CHRONOLOGIES FROM TEMPERATURE-SENSITIVE BRISTLECONE PINES AT UPPER TREELINE IN WESTERN UNITED STATES

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ABSTRACT

Ring-width variation in trees at upper treeline in the high mountains of temperate latitudes is a potentially important indicator of past climatic variations, especially temperature variations. Bristlecone pines (*Pinus longaeva* D.K. Bailey and *P. aristata* Engelm.) were sampled at nine sites in western United States. Plotted annual ring-width indices are given for chronologies that range in length from 532 years in New Mexico, 1409 years in Colorado, and 1239 years in Nevada to 1501 years in eastern California. Possibilities for increasing the length of these chronologies by incorporating tree-ring data from logs and remnants are good in several of the areas, and a 5405-year upper treeline chronology has been developed in California.

Tree-ring statistics show that crossdating is poorer, the climatic response is smaller, and the autocorrelation (a measure of year-to-year persistence) is greater in trees at upper treeline sites than at sites near the arid lower forest border. Climatic response functions differ in many details, but generally indicate a positive response of ring growth to warm temperatures in the previous late summer and autumn and current spring and summer. There is a negative response to warm temperatures during some winter and early spring months at several of the sites. The effect of precipitation varies greatly, but a positive response to precipitation during the previous summer or autumn, and during the current spring or summer is indicated. Variations in needle length are related to summer temperature, and may be important in explaining the high autocorrelation of upper treeline ring-width series.

Ring-width departures from the long-term mean during the past 500 years were calculated from upper treeline data for 30-year subperiods. The departures are in the same direction over the whole region during many of these subperiods, indicating that climate, rather than local ecological factors, is responsible for the ring-width variations. Comparison of tree-growth fluctuations with meteorological observations at selected stations shows that a general warming trend between the periods 1901-1930 and 1931-1960 is reflected by an upward trend in tree growth. However, low rates of tree growth during an earlier warm period (1850-1869) may be due to a lag in the response of ring-width growth to climatic changes at upper treeline.

INTRODUCTION

The best correlations between variations in width of annual rings of trees and meteorological records have generally been obtained near climatically determined forest limits, such as the arid lower forest border and the sub-Arctic treeline. In these extreme environments, even small departures from the climatic norm may directly or indirectly limit growth processes within a tree.

In arid regions, decreasing precipitation and increasing temperatures cause a rapid drop in soil moisture available for growth at progressively lower altitudes, and thus are major factors in determining the lower limit of distribution of a given tree species (Shreve 1915). There are changes in tree-ring characteristics that parallel these environmental changes along a gradient from the forest interior to the lower forest border (Fritts and others 1965). Trees closest to their arid lower limits show the greatest year-to-year differences and the highest common variation in ring widths. Furthermore, their growth records yield the highest correlations with concurrent meteorological records. In this environment, narrow rings are associated with low precipitation and high temperatures (Schulman 1956; Fritts 1966).

In the sub-Arctic, the northern forest limits are determined mainly by the length of the warm season and by the daily maximum temperatures, both of which decrease with increasing latitude. Here, as in the arid regions, the trees nearest the forest border are most responsive to year-to-year departures from the climatic norm (Mikola 1962). However, the meteorological element most strongly influencing tree-ring growth is low temperature rather than low precipitation. At the northern treeline, the temperature of the warmest months, or some measure of the heat sum for the warm period, are the only factors significantly correlated with tree-ring growth (Eklund 1957; Giddings 1943; Hustich 1945, 1948; Mikola 1962).

Another important forest boundary is the alpine treeline of the mountains of temperate regions. The climatic information that may be contained in long tree-ring records from this environment is little known, but the possibility of relating ring-width variation in trees at the alpine treeline to meteorological records is suggested by several lines of evidence. The role of temperature in setting the upper altitudinal limits for tree growth has been described (Daubenmire 1954) as "a major autecological principle." Of particular significance are the results of physiological experiments involving high-altitude pines (Tranquillini 1964, 1967; Schulze and others 1968; Mooney and others 1966). These results indicate that the upper treeline marks a critical altitude, above which annual net photosynthesis is insufficient for tree growth because of the short warm season and the low daily maximum temperatures. An important corollary is that at the treeline, successive annual rings would be expected to differ in width as a result of year-to-year differences in the temperature regime. The few studies that have been made, relating high-altitude tree growth to climate, lend support to this hypothesis (Artmann 1949; Brehme 1951; Leopold 1953).

In this report, tree-ring chronologies for bristlecone pines (*Pinus aristata* Engelm. and *P. longaeva* D.K. Bailey) at upper treeline sites in several western states are presented, and some relationships between climate and tree-ring growth in this environment are described. The bristlecone pine was chosen for this study because of the long tree-ring records that can be developed for these species, owing to the unusual longevity of individual trees (LaMarche 1969) as well as the possibility of incorporating data from logs and wood remnants to extend chronologies back thousands of years prior to the establishment of even the oldest living trees (Ferguson 1968).

Dendrochronological applications in western United States have traditionally relied on conifers of the woodland and montane forest zones. Interest in higher altitude species has developed since the 1950's, when Edmund Schulman discovered that certain subalpine conifers, notably the limber pine (*Pinus flexilis* James) and the bristlecone pine could provide climatically sensitive records thousands of years in length. However, after some initial sampling of relatively high elevation trees (Schulman 1956; Schulman and Ferguson 1956), subsequent dendrochronological studies of bristlecone pine were limited mainly to trees on xeric sites near its lower altitudinal limits, particularly in the White Mountains of eastern California. These "drought-sensitive" trees appeared to offer the best possibilities for climatic reconstruction and for development of chronologies of maximum possible length. However, the dendroclimatic potential of higher altitude trees should not be neglected, because they may contain paleoclimatic information that complements that obtained from trees at lower altitudes in the same area (LaMarche 1974).

Tree-Ring Sites

Bristlecone pines were sampled at nine upper treeline sites in four western States (Figure 1). The Rocky Mountain bristlecone pine (*P. aristata* Engelm.) is represented by three sites in the Sangre de Cristo Range of northern New Mexico and southern Colorado and by two sites in the Colorado Front Range. The Great Basin bristlecone pine (*P. longaeva* D. K. Bailey) was sampled on Mount Washington in the Snake Range of east central Nevada and at three sites in the White Mountains, California. In each area, an attempt was made to locate and sample the highest full-sized erect trees. Krummholz forms, which are developed in all areas but the White Mountains (LaMarche and Mooney 1972), were not sampled because of their distorted radial growth patterns and apparent low ages. Table 1 gives information of each site.

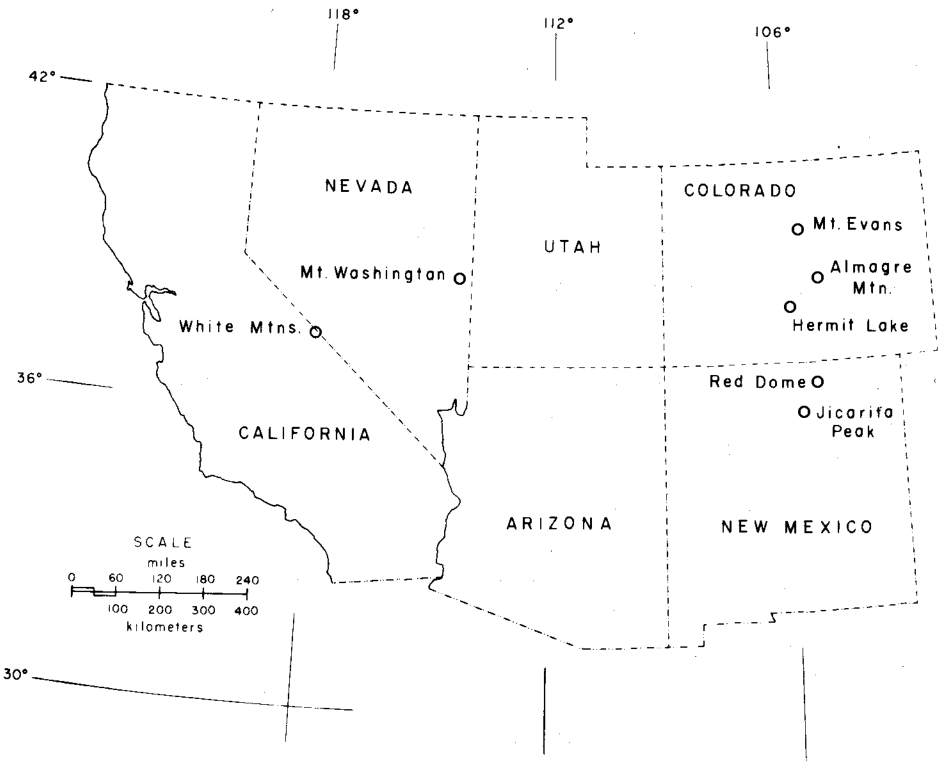


Figure 1. Location of upper treeline samples.

Table 1. Site characteristics.

	Sangre de Cristo Range		
	Jicarita Peak, N.M.	Red Dome, N.M.	Hermit Lake, Colo.
Latitude	36° 03′	36° 33′	38° 06′
Longitude	105° 32′	105° 23′	105° 37′
Altitude, m	3718	3695	3718
Slope Direction	S	SE	S
Slope Angle	35°	25°	35°
Substrate	sandstone	sandstone	sandstone

	Front Range	
	Almagre Mtn., Colo.	Mt. Evans, Colo.
Latitude	38° 46′	39° 38′
Longitude	104° 59′	105° 35′
Altitude, m	3535	3535
Slope Direction	W	S
Slope Angle	30°	15°
Substrate	granite	granite

	Great Basin Ranges			
	Mt. Washington Nev.	Cottonwood Calif.	Sheep Mtn. Calif.	Campito Mtn. Calif.
Latitude	38° 54′	37° 33′	37° 32′	37° 30′
Longitude	114° 18′	118° 13′	118° 13′	118° 12′
Altitude, m	3383	3474	3505	3383
Slope Direction	S	N	E	NW
Slope Angle	10°	30°	20°	25°
Substrate	limestone	dolomite	dolomite	sandstone

Processing

Increment cores obtained in field sampling operations were mounted, surfaced, and dated using standard techniques (Stokes and Smiley 1968). Because crossdating with available low-altitude chronologies was poor or nonexistent in many cases, chronology development was carried out independently at each site. Frost rings were used as a supplementary dating aid (LaMarche 1970).

Ring widths on selected radii were measured to the nearest 0.01 mm, tabulated and punched on cards. The ring widths for each measured radius were then transformed to ring-width indices using either an exponential curve or straight line of zero or negative slope (Fritts and others 1969). This transformation is designed to remove the effects of differences in average growth rates between trees, as well as biological age trends.

Two mean index chronologies were developed for most sites. One of these contains ring-width indices for all of the well-dated and continuously measured radii. The other represents a smaller subsample of trees for which measurements along two radii were available. Such replicated subsamples are required for analysis of variance and for evaluation of correlation between radii within trees.

A set of sample statistics was calculated for the total period covered by each chronology (Table 2) including sample size, mean ring width and the percentage of locally absent rings. The first-order autocorrelation coefficient, standard deviation and mean sensitivity of the mean site chronology are also given. Statistics similar to those in Table 2 are presented for the replicated subsamples (Table 3) based on a period encompassing only the past 100 to 110 years. Results of analysis of variance and cross-correlation for the replicated subsamples for the same period are given in Table 4.

Chronologies representing the maximum length of record obtained at each site are shown in Figures 2 through 5. These indices are being published in tabular form in the Laboratory of Tree-Ring Research Chronology Series (Drew 1972).

Colorado – New Mexico Chronologies

The Front Range chronologies (Almagre Mountain and Mount Evans) are longer and of better quality than those obtained from sites in the Sangre de Cristo Range to the south (Jicarita Peak, Red Dome, and Hermit Lake). A notable feature of all but the Mount Evans record is a pronounced upward trend in ring width since the mid 1800's. Another common feature, particularly pronounced in the New Mexico sites, is an interval of extremely low growth rates during the late 1830's and 1840's. Although some crossdating is apparent, most of the common variance is accounted for by longer-term growth fluctuations. The high autocorrelation coefficients in all the chronologies (Table 2) is a reflection of the large long-term variations.

Possibilities exist for chronology extension in time prior to the records contained in the oldest living trees. This is demonstrated by radiocarbon-based dates for large remnants at and above present treeline on Almagre Mountain that range back to 1300 B.C., whereas the modern chronology from living trees begins only in A.D. 560.

Great Basin Chronologies

The upper treeline chronologies from Mount Washington, Nevada, and from sites in the White Mountains, California, show many of the characteristics of chronologies from the Rocky Mountains. Autocorrelation is high, low frequency fluctuations are dominant, and there has been a pronounced increase in growth rates since about 1850.

The Mount Washington chronology could be extended through use of wood from standing dead snags and remnants, some of which date back to about 2000 B.C. (LaMarche and Mooney 1972). However, crossdating is relatively poor.

The Cottonwood chronology from the White Mountains was obtained from sampling a small stand of old trees on a high-altitude site that is less than 100 m below treeline. The Sheep Mountain samples come from trees at the present upper treeline. Although remnants nearly 6000 years old are found on Sheep Mountain (La Marche 1973), they contain relatively short records and have poor crossdating qualities, so that it would be difficult to extend this chronology back in time.

The Campito Mountain chronology represents a site quite different from Cottonwood and Sheep Mountain. It is at a somewhat lower altitude and is on a sandstone rather than dolomite substrate. Crossdating is good, and the presence of

Table 2. Chronology statistics – Total period.

Site	I.D. No.	No. Trees	No. Radii	Interval Years A.D.	Mean Ring Width, mm	% Locally Absent	First Order Autocorrelation	Standard Deviation	Mean Sensitivity
Jicarita Peak, N.M.	091519	6	13	1436-1968	0.63	0.50	0.87	0.40	0.19
Red Dome, N.M.	092519	7	14	1535-1968	0.63	0.27	0.88	0.31	0.12
Hermit Lake, Colo.	093519	11	17	1259-1968	0.64	0.07	0.82	0.31	0.15
Almagre Mtn., Colo.	095519	13	25	560-1968	–	–	0.70	0.26	0.17
Mt. Evans, Colo.	096510	5	10	977-1968	0.39	0.06	0.66	0.24	0.16
Mt. Washington, Nev.	076519	10	15	737-1965	0.49	0.10	0.68	0.34	0.22
Cottonwood, Calif.	002515	13	23	590-1969	–	–	0.58	0.31	0.26
Sheep Mtn., Calif.	002519	10	21	470-1970	–	–	0.77	0.31	0.17
Campito Mtn., Calif.	001510	10	20	1170-1970	0.38	1.28	0.62	0.33	0.26
Schulman Grove Crest, Calif.*	–	10	20	1860-1962	0.26	3.75	0.21	0.37	0.43

*lower forest border

Table 3. Sample statistics – ANOVA period.

	Mean Index Chronology						
	Period of Analysis	I.D. No.	No. Trees	No. Radii	Mean Ring Width	% Absent	Mean Standard Error
			UPPER TREELINE				
Jicarita Peak, N.M.	1860-1968	091510	6	12	0.74	0.0	0.14
Red Dome, N.M.	1860-1967	092510	5	10	0.63	0.0	0.12
Hermit Lake, Colo.	1860-1968	093510	6	12	0.56	0.3	0.13
Almagre Mtn., Colo.	1860-1968	095510	8	16	0.47	0.0	0.10
Mt. Evans, Colo.	1864-1964	096510	5	10	0.50	0.0	0.11
Mt. Washington, Nev.	1860-1965	076510	5	10	0.52	0.0	0.11
Cottonwood, Calif.				no analysis			
Sheep Mtn., Calif.	1860-1963	002510	9	18	0.80	0.1	0.07
Campito Mtn., Calif.	1960-1970	001510	10	20	0.43	0.9	0.08
			LOWER FOREST BORDER				
Schulman Grove Crest, Calif.	1860-1962	–	10	20	0.26	3.8	0.07

Table 4. ANOVA and cross-correlation data.

	Analysis of Variance			Cross-Correlation Analysis		
	% of chronology variance related to:			Mean correlation coefficient between:		
	common variation	differences between trees	unexplained	radii within trees	radii between trees	mean tree chronologies
UPPER TREELINE						
Jicarita Peak, N.M.	51	27	22	0.80	0.51	0.59
Red Dome, N.M.	30	25	45	0.55	0.30	0.38
Hermit Lake, Colo.	38	30	32	0.70	0.40	0.45
Almagre Mtn., Colo.	28	23	49	0.48	0.31	0.41
Mt. Evans, Colo.	20	49	31	0.63	0.23	0.29
Mt. Washington, Nev.	43	26	31	0.70	0.45	0.53
Cottonwood, Calif.	no analysis					
Sheep Mtn., Calif.	33	15	52	0.46	0.33	0.47
Campito Mtn., Calif.	37	12	51	0.53	0.39	0.51
LOWER FOREST BORDER						
Schulman Grove Crest, Calif.	67	17	16	0.85	0.68	0.74

abundant, large remnants has permitted development of a 5405-year chronology (LaMarche and Harlan 1973).

Tree-Ring Response to Climate at Upper Treeline

The usefulness of long tree-ring records for paleoclimatic inference basically depends on the degree to which climate influences ring width. The strength of the climatic "signal" in tree-ring records can often be indirectly inferred from their statistical properties, or more directly by comparison of tree-ring and climatic data.

The statistical properties of ring-width data from the upper treeline sites (Tables 2, 3, and 4) permits evaluation of relative "quality" for dendroclimatic purposes. In Tables 2, 3 and 4, data from bristlecone pines on a superior lower forest border site in the White Mountains (Fritts 1969) are given for comparative purposes. The chronology standard deviation (Table 2) is a measure of the total amount of ring-width variation through time, and thus the magnitude of the environmental "signal" (not necessarily climatic) present in the mean record. Values range from 0.24 to 0.40 (relative to a mean of 1.00 in all cases), with most values from upper treeline falling below that for the lower forest border sites (0.37). The first-order autocorrelation coefficient (r_1) (Table 2) describes the average dependence of the ring-width value for a given year on the value for

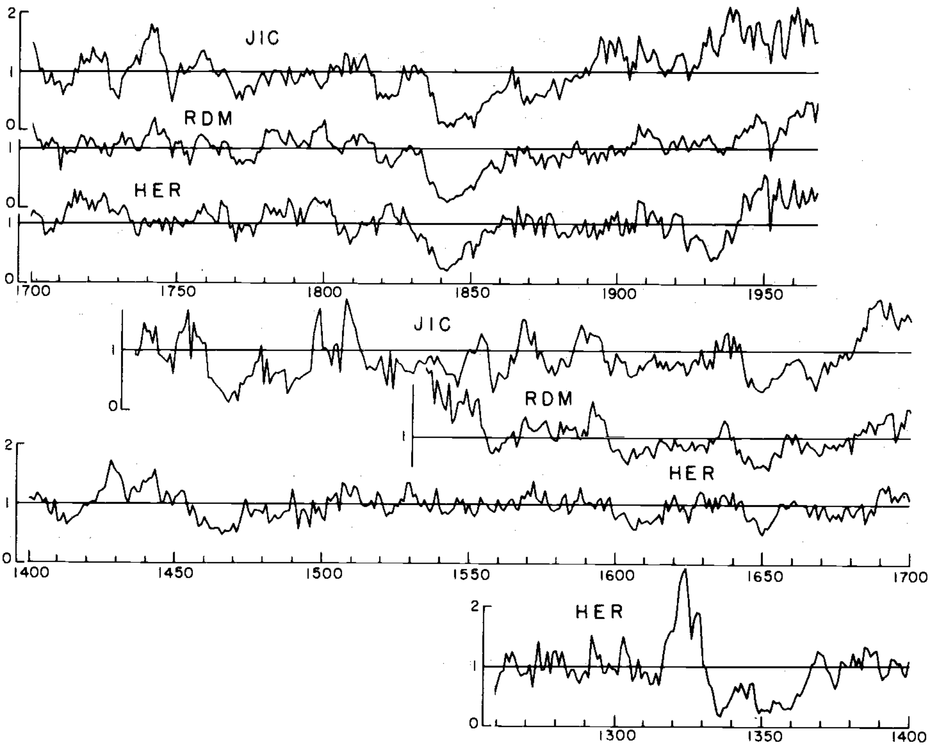


Figure 2. Ring-width indices for localities in the Sangre de Cristo Range: Jicarita Peak (JIC) and Red Dome (RDM), New Mexico; Hermit Lake (HER), Colorado.

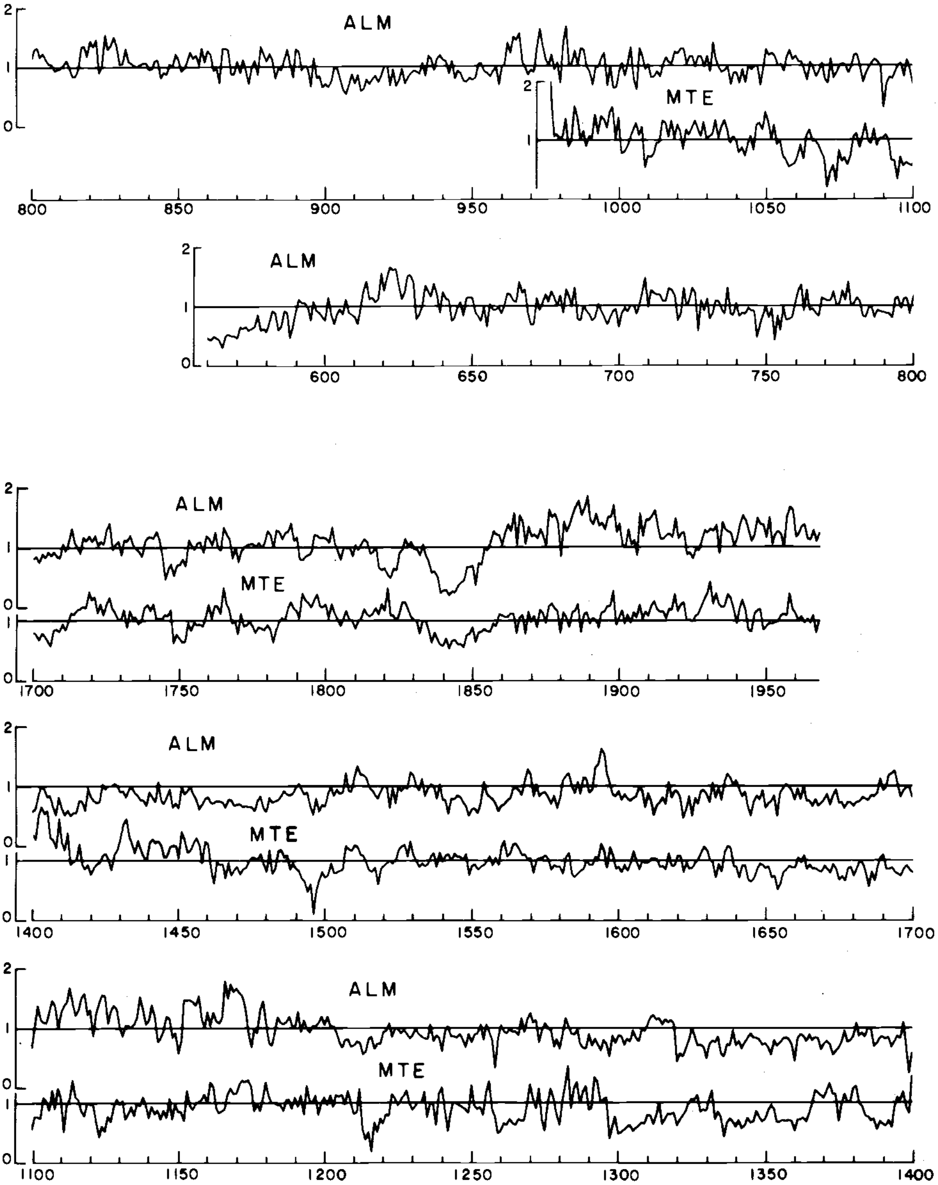


Figure 3. Ring-width indices for Front Range localities: Almagre Mountain (ALM) and Mount Evans (MTE), Colorado.

the year previous. It is thus a measure of the importance of persistent trends or fluctuations in the record or of the influence of moving-average or autoregressive processes. Values of r_1 at upper treeline range from 0.58 to 0.88, and are much higher than values typical of the lower forest border (0.2-0.3). The autocorrelation in upper treeline ring-width chronologies is also much larger than autocorrelation in such climatic variables as seasonal mean temperature and precipitation, suggesting that biological sources of persistence are operating to produce persistence in the tree-ring series. The mean sensitivity (Table 2) is the average absolute difference between two successive ring-width values divided by their mean value. A high mean sensitivity chracterizes a series with large year-to-year differences in ring width. Thus, it is directly proportional to standard deviation, but inversely proportional to r_1. It is the width of an annual ring relative to width of the immediately preceding and following rings that provides the basis for crossdating of ring sequences. Therefore, the relatively low mean sensitivities (0.12 to 0.26) of the upper treeline series compared to those near the lower forest border (0.43) in part explain the generally poorer crossdating qualities of upper treeline material (Schulman and Ferguson 1956).

Another measure of dendroclimatic potential is provided by the degree of common variability present in ring-width series from different radii and from different trees on the same site. Table 4 gives results of analysis of variance (ANOVA) and cross-correlation

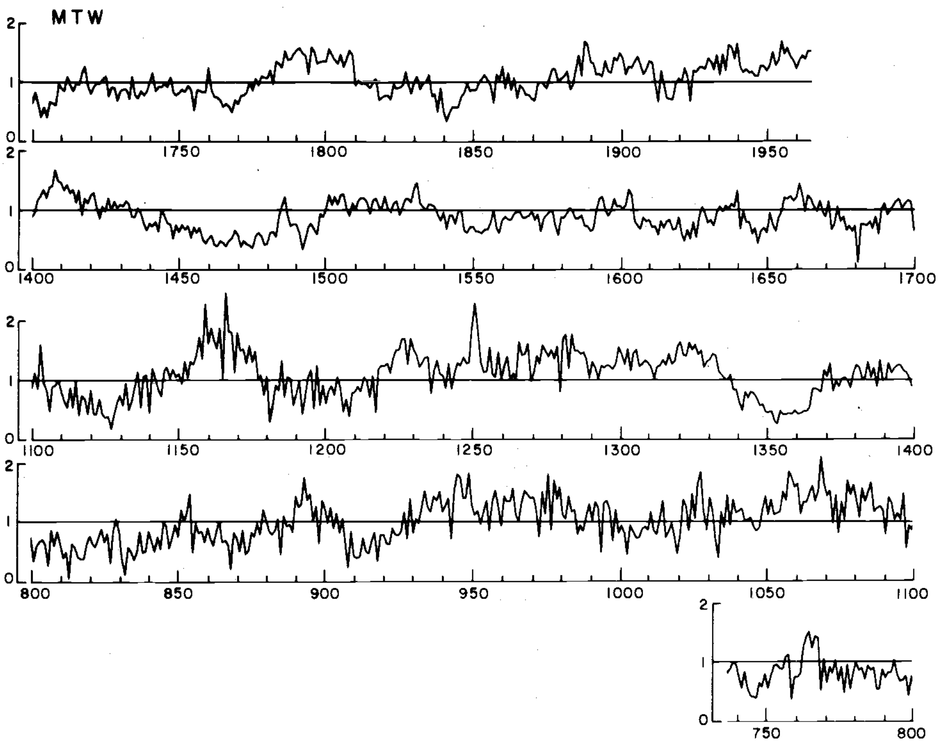


Figure 4. Ring-width indices for Mount Washington (MTW), Nevada.

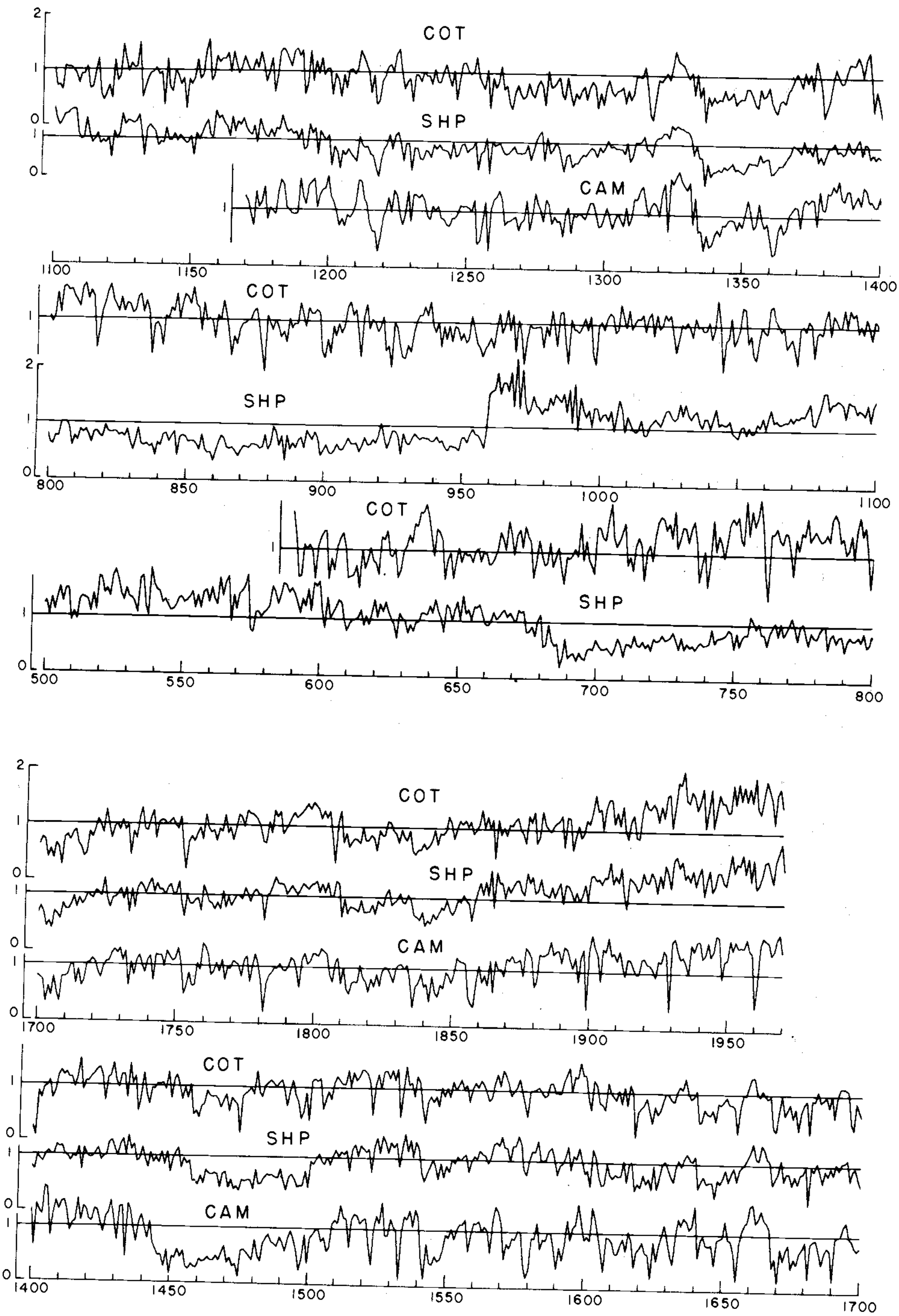


Figure 5. Ring-width indices for localities in the White Mountains, California: Cottonwood (COT), Sheep Mountain (SHP), and Campito Mountain (CAM).

Table 5. Response function parameters.

Chronology	Climatic Station	Data Period	Percent Variance Explained		Step[1]	F-Level[2]
			Total	Prior Growth		
NNM	Taos, N.M.	1903-1968	72	59	12	1.09
HER	Cañon City, Colo.	1897-1968	70	56	9	1.11
ALM	Lake Moraine, Colo.	1897-1959	48	25	11	1.42
MTE	Idaho Springs, Colo.	1905-1968	45	20	8	1.30
MTW	Fillmore, Utah	1900-1965	48	42	7	1.03
CAM	Mina, Nev.	1908-1969	27	12	7	1.12
SHP	Mina, Nev.	1908-1969	41	11	10	1.70
COT	Mina, Nev.	1908-1969	40	22	9	1.04

[1]Number of independent variables used in regression.

[2]F-level at which last independent variable entered regression.

analyses. The first column of the ANOVA results is most important, because it gives the percentage of total variance that is retained by the mean chronology. It ranges from 20 to 51 percent for upper treeline sites, which compare poorly with the lower forest border site (67 percent). Differences between trees account for more variance in the Rocky Mountain and Nevada sites than in the White Mountains. The outstanding result of the correlation analysis is the much poorer degree of correlation within trees and between average records from individual trees at upper treeline (0.29-0.59), as compared with the lower forest border (0.74). The results of these analyses must be viewed with caution, however, because the period of analysis coincides with a period of major growth trend in many of the upper treeline records. The trend dominates the analyses and obscures the relatively poor correspondence of the year-to-year variations on many of these sites.

Empirical comparison of series of ring-width indices with meteorological records is a way of directly evaluating the degree and kind of climatic influence on tree-ring growth. Multiple linear regression analysis using monthly temperature and precipitation as independent variables (Fritts 1962) was initially used in this work, but was unsatisfactory, at least in part because of the intercorrelation of the temperature and precipitation variables. More success was achieved using a more recently developed modelling procedure (Fritts and others 1971). This procedure involves stepwise multiple linear regression, but the climatic variables used in the regression analysis are first transformed into a new set of uncorrelated variables using principal component analysis. The advantages are first, that the new independent variables are uncorrelated, and second, that the number of independent variables can be reduced, yielding additional degrees of freedom for statistical tests of significance of the regression coefficients.

The response functions obtained (Table 5) from the results of the regression analyses show how normalized precipitation and temperature departures influence tree-ring width during the following or current growing season. Average monthly mean temperatures and total monthly precipitation recorded at the nearest station with a relatively long record were used in the analyses (U.S. Government, 1896-1970). Meteorological data for a 14-month period were used, beginning with the July prior to the growing season in which the annual ring is formed and ending with August of the growing season concurrent with formation of the annual ring. Phenological evidence shows that in at least some years, ring growth in upper treeline bristlecone pines continues into late August or even early September. The widths of the annual rings formed one, two, and three years prior to the current growing season are also included as variables in the regression analysis, to help account for direct and indirect lagged effects. Inclusion of these prior growth variables helps to reduce the influence of biological persistence on the climatic model.

The results of climatic modelling are shown in Figure 6. The two northern New Mexico chronologies (Jicarita Peak and Red Dome) were combined into a single regional chronology (NNM) for purpose of this analysis. Three of the Rocky Mountain chronologies (all except Mount Evans) show qualitatively similar response functions (Figure 6, *upper*). Temperatures during the previous late summer and autumn and current summer are positively correlated with ring width, while temperature during May and June is negatively correlated with growth. The effect of precipitation seems most important at the Almagre Mountain site, where it is positively associated with growth except during the previous July and August, during mid winter and in the current August. At the northern New Mexico sites (NNM) precipitation during the previous autumn and current spring and summer is positively correlated with growth, but inversely correlated during most winter months. The response function for Mount Evans is quite different from those found at other Rocky Mountain sites. Here, temperature is negatively correlated with growth in all but the late spring and summer months in the year concurrent with growth. Precipitation in most months is negatively correlated with ring width. This response function should be viewed with caution, because of the anomalous behavior of the Mount Evans chronology within the period of weather records. Based on the total number of significant response function weights, the Almagre Mountain chronology appears to present the best basis for paleoclimatic estimation.

Response functions for the Great Basin bristlecone pine sites are shown in Figure 6, *lower*. Temperature responses are generally similar, with temperatures of the previous autumn and current summer being positively correlated with growth. Temperature in the late winter and spring is generally negatively correlated with growth in the following summer. The high-altitude Sheep Mountain site yielded the chronology with the greatest temperature response. Precipitation in the previous summer and in mid-winter is positively correlated with growth; late autumn and early winter precipitation are negatively correlated with growth. The lower-altitude and generally more xeric Campito Mountain site has trees showing the greatest precipitation response.

The temperature response functions for most of the upper treeline sites are broadly similar, and can be partly explained by the results of physiological experiments on high altitude pines (LaMarche 1973). First, rates of net photosynthesis at upper treeline are directly proportional to air temperature, so that more photosynthates will be produced during a warm summer than a cool one. Second, because the photosynthetic "mechanism" is in part controlled by the temperature regime, a late occurrence of spring warming and early onset of winter cold restrict the period during which the trces are capable of photosynthesis. Finally, bristlecone pines can lose important amounts of stored photosynthates by respiration on warm days during the winter period of photosynthetic dormancy. To the extent to which production and storage of the products of photosynthesis affect subsequent and urrent ring growth, these temperature effects provide a basis for explaining some major features of the temperature response functions.

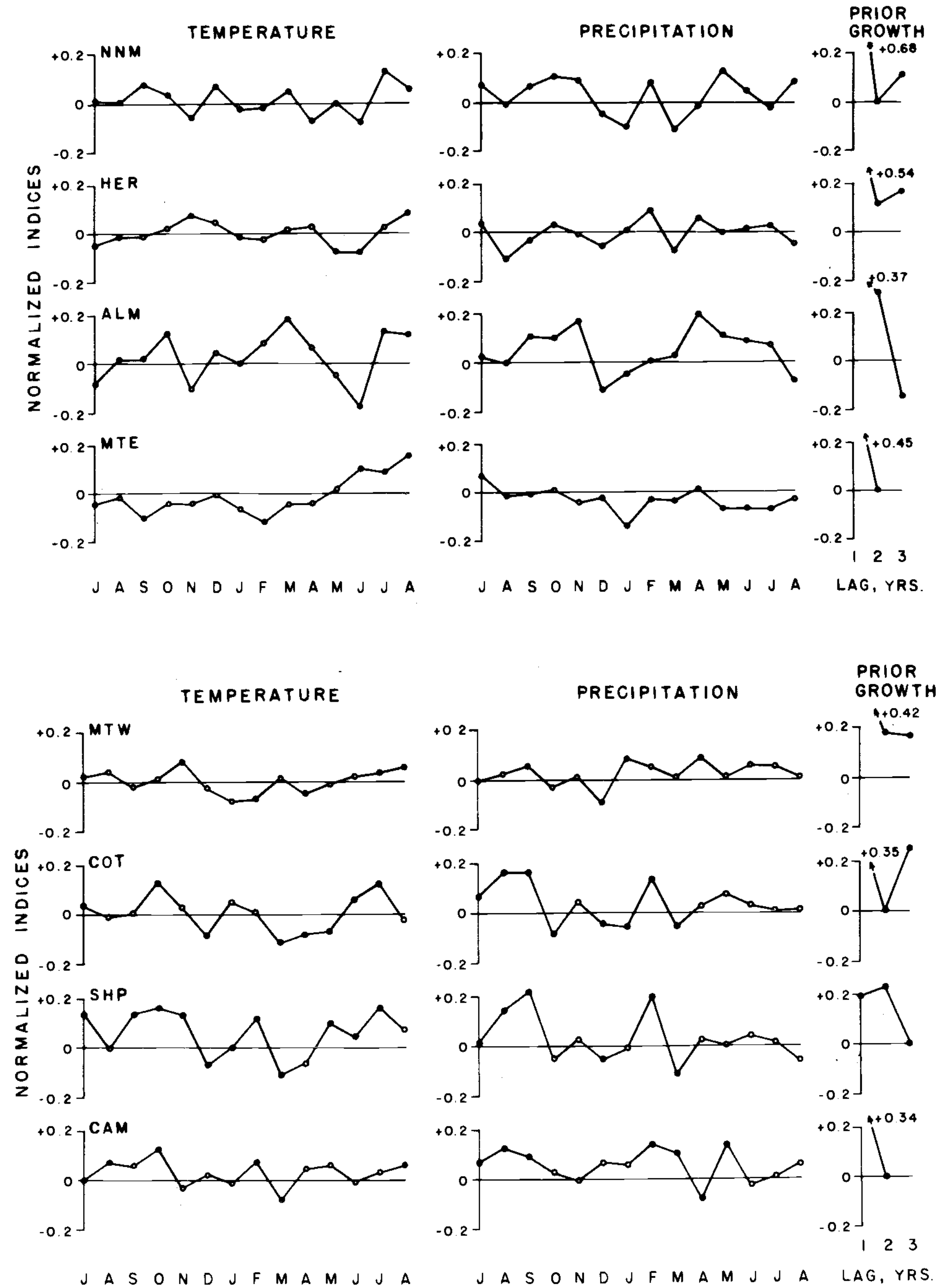


Figure 6. Response functions showing effects of precipitation, temperature, and ring widths in previous years on ring-width indices in upper treeline bristlecone pines. *Upper*, Rocky Mountain localities — NNM represents the mean Jicarita Peak-Red Dome chronology. *Lower*, Great Basin localities.

The positive response to warm, prior autumn (after the end of the previous growing season) may reflect increased net photosynthesis, the products of which are stored and utilized for ring growth the following summer. The negative response to temperature in late winter could be due to the loss of stored photosynthates on warm days during the dormant season. The generally positive response to warmth during the growing season may be attributed to the contribution of current photosynthetic production to annual ring growth, although direct temperature effects on cell division and enlargement are also possible.

Study of another phenomenon suggests that empirical modelling of the type used to obtain the response functions does not adequately portray the role of temperature on tree-ring growth at upper treeline. Bristlecone pines retain their needles for at least ten years; retention for thirty years or more is not uncommon, and as many as 58 successive annual needle clusters have been counted (Bailey 1970). There are large year-to-year variations in needle length that are closely related to summer temperature (Figure 7). Comparison with weather data shows that low temperatures in the summer during which needle elongation takes place result in formation of very short needles. Although the older needles decrease in photosynthetic efficiency, they still represent a major part of the total photosynthetic area of a bristlecone pine. Clearly, a succession of unusually cool or unusually warm summers would result in large changes in photosynthetic area, and consequently, large changes in total net photosynthesis that should be reflected in ring widths. Ring-width variation could be affected in two ways. First, the affect of a few cool summers would be spread out over several subsequent years, a phenomenon that might explain the unusually high autocorrelation coefficients that characterize the upper treeline chronologies. Second, the tree-ring response to a fluctuation in climate would lag behind the climatic event, because several years must elapse before the foliage area can reflect the influence of the changed conditions.

UPPER TREELINE CHRONOLOGIES AS PALEOTEMPERATURE INDICATORS

Physiological considerations and the results of empirical modelling indicate that ring-width chronologies from upper treeline bristlecone pines contain at least some paleoclimatic "information." However, the high degree of persistence in these series suggest that one or more biological smoothing mechanism is operating. One such possible mechanism is the slow response of foliage area to summer temperature changes.

Another approach to the evaluation of the climatic significance of long-term tree growth fluctuations is the consistency of such fluctuations over broad geographic areas. If such consistency is found, it strongly suggests that climate rather than local disturbances, ecological changes, insects, or disease is responsible. The upper treeline chronologies do show broad general agreement in trends over large areas. The upper treeline records can be compared in several ways. The plotted data in Figures 3, 4 and 5 show that there is agreement of the long-term fluctuations in tree-ring width between areas more than 1000 km apart. These relationships are summarized in Figure 8, where the normalized departures of successive 30 year mean ring-width indices are presented for the period of record common to all series (A.D. 1541-1965).

There is a tendency for tree growth to be above (below) normal in the Great Basin and central Rocky Mountains when it is below (above) normal in the southern Rocky Mountains (1661-1690, 1691-1720, 1871-1900). During some subperiods, there is poor

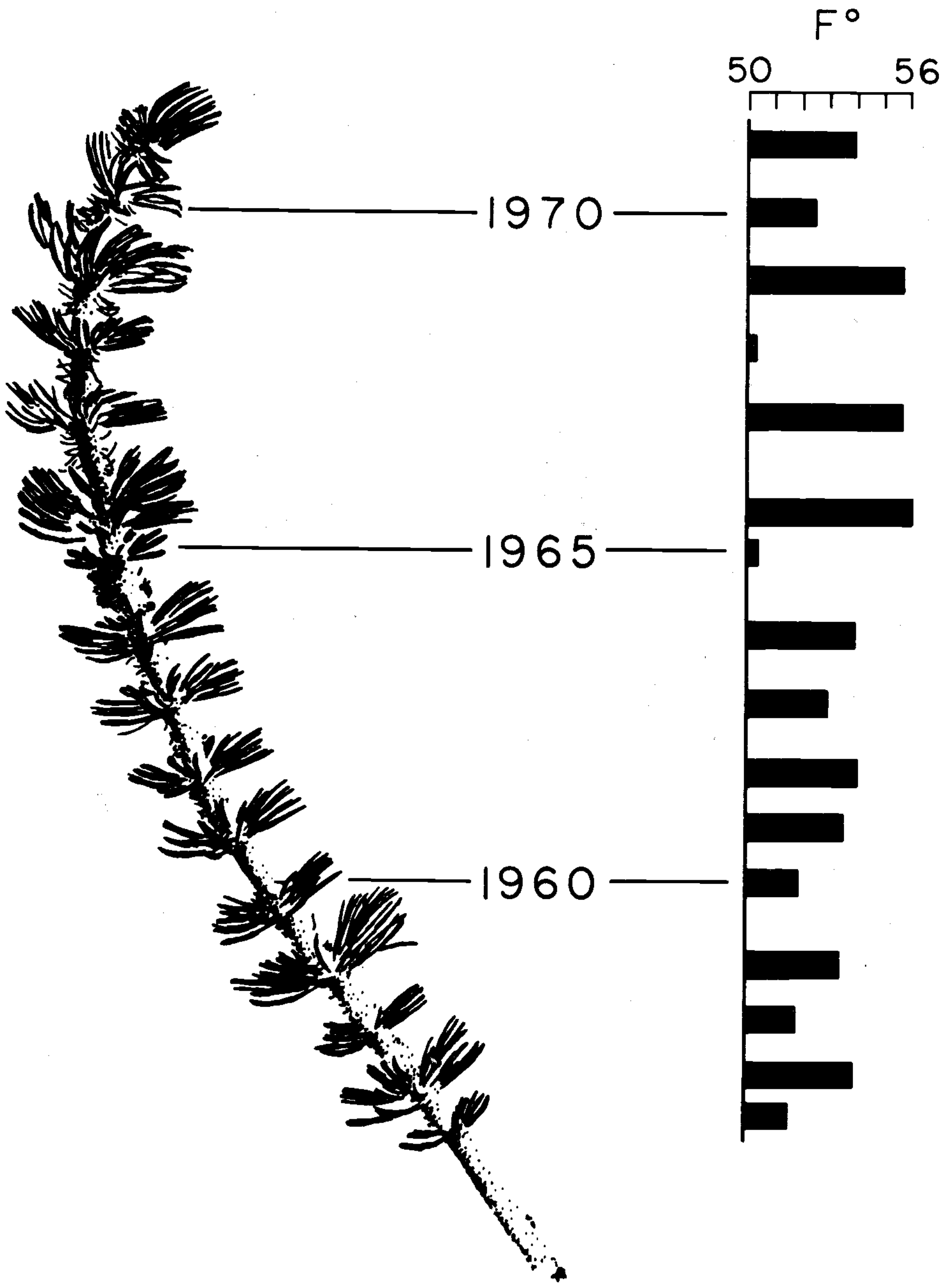
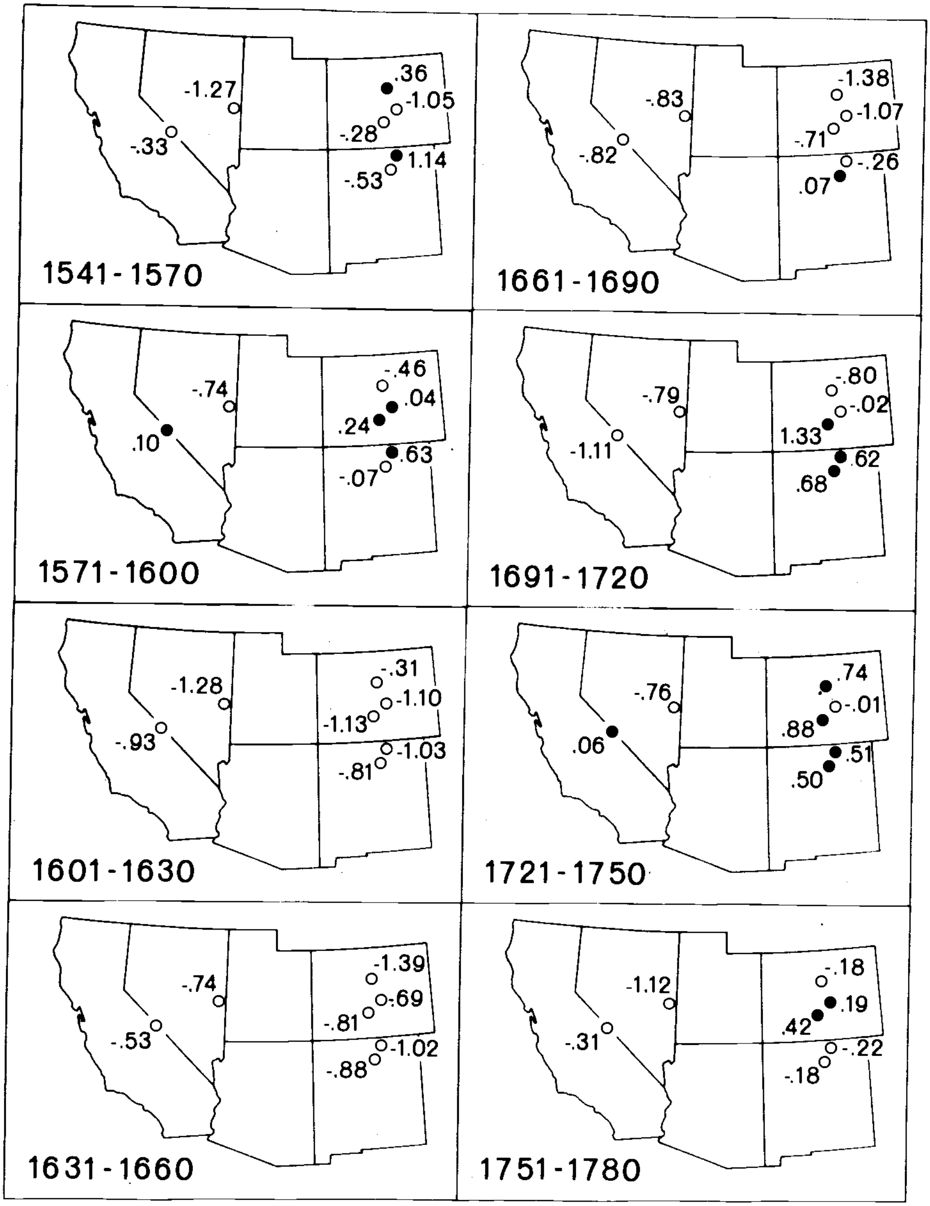


Figure 7. Needle length compared with summer (J, J, A) temperature.


.36
-1.27
-1.05
-.28
-.33
1.14
-.53
1541-1570
-.46
-.74
.04
.24
.10
.63
-.07
1571-1600
-.31
-1.28
-1.10
-1.13
-.93
-1.03
-.81
1601-1630
-1.39
-.74
-.69
-.81
-.53
-1.02
-.88
1631-1660
-1.38
-.83
-1.07
-.71
-.82
-.26
.07
1661-1690
-.80
-.79
-.02
1.33
-1.11
.62
.68
1691-1720
.74
-.76
-.01
.88
.06
.51
.50
1721-1750
-.18
-1.12
.19
.42
-.31
-.22
-.18
1751-1780

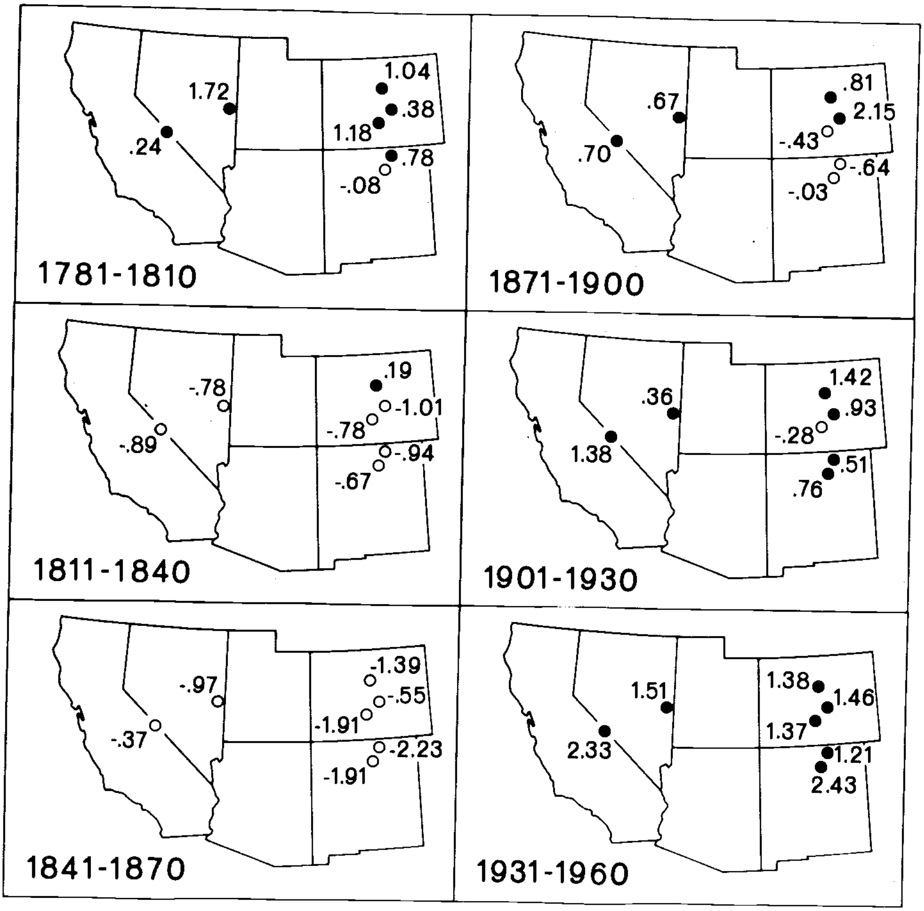


Figure 8. Patterns of tree-growth departures in bristlecone pine at upper treeline. Values are normalized departures of consecutive 30-year mean indices from the long-term (1541-1965) mean at each site.

agreement in the signs of tree-growth departures at sites in the same region (1541-1570, 1721-1750, 1751-1780). However, in most of the 30-year subperiods, the sign and magnitude of the growth departure are similar at nearly all the sites. Thus, it appears that long-term fluctuations in tree growth at upper treeline in southwestern United States do reflect regional trends in climate. Anomalous departures at some of the sites may represent non-climatic effects or real climatic anomaly patterns on a smaller spatial scale.

The broad pattern of tree-ring width departures in western United States also agrees with observed patterns of seasonal temperature departures based on meteorological records during the first 60 years of the twentieth century. In Figure 9, generalized contours show departures of the 1901-1930 mean from the 1931-1960 mean at selected stations in southwestern United States in spring (A), summer (B) and autumn (C). They indicate a trend toward warmer conditions between 1901-1930 and 1931-1960 in the warm season (April-October) over most of this region. Normalized ring-width index departures between the same periods are also shown. The increase in average ring width between 1901-1930 and 1931-1960 at most sites is consistent with the conclusion from biological evidence, that increased warm-season temperatures should result in wider

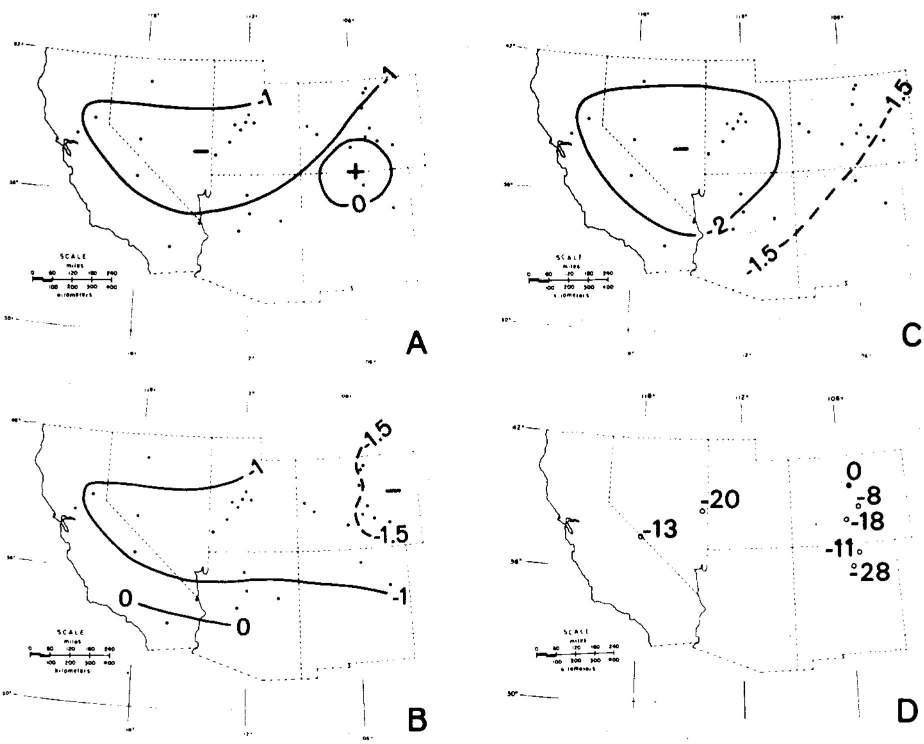


Figure 9. Trends in temperature and in tree growth at upper treeline in southwestern United States since 1901.

Contours show departures of 1901-1930 mean temperatures (F°) from 1931-1960 normals at selected stations for: A. spring (M, A, M) B. summer (J, J, A) and C. autumn (S, O). Mean ring-width indices for 1901-1930 are shown as percentage departures from the 1931-1960 mean at each locality (the White Mountains, California, chronologies were averaged for this analysis).

annual rings at upper treeline. However, the tree-ring records are not in agreement with other evidence for secular climatic changes in western U.S. between 1850 and 1900. Comparison of the tree-ring records for upper treeline sites with meteorological records does show some inconsistencies. Wahl and Lawson (1970) concluded, from a study of early meteorological records, that seasonal temperatures during the period 1850-1869 were higher than those of the 1931-1960 normal period in interior western United States. Bradley and Barry (1973) found much the same results in a study of data for southwestern Colorado. In contrast, nearly all the tree-ring series show higher average growth rates for 1931-1960 than 1850-1869 (Figures 3, 4, 5, 7). The explanation for this discrepancy may lie in the lag in tree-growth response to climatic change postulated from observations of needle length variations. At all the sites, tree growth was much below normal in the 1830's and 1840's, but especially so in southern Colorado and northern New Mexico. Bradley and Barry (1973) note that temperatures rose rapidly in the 1850's in Colorado, but if photosynthetic mass had been reduced by adverse conditions in the immediately preceding decades, then the potential for rapid growth in bristlecone pine at upper treeline sites in this region would remain correspondingly low, until photosynthetic mass had sufficient time to accumulate. In contrast, the unusually warm temperatures and high tree-growth rates of the 1960's (Wahl and Lawson 1970: 264; Namias 1970) followed a long period of relatively high temperatures. With a correspondingly large foliage volume, the trees could fully respond to a favorable temperature regime.

CLIMATIC DATA COLLECTION AND ANALYSIS FOR SOUTHWESTERN UNITED STATES

The primary purpose for collection of the climatic data was calibration with tree-ring data that had already been collected. Therefore, our initial selection of stations was based on proximity to the tree-ring data sites and length of record. Our objective was a grid of reasonably homogenious climatic records representative of climate in southwestern United States over the past 70 years. We initially limited our selection to those stations not situated in large urban centers and to those whose records were approximately 70 years (1900-1969) in length. As a result, our initial selection included about 50 stations.

The monthly data for the precipitation and temperature records from these stations were collected and tabulated from the *Annual Summaries of Climatological Data* published by ESSA. For those months in which there were occasionally missing values, estimates were used. For missing precipitation data, we used the estimation technique as outlined by McDonald (1957), and at least two nearby estimation stations records were used. For missing monthly temperature values, we used a simple linear regression technique. For the estimator station, we used a nearby station of comparable elevation and only then if the correlation coefficient for approximately 30 years of simultaneous record was equal to or greater than 0.70.

After tabulation of the data, the data were keypunched onto computer cards and verified. The data for each station were then seasonalized according to the following monthly distribution: winter – November, December, January, and February; spring – March, April, and May; summer – June, July, and August; autumn – September and October. These so-called "natural" seasons were selected based on known or suspected seasonal distributions affecting high elevation tree growth and inter-monthly correlation within the climatic data themselves.

Following seasonalization, each seasonal record for each station was analyzed for homogeneity. This included the following approach. Each seasonal record was first plotted by the computer, and the plot was scrutinized for anomalous trends and values. Any records with unique trends were eliminated at this point or at least placed in a suspect category. Each seasonal precipitation record was checked for homogeneity by use of the double-mass analysis approach as outlined by Kohler (1949). The technique has been programmed for the CDC 6400, so that the evaluation of each seasonal record involved visually analyzing the double-mass diagrams plotted by the computer for linearity. By necessity, this analysis involves a certain amount of subjectivity, as the tendency is for the double-mass diagrams to oscillate about a straight line. For our purposes, we considered the double-mass diagram to indicate inhomogeneity only if a definite and continuous change in slope could be detected.

The seasonal temperature records were also analyzed for inhomogeneities. the technique we used is partly fashioned after that of Mitchell (1961). The series of annual values from a particular station for one season was transformed to a first-difference series. An unusually large first difference between years bracketing a stations move or observer change is indicative of a non-climatic effect on the record. The cumulative first differences were also calculated and plotted to emphasize the effect of a permanent shift of mean values in the temperature record that might be related to non-climatic influences.

Our final selection of stations chosen for the climatic calibration network is listed in Table 6 and shown on the map of Figure 10. In many cases we were not entirely

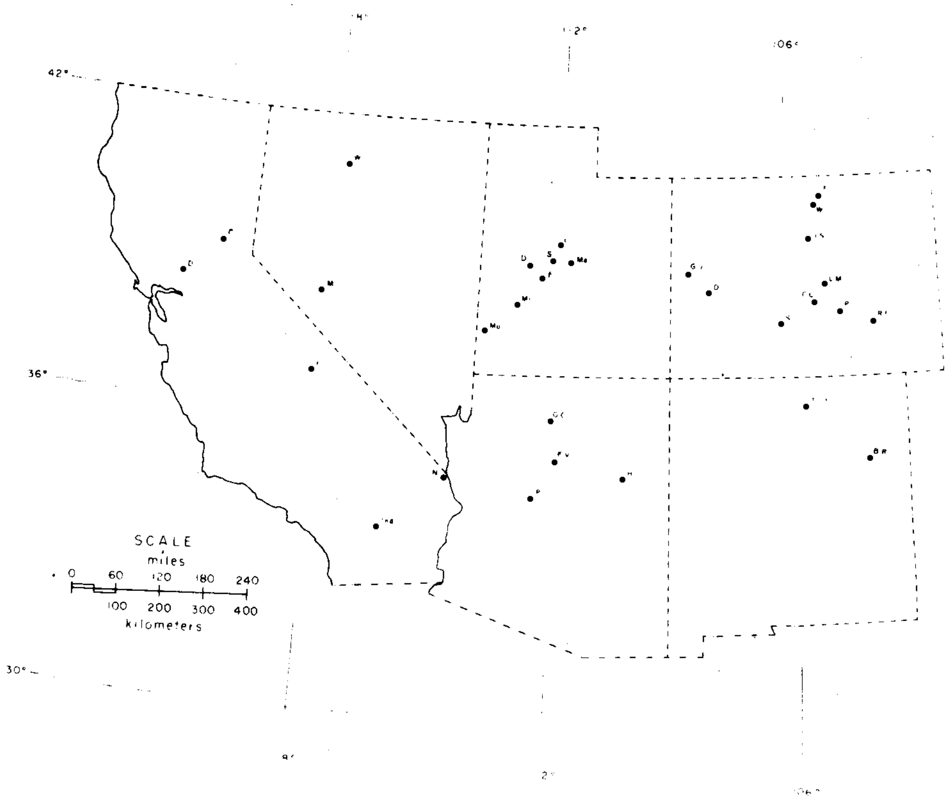


Figure 10. Location of meteorological stations.

Table 6. Meteorological data network.

Station	Map Symbol[1]	Degrees North Latitude	Degrees West Longitude	Elevation In Feet A.M.S.L.	Period of Record	Moves[2]
Colfax, Calif.	C	39.06	120.57	2418	1898-1969	None
Davis, Calif.	D	38.32	121.46	60	1899-1969	5
Independence, Calif.	I	36.48	118.12	3950	1899-1969	11
Needles, Calif.	N	34.46	114.37	913	1898-1969	5
Indio, Calif.	Ind.	33.44	116.15	11	1898-1969	3
Winnemucca, Nev.	W	40.54	117.48	4301	1901-1969	8
Mina, Nev.[3]	Mi	38.23	118.06	4552	1907-1969	2
Modena, Utah	Mo	37.48	113.55	5460	1902-1969	3
Milford, Utah	Mi	38.26	113.01	5018	1909-1969	11
Fillmore, Utah[3]	F	38.57	112.19	5160	1898-1969	3
Deseret, Utah	D	39.17	112.39	4585	1900-1969	5
Scipio, Utah	S	39.15	112.06	5306	1899-1969	3
Levan,Utah	L	39.33	111.52	5300	1900-1969	6
Manti, Utah	Ma	39.15	111.38	5740	1900-1969	7
Grand Canyon, Ariz.	GC	36.03	112.08	6950	1904-1969	1
Fort Valley, Ariz.	FV	35.16	111.44	7347	1910-1969	3
Prescott, Ariz.	P	34.34	112.28	5510	1899-1969	6
Holbrook, Ariz.	H	34.54	110.10	5069	1894-1969	5
Taos, N.M.[3]	T	36.22	105.37	6945	1903-1969	4
Bell Ranch, N.M.	BR	35.32	104.06	4500	1906-1969	None
Grand Canyon, Colo.	GJ	39.07	108.32	4855	1987-1969	7
Delta, Colo.	D	38.46	108.07	5055	1897-1969	5
Saguache, Colo.	S	38.05	106.09	7697	1897-1969	3
Canon City, Colo.[3]	CC	38.26	105.16	5343	1897-1969	9
Pueblo, Colo.	P	38.17	104.31	4639	1898-1969	1
Rocky Ford, Colo.	RF	38.02	103.42	4178	1897-1969	None
Lake Moraine, Colo.	LM	38.49	105.01	10265	1897-1969	None
Idaho Springs, Colo.	IS	39.45	105.31	7555	1896.1969	4
Waterdale, Colo.	W	40.25	105.12	5260	1903-1969	None
Fort Collins, Colo.	FC	40.35	105.051	5001	1896-1969	2

[1] See Figure 10

[2] This column contains the number of documented moves the station has undergone during the period of record.

[3] Meteorological data used in modelling response function at nearby tree-ring site

satisfied that we were selecting ideally homogeneous records, but based on proximity to our tree-ring data sites and length of record, we considered this nerwork as being the best available.

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REFERENCES

Artmann, A.
1949 Jahrringschronologische und Klimatologische Untersuchungen an der Zirbe und Anderen Baumen das Hochsgebirges. MS. Doctoral dissertation, University of Munich.
Bailey, D. K.
1970 Phytogeography and taxonomy of pinus subsection balfourianae. *Annals of the Missouri Botanical Gardens* 57:210-49.
Bradley, R. S. and R. G. Barry
1973 Secular climatic fluctuations in southwestern Colorado. *Monthly Weather Review* 101:264-70.
Brehme, K.
1951 Jahrringchronologische und-klimatologische Untersuchungen an Hochgebirgslärchen des Berchtesgadener Landes. *Zeitschr. Weltforstwirtschraft* 14:65-80.
Daubenmire, R.
1954 Alpine timberlines in the Americas and their interpretation. *Butler University Botanical Studies* 11:119-36.
Drew, L. G., editor
1972 Tree-ring chronologies of western America. III. California and Nevada. *Laboratory of Tree-Ring Research, Chronology Series* 1.
Eklund, B.
1957 Om granens arsringsvariationer inom mellersta Norrland och deras samband med klimatet. *Meddelanden Fran Statens Skogsforsknings-institut* 47.
Environmental Science Services Administration, U.S. Weather Bureau.
1896- Climatological Data, Annual Summary (published annually for State of geographical
1970 sections). Asheville, North Carolina.
Ferguson, C. W.
1968 Bristlecone pine: Science and esthetics. *Science* 159:839-46.
Fritts, H. C.
1962 An approach to dendroclimatology: Screening by means of multiple regression techniques. *Journal of Geophysical Research* 67:1413-20.
1966 Growth rings of trees: Their correlation with climate. *Science* 154:973-79.
1969 Bristlecone pine in the White Mountains of California: Growth and ring-width characteristics. *Papers of the Laboratory of Tree-Ring Research* 4, The University of Arizona Press, Tucson.
Fritts, H. C., D. G. Smith, J. W. Cardis, and C. A. Budelsky
1965 Tree-ring characteristics along a vegetation gradient in northern Arizona. *Ecology* 46:393-401.
Fritts, H. C., J. E. Mosimann, and C. P. Bottorff
1969 A revised computer program for standardizing tree-ring series. *Tree-Ring Bulletin* 29:15-20.
Fritts, H. C., T. J. Blasing, B. P. Hayden, and J. E. Kutzbach
1971 Multivariate techniques for specifying tree-growth and climate relationships and for reconstructing anomalies in paleoclimate. *Journal of Applied Meteorology* 10:845-64.
Giddings, J. L., Jr.
1943 Some climatic aspects of tree growth in Alaska. *Tree-Ring Bulletin* 9:26-32.
Hustich, I.
1945 The radial growth of the pine at the forest limit and its dependence on the climate. *Societas Scientiarum Fennica, Commentationes Biologicae* IX.
1948 The scotch pine in northernmost Finland and its dependence on the climate in the last decades. *Acta Botanica Fennica* 42:1-75.