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Paleoclimatic Inferences from Long Tree-Ring Records

Intersite comparison shows climatic anomalies that may be linked to features of the general circulation.

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There is an increasing need for information about past climatic variations. This need stems, in part, from a growing concern that man's activities may influence climate and from the belief that a better understanding of the behavior of the atmosphere may permit us to anticipate, and possibly avert, adverse climatic changes, whether from natural or artificial causes. The study of climatic variations cannot depend entirely on recorded observations of meteorological elements. These records extend back only a relatively short period and may not adequately represent the range of natural climatic states that have existed in the geologically recent past and that could recur fairly soon. For this reason, a variety of natural and cultural phenomena linked in some fashion to climate have been investigated in attempts to better characterize past climatic states.

The annual rings of trees are an important source of paleoclimatic data because tree-ring series several centuries long are available, or can be developed, in many regions of the world; because they can be accurately dated; and because the properties of tree rings can vary in response to changes in climate (*1*). In recent years, dendroclimatologists have had great success in relating spatial anomalies in tree growth in southwestern Canada, western United States, and northern Mexico to associated anomalies in such climatic variables as precipitation and atmospheric pressure (*2*). This permits them to estimate or reconstruct variations in climatic parameters on a subhemispheric scale for long periods before instrumental observations began. However, this approach is ultimately limited by the scarcity of tree-ring records more than about 500 years long. Although a few tree-ring series from 1000 to 8000 years long have been developed, it is unlikely that a sufficiently dense and widespread network will ever be available for use of this approach based on tree-ring data alone. In this article, I explore some alternative approaches to the exploitation of paleoclimatic information in millenia-long records of ring-width variation, using as examples data from bristlecone pines in the southwestern United States.

Long Tree-Ring Records

Bristlecone pines (*Pinus longaeva* D. K. Bailey and *P. aristata* Engelm.) are important for paleoclimatic research because the great age of individual trees and the persistence of dead wood permit one to develop unusually long ring-width chronologies by means of cross dating (*3*). Cross dating is the matching of sequences of wide and narrow annual rings, and it depends on the common response of trees in the same general area to limiting climatic conditions during particular years. Tree-ring studies of bristlecone pine were begun in the White Mountains of eastern California in the early 1950's and were based on specimens showing the "drought-sensitive" climatic response typical of trees near the arid lower forest border. This work has resulted in the development of a chronology over 8200 years long (*4*). Although a 7104-year segment of this record has been published (*5*), it is designed for use in cross dating rather than for climatic inference. Because of inhomogeneities, processing techniques, and small size of the sample, the longer-term fluctuations in growth were thought to be untrustworthy indices of climatic variation and were therefore removed through use of a high-pass digital filter. However, an 1100-year record of unfiltered tree-ring indices from a large sample of living trees in the same area has recently become available (*6*) and is used in this article.

Work begun more recently has led to independent development of a long tree-ring record for bristlecone pine at the upper tree line in the White Mountains. In the southern White Mountains, dead trees, logs, and wood remnants are found in abundance at altitudes up to 150 meters above the present tree line (*7*). Samples of this material, combined with increment cores from nearby living trees, provided the basis for constructing a 5405-year record of mean annual ring widths for the upper tree line, beginning in 3435 B.C. Calendar dates assigned to annual rings on the basis of this record show excellent agreement with the dates published by Ferguson. After minor correction to account for two locally absent rings, the dates are believed to be certain (*8*). Because of the differences in trees' growth response to climatic variations in the lower forest border and the upper tree line, comparison of their ring-width records yields paleoclimatic insight unobtainable from either record alone.

Cross dating of the two records is possible because relatively narrow rings are often produced in the same year by trees in both environments. Such correlative rings are narrow only in relation to the rings immediately ad-

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jacent; their widths are not necessarily small in absolute value. The correlation between the two records is highly dependent on the frequencies considered. Cross-spectral analysis (*9*) shows that the square of the coherency (a frequency-dependent measure of association between two time series) is high for variations at frequencies of from 0.5 per year to 0.1 per year but drops rapidly to values near zero at lower frequencies. That is, the high frequency variations in the two series are positively correlated, but the low frequency variations show no consistent relationship. As a result, the cross correlation is enhanced when the lower frequencies are removed by "prewhitening" with a high-pass digital filter (a procedure analogous to cross dating). For example, cross-correlation analysis of 53 consecutive 100-year segments of the two series after such filtering yields highly significant cross-correlation coefficients, averaging about 0.6, whereas the correlation is only about 0.4 when all frequencies are considered. The reasons for this frequency-dependent relationship seem to lie in differences in the ways in which climate influences tree growth in the two environments.

Ring Width and Climate

It has long been known that the properties of ring-width series are intimately related to the environment in which a tree grows and that maximum response to departures from climatic means is found in trees near climatically determined limits of distribution. In a study in northern Arizona, Fritts and his co-workers (*10*) studied ring-width characteristics in trees of woodland and montane forest species located at sites ranging from the xeric forest border to the mesic forest interior. Among the changes they found in moving away from the forest border were decreased correlation of ring-width series within and between trees and decreased standard deviation and mean sensitivity (a measure of year-to-year differences in ring width) of the series. These trends reflect a decrease in the frequency of drought conditions, which are limiting to growth processes in the trees and parallel the gradients of increasing average precipitation and decreasing average temperature. When a similar analysis is made of trends in tree-ring statistics for bristlecone pine, a different pattern emerges. This subalpine conifer has both lower and upper distributional limits that appear closely related to climate. Ring-width statistics for bristlecone pines along an altitudinal gradient in the mountains of eastern Nevada are shown in Fig. 1. The high values in the lower range of altitudes are those expected near the lower forest border, but the values are also large near the upper tree line. In this case, enhanced climatic sensitivity is found at both climatically determined limits. However, there are important differences in the ways in which climate influences tree-ring growth at these extremes of altitude.

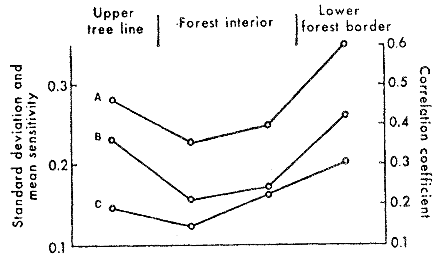

Fig. 1. Tree-ring statistics for bristlecone pines at four sites along an altitudinal gradient. The average correlation between ring-width series from individual radii of different trees at each site (*A*) and the standard deviation (*B*) and mean sensitivity (*C*) of the mean site chronology all indicate increased environmental stress at the lower and upper distributional limits.

The width of the annual ring formed in low-altitude bristlecone pines is largely dependent on moisture (*1*). As shown in Fig. 2, high precipitation, particularly in the previous summer and autumn and in the current spring, favors growth of a wide ring during the short summer growing season. High temperatures in the same period lead to depletion of the moisture in the soil and drought stress within the trees, adversely affecting net assimilation of carbon dioxide and leaving less food available for subsequent ring growth. The most important single variable appears to be a deficit of soil moisture in the spring (*11*); evapotranspiration is negatively correlated with ring width.

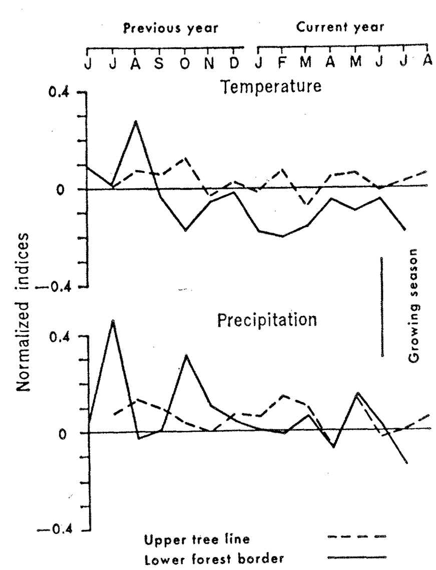

Fig. 2. Effect of climate on tree-ring width in White Mountain bristlecone pines. Response function (*2*) relates normalized ring-width indices to temperature and precipitation during a 14-month period prior to and including the growing season. The generally positive effect of high temperatures on ring width at the upper tree line contrasts with a predominantly negative effect at the lower forest border. Precipitation is normally favorable to growth at both sites.

In the White Mountains, the upper tree line lies some 800 m above the lower limits of subalpine forest. Mean annual precipitation probably increases from 250 to over 400 millimeters within this range of altitudes, and estimated maximum daily temperatures in July decrease from about 21°C to about 14°C between the lower and upper forest limits (*12*). Growth response to climate also changes along this environmental gradient.

At the upper tree line, depletion of moisture in the soil limits growth processes less frequently than it does at lower elevations, while low, rather than high, temperatures in most months affect growth adversely. The results of gas-exchange experiments form part of the biological basis for the empirical relationships shown in Fig. 2. These experiments show that at high altitudes there are several ways in which low temperatures can limit net uptake and assimilation of carbon dioxide. First, the decrease in daytime temperatures associated with increasing altitude results in decreased daily net photosynthesis, because rates of photosynthesis under these conditions vary directly with temperature (given adequate soil moisture) (*13*). Thus, less photosynthate will be produced in a cool summer than in a warm one. Second, photosynthesis is limited to the warmer months of the year, because very low temperatures induce photosynthetic dormancy in bristlecone pines (*14*). Thus, a long warm season is also favorable to high seasonal net photosynthesis. Bristlecone pines lose large amounts of photosynthate during the winter; therefore, a long winter could result

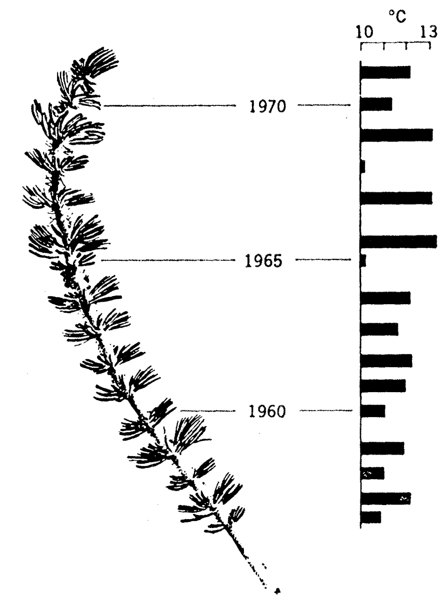

Fig. 3. Variations in needle length of bristlecone pine at the upper tree line related to temperatures in the summer, in which needle elongation takes place. Large fluctuations in the total photosynthetic area of a tree could be produced by sequences of unusually cool or unusually warm summers. Temperature data are July-August mean maximum temperatures, 1958 to 1971.

in greater loss of stored food (*14*), leaving less available for growth the following summer. These processes provide a basis for relating the temperature regime in a particular year to ring-width growth in that year or the following year.

There is another phenomenon that seems to relate summer temperatures to longer-term trends and fluctuations in tree growth at the upper tree line. Bristlecone pines retain their needles for at least 10 years, and 30 years or more is not uncommon. Although the older foliage loses some photosynthetic efficiency (*15*), it is an important part of the total photosynthetic area of the tree. At the upper tree line, there is striking year-to-year variation in needle length. This variation is closely related to temperatures in the summer, when needle elongation takes place (Fig. 3). Short needles are formed during cool summers. A succession of unusually cool or unusually warm summers could thus cause large changes in total photosynthetic area in trees near the upper tree line and therefore significantly affect the trees' capacity for net photosynthesis. This phenomenon could be expected to influence ring width in two general ways. First, growth response to a decrease in summer temperature would lag by several years because of the long needle retention. Second, the influence on growth of an unusually cool summer would be reduced, but it would be spread over several years. This smoothing effect seems to explain the unusually high first-order autocorrelation coefficients found in the upper tree line ring-width series (0.6 to 0.8), as compared with those for the lower forest border (0.2 to 0.3). As a consequence of both of these effects, the weights assigned to summer temperature variables in the kind of multivariate model illustrated in Fig. 2 may seriously underestimate the importance of summer temperature to tree-ring growth at the upper tree line because climatic variables are made to lag only up to 1 year. Indeed, ring-width variations over periods of several hundred years or more seem much more closely dependent on warm-season temperatures than would be indicated by comparison with local climatic data for only the past few decades. This is illustrated in Fig. 4, where 20-year means of the annual ring widths at the upper tree line for the period A.D. 800 to A.D. 1959 are shown, together with mean annual temperatures for the same period independently estimated for other parts of the Northern Hemisphere. The close agreement with the data for England indicates that long-term climatic anomalies in these sectors tend to be in phase. The pronounced increase in growth rates since the mid-1800's seems to parallel the global temperature increase seen in meteorological records.

Late Holocene Paleotemperatures

The 5405-year record of mean annual ring widths in bristlecone pine at the upper tree line can be regarded as an approximate record of warm-season temperatures in the White Mountains. Biological evidence, multivariate analysis based on meteorological records, and comparison with other evidence for long-term temperature variations in the Northern Hemisphere all indicate that tree growth trends in this environment are positively related to temperature.

Ring-width measurements are normally reduced to dimensionless indices before being averaged to obtain a series of mean indices characterizing ring-width variation through time at a particular site (*16*). This transformation is designed to remove biological age trend from ring-width series and to minimize the effects of differences in average growth rates between trees. It is appro-

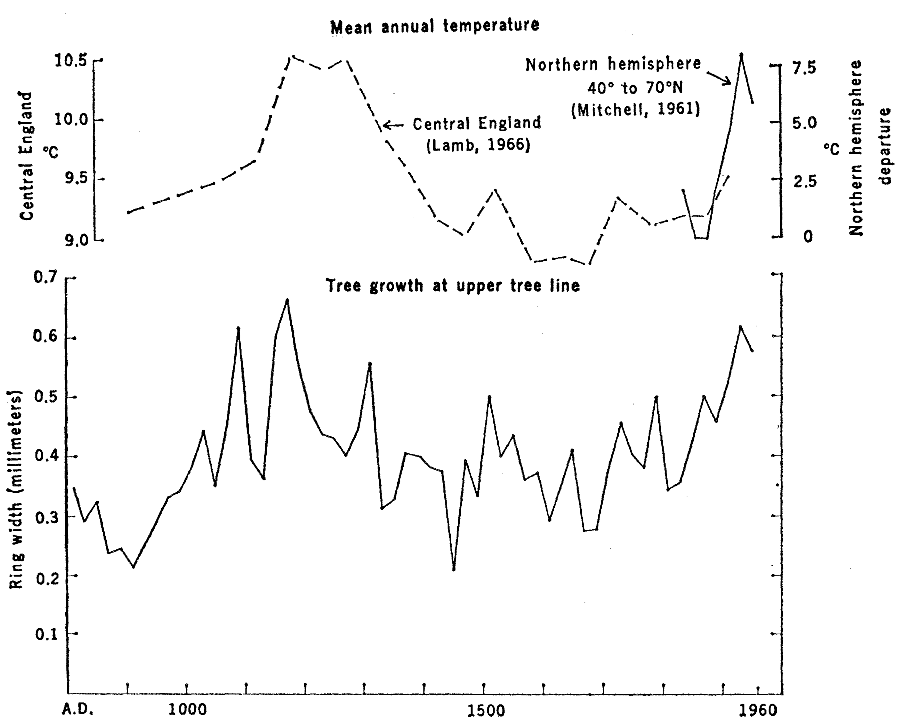

Fig. 4. Average ring widths (20-year means) in bristlecone pines at the upper tree line in White Mountains, California, compared with regional and global estimates of mean annual temperature (from *26*), A.D. 800 to A.D. 1960. Northern Hemisphere data are departures from the 1880 to 1884 means. The low frequency fluctuations in tree growth reflect temperature variations.

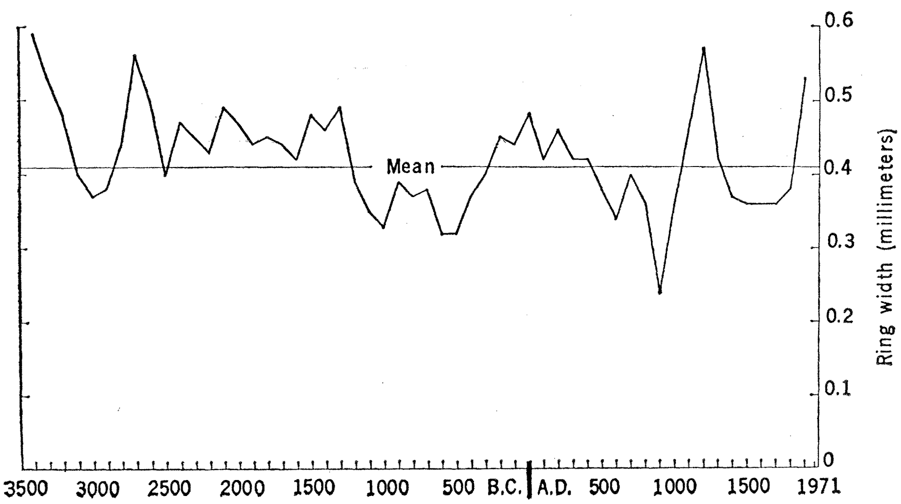

Fig. 5. Average ring widths (100-year means) at the upper tree line, 3551 B.C. to A.D. 1950. Positive departures from mean growth indicate warm season (April-October) temperatures above the long-term mean. Negative departures suggest cool conditions. Total temperature range from other local evidence (*7*) is about 2°C.

priate for use in reducing the error in ring-width data from groups of living trees, where all the series cover about the same time period. This transformation must be used with caution, however, when a long tree-ring record is constructed by overlapping a large number of relatively short series. The reason is that, if each component series is first transformed to an index series with a mean of 1.0, then as component length decreases the averaged annual values will approach unity. Thus, any evidence of trends over periods greater than the length of the component series would be subdued or eliminated. At the risk of greater error in the estimates of annual mean ring widths, the upper tree line data are not transformed to indices, but are expressed as simple mean ring widths in order to retain information about long-term fluctuations. Care was taken to exclude ring-width measurements from near the centers of some trees, where rapid growth reflects the vigor of youth rather than the influence of climate.

Figure 5 shows mean ring widths from 3551 B.C. to A.D. 1950 averaged for successive 100-year intervals and centered on the first year of each century. Relative warmth is indicated by high, sustained growth rates for most of the period between 3500 and 1300 B.C., corresponding to a time when the local tree lines were very high—about 150 m above those of the past few centuries (*7*). Since the tree line is itself an indicator of warm-season temperatures, there is good agreement between these two kinds of evidence. Cool summers are indicated for the interval from 1300 B.C. to 200 B.C. Tree lines became lower in the White Mountains, and mountain glaciers advanced throughout the North American cordillera at about this time (*17*). In the nearby Sierra Nevada, pollen evidence (*18*) also indicates the onset of cooler and wetter conditions. Warmer summers prevailed between 200 B.C. and about A.D. 300, but renewed cooling after this time is reflected in the tree-ring record and by glacial readvances in the Sierra Nevada (*19*) and Rocky Mountains (*20*). A brief but pronounced warm period occurred around A.D. 1200, followed by an extended cool period during which the local tree line again lowered precipitously (*7*). Growth rates of trees have been very high during the past century and indicate a warming trend. Comparison of the tree-ring record at the upper tree line for the past several thousand years with other evidence of regional climatic trends thus indicates that even a single, long record from climatically sensitive trees can be used to gain insight into some aspects of past climatic variation.

Intersite Comparison

Although an individual ring-width record may serve as a paleoclimatic indicator, the differences in trees' growth response to climate on different sites can be exploited to better characterize past climatic anomalies. Because insufficient soil moisture may limit growth at both the upper tree line and the lower forest border in the White Mountains, high precipitation favors high average growth rates in both environments. However, because temperature influences growth in the two environments in opposite ways, anomalously high or low temperatures will result in different departures from normal growth. The formation of a wide ring at both the upper tree line and the lower forest border indicates warm, moist conditions during at least the warmer part of the year. A wide ring at the upper tree line and a narrow ring at the lower forest border suggests that warm, dry conditions prevailed, whereas a narrow ring at the upper tree line and a wide ring at lower altitudes should reflect cool, moist conditions. Formation of a narrow ring in both environments is indicative of a cool, dry climatic regime. Thus, if the ring-width records from these two different environments show consistent departures, either the same as or the opposite of each other, one can infer the associated precipitation and temperature anomalies.

Figure 6 shows the tree-ring records for both the lower forest border and the upper tree line in the White Mountains from A.D. 800 to A.D. 1959. There are several periods, a century or more in length, during which departures from normal growth tended to persist at each site. These have been interpreted as indicating anomalies in temperature and precipitation. The significance of this kind of paleoclimatic reconstruction lies in the possibility of linking the inferred temperature-precipitation anomalies to features of the general circulation.

The climate of the White Mountains is influenced by two major circulation regimes (*21*). In the fall, winter, and spring months, precipitation is closely linked to cyclonic storms from the Pacific Ocean. In summer, such migratory depressions are normally blocked by northward expansion of the subtropical Pacific high, while moist tropical air invades the region around the south and west sides of the expanded North Atlantic (Bermuda) high, causing afternoon and evening thunderstorms. However, these general patterns are subject to considerable variations. Differences in the upper-level circulation cause many more storms to cross the area in some winters than in others, and winter-like weather can occur in summer.

Climatic data from the White Mountains were used to study the relationships between temperature and precipitation anomalies and circulation features. Contingency analysis shows that the most common anomalies in recent decades have been in the cool, wet and warm, dry situations, which have occurred most frequently in the spring and autumn months. Cool, dry and warm, wet anomalies have also occurred, particularly in summer. Such anomalies can often be associated with particular circulation patterns, as inferred from the mean 700-millibar height charts for months in which data show large combined departures from the norm in temperature and precipitation. The lines of constant elevation of the 700-millibar surface shown on these charts indicate pressure gradients at upper levels, and thus the direction of flow of air. Unusually cool and wet spring, summer, and autumn months are characterized by an upper-level trough centered over the Pacific Coast (Fig. 7A). Migratory depressions from the North Pacific enter the continent well south of the normal track, bringing heavy precipitation to the White Mountains. Cool, dry conditions are associated with a northeastward-trending trough, which brings cold, dry, descending air into the region on the east side of an expanded upper-level high (Fig. 7B). An upper-level ridge in the same position (Fig. 7C) causes the depression track to shift northward, and warm, dry conditions prevail. The less frequent warm, wet anomalies sometimes occur in summer and seem to be related to westward and northward expansion (Fig. 7D) of the Bermuda high beyond its normal position (Fig. 7F). In some months with an expanded high, however, closed upper-level circulation in the western part of the high pressure area can preclude the flow of moist air into the region and cause warm, dry conditions.

Each of the types of temperature-precipitation anomalies inferred from intersite comparison of tree-growth records for the past 1100 years has occurred in one or more months during the past two decades. The explanation for persistent climatic anomalies in the past could lie in changes in the average frequency of the circulation patterns associated with these types of anomalies. These regional patterns are, in turn, linked to the general characteristics of the global circulation. It is well established that the period from about 1850 to 1940 was characterized by increased vigor of the circulation, as compared with the centuries immediately preceding. In the associated zonal circulation pattern, there are normally few semipermanent waves in the upper westerlies. A broad mean ridge at upper levels over western North America seems to

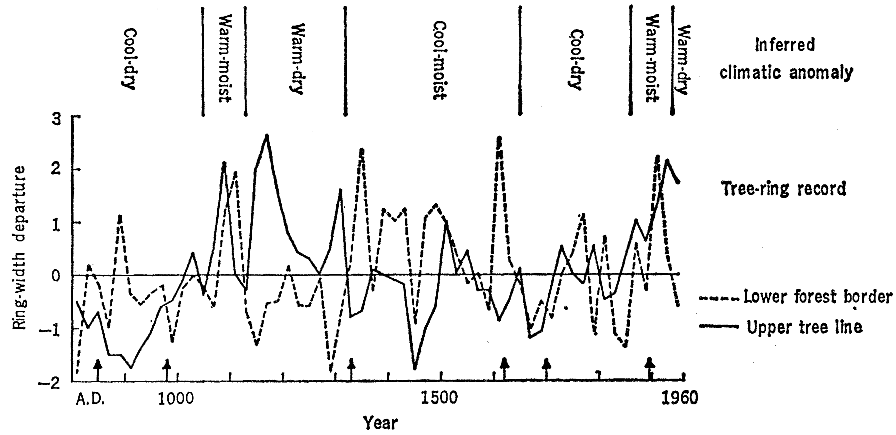

Fig. 6. Departures from mean growth (normalized 20-year means) trees on ecologically contrasting sites in the White Mountains and inferred climatic anomalies. Arrows show dates of glacial moraines in the nearby Sierra Nevada (*19*); all except the youngest were formed during periods judged to be relatively cool from the tree-ring evidence. Glacial advances of the early 1300's and early 1600's also coincide with unusually wet periods.

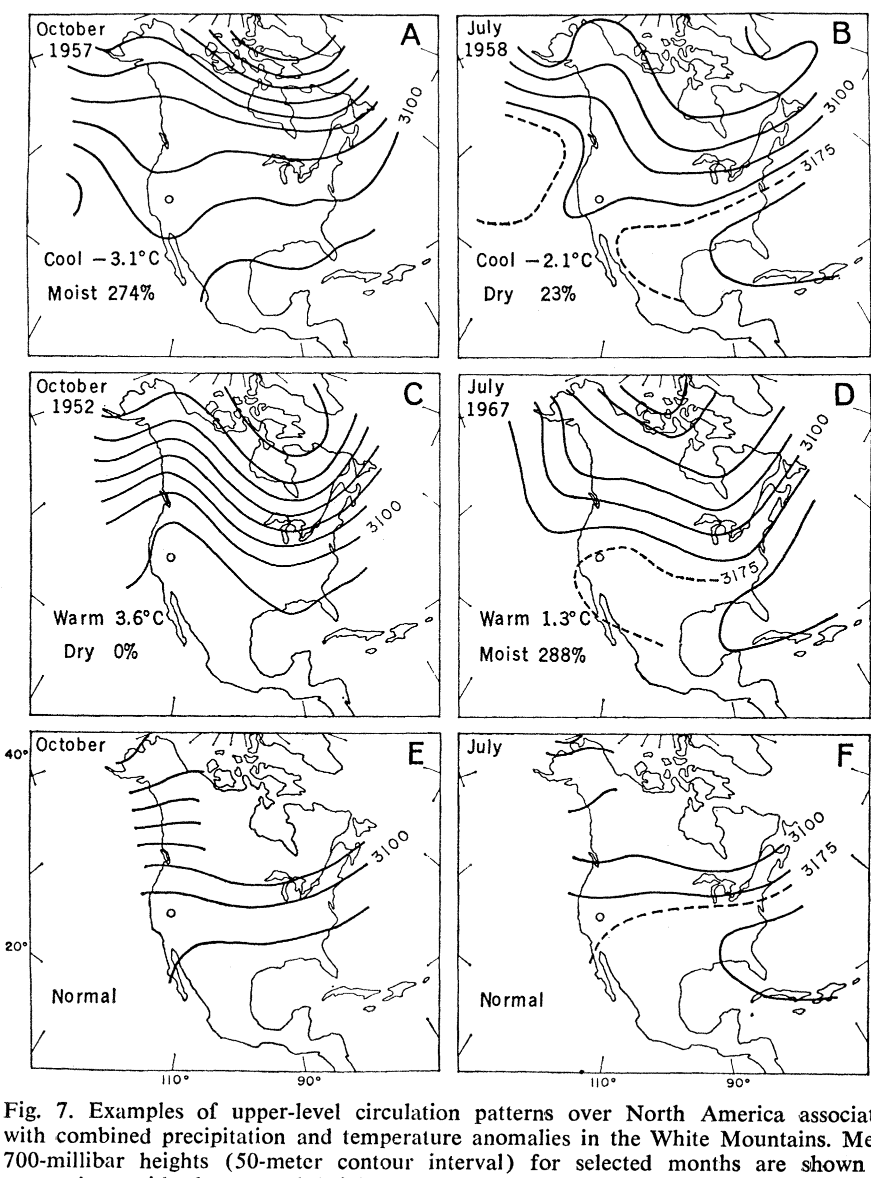

Fig. 7. Examples of upper-level circulation patterns over North America associated with combined precipitation and temperature anomalies in the White Mountains. Mean 700-millibar heights (50-meter contour interval) for selected months are shown in comparison with the normal heights for 1946 to 1955. Monthly temperature is expressed as departure from the 1952–1971 mean; precipitation as a percentage of the mean for same period. Circle shows location of White Mountains. Higher frequencies of these or similar patterns in the past may explain anomalies inferred from intersite comparison of tree-ring records (see Fig. 6).

be characteristic. The period from about A.D. 1000 to A.D. 1200 was apparently the warmest period in temperate latitudes of the Northern Hemisphere in the millennium prior to A.D. 1850. Lamb (*22*) has inferred, primarily from evidence in the Atlantic sector, that the vigor of the general circulation and the upper-level patterns at that time were quite similar to those of the first half of the 20th century. In the White Mountains, the tree-ring data for this period also indicate warm, moist and warm, dry climates similar to those of the recent past, suggesting that the average position of the upper-level trough was well offshore over the Pacific Ocean (Fig. 7E), which fits Lamb's reconstruction (*22*). Low-index conditions are thought to have prevailed through much of the "Little Ice Age" (approximately A.D. 1430 to A.D. 1850). The associated meridional pattern consists of a relatively large number of deep troughs and ridges at upper levels. The prevalence of cool, moist or cool, dry climates in the White Mountains throughout this period is consistent with a meridional flow pattern, with a deep upper-level trough developing frequently along the Pacific Coast in summer (Fig. 7, A and B), as predicted by Lamb (*22*).

Many workers have used the records of climatically sensitive phenomena, as well as long meteorological records, to infer past circulation features. Although data from only one locality may not completely define the larger pattern associated with a particular local surface anomaly, such data—as I have illustrated—can be used to develop tentative models of the circulation in the past. Considering other evidence on a regional hemispheric, or even global scale, we can expand and improve such models by repeated testing and modification.

Other Approaches

Virtually all research in which tree rings are used to estimate past climate has been based on a single variable—the width of the annual ring. In particular, interest has focused on the departure of the mean value from the norm, which is obtained by averaging ring widths or ring-width indices. Little use has been made of statistics other than the mean. Other statistical properties of ring-width series, such as standard deviation and cross-correlation coefficient, show regular trends along altitudinal or other environmental gradients (Fig. 1). These properties could possibly be used as paleoenvironmental indicators in much the same way as pollen frequencies, for example. Thus knowledge of the "apparent altitude" or "apparent location" of a site in the past could yield paleoclimatic estimates.

Although ring-width variability has been exploited with considerable success, and will continue to provide valuable information, a new class of paleoclimatic indicators is now evolving, based on physical and chemical properties of the annual ring. One technique uses x-ray microdensitometry to measure variations in wood density (*23*). Preliminary work indicates that wood density is highly sensitive to environmental conditions during the growing season, and very high correlations have been found with variables such as mean August temperature and total April-May precipitation. Measurement of ratios of stable isotopes in wood is another promising approach now in the exploratory stage (*24*). The deuterium-hydrogen ratio, for example, could indicate the isotopic composition of precipitation in a manner analogous to the use of oxygen isotope ratios in glacial ice.

Finally, tree-ring data can be combined with measures of other kinds of climatically sensitive variables such as pollen frequency, varve thickness, and isotope ratios in glacial ice to provide large arrays of grid points for multivariate analyses. Calibration with climatic parameters during the recent period of meteorological record may then permit more objective reconstruction of past climates (*2*, *25*).

Summary

Tree-ring data contribute to a better understanding of the nature of past climatic variations. Annual ring records several thousand years long can be constructed for a few areas, but interpretation of them requires the development of new approaches. For example, a single record of average ring width in the upper tree line environment provides a guide to past temperature fluctuations. However, comparison of this record with another, that of the arid lower forest border, from the same area permits characterization of associated precipitation and temperature anomalies that may, in turn, be linked to features of the general circulation. Other approaches that promise to be very fruitful include study of the variation of ring-width statistics through time, investigation of the physical and chemical properties of wood, and combined multivariate analysis of data for a variety of paleoclimatic indicators.

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