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Tree Ring-Based Reconstruction of Annual Precipitation in the South-Central United States From 1750 to 1980

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A 231-year reconstruction of annual precipitation, from 1750 through 1980 A.D., was developed from 10 tree ring chronologies (9 post oak, *Quercus stellata*, and 1 white oak, *Q. alba*, series) in the south-central United States. Straight line regression was used to calibrate regionally averaged precipitation with ring width data, and the derived reconstruction was verified with independent climatic data and historical evidence. A variance trend in the tree ring data, which may have resulted from nonclimatic factors, was removed. The reconstructed precipitation series indicates that (1) a drought which appears to have been more severe than any in the instrumental record occurred about 1860 and (2) severe and prolonged droughts comparable to twentieth century events have occurred at roughly 15- to 25-year intervals throughout the past 231 years. It follows that serious droughts in the south-central United States could be expected to recur even in the absence of projected CO_2-induced warming.

INTRODUCTION

Dendroclimatology, the reconstruction of past climate from tree ring data, has been extensively applied in semiarid, subalpine, and subarctic regions [e.g., *LaMarche* 1974; *Blasing and Fritts*, 1975, 1976; *Jacoby and Cook*, 1981], but has only recently proven successful in more temperate climates. *Cook and Jacoby* [1977] reconstructed a drought history of the Hudson Valley, New York, back to 1728, and in a later paper [*Cook and Jacoby*, 1983] they reconstructed annual streamflow in the Potomac River back to 1730. Streamflow in the Occoquan River, Virginia, was reconstructed by *Phipps* [1983]. *Brinkmann* [1987] has used tree ring data to reconstruct water supplies to the Great Lakes. *Duvick and Blasing* [1981] reconstructed annual precipitation for Iowa back to 1680, and *Blasing and Duvick* [1984] extended this work to the western corn belt (Iowa and Illinois) and improved upon the accuracy of the precipitation reconstructions previously obtained for Iowa only. *Stockton and Meko* [1983] reconstructed annual precipitation for four regions of the central United States, verified the reconstructions on independent data, and examined the reconstructed time series with regard to the spatial and temporal characteristics of multiyear drought episodes. The four regions they investigated included Iowa, where they used the ring width chronologies of *Duvick and Blasing* [1981]. They also examined two adjacent regions that together included western portions of Nebraska and the Dakotas, eastern Wyoming, and southeastern Montana. Their fourth region included much of Oklahoma and northwestern Arkansas. In the present study, we present reconstructions of annual precipitation for a much larger portion of the south-central United States than was covered in the earlier study of *Stockton and Meko* [1983]. By use of more ring width chronologies and different analytical techniques we were able to include more of northern Texas and southwestern Arkansas in our area of study (Figure 1) as well as to improve substantially on the accuracy of the previous reconstruction by Stockton and Meko. The procedures used to verify our reconstruction parallel those of Stockton and Meko and *Blasing and Duvick* [1984]. In the present paper, however, we also use historical evidence from before the beginning of recorded numeric data to verify the reconstruction of a severe drought around 1860. The results indicate that ring widths of deciduous trees can be used to provide accurate reconstructions of past precipitation for the south-central United States. In this paper we present our reconstruction back to 1750 A.D. and discuss its implications for an increasingly populated and important agricultural region where crop yields and surface water supplies are vulnerable to adverse climate fluctuations [*Newman*, 1978].

TREE RING DATA AND ITS ASSOCIATION WITH CLIMATE

A Swedish increment borer was used to extract core samples from opposite radii of post oak (*Q. stellata*) trees at nine sites in Texas, Oklahoma, and Arkansas, and from white oak (*Q. alba*) at one site in Arkansas (Figure 1). Each of the 10 chronologies include core samples from 21 or more trees and date from at least 1750–1980 A.D., except for the Navarro County, Texas, post oak chronology which includes cores from 14 trees and ends at 1974 [*DeWitt and Ames*, 1978]. At least two cores extend to 1750 for each chronology, and a total of 73 cores from over 50 trees in the complete set of chronologies date back to 1750. The growth rings in each core were crossdated, measured, and trans-

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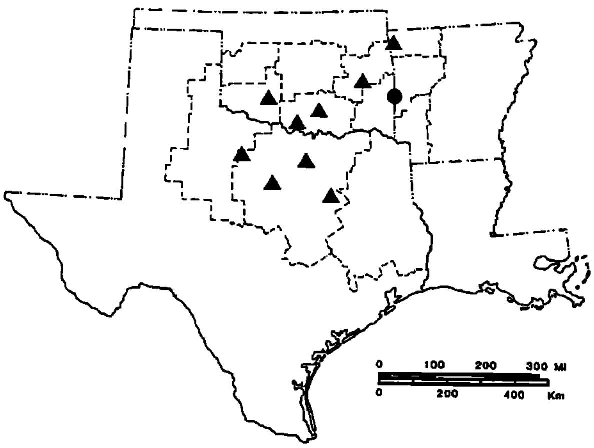

Fig. 1. Locations of the 10 tree ring chronologies used to reconstruct the average total annual precipitation for the 12 climatic divisions shown (triangles indicate post oak chronologies; the circle indicates white oak). Southernmost chronology plotted is the Oak Park site, Texas, reported by *DeWitt and Ames* [1978].

rings in each core were crossdated, measured, and transformed into ring width indices following the standard procedures outlined by *Fritts* [1976]. Inherent in this transformation of ring width series is the filtering of low-frequency nonclimatic variance due to biological or environmental factors. The technique involves fitting a curve to the ring width series so that the curve describes primarily the effects of those nonclimatic factors. Each ring width value is then divided by the corresponding value of the curve to obtain a ring width index value. Division, rather than subtraction of the curve value, is used because the variance of a ring width series is generally not constant, but instead varies approximately in proportion to the mean of the corresponding segment of the ring width series. Subtraction of the curve values from the ring width values would therefore result in a residual time series with temporal trends in the variance. Division by the curve value tends to eliminate this problem, though not always completely. The resulting ring width series usually follow a normal distribution, though examples of slight skewness have sometimes been noted [*Duvick and Blasing*, 1981].

Traditional transformation procedures [*Fritts*, 1976] were used rather than alternative procedures incorporating spline functions [*Cook and Peters*, 1981; *Blasing et al.*, 1983] or a recently developed approach [*Cook*, 1985] based on the time series methods of *Box and Jenkins* [1976]. Although low-frequency climate variance may be removed along with nonclimatic variance at the same frequencies by the ring width filtering techniques used in this study, this potential problem was minimized by the selection of relatively undisturbed forest sites, the large sample size included in each chronology, specimen selection, and the conservative application of curve-fitting techniques. Only half of the specimens included in this study were standardized with low-order polynomial growth curves (only very rarely greater than order four, and usually of order three or less), and negative exponential or linear regression lines were used for remaining specimens.

A ring width chronology was developed for each site by averaging, for each year, the transformed ring width values (ring width indices) from all cores at the site. The 10-site chronologies were then averaged to form a regional chronology. Weighting the chronology for each site by its corresponding number of trees can bias the regional chronology toward a particular area, so we did not weight the regional average chronology in that way.

A systematic decrease in ring width variance with increasing tree age has been observed in standardized tree ring chronologies of several species of oak [*Hill*, 1980; *Stahle and Hehr*, 1984; H. C. Fritts and E. R. Cook, personal communications in recent years]. This unexplained variance trend (heteroscedacity) is present in some post oak chronologies from the south-central United States and is reflected in the regionally averaged chronology developed here. This variance trend is not sufficient to appreciably affect the relationship between the regional tree ring chronology and precipitation since 1893 (the first year of regionally averaged precipitation data used in this analysis). Identical values of the coefficient of determination r^2 and of the reduction-of-error statistic (discussed later) were calculated (using climatic data available back to 1893) before and after the tree ring-based reconstructions were adjusted by removing the variance trend. However, even a slight variance trend extending back over 200 years could affect the interpretation of an unadjusted reconstruction by suggesting more pronounced amplitudes in the climatic anomalies estimated for the earliest years of data. This would have implications regarding the hypothesis that cooler climatic episodes have also been more climatically variable. (See *Brinkmann* [1983] and associated references for more information about this hypothesis.) At this point, we would rather not take the risk of inadvertently providing false evidence for that hypothesis, but would rather eliminate the variance trend from the reconstruction until we are more certain of its causes. Thus the lack of trend in the variance of the reconstructed precipitation series should not be construed as being contradictory to the hypothesis that cooler periods were more climatically variable, as we have, for reasons explained above, eliminated any such evidence that might be present in the tree ring series.

We are currently comparing variances of tree ring chronologies from young and old trees during the same time period (same climatic data), and preliminary results suggest the variance trend in these tree ring chronologies may be related to tree age rather than to climate. To ensure that any heteroscedacity of possible biological origin will not be interpreted as a climatic phenomenon, we removed the variance trend from the regional ring width index chronology as follows. We first took all negative departures from the average ring width index value of 1.0 and converted these to positive values. We then fit a regression line to the resulting time series of absolute values. Each ring width index value was divided by the corresponding value of the straight line, and the values of the resulting series were converted back to negative values where appropriate. The variance was then calculated for each of 10 sequential nonoverlapping subperiods of 23 years each, beginning in 1750. A straight line trend was then fit to these 10 sequential variances. If these variances still showed any trend, the slope of the regression line that had been fit to the absolute values of the ring width index departures was increased (in absolute value) by an arbitrary amount (10% of the previous value worked well) if the sign of the variance trend was still negative (and decreased by the same percentage if the variance trend was positive). The absolute values of the

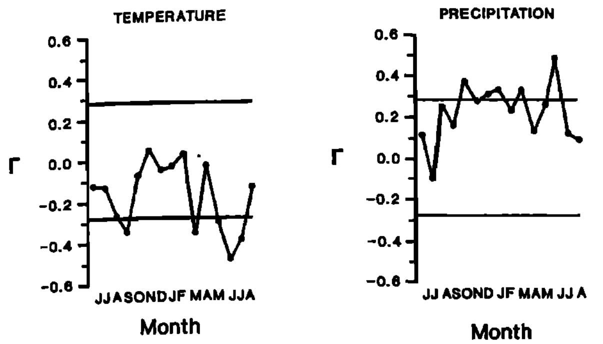

Fig. 2. Correlation coefficients *r* between the regionally averaged tree ring chronology and monthly temperature and precipitation averaged over the 12 climatic divisions shown in Figure 1. Horizontal lines indicate the 95% confidence levels, which should be exceeded only one time in 20 if no relationship exists.

original ring width index departures were then divided by the corresponding values of the adjusted regression line and converted back to negative values where appropriate. This procedure was repeated until the 10 sequential variances of the adjusted ring width indices (calculated as indicated above) showed no statistically detectable linear trend (*F* ratio (mean square due to regression/residual mean square) < 1.00). This iterative procedure was necessary because a least squares fit to the data does not necessarily remove all of the trend in the variance of the data. The final result was an adjusted regional average ring width chronology that was used to reconstruct precipitation over the 12-division area.

Deciduous oaks in the central United States, such as white oak, post oak, and bur oak (*Q. macrocarpa*) have been found to respond to precipitation over a 12-month period from the end of the growing season of the year preceding ring formation through the end of the growing season in which the ring was formed [*Lawson et al.*, 1980; *Duvick and Blasing*, 1981; *Stahle and Hehr*, 1984]. *Duvick and Blasing* [1981] used white oak to reconstruct annual precipitation from August of the year preceding ring formation through July of the year concurrent with ring formation, though they noted that other annualizing periods, especially July through June, would give comparable results. *Stockton and Meko* [1983] obtained good correlations between September through August precipitation in Oklahoma and the five northernmost ring width chronologies used in the present study.

Regionally averaged climatic variables used in the present study were, for each year, the area-weighted averages of the monthly mean temperature and total precipitation values over the 12 climatic divisions shown in Figure 1. Annual values of the regional ring width chronology from 1932 through 1980 were used along with corresponding values of each monthly climatic variable from June 1931 through August 1980 to calculate the correlation coefficients between the regional ring width index chronology and the regional monthly temperature and precipitation variables plotted in Figure 2. A series of positive correlations between precipitation and ring width begins in August of the year before ring formation and continues through July of the growing season concurrent with ring formation. These results suggest that the best annualizing period for precipitation is from August of the prior year through July of the year of ring formation.

In another experiment, several annualizing periods were compared by using the ring width index as the predictor variable in linear regression to estimate total precipitation for each of the several candidate 12-month periods. The percentage of precipitation variance accounted for by regression for each 12-month period considered is plotted in Figure 3. From these results it would seem that July through June is the best annualizing period, rather than the August through July period suggested in Figure 2. However, the slightly higher value of climatic variance accounted for in the July through June period could be a statistical artifact of the slightly higher first-order autocorrelation for those precipitation values ($r_1 = 0.159$ for July through June; $r_1 = 0.028$ for August through July). The generic result, however, is that these oaks respond to precipitation integrated over an annual period from the end of the previous growing season through the end of the growing season in which the ring is formed, and the timing of the growing season does not necessarily correspond to the first day of any particular calendar month. Further, soil moisture availability in late summer can influence somewhat the time at which radial growth effectively stops [*Boggess*, 1957]. Our results are in agreement with those of *Duvick and Blasing* [1981], who investigated white oak in Iowa. The September through August annualization period of *Stockton and Meko* [1983] appears to have been about a month away from the optimal annualization period for the reconstruction of annual precipitation amounts in the central United States from ring widths of oaks.

The correlation coefficients in Figure 2 suggest that temperature is also an important variable in determining ring width and therefore that some variable incorporating both precipitation and temperature, such as the Palmer Drought Severity Index, might be better correlated with ring width than precipitation alone would be. However, when June and July drought indices were estimated from the tree ring data for the periods 1956–1980 and 1932–1955 (four sets of estimates), the percentage of drought index variance that was

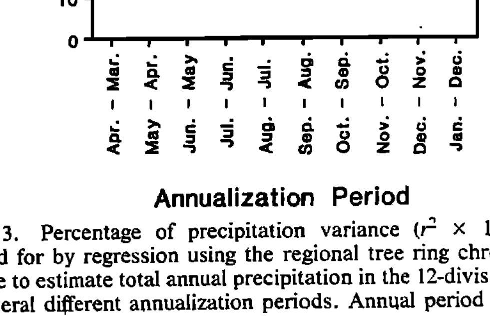

Fig. 3. Percentage of precipitation variance ($r^2 \times 100$) accounted for by regression using the regional tree ring chronology average to estimate total annual precipitation in the 12-division area for several different annualization periods. Annual period running from the previous July to June of the growing season concurrent with ring formation maximizes the precipitation variance accounted for by regression. Including tree ring data from following years in the regression model to account for possible lag relationships between climate and tree growth did not appreciably alter the results plotted. Tree ring data from 1932 to 1980 and corresponding precipitation data were used.

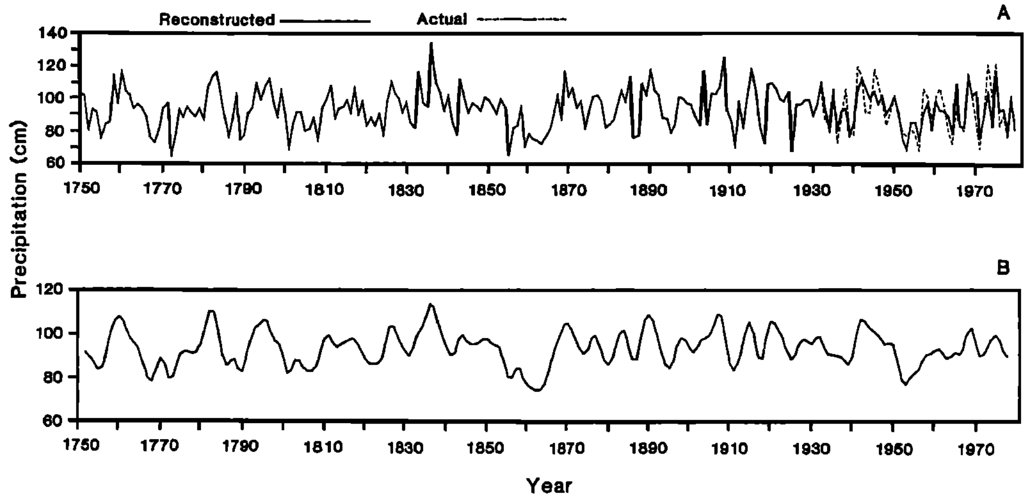

Fig. 4. (*a*) Total annual precipitation (July–June) from 1750 to 1980 reconstructed for the 12-division area shown in Figure 1. Observed total annual precipitation for the 12-division area is also plotted (dashed curve) from 1931 to 1980. (*b*) Reconstructed precipitation values after smoothing with a five-weight binomial filter.

accounted for averaged about 19% less than the corresponding value for annualized precipitation. The lack of increase in "explained" variance may be largely due to the high negative correlation between temperature and precipitation in the region, especially during the growing season (the correlation coefficient between June temperature and precipitation is −0.64 for the 12-division average). Also, the correlation coefficients in Figure 2 indicate a roughly equal contribution to ring width for each month's precipitation, but the Palmer Index is an integration of precipitation in which the contribution of each successive month is given an increasing weight, up to the month for which the drought index is computed. This mismatch in the way precipitation is integrated over the year may detract from the accuracy of the drought index reconstructions obtained using these tree ring data.

The Palmer Index incorporates temperature as a variable affecting evapotranspiration, but temperature may also be related to other things affecting tree growth (e.g., respiration). However, statistical removal of temperature effects from the ring width series would likely have removed some of the precipitation effects with which they were correlated. Further, there would be no way of removing the temperature variance for the period of climatic reconstruction, before temperature records were kept, so such an approach is not functional for purposes of climatic reconstruction.

Based on the results shown in Figures 2 and 3, it would seem logical to use either July through June or August through July as the annual precipitation period. The final decision to use the July through June period took into consideration the planting of spring and fall crops in the region. Spring maturing crops are typically harvested before midsummer and fall crops are then planted, so a reconstruction for the July through June period should provide annual precipitation estimates relevant to both crop periods, especially to the spring period.

Having selected the climatic variable to be reconstructed, we derived a straight line regression equation to provide estimates of the values of annual (July through June) precipitation for the 12-division area from the corresponding values of the regional tree ring chronology (after adjustment for heteroscedacity as described above). The ring width data represented rings formed from 1932 through 1980, and the precipitation data consisted of the 49 corresponding annual precipitation values from July 1931 through June 1980. We did not try other forms of regression because the straight line form is simple and worked well, and our experience in other studies has been that higher-order terms do not reduce the mean-square-error when ring width data are used to reconstruct precipitation.

RESULTS: PRECIPITATION RECONSTRUCTIONS AND THEIR ANALYSIS

The regression equation derived from the data as described above is

$$\hat{Y} = 93.684 + 9.153X$$

where $\hat{Y}$ is the estimate of annual precipitation (in centimeters) and X is the corresponding value for the adjusted regional ring-width index obtained as explained above (note that in this equation the X are expressed as positive or negative departures from the mean). This equation was used to reconstruct annual precipitation totals back to the year ending in June 1750. The reconstructed precipitation series is shown in Figure 4.

To demonstrate temporal stability in the calibrated relationship between radial tree growth and annual precipitation, we developed another calibration between the regional tree ring data and a two-state average of total annual precipitation (July through June) for Oklahoma and Texas from 1932 to 1980 and verified the derived estimates against the independent climatic data from 1893 through 1931, available for the (longer) two-state average record.

While these two states cover a much larger area than do the tree ring data, the state averages were the only area-averaged precipitation values readily available before 1931. Accurate estimates of precipitation for a small region can also often provide reasonably accurate estimates of precipitation variations over a much larger area on seasonal to annual time scales. For example, *Duvick and Blasing* [1981] obtained accurate estimates of Iowa state-averaged precipitation from white oak ring widths at three sites located near

TABLE 1. Calibration and Verification Statistics Using the Regional Tree Ring Index Chronology (Adjusted for Heteroscedacity) and the Two-State Average of Total Annual Precipitation for Oklahoma and Texas and Same Statistics Calculated for the Shorter Subperiods of the 12-Division Average of Total Annual Precipitation

Calibration Period	r^2	Verification Period	r^2	*RE*
Two-state average, 1932–1980	0.64	1893–1931	0.77	+0.72
Twelve-division average, 1956–1980	0.60	1932–1955	0.66	+0.66

each other in the central part of the state. Such a procedure would not be expected to work as well for a region as large and climatically diverse as Texas, however, and we use the two-state average of precipitation for Oklahoma and Texas only to demonstrate temporal stability in the growth-climate relationship.

The calibration and verification results for the two-state average are summarized by the common variance between estimated and observed values r^2 and the reduction-of-error RE statistic in Table 1 (two-state average). The *RE* statistic is defined as follows:

$$\mathrm{RE} = 1 - [\Sigma(Y_i - \hat{Y}_i)^2/(Y_i - \bar{Y})^2] \qquad i = 1, n$$

where Y_i is the ith precipitation value, $\hat{Y}_i$ is its estimate, and $\bar{Y}$ is the mean of the annual precipitation values used in calculating the regression coefficients. The mean of the independent precipitation data is not used here, because if that mean is known then those data are not really independent. The RE statistic [*Lorenz*, 1956] is equal to r^2 when calculated from the calibration data (data used to calculate least squares regression coefficients) but, when applied to different (independent or verification) data, RE measures the accuracy gained by using the regression equation instead of using the mean value of the calibration sample as the estimate of each value of Y_i. The RE statistic is now conventionally used for independent verification of dendroclimatic reconstructions [e.g., *Fritts et al.*, 1979; *Garfinkel and Brubaker*, 1980; *Duvick and Blasing*, 1981; *Cook and Jacoby*, 1983; *Blasing and Duvick*, 1984; *Hughes et al.*, 1984]. According to *Fritts et al.* [1979], RE is "a most rigorous verification statistic" and "any positive value indicates there is some information in the reconstruction." For particularly stable relationships between tree rings and climate, the RE on the independent data is often approximately equal to r^2 for the data used to calculate the regression coefficients and also approximately equal to the square of the correlation coefficient between actual and estimated values of the independent data. Such results have been obtained by *Duvick and Blasing* [1981], *Blasing and Duvick* [1984], *Cook and Jacoby* [1983], and in this study (Table 1).

The statistics in Table 1 (two-state average) show that the regional tree ring data can be used to reconstruct 64% of the variance ($r^2 \times 100$) in the two-state precipitation average during the calibration period (1932–1980) and 77% in the verification period (1893–1931). The strong positive RE (+0.72, Table 1 (two-state average)) indicates that the tree ring reconstruction of annual rainfall is both quite accurate and temporally stable. To further test the stability of the growth climate model, we split the 12-division average of total annual precipitation into two subperiods (1932–1955 and 1956–1980) and performed another calibration and verification analysis using the same adjusted regional tree ring chronology average (Table 1 twelve-division average). Although the calibration period was limited to only 25 years, the results are comparable to the statistics based on the two-state average (Table 1). Data from these analyses were approximately normally distributed. Skewness coefficients for the tree ring chronology values from 1932 through 1980 and for the corresponding (July through June) values of 12-division and 2-state precipitation were +0.02, +0.32, and +0.12, respectively. First-order autocorrelations were +0.09, +0.16, and +0.19, respectively.

These verification tests on independent climate data provide a demonstration of the accuracy and reliability of the precipitation reconstruction (Figure 4). These results are substantially better than those of tree ring-reconstructed annual rainfall (September–August) reported for a smaller region in Oklahoma and western Arkansas by *Stockton and Meko* [1983], who obtained correlation coefficients (r) of +0.60 between actual and reconstructed values. Although five of the same chronologies were used in both this study and the study by Stockton and Meko, we attribute the improved verification to our use of (1) five additional tree ring chronologies, (2) a different annualizing period for precipitation, (3) a slightly longer calibration period, and (4) our verification against regionally averaged as opposed to the single-station precipitation data (Oklahoma City) used by *Stockton and Meko* [1983].

DISCUSSION OF THE PRECIPITATION RECONSTRUCTION

The reconstructed precipitation values are plotted along with the actual values in Figure 4. While drought years were reconstructed accurately, the precipitation during wet years was often underestimated, apparently because moisture is not limiting to growth of the subject trees during wet years. This phenomenon was also noted by *Blasing and Duvick* [1984] in their reconstruction of annual precipitation values in Iowa and Illinois, and by *Cook and Jacoby* [1977] in their reconstruction of the Palmer Drought Severity Index in the Hudson Valley, New York. The notable drought of the 1950s was more severe than the 1930s drought in the smoothed precipitation reconstruction (Figure 4*b*). Perhaps the most severe drought since 1750 occurred between 1855 and 1864. It appears from these reconstructions that no drought of such severity and duration has occurred in the region of study during the period of instrument records. This inference is in agreement with the reconstructions presented in Figure 3 of *Stockton and Meko* [1983], derived from the five northernmost ring width chronologies shown in Figure 1 of the present study.

Historical accounts of regional weather in the mid-19th century substantiate the reconstructed drought for the 1855–1864 period and provide vivid images of the drought impact. *Foreman* [1942] mentions "a general drought and consequent shortage of food in 1854–55" in Oklahoma. *Neighbors* [1975] noted the weather in northwestern Texas was also "very dry" in 1855. *Richardson* [1963] cited anecdotal evidence provided by troops stationed in northeastern Texas, including Robert E. Lee, to conclude that drought conditions prevailed during 1856 and 1857. *Rister* [1956] stated in 1856 "drought had blighted the land." Camp

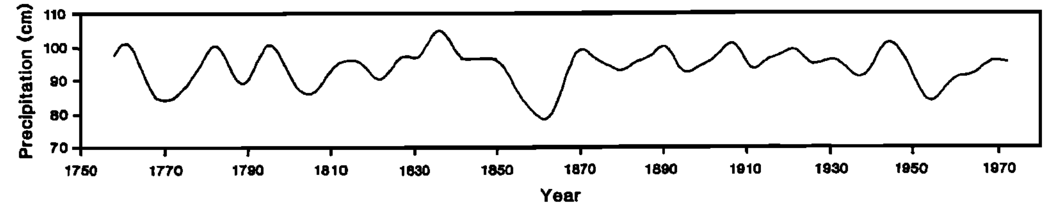

Fig. 5. Reconstructed precipitation values plotted in Figure 4*a* after smoothing with a 17-weight Gaussian filter.

described as "a collection of tents on a poorly chosen site, and sandstorms plagued the camp one week and dry northers the next" [*Rister*, 1956]. The Elm Fork of the Trinity River had stopped running in 1856, and some persons stated that it had not run for 2 years [*Richardson*, 1963].

Little weather information is available for Oklahoma or Texas during the Civil War years of the 1860s but *Richardson* [1963] states that in northern Texas, "The year 1862 was remembered for inadequate moisture, and in 1864 many farmers failed to make seed for the next year." Several accounts of drought conditions circa 1860 are available from Kansas, slightly north of our study area [*Bark*, 1978; *Wilhite*, 1980, 1983]. *Tannehill* [1947] mentions the severe drought of 1860 in Kansas and in adjacent states and another Kansas drought in 1863–1864. Tannehill then notes that after 1864 and "until the middle eighties rainfall was generally more plentiful and droughts less disturbing."

From all accounts the reconstructed severe drought around 1860 seems to have been a real phenomenon and could well have been the worst drought in the south-central United States for the last 231 years, exceeding any drought measured since the period of instrumental climatic or hydrologic records began. Other major dry spells reconstructed during the last 231 years include droughts around 1770, 1790, 1805, 1895, 1910, and 1935 (Figure 4).

Observed and reconstructed rainfall data both indicate that the 1950s drought was the most severe of the 20th century in the south-central United States [*Diaz*, 1983; this study]. However, the 1950s drought was not as pronounced in the north-central United States (e.g., Iowa-Illinois), where the 1930s drought was the most severe of this century [*Warrick*, 1980; *Blasing and Duvick*, 1984]. This comparison and many others between the long rainfall reconstructions now available for Iowa-Illinois [*Blasing and Duvick*, 1984] and Oklahoma-Texas document long-term regional differences in timing, intensity, and duration of droughts in the central United States.

In spite of these regional differences in reconstructed rainfall, the probability of severe and prolonged drought similar to 20th century dry spells does not appear to have increased in either Iowa-Illinois [*Blasing and Duvick*, 1984] or Oklahoma-Texas as a result of the Northern Hemisphere warming which began around 1900. Drought associated with CO_2-induced climatic change has been projected in some climate model simulations [e.g., *Manabe et al.*, 1981; *Washington and Meehl*, 1983; *Manabe and Wetherald*, 1986]. In terms of recent projections of CO_2-induced climatic warming our precipitation reconstructions have at least two implications: (1) tree ring reconstructions indicate that drought periods comparable to the most severe 20th century events occurred throughout the last 231 to 300 years [*Blasing and Duvick*, 1984; this study], and therefore similar droughts can be expected to recur even in the absence of further warming; and (2) because the relatively warm 20th century has not been characterized by an obvious increase in the frequency of droughts, the possible effect of a further warming, regardless of cause, on the recurrence of prolonged droughts in the central United States is not clear in light of available climatic data or tree ring evidence.

The droughts before 1870 appear to have lasted longer than droughts after that date (Figure 4). We noted a tendency for more low-frequency variance in general before about 1870. This feature is demonstrated more clearly when high-frequency variance is filtered from the reconstruction by applying a 17-weight Gaussian filter (Figure 5) instead of the 5-weight binomial filter used in Figure 4. The apparent decrease in low-frequency variance after about 1870 could be climatic, biological, or ecological (e.g., tree age or changes in competition from neighboring trees), or a statistical artifact of the way the ring-width series were analyzed. Until it is further explained, changes in reconstructed drought duration and in other time series characteristics of the reconstruction should be interpreted cautiously.

The autocorrelation function for the reconstructed precipitation values is shown in Figure 6. It suggests a weak tendency for an 18- to 19-year periodicity in these data. *Stockton and Meko* [1983] noted a similar (17 year) periodicity in their precipitation reconstructions for Oklahoma, but they cautioned it was not stable over time, being closer to 15 years in the eighteenth century and to 22 years since 1890. Figure 6 also shows the autocorrelation function for the periods 1750–1869 and 1870–1980. A weak cyclic tendency of approximately 17 years can be seen for the first period (Figure 6*b*), but no evidence of any cycle is obvious in the second period (Figure 6*c*). Also, the first-order autocorrelation was higher before 1870. As is emphasized above, the cause of this change in time series characteristics is not understood. However, there is no apparent evidence for any temporally consistent influence of either a Hale solar cycle (22 years) or an 18.6-year tidal cycle in these particular regional reconstructions. *Meko et al.* [1985] noted that drought periodicity near 20 years in the corn belt is too weak and irregular to be of use in drought forecasting, and our findings suggest that this may also be true for the south-central United States.

Long records of climatic information may aid in discovering whether major volcanic eruptions had any effects on climate. However, apparent relationships between geophysical phenomena at great distances from each other should be viewed with caution and, if they are real, should be expected to occur in the context of some larger-scale pattern of events. *Blasing and Duvick* [1984] conclude from their reconstructions that it was possible for a drought in Iowa-Illinois to follow a major volcanic eruption thousands of kilometers away. They noted a drought reconstructed in 1816 and for some years thereafter in Iowa to Illinois.

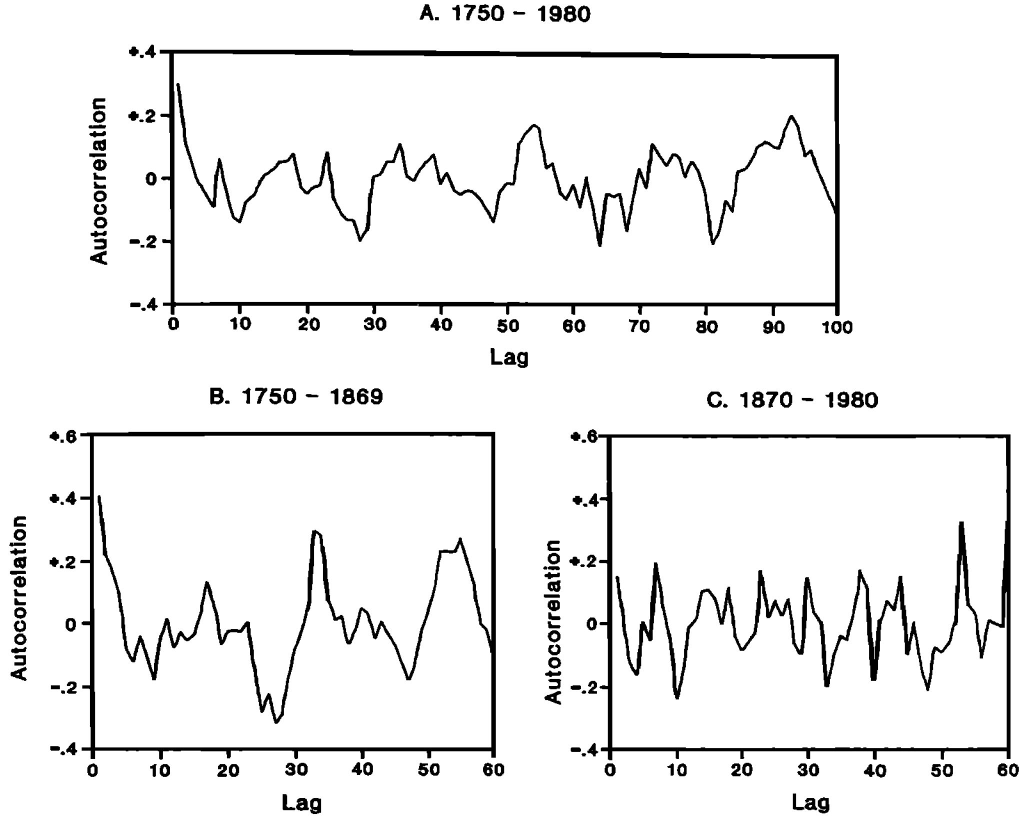

Fig. 6. First 100 elements of the autocorrelation function calculated for (*a*) the entire 231-year precipitation reconstruction and the first 60 elements of the autocorrelation function calculated from the reconstruction for the subperiods (*b*) 1750–1869 and (*c*) 1870–1980.

structed in 1816 and for some years thereafter in Iowa to Illinois. (Tambora, east of Java, had erupted in 1815, and 1816 was the "year without a summer" in much of eastern North America and Europe.) In the south-central United States, however, there is no evidence of a major drought at that time. Krakatau, west of Java, erupted in 1883, and dry years did not follow in the south-central United States until 1886 and 1887.

The probability of a multiyear drought in the south-central United States does not appear to be related in any simple way to extraterrestrial cycles, volcanoes, or nothern hemisphere temperature trends. When our reconstructions are superimposed on the Northern Hemisphere temperature data or the corresponding volcanic-eruption chronology presented by *Hirschboeck* [1980], the probability of a major multiyear drought appears just about as great in the relatively cool and volcanically active period before 1900 as in the relatively warm and volcanically inactive period from about 1920 through the 1950s.

Summary and Conclusions

A tree ring-based reconstruction of annual precipitation in the south-central United States has been developed and verified against independent numerical climate data beginning in 1893 and with qualitative historical data available for the midnineteenth century. The smoothed time series of reconstructed precipitation for the south-central United States indicates only one drought of greater severity than that of the 1950s, which was the most severe drought in the period of meteorological record. However, the duration of precipitation excursions below the 231-year mean was reconstructed to be generally greater before 1870 and, in general, there is more low-frequency variance in the series before about 1870. It is not clear, however, whether this is due entirely or even partially to climatic phenomena. The ring width index series was adjusted before calibration so that there would be no trend in the overall variance. However, it is possible that we did not remove all biological trends from all components of the variance.

Over the last 231 years the probability of drought in the south-central United States has no simple or obvious relationship to volcanic activity, Northern Hemisphere temperature trends, or solar quasi cycles. However, our findings do support the statement of *Stockton and Meko* [1983] that for localized areas, "drought appears to recur at ill-defined intervals of from 15 to 25 years." Further, droughts of greater severity and duration than any recorded during the period of conventional meteorological record are possible in the south-central United States, based on our reconstructed precipitation series from which the linear trend in overall variance was removed. This conclusion was given for the Great Plains as a whole by *Stockton and Meko* [1983]. The occurrence of a drought of greater severity and duration than any drought in the meteorological record implies that planning for only those possibilities indicated by the conventional meteorological data may underestimate naturally occurring drought extremes and that droughts of greater severity and duration than any recorded can occur whether or not a CO_2-induced warming, or any warming, occurs. The serious drought circa 1860 occurred before the twentieth century warming of the Northern Hemisphere and before recent increases of CO_2 in the atmosphere.

The climatic response of white oak and post oak in the north-central and south-central United States is quite similar [*Duvick and Blasing*, 1981; this study]. Both species integrate an annual precipitation signal over a 12-month period extending roughly from the previous July (or August) to June (or July) of the year of ring formation. Recently, the geographic network of climate-sensitive oak chronologies in the central United States has been greatly expanded [*Stahle et al.*, 1985]. With the use of multivariate analytical techniques, these data should provide greatly improved estimates of the temporal and spatial variability in hydrologic conditions over the agriculturally important central United States.

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