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THE DENDROCHRONOLOGICAL SIGNAL OF PINE TREES (*PINUS* SPP.) IN SPAIN

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ABSTRACT

Thirty-one old-age pine stands in nine mountainous regions of Spain were studied in order to delineate dendrochronologically uniform areas. A country-wide cross-correlation analysis of the autoregressively standardized site chronologies showed the dendrochronological signal decreasing with distance so that beyond about 450 km crossdating becomes less reliable, but even over 630 km, the correlation coefficient is sometimes significantly high. A principal components analysis of the variance among the site chronologies segregated the chronologies into a northern and a southern group roughly along a line from Madrid to Barcelona. Two low-elevation northern sites were grouped with the southern sites. Moisture supply limits the growth of the pines in this group. In contrast, the high-elevation northern sites do not suffer from prolonged droughts. According to the uniform and extensive tree-ring signal in the south of the peninsula, the potential of dendrochronology for dating cultural objects is predicted to be favorable. Because of the greater variability between sites in the north, further studies are necessary to delineate uniform areas.

In neun Gebirgsregionen Spaniens wurden zur Abgrenzung dendrochronologisch homogener Räume 31 Kiefernaltbestände untersucht. Eine landesweite Korrelations-Entfernungsanalyse der autoregressiv standardisierten Standortindexchronologien ergab eine Abnahme des dendrochronologischen Signals zwischen den Standorten mit zunehmender Entfernung. Bei Distanzen von über 450 km wird die Synchronisation weniger zuverlässig, aber selbst bei 630 km Entfernung kann der Korrelationskoeffizient mitunter noch signifikant hoch sein. Eine Hauptkomponentenzerlegung der Varianz der Standortchronologien führte zu einer Gruppierung etwa entlang einer Linie von Madrid nach Barcelona in eine nördliche und eine südlich Region. Zwei der nördlichen Standorte, die zugleich Tieflagenstandorte darstellen, wurden dem südlichen Kollektiv zugeordnet. Als Ursache für diese Differenzierung kommt die Feuchtigkeitsverfügbarkeit in Betracht, die an allen südlichen Standorten sowie an den zwei nördlichen Tieflagenstandorten das Kiefernwachstum limitiert. Die Hochlagenstandorte im Norden sind keinem langanhaltenden Trockenstreß ausgesetzt. Das für den Süden der Halbinsel nachgewiesene einheitliche und weitreichende Jahrring-Signal läßt die

Möglichkeit für eine kulturhistorische Anwendung der Dendrochronologie günstig beurteilen. Im Norden sind wegen der größeren Standortvariabilität weitere Untersuchungen zur Abgrenzung homogener Räume nötig.

Trente et un sites de pins âgés provenant de neuf régions montagneuses d'Espagne, ont été étudiés en vue de délimiter des zones dendrochronologiques uniformes. Une analyse de corrélation portant sur des chronologies de sites standardisées par autorégression et realisée sur l'ensemble du pays a montré que le signal dendrochronologique diminuait avec la distance de telle maniére qu'au-delà de 450 km les datations croisées devenaient moins certaines même si à plus de 630 km le coefficient de corrélation demeure parfois significativement élevé. Une analyse en composante principale portant sur la variance entre les chronologies de sites, sépare celles ci en un groupe septentrional et un groupe méridional de part et d'autre d'une ligne reliant approximativement Madrid à Barcelone. Deux sites nordiques de basse altitude ont été groupés avec les pins de l'ensemble méridional. La disponibilité en humidité y limite la croissance, au contraire des sites de haute altitude du groupe septentrional qui ne subissent pas l'effet de sécheresses prolongées. En raison du signal largement homogène dans le sud de la péninsule, on peut envisager favorablement l'utilisation de la dendrochronologie pour dater des objets culturels. La plus grande variabilité existant entre les sites du nord, nécessitera de nouvelles études pour définir des zones uniformes.

INTRODUCTION

A spatially dense and temporally continuous network of tree-ring chronologies is needed for reconstructing climatic and environmental changes and for dating purposes (Hughes 1987). In the Mediterranean area, dendrochronology sometimes faces particular difficulties (e.g. Liphschitz 1986; Munaut and Serre-Bachet 1982). The location of the Iberian Peninsula in the westernmost part of the Mediterranean area between the Atlantic Ocean and the Mediterranean Sea has led to a great variety of and large contrasts in climate and vegetation (Lautensach 1964).

Dendrochronology in Spain started relatively late and concentrated on the northeastern part of the country (Creus and Puigdefábregas 1976; Génova 1986, 1987; Génova and Gracía 1984; Gutiérrez 1987, Tomás 1982). The first transregional comparisons of tree-ring series were done by Bräker and Schweingruber (1984) with pine and fir species from several temperature-sensitive sites in the Pyrenees and the Central Plateau. According to their study, latewood width and maximum density of the tree rings, but not ring width, were very similar both between regions and among species.

The objective of the present study was to establish a network of tree-ring chronologies for Spain using old trees of various pine species in numerous localities to delineate dendrochronologically uniform areas. Pines occur naturally in nearly every part of Spain and were used preferentially as building timber in historic and prehistoric times (Bauer 1980; Rábanos Faci et al. 1981). Long regional pine chronologies extended with timbers from old buildings have been used to reconstruct summer rainfall (Richter and Eckstein 1990) and to date buildings of cultural and ethnographic importance (Richter 1985/86; Richter and Eckstein 1986).

STUDY AREA

Twenty-four percent of Spain is covered by forests of coniferous and broadleaved trees in roughly equal proportions. Local distributions depend on the climate, soil, elevation, and exposure. The dendrochronological sampling reported here included 31 sites in nine forest areas (Figure 1) using information available on old-age pine stands (Ceballos 1966; Ceballos and Ruiz 1979; ICONA 1979). Pine sites were chosen at the upper treeline (Figures 2 and 3) as well as at medium and low elevations and along elevational transects. Altogether, four pine species (*Pinus sylvestris* L., *P. nigra* Arnold, *P. pinaster* Ait., *P. mugo* ssp. *uncinata* Turra) were sampled to compare intraspecies growth behavior. At 22 sites, at least 10 to 12 trees were sampled by taking two increment cores per tree. Due to local conditions, fewer than 10 trees were available for coring at 9 sites. All 348 sampled trees were dominant or codominant individuals without visible damage. The sites and sample depths are described in Table 1.

PROCEDURES

The tree-ring widths were measured with a mechanical, hand-driven Eklund measuring machine interfaced with a microcomputer. Data storage and retrieval and the crossdating of the tree-ring series were carried out using computer program CATRAS (Aniol 1983). The quality of crossdating was checked both visually and statistically using the nonparametric per-

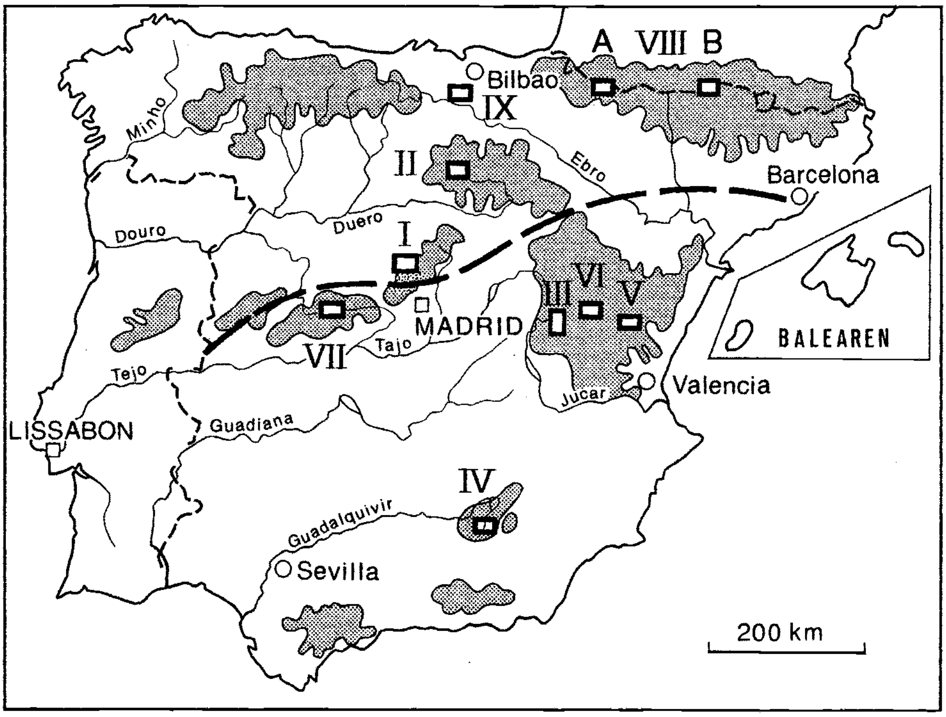

Figure 1. Map of the Iberian Peninsula showing mountainous regions (stippled) and areas sampled (rectangles). The dashed line separates the northern and southern regions as expressed in Figure 6. The regions indicated by Roman numerals are: I = Sierra de Guadarrama (Code GUA), II = Sierra de Urbión (URB), III = Serranía de Cuenca (CUE), IV = Sierra de Cazorla (CAZ), V = Sierra de Gudar (GUD), VI = Sierra de Albarracín (ALB), VII = Sierra de Gredos (GRE), VIII = Pirineos, IX = Montes de Burgos (ZAD).

Figure 2. *Pinus nigra* in the Serranía de Cuenca at 1400 m.

Figure 3. *Pinus sylvestris* at the upper tree line in the Sierra de Guadarrama at 2000 m.

Table 1. Descriptive statistics of 31 tree-ring site collections in Spain.

Site Name	Site Code (see Fig.1)	Region (see Fig.1)	Species	Latitude N	Longitude W	Elevation Meters	Exposure	Slope	Trees Sampled
Valsaín-Iniesto	GUA1	I	P. *syl.*	40°48'	3°59'	1625-2050	S-SW	15-25°	25
Valsaín-Camorca	GUA2	I	P. *syl.*	40°49'	4°03'	1300-1800	E	12-20°	17
Rascafría	GUA3	I	P. *syl.*	40°48'	3°57'	1780-1920	NE	15-35°	12
Navacerrada	GUA4	I	P. *syl.*	40°47'	3°48'	1850-2050	NW	25-45°	15
Vinuesa	URB1	II	P. *syl.*	42°00'	2°51'	1750	S-SE	-	4
Duruelo d.1.S	URB2	II	P. *syl.*	42°01'	2°54'	1800-1875	S	6°	9
Covaleda	URB3	II	P. *syl.*	41°59'	2°52'	1640-1850	S	10-15°	14
Quintenar d.1.S	URB4	II	P. *syl.*	42°02'	3°02'	1780-1900	S-SE	5-15°	13
Las Torcas	CUE1	III	P. *nigra*	40°00'	1°59'	1150-1300	-	-	3
Buenache	CUE2	III	P. *nigra*	40°09'	1°54'	1370-1400	-	-	5
Las Majadas	CUE3	III	P. *syl.*	40°20'	1°59'	1400	-	-	3
Uña I	CUE4	III	P. *nigra*	40°15'	1°56'	1360-1410	N	15-20°	12
Vega d. Cordono	CUE5	III	P. *nigra*	40°26'	1°54'	1400-1480	S-SE	20°	7
Uña II	CUE6	III	P. *nigra*	40°16'	1°56'	1400-1480	S-SW	5-10°	14
Las Bañas I	CAZ1	IV	P. *nigra*	37°57'	2°56'	1380-1430	S-SE	8-15°	14
Pto. Llano	CAZ2	IV	P. *nigra*	37°49'	2°57'	1800	W	-	12
Cañada d.1.F.	CAZ3	IV	P. *nigra*	37°50'	2°56'	1400-1500	N-NW	10-25°	17
Las Bañas II	CAZ4	IV	P. *pinaster*	37°58'	2°56'	1360-1400	W	25-40°	12
Fuentenarices	GUD1	V	P. *nigra*	40°18'	0°44'	1450	NW	10°	2
Pradillo	GUD2	V	P. *syl.*	40°18'	0°41'	1600-1700	SE	25-30°	5
Las Roquetas	GUD3	V	P. *nigra*	40°17'	0°42'	1450-1500	SE	15°	11
Cantavieja	GUD4	V	P. *syl.*	40°34'	0°29'	1750	W	no data	10
Villarluengo	GUD5	V	P. *nigra*	40°38'	0°29'	1500	SW	no data	11

Table 1. (cont.)

Site Name	Site Code (see Fig.1)	Region (see Fig.1)	Species	Latitude N	Longitude W	Elevation Meters	Exposure	Slope	Trees Sampled
Valdecuenca	ALB1	VI	P. *nigra* + P. *syl.*	40°17'	1°27'	1500-1600	E-NE	15°	10
Bezas	ALB2	VI	P. *pinaster*	40°18'	1°20'	1200-1250	S	10-15°	11
Navarredonda d.1.S.	GRE1	VII	P. *syl.*	40°20'	5°08'	1440-1500	W	10-25°	12
Hoyos d.Espino	GRE2	VII	P. *syl.*	40°20'	5°10'	1450-1480	N-E-S-W	10-20°	12
Puerto de Acher	PYR1	VIII A	P. *syl.* + P. *uncin.*	42°48'	0°42'	1550-1700	NW-SW	35-55°	12
Ansó-Zuriza	PYR2	VIII A	P. *syl.*	42°50'	0°47'	1250-1300	S-SE	25°	4
Viella	PYR3	VIII B	P. *syl.*	42°44'	0°47'E	1840-2000	S	30-45°	15
San Zadornil	ZAD	IX	P. *syl.*	42°50'	3°10'	810-950	S-SW	5°	14

centage of agreement (Eckstein and Bauch 1969) and the parametric t-value (Baillie and Pilcher 1973). After correction for missing and double rings, the tree-ring series were dated absolutely and rechecked using computer program COFECHA (Holmes 1983). The checking procedures eliminated the tree-ring series of 33 trees from further processing because of heavy disturbances, so that altogether 315 pines from 31 sites entered the final analysis. These tree-ring series were standardized and autoregressively transformed by program ARSTAN (Cook and Holmes 1986) to remove the age trend and nonclimatic disturbances and then assembled into site chronologies using robust estimation of the mean value function. These site chronologies were used in an analysis of correlation with distance and a principal components analysis.

RESULTS AND DISCUSSION

The raw ring-width data of the 31 sites are characterized by high first order autocorrelations (mean = 0.85, range = 0.64 to 0.96) and low mean sensitivities (mean = 0.19, range = 0.13 to 0.29). After being autoregressively modeled and transformed, the autocorrelations are zero, and the mean sensitivities increase slightly (mean = 0.23, range = 0.16 to 0.34). The variance accounted for by the first eigenvector of the transformed tree-ring series averages 48% and ranges from 35% to 64%, indicating good homogeneity within the sites. Thirty of the 31 site index chronologies were correlated with each other within a common time interval from 1861 to 1983. One of the chronologies (Valdecuenca) of the Sierra de Albarracín (Region VI) was removed from this analysis because of its short span of only 99 years. The average correlation coefficient of the 435 possible combinations equalled 0.31. The results (Figure 4) suggest a division of the sites into two regions, one including the Guadarrama, Urbión, and Pyrenees areas (Regions I, II and VIII), another including the Cuenca, Cazorla, Gudar, and Gredos areas (Regions III, IV, V and VII). Sites PYR2 (Region VIII) and ZAD (Region IX) fit somewhat better with the southern group. The similarity between the site chronologies is high within each of these groups, but often low or even missing between the

Site-Code	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1 GUA1	***																													
2 GUA2	.70	***																												
3 GUA3	.59	.37	***																											
4 GUA4	.70	.50	.76	***																										
5 URB1	.38	.28	.51	.52	***																									
6 URB2	.47	.37	.48	.55	.50	***																								
7 URB3	.48	.38	.54	.51	.65	.66	***																							
8 URB4	.38	.30	.50	.54	.57	.60	.72	***																						
9 CUE1	.27	.13	.13	.08	-.00	.11	.16	.23	***																					
10 CUE2	.37	.19	.29	.23	.22	.20	.35	.30	.50	***																				
11 CUE3	.25	.19	.18	.10	.20	.17	.31	.30	.39	.43	***																			
12 CUE4	.33	.19	.25	.19	.15	.15	.34	.36	.59	.60	.55	***																		
13 CUE5	.37	.14	.36	.23	.26	.24	.47	.37	.49	.58	.46	.58	***																	
14 CUE6	.39	.22	.33	.23	.23	.20	.41	.36	.57	.57	.49	.81	.67	***																
15 CAZ1	.31	.27	.17	.16	.14	.13	.28	.25	.43	.37	.40	.51	.40	.52	***															
16 CAZ2	.45	.27	.29	.28	.16	.32	.37	.33	.37	.49	.32	.54	.54	.53	.50	***														
17 CAZ3	.34	.19	.23	.19	.09	.23	.29	.24	.48	.50	.36	.59	.52	.55	.59	.68	***													
18 CAZ4	.31	.23	.11	.12	.05	-.00	.24	.14	.33	.28	.39	.48	.41	.50	.62	.40	.42	***												
19 GUD1	.26	.04	.16	.14	.07	.07	.25	.17	.28	.25	.25	.33	.35	.33	.22	.24	.28	.20	***											
20 GUD2	.27	.07	.17	.07	.08	.19	.24	.23	.35	.29	.31	.36	.35	.29	.22	.24	.25	.27	.44	***										
21 GUD3	.08	-.06	.11	-.02	-.05	.09	.15	.13	.36	.19	.31	.42	.37	.37	.31	.32	.40	.13	.53	.46	***									
22 GUD4	.39	.27	.30	.30	.32	.19	.37	.43	.27	.36	.43	.47	.38	.40	.39	.28	.38	.28	.26	.38	.31	***								
23 GUD5	.23	.04	.22	.15	.16	.10	.24	.31	.40	.33	.40	.48	.46	.40	.30	.24	.50	.30	.34	.44	.59	.70	***							
24 ALB2	-.10	-.12	-.03	-.10	-.17	-.07	-.10	.07	.35	.12	.35	.35	.24	.23	.13	.07	.24	.15	.34	.41	.54	.17	.47	***						
25 GRE1	.36	.32	.18	.11	.06	.17	.30	.24	.41	.48	.40	.40	.48	.50	.42	.40	.38	.23	.28	.15	.25	.32	.22	.03	***					
26 GRE2	.26	.20	.15	.08	.08	.10	.17	.23	.38	.33	.29	.34	.40	.42	.34	.32	.38	.20	.22	.06	.29	.23	.22	.14	.76	***				
27 PYR1	.33	.16	.46	.36	.58	.36	.52	.56	.19	.27	.21	.22	.40	.25	.24	.24	.26	.10	.20	.25	.18	.38	.28	.01	.32	.25	***			
28 PYR2	.27	.17	.19	.15	.17	.16	.37	.32	.37	.33	.45	.43	.40	.39	.36	.34	.40	.35	.42	.30	.32	.43	.37	.12	.37	.22	.47	***		
29 PYR3	.33	.22	.37	.26	.45	.38	.49	.53	.30	.25	.23	.31	.30	.32	.21	.33	.32	.09	.16	.28	.15	.31	.24	-.07	.25	.13	.70	.41	***	
30 ZAD	.21	.21	.01	.01	.11	.17	.28	.36	.39	.35	.40	.37	.44	.39	.23	.27	.34	.23	.16	.19	.11	.29	.22	.04	.30	.29	.14	.45	.27	***

Figure 4. Correlation matrix for 30 site index chronologies from 1861 to 1983; the heavy lines enclose northern sites, the light line encloses the southern sites.

groups. In Figure 5, all 435 correlation coefficients are plotted against distance from each site. As expected, similarity between sites decreases with distance. In some cases, however, wide variation in the correlation coefficients is evident between sites equidistant from one other. Between 220 and 320 km, the low or even absent similarity (expressed by negative correlation coefficients) is obvious for specific sites such as Las Roquetas (Region V) and Bezas (Region VI). The linear negative relationship (r = -0.49) is of the same order as those reported, for example, by Ahmed and Ogden (1985) for 11 *Nothofagus* chronologies in New Zealand and by Briffa (1984) for 36 oak chronologies in Great Britain and France. In western North America, 65 conifer chronologies correlate at the 99% level over distances of 992 km (Cropper and Fritts 1982). In Spain, sufficient crossdating quality between pine chronologies can be expected within an average range of some 450 km.

To derive the contours of dendrochronologically uniform regions more clearly, a principal components analysis was performed (Figure 6). The first eigenvector accounts for 34% of

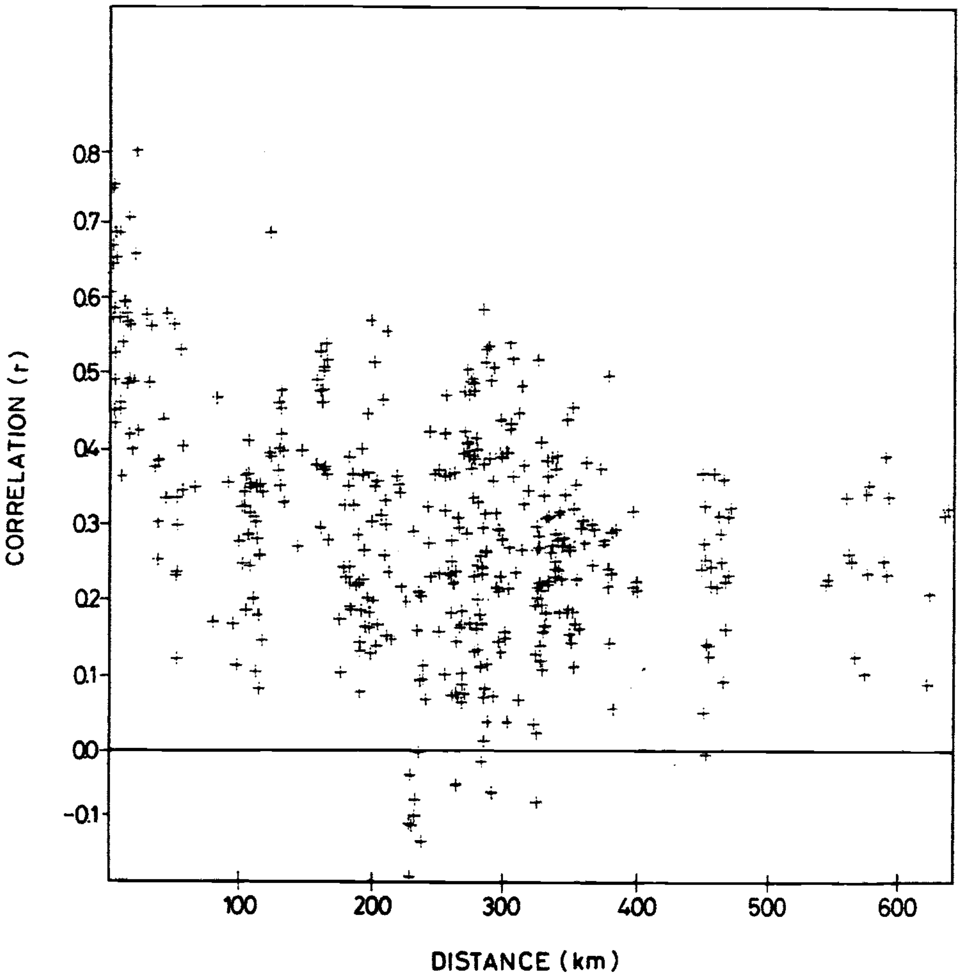

Figure 5. Correlation-by-distance plot of 30 site index chronologies for the common interval from 1861 to 1983.

the variance among all chronologies. Since 29 of the 30 site chronologies cluster tightly, a high common variance all over Spain is indicated. Presumably the cause of this clustering is the overall temperature, which varies less over wide areas than precipitation. The second eigenvector accounts for 13% of the variance among chronologies and divides the chronologies into two groups. At first sight, this grouping seems to express the northern and southern locations of the sites, but two northern sites (PYR2, ZAD) — the same sites as in the cross correlation analysis — are included with the southern sites. This grouping becomes more understandable, however, when the elevations of the sites are considered (Figure 6). North of the Cordillera Central, the upper treeline sites (1600-2000 m) can be distinguished from medium and low elevation sites, which are similar to the southern sites. This apparent elevational influence is indirect; the real cause of the grouping is rather precipitation. Summer drought is one of the growth-limiting factors on the semiarid southern sites (Richter 1988). The two northern sites grouped with the southern sites are located in the rain shadow of the mountains so that summer droughts may occur here as well. Figure 7 illustrates the climate-growth relationship for the pines in southeastern Spain derived by a response function analysis from a transregional climatic record and a ring chronology made of nine sites (Regions III, IV and V) for a calibration period from 1902 to 1984. In addition to summer rainfall, winter temperature is beneficial to the growth of the pines. The variance of tree-ring widths explained by climate amounts to 67%.

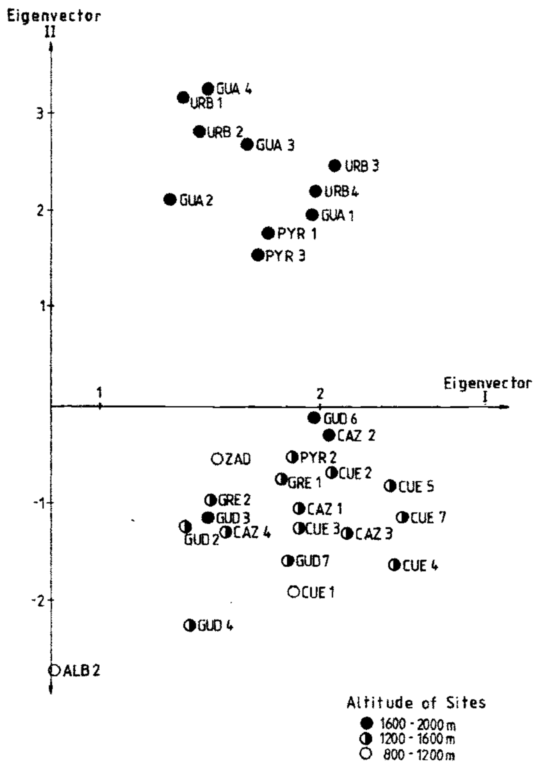

Figure 6. Comparison of the weights of the first and second eigenvectors of 30 site index chronologies.

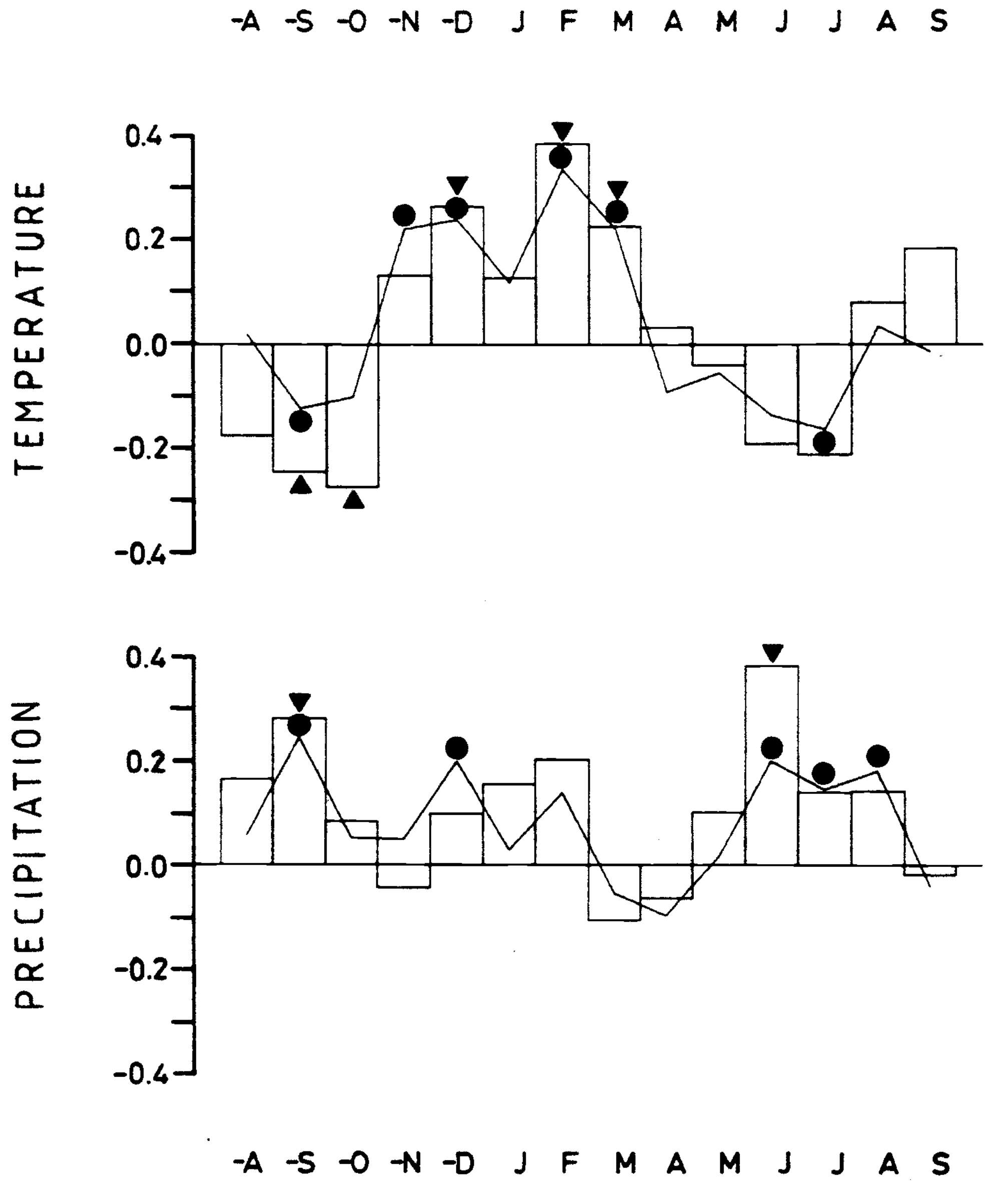

Figure 7. Response function (line) and correlation function (bars) for pines in nine sites in Regions III, IV and V, for monthly temperature and precipitation from previous August to current September; the dots and triangles indicate significance at the 95% level.

For further investigations, it is worth mentioning that correlations between sites of different species are as high as those between sites of the same species. Therefore, the four pine species studied can dendrochronologically be treated together. Bräker and Schweingruber (1984), Génova (1986) and Gutiérrez (1987) found a fairly high correlation between *Pinus sylvestris* and *P. uncinata* in the northeast of the peninsula. Kuniholm and Striker (1983) reported a great similarity between *P. sylvestris* and *P. nigra* in the Aegean area even over great distances. The correlative behavior of *P. sylvestris/nigra* and *P. pinaster* has not been studied so far. Groups of both pines occur in the Sierra de Cazorla (Region IV) and Sierra de Gudar (Region V). They are different in their ecological demands but crossdate with each other, so that, at least for dating purposes, chronologies of mixed species can be used. Regional climate obviously influences the cambial activity more than genetic differences.

A further practical aspect is that, if the site chronologies in an area are merged into chronologies with sample depths of some 20 trees, reasonable similarities are evident at distances up to 630 km, even between climatically different areas. However, distance is not the only relevant aspect, since, for example, the Sierra de Gredos (Region VII) *P. sylvestris* chronology is more similar to the regional *P. nigra* chronologies of the Sierra de Cuenca (Region III) and Sierra de Cazorla (Region IV) than to the regional *P. sylvestris* chronology of the much nearer Sierra de Guadarrama (Region I). The reason for this behavior is the different elevations of the sites, as can be seen in Figure 6.

CONCLUSIONS

The present study demonstrates that the four pine species studied, *Pinus sylvestris, P. uncinata, P. nigra* and *P. pinaster*, do not show growth differences within the same forest region and therefore can be considered to be dendrochronologically homogeneous. The correlation of the ring-width signal decreases with distance. Fairly good crossdating, however, can be expected up to distances of 450 km. The delineation of northern and southern areas is important for future dendrochronological work. This purely geographical criterion does not sufficiently explain the grouping of the sites, because some of the northern site chronologies correspond better with the southern group. Therefore, climatic factors, elevation, and topography also need to be considered. In the south, the common tree-ring signal covers a wider area than in the north. This is because moisture is more uniformly limiting to tree growth throughout the southern area, whereas local growing conditions and elevation are more influential on tree growth in the north. Consequently, the potential for dendrochronological dating of wooden objects and the extension of chronologies into the past is considered to be better in the south than in the north. Greater variability between sites in the north calls for further study, concentrating on medium and low elevation sites to delineate areas of coherent dendrochronological signal.

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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

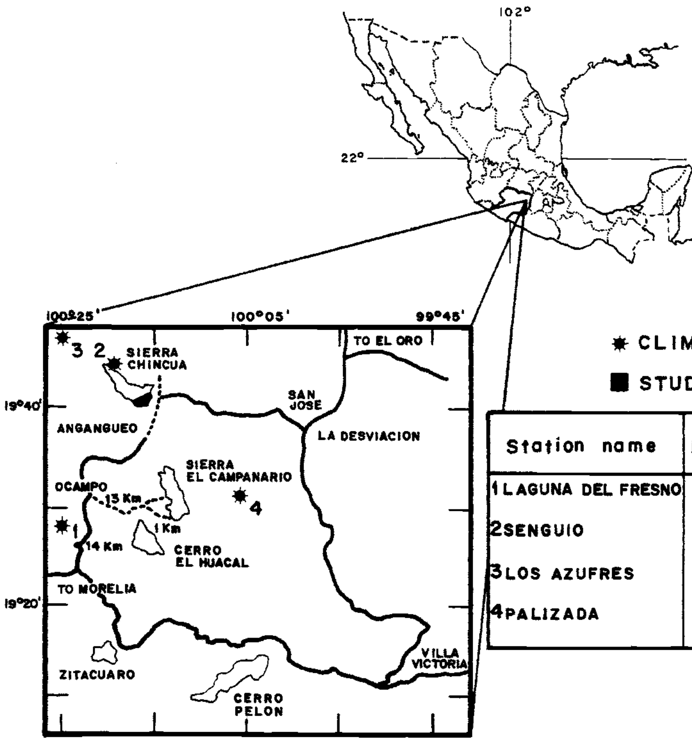
This work is intended as a contribution to the ecological knowledge of *Abies religiosa* (H.B.K.) Schlecht. & Cham., whose forest habitat is part of the winter refuge of the migratory Monarch Butterfly (*Danaus plexippus* L.). The importance of maintaining the forest integrity and cover in this area 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.



✱ CLIMATOLOGICAL STATION
■ STUDY AREA

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.

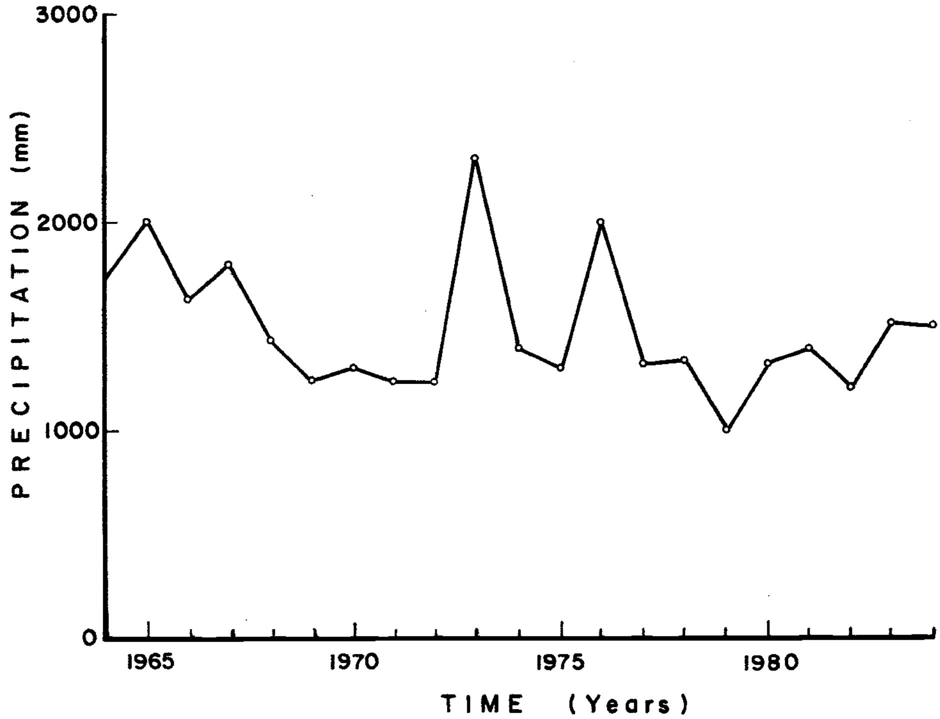


Figure 2. Total annual precipitation at the Los Azufres meteorological station (1967-1984).

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)

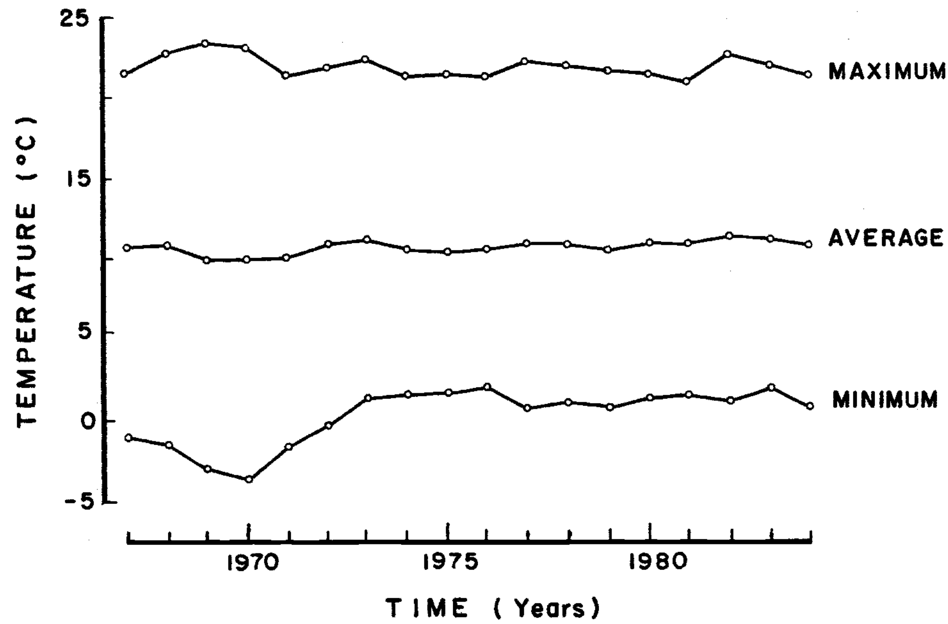


Figure 3. Annual minimum, maximum, and average temperature at the Los Azufres meteorological station (1967 - 1984).

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-

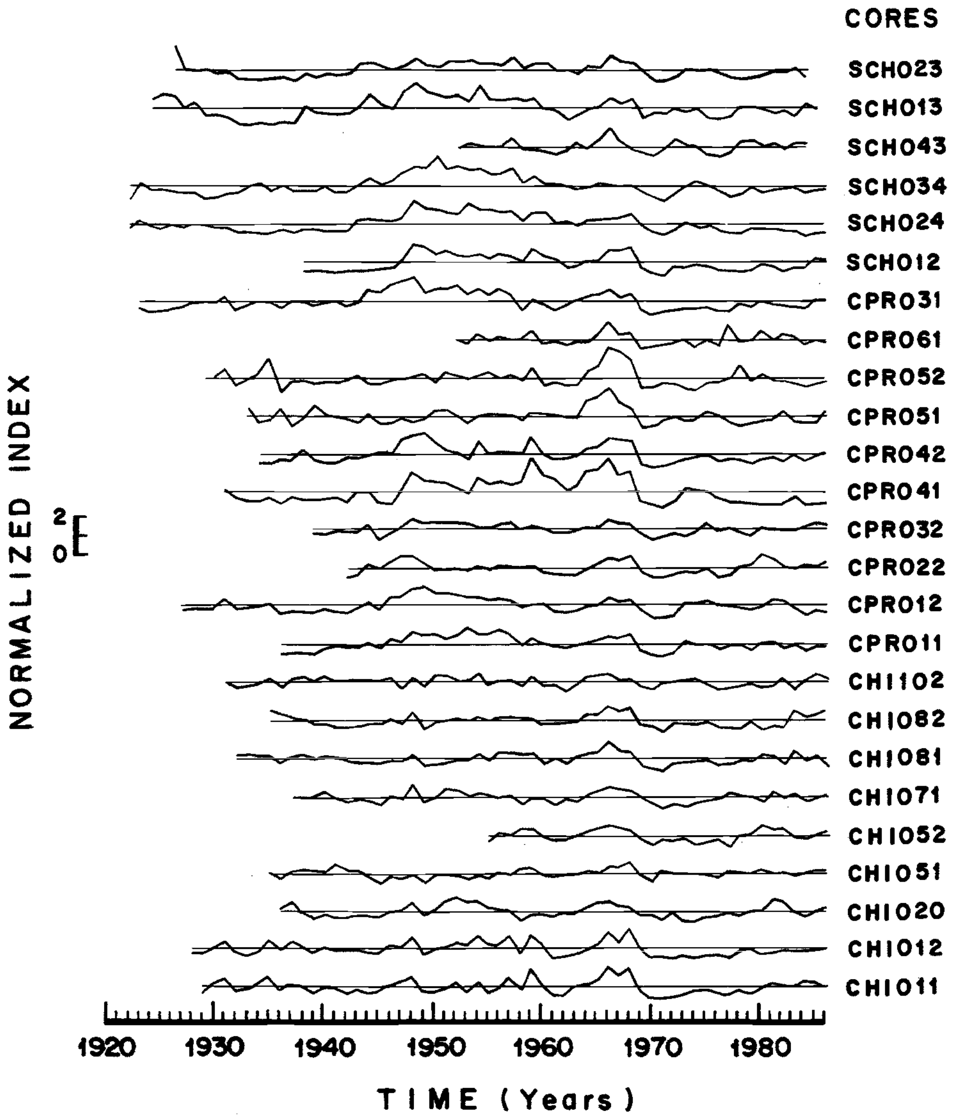


Figure 4. Index series of individual core samples from Michoacan, Mexico.

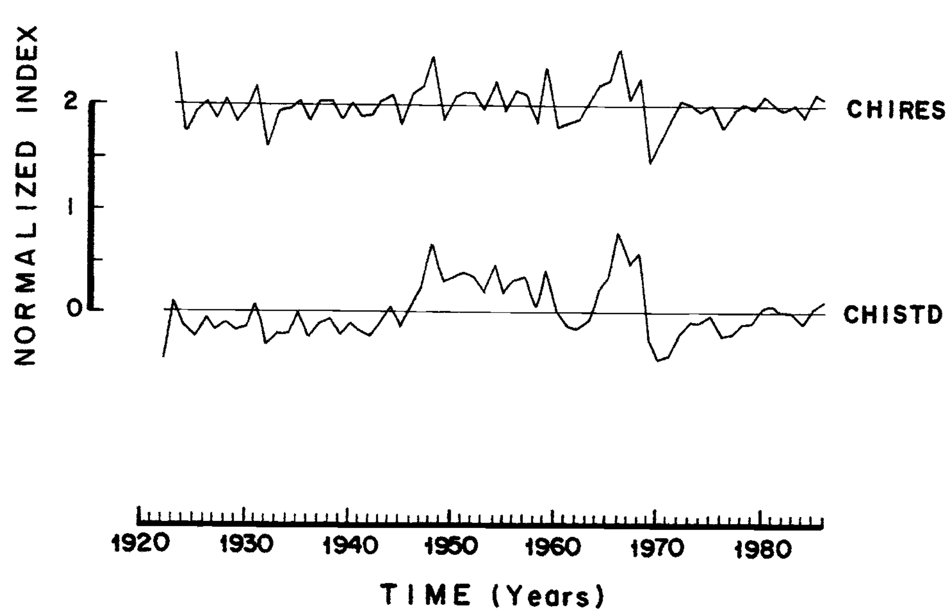


Figure 5. Master chronologies of residual (CHIRES) and standard series (CHISTD) from 1922 to 1986.

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-

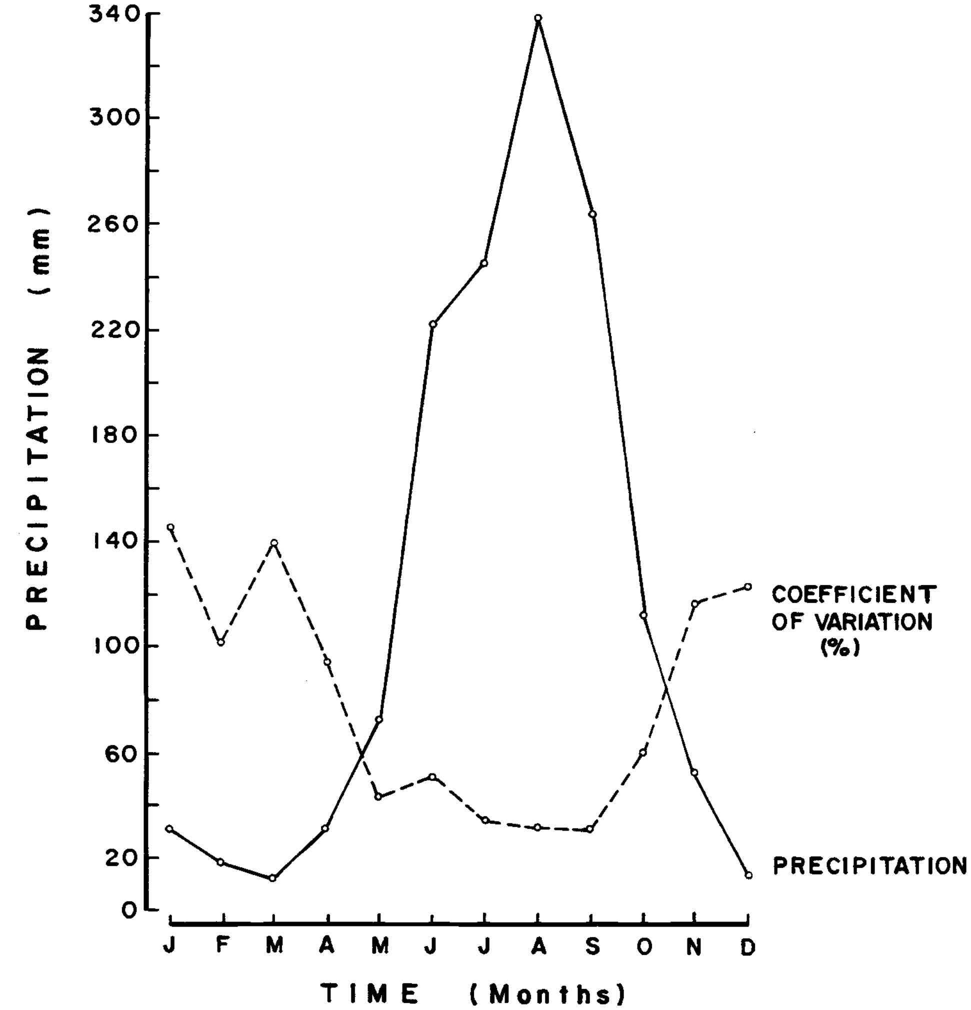


Figure 6. Monthly distribution of precipitation at Los Azufres meteorological station (1967-1984).

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-

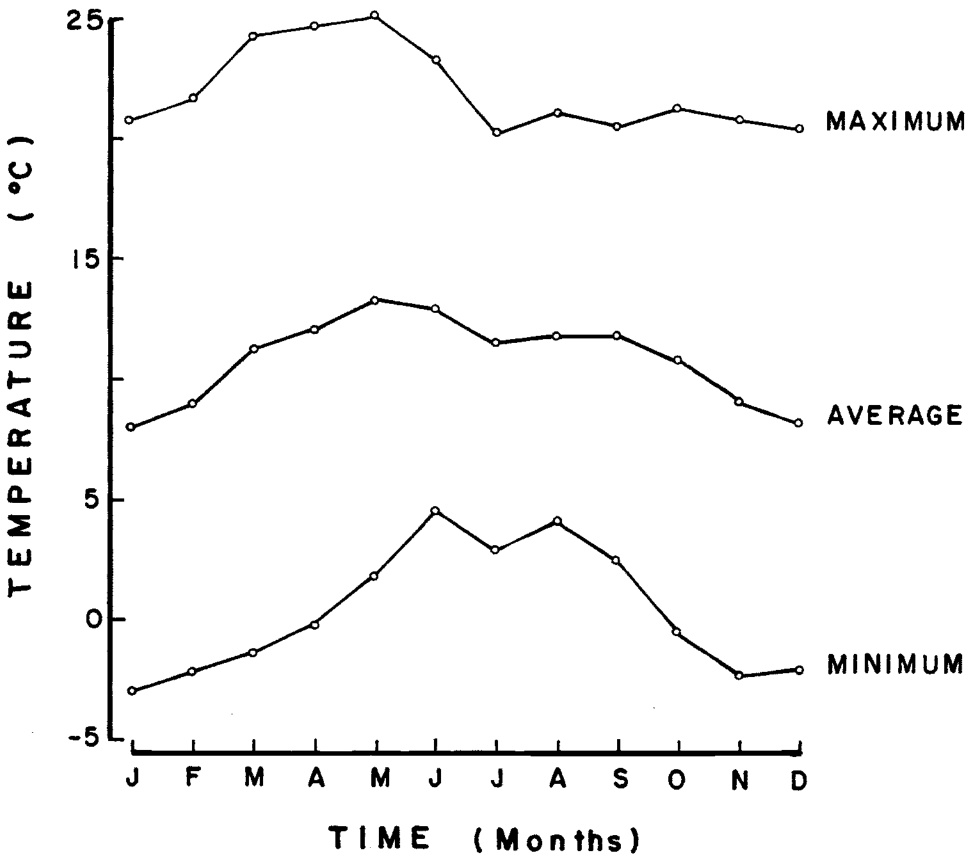


Figure 7. Monthly distribution of maximum, average, and minimum temperatures at Los Azufres meteorological station (1967-1984).

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.

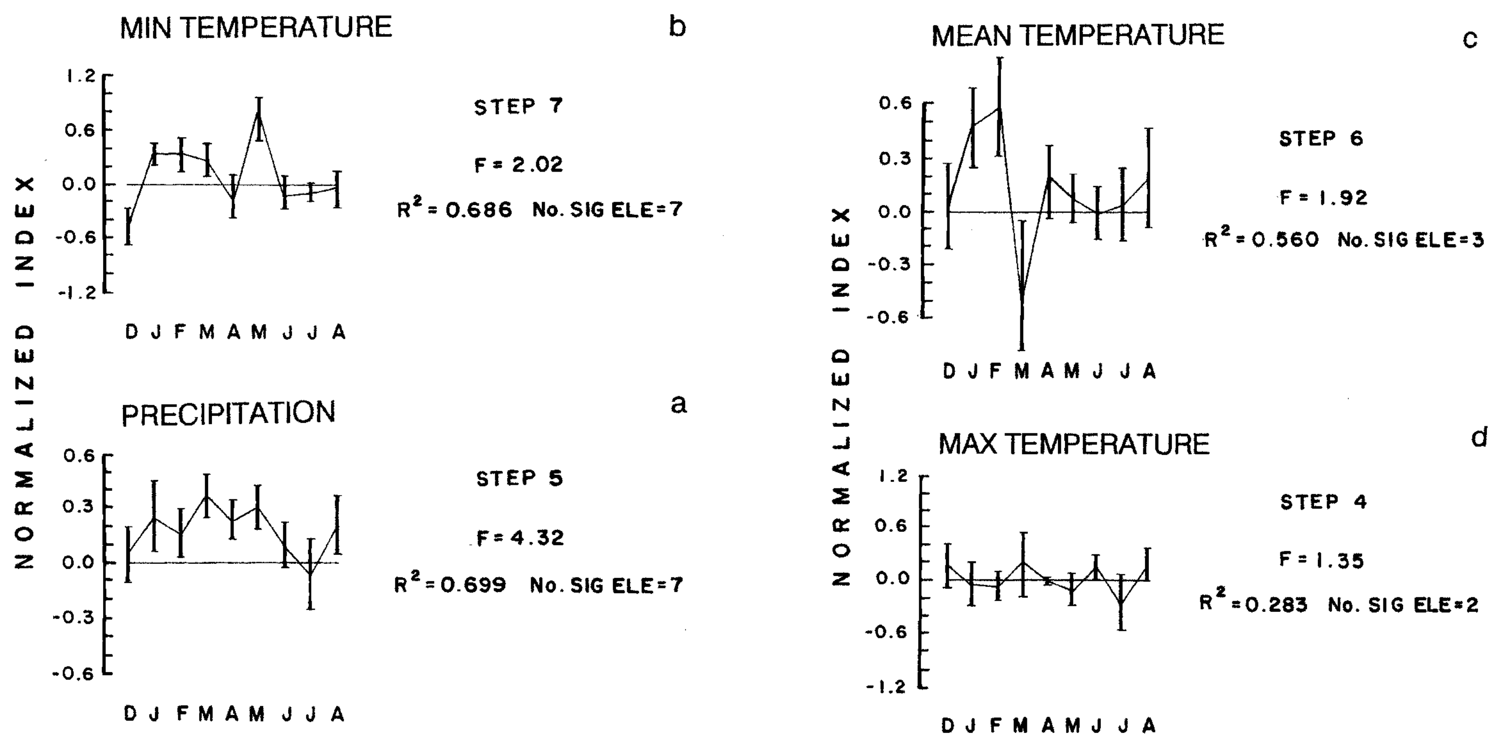


Figure 8. Response functions of residual *Abies religiosa* chronology and monthly precipitation, minimum temperature, mean temperature, and maximum temperature. The F value, the coefficient of determination (R^2), and the number of significant elements (No. SIG ELE) are indicated.

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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IDENTIFYING LOW-FREQUENCY TREE-RING VARIATION

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ABSTRACT

I propose an approach to provide 95% confidence intervals for a chronology of low-frequency tree-ring variation so that a level of significance or importance for trends can be inferred. The approach also visually reveals the portions of a chronology in which sample depth is so poor that low-frequency variation is not robustly estimated. A key characteristic of the approach is that it is essentially a reordering of the individual steps commonly used in constructing standard tree-ring chronologies; consequently, it is computationally simple for researchers who already routinely construct standard tree-ring chronologies. The most important ramification of the approach is that each year of the chronology has a distribution of smoothed index values with which to estimate confidence intervals around the chronology of low-frequency variation. It can be argued that the approach constitutes multiple significance testing of means, which causes the α level for the confidence interval to be unknown. Nonetheless, the approach is still useful in that it provides a way to evaluate the probable importance of low-frequency trends expressed in tree-ring chronologies.

Es wird ein Ansatz vorgeschlagen, der es ermöglicht, den 95% - Vertrauensbereich für eine Chronologie aus niederfrequenten Jahrringbreitenstreuungen anzugeben, so daß die statistische Signifikanz oder Wichtigkeit von Trends abgeleitet werden kann. Dieser Ansatz weist auch auf Chronologie-Abschnitte mit unzureichender Belegdichte hin, so daß dort die niederfrequente Schwankung nicht robust abschätzbar ist. Es ist ein Schlüsselmerkmal dieses Ansatzes, daß er die einzelnen Schritte, die normalerweise beim Aufbau von standardisierten Jahrringchronologien ablaufen, umordnet; folglich ist dieser Ansatz für diejenigen rechnerisch einfach, die schon routinemäßig standardisierte Jahrringchronologien aufgebaut haben. Die wichtigste Folge dieses Ansatzes ist die Tatsache, daß in jedem Jahr der Chronologie eine Verteilung aus geglätteten Jahrringindex-Werten vorliegt, womit die Vertrauensbereiche für die niederfrequente Chronologie geschätzt werden. Es kann eingewendet werden, daß dieser Ansatz aus einer multiplen Siknifikanzprüfung von Mittelwerten besteht, was die Stufe des Vertrauensbereiches unbekannt sein läßt. Dennoch ist der Ansatz nützlich, da er eine Möglichkeit eröffnet, die wahrscheinliche Bedeutung von niederfrequenten Trends in Jahrringchronologien zu schätzen.

Nous proposons une approche susceptible de procurer des intervalles de confiance à 95% pour une chronologie des variations de basse fréquence présente dans les cernes, approche telle que un niveau de signification ou d'importance des tendances puisse en être déduit. Cette méthode met également en évidence de façon visuelle les portions de la chronologie pour lesquelles la densité d'échantillonnage est trop faible pour que les variation de base fréquence puissent être estimées. Une caractéristique de cette approche résulte du fait qu'elle consiste principalement en un réarrangement des étapes individuelles généralement utilisées pour construire des chronologies standard et qu'elle est donc simple du point de vue de son calcul, pour les chercheurs qui construisent déjà en routine de telles chronologies. Un aspect très important de la méthode résulte du fait que à chaque année de la chronologie correspond une distribution des valeurs indicielles lissées permettant d'estimer des intervalles de confiance autour de la chronologie des variations de basse fréquence. On peut soutenir que cette approche constitue un test de moyenne de signification multiple, de telle manière que le niveau de l'intervalle de confiance reste inconnu. Néanmoins cette approche resteutile du fait qu'elle procure un moyen d'évaluer l'importance probable des tendances de basse fréquence qui sontiexprimées par les chronologies.

INTRODUCTION

The dendrochronological literature is replete with studies that, in part, identify and interpret low-frequency variation, e.g., period length >10 years, as expressed by tree-ring chronologies (e.g., LaMarche 1974, Jacoby et al. 1985, Norton et al. 1989, Briffa et al. 1990). A common approach to identifying low-frequency tree-ring variation is (1) to construct a standard index chronology using several samples from a homogeneous stand of trees (Fritts 1976), (2) to generate a smoothed index series from that standard chronology, e.g., with a cubic smoothing spline (Cook and Peters 1981), and (3) to overlay plot the standard chronology with its smoothed index series. Trends in low-frequency variation, i.e., departures from a reference line, are commonly interpreted as possibly being caused by a biological or physical mechanism.

There are, however, two inadequacies with this approach as stated, both of which arise from the fact that the smoothed index series is generated from only a single time series. First, the smoothed index series does not have accompanying confidence intervals with which trends might be evaluated as being significant or important. Second, the smoothed index series does not reflect changing sample depth through time, even though sample depths of tree-ring chronologies commonly range from as low as a single sample at the beginning year to a maximum value sometime before the ending year. While it might be tempting to interpret low-frequency trends for the full length of a chronology, there should be some distinction between well-replicated portions of a chronology, where low-frequency variation is robustly estimated, and poorly replicated portions of a chronology, where low-frequency variation is weakly estimated (Shiyatov et al. 1990).

I propose an approach to overcome these two inadequacies. Specifically this approach provides approximate 95% confidence intervals for a chronology of low-frequency variation so that a level of significance or importance for trends may be inferred. The approach also visually reveals the portions of a chronology in which sample depth is so poor that low-frequency variation is not robustly estimated, i.e., when the mean value is potentially affected by the addition or deletion of a single sample. Essentially, this approach reorders the individual steps commonly used in constructing standard tree-ring chronologies. Consequently, it is computationally simple for researchers who already routinely construct standard tree-ring chronologies, especially those who have access to the library of tree-ring data-reduction programs compiled under the auspices of the International Tree-Ring Data Bank, Paleoclimatology Program, National Geophysical Data Center, National Oceanic and Atmospheric Administration.

METHODS

Constructing a Standard Tree-Ring Chronology

A standard tree-ring chronology is constructed by the method described by Fritts (1976) and outlined in Table 1, left column. The deterministic, series-length trend of each individual ring-width series is removed by fitting and dividing out either a modified negative exponential curve (Fritts et al. 1969) or a linear regression line. This step removes variation at frequencies longer than the fundamental frequency of 1/n, where n is the series length; frequencies longer than the series length are difficult to interpret with respect to causal mechanisms because they can not be differentiated from pure trend (Cook et al. 1990). Finally, the detrended index series are averaged to form a standard chronology.

Table 1. Steps in constructing a standard tree-ring chronology and a chronology of low-frequency variation with associated confidence intervals

Standard Tree-Ring Chronology	Low-Frequency Chronology
1. Create index series by removing the-series-length trend from each ring-width series.	1. Create index series by removing the series-length trend from each ring-width series (1).[1]
2. Average the index series into a standard chronology.	2. Determine the variation frequency of interest (3).
3. Determine the variation frequency of interest.	3. Generate a smoothed low-frequency series for each index series (4).
4. Generate a smoothed low-frequency series for the single, standard chronology.	4. Average the smoothed index series into a chronology of low-frequency variation (2).
5. Overlay plot the standard chronology and the smoother low-frequency series.	5. Overlay plot the standard chronology and the chronology of low-frequency variation (5).
	6. Calculate the 95% confidence interval for each mean value of the low-frequency chronology.
	7. Overlay plot the 95% confidence intervals with the low-frequency chronology.

[1] Number in parentheses refers to corresponding step in constructing a standard tree-ring chronology (left column).

Determining the variation frequency of interest can be accomplished in various ways. In some cases, researchers may hypothesize *a priori* the existence of a specific causal mechanism, with a known frequency of variation, that might affect tree growth. Such mechanisms include regimes of periodic wildfire, cyclic budworm infestations, or any of the many solar cycles that might affect climate. In these cases, researchers have essentially already determined the frequency of variation that is pertinent to their study.

Lacking an *a priori* hypothesis, researchers could use the standard chronology itself to determine the frequency of variation to analyze. If a chronology expresses a sine wave pattern, researchers could simply approximate the frequency of variation visually, as observed in a time-series plot of the chronology, or they could analyze the time series for its peak spectral density value to determine the frequency more precisely (Mazepa 1990).

Having determined the variation frequency of interest, a smoothed index series to represent that frequency is generated by fitting an appropriate cubic smoothing spline to the standard chronology. I fit the spline with a frequency response retention of 90% of the variation frequency of interest. Finally, the smoothed index series of low-frequency variation is plotted over the standard chronology.

Reordered Approach

The reordered approach uses essentially the same steps used to construct the standard tree-ring chronology, but the steps are executed in a different order (Table 1, right column). Indeed, as a result of having constructed the standard tree-ring chronology, the individual index series are already created, and the pertinent frequency of variation is already determined. Smoothed index series to represent that frequency are generated by fitting to all individual index series a cubic smoothing spline with the same rigidity (frequency response retention) that was used on the standard chronology. Fitting the spline to all index series produces a distribution of smoothed index values for each year of the chronology. Averaging the smoothed index values for each distribution, i.e., for each year of the chronology, creates a chronology of low-frequency variation.

The most important implication of the fact that each year of the chronology now has a distribution of smoothed index values is that confidence intervals around the chronology of low-frequency variation can be estimated. One method for estimating confidence intervals around tree-ring data is bootstrap sampling, i.e., sampling the distributions of values for up to hundreds — or even thousands — of times, as demonstrated by Cook (1990) for smoothed ring-width chronologies. Cook opted for bootstrap estimation of confidence intervals primarily because distributions of smoothed ring-width values may not be normal.

However, a useful side effect of standardizing the ring-width series into index series is that distributions of smoothed index values are less likely to violate the assumption of normality. Consequently, I estimate confidence intervals by using the usual parametric equation (Sokal and Rohlf 1981), which is computationally less arduous than bootstrap estimation. Thus, given a distribution of smoothed index values for each year, the 95% confidence intervals are calculated as follows:

$$95\%\ \text{confidence interval}_t = \bar{x}_t \pm se_{\bar{x}(t)} \bullet t_{0.05[d.f.(t)]}$$

where $\bar{x}_t$ is the mean smoothed index value of the t^{th} year, $se_{\bar{x}(t)}$ is the standard error of the mean of the t^{th} year, and $t_{0.05[d.f.(t)]}$ is the critical value of the Student's t distribution for $\alpha = 0.05$ and degrees of freedom (sample depth - 1) of the t^{th} year (Rohlf and Sokal 1981). Finally, the associated 95% confidence intervals are plotted over the low-frequency chronology, and the presence or absence of departures from a reference line is interpreted.

RESULTS

Coddington Lake, Minnesota (47°44′N, 94°03′W, 128 m), White Oak (*Quercus alba*)

The Coddington Lake oak standard tree-ring chronology clearly expresses sine wave variation (Figure 1a). Indeed, this chronology demonstrates a strong low-frequency signal, i.e., variation held synchronously across samples (Cook et al. 1990), as evidenced by a representative subset of three of the site's individual detrended index series (Figure 1b). Spectral analysis was used to determine that the prominent frequency of variation in this standard chronology is at 74 years, and the 43-year cubic smoothing spline was generated to retain 90% of the 74-year-period variation (Figure 1a).

Each individual index series was also fit with a 43-year spline (Figure 1b), i.e., the same spline that was used with the standard chronology, and these spline series were averaged into a chronology of low-frequency variation. This low-frequency chronology (Figure 1c) appears

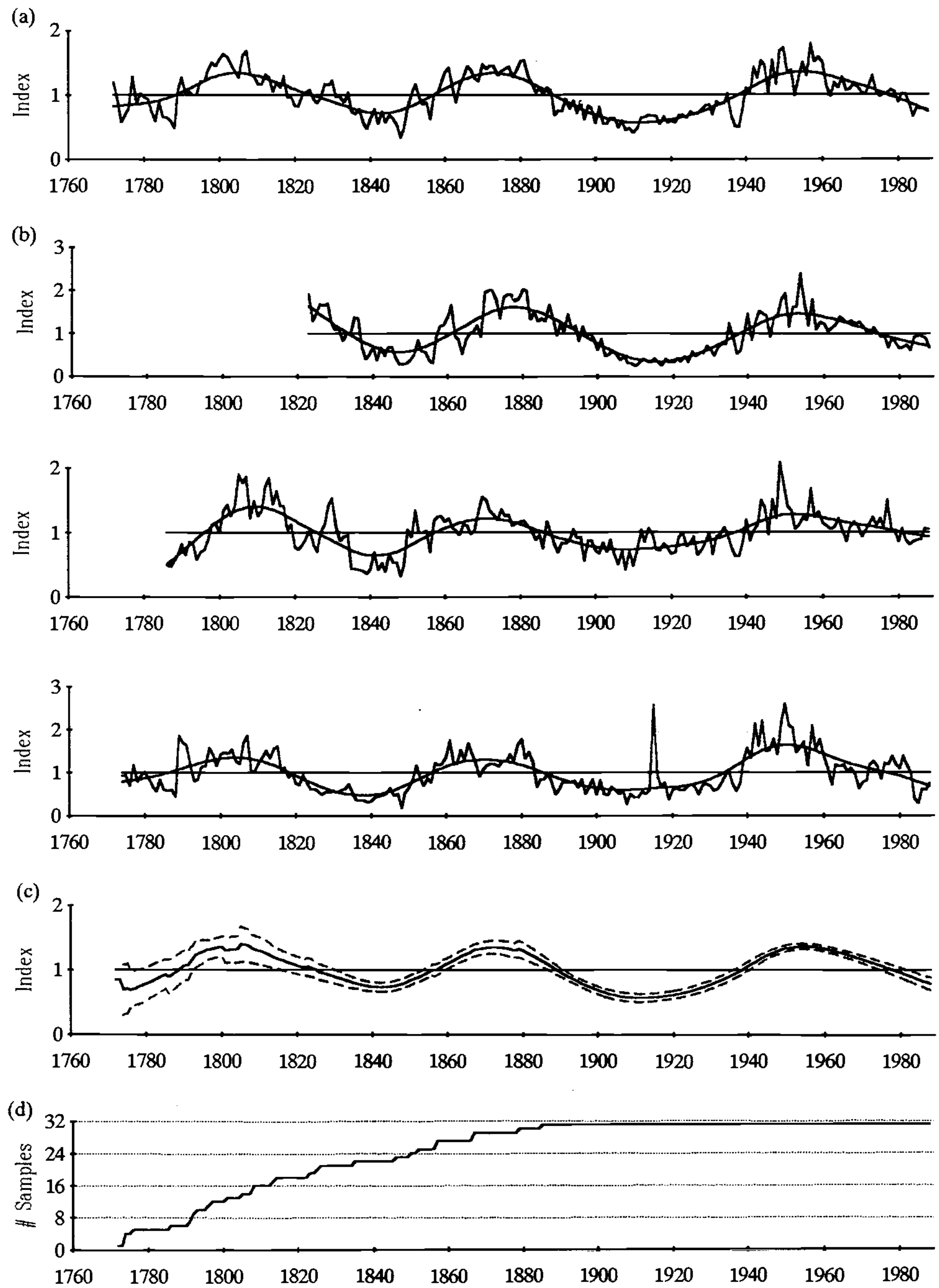

Figure 1. Coddington Lake, Minnesota, white oak time series: (a) standard index chronology with a 43-year spline series, (b) three representative individual index series, each with a 43-year spline series, (c) low-frequency chronology (solid line) with its associated 95% confidence intervals (dashed lines), and (d) chronology sample depth through time.

to be very similar to the 43-year spline generated from the standard chronology (Figure 1a) with differences restricted to the first few decades of the chronology.

The slight flaring of the 95% confidence intervals in the late part of the chronology (after 1970, Figure 1c) occurs because smoothing spline values are successively less influenced at that point by future index values, which do not exist. This flaring illustrates the end-effect phenomenon, whereby values at the end of a time series exert more influence on an estimated fit line than do values in the middle of a time series. The much wider flaring of the 95% confidence intervals in the early part of the chronology (Figure 1c) occurs because of low sample depth (Figure 1d), which leads to poor estimation of the standard error of the mean and to large critical values of the Student's *t* distribution that are associated with few degrees of freedom (Rohlf and Sokal 1981). The flaring of 95% confidence intervals with low sample depth should occur in most applications of this approach.

The low-frequency chronology and its 95% confidence intervals permit visual identification of important low-frequency tree-ring variation (Figure 1c). Negative departures from 1825 to 1855 and from 1890 to 1935 are significant and worthy of interpretation, as are positive departures from 1855 to 1890 and from 1935 to 1980. Furthermore, by the erratic nature of the low-frequency chronology and its wide 95% confidence intervals prior to 1820 (Figure 1c), it is apparent that low-frequency variation is not robustly estimated during the chronology's first 50 years, primarily due to poor sample depth (Figure 1d). Interpreting low-frequency variation of this chronology prior to 1820 is not prudent.

Gaylor Lakes, California (37°55′N, 119°16′W, 3,100 m), Lodgepole Pine (*Pinus contorta*)

Because lodgepole pines at Gaylor Lakes are growing at the upper treeline, I suspected that their growth might be sensitive to variation in ambient temperature (Fritts 1976). Therefore, I hypothesized *a priori* that tree growth at this site might reflect influences of the climatic anomaly referred to as the Little Ice Age (~1550 to the late 1800s), which is presumed to have been a period of below-average temperatures (Lamb 1977). Consequently, for this chronology I decided to investigate low-frequency tree-ring variation at the 100-year period. This variation frequency was represented by the 58-year spline, which retained 90% of the 100-year-period variation expressed by the standard chronology (Figure 2a). Individual index series were also fit with a 58-year spline, i.e., the same spline that was used with the standard chronology, and these spline series were averaged into a chronology of low-frequency variation. This low-frequency chronology (Figure 2b) appears to be very similar to the 58-year spline generated from the standard chronology (Figure 2a); as with the Coddington Lake oak site, differences between these two smoothed series are restricted to the first several decades of the chronology.

The low-frequency chronology and its 95% confidence intervals (Figure 2b) show that relatively little of the 100-year-period variation departs significantly from the 1.0 reference line. Only the negative departure from 1785 to 1870 and the positive departure from 1870 to 1910 are strong enough so that the associated 95% confidence intervals do not enclose the 1.0 reference line (Figure 2b). If the low-frequency variation of this chronology were associated with low-frequency variation in ambient temperature, the negative departure might represent a response to the latter third of the Little Ice Age. However, by the erratic nature of the low-frequency chronology and its wide 95% confidence intervals prior to 1680 (Figure 2b), it is apparent that low-frequency variation is not robustly estimated during the chronology's first 170 years, primarily due to poor sample depth (Figure 2c). Interpreting low-frequency variation of this chronology prior to 1680 is not prudent.

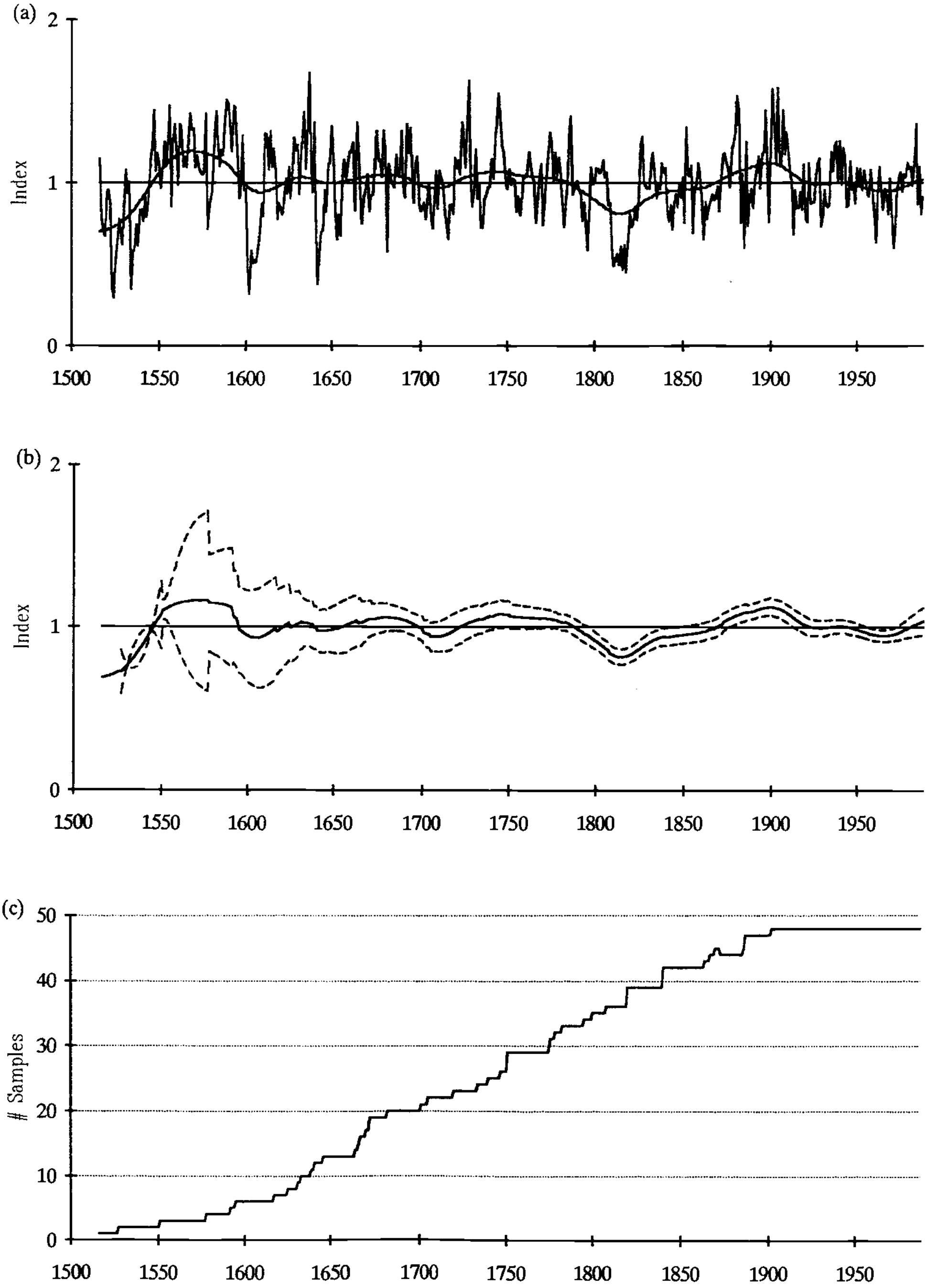

Figure 2. Gaylor Lakes, California, lodgepole pine time series: (a) standard index chronology with a 58-year spline series, (b) low-frequency chronology (solid line) with its associated 95% confidence intervals (dashed lines), and (c) chronology sample depth through time.

DISCUSSION

At first glance, this approach appears to provide a basis for testing the significance of low-frequency departures from the 1.0 reference line. It could be argued, however, that this approach also constitutes multiple significance testing of means, which causes the α level for the confidence interval to be unknown (Sokal and Rohlf 1981); because of this, it is difficult to know the level of significance for low-frequency tree-ring trends. Assuming that a chronology constitutes a single experiment of multiple tests (Miller 1981), i.e., a collection of as many tests of significance as the chronology is long, a new error level (α') would be necessary for each test in order to yield a known error level (α) for the single experiment. The new error level could be determined as follows:

$$\alpha' = 1 - (1 - \alpha)^{1/k}$$

where α' is the error level for each of the k tests and α is the error level of the single experiment (Sokal and Rohlf 1981). In the case of the Coddington Lake chronology, for an experiment with $\alpha = 0.05$ and $k = 215$ tests, α' must be ~0.0002. Regardless of sample depth for any year of the chronology, the critical values of the Student's *t* distribution that correspond to an α' of ~0.0002 are very large. Such a conservative adjustment would make it highly unlikely that any departure could be deemed significant at the experiment α level of 0.05.

However, adjusting the α level to account for multiple significance testing assumes that the k tests are independent, which clearly is not true in this case; indeed, the low-frequency chronology is an example of a time series with extreme autocorrelation. Because of this, the number of actual tests (k) should be adjusted downward to a number of effective, independent tests (k′) as follows:

$$\frac{k'}{k'-1} = \left[1 - \frac{1-r^2}{k(1-r)^2} + \frac{2r(1-r^k)}{k^2(1-r)^2}\right]^{-1}$$

where k′ is the number of effective, independent tests, r is the estimated AR(1) coefficient of the low-frequency chronology, and k is the number of actual tests, i.e., the length of the chronology (Dawdy and Matalas 1969, modified from equations 8-III-41 and 8-III-42). In the case of the Coddington Lake low-frequency chronology with an AR(1) coefficient estimated to be 0.9977, the k of 217 actual tests is reduced to a k′ of ~1 effective, independent test, which nullifies the adjustment of α levels to account for multiple significance testing. Thus, the desired experiment α level of 0.05 is approximately obtained even when the α' level of 0.05 is used for the calculation of the confidence interval around each mean. Because any low-frequency chronology constructed using this approach will be extremely autocorrelated, i.e., AR(1) $\rightarrow$ 1.0, this correspondence between α and α' will be true in general when using this approach. Thus, given that the experiment error level is considered to be known, i.e., $\alpha \approx 0.05$, this approach provides the basis for identifying periods of a chronology where low-frequency variation departs significantly from the 1.0 reference line.

However, if the experiment error level is considered to be known only approximately, this approach remains useful in that it still provides the means to evaluate the probable importance of low-frequency departures expressed in tree-ring chronologies. In the Coddington Lake oak chronology (Figure 1c), the approximate 95% confidence intervals associated with trends since 1790 clearly do not enclose the 1.0 reference line; it cannot be argued reasonably that these trends do not exist. Thus, this approach demonstrates that the sine wave variation expressed by the Coddington Lake oak chronology is real and important, and an investigation into the mechanism that caused this low-frequency variation is warranted.

Similarly, even if a level of significance cannot be stated precisely for the trends expressed by the Gaylor Lakes lodgepole pine chronology (Figure 2b), it still appears that this chronology expresses an important negative departure from 1785 to 1870. Thus, this approach demonstrates that this chronology may confirm the influence of the Little Ice Age at Gaylor Lakes, California. However, this approach also demonstrates that the sample depth of the Gaylor Lakes lodgepole pine chronology is not adequate from its beginning year to 1680, and it is not prudent to interpret the effects of the Little Ice Age in this part of the chronology until its sample depth is improved.

CONCLUSIONS

I recommend that this approach be used especially in studies that have the primary objective of identifying and interpreting low-frequency tree-ring variation. By merely reordering the individual steps used to construct the standard tree-ring chronology, this approach provides a low-frequency chronology with accompanying confidence intervals. Regardless of whether an exact level of significance can be stated for low-frequency tree-ring variation, this approach provides the means to evaluate the importance of trends expressed by standard chronologies.

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RESEARCH REPORT

THE BOOTSTRAPPED RESPONSE FUNCTION

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ABSTRACT

The bootstrap procedure provides a way to test the significance of the regression coefficients and the stability of the estimates in response functions generated by regression on principal components. A subroutine RESBO, which calculates a bootstrapped response function, has been added to Fritts' program PRECON.

The principle of the response function is described in Fritts (1976) and discussed in Hughes, et al. (1982). To avoid problems with the great number of predictors and their intercorrelation, Fritts et al. (1971) introduced regression on principal components. As with all regression methods, the main problems with this procedure are testing the significance of the coefficients and the stability of the estimates. The response function obtained on a sample is considered satisfactory only if it explains the growth over independent years. The most straightforward way to assess the stability is to divide climatic and tree-ring data into a dependent calibration set and an independent verification set (Fritts 1976). If the set of tree-ring indices estimated from the verification-set climate data using the regression coefficients that were derived from the calibration data set is close to the observed values, the response function is judged as reliable.

Gordon et al. (1982) clearly set out the problem of verifying the predictive ability of a model calibrated on one data set when applied to another data set. Because regression coefficients are validated only to the dependent data, they result in overconfidence in the predictive power of the model. We can be convinced of that by simulating tree-ring indices by random numbers and by calculating response functions with real climatic data (Guiot 1981; Cropper 1985). These authors showed that simulated tree-ring series also can produce regression coefficients judged significant by standard Student's tests. This result is due mainly to an inadequate number of degrees of freedom. To test regression coefficients, Student's test involves $n-k-1$ degrees of freedom where n is the number of observations and k the number of regressors. If k is set to the number of principal components actually introduced into the regression on the basis of their correlation with the predictand (stepwise regression), the significance of the coefficients is overestimated; therefore, the number k must be chosen by *a priori* considerations independent of the predictand. A good practice is to select a relatively large number of principal components taking into account say 90 or 95% of the variance of the climatic data - or using the PVP criterion of Guiot (1981, 1985). The number k is then the number of principal components selected by such an *a priori* criterion.

The bootstrap procedure of Efron (1979) provides an interesting method to simultaneously test the regression coefficients and the stability of the response function. It has been applied to tree-ring data by Guiot (1990a) and Till and Guiot (1990). The idea is to replace the lack of information on the statistical properties of the data by a great number of estimates, each based on different subsamples of data. The comparison of these estimates shows the variability of the estimates. The subsampling is done by random extraction with replacement from the initial data set. The size of each subsample is the same as that of the initial data set (n) to avoid bias (Efron 1983). Each subsample forms a bootstrap test useful for cross-validation. Guiot (1990a) has shown that beyond 50 subsamples, the results do not change significantly, even if more than 1000 replications usually are recommended.

For each subsample, the regression coefficients and the multiple correlation are computed on the observations randomly selected (some observations of the initial data set are used repeatedly while others are omitted). An independent verification is done on the observations omitted from the subsample. Repeated 50 times, this procedure yields 50 sets of regression coefficients, 50 multiple correlations, and 50 independent verification correlations. A mean regression coefficients set with standard deviations is computed on these 50 estimates. Means and standard deviations are also computed for the multiple correlation and the independent correlation sets. The bootstrapped regression coefficients are judged significant at the 95% level if they are twice, in absolute value, their standard deviation (see Fritts and Dean 1991). A more precise method is to compute the interval between the 2.5th and the 97.5th percentile, which equals the 95% confidence level.

We also can predict a tree-ring index from climate using these 50 response functions accompanied with a confidence interval. This feature can be used to measure the reliability of the results and to improve simulation studies. For example, in the spirit of the paper of Fritts and Dean (1993), the amount of precipitation that must be added to or substracted from the real precipitation series to produce a significant growth shift can be easily quantified.

A subroutine RESBO, which computes a bootstrapped response function, has been added to the program PRECON of H. Fritts. In this interactive program, the user can monitor in real time the step by step evolution of the multiple correlations and stop the program when no significant change is detected. A complete package of statistical programs, including bootstrapped regression (but also time series analyses, multivariate analyses, and transfer functions) with a users' guide of 250 pages (Guiot 1990b) is available from the author.

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RESEARCH REPORT

SPECIAL SANDING FILMS AND SANDPAPERS FOR SURFACING NARROW-RING INCREMENT CORES

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ABSTRACT

Special sanding films (400 grit to 23 micron) and fine sandpapers (1200-1500 grit) can be used to surface increment cores containing narrow rings (e.g., >50 rings per cm) so that rings are clearly visible for microscopy and photography.

INTRODUCTION

Careful surface preparation of increment cores is necessary to make their annual rings distinct for microscopy. As tree-ring research increasingly utilizes slow-growing species having narrow rings (e.g., *Taxodium distichum* (L.) Rich. [Stahle et al. 1988]; *Pinus balfouriana* Grev. and Balf. [Scuderi 1990]; *Larix lyallii* Parl. [Colenutt and Luckman 1991]; *P. aristata* Engelm. [Brunstein and Yamaguchi 1992]), core preparation becomes especially critical. Scratch-free polishing is also vital for producing clear photographs of rings.

Conventional core surfacing methods generally involve sanding with standard sandpaper ranging from 60 to 600 grit (Stokes and Smiley 1968, Swetnam et al. 1985, Phipps 1985, Yamaguchi 1991). Krebs (1972) describes the use of fine steel wool in alternation with sandpaper on *P. aristata* cores to remove resin that otherwise clogs sandpaper. In our work, we have found that the finest two grades of steel wool (#000 extra fine and #0000 finest) work well to remove resin or, for wide-ring cores, to remove grit left in cell lumens by 400 or 600 grit sandpaper.

Standard sandpaper and steel wool, however, are occasionally inadequate for preparing narrow-ring samples (e.g., those containing more than 50 rings per cm) or samples containing occasional narrow rings, locally present rings (rings that disappear along some tree radii), or coniferous frost rings (rings with cold-induced crushed tracheid cells [LaMarche and Hirschboeck 1984]). We have found several special sanding films and sandpapers useful for preparing such difficult samples.

MATERIALS

The films are "Flex-i-grit" regular and micro-fine sanding films (Table 1). Abrasive particles are mounted on thin, flexible plastic sheets instead of paper. The films are available in a range of grits. They are manufactured with stricter quality control standards, in terms of uniformity of particle size, than conventional sandpaper (Clarence Bartron, Bartron's and Co., personal communication, 1991). Thus, they are less prone to scratch core surfaces than are comparable grades of sandpaper. The sanding films are widely available in hobby shops where they are sold for sanding models. They are also available from the manufacturer, where they are typically purchased for use in dentistry and for polishing computer heads.

The special sandpapers are "micro-fine" wet-or-dry sandpapers (Table 1). These sandpapers are available in large hardware stores.

DISCUSSION

The sanding films and micro-fine sandpapers are commercially available in sheets that are large enough (10 x 13 cm films, 14 x 28 cm sandpapers) for use on electric finishing sanders. Alternatively, one can use both for hand sanding after wrapping them around sanding blocks (e.g., rectangular rubber erasers).

The sanding films and micro-fine sandpapers make possible an exceptional degree of ring clarity in prepared core samples. Our work with *P. aristata* has shown that 400 or 600 grit sanding films produce a surface equal to or slightly better than the 1500-grit sandpaper. In contrast, we found that surfaces prepared with the 1200-grit sandpaper are not entirely scratch-free. They should thus also be sanded with either the 1500-grit sandpaper or with the 400 or 600 grit sanding films.

The finest micro-fine sanding films in Table 1 are probably more than are needed for preparing even extremely narrow-ring increment cores. The 23 micron sanding films are the finest that we have found effective on the *P. aristata* cores we prepare. However, we list all the micro-fine films here, coarse through ultra fine, for completeness.

The new abrasives provide a practical and inexpensive alternative to scanning electron microscopy (Revel 1982) or microtome thin sections (Telewski et al. 1987) for preparing narrow-ring cores. We recommend them because they make working with such cores less exasperating.

Table 1. Sanding films and fine sandpapers for preparing narrow-ring increment cores.

Grit[a]	Name	Abrasive	Color
Regular sanding films[b]			
400	Extra fine	Aluminum oxide	Gray-brown
600	Ultra fine	Aluminum oxide	Red
Micro-fine sanding films[b]			
44	Coarse	Silicon carbide	Dark gray
23	Medium	Aluminum oxide	Light gray
23	Medium	Silicon carbide	Black
8	Fine	Silicon carbide	Gray
1.5	Extra fine	Cerium oxide	Pink
0.5	Ultra fine	Chromium oxide	Green
Wet-or-dry sandpaper[c]			
1200	Micro fine	Silicon carbide	Gray
1500	Micro fine	Silicon carbide	Gray

[a] Grit denotes fineness of screen mesh (openings per inch, 1 in. = 25.4 mm) through which abrasive particles pass (Salmon 1992). Micro-fine sanding film numbers are particle sizes in microns.

[b] "Flex-i-grit" sanding films are distributed to hobby shops by K and S Engineering Co., Chicago, IL 60638, U.S.A., 312-586-8503. If not locally available, they can be purchased from Bartron's and Co., 1537 St. James Place, Roslyn, PA 19001, U.S.A., 215-659-6184. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U. S. Government.

[c] Made by 3M Corp., St. Paul, MN 55144, U.S.A.

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International Conference on Tree Rings, Environment, And Humanity: Relationships and Processes

Tree-ring data are used to address an increasing range of scientific questions that span many disciplines. The 1994 International Conference will offer an opportunity for individuals interested in tree-ring research to meet and discuss current progress and future directions of dendrochronology. The theme of the conference, Relationships and Processes, stresses the contributions of tree-ring research to understanding environmental and cultural processes. The conference will address aspects of the past and future Earth, including its physical, biological, and social systems. Invited papers will assess the contribution of dendrochronology to recent advances in a wide range of disciplines. Contributed papers will present research results, case studies, and methodological innovations. Participation by students and young scientists is especially encouraged and supported.

The International Conference will be held at the Hotel Park Tucson in Tucson, Arizona, USA on 17-21 May 1994 and will be hosted by the Laboratory of Tree-Ring Research at The University of Arizona. The five-day program will be organized into paper and poster sessions on Tuesday, Wednesday, Friday, and Saturday with Thursday devoted to elective activities including day-long field trips and workshops offered by the Tree-Ring Laboratory and optional activities of individual choice.

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Registration fees are $150.00 for regular participants and $50.00 for students. The regular fee includes a reception, coffee breaks, and lunches during the meetings, a conference program, and abstracts of the papers and posters. Registration at the Hotel Park Tucson includes breakfast. Elective field trips and workshops will be subscribed separately.

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