Climatic, Hydrologic & Water Supply Inferences From Tree Rings

Tree-ring analysis can be utilized as one means of obtaining such necessary environmental information as extended time series of precipitation data.

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The earth is continually subjected to extreme periods of heat, cold, droughts and floods. Are these climatic and hydrologic extremes anomalies, or are they phenomena that may occur either randomly or in some periodic fashion? In general, instrumented climatic records do not extend far back enough in the past to provide an answer to this question. Fortunately, there are sources of proxy data that may provide information on long-term climatic variations and trends. These data include stratified sediments in streams lakes and swamps, pollen profiles, layered ice cores and tree rings. Tree rings are superior to other proxy data sources because they can be precisely dated as to the year of formation, both low frequency (long term) and high frequency (short term) variations are preserved, and samples can be obtained and replicated from many parts of the world with relatively small investment in time and effort. The time span covered by tree-ring series, however, is relatively short when compared with other sources such as pollen profiles or ice cores.

The usefulness of tree rings for climatic and hydrologic reconstructions is based on the fact that the annual growth rings of many tree species in temperate and sub-polar regions reflect the environmental conditions of the sites where they grow. These conditions when correlated with normal genetic and physiologic factors yield rings of varying widths. In temperate climates, ring widths generally reflect moisture conditions during and prior to individual growing seasons. Narrow rings are produced when moisture is deficient and correspondingly wider rings are produced when moisture supplies are adequate for growth.

The discipline concerned with the use of tree rings for dating past events is known as *dendrochronology*. Two other subdisciplines, *dendroclimatology* and *dendrohydrology*, have developed rapidly during recent years and involve, respectively, the reconstruction of climatic and hydrologic events. This rapid development has been made possible by the evolution of high speed computers capable of handling large amounts of data, and more sophisticated statistical methods that facilitate the development of complex relationships between ring width characteristics and climatic and hydrologic parameters.

Dendrochronological Techniques

Site Selection and Sampling. As mentioned earlier, the width of annual growth rings represents an integration of genetic, physiologic and environmental factors. As a result, there is considerable variation in the amount and kind of information that can be extracted from tree rings. Site selection and sampling is, therefore, of paramount importance, especially when the data are to be used for climatic or hydrologic reconstructions.

In general, the greatest amount of climatic information can be obtained from trees growing on sites where moisture is apt to be limiting and which have not been influenced by external factors such as fire, insects, disease and human intervention. In the southwest, for example, the most "climatically sensitive" trees are those growing on exposed sites with shallow soil and that are free from the influence of groundwater. These trees typically have thin crowns, spike tops and an overall stunted appearance. Radial growth depends on soil moisture whose source is precipitation.

An adequate number of samples is essential to minimize the between-tree variance. Although complete cross-sections are most desirable, they are seldom available. Thus, in most cases, trees are sampled by removing pencil-size cores from each tree with an increment borer (a tool widely used in forestry). Two cores are usually extracted from opposite sides of each tree. For the most climatically sensitive sites, samples from a minimum of ten trees may be sufficient to yield reliable inference data. Two to three times that number may be required if there is considerable variation between trees.

Dating and Measuring. Each tree ring in a sample must be accurately dated as to the year of formation regardless of whether the intended use is for archaeological dating or for climatic reconstruction. In concept, dating should merely involve counting the rings back from the one formed during the year of sampling. Unfortunately, this procedure is not thoroughly accurate because environmental conditions often result in multiple or locally absent (missing) rings. For example, if soil moisture has been limiting for a significant amount of the growing season, growth may not even be initiated and a ring will not be present for that year. Multiple rings, in contrast may be formed if growth is interrupted during the growing season by unfavorable conditions (*e.g.*, a period of dry weather) and then resumes again if conditions improve.

Ring-width anomalies, such as missing or multiple rings, can only be solved by cross-dating. This technique involves matching the pattern of narrow and wide rings on a year-to-year basis, both within and between trees. A graphic representation of ring widths from each sample, known as a skeleton plot, is very useful in dating samples where anomalies are present. After skeleton plots have been developed for cores from a given site, they can be compared to determine similarities in ring patterns. These patterns can then be used to identify the occurrence of missing and multiple rings and identify the date that the anomaly occurred. After the anomalies have been reconciled, dating of the sample can be completed. This entire procedure is described in detail by Stokes and Smiley.[1]

Although continual improvements have been made in the measuring instruments, the basic aspects of measuring tree rings have changed little over the years. Standard equipment usually includes a binocular microscope coupled with a calibrated moving stage that allows the core to be aligned with the microscope crosshair for measurement.

Dramatic improvements have been made for encoding and processing measurements. At the Laboratory of Tree-Ring Research at the University of Arizona, for example, the present system uses precision screw stages fitted with optical incremental shaft encoders and interfaced with a microcomputer. Software has been developed for direct transmission of ring-width data to mainframe computers for various statistical procedures and analyses.

Standardization of Ring-Width Series. When raw ring-width measurements are plotted against time, a decreasing exponential curve is evident for many tree species. This trend reflects the aging process and must be removed before the data can be statistically analyzed. This adjustment is accomplished by fitting an appropriate curve to the data and then deriving an index by dividing the actual ring width for a given year by its corresponding curve value. This process is known as standardization. Curve fitting ranges from using a modified exponential to orthogonal polynomials and cubic splines, depending on the complexity of the curve function.[2,3] The ring-width indices have a mean value of 1.00 when plotted against time for a *standardized ring-width chronology,* which is weakly stationary. The standardized chronologies can be combined to form a mean value function or site chronology. In addition to removing the biologically-induced growth trend, standardization also prevents a chronology developed from fast-growing trees from dominating others developed from more slowly growing trees where various series are combined.[4]

Several statistical parameters are routinely used to characterize standardized chronologies. These parameters include the mean, variance, standard deviation, standard error, serial correlation and mean sensitivity. The latter, mean sensitivity, is unique to dendrochronology and is determined by dividing the absolute difference between adjacent rings by their mean. Although mean sensitivity is a measure of high frequency variation, little is know about its distribution and power. Chronologies containing the greatest amount of climatic information usually have high mean sensitivities, large standard deviations and low first-order correlations.

Reconstruction Methods. At the outset it is important to recognize that tree-ring chronologies reflect the climatic and environmental conditions of the sites where the samples were taken. Hence, each ring represents an integrated response to a highly complex interaction of site and climatic factors acting in concert with the genetic characteristics of individual trees and their physiological responses to all of these factors. It is possible to maximize desired climatic signals by careful sampling. Maximum response to precipitation can be obtained by sampling trees from moisture-stressed sites. Conversely, samples should be taken from trees growing on flood plains if the objective of the study is to obtain data on groundwater fluctuations.

A period of overlap between tree-ring chronologies and instrumented weather records is essential for climatic reconstructions. A portion of the overlapping record is used to develop mathematical relationships between the measured parameters and the ring-width indices, a procedure known as *calibration.* The remaining overlap is then used to verify the established relationships; this procedure is termed *verification.*

Multiple step-wise regression was used in earlier reconstructions to select a small set of independent variables from a much larger group. This procedure was flawed because of high intercorrelations between the independent variables. This disadvantage has been circumvented by using principal component analysis to develop new sets of uncorrelated variables called empirical orthogonal functions (EOFs).[5,6] EOFs are developed from a matrix of correlation coefficients among the independent variables and the first few usually represent most of the variability in the dendroclimatic data. Higher order EOFs are usually discarded as they may well be mathematical artifacts of the technique and unrelated to the data.

Critical to climatic reconstructions is the development of transfer functions in the calibration procedure to extract climatic signals from the tree-ring data. Transfer functions come in many forms with some utilizing single series and others sets of series. Since they are empirically developed, it is necessary to proof-test (verify) numerous transfer functions. A portion of the data used for calibration is held back for proof-testing the transfer functions so they can be evaluated on data not used in their development. After selecting an appropriate function, the final transfer function is developed from the entire data set.

Persistence in tree-ring series, which may represent a biological memory of climate coupled with a direct record of climatic persistence, creates problems in climatic reconstructions. Earlier workers attempted to solve this problem by using moving averages with arbitrarily chosen coefficients or weights. Although results improved, unaccountable shifts in critical events occurred due to the effects of moving averages.

In more recent work, lagged tree-ring variables[7] and multivariate statistical techniques have been used to determine the sign and magnitude of the coefficients used to transfer ring-width variances at different lags into an estimate of specific climatic variables.[8] Box-Jenkins modeling can also be used to determine the appropriate persistence model by successive testing. Models range from a simple autoregressive (AR) or moving average (MA) to more complex autoregressive moving averages (ARMA).

Meko evaluated both approaches and found that each method had advantages and disadvantages depending on data conditions.[9] Where tree-ring series had appreciable autocorrelation, the Box-Jenkins approach provided a generally flatter response than the lagged predictor method. This evenness of response, however, sacrificed accuracy at longer wavelengths by underestimating the amplitude of broad swings from the mean. The Box-Jenkins method is preferable if the spectrum of the long-term reconstruction is of interest because the method attempts to minimize the distortion of persistence. In contrast, the lagged predictor method accepts frequency distortion as a trade-off for higher total variance.

Climatic & Hydrologic Reconstructions: Early Studies

Some of the early work relating ring widths to climatic factors in the northeastern United States was performed by Charles J. Lyon of the Department of Botany at Dartmouth. Lyon examined complete cross-sections from two eastern hemlock (*Tsuga canadensis*) trees that had been felled near Wakefield, New Hampshire, and correlated the ring widths with precipitation records dating back to 1857 from a weather station at Lakeport some 20 miles away.[10] He found that wide and narrow rings correlated reasonably with precipitation during the months of April through August and that the ring patterns indicated numerous periods of wet and dry seasons during the past. Lyon expanded his work by examining sections of hemlock trees from five additional sites, three in New Hampshire and two in nearby Vermont.[11] These additional data confirmed, in general, his earlier observations on the relationship between ring widths and growing season precipitation, and further indicated the importance that precipitation during the fall preceding an individual growing season might have on growth.

Lyon took advantage of the "blowdown" caused by the New England hurricane of September, 1938, and obtained sections from seven white pine (*Pinus strobus*) and four hemlock sites in northeastern Massachusetts (most sites were within 25 miles of Boston).[12] This expanded data set further emphasized the importance of soil moisture availability during the growing season on ring widths. The lag effect of antecedent moisture was also evident to a lesser degree.

Work such as that of Lyon might be considered insignificant in view of present knowledge and status of dendrochronology. It should be recognized, however, that until a decade or so ago few people believed that tree-ring data could be successfully used for climatic reconstructions in the humid climate of the eastern Untied States. Thus, this early work, which established a positive relationship between available moisture and ring widths, assumes a position of greater importance.

The most significant early work in climatic and hydrologic reconstructions was that of Edmund Schulman working at the University of Arizona's Laboratory of Tree-Ring Research. Schulman was an indefatigable collector and published numerous papers from 1936 until his death in 1957. His earlier work dealt largely with the reconstruction of precipitation in the southwest. His first hydrologic reconstructions, based on his doctoral dissertation at Harvard University[13] were published in 1945 and dealt with the Colorado River Basin[14] and the Pacific Slope in California.[15] His many works are summarized in a classic publication, *Dendroclimatic Changes in Semiarid North America.*[16]

The importance of Schulman's contributions to dendrochronology and its subdisciplines simply cannot be overestimated. During that period, the slide rule and calculator represented the state of the art in data handling. Certainly, Schulman provided a firm background for both dendroclimatology and dendrohydrology, areas that have developed rapidly during the past two decades.

Although climatic reconstructions are not involved, the classic work of H.E. Hurst in quantifying climatic persistence in hydrologic time series deserves mention for two reasons.[17,18] First, he used long-term tree-ring series from the western United States in his investigations. Secondly, Hurst's coefficient has been employed to characterize persistence in reconstructed drought series.

While working as a hydrologic engineer concerned with reservoir design on the Nile River in Egypt, Hurst used the river's long-term flow records to investigate persistence in periods of high and low flow. He reasoned that the maximum and minimum of the cumulative departures from the mean might provide a useful statistic for measuring long-term fluctuations in the geophysical time series. The relationship is expressed as:

$$(R/S) = (N/2)^h$$

where:

R = Range (maximum - minimum) of cumulative departures from the mean of a time series

S = Standard deviation

N = Length of record

h = Exponent that Hurst found to range from 0.46 to 0.96 with a mean of 0.726

The theoretical value of h equals 0.5 for a series of purely random events and those with short memory (*e.g.*, first order Markov Processes). It now seems apparent that Hurst's work demonstrated the fact that h is greater than 0.5 because of the climatically-induced low-frequency signal (his original conjecture). Furthermore, it can be seen that climate is not necessarily a purely random function of time. These two points are extremely important in water resource planning.

Climatic & Hydrologic Reconstructions: Case Studies

Reconstruction of Colorado River Flow. The Colorado River is a major source of surface water for agricultural, industrial and municipal use in the southwestern United States. This 1,440-mile long river drains some 244,000 square miles and flows through some of the most arid and spectacular scenery in the United States. Most of the flow originates in the high mountains of the Upper Basin which comprises about 20 percent of the total drainage area. The average annual flow is about 13.5 million acre feet (maf) of which about 5 maf are diverted out of the basin. This diversion is the largest interbasin transfer in the country.

Since its drainage basin involves several states, water from the river was allocated between the upper and lower basins by the Colorado River Compact of 1922. Equal amounts, 7.5 maf, were allocated to each basin and, in a later treaty, 1.5 maf to Mexico. The allocations totalled 16.5 maf and were based on an estimated annual flow of 16.2 maf. Ironically, the river did not reach this volume of flow until the years of extremely heavy snowfall in the mid-1980s. Clearly, the flow of the Colorado was over allocated by the 1922 compact. Serious shortages have not yet occurred because of the large amount of reservoir storage present and the fact that the upper basin has not fully used its allocation. Because of the potential for serious shortages, a tree-ring study was initiated to reconstruct the river flow back in time well beyond the period covered by instrumented records.[19,20,21]

The reconstruction was based on tree-ring data from 30 sites located in the upper basin and selected to represent as many major runoff-producing sites as possible (see Figure 1). Based on several models and combinations of tree-ring sites, the estimated flow of the river at Lees Ferry, Arizona (the dividing point between the upper and lower basins), is 13.5 ±0.5

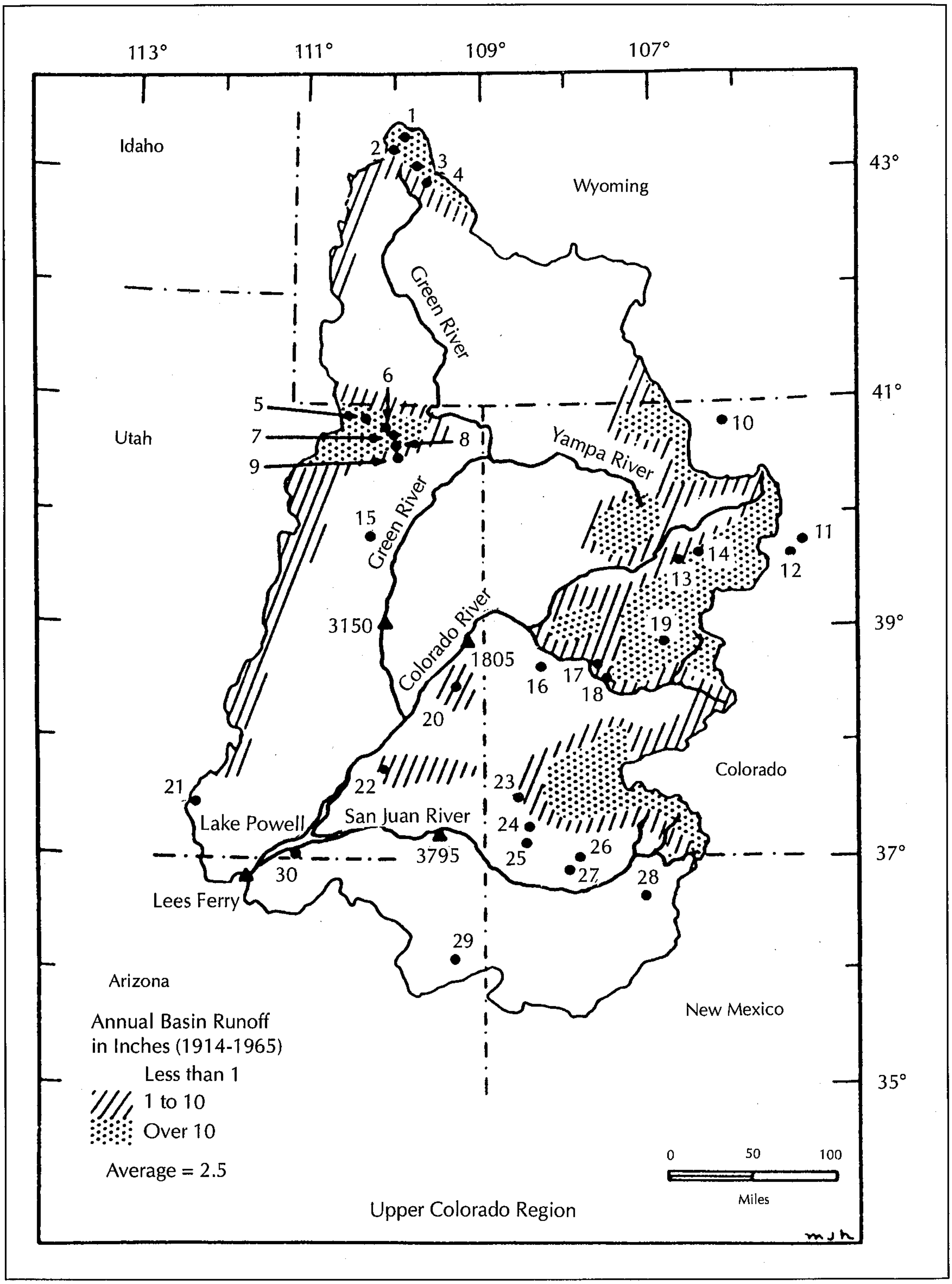


FIGURE 1. Upper Colorado River Basin showing the annual runoff areas (shaded), the location of the tree ring sites (dots) and four major gaging stations (triangles).

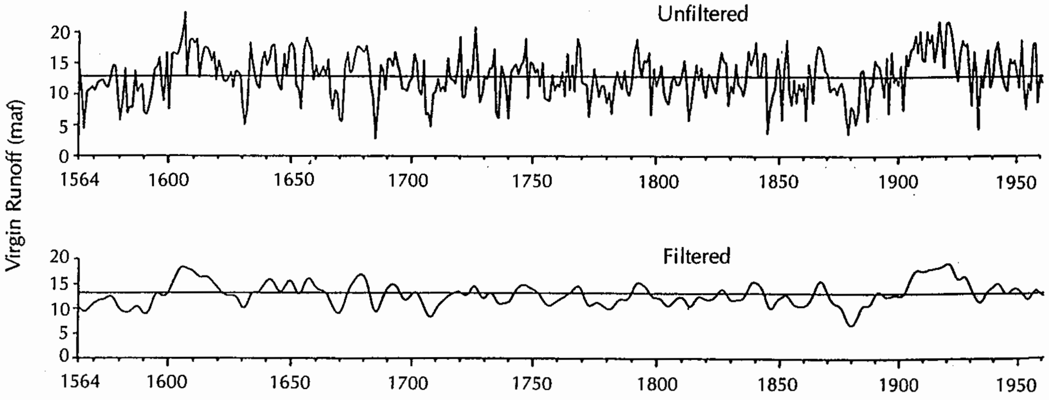


FIGURE 2. Reconstructed flow for the Colorado River at Lees Ferry, Arizona, for the years 1564 to 1961. Actual data plotted on the upper graph. The lower graph shows data after treatment with a ten-year moving average filter.

maf. A hydrograph of the river flow back to 1564 is shown on Figure 2. Of special interest is the high flow period from 1906 through 1930, which is the highest during the entire period of this reconstruction. The Colorado River Compact was based on flow data for this anomalously high period. The data present an extremely important, and often overlooked point in hydrologic forecasting — *i.e.*, there is no assurance that any given period of gaged record for a river represents a random sample of the infinite number of past events. Although the compact was based on the best data available at the time, it simply was not typical of the long-term river flow.

Drought in the Western United States. Periods of short-term or prolonged deficiencies in precipitation, generally known as droughts, are common occurrences in global climatic regimes and it would be rare indeed to find a time when the earth was free of drought. Sustained droughts can cause great human suffering due to shortages of food and water. Thus, their severity, duration and recurrence interval are of vital concern to all segments of society.

Some areas are more drought prone than others. The western United States, especially the Great Plains, is one such region where droughts seem to occur at relatively regular intervals. Some insights into this aspect of drought occurrence have been gained by reconstructing the climatic history of the western United States from tree-ring data dating back to 1700.[19]

This climatic reconstruction was accomplished by developing a causal relationship between ring-width indices from 40 to 65 sites and the Palmer Drought Severity Index (PDSI).[22] This index uses an empirical water balance approach to develop measures of drought as shown in Table 1. The index values indicate the same degree of drought from one region to another, which is an advantage when drought comparisons are made over a large area.

Monthly PDSI values covering the period from 1931 to 1970 for the 204 climatic divisions in the western United States were obtained from the National Climatic Data Center in Asheville, North Carolina. The 204 climatic divisions were combined into 40 regions that had reasonably homogeneous climatic characteristics. A regional PDSI was developed by adding the PDSI values for all divisions within a specific region.

Since tree-rings represent a yearly value as compared to monthly data for the PDSI, it was necessary to select a single value for the former so the data sets would be compatible. The July PDSI was selected because diameter growth for

TABLE 1
Palmer's Classification of Drought

Palmer Index					Degree of Drought
		PDSI	≤	-4.0	Extremely Dry
-4.0	<	PDSI	≤	-3.0	Severely Dry
-3.0	<	PDSI	≤	-2.0	Moderately Dry
-2.0	<	PDSI	≤	-1.0	Mildly Dry
-1.0	<	PDSI	<	+1.0	Near Normal
+1.0	≤	PDSI	<	+2.0	Mildly Wet
+2.0	≤	PDSI	<	+3.0	Moderately Wet
+3.0	≤	PDSI	<	+4.0	Severely Wet
+4.0	≤	PDSI			Extremely Wet

the tree species used is essentially complete by the end of July. Also, droughts tend to peak in July when demands are greatest for growing plants as well as for animals and human consumption.

A Drought Area Index (DAI) was developed through multivariate analysis to indicate large-scale drought patterns. An eigenvector analysis was applied to the 40 regional PDSI values and the tree-ring series from the appropriate grid. A few of the eigenvectors were chosen from each field that represented a high percentage of the total variance.

The eigenvector amplitudes for the period of overlap between the PDSI and tree-ring series (1931 to 1970) were then related to each other by canonical analysis. The resulting transfer function was then used to translate the tree-ring data into PDSI units for each year back to the year 1700. Annual DAI values were calculated for PDSI values of -1, -2, -3 and -4. The DAI of a PDSI -2, for example, would be the total number of regions (out of the total of 40) that had a PDSI of -2 or greater.

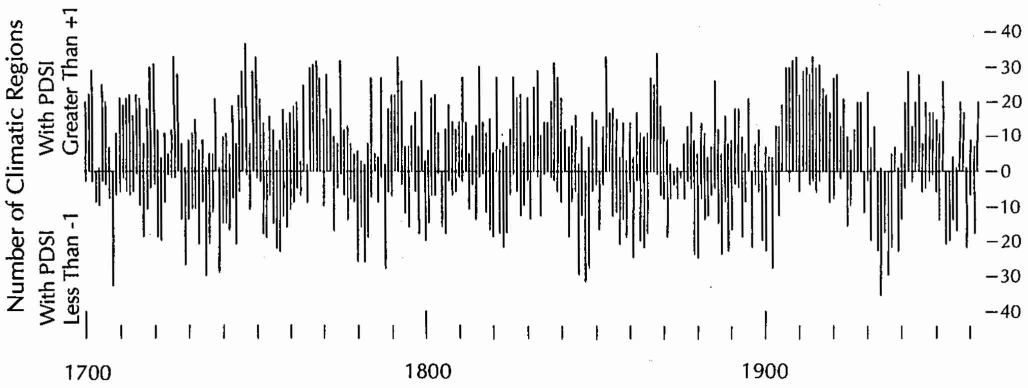


FIGURE 3. The number of climatic regions reconstructed as drier and wetter than normal for the years 1700 to 1962 (S40 grid).

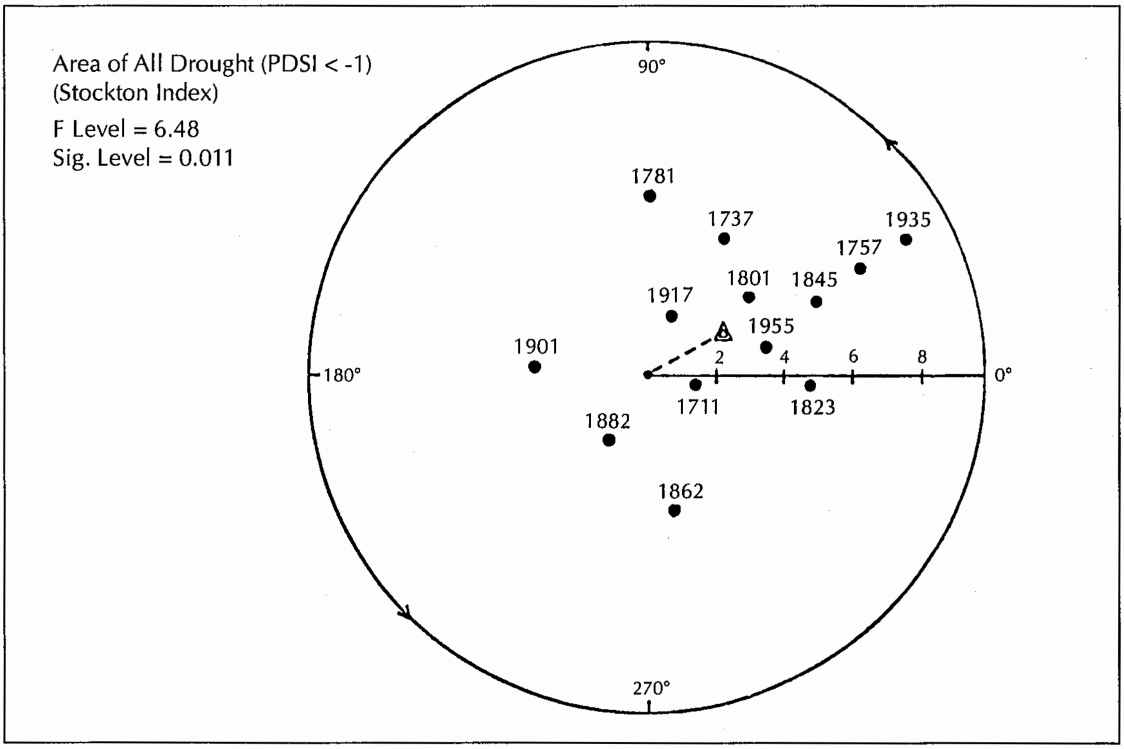


FIGURE 4. Harmonic dial based on reconstructed DAI series for Palmer Index less than or equal to -1 and on Hale sunspot series. Triangle marks centroid.

A distinct periodicity in the occurrence of dry periods is shown when the annual DAI series is plotted against time (see Figure 3). The periodicity was confirmed by spectral analysis that peaked at 22 years and that was significant at the 99 percent level. The periodicity diminished at more intense drought categories; significance was above 95 percent for PDSI less than -2 and less than 95 percent for values of -3 and -4.[23,24]

This highly significant periodicity of 22 years suggested a possible relationship with the Hale Solar Cycle that has a similar period of occurrence. Both cross-spectral and harmonic dial analyses were used to investigate this possible relationship. Squared coherency between the DAI and Hale sunspot series peaked significantly (95 percent level) near 22 years. This relationship was strongest for the most severe drought (PDSI less than -3) category tested.

Harmonic dial analysis was used to test the degree of consistency in which the DAI and Hale sunspot series progressed on a year-to-year basis. Both series were first filtered to emphasize variance near 22 years. Maxima from the filtered DAI series were plotted on a dial with the position of each peak determined by the number of years since the preceding sunspot maximum and the amplitude of the DAI peak. The clustering of points along one radial direction far from the center of the dial indicates strong phase locking. The procedure is illustrated by the plot in Figure 4. The maximum area in drought tends to lag the sunspot numbers by about two years with a significance of 99 percent.

The drought area index shown in Figure 3 (drought side only) was examined and an equation was developed for comparison with possible solar and lunar influences.[25] The relationship that extended beyond 1965 (the end of the database) is shown in Figure 5. It shows that expanded areas of drought might be expected in the western United States for 1976, 1990 (approximately) and 1996 (approximately).

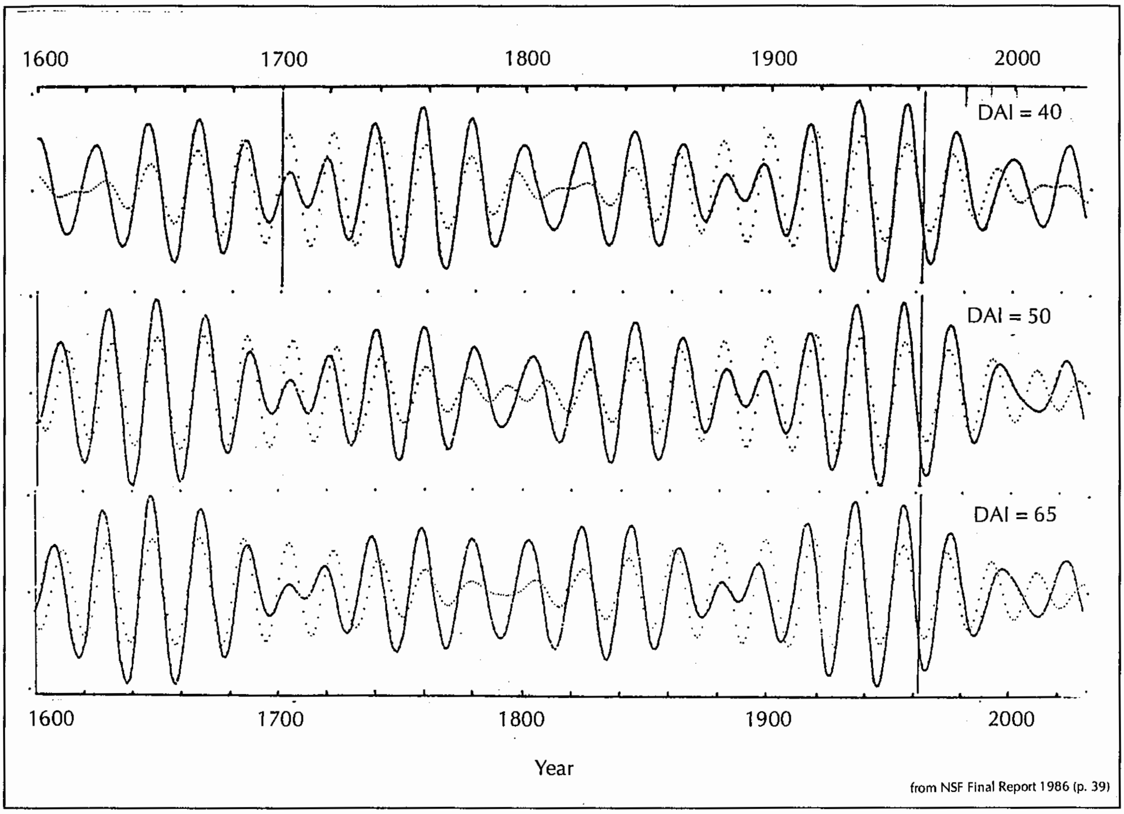


FIGURE 5. Time series plot of "lunar" (dotted lines) and combined "solar" and "lunar" variations of DAI for the years 1600 to 2030.

However, it should be emphasized that these data merely represent a possible relationship between the occurrence of widespread drought and solar activity. No claim is made as to physical factors or any other possible forcing actions involved, or whether the relationship will hold in data sets from other parts of the world.

Annual Precipitation in Iowa. Duvick and Blasing reconstructed annual precipitation in Iowa back to the year 1680 based on tree-ring series from three sites of white oak (see Figure 6).[26] They found that five ten-year periods during the last 300 years were comparable in dryness to the severe drought of the 1930s. An extremely long drought was apparent in the tree-ring series from 1816 to 1827. The standard normal period, from 1931 to 1960, was one of the driest 30-year periods in the last 300 years, but the more recent period from 1941 to 1970 was the same as the average for the entire period of reconstruction.

Precipitation in the South-Central United States. Blasing, Duvick and Stahle used tree-ring series from ten sites in Texas, Oklahoma and Arkansas to develop a 231-year reconstruction of annual precipitation for 12 climatic divisions in the same three states (see Figure 7).[27] Their results indicate that the severe and prolonged drought of the 1950s was exceeded only once (about 1860). Severe droughts, in general, have occurred in the past at intervals of 15 to 25 years. The data suggest that serious droughts are likely to occur in the future even in the absence of projected "greenhouse" warming.

Climatic Change in North Carolina. Tree-ring chronologies from millennium-old bald cypress trees were used by Stahle, Cleaveland and Hehr to reconstruct the climatic history of North Carolina from the year 372 to 1985. Based on reconstructions of the PDSI for the month of

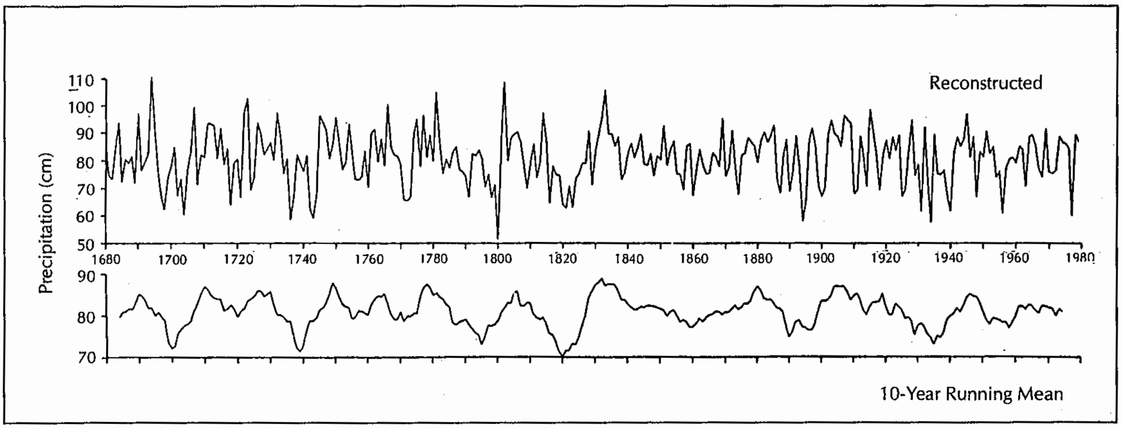


FIGURE 6. Reconstructed annual precipitation (August-July) for Iowa-Illinois for the years 1680 to 1979 (top) and their ten-year running means for the fifth year of each ten-year sequence (bottom).

June, they found that several prolonged droughts occurred during the Medieval Warm Epoch (1000 to 1300). Relatively wet conditions prevailed during the later stages of the Little Ice Age (1650 to 1750), and since that time there has been a long-term increase in the average PDSI for June. The record drought of 1985-86 and the preceding three decades of much wetter than average conditions both appear to have been rare climatic events since the start of the study. Results also suggest that the growing season of North Carolina has undergone statistically significant changes both in average conditions on a 30-year time scale and interannual variability on a time scale of ten years.[28]

Drought in Morocco. From 1979 to 1984 the Kingdom of Morocco, as well as much of Africa, was in the grip of extreme drought. The

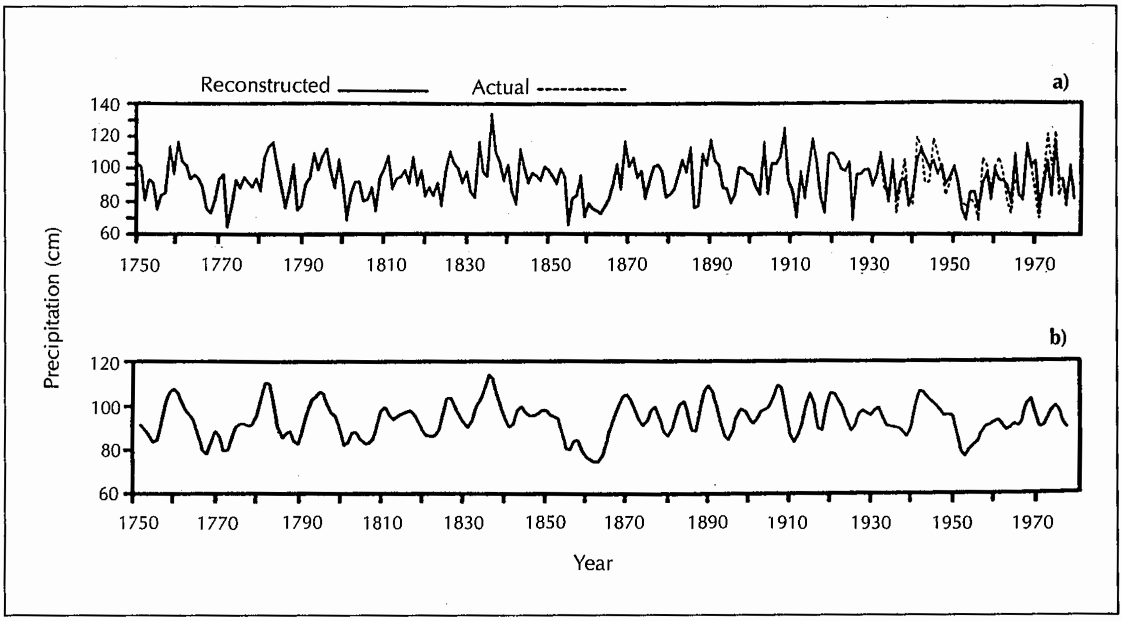


FIGURE 7. Reconstructed annual precipitation (July-June) for Texas-Arkansas from 1750 to 1980 (a), and after smoothing with a five-weight binomial filter (b).

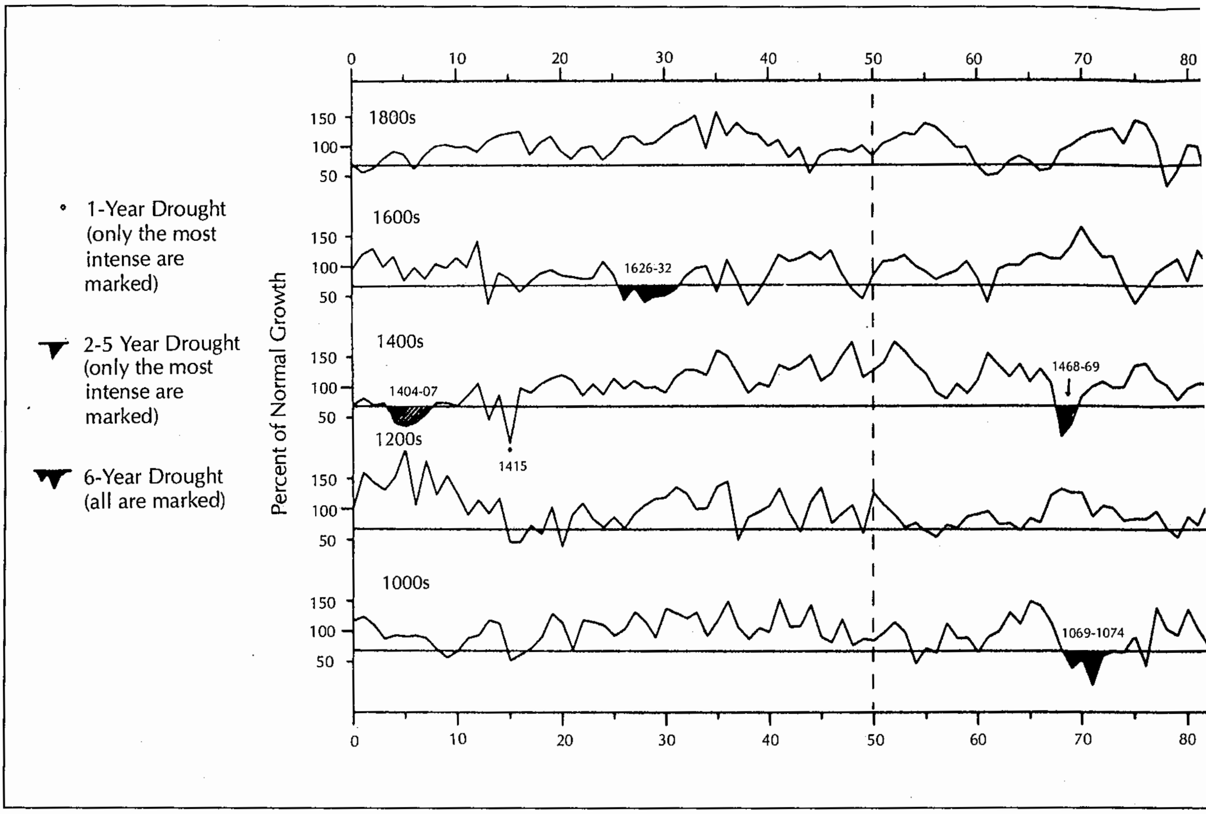


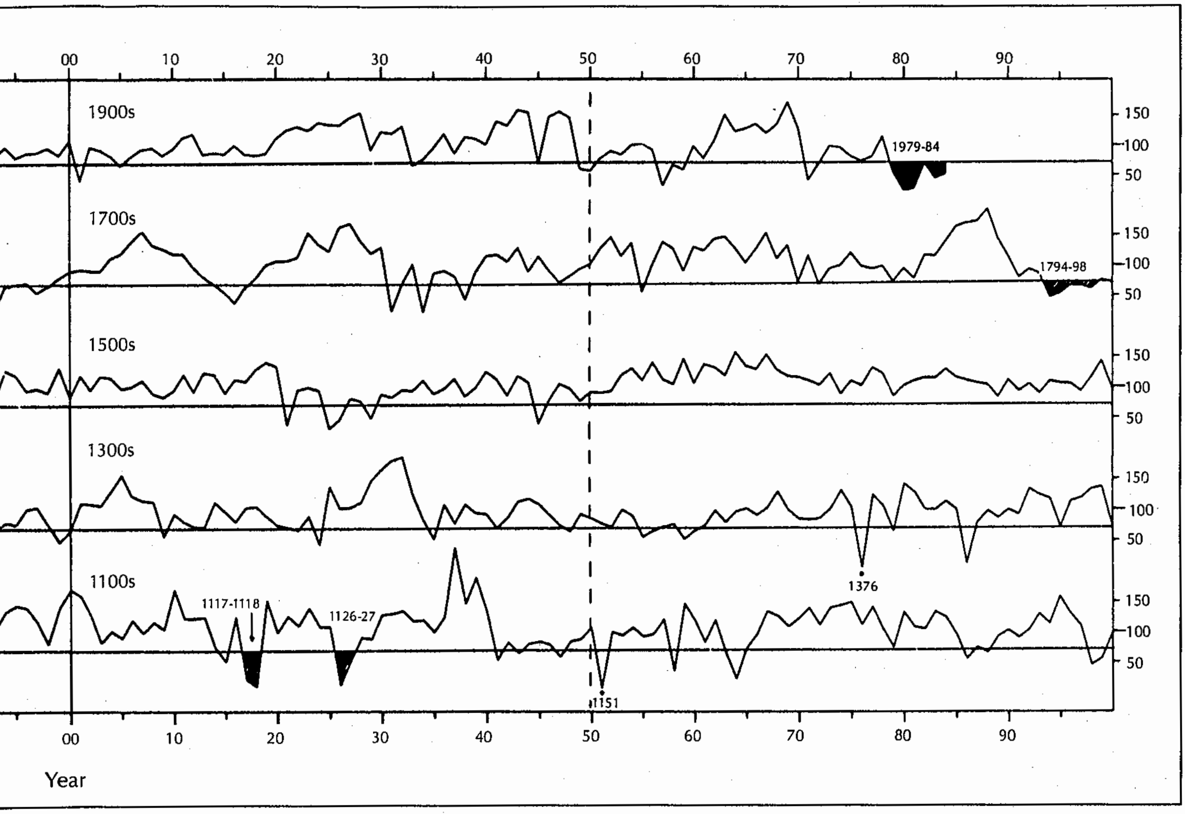
FIGURE 8. **Plot of runs analysis on Col du Zad, Morocco, series. The horizontal line is the 70 percent threshold used to define drought occurrence. The shaded areas show the longer drought periods from the year 1000 to 1984.**

Moroccan government asked the Laboratory of Tree-Ring Research to undertake a tree-ring study and attempt to determine the following:

- Whether the drought from 1979 to 1984 represented, as many feared, a trend toward greater aridity.
- Whether similar periods of drought had occurred in the past.
- To place the 1979 to 1984 drought in proper historical perspective with regard to duration and severity.
- Whether either an 18.6- or 22-year periodicity in the occurrence of drought could be detected in the tree-ring series.

Climatic data from Moroccan weather stations were used along with tree-ring series from six sites that were sufficiently sensitive to climate so that they could be used in reconstructing drought history back to the year 1750. A subset of three sites was used to determine relationships with cool-season precipitation, the most important period of runoff in Morocco. Another site, dating back to the year 984, provided valuable information on drought occurrence, severity and duration for the past 1,000 years.[29,30]

Based on the oldest series (Figure 8), it appears that droughts in central Morocco occur on an average of once every eleven years. The duration is rather short, averaging about 1.6 years with most ranging from 0.5 to 2.7 years. Droughts of longer duration are relatively rare. Six-year droughts like the most recent (1979 to 1984) occurred only once in every 455 years. Other six-year droughts occurred from the years 1069 to 1074 and 1626 to 1632. One severe five-year drought extended from 1794 to 1798, and two severe four-year droughts occurred



from 1404 to 1407 and 1714 to 1717. Droughts lasting three years occurred from 1693 to 1695, from 1860 to 1862, and from 1957 to 1959. There were 26 droughts of two-year duration and 54 lasting one year.

Moroccan weather records indicate that the winter of 1944-45 was unequalled in drought area and severity during the past 50 years of record. Tree-ring records, however, suggest that this drought year was exceeded in severity many times during the past 1,000 years.

The full set of tree-ring data indicate that the 1979 to 1984 drought was equalled only once, in the years from 1878 to 1882, in the period starting in 1750 and ending in 1984. The 1,000-year record suggests that the most recent drought was also equalled or surpassed in 1069 to 1074 and 1626 to 1632.

The data showed no evidence that the recent extended dry period represented a unique change toward a more arid climatic regime. Similar periods have occurred in the past and will most likely occur again. Future droughts may, indeed, be more frequent based on predictions of climatic warming due to increasing amounts of "greenhouse" gases in the atmosphere. Morocco is in the latitudinal zone where some models predict that increasing temperatures will be accompanied by more arid conditions.

Tree-Ring Data & General Climatic Patterns

An important outcome of this research is its relevance to the North Atlantic Oscillation (NAO) in surface atmospheric pressure and associated rainfall in Morocco. Lamb and Peppler have shown that there is an association between extended drought periods (and wetness) in Morocco and winter surface pressure distribution reversals in the North Atlantic (see Figure 9).[31] This relationship may offer some insight into the prediction of future droughts if an association with sea surface temperature variations can be demonstrated as happened with the El Nino/Southern Oscillation phenomenon. Utilizing the association of the tree-ring data with Moroccan precipitation, it

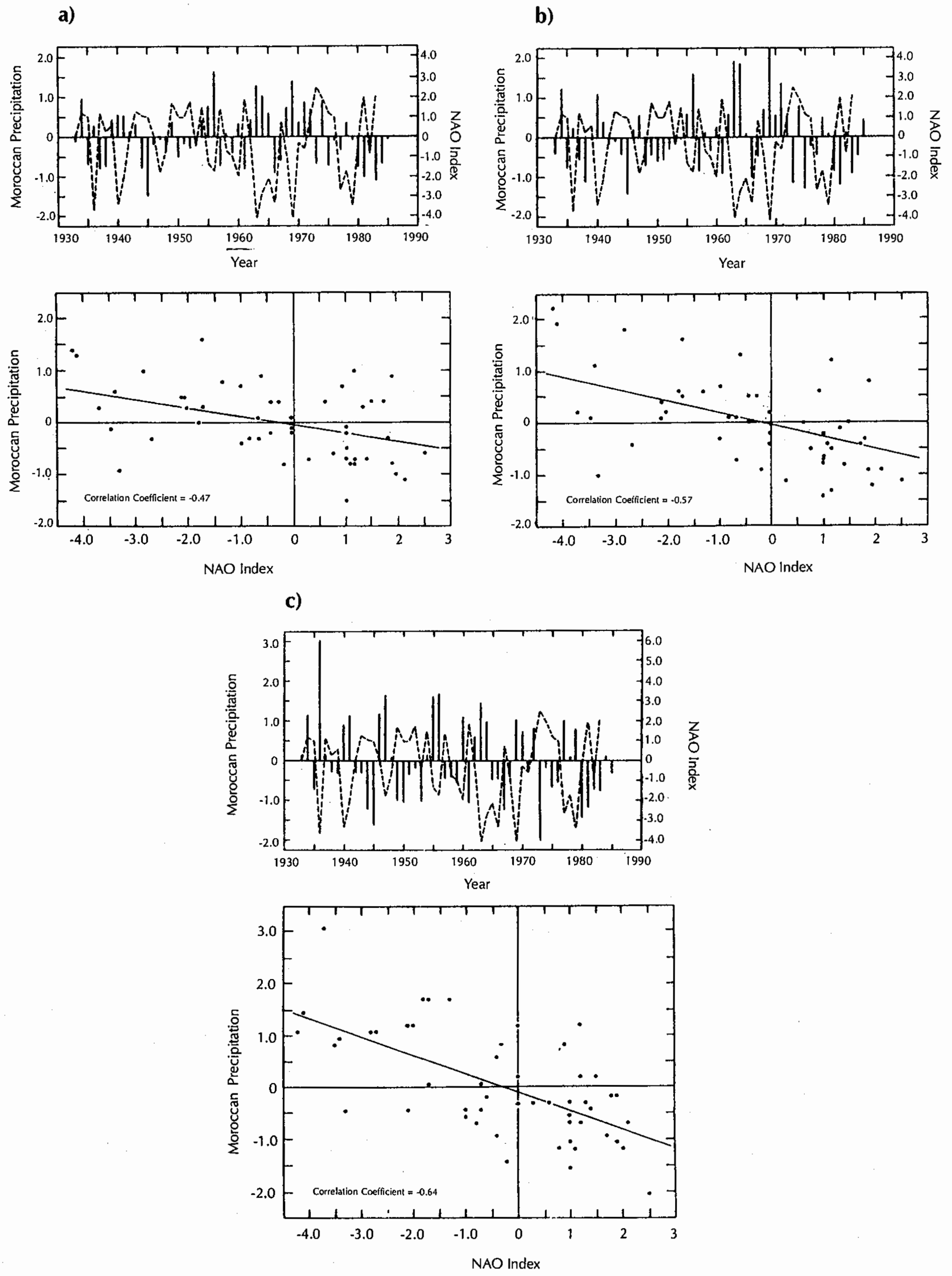


FIGURE 9. Relation between Moroccan November-April precipitation and December-February NAO Index for 1933 to 1983.

may be possible to extend the reversal of the NAO to include critical periods in the past and improve knowledge of the frequency of winter pressure distribution reversals over the North Atlantic.

The tree-ring data exhibit some evidence of a periodic tendency in drought occurrence (about 22 years), at least in north-central Morocco. This component may be the combined influence of 18.6-year lunar nodal cycle and the 22-year magnetic solar cycle. It should be emphasized that this relationship is based on very limited data. It does, however, lend support to earlier findings on drought occurrence in the western United States.

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