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MULTIVARIATE TECHNIQUES FOR SPECIFYING TREE-GROWTH AND CLIMATE RELATIONSHIPS AND FOR RECONSTRUCTING ANOMALIES IN PALEOCLIMATE

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Project: Dendroclimatic History of the United States
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1970 Final Report Prepared for:
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ABSTRACT

Ring widths from trees on certain sites reflect climatic variation. Therefore, long time series derived from replicated and precisely dated ring-width chronologies may be utilized to extend climatic records into prehistoric times. Multivariate analyses of tree-ring chronologies from western North America are used to derive response functions from which one can ascertain what climatic information each ring-width chronology contains. In addition, multivariate analyses are utilized to calibrate a large number of ring-width chronologies of diverse response functions and from widely dispersed sites with a large number of regional climatic variables. A series of transfer functions are derived which allow estimates of anomalous climatic variation from tree-ring records. Reconstructions of anomalous variation in atmospheric circulation for portions of the northern hemisphere back to A.D. 1700 are obtained by applying the transfer functions to tree-ring data for time periods when ring data are available but climatic data are not.

INTRODUCTION

Most climatic and hydrologic records in western North America are relatively short and inadequate for assessing long-term climatic variation. The mean and variance of such records are biased by recent anomalous variation in climate such as occurred since A.D. 1900 (Lamb, 1969; Fritts, 1969b). Because of the recent settlement and low population of western North America, few long climatic records are available. Still, less is known about climatic anomalies over the Pacific Ocean.

The rings of trees in certain sites from western North America provide a unique source of information on past variations of climate and other environmental factors which prevailed over North America and the adjoining oceans. Tree-rings can be precisely dated (Stokes and Smiley, 1968), and their widths can be used to extend the climatic record back in time (Fritts, 1969b).

However, extraction of this climatic information from tree-rings has been limited, until very recently, because techniques were inadequate to handle the large number of variables that must often be considered. In the past it has been necessary to select highly stratified samples of trees whose growth has been similarly limited by a relatively small number of environmental variables, such as low precipitation and high temperature (at the arid forest border) or by low temperature and a short growing season (at the Arctic treeline) (Fritts, 1969b). Although considerable success in reconstructing climate has been achieved by such stratified sampling of trees (Fritts, 1965), old-aged trees on less extreme sites have not been utilized and much available environmental information has probably been lost.

Recent advances in multivariate analysis and the availability of modern, high-speed computers now make feasible the objective analysis of tree-ring data representing a great diversity of responses to the environment. Subtle variations in a variety of environmental relationships can be evaluated, and differences as well as similarities in the tree-growth response can be used to reconstruct variations in paleoclimate.

RECENT DENDROCHRONOLOGICAL DEVELOPMENTS

For many years dendrochronologists have claimed that ring-widths from trees on arid or extremely cold sites are natural records of the variability in past climate. More recent investigations show that highly significant statistical relationships exist between growth of trees on arid sites and climatic data (Fritts, 1965, 1969a; Fritts, Smith and Stokes, 1965) and that the statistical correlations are supported by reasonable cause and effect relationships (Fritts, 1969a, b). The model for the physiological relationships, which are involved in growth on arid sites, are shown in Figures 1 and 2 and are discussed elsewhere by Fritts (1969c).

In addition, a new technology has been developed in computer processing (Fritts, 1963; Fritts et al, 1969) and in statistical analysis, (Fritts, 1969a, b; Julian and Fritts, 1968). This has facilitated the efficient sampling and processing of tree-ring data and aided in the objective establishment of more than 200 new replicated tree-ring chronologies from western North America representing a large geographic area and diverse species and sites.

It is possible to select a highly stratified sample of drought sensitive tree-ring chronologies distributed over a wide geographic area and map and plot departures in growth as if they were actual occurrences of drought (Fritts, 1965). However, even in such a highly selected set of data there is some unexplained variability or "noise" because not all the sampled trees have identical responses to environmental factors.

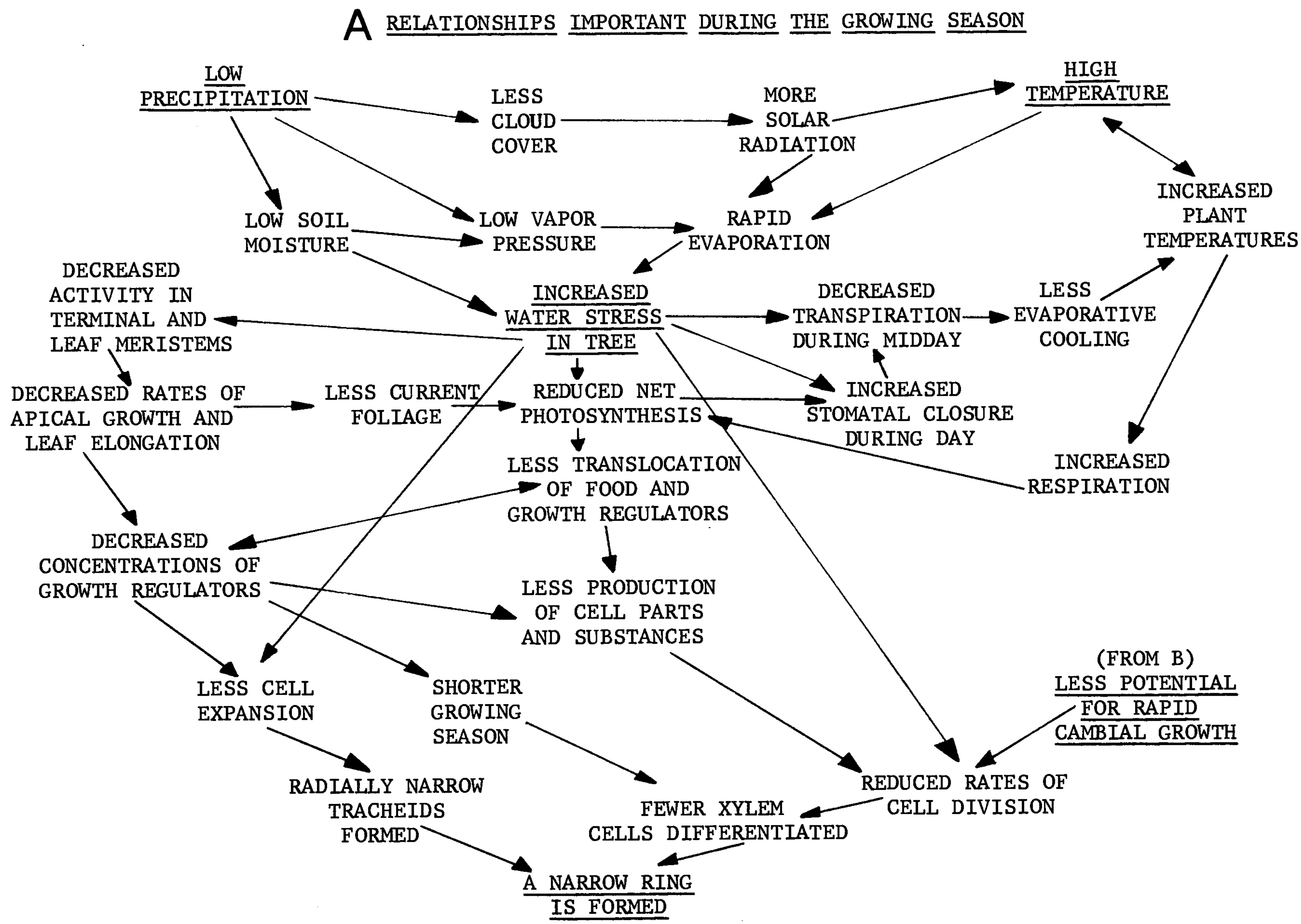

FIGURE 1. Environmental and physiological relationships important during the growing season which will lead to the formation of a narrow ring in conifers growing on semiarid sites.

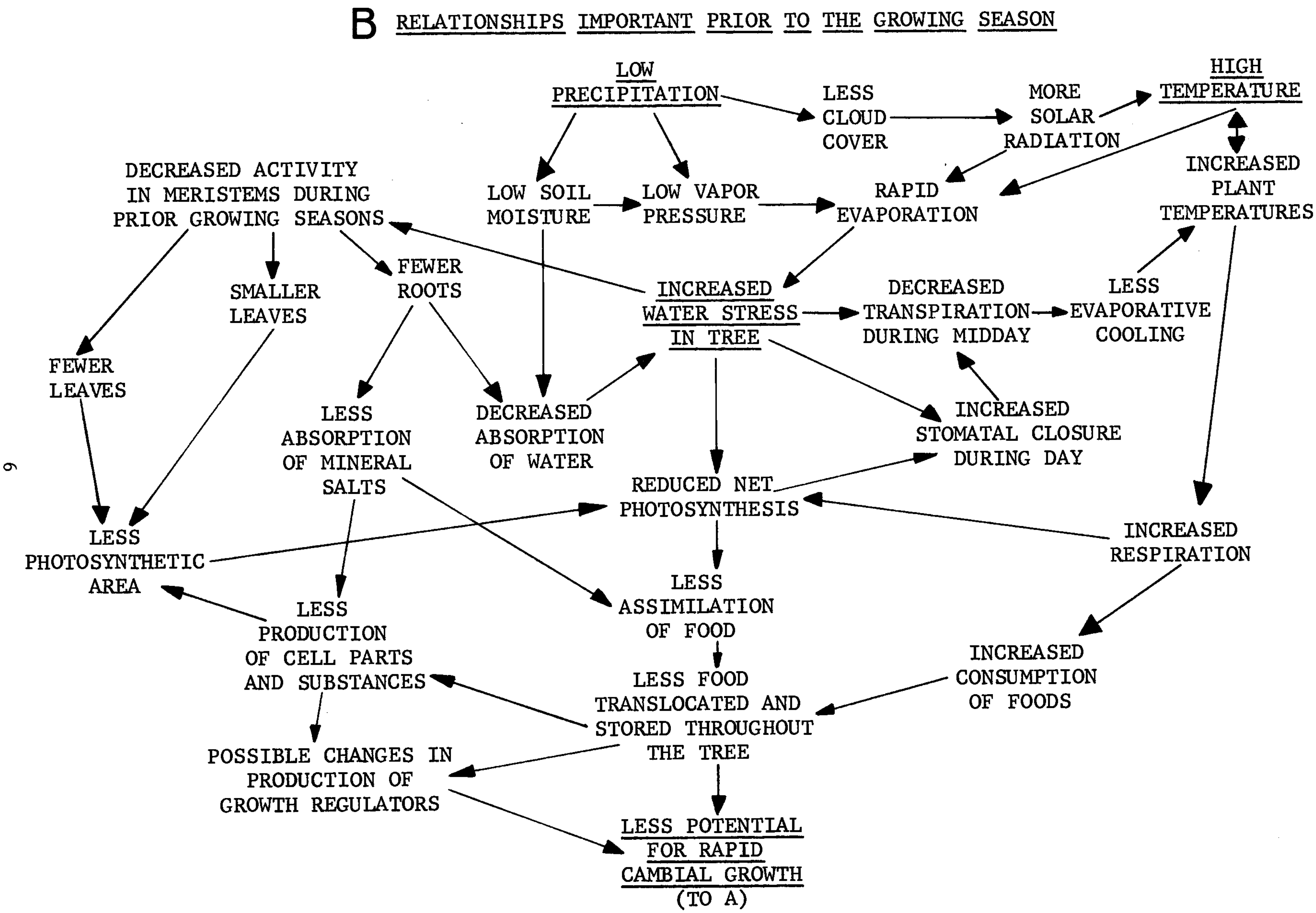

FIGURE 2. Environmental and physiological relationships important prior to the growing season which will lead to the formation of a narrow ring in conifers growing on semiarid sites.

In addition, there are many lengthy, well-dated ring-width chronologies containing highly significant information on climatic factors which are unuseable in the above approach because growth was affected by factors other than drought during some portion of the year. For example, at certain times in the year, high precipitation and low temperatures may actually produce conditions that ultimately limit subsequent growth. The explanations for many of these relationships are well reported in the physiological and ecological literature, and some of the relationships that are pertinent to the tree-ring samples are diagrammatically shown in Figure 3. In general, as one proceeds northward from southwestern North America, or moves to higher elevations, the conditions shown in Figure 3 become more and more important while those shown in Figures 1 and 2 become less important.

Multivariate techniques provide a means of objectively defining how the ring-width growth relates to climatic factors at different periods during the growing season. They also provide a means of handling and relating two diverse data sets made up of many correlated variables. This paper describes two applications of multivariate techniques to problems of tree growth and climate which offer promising possibilities for paleoclimatic research.

C HIGH PRECIPITATION AND LOW TEMPERATURES MAY IN CERTAIN CIRCUMSTANCES LEAD TO LOW GROWTH

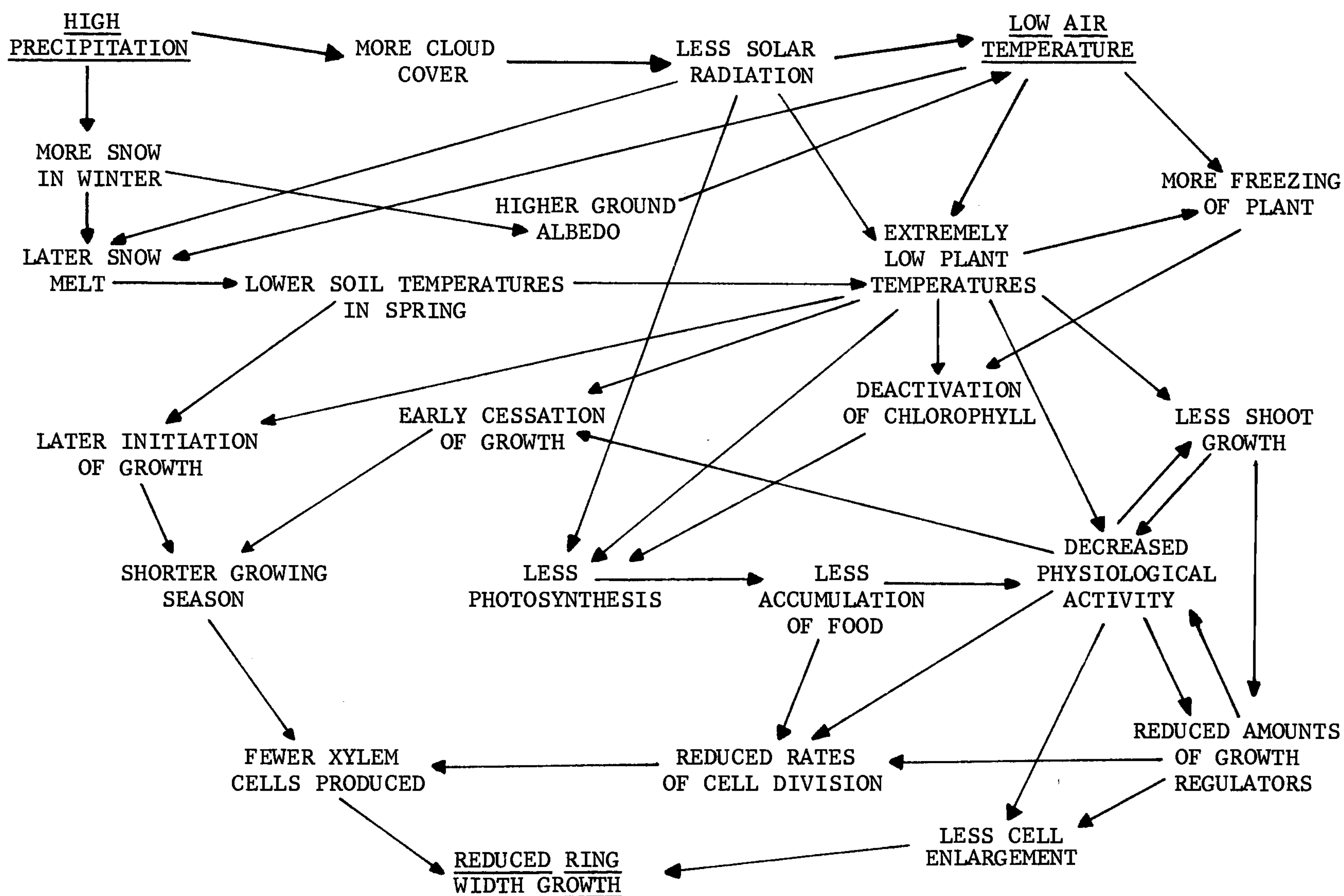

FIGURE 3. Relationships that are opposite in effect from those shown in Figures 1 and 2 which under certain circumstances may contribute to narrow rings.

DEFINITIONS AND GENERAL MODEL

Definitions:

${}_m F_n$ is an array of original data consisting of _n_ observations of _m_ variables.

${}_m E_p$ is the matrix of _p_ eigenvectors representing modes or patterns of behavior of the data assemblage contained in ${}_m F_n$. They are derived under certain constraints depending on whether principal component or canonical analysis is used. These eigenvectors can be thought of as "new variables," which are mutually orthogonal.

${}_p X_n$ is the matrix of the coefficients or multipliers of the "new variables," which will be called amplitudes. They are derived from the product of eigenvectors contained in ${}_m E_p$ and the data, ${}_m F_n$.

$$ {}_p X_n = {}_p E'_m F_n \qquad (1)$$

where the prime denotes the transpose of a matrix.

${}_k \hat{P}_n$ is the predictand matrix (the quantities to be specified). ${}_k \hat{P}_n$ denotes estimates of _k_ parameters of some variable, ${}_k P_n$.

${}_k R_p$ is the matrix of the _p_ regression coefficients corresponding to the _p_ "new variables," ${}_p X_n$, used in developing the model.

$$ {}_k \hat{P}_n = {}_k R_p X_n \qquad (2)$$

Equations of Model:

Substituting equation 1 into equation 2

$$ {}_k\hat{P}_n = {}_kR_p E'_m F_n \tag{3} $$

The predictand matrix can be written in terms of the array of original variables, ${}_mF_n$, and a response function (or transfer function), ${}_kT_m$, where

$$ {}_kT_m = {}_kR_p E'_m \tag{4} $$

and

$$ {}_k\hat{P}_n = {}_kT_m F_n \tag{5} $$

Thus the matrix, ${}_kT_m$, is the weighted combination of eigenvectors which best estimates or predicts ${}_kP_p$.

It is desirable to utilize such matrix manipulations involving eigenvectors because the values of new variables, ${}_pX_n$, are unlike the original data, ${}_mF_n$, in that they are orthogonal or uncorrelated. This orthogonality allows the efficient and valid use of stepwise multiple regression techniques to obtain ${}_kR_p$ and then ${}_kT_m$. The variables of ${}_kT_m$ transform ${}_mF_n$ to ${}_k\hat{P}_n$, or in other applications estimate the response of ${}_kP_n$ to ${}_mF_n$.

In practice, not all of the eigenvectors are used. Those which explain only a small percentage of the variance are eliminated and only the first p eigenvectors are retained for further analysis. The index p in our general model is allowed to vary from site to site depending upon the variance in the original data explained by the eigenvectors and their statistical significance in the tree-ring relationships under study.

RESPONSE FUNCTIONS

In this section, response functions relating ring-width chronologies to chronologies of the seasonal march of climate will be derived. Climatic data were taken from the Decennial Census of the U.S. Climate. Each datum was a monthly average for a state climatic division (U.S. Weather Bureau, 1961, 1962 and 1963). A total of 28 climatic regions were selected which were distributed over the western mountain states. Each region either included or was near one or more sites from which the tree-rings were sampled. Monthly mean temperatures and total precipitation for a given July and the thirteen preceding months through June of the previous year were chosen as the 28 original variables, ${}_mF_n$, from each region. Thirty-one observations on each of the 28 variables were utilized including data for 1931 through 1962.

All 31 observations were used to compute the mean and variance of each variable at each of the 28 regions. The data were normalized for each variable and for each station to remove the average conditions of the region but preserve the anomaly patterns of variance in climate. Thus the array, ${}_mF_n$, of 28 variables was made up of 868 observations (28 regions x 31 observations per region). The pooling of regions provides stability and saves computational time. However, separate analyses of each climatic region or of specific climatic stations provide results that are comparable.

These normalized data were subjected to routine principal component analysis as follows:

$$ {}_{28}C_{28}E_{28} = {}_{28}E_{28}L_{28} \qquad (6) $$

where

$$ {}_{28}C_{28} = \frac{1}{868}\, {}_{28}F_{868}F'_{28} \qquad (7) $$

is the correlation matrix and ${}_{28}L_{28}$ is the (diagonal) matrix of eigenvalues (diagonalized form of C).

${}_{28}E_{28}$ is the complete eigenvector matrix corresponding to the eigenvalues L_i, i = 1, 28. The most important orthogonal eigenvectors are selected from the eigenvector matrix and represent p ways that temperature and precipitation may jointly vary throughout the year. The amplitudes, ${}_pX_n$, are then obtained from equation 1. Stepwise multiple regression is used to estimate ${}_1P_{31}$, which in this case is a ring-width chronology within or near a climatic region, using equation 2:

$$ {}_1\hat{P}_{31} = {}_1R_pX_{31} \qquad (8) $$

where ${}_1R_p$ is a row vector of significant regression coefficients (all insignificant ones are assigned a value of zero). Using equations 1 and 4

$$ {}_1\hat{P}_{31} = {}_1R_pE'_{28}F_{31} = {}_1T_{28}F_{31} \qquad (9) $$

Thus climatic data, ${}_{28}F_{31}$, are transformed into estimates of ring-width indices, ${}_1\hat{P}_{31}$, via a transfer or response function, ${}_1R_pE_{28}$, denoted by the column vector ${}_1T_{28}$. The same eigenvectors and amplitudes may be used to derive transfer functions for several chronologies in a given region, because only the regression coefficients vary. In the above application, the same eigenvectors are used to derive amplitudes, ${}_{p}X_{31}$, for each climatic region but the data, ${}_{28}F_{31}$, vary.

The ring-width index is not independent of prior growth. This effect can be assessed by including in analyses the values of the three prior ring indices (1st, 2nd, and 3rd order auto-correlation). The estimation of ${}_{1}P_{31}$ made with the enlarged set or predictors is accomplished by adding ${}_{1}R^{*}_{3}Z_{31}$ to the original estimates, ${}_{1}\hat{P}_{31}$, where ${}_{3}Z_{31}$ is a matrix of the growth indices for the three years prior to each yearly value of ring index entered in the column vector ${}_{1}P_{31}$.

When calculating ${}_{1}\hat{P}_{31}$ with the original ${}_{1}T_{28}$ the variance accounted for in ${}_{1}P_{31}$ is a direct measure of the amount of information contained in the chronology on climate. The second calculation of ${}_{1}\hat{P}_{31}$ with the enlarged ${}_{1}T_{28}$ (which includes regressions for prior growth) accounts for more variance in ${}_{1}P_{31}$ if auto-correlation in the ring-width chronology is important. The difference in the variance accounted for in the above two calculations provides a measure of the variance in the chronology attributed to auto-correlation and represents a lag of one to three years in the response of growth to climate (Table 1).

A check is made on the residuals of ${}_{1}\hat{P}_{31}$ from the actual data ${}_{1}P_{31}$ to assure that the error is randomly distributed.

At present we have calculated the transfer (response) functions for a sample of approximately 120 ring-width chronologies, many of which have been previously analyzed by other means (Fritts, 1965; Fritts, Smith and Stokes, 1965; Julian and Fritts, 1968; Fritts, 1969a).

TABLE 1

The percentage of variance in selected ring-width chronologies that is related to climate and related to the growth for prior years. The total explained variance, which is the sum of the first two columns, is also shown.

Chronologies	Percent Variance Related to Climate	Percent Variance Related to Prior Growth	Total Percent Explained Variance
Owl Canyon Pinyon Pine	.62	.30	.92
Colorado Transect Av. Ponderosa Pine	.65	.27	.92
Colorado Transect Av. Douglas-Fir	.82	.03	.85
Arizona Forest Interior Ponderosa Pine	.49	.40	.89
Arizona Forest Border Ponderosa Pine	.76	.07	.83

The median percent variance (or information) in the ring-width chronologies that is related to climate is approximately 60 to 65. This percentage is equivalent to the coefficient of determination or to simple correlations of .77 through .81. Only 20 percent of the chronologies have less than 50 percent variance related to climate, while 20 percent of the chronologies contained more than 80 percent variance that is related to climate.

Since many sites were located at the margin and some are outside of the selected climatic regions, it is remarkable that more than half the variance in 80 percent of the ring-width chronologies is directly attributable to climate. The median variance attributed to auto-correlation within each ring-width chronology is 15 percent and the median total variance accounted for when including prior ring-width indices is 85 to 90 percent.

A survey of the plotted response functions, ${}_{1}T_{28}$, shows considerable detail, and the results are more meaningful in terms of the models shown in Figures 1, 2 and 3 than similar results obtained in earlier studies using stepwise multiple regression with actual climatic data (Fritts, 1962). The models are relatively consistent within specific sites even among different species. For example, the averages of the response functions are similar for six separate Pinus ponderosa (PP) sites and four separate Pseudotsuga menziesii (DF) sites (Table 1) along a transect at the edge of the Colorado Front Range (Figure 4) (Julian and Fritts, 1968). The ring-width index is directly related to temperature in September and May and precipitation in the previous June, September, October, and February through June, while it is generally inversely related to temperatures during other months of the year and to precipitation in late summer of the prior year and during early or mid-winter. However, the growth of P. ponderosa is more related to the amounts of prior growth (auto-correlation) than P. menziesii (Table 1), and the response functions vary more from site to site (Figure 4). The response function for a Pinus edulis (Pnn) stand in the same area is also shown. This species is at its northern limit and exhibits some differences in response, but its chronology contains almost as much information on climate (Table 1). Temperatures in September, November and the following June are directly correlated with growth. High temperatures at the beginning or end of the growing season may extend its length, which favors the formation of a wide ring. At other times, except for November, temperatures are inversely correlated with growth as they may enhance water loss and respiration which

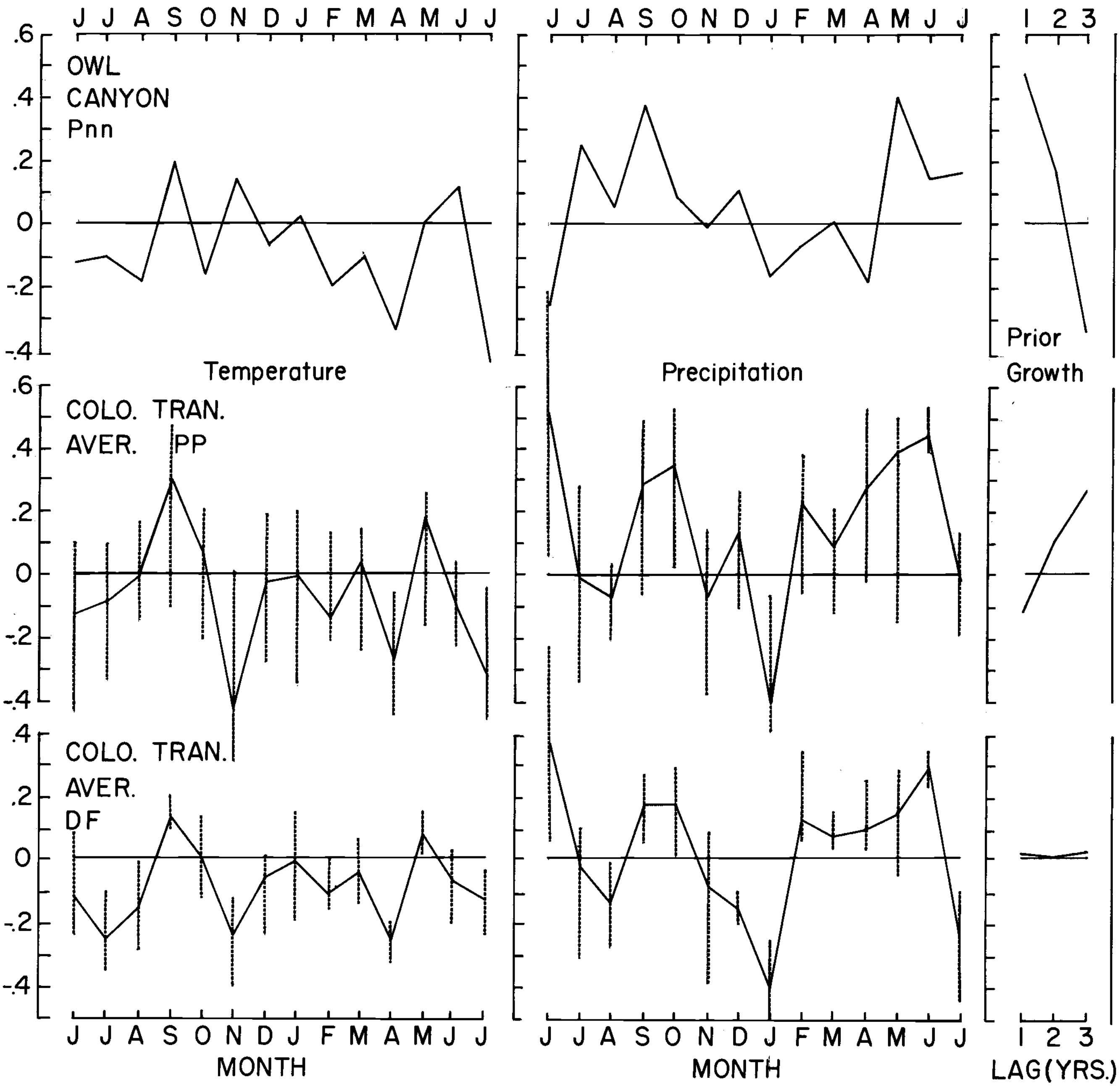

FIGURE 4. The average response function, $_1T_{28}$, relating standardized ring widths for three species in Colorado to standardized average monthly temperature and standardized total monthly precipitation during the fourteen months prior to and including the initiation of growth. Each point may be considered a weight associated with each climatic variable that will provide maximum reconstruction of the tree-ring chronology from the monthly climatic data. The plots may also be interpreted as the probably relative effect of a unit change in each climatic variable on a unit change in tree growth. The three variables on the right show the probable relationship with the width of the three prior rings. The dashed vertical lines show the maximum scatter of values obtained from separate analysis of individual sites. Pnn — *Pinus edulis*, PP — *Pinus ponderosa*, DF — *Pseudotsuga menziesii*.

consume available moisture and stored foods. Precipitation is directly related to growth except late in the prior summer and during mid-winter when heavy snow cover, reduction of light intensities due to cloud cover and low temperatures may adversely influence the trees and affect the next year's growth (see Figures 1, 2 and 3). Other plots of response functions show systematic changes from low to high latitude sites and from low to high elevations.

A somewhat different representation of the response functions is shown in Figure 5. Each element of the response or transfer function, ${}_1T_{28}$, is divided by the standard deviation of the corresponding set of climatic data. This converts the elements to relative measures of the effect of a degree rise in temperature and an inch increase in precipitation for separate months of the year upon ring-width growth. Response functions of this form are shown for two groups of P. ponderosa. One is a stand near the arid lower forest border (solid line) and the other a stand in the forest interior near Fort Valley, Arizona (dashed line) (Fritts, Smith, Cardis, and Budelsky, 1965). A total of 76 percent of the tree-ring variance of the forest border stand is related to climate as the trees were highly limited by environmental variables (Table 1). Only 49 percent of the variance of the chronology from the forest interior stand is related to climate. These forest interior trees have also been intensively investigated by Glock and others (1964, 1969).

The figure shows marked differences between the growth responses of trees along the forest border and trees in the forest interior. The response to temperature on the two sites is diametrically opposite in sign. The response to precipitation on the arid site is marked and direct for ten

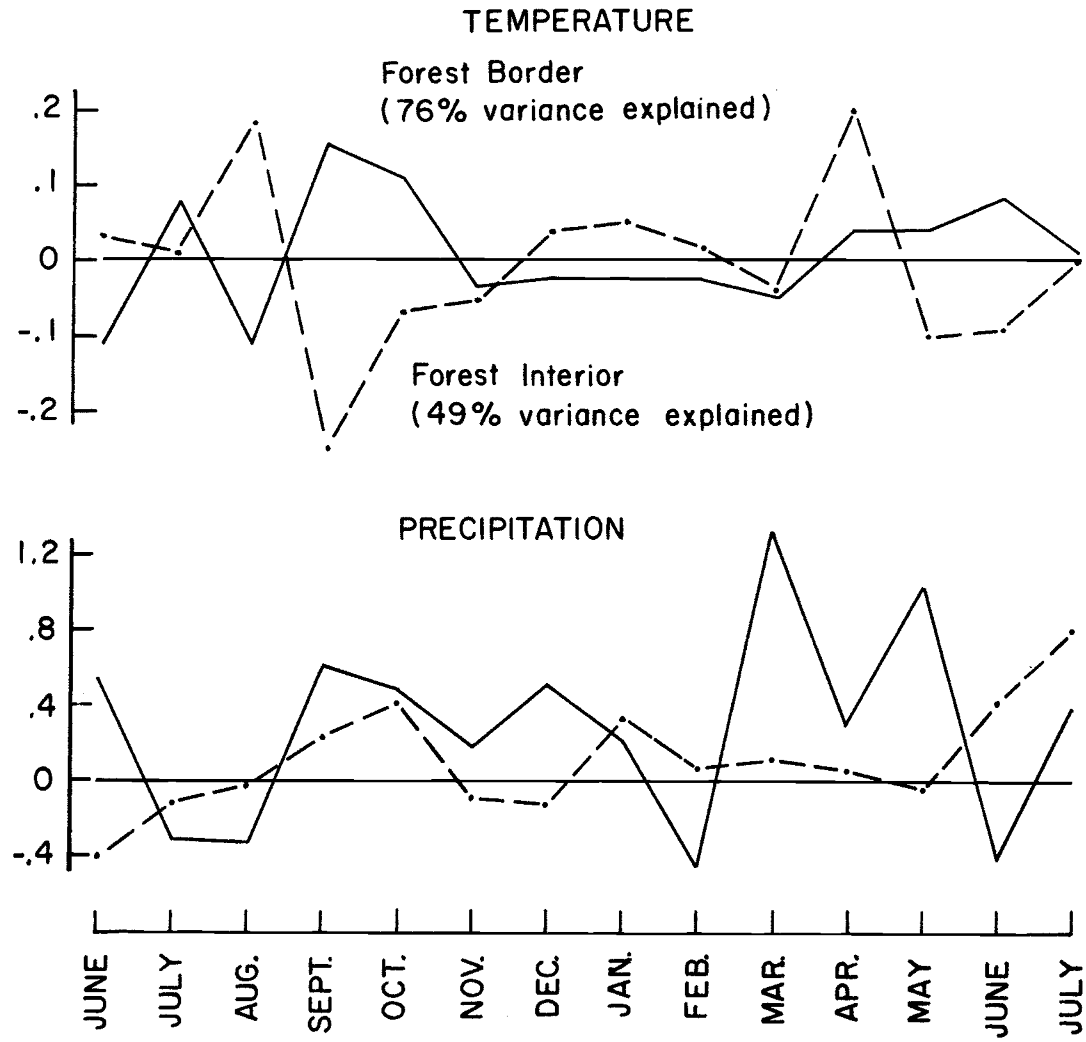

FIGURE 5. The response function for ponderosa pine near the forest border (solid line) and in the forest interior (dotted line) of northern Arizona (Fritts, Smith, Cardis, Budelsky, 1965). Plots differ from those shown in Figure 4 in that the weight for each climatic variable is divided by the standard deviation for that variable. In this form the plots may be interpreted as the relative effect of a degree rise in mean temperature for the month and an inch increase of monthly precipitation on ring-width growth.

months in the year and inverse only for the previous July, August and February and the current June. The response for forest interior trees to precipitation is most marked in June and July. Apparently growth of trees on the forest border site is more influenced than growth of trees on the forest interior site by precipitation falling at times other than the growing season. The differences shown in these plots explain how forest interior trees like those reported by Glock (1969) differ in their response to climate from trees on the more limiting, warm and arid sites reported by Fritts (1965). They also show the wide diversity in response obtainable from trees on neighboring but ecologically contrasting sites.

RECONSTRUCTING ANOMALIES IN PAST CLIMATE

The Model

It is well accepted that variations in the width of the annual rings of trees on a given site may reflect a significant amount of information about fluctuations of the local environment. However, these fluctuations also may be manifestations of large-scale regional anomalies. These regional anomalies will be systematically reflected in spatial anomaly patterns of ring-widths from groups of trees representing sampled sites. Such regional patterns in tree-ring-widths have been identified via principal component analysis (LaMarche and Fritts, in press). The results indicate that a large percentage of tree-ring variance is incorporated into regional anomaly patterns which cannot be a reflection of purely local factors but may be closely related to large-scale anomalies in the general atmospheric circulation (Sellers, 1968). These anomalies may occur in the year prior to, as well as in the year during which growth takes place. It is the purpose of this section to identify some seasonal climatic anomaly patterns which can be specified from given tree-ring data, to quantify our estimating procedure using recorded climatic data for calibration, and to extend the resulting statistical relationships to estimate patterns of circulation anomaly during periods for which tree-ring data are available but climatic data are not.

Previously selected replicated tree-ring chronologies at 49 locations in western North America were used as original variables for this analysis. The first 4 principal component patterns of tree growth (eigenvectors of the correlation matrix formed from the 49 chronologies) are presented by LaMarche and Fritts (in press). The first 7 principal components describe large-scale regional patterns and they explain 57 percent of the total tree-ring variance for the period A.D. 1700-1930. This result suggests that over half of the tree-growth variance is related to large-scale macroclimatic anomalies and that spatial patterns of tree-growth chronologies may be used to reconstruct the patterns of atmospheric circulation that produce the macroclimatic anomalies.

As noted above, the present analysis is concerned with the estimation of seasonal rather than monthly circulation patterns. A seasonal climatic anomaly pattern is taken to be the pressure anomaly field for a three-month period. The seasons were chosen to correspond with particular growing seasons (spring and early summer) in which each annual ring was formed. The "leading" season was the summer preceding the growth of the ring. Autumn, winter and spring followed. The months comprising each season were selected so as to correspond to the "natural" seasons and subseasons as presented by Bryson and Lahey (1958). Thus we have

Summer: July, August, September

Autumn: October, November, December

Winter: January, February, March

Spring: April, May, June

Normalized values of the seasonal sea-level pressure at 100 grid intersections over the western half of the Northern Hemisphere were used as climatic data. These values were computed from the monthly values provided by the Extended Forecast Branch of the U.S. Weather Bureau. These data extended from 1899 to 1966 exclusive of the years 1939-1944.

The first 8 principal components of the pressure anomaly field for each season were computed. The resulting 32 principal components of pressure and the 7 principal components of tree growth comprise 2 sets of variables. The values or multipliers of these "new" variables are given by their amplitudes, ${}_{p}X_{n}$, which are defined by equation 1.

The amplitudes of the new variables were then subjected to a canonical correlation analysis as presented by Glahn (1968). The components of the resulting canonical variates weight the amplitudes of the new variables of tree growth in such a way that they are canonically correlated with weighted amplitudes of the new pressure variables. Since input pressure variables were the principal components of pressure <u>for all seasons</u>, the weighted assemblages of the principal components of tree-growth patterns are related to weighted assemblages of the principal components of pressure patterns for all seasons.

Estimates of the normalized pressure anomalies at each grid point were made by multiple regression functions of the canonically weighted principal components of tree growth. The equations are identical to those used in the previous section except for the introduction of the additional canonical weighting functions. Thus,

$$ {}_1\hat{P}_n = {}_1R_p X^*_n \tag{10} $$

where ${}_1\hat{P}_n$ denotes the estimates of pressure anomaly, ${}_1P_n$, at a grid point; ${}_1R_p$ is the row vector of multiple regression parameters; and ${}_pX^*_n$ is the matrix of weighted amplitudes of the principal components of tree growth. That is

$$ {}_pX^*_n = {}_pW_p X_n \tag{11} $$

where ${}_pW_p$ is the complete matrix of canonical variates corresponding to tree growth variables. Thus, substituting equation 11 into equation 10, and making use of equation 1,

$$ {}_1\hat{P}_n = {}_1R_p W_p X_n = {}_1R_p W_p E'_m F_n \tag{12} $$

By defining a transfer function, ${}_1T_m$, such that

$$ {}_1T_m = {}_1R_p W_p E'_m \tag{13} $$

one obtains

$$ {}_1\hat{P}_n = {}_1T_m F_n \tag{14} $$

This transfer function transforms a matrix of normalized tree-ring data into estimates of seasonal pressure anomaly at an individual grid point and is identical in form to equation 5. The purpose of the matrix ${}_pW_p$ is to weight the principal components of tree growth such that their correlation is maintained with spatial patterns of pressure anomaly throughout an entire year. The weighted eigenvectors of tree growth, ${}_7W_7E'_{49}$, in equation 13 are shown in Figure 6 and the weighted amplitudes, ${}_7X^*_{263}$, in equation 11 are shown in Figure 7.

Maps of the regression parameters, ${}_1R_3$, which transform the first three tree-growth patterns into pressure estimates at each of the 100 grid points are presented, for each season, as Figures 8, 9, and 10. The values of the regression weights are contoured and the figures may be interpreted as the standardized pressure fields giving rise to the circulation patterns that are associated with the anomalous patterns of ring-width growth specified in Figure 6.

Spatial patterns of the percentage of pressure variance explained using equation 14 over the period of the dependent data (1900-1939, 1945-1962) are shown in Figure 11. These patterns indicate where the best estimation of pressure was obtained. The total percent of normalized pressure variance accounted for by the equations for each season was: summer - 23.7%, autumn - 20.6%, winter - 24.0%, and spring - 18.5%. These spatially averaged percentages are deceptively low as they include areas of good prediction (these are often areas where the mean circulations are related to the weather over the sites of tree growth) as well as areas of poor prediction (these are often located "downstream" of the tree sites - see Figure 11). Higher percentages of variance would probably have been obtained if the pressure grid had been chosen differently.

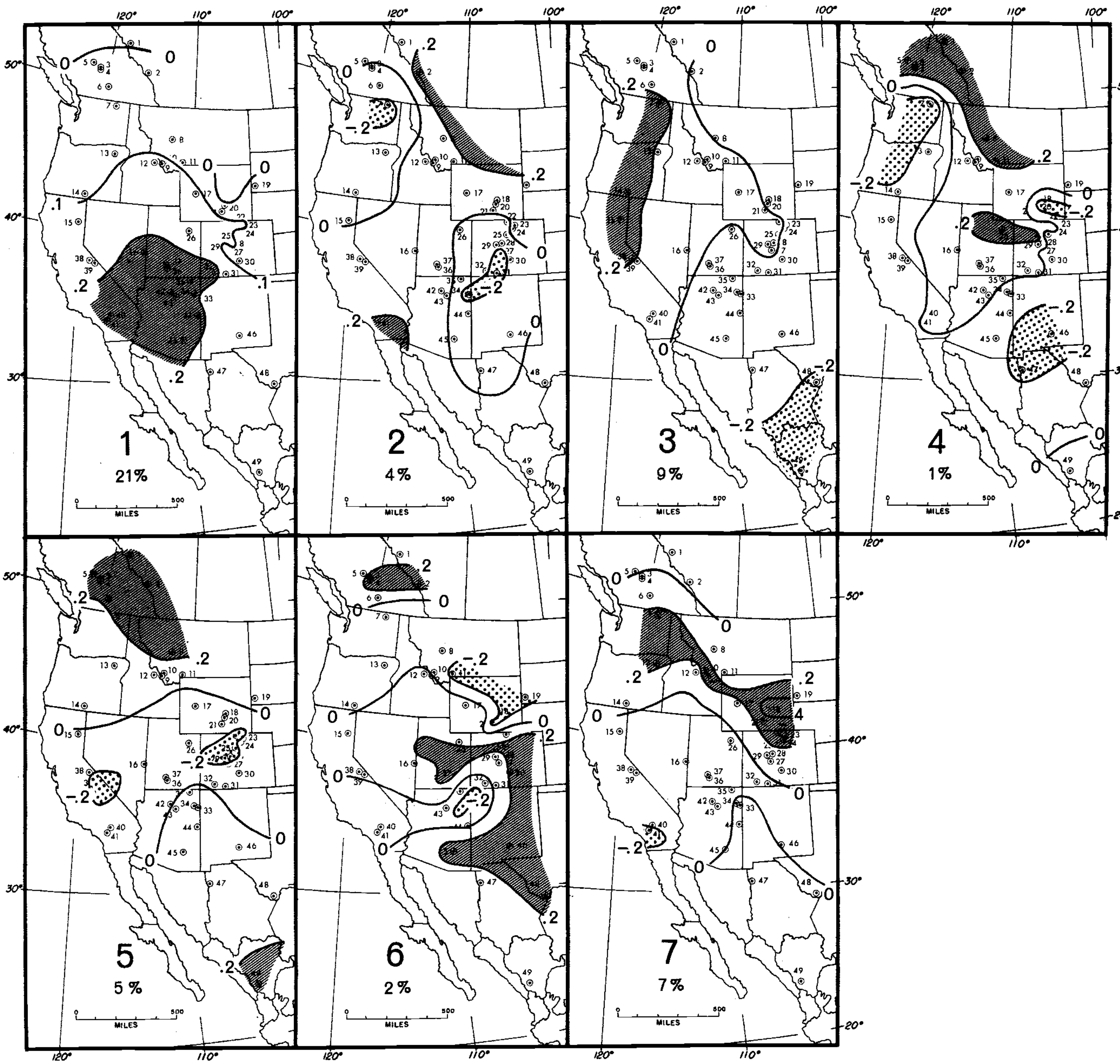

FIGURE 6. Plots of the seven eigenvectors of anomalous tree growth, ${}_7W_7\hat{E}_{49}$, weighted to give maximum correlation with surface pressure anomalies. Plots are ranked from high to low correlation with pressure anomalies and the percentage represents the variance in tree growth explained by each eigenvector. Dots on maps locate the 49 tree-ring collection sites.

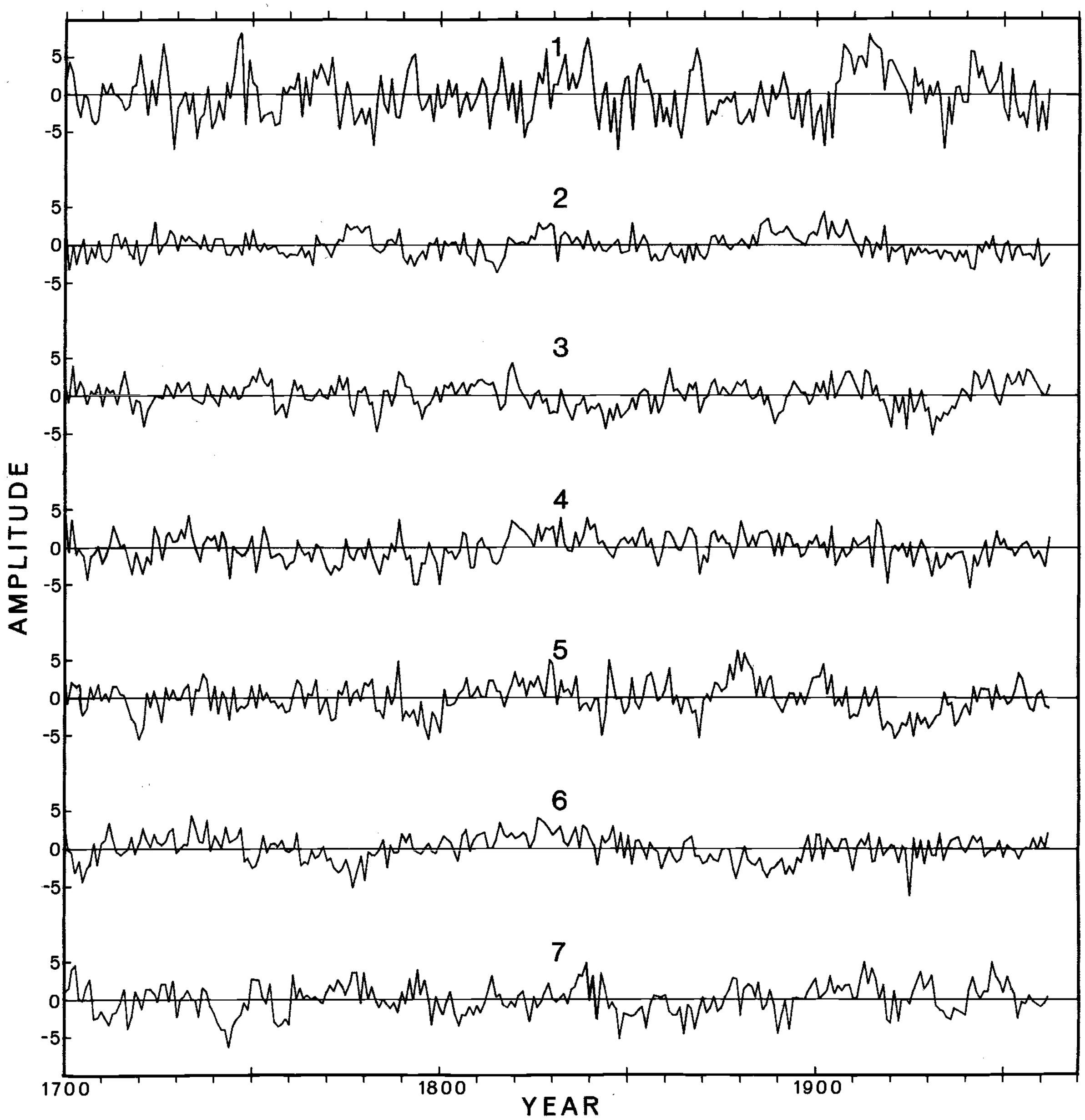

FIGURE 7. Plots of the amplitudes for the seven eigenvectors of anomalous tree growth, ${}_7X^*_{263}$, weighted to give maximum correlation with surface pressure anomalies. Plots are ranked from high to low correlation with pressure anomalies.

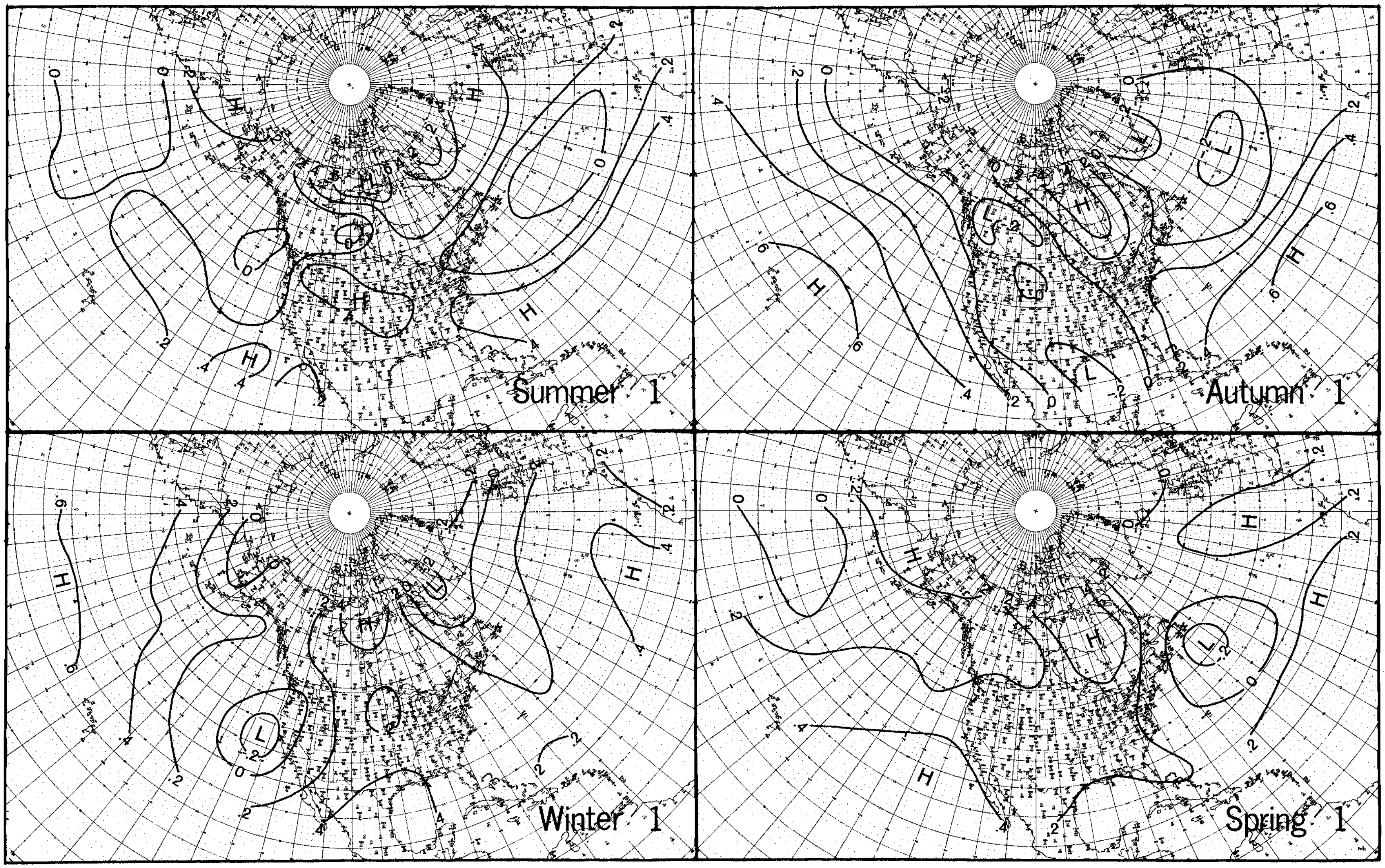

FIGURE 8. Maps of the regression weights, ${}_1R_1$, relating tree growth variable 1 to pressure anomalies in each of the four seasons. Each regression weight is plotted at the corresponding station location so that contours show the anomalous circulation patterns that are associated with patterns of anomalous growth shown in Figures 6 and 7. High growth in Arizona and southern California results from increased flow of moisture into the region associated with increased southern flow over southwestern North America in summer and winter. Associated features indicated by the maps include: 1) In summer an apparent subtropical high pressure system extends across the United States and flow is more zonal over the central North Atlantic. 2) In autumn there are two regions of increased cyclonic activity over Alberta and Texas. The flow is zonal over the Atlantic and Pacific. 3) In winter a region of low pressure anomaly persists off the California coast, and the Icelandic Low is displaced westward and intensified. Subtropical highs are also intensified. 4) In spring higher than normal pressures dominate North America particularly over Hudson's Bay and a low pressure anomaly is conspicuous off the Newfoundland coast increasing meridianal flow off the east coast of North America.

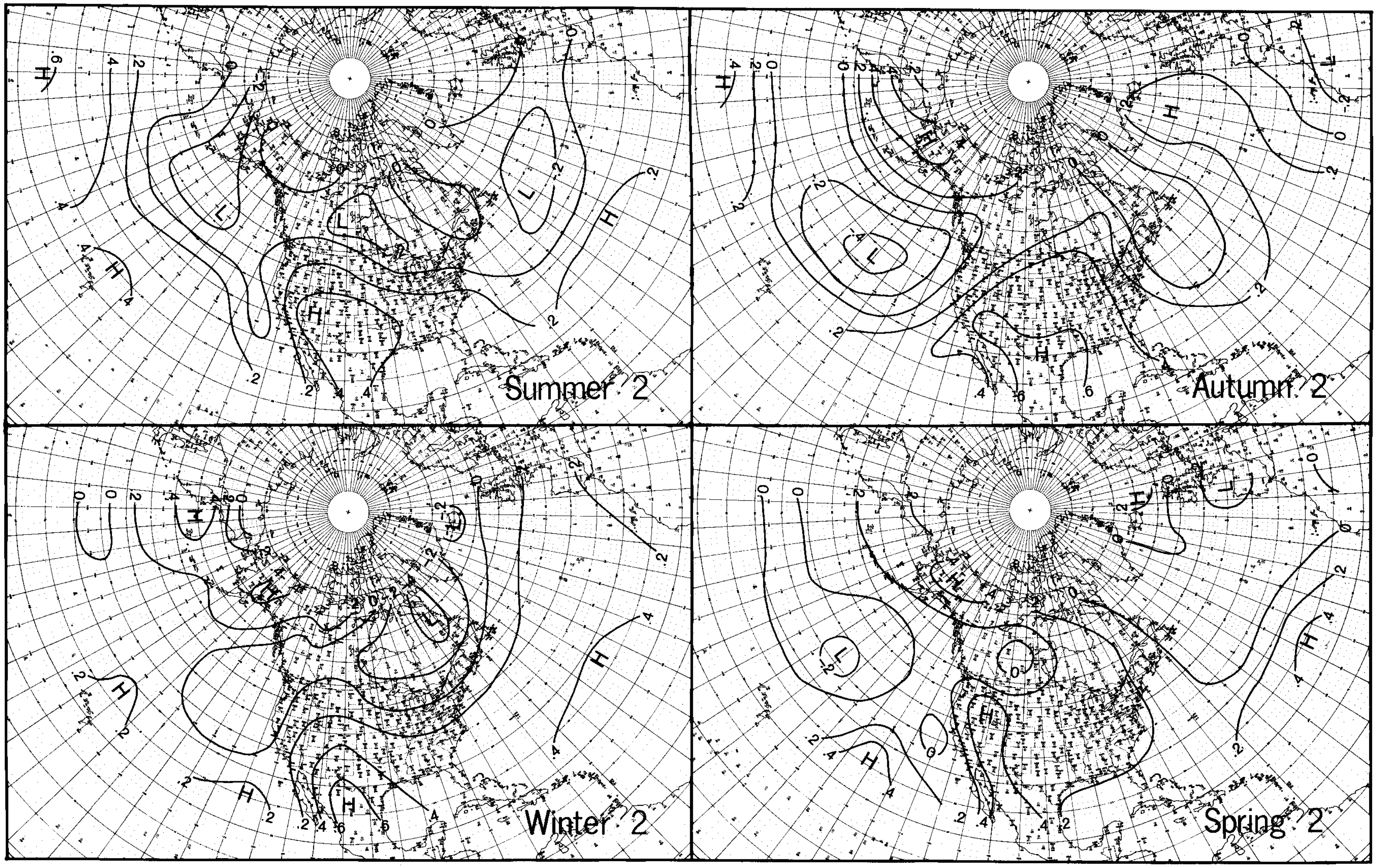

FIGURE 9. Maps of the regression weights, ${}_1R_1$, relating tree growth variable 2 (Figures 6 and 7) to pressure anomalies in each of the four seasons (see legend to Figure 8). High growth centering in the regions on the east slope of the Northern Rockies and in southern California is associated with low growth in the southern Rocky Mountains and in the Pacific Northwest. This pattern is associated with positive pressure anomalies in all seasons over the southwestern deserts and in the Great Basin; so the flow from the Gulf of Mexico into the southern Rocky Mountains is minimal. The low growth in the Pacific Northwest results from an apparent deflection of storm tracks to the north of that area especially in spring and summer. Associated features indicated are: 1) In summer the subtropical highs are weakened or displaced southward over the oceans. 2) In autumn the Aleutian Low is expanded and/or displaced southward; pressures are anomalously high over North America except for the Northeast Coast, and there is blocking over the eastern Atlantic. 3) In winter the Icelandic Low appears expanded, intensified, and perhaps displaced to the southwest. 4) In spring, the Aleutian Low is displaced southward.

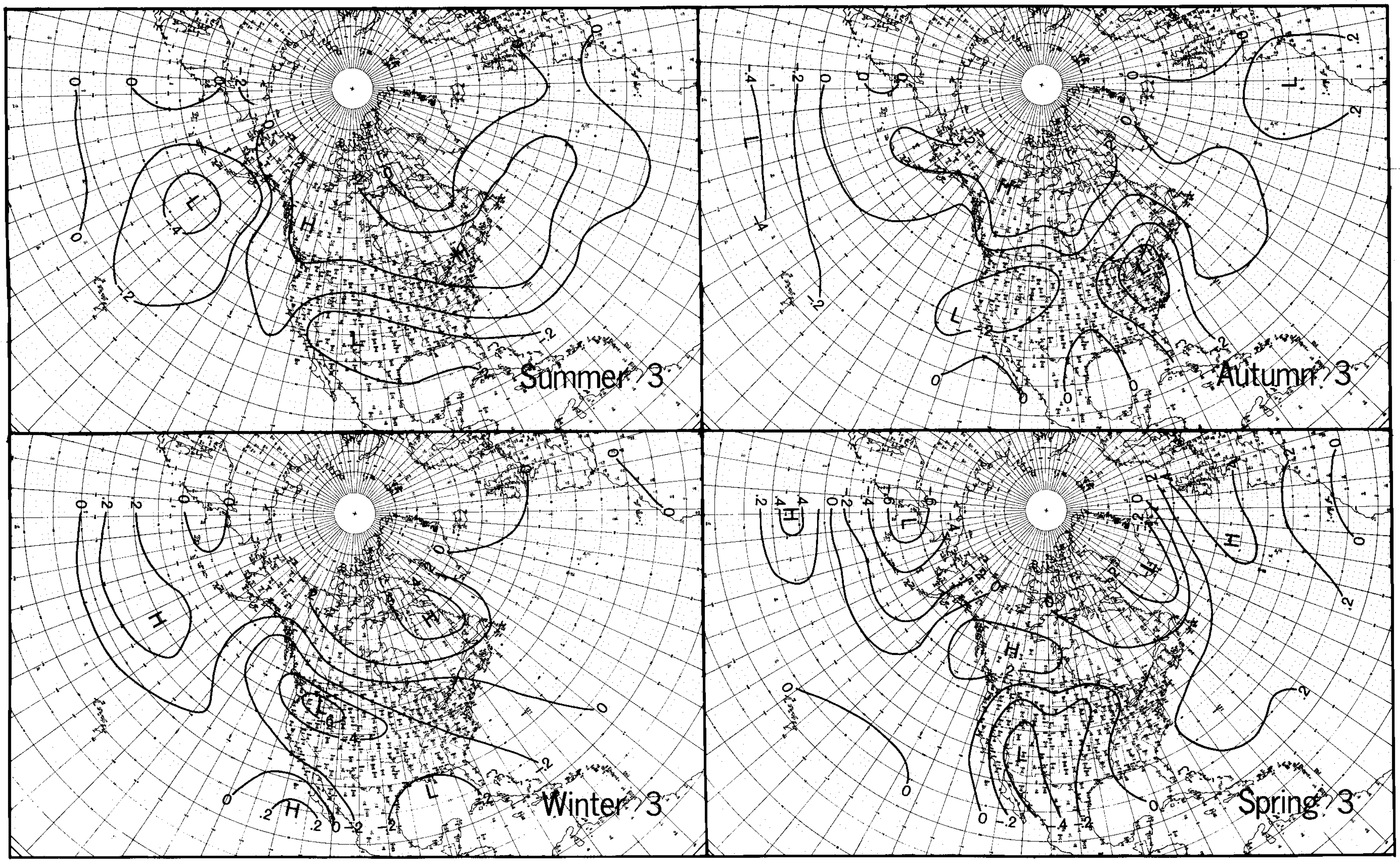

FIGURE 10. Maps of the regression weights, ${}_{3}R_{1}$, relating tree growth variable 3 (Figures 6 and 7) to pressure anomalies in each of the four seasons (see legend to Figure 8). High growth in Washington, Oregon and northern California along with low growth in west Texas and western Mexico is associated with favorable temperature and moisture (without extremely cold weather) over the Northwest and dry conditions in the Southwest. These conditions result from a generally weakened zonal flow over North America in all four seasons. Associated features indicated by the map are: 1) In summer, the Pacific high is weak and the Bermuda high does not extend westward so little moist air flows into the Southwest. 2) In autumn, there is increased cyclonic activity over the Great Basin and eastern North America. The Pacific high is weak and zonal flow is reduced over the central Pacific. 3) In winter normalized anomalous cyclonic activity is restricted to the Pacific Northwest. 4) In spring both the Aleutian and Icelandic lows are displaced westward and a low is well developed over Arizona, bringing dry warm air from Mexico.

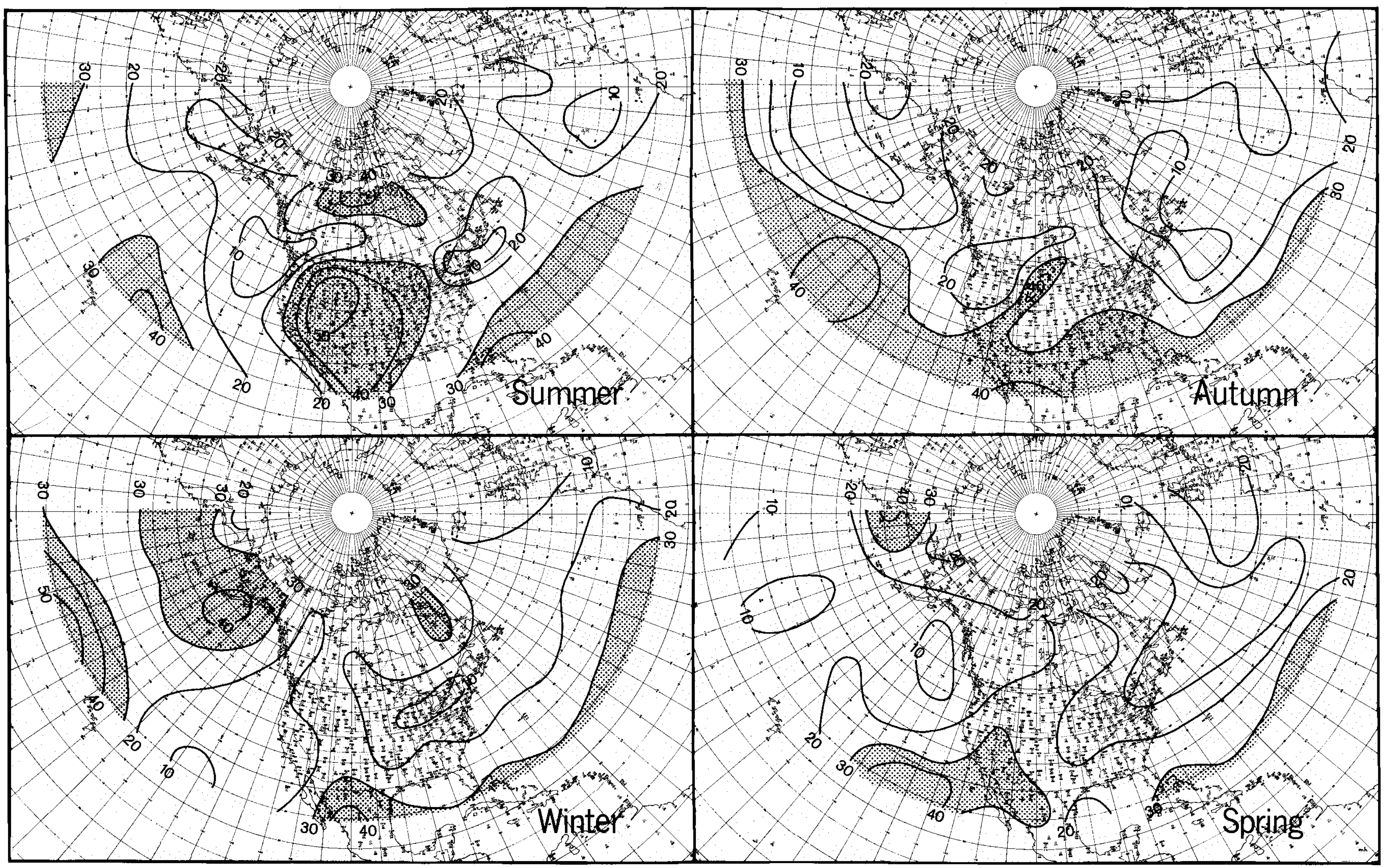

FIGURE 11. The percentage variance in surface pressure anomalies explained by the tree-ring data for the period 1900–1939, 1945–1962. The shaded areas represent areas where the explained variance is most significant (>30%). During all four seasons prediction is high over the tropical and mid-latitude oceans. Prediction is greatest during summer over western North America and north-central Canada, during autumn over the high plains, during winter over the Aleutian Islands and Coast of Labrador, and during spring over the Bering Sea.

Application of Model and Its Verification

The tree-ring data for each year of the period 1700-1899 were used to reconstruct or estimate past anomalous variations in pressure, ${}_{400}P_{200}$, with the aid of equation 14. The estimated normalized pressure anomalies for each season and each year, ${}_{400}\hat{P}_{200}$, were then converted to millibar pressure anomalies by multiplying each normalized pressure estimate by the standard deviation of pressure at the corresponding grid point and season for the dependent period. Estimates of mean pressure for each season and year of the period 1700-1899 were obtained by adding to the millibar anomaly the mean pressure at each point and season of the dependent period.

The estimated mean and anomalous pressure for each season, averaged by pentads and by decades, were plotted and contoured by computer. Only the winter and summer maps have been analyzed thus far. Selected pressure anomaly maps (in millibars) for winter are shown in Figures 12, 13, and 14. The square dots indicate that the five-year mean departures are greater than twice the standard error.

A preliminary attempt has been made to provide some measure of verification of the reconstructed pressure maps using Lamb's (1966) published decadal maps of January and July pressure which cover the North Atlantic sector since 1800. Unfortunately, the reliability of the reconstructed maps is expected to be poor over the North Atlantic as the explained dependent variance is particularly low in this sector (Figure 11). In addition, Lamb's maps are for monthly means while the reconstructed maps are for the entire season. However, Lamb (1966) points out that circulation patterns of selected months can serve as indicators of seasonal regimes.

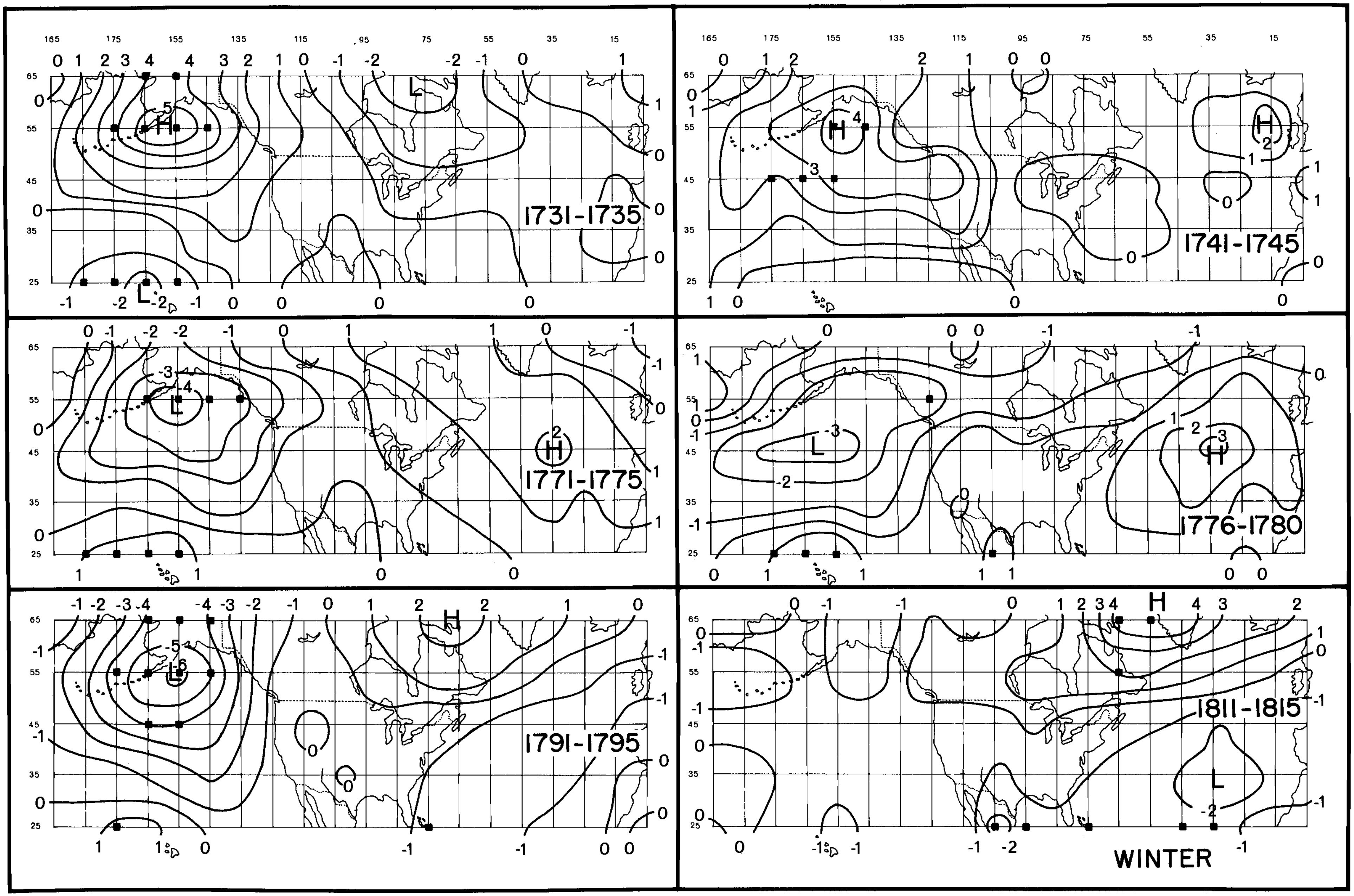

FIGURE 12. January through March pressure anomalies from A.D. 1700–1815 expressed in millibars and averaged for selected pentads, as specified from anomalies in tree growth. A square dot indicates that the five-year mean anomaly at the grid point was greater than twice the standard error, $\sigma/\sqrt{5}$, where σ is the standard deviation of the residuals, ${}_1P_{57} - {}_1\hat{P}_{57}$. Only maps with five or more departures exceeding two standard errors are shown.

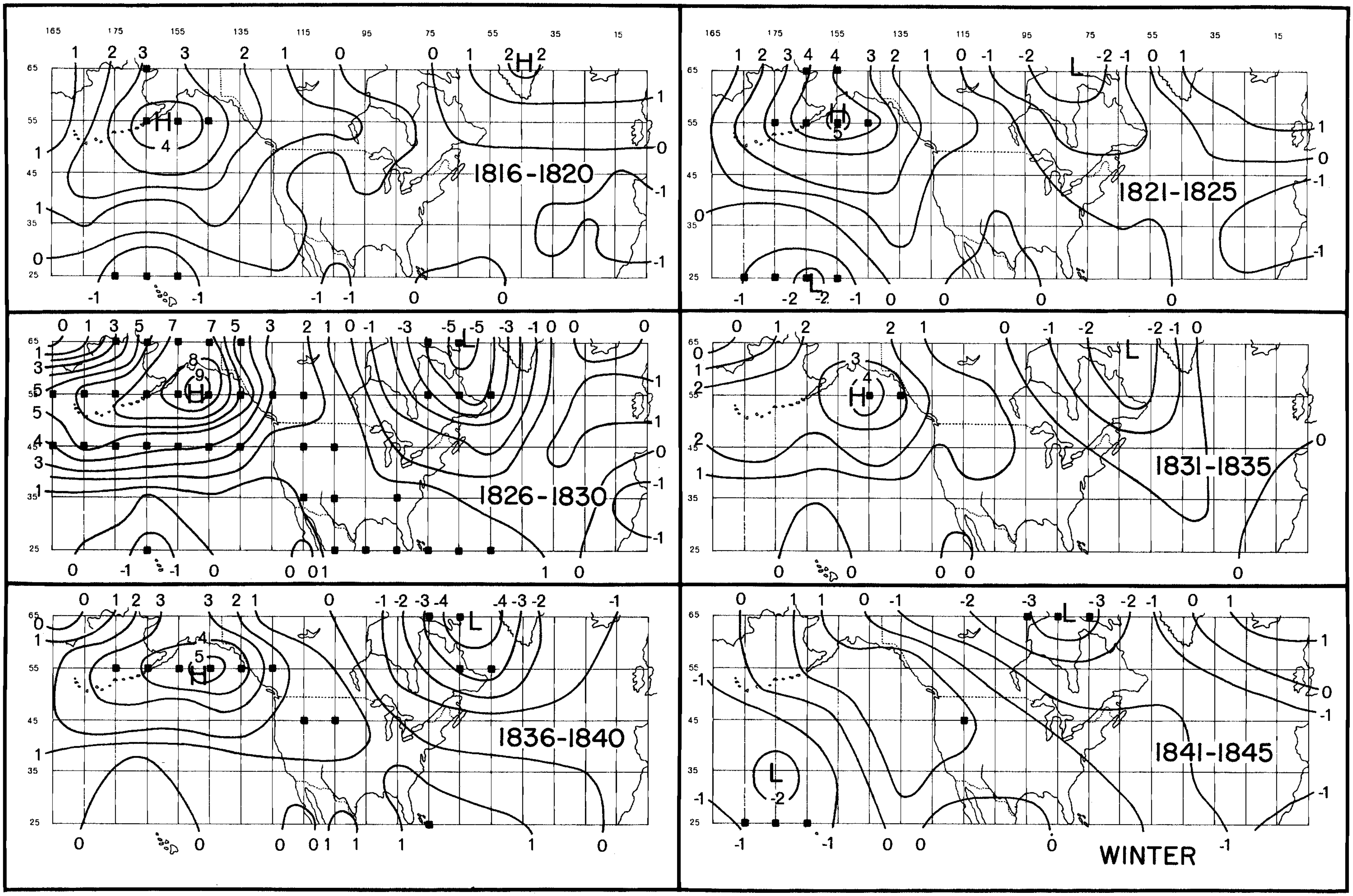

FIGURE 13. January through March pressure anomalies from A.D. 1816–1845 expressed in millibars and averaged by pentads as specified from anomalies in tree growth. A square dot indicates that the five-year mean anomaly at the grid point was greater than twice the standard error, $\sigma/\sqrt{5}$, where σ is the standard deviation of the residuals, ${}_1P_{57} - {}_1\hat{P}_{57}$.

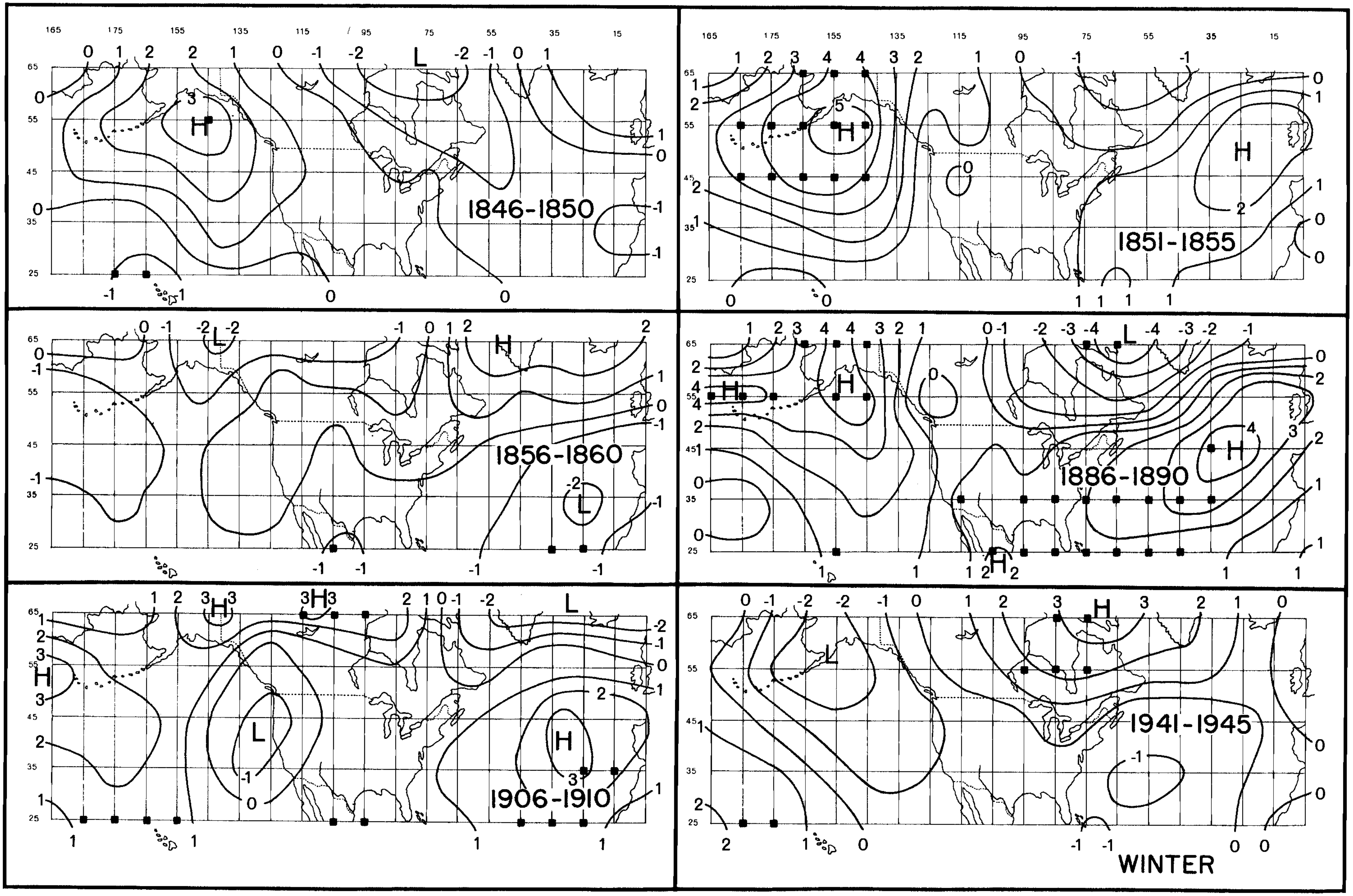

FIGURE 14. January through March pressure anomalies from A.D. 1846–1960 expressed in millibars and averaged by pentads as specified from anomalies in tree growth. A square dot indicates that the five-year mean anomaly at the grid point was greater than twice the standard error, $\sigma/\sqrt{5}$, where σ is the standard deviation of the residuals, ${}_1P_{57} - {}_1\hat{P}_{57}$. After 1860 only maps with five or more departures exceeding two standard errors are shown.

Thus, the preliminary verification presented below cannot be considered a fair test of the model.

Three broad comparisons of the North Atlantic sector of the reconstructed maps with the maps of Lamb are summarized in contingency diagrams in Table 2. In general, the pressure maps reconstructed from tree rings do provide information about the position of the Icelandic Low (Table 2a); however, it was found that specifications of its intensity were not accurate. Since predictions were based upon regressions for each grid point, it is to be expected that the position of the Icelandic Low could be specified more precisely than its central value. The pressure anomalies predicted from tree-rings also provide some information on the intensity (Tables 2b and 2c) and approximate location of the subtropical anticyclone, although detailed specification of its position was not obtained. An apparent reduction in prediction of pressure anomalies lasting several decades was also noted. This reduction of prediction is to be expected because the density of forest stands on semiarid sites may change slowly in response to persistent anomalies in climate. Such changes reduce the amount of low frequency variance that can be retained in the ring-width record (Fritts, 1969b), so that it becomes a source of information emphasizing relatively short-term climatic changes.

While the verification results in the Atlantic sector do not indicate strong quantitative association, there is an apparent qualitative association between Lamb's maps and those derived from tree-ring information. Thus, considering that the verification scheme compares seasons (winter, summer) with months (January, July) and considering that the explained variance for the dependent sample was low in the North Atlantic sector,

TABLE 2

A comparison for the North Atlantic sector of decade maps of pressure during the 19th century derived from tree-ring data with the historical data published by Lamb (1966).

a. Longitude of lowest pressure of the Icelandic Low along 65° N. latitude.

DATA FROM TREE RINGS	DATA OF LAMB: West of Greenland	Near Greenland	East of Greenland
West of Greenland	2	0	0
Near Greenland	0	2	0
East of Greenland	0	1	4

b. Pressure of the subtropical anticyclone near the east coast of North America.

DATA FROM TREE RINGS	DATA OF LAMB: Low	Near Normal	High
Low	2	0	0
Near Normal	0	2	3
High	2	0	1

c. Pressure of the subtropical anticyclone near the west coast of Africa.

DATA FROM TREE RINGS	DATA OF LAMB: Low	Near Normal	High
Low	2	2	0
Near Normal	1	0	2
High	0	1	2

there is reason to expect more reliable paleoclimatic reconstruction in areas of higher explained variance over North America and the North Pacific (Figure 11), especially in regions that coincide with prominent features of the general circulation, such as the Aleutian Low and the Pacific subtropical high.

It should be mentioned here that the 20% of pressure variance explained on the average in each season is more significant than it might at first appear, for the ring-width variability of the trees used in this analyses is an integrated measure of the limiting effect of low moisture and high temperatures throughout all seasons of the year (Figures 1 and 2). Thus, assuming the possibility of a perfect response of these particular tree-rings to climate at all pressure grid points and all four seasons without regard to their proximity to the tree-ring sites, one would expect no more than an average of 25% of variance explained in any one season. It would therefore appear that an average of 20% for each season is an encouraging result, especially with the choice of such a large grid of data points, ${}_{100}P_1$. As new species, and trees with more diverse response functions are added to the original tree-ring data set, and the areal coverage of the pressure grid is reduced, it should be possible to utilize differences as well as similarities in responses to improve prediction of the anomalies in climate for the separate seasons. This should increase the theoretical maximum predictions for each season to values greater than 25%.

Finally, it should be noted that the reconstructed pressure maps have great potential for studying and testing hypotheses about climatic variation and change. For example, a number of characteristic circulation patterns over the Atlantic and Pacific sectors have been recognized in the modern record - 1899-1969 (Kutzbach, 1970; Kutzbach, Hayden and Blasing, 1970). Similar anomaly patterns can be recognized in the pressure data estimated from tree rings for 1700 through 1900 (Figures 12, 13, and 14), although the past patterns differ from the modern record in their intensity and frequency of occurrence. Further studies are in progress which are aimed at refining the model, verifying the reconstructions and utilizing the results.

DISCUSSION AND CONCLUSIONS

Multivariate analyses seem particularly well-suited for tree-ring research. Principal component (eigenvector) analysis can be used to transform tree-ring or climatic data to a reduced number of orthogonal variables. Selection of the most important of these variables enables one to retain the large-scale regional components which may represent the macroclimatic "signal" and to eliminate the more random components or "noise."

Since the new set of transformed data are orthogonal variables, it is efficient to use the new variables in stepwise multiple regression analyses for prediction of dependent data such as tree growth. The transfer or response functions can be obtained by combining multivariate and multiple regression techniques. These transfer functions allow the measurement of rather subtle differences in the growth responses among trees on different sites.

The results from such use of multivariate analyses do not prove causation. However, they can be interpreted in terms of cause and effect if they are reasonable and consistent with expected physiological models and with current knowledge of the energy and water budgets of the respective trees and sites. For example, when temperature and precipitation for any given month are highly correlated, they will both be included in some of the same principal components and are both likely to appear in the values of the final response. Many of the response functions from arid-site trees show that high temperatures and low precipitation are jointly associated with low growth. It could be argued that only one of these variables actually limited growth, but because of the inter-correlation, it would be impossible in the above type of analysis to distinguish which is a causal and which is a correlated effect. However, it can be shown that temperature and precipitation are not only highly correlated, but that they interact by jointly affecting water relations and physiological processes that become limiting to growth of trees on semi-arid sites. Since these two factors can be shown to act in consort, they should both be considered as a part of a factor complex which limits growth.

In other cases, such as in analysis of trees from well-drained sites at the upper timberline, there is good evidence that low temperature rather than high moisture may become limiting to growth. In such cases, when both variables are entered in the response functions in an inverse manner, it would be most appropriate to interpret the apparent inverse relationship between growth and precipitation as a correlated rather than a causal effect.

In the second portion of this study, it was shown that canonical correlation and regression analyses make it possible to utilize many tree-ring chronologies to reconstruct anomalies in climatic variables such as pressure at different seasons and at a variety of grid points over the Northern Hemisphere. When the number of original variables under consideration is large, and they are likely to be correlated, it is helpful to first reduce the variables of each data set to their orthogonal principal components. Then the canonical correlation and regression analysis may be obtained and the calculated weights can be expressed in terms of the original variables by simple multiplications.

The amplitudes for the seven eigenvectors of anomalous tree growth which are weighted to give maximum correlation with surface pressure anomalies for the year (Figure 7) may also provide information on other climatic variables correlated with surface pressure. Thus, it seems plausible that these amplitudes may be used in equation 10 as predictors of such variables as temperature, precipitation, or other climatic variables associated with the regions of high predictability of pressure shown in Figure 11. The multiple regression weights, ${}_1R_p$, may be estimated for any common calibration period, and the canonically weighted tree-ring chronologies may then be used with the regression weights to reconstruct the particular climatic data for earlier years.

It is recognized that the predictions of individual seasonal anomalies obtained in the preliminary tests are undoubtedly subject to sizable error (Figure 11). Some failure of prediction could be attributed to the uniformity in the type of tree-ring data used in this preliminary analysis, to the fact that the eigenvectors of tree-ring data did not include rings formed after 1930, to some errors in the tree-ring data which are now corrected, to the choice of grid size and location, and to the arbitrary classification of the four 3-month seasonal periods. Correction of these difficulties will be attempted in future work. A certain portion of the lack of prediction will never be overcome, as tree rings, which respond to the climate during all seasons, cannot estimate climatic variation perfectly in any one season because they are also influenced by the variation in climate during the other three seasons.

It is also recognized that there may be a certain amount of non-stationarity and heteroscedasticity (Julian 1969) in tree-ring and climatic data. However, there is good evidence (LaMarche and Fritts, in press) that the tree-growth anomaly patterns of the present (1931-1962) are similar to the anomaly patterns of the past, (1700-1930). Also, the sampling replication and the standardizing routines used in compiling the 49 tree-ring chronologies give a measure of objectivity and stability as the non-stationarity due to the aging of trees is removed.

Since multivariate analysis is suitable for data diversity, it is now possible to relax to some extent our criteria for extreme selectivity of trees from arid sites (Fritts, 1969b). It appears that one can obtain more information on seasonal variations if a number of ring-width chronologies are used that respond differently to climate throughout each season. The response functions can be utilized to select those chronologies with diverse responses. In future work, selections will also be made for chronology length and the widest geographic coverage in order to obtain a new set of chronologies that are continuous back to A.D. 1500. Canonical analyses similar to that described here, as well as canonical regression, as described by Glahn (1968), will be made. This latter analysis allows use of information about spatial covariance in arriving at the final regression weights. We plan to utilize atmospheric pressure for the summer season concurrent with, as well as that preceding, the period of growth. It may also be possible to utilize a grid of climatic stations following procedures of Kutzbach (1967), and include temperature and precipitation as well as pressure.

We conclude from the preliminary studies that multivariate analyses coupled with multiple regression now makes it possible to readily and objectively evaluate the climatic information in ring-width chronologies. This information may be used to make reliable quantitative estimates of climatic or environmental variability, especially that which has occurred over North America and the western sector of the Northern Hemisphere since A.D. 1500.

SIGNIFICANCE

We believe that these multivariate approaches described herein could revolutionalize dendroclimatic analysis. The physiological models are sufficiently adequate that meaningful interpretations will not be difficult to obtain. Well-defined statistical models for the response of trees to their environment can be derived readily and these can be utilized to study tree growth and environmental relationships, select tree-ring chronologies and structure new dendrochronologic sampling designs. The improved data sets should provide more reliable estimates of past atmospheric circulation and related variables of temperature and precipitation.

The response functions appear relatively stable, i.e., similar functions are recoverable when analyses are run on chronologies derived from separate sets of trees in the same site. Sometimes the response functions of two chronologies differ only in one climatic element such as precipitation during winter. If the difference is significant (did not arise by chance), the particular climatic element may be estimated from the differences between the respective chronologies. By utilizing response functions in this way, it should be possible to develop methods of manipulating dendrochronological data to evaluate a variety of problems dealing with environment. Also the response function as shown in Figure 5 is ideally suited for assessing the effects of possible weather modification. It can be used to calculate the probable effect on tree growth of a specified change in climate, such as a rise in mean temperature or precipitation during a given month.

The multivariate methods of calibration as described in the second application, when used on the improved set of ring-width chronologies, are expected to yield a wealth of climatic information which is not only objectively derived, but is dated to the exact year corresponding to the tree-rings. Such data will provide a means for studying past climatic variability beyond existing climatic records. It appears that significant information on pressure over the Pacific and Atlantic Oceans as well as over North America will be obtained.

One approach to the study and evaluation of possible future climates is a study of past climates. A long climatic record can serve to identify the range or possible climates and the characteristics of possible climatic "modes." The work of Lamb (1963, 1966, 1969) has served to establish estimates of the characteristics of natural climatic variability for the past thousand years. His work, however, is largely restricted to the North Atlantic sector and knowledge of climatic variability elsewhere in the Western Hemisphere is less quantitative. Although prediction of climatic changes remains a task for the future, some estimates of "possible" climates would be useful for planning purposes. Furthermore, as sophistication in the modelling of present climate is achieved (e.g., Manabe, et al, 1970) and attempts to simulate recent past climates are begun (Mintz, 1968), it becomes essential that accurate maps of past climatic patterns be available for making comparisons (Sheppard, 1966). Finally, the need for a clearer understanding of "natural" modes of climatic variability is enhanced by recent hypotheses regarding man's inadvertent role in changing climate. That is, knowledge of past climatic variability may help to discriminate between "natural" and "man-produced" or "man-accentuated" changes.

More specifically, with continued additions of CO_2 and dust for the foreseeable future, several questions require answers. 1) What are the climatic modes of the recent past (A.D. 1500-1970)? 2) What are some of the essential characteristics of recent climatic modes? 3) Are the climatic modes resultant from man's activities unique or is there historical evidence for their past occurrence? Initial dendroclimatic work using multivariate techniques show great potential in offering the data input needed to answer these questions.

It is further proposed that natural integrating climatic sensors such as tree rings may possess several advantages over conventional sensors, such as thermometers and rain gauges. For example: 1) Recent studies of the variations of mean world temperature (1880-1970) are primarily based on temperature data from cities. Conventional climatic measurement may therefore include components of city climate. The use of well chosen, long chronologies of natural integrating sensors such as tree rings are not biased by urban climate. 2) Errors in climatic station data due to faulty instruments or improper recording cannot be corrected after the fact. Time series of tree-ring data can be replicated and re-analyzed in the event of apparent contradictions, i.e., one can check premises by the analysis of additional chronologies collected from the same site. 3) Standard climatic measures such as precipitation and temperature are, to some extent, limited by the tools of measurement and do not necessarily record natural complexes of climate. An organism such as a tree is a natural integrator of the climatic complex, and ring width is a direct measure of the natural climatic complexes limiting tree growth. Tree-ring chronologies may represent particular climatic complexes, characteristics or modes that may be less obvious in man's measurements of climate.

Tree rings thus offer a valuable adjunct to modern meteorological data and an invaluable contribution to the climatic record prior to and in conjunction with man's measurement of climate.

In the future more well-dated tree-ring chronologies and other well-dated proxy series of climate will undoubtedly become available from other sectors of the Northern Hemisphere and Southern Hemisphere. The same techniques can be utilized to transform the information from diverse proxy series into estimates of anomalies in pressure. Such estimates from an enlarged set of proxy series may allow the reconstruction of global variations in the world's circulation and could provide an extended, worldwide estimate of year-by-year climatic variability and change.

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REFERENCES

Bryson, R. A. and J. F. Lahey, 1958. The march of the seasons. University of Wisconsin, Final Report Contract AF 19-(604)-992, 41 pp.

Fritts, H. C., 1962. An approach to dendroclimatology: screening by means of multiple regression techniques. Journal Geophysical Res. 67(4):1413-1420.

___________, 1963. Computer programs for tree-ring research. Tree-Ring Bulletin 25(3-4):2-7.

___________, 1965. Tree-ring evidence for climatic changes in western North America. Monthly Weather Review 93(7):421-443.

___________, 1969a. Bristlecone pine in the White Mountains of California: growth and ring-width characteristics. Papers of the Laboratory of Tree-Ring Research, No. 4, The University of Arizona Press, Tucson, 44 pp.

___________, 1969b. Tree-ring analysis: a tool for water resources research. Transactions, American Geophysical Union 50(1):22-29.

___________, 1969c. A study of the physiological relationships underlying correlations of tree-ring width and climate. Final report on NSF Grant GB-3658, 35 pp.

Fritts, H. C., David G. Smith and Marvin A. Stokes, 1965. The biological model for paleoclimatic interpretation of Mesa Verde tree-ring series. American Antiquity 31(No. 2, Part 2):101-121.

Fritts, H. C., David G. Smith, J. W. Cardis and C. A. Budelsky, 1965. Tree-ring characteristics along a vegetation gradient in northern Arizona. Ecology 46(4):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(1-2):15-20.

Glahn, H. R., 1968. Canonical correlation and its relationship to discriminant analysis and multiple regression. Journal of Atmospheric Sciences 25:23-31.

Glock, W. S., E. M. Gaines and S. R. Agerter, 1964. Soil-moisture fluctuations under two Ponderosa pine stands in northern Arizona. U.S. Forest Service Research Paper RM-9.

Glock, W. S. and S. R. Agerter, 1969. Tree growth and precipitation near Flagstaff, Arizona. Yearbook of the Association of Pacific Coast Geographers 30:79-106.

Kutzbach, J. E., 1967. Empirical eigenvectors of sea-level pressure, surface temperature and precipitation complexes over North America. Journal of Applied Meteorology 6:791-802.

___________, 1970. Large-scale features of monthly mean Northern Hemisphere anomaly maps of sea-level pressure. Monthly Weather Review 98(9):708-716.

___________, B. P. Hayden and T. J. Blasing, 1970. Diagnostic study of present circulation variability and inferred circulation variability since 1000 A.D. Unpublished manuscript.

Julian, P. R., 1969. An application of rank-order statistics to the joint spacial and temporal variations of meteorological elements. Monthly Weather Review 98:142-153.

Julian, P. R. and H. C. Fritts, 1968. On the possibility of quantitatively extending climatic records by means of dendroclimatological analysis. Proceedings of the First Statistical Meteorological Conference, American Meteorological Society, Hartford, Connecticut, May, 1968, pp. 76-82.

LaMarche, V. C., Jr. and H. C. Fritts, in press. Anomaly patterns of climate over western United States, 1700-1930, derived from principal component analysis of tree-ring data. Monthly Weather Review.

Lamb, H. H., 1963. On the nature of certain climatic epochs which differed from the modern (1900-1939) normal. Changes of Climate UNESCO Arid Zone Research Series XX, 125-150, Paris.

___________, 1966. Secular variations of the atmospheric circulation since 1750. Geophysical Memoirs No. 110, Meteorological Office, London, H.M.S.O., 125 pp.

___________, 1969. The new look of climatology. Nature 223:1209-1215.

Manabe, Syukuro, Joseph Smogorinsky, J. Leith Holloway, Jr., and Hugh M. Stone, 1970. Simulated climatology of a general circulation model with a hydrologic cycle: III. Effects of increased horizontal computational resolution. Monthly Weather Review 98:172-212.

Mintz, Y., 1968. Very long-term global integration of the primitive equations of atmospheric motion: an experiment in climatic simulation. Meteorological Monographs 8:20-36.

Sellers, William D., 1968. Climatology of monthly precipitation patterns in the Western United States, 1931-1966. Monthly Weather Review 96(9):585-595.

Sheppard, P. A., 1966. Preface, World Climate from 8000 to 0 B.C., page 1, Royal Meteorological Society, London.

Stokes, M. A. and T. L. Smiley, 1968. An introduction to tree-ring dating. University of Chicago Press, 73 pp.

U.S. Weather Bureau, 1961, 1962. Climatological data, Asheville, North Carolina 48, 49, No. 1-13.

___________, 1963. Decennial census of United States climate, monthly averages for state climatic divisions, 1931-1960. Climatography of the United States No. 85, Washington, D. C.