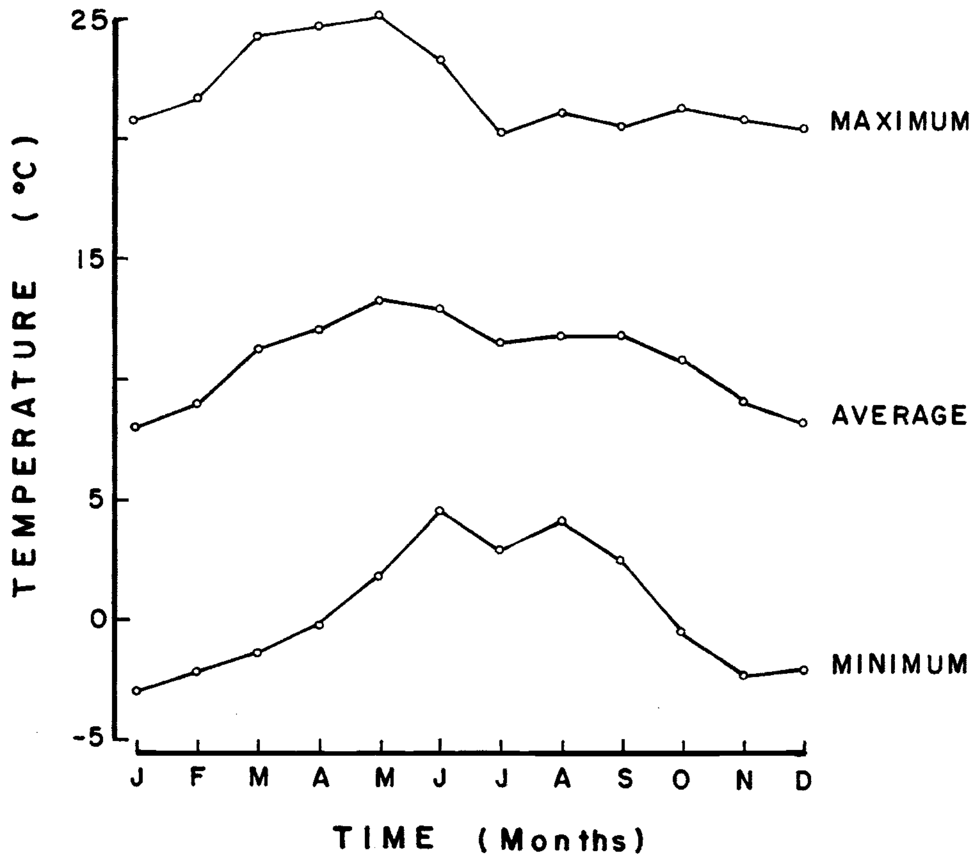


Figure 7. Monthly distribution of maximum, average, and minimum temperatures at Los Azufres meteorological station (1967-1984).

cates that a common signal, most probably climatic, is present in these series. The correlation with the rather short weather records suggests that precipitation is limiting to *Abies religiosa* tree-growth and that spring rainfall is most important. The response functions also indicate a dry season response (i.e., approximately December through May). If these results hold up in future dendroclimatic studies involving additional tree-ring sites and meteorological stations in this region, it would suggest that very useful paleoclimatic and ecological information may be obtained from *Abies* forests. For example, a precipitation teleconnection to El Niño phenomenon is apparently strongest in the months from October to March (Ropelewski and Halpert 1987).

Temperature also appears to be important to tree growth, especially as a positive effect of mean temperature in January and February. The temperature results, however, should be viewed with great caution and skepticism. The unusual and unexpected significant correlations, which reverse sign from October to November, are puzzling. The very low variability and high autocorrelation (about 0.7) of this series has very likely resulted in inflated and perhaps spurious correlations. The shortness of the climate and tree-ring records, and especially the low variability of the temperature data, limit the generality of and confidence in these results.

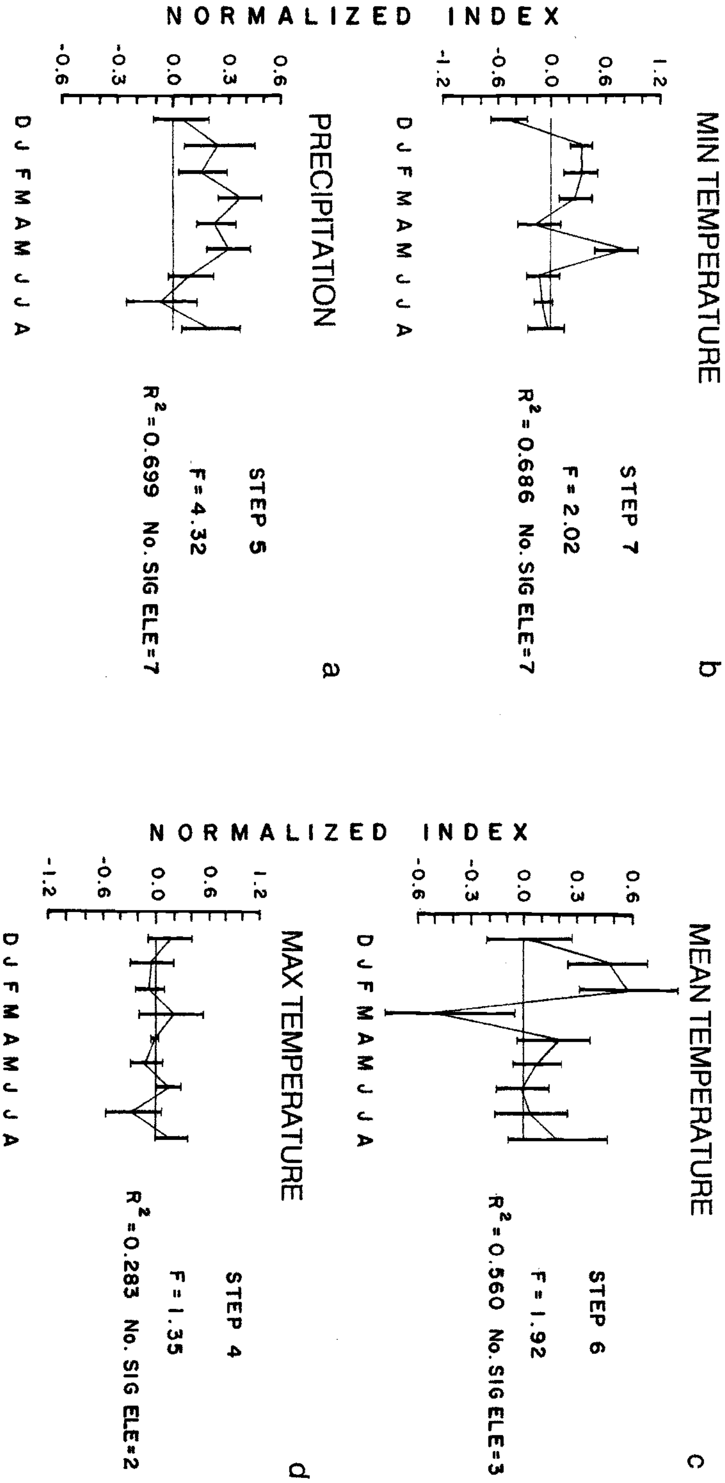


Figure 8. Response functions of residual *Abies religiosa* chronology and monthly precipitation, minimum temperature, mean temperature, and maximum temperature. The F value, the coefficient of determination (R^2), and the number of significant elements (No. SIG ELE) are indicated.

Additional collections in *Abies religiosa* forests and dendroclimatic study are planned. Longer meteorological data sets are currently being compiled for central Mexico, and there is good potential for obtaining longer tree-ring chronologies (perhaps exceeding 200 years) from other mountainous locales and different species. Potential target species that may be exploited for dendroclimatic information include *Pinus hartwegii*, *P. montezumae*, and *P. ayacahuite* which extend in some areas to or near timberline. Additionally, *P. cembroides* is widespread in more arid mid-elevations and lowlands, and *P. oocarpa* is found near more mesic tropical deciduous forests. Preliminary collection and observation of these species in selected sites indicates that clear annual ring boundaries and some total ring-width and latewood-width variability are present. Future crossdating efforts will determine whether subsequent dendrochronological study is feasible.

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