

## Texas Drought History Reconstructed and Analyzed from 1698 to 1980

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(Manuscript received 25 March 1987, in final form 25 September 1987)

### ABSTRACT

A selected group of nine climate-sensitive tree-ring chronologies from old post oak trees are used to reconstruct the June Palmer Drought Severity Index (PDSI) from 1698 to 1980 for two large regions in northern and southern Texas. Analysis of tree growth and monthly climate variables indicate that the June PDSI is the most robust climate signal evident in these chronologies, and principal component analysis (PCA) reveals a north-south geographic pattern in the relationships between the regional tree-ring time series. Serially random amplitude series from the first two significant eigenvectors of tree growth, which explain 65% of the total variance in the tree-ring data, were entered into stepwise multiple regression as predictors of regionally averaged June PDSI in north and south Texas for the common interval 1931–80. The regression models explain 59% and 60% of the variance in north and south Texas June PDSI, respectively, and both reconstructions are well verified against independent June PDSI data available on a statewide basis from 1888 to 1930. The weak persistence present in the observed June PDSI series was added to the serially random tree-ring reconstructions prior to verification, using autoregressive modeling procedures.

The mean and variance of June PDSI during the 50-yr period of meteorological observation (1931–80) appear to be representative of the last 283 yr, but significant changes in average June PDSI for Texas appear to have occurred over both 30 and ~90-yr time intervals. Moderate or more severe June droughts ( $\text{PDSI} \leq -2.0$ ) have an estimated recurrence probability of over 90% each decade, and the risk of extreme June drought ( $\text{PDSI} \leq -4.0$ ) is estimated at over 50% every 15 yr in north Texas and every 10 yr in south Texas. The reconstructions faithfully reproduce the frequency domain properties of the actual June PDSI, and marginally significant spectral peaks are present at 2.3 yr and between 14 and 18.67 yr in both reconstructions. Significant interannual persistence of June moisture extremes apparent in the statewide June temperature, precipitation, and PDSI data from 1888 to 1982 is also present in both regional reconstructions from 1698 to 1980. The reconstructions indicate that the risk for below average June moisture conditions increases to at least 65% in north and south Texas in the summer following a June drought ( $\text{PDSI} \leq -2.0$ ). Interannual persistence is also indicated for June wetness anomalies and may have some modest value in statistical forecasts of growing season moisture conditions in Texas.

### 1. Introduction

Recent analyses of the temporal and spatial characteristics of recorded drought data (Karl and Koscielny, 1982; Diaz, 1983) confirm the casual observations of many residents that Texas is one of the most drought-prone regions of the United States. Unfortunately, the economies of Texas and the entire country have become increasingly sensitive to drought due to higher energy costs and growing pressure on limited surface and groundwater supplies from agricultural, industrial, and municipal interests (e.g., Karl and Koscielny, 1982). The 1980 summer heat wave, for example, cost the nation an estimated \$16 billion, including some \$1.5 billion in losses for Texas alone (Karl and Quayle, 1981).

Systematic meteorological observations in Texas began about 1880, but the continuity and spatial cov-

erage of the earliest data are not uniform (Griffiths and Ainsworth, 1981). Only 24 moderate June droughts (or worse) are recorded on a statewide basis since 1888 (Karl et al., 1983), and six of these occurred consecutively from 1951 to 1956 during the worst multiyear drought episode in the recorded history of Texas. This limited sample of single and multiyear droughts for even a drought-prone region may not be adequate to define confidently the probability distribution of drought occurrence, thus limiting the application of statistical techniques for the characterization and long-range forecasting of drought events (Namias, 1981).

Old climate-sensitive trees from undisturbed native forests offer one of the best means to extend annual drought records for the past few centuries (Stockton, 1975; Fritts, 1976). Analysis of these unique proxy tree-ring series may provide insight into past climate variation and allow better estimation of drought probabilities (Wallis, 1977). In this study, nine climate-sensitive post oak (*Quercus stellata*) chronologies are used to reconstruct the June Palmer Drought Severity Index (PDSI; Palmer, 1965) for two large regions in northern

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and southern Texas from 1698 to 1980. These long proxy drought records are then used to 1) describe an important component of the growing season climate history of Texas for the past 283 years, 2) investigate the possible interannual persistence of moisture extremes, 3) estimate the recurrence probabilities for drought and wetness categories of increasing severity, 4) estimate the extent of possible bias in the 50 years of observed June PDSI data through comparisons with the 283 yr reconstructed series, and 5) to compare the frequency characteristics of the observed and reconstructed series and identify any long-term, quasi-periodic components that might provide practical or theoretical insight into drought recurrence in Texas.

## 2. Previous research

A number of recent studies have illustrated the use of tree-ring data for the reconstruction of regional precipitation and drought index series in both humid and semi-arid regions of the United States (e.g., Cook and Jacoby, 1977; Meko et al., 1980; Duvick and Blasing, 1981; Stahle et al., 1985a). Stockton and Meko (1983) used tree-ring data to investigate drought history and the periodic components of reconstructed annual precipitation in four regions of the Great Plains. Their reconstruction for portions of Oklahoma and western Arkansas was based on five oak chronologies, including data from two of the sites used in this study. Stockton and Meko (1983) documented a rather ill-defined rhythmic nature of drought recurrence in the Great Plains since 1700, but low sample size (and probably heteroscedastic tree-ring data) restricted their interpretations prior to 1750 in the Oklahoma–Arkansas sector.

Blasing et al. (1988) used a larger network of ten tree-ring chronologies (post oak and white oak, *Q. alba*, including earlier data from the four northernmost sites used in this study) to reconstruct annual precipitation amounts for a large regional average of 12 climatic divisions in northern Texas, southern Oklahoma, and western Arkansas from 1750 to 1980. They concluded that the prolonged drought reconstructed from 1855 to 1864 was the most severe regional drought event in the 231-yr period, and that severe drought can be expected to return even in the absence of projected CO<sub>2</sub> warming.

The present study differs from the foregoing dendroclimatic research in several fundamental respects, including (1) our use of five new tree-ring chronologies, the first available for south central Texas; (2) selection of the nine predictor chronologies from an available network of 20 chronologies in Texas and southern Oklahoma (Stahle et al., 1985b) on the basis of total length and favorable chronology statistics (Fritts and Shatz, 1975); (3) the use of homoscedastic and serially random principal component eigenvector amplitudes of tree growth as predictors of climate; (4) the specific focus on Texas; (5) the reconstruction of June PDSI;

(6) the time period of the reconstruction which extends from 1698 to 1980; and (7) our analysis of the persistence and recurrence probabilities associated with June PDSI.

## 3. The data

In the past 5 years, 47 new tree-ring chronologies have been developed in the south central United States (Stahle et al., 1985b), adding to the greatly expanded tree-ring data base for North America. The network for the south central United States includes chronologies of five species which average from 250 to 300 yr long, but the post oak chronologies of the prairie–forest transition zone in Oklahoma and Texas often contain the highest quality climate signal of any tree-ring chronologies in the region, and are among the most climate-sensitive tree-ring chronologies available anywhere (Stahle and Hehr, 1984). For this study, we have selected the nine best post oak chronologies available in or near Texas which date from at least 1698 (Fig. 1).

The nine post oak chronologies are based on multiple increment cores from 25 to 50 individual trees per site, which were processed and carefully cross-dated according to established procedures (Douglass, 1941; Stokes and Smiley, 1968). The exactly dated tree rings were measured to 0.01 mm. Cross-dating and measurement accuracy were checked and confirmed with the computer program COFECHA by correlating

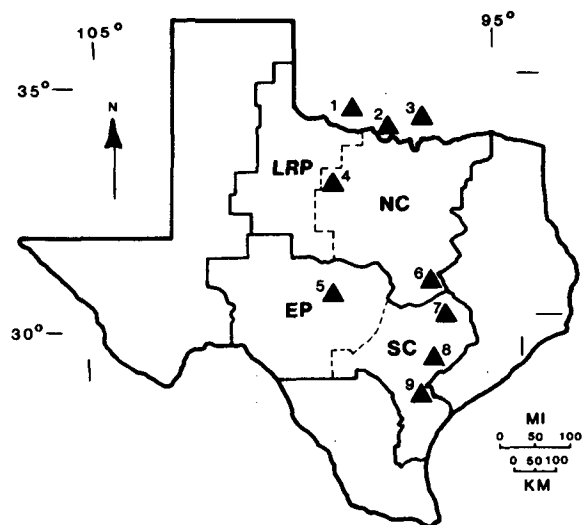


FIG. 1. Site locations of the tree-ring chronologies used to reconstruct the June Palmer Drought Severity Index (PDSI) for the north and south Texas regions. The tree-ring data were calibrated with 50 yr of actual June PDSI data (1931–80) averaged from the North Central (NC) and Low Rolling Plains (LRP) climatic divisions in the north Texas region, and the South Central (SC) and Edwards Plateau (EP) divisions in the south. The numbered tree-ring collection sites are 1) Quanah Mountain, Okla., 2) Mud Creek, Okla., 3) Lake Arbuckle, Okla., 4) Nichols Ranch, Tex., 5) Mason Mountain, Tex., 6) Brazos River, Tex., 7) Yegua Creek, Tex., 8) Lavaca River, Tex., and 9) Coletto Creek, Tex.

overlapping 50-yr segments of all measured series (Holmes, 1983). The computer program ARSTND was used to detrend each ring measurement series and to calculate the average site chronology as the biweight or robust mean value function of all available ring measurement series (Cook, 1985; Cook and Holmes, 1985). Detrending and indexing of the ring measurement series are necessary to remove low-frequency variance associated with increasing age and circumference of trees and to eliminate differences in mean growth rates among trees (Fritts, 1976). A trend of decreasing variance remained in some final chronologies and was removed by fitting an inflexible spline to the variance (Cook and Holmes, 1985). This variance trend is believed to result from declining growth vigor of the old trees sampled and from increasing sample size in the most recent years (Stahle et al., 1985b).

Divisional climate data available on a monthly basis since 1931 (Karl et al., 1983) were used to investigate the post oak growth-climate relationship and to calibrate the tree-ring and climatic data (Fig. 1). Divisional climate averages avoid many problems sometimes associated with single station data such as record inhomogeneities and differing station microclimates, and usually provide better tree-ring reconstructions of climate (e.g., Blasing et al., 1981).

Average monthly PDSI data are also available on a statewide basis for Texas back to 1888, although the number of individual reporting stations declines and the stations become less evenly distributed within the state during the earliest years of record (Karl et al., 1983). The statewide PDSI data from 1888 to 1930 are used for independent verification of the tree-ring reconstructions based on the 1931-80 calibration period.

#### 4. Post oak growth and climate

Correlation and response function analyses (Fritts, 1976) between the post oak chronologies and monthly climate variables have consistently demonstrated a positive growth response to precipitation and a negative response to temperature throughout most of the year (Stahle and Hehr, 1984; Blasing et al., 1988). The radial growth response to temperature and precipitation is strongest during the growing season from March through July and appears primarily to reflect variations in evapotranspiration demand. This suggests that a meteorological drought measure such as the Palmer Index which integrates the combined effects of both temperature and precipitation would be a suitable climate variable for reconstruction. This is supported by correlations between the post oak chronologies and PDSI values for growing-season months, which are uniformly higher than correlations with monthly or seasonalized temperature and precipitation separately.

Correlation and principal component analysis (PCA; Cooley and Lohnes, 1971) were used to determine if the tree-ring and climate data might be more effectively

analyzed as a single large-scale average or segregated into regional groups. All nine tree-ring chronologies are well correlated and load highly with nearly identical coefficients of the same sign on the first eigenvector, which explains 47% of the total variance in the tree-ring data and is believed to represent regional moisture anomalies. Two clear geographical areas are, nevertheless, apparent in the correlation matrix and in the loadings on the second eigenvector, which explains an additional 18% of the variance in the tree-ring chronology network. The four northern chronologies share the highest intercorrelations and similar positive loadings on both eigenvectors, and the five southern chronologies share similar intercorrelations but load negatively on the second eigenvector. The observed PDSI data for the four adjacent climatic divisions are all significantly correlated, but the two northern and southernmost divisions also share the greatest common variance. For these reasons, the tree-ring and climate data were subdivided into the "north Texas" and "south Texas" regions. The monthly PDSI data for the North Central and Low Rolling Plains divisions were averaged from 1931 to 1980 for north Texas, and the South Central and Edwards Plateau divisions were averaged for south Texas (Fig. 1).

The regionally coherent pattern in the first eigenvector of tree growth is consistent with the larger-scale analysis of monthly PDSI data for the continental United States and is attributed to the unique synoptic climatology of the region centered on Texas and Oklahoma (Karl and Koscielny, 1982). The north-south pattern evident in the tree-ring and divisional PDSI data for Texas is not readily apparent in the continental-scale analysis (Karl and Koscielny, 1982), but the stepwise multiple regression results reported below provide empirical support for the physical significance of this pattern because the second eigenvector of tree growth is a significant predictor of June PDSI in only the south Texas region. The strong regional gradient in annual potential evapotranspiration (Thorntwaite, 1948) is parallel with the zero line separating opposite loadings on the second eigenvector and may be one physical component of the apparent difference between northern and southern Texas.

Correlation analysis between simple regionally averaged tree-ring chronologies and monthly PDSI data for north Texas identified significant ( $P < 0.001$ ) and highly positive correlations during May, June, and July, with the highest correlation observed for June PDSI. Significant correlations were observed for the same months in south Texas, although the highest was observed during May. The slightly higher correlation with May PDSI for the south Texas chronology probably reflects phenological differences between northern and southern Texas, with an earlier growing season maximum in the south.

June PDSI was selected for reconstruction in both areas because it represents the best composite of the

monthly drought signal strongly expressed in the regional tree-ring data. Also, the seasonal distribution of rainfall is very similar for all four climatic divisions under consideration, with two broad rainfall peaks occurring from April through June, and September through October (Griffiths and Strauss, 1985). The spring-early summer rainfall peak is most significant to regional agriculture. The June PDSI should provide a good representation of the spring rainfall maximum because the Palmer Index represents a weighted average of temperature and rainfall conditions for the current and several preceding months.

The identification of June PDSI as the most robust climate signal in the Texas post oak data contrasts with earlier results reported by Blasing et al. (1988), who found that a regional average of ten tree-ring chronologies was a better predictor of annual (July-June) precipitation than monthly PDSI values for a large area of western Arkansas, Oklahoma, and northern Texas. The explanation for these differences may include our use of (1) five new tree-ring chronologies from south central Texas, (2) serially random tree-ring predictors derived from PCA of the nine-chronology network, and (3) our reconstruction of smaller regional climate averages. While the nine chronologies used in this study are certainly well correlated with annual precipitation for Texas, the June PDSI provides better regression results and may often be a better measure of agricultural drought in Texas than annual precipitation data. Late summer tropical storms may produce huge rainfall amounts that can significantly affect annual precipitation totals in Texas and obscure the actual economic impact of droughts earlier in the growing season.

### 5. Calibration and verification results

The eigenvector amplitude series from the first two principal components for the nine-chronology network had eigenvalues  $> 1.0$  and were used to reconstruct drought in north and south Texas. The amplitudes were used rather than the regional chronology averages because they consistently produced the best calibration results. Autoregressive (AR) modeling was used to identify the autocorrelation structure of the tree-ring and climate data, which contain differing degrees of persistence. Serial persistence in the annual tree-ring data and resulting eigenvector amplitude series is generally more pronounced than in the climate data and is largely attributed to the combined effects of climate, ecological, and physiological factors regulating the storage and depletion of food reserves (Fritts, 1976; Meko, 1981; Cook, 1985). The first eigenvector amplitude series of regional tree growth was adequately modeled as an AR(1) process with a coefficient of 0.171, determined using the Akaike information criterion (Akaike, 1974). The second tree-ring amplitude series was modeled as an AR(2) process, with coefficients of 0.282 and 0.113. The observed June PDSI for north

Texas (1931-80) was modeled as an AR(0), but the nonsignificant autocorrelation at lag 1 was removed with an AR(1) coefficient of 0.145. The south Texas June PDSI series was modeled as an AR(1) process with a coefficient of 0.235.

The two serially random (AR modeled) tree-ring amplitude series were entered into stepwise multiple regression to predict AR modeled June PDSI for north and south Texas from 1931 to 1980 (Draper and Smith, 1981; SAS Institute Inc., 1985). Only the first tree-ring amplitude series entered the regression model for north Texas June PDSI, while both amplitudes were significant predictors of June drought in south Texas (Table 1).

The transfer function coefficients applied to the tree-ring amplitudes from 1698 to 1980 are listed in Table 1. The drought reconstructions were completed when the first-order persistence models identified for the observed June PDSI data from north and south Texas were added into the transformed tree-ring amplitude series. Adding the observed climate persistence into the serially random tree-ring estimates avoids potential problems related to the complicated persistence structure inherent in the tree-ring data and should provide the best possible PDSI estimates in the time and frequency domains (Meko, 1981).

The explained climate variance is similar and highly significant for both regional reconstructions (Table 1). The reconstructions account for 59% and 60% of the variance in June PDSI from 1931 to 1980 in north and south Texas, respectively ( $R_{adj}^2$ , adjusted for loss of degrees of freedom; Draper and Smith, 1981). The Durbin-Watson test indicates that the regression residuals are not significantly autocorrelated in north Texas but are in south Texas (Table 1).

The observed and reconstructed June PDSI data for the north and south Texas regions are plotted from 1931 to 1980 in Fig. 2, and the close fit between the actual and estimated time series is apparent in both regions. Although the reconstructions explain a highly significant proportion of the observed climate variance during the calibration period, the regional reconstructions do not always reflect the moisture extremes, especially the positive extremes (Fig. 2). This is a frequently observed feature of dendroclimatic reconstructions usually attributed to the tendency for regression analysis to underestimate extreme values, and because tree growth only partially reflects climate variation. Drought years are usually better estimated than wet years, because moisture deficits become more growth-limiting, while a host of nonclimatic growth-limiting factors such as inadequate nutrient supply, crowding, or disease may prevent a maximized growth response to favorable moisture conditions (Fritts, 1976; Duvick and Blasing, 1981). These considerations suggest that the June PDSI reconstructions may often represent a conservative estimate of the actual moisture extremes, particularly during abnormally wet years.

TABLE 1. Transfer function coefficients and the calibration and verification statistics derived for the tree-ring reconstructions of north and south Texas June PDSI. Average statewide June PDSI for Texas from 1888 to 1930 was used for the independent verification of both calibration models.

Region	Calibration [1931-80 ( <i>n</i> = 50)]					Verification [1888-1930 ( <i>n</i> = 43)]					
	<i>b</i> <sub>0</sub>	<i>b</i> <sub>1</sub>	<i>b</i> <sub>2</sub>	<i>R</i> <sup>2</sup> <sub>adj</sub>	Residual <sup>†</sup> autocorr.	Corr.	1st Dif. Corr.	Sign test		<i>t</i> -test of cross-product means	RE
								Pos.	Neg.		
North Texas	0.03	0.88	—	0.59***	0.08 ns <sup>‡</sup>	0.74***	0.62***	31**	12	-4.10***	+0.54
South Texas	0.04	0.92	-0.49	0.60***	0.25*	0.66***	0.49***	32**	11	-3.20**	+0.42

\* = *P* ≤ 0.05.  
 \*\* = *P* ≤ 0.01.  
 \*\*\* = *P* ≤ 0.001.  
<sup>†</sup> Durbin-Watson test for autocorrelation of residuals.  
<sup>‡</sup> ns = not significant, *P* > 0.05.

In spite of the underestimates of moisture extremes, the verification results for both regions are very favorable. Both reconstructions are well correlated with the independent statewide PDSI data from 1888 to 1930 (Table 1). The first difference correlations are also positive (Table 1), indicating significant coherence in the direction of moisture anomaly changes from year to year between the observed and reconstructed data. The sign of the reconstructed and actual June PDSI departures from the mean are identical in over 72% of the

cases for both regions during the verification period (*P* < 0.01), and the *t*-tests on the cross-product means are both significant (*P* < 0.01) indicating that reconstructed and observed values with different signs are usually close to the mean.

The reduction of error statistic (RE) is widely used in the verification of dendroclimatic reconstructions and is discussed by Gordon (1982), Gordon and Leduc (1981), and Fritts (1976). Confidence limits are not calculated for the RE, but Monte Carlo experiments suggest that the approximate 95% confidence limit for *n* > 10 is RE ≥ 0.0 (Gordon and LeDuc, 1981). The theoretical RE ranges from -∞ to +1.0, and a positive RE indicates that the predicted values for the verification period are more accurate than hypothetical predictions based only on the observed data mean during the calibration period. The RE statistic for both regions is strongly positive, particularly for the north Texas reconstruction. These verification tests on independent climate data outside the calibration period demonstrate the stability of the regression models and provide strong evidence concerning the overall accuracy of the reconstructions.

The reconstructions are well verified in both regions, but the relatively lower verification statistics for south Texas may reflect certain data-specific problems unrelated to the true accuracy of the reconstruction (Table 1). Both reconstructions were verified using statewide June PDSI data available from 1888 to 1930 (Karl et al., 1983), but there was a greater concentration of reporting stations in northern Texas during the earliest years of record (Griffiths and Ainsworth, 1981). Consequently, the better verification results for north Texas may simply reflect greater common variance between the North Central-Low Rolling Plains average and the statewide average prior to 1930 (Karl et al., 1983). However, the greater uncertainty concerning the regression coefficients for south Texas indicated by the autocorrelated residuals may also be reflected by the lowered verification for south Texas.

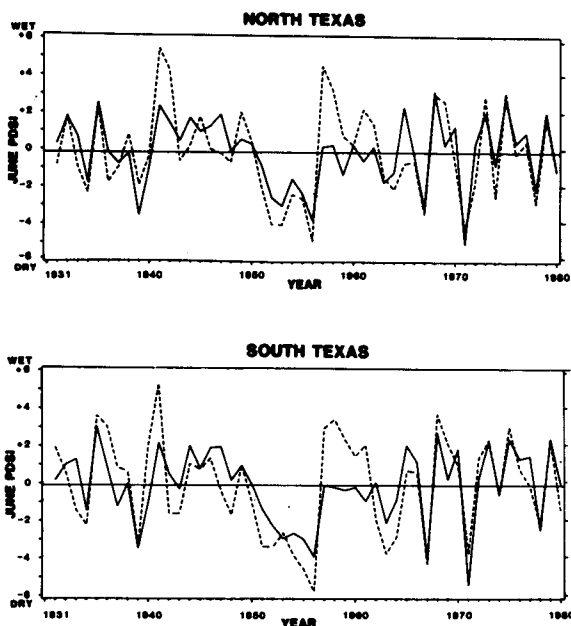


FIG. 2. Observed (dashed lines) and reconstructed (solid lines) June PDSI for the calibration period 1931-80 in north and south Texas. The Palmer Index scales drought and wetness anomalies as 0 to ±1, near normal; ±1 to ±2, mild wetness or drought; ±2 to ±3, moderate wetness or drought; ±3 to ±4, severe wetness or drought; greater than +4, extreme wetness; and less than -4, extreme drought.



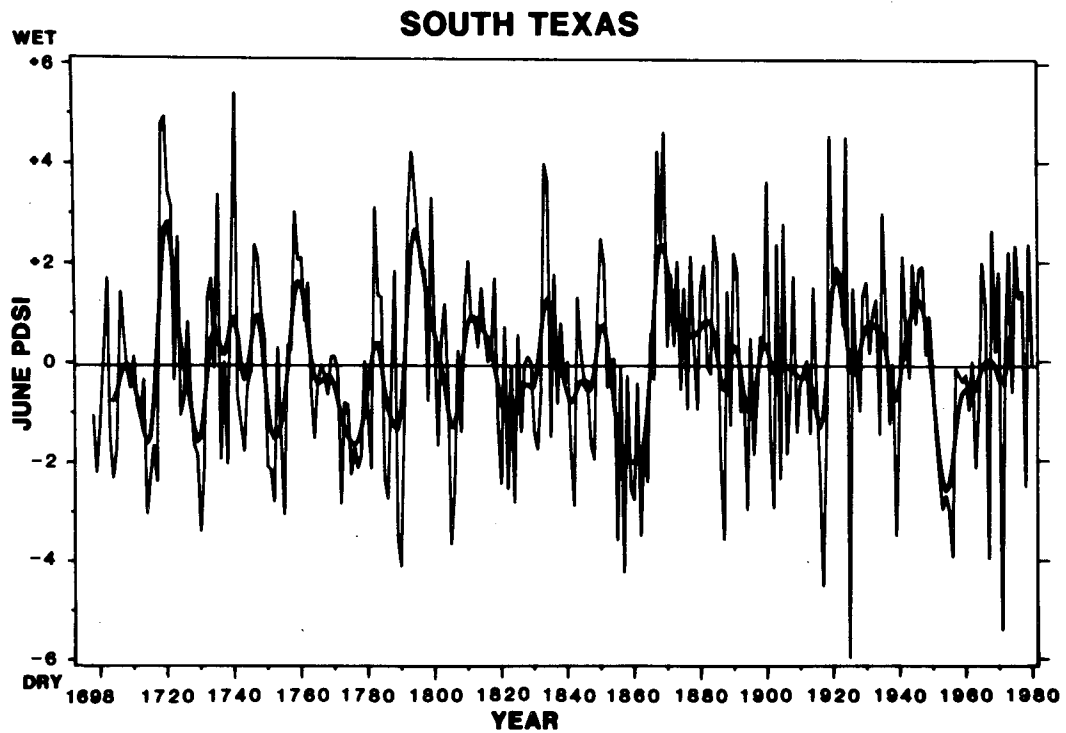
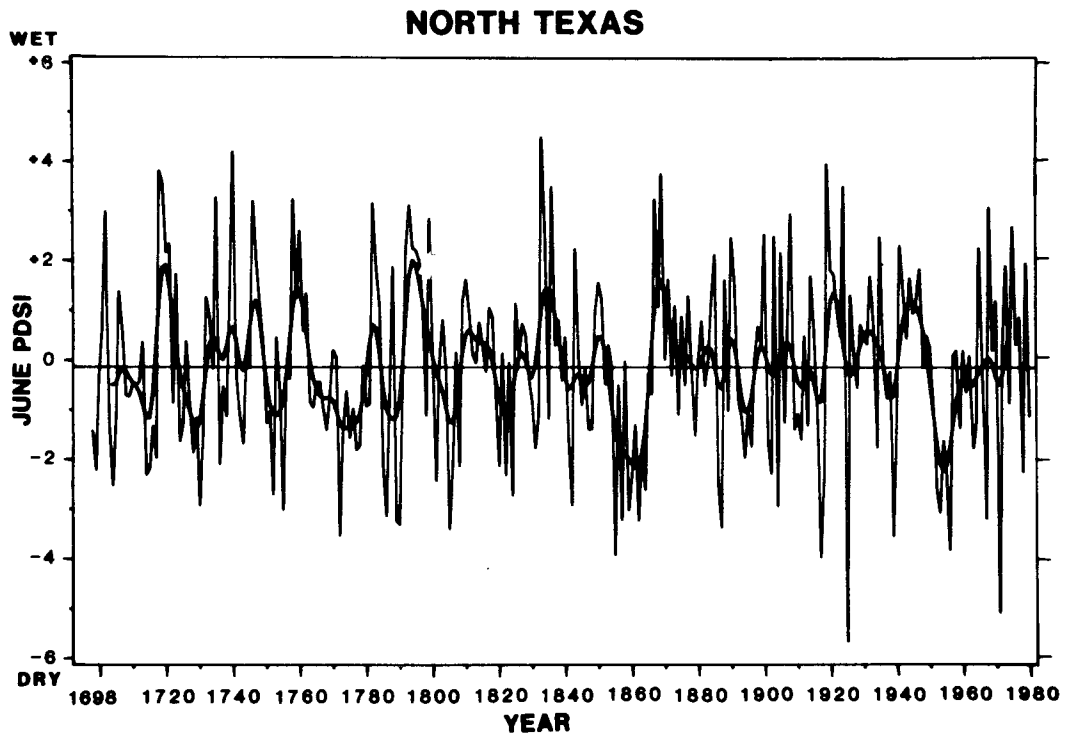


FIG. 3. Reconstructed June PDSI for north and south Texas plotted annually from 1698 to 1980, and smoothed with a low-pass filter passing variance with a frequency of  $\geq \sim 8$  yr (Fritts, 1976). The two regional reconstructions are highly correlated over the 283-yr common period ( $r = 0.95$ ,  $P < 0.0001$ ).

## 6. Texas climate history: 1698–1980

The June PDSI reconstructions for north and south Texas from 1698 to 1980 are listed in Table 2 and plotted in Fig. 3. The strong positive correlation between the two long reconstructions is readily apparent (Fig. 3) and suggests that the same large-scale circulation features are usually responsible for growing season climate variability in both regions.

The statistical properties of both reconstructions are compared with the observed June PDSI statistics in Table 3 and indicate the generally close agreement between the characteristics of the observed and reconstructed data. The variance statistics of the reconstructed series are consistently below the actual data, however, as was previously indicated by the calibration results. Because the reconstructions systematically underestimate the actual June PDSI extremes (Fig. 2; Table 3), the reconstructed values that are equivalent to the actual levels of drought or wetness in terms of their probability of occurrence have been computed during the common period from 1931 to 1980. Reconstructed June PDSI values of  $-1.60$ ,  $-2.39$ , and  $-3.11$  in north Texas, and  $-1.58$ ,  $-2.36$ , and  $-3.07$  in south Texas are equivalent to the actual levels of moderate, severe, and extreme drought (observed PDSI =  $-2.0$ ,  $-3.0$ , and  $-4.0$ , respectively). Reconstructed values of  $+1.55$ ,  $+2.32$ , and  $+3.01$  in the north, and  $+1.52$ ,  $+2.28$ , and  $+2.96$  in the south are equivalent to actual levels of moderate, severe, and extreme wetness (observed PDSI =  $+2.0$ ,  $+3.0$ , and  $+4.0$ , respectively). The relatively larger differences between equal probabilities of observed and reconstructed wetness illustrate the asymmetry in growth response to surplus and deficit moisture.

The reconstructed June PDSI series reveal several interesting aspects of Texas climate history (Table 2; Fig. 3). The most severe and protracted period of con-

secutive June droughts since 1698 appears to have occurred from 1951 to 1956 in both north and south Texas (although the drought actually began as early as June 1947 in the South Central climatic division; Karl et al., 1983). The reconstructed June PDSI averaged  $-2.40$  in north Texas and  $-2.70$  in south Texas (both equivalent to severe drought), compared to the actual regional averages of  $-3.38$  and  $-3.94$  over this entire 6-yr period of record drought. This example illustrates both the conservative bias of the reconstructed June PDSI series and the need to assess the reconstructions in probability terms equivalent to the actual June PDSI.

The most severe uninterrupted sequence of June droughts since 1698 in Texas appears to have occurred in the 1950s, but the driest decades in both the northern and southern regions are estimated to have occurred from 1855–64, followed by the decades of 1950–59 and 1772–81 (Table 2; Fig. 3). These dry decades were all interrupted by some years of near normal to above average moisture conditions, but the temporarily improved conditions were probably not sufficient to mitigate the long-term environmental or economic impact of these historic drought eras.

Four of the five wettest decades estimated since 1698 are also identical in both regions, including the wettest decade from 1791–1800. Most prolonged drought episodes were, in fact, preceded and/or followed by extended wet periods (Fig. 3), suggesting a weak oscillatory behavior in extended moisture anomalies in Texas.

The prevalence of record droughts in recent decades is suggested by the estimated occurrence since 1917 of five out of the six most severe June droughts over the last 283 yr in north Texas, and five of the seven worst in south Texas (Table 2). Although record droughts may have been somewhat more prevalent over the last few decades, no significant differences in the mean or variance of reconstructed June PDSI is apparent for the nonoverlapping 50 yr periods running from 1731

TABLE 3. Statistical characteristics of observed and reconstructed June PDSI in the north and south Texas regions.

Statistic	Observed PDSI 1931–80		Reconstructed PDSI 1931–80		Reconstructed PDSI 1698–1980	
	North Texas	South Texas	North Texas	South Texas	North Texas	South Texas
Mean	-0.18	-0.12	-0.17	-0.13	-0.13	-0.06
Standard deviation	2.42	2.60	1.84	1.96	1.81	2.00
Maximum	5.43	5.29	3.11	3.02	4.52	5.41
Minimum	-4.94	-5.77	-5.09	-5.40	-5.67	-5.96
Range	10.37	11.06	8.20	8.42	10.19	11.37
Median	-0.48	0.61	0.15	0.02	-0.17	-0.08
Serial correlation	0.16 ns <sup>†</sup>	0.24 ns	0.03 ns	0.07 ns	0.14*	0.20**
Skewness	0.21	-0.20	-0.50	-0.64	0.04	0.09
Kurtosis	-0.42	-0.82	-0.03	-0.08	-0.11	-0.06
Normal	Yes*	Yes*	Yes*	Yes*	Yes*	Yes*
Number of years	50	50	50	50	283	283

\* =  $P \leq 0.05$ .

\*\* =  $P \leq 0.01$ .

<sup>†</sup> ns = not significant,  $P > 0.05$ .



to 1980. These observations and the statistical comparisons in Table 3 indicate that the 50 yr of observed June PDSI data from 1931 to 1980 appear to be representative of June moisture conditions over the past 283 yr.

When time scales shorter and longer than 50 yr are considered, however, there does appear to be some evidence for climatic changes over Texas. If the reconstructed series are subdivided into 30-yr intervals, the means of certain consecutive periods are significantly different ( $t$ -tests,  $P < 0.10$ ; Steel and Torrie, 1980; SAS Institute Inc., 1985). The period 1951–80 was drier than the period 1921–50 in both north and south Texas reconstructions. The same two periods are also different in the state average June PDSI ( $P < 0.10$ ; Karl et al., 1983), indicating a high degree of short- and long-term variability in the growing season climate of Texas during the twentieth century. These differences support the notion that the 30-yr “standard normal” climate periods provide a reasonable measure of the current growing season moisture regime, but are less suitable estimates of long-term drought conditions in Texas.

Both reconstructions also indicate a very long-term positive trend in June PDSI since the eighteenth century (Fig. 3). The mean June PDSI from 1698 to 1791 was  $-0.265$  and  $-0.275$ , compared with  $+0.193$  and  $+0.364$  from 1867 to 1950 in north and south Texas, respectively. These long-term differences in average June PDSI are statistically significant for both north ( $P < 0.10$ ) and south Texas ( $P < 0.05$ ). A positive trend since the eighteenth century is also apparent in reconstructed June PDSI data for North Carolina (Stahle et al., 1988), and this low-frequency signal is generally consistent with the long-term trend in annual precipitation data actually recorded for the continental United States from 1851 to 1984 (Bradley et al., 1987). The strongly positive departures since the mid-1950s apparent in both the North Carolina PDSI and continental precipitation data are not evident in the Texas reconstructions, although they may be present in the actual June PDSI data for north and south Texas (Fig. 2). Nevertheless, because the low-frequency signal is apparent in reconstructed June PDSI data for Texas and North Carolina since the eighteenth century, it may be part of a regional climate trend unrelated to  $\text{CO}_2$  pollution until, perhaps, very recently.

Examination of Fig. 3 reveals that drought, and to a lesser extent wetness anomalies, have been somewhat more frequent in south Texas. In the last 283 years, 66 moderate or worse droughts (PDSI equivalent  $\leq -1.58$ ) and 61 moderate or worse wet years (PDSI equivalent  $\geq +1.52$ ) were reconstructed in south Texas compared with only 58 and 50 comparable drought and wetness anomalies in north Texas (PDSI equivalents  $\leq -1.60$  and  $\geq +1.55$ , respectively; Table 2). These intrastate comparisons are consistent with the observed data and suggest that the summer climate of

southern Texas is both somewhat more variable and drought prone than northern Texas.

## 7. Interannual persistence of moisture extremes in Texas

Careful examination of the reconstructed series suggests that June drought or wetness extremes tend to be followed by similar dry or wet conditions during the next summer (Table 2; Fig. 3). This apparent interannual persistence of growing season moisture anomalies is statistically significant, and the increased risk for a particular moisture regime in the summer following an observed June moisture anomaly may have modest value in statistical forecasts of Texas climate.

The interannual persistence of summer moisture anomalies in Texas is tabulated in Table 4. The number of years that were at least moderately wet or dry are listed for both 283-yr reconstructions and for the 95 yr of actual June PDSI recorded on a statewide basis since 1888 (Karl et al., 1983). The thresholds of moderately wet or dry years in the reconstructed series represent equivalent levels of moderate drought or wetness actually recorded in the statewide data (see section 6 above). The number of June moisture anomalies (PDSI  $\leq -2.0$  and  $\geq +2.0$ , or equivalents) that followed moderate drought or wetness during the previous summer are then listed in Table 4. The statistical significance of the apparent interannual persistence was assessed using a normal approximation to the distribution of the number of joint or consecutive occurrences of moderate or more severe June drought or wetness (Table 4; Appendix). Finally, the increased likelihood of a particular June moisture regime in the summer following a wet or dry June is also listed in Table 4 (i.e., the observed percentage of at least moderately wet or dry Junes, and just above or below average June conditions for the following summer are compared with the percentages expected to occur at random).

The results in Table 4 indicate that the tendency for drought and wetness anomalies to persist for two or more growing seasons is statistically significant in most cases, especially in the south Texas region. The chance of experiencing a moderate or more severe June drought in south Texas increases to 39% in the summer following a June drought, compared with an estimated random chance of only 23% (Table 4). The potential for June conditions that are at least moderately wet also increases in the summer following a wet June in south Texas only, but the increase is not quite as large. This interannual persistence is reinforced when assessed only in terms of above or below average moisture conditions in the year following a June moisture anomaly. The June PDSI was below average ( $\leq 0.0$ ) in 66% and 65% of all summers following a moderate drought or worse in north and south Texas, respectively (Table 4). The results based on the reconstructed data in Table 4 are probably conservative since several interannual

TABLE 4. Interannual persistence of growing season moisture anomalies in north and south Texas, based on an actual statewide June PDSI threshold of at least  $\pm 2.0$  and equivalent levels of reconstructed drought and wetness. The increased chance for a particular June moisture regime in the summer following a wet or dry June is compared with the expected chance assuming random interannual occurrence (shown in parentheses).

June PDSI series	Time period	Years $\leq -2.0$	Years $\leq -2.0$ following $\leq -2.0$ actual and (expected)	Standard deviation of expected $\leq -2.0$ following $\leq -2.0$	Percent occurrence for actual and (expected)	
					$\leq -2.0$	$\leq 0.0$
<i>Drought</i>						
Actual statewide	1888–1982	24	11** (5.8)	1.82	46 (24)	54 (51)
North Texas	1698–1980	58	16† (11.7)	2.73	28 (20)	66 (54)
South Texas	1698–1980	66	26*** (15.2)	2.99	39 (23)	65 (53)
<i>Wetness</i>						
		Years $\geq +2.0$	Years $\geq +2.0$ following $\geq +2.0$ actual and (expected)	Standard deviation of expected $\geq +2.0$ following $\geq +2.0$	Percent occurrence for actual and (expected)	
					$\geq +2.0$	$\geq 0.0$
Actual statewide	1888–1982	26	10* (6.8)	1.92	38 (27)	58 (49)
North Texas	1698–1980	52	12 ns† (9.4)	2.51	23 (18)	60 (46)
South Texas	1698–1980	65	22** (14.7)	2.96	34 (23)	60 (47)

\* =  $P \leq 0.05$ .

\*\* =  $P \leq 0.01$ .

\*\*\* =  $P \leq 0.001$ .

† =  $P \leq 0.10$ .

‡ ns = not significant,  $P > 0.10$ .

moisture anomaly pairs near the average and moderate thresholds were not included (Table 2).

Significant interannual persistence of June PDSI extremes is also apparent in the actual statewide data available from 1888 to 1982 (Table 4), in spite of the relatively short length of record. The ten moderately wet Junes that followed wet conditions in the previous summer occurred in seven separate episodes and appear to approximate the interannual persistence of wet growing seasons estimated for the past 283 yr in south Texas (Table 4). The interannual persistence of drought, based only on the 95 years of actual statewide data (Table 4), however, may be biased because the 11 moderate or worse June droughts that followed droughts during the previous summer occurred in just five multiyear drought episodes (Karl et al., 1983). These multiyear drought episodes include the historic Texas drought of the 1950s when moderate to extremely dry conditions in June lasted for six consecutive years.

The reconstructed data do not appear to be seriously biased by the prolonged droughts of either the 1860s or 1950s, particularly in south Texas. The 26 moderate or worse June droughts in south Texas that followed a moderate or worse June drought during the previous summer occurred in 15 separate episodes (Table 2), and the interannual persistence of drought in this region remains significant when the 1860 and 1950 droughts are omitted from the analysis ( $P < 0.01$ ). Interannual

drought persistence is not significant in north Texas when these two prolonged droughts are omitted, but there is still a 60% chance for below average conditions in the summer following a June drought.

The interannual persistence of growing season moisture extremes does not appear to be a spurious result of biological growth persistence in trees because the reconstructions are based on serially random principal component amplitude series of tree growth, and because significant interannual persistence of June moisture extremes is present in the actual statewide PDSI data from 1888 to 1982 (Table 4). Significant interannual persistence of abnormal June temperature and precipitation was also found on a statewide basis for Texas (1888–1982). This indicates that the persistence in the PDSI data is not due simply to low interannual persistence arising from the strong month-to-month autocorrelation built into the Palmer Index in order to model the effects of climate on slower-changing soil moisture conditions. [The prescribed monthly autocorrelation term in the Palmer model is +0.897 (Palmer, 1965), resulting in an interannual autocorrelation that theoretically can be as high as +0.27.] To test for persistence, the statewide temperature and precipitation data were divided into three equal classes (above average, average, and below average). These tests indicate significant interannual persistence for warmer than average June temperatures ( $P < 0.001$ ), and above average June precipitation ( $P < 0.05$ ). The statewide

June precipitation data are not normally distributed, but the test for persistence (Appendix) is not sensitive to violations of normality. Finally, the look-ahead features of the Palmer Index associated with the termination of wet or dry spells (Karl, 1983) do not appear to be a serious problem because the evidence indicates persistence over a full 12-month interval.

Significant interannual persistence has been noted for summer 700 mb height departures over the Southern Plains (Namias, 1960), and between current surface temperature in this region during spring-summer and the regional 700 mb height departure of the previous summer (Erickson, 1983). These results are based on continuous temperature and pressure variables representing different spring-summer averages, but nevertheless tend to substantiate the interannual persistence of summer moisture extremes reported here for Texas.

The apparent persistence of midtropospheric pressure heights during summer is potentially an important link in the chain of physical causes that might be involved in the interannual persistence of summer moisture extremes over the Southern Plains. These physical mechanisms may include prolonged sea surface temperature anomalies in the North Pacific and North Atlantic Oceans (Namias, 1960; Erickson, 1983), and the various potential feedback processes associated with large regions of abnormally wet or dry soil (Twomey and Squires, 1959; Namias, 1960; Charney, 1975). The specific role of these and other potential physical causes of interannual persistence in summer moisture anomalies over Texas remains to be demonstrated, but the increased potential for dry or wet conditions in the summer following a June moisture anomaly may have modest forecast value even in the absence of a well-documented physical model.

**8. Return time analysis**

Return time analysis (Viessman et al., 1972) provides a longer statistical perspective on the recurrence of drought or wetness anomalies in Texas. Recurrence probability curves have been calculated for six levels of reconstructed drought or wetness severity over time intervals from 2 to 100 yr (June PDSI = ±1.0, ±2.0, . . . ±6.0). The return curves were first calculated using the reconstructed data from 1698 to 1980, and also for discrete 50-yr intervals from 1731 to 1980. These results indicate little difference between the recurrence probabilities for the various levels of drought or wetness when calculated for the entire 283-yr reconstruction or for any of the shorter 50-yr segments. These temporal comparisons indicate again that the 50 years of June PDSI observations from 1931 to 1980 appear to have been generally representative of the last 283 years in Texas.

Because the reconstructions underestimate actual June PDSI, however, the recurrence intervals based on

the reconstructions are usually longer than the intervals calculated for the observed PDSI data (1931-80), especially at the more extreme levels. Consequently, the recurrence probability curves in Fig. 4 have been adjusted by multiplying each annual recurrence probability from 2 to 100 yr by the ratio of observed to reconstructed probabilities determined for each interval during the 1931-80 common period. This adjustment expresses the return curves based on the long reconstruction in terms of the actual June PDSI probabilities for 1931-80, and is warranted in part because the 50-yr common period appears to have been representative of the drought and wetness recurrence probabilities over the past 283 yr.

The adjusted return curves in Fig. 4 indicate a near certainty for the occurrence of a moderate-or-worse growing season drought each decade in both north and south Texas (June PDSI ≤ -2.0, P = 0.90 and 0.92, respectively). There is a better than 50% chance for the

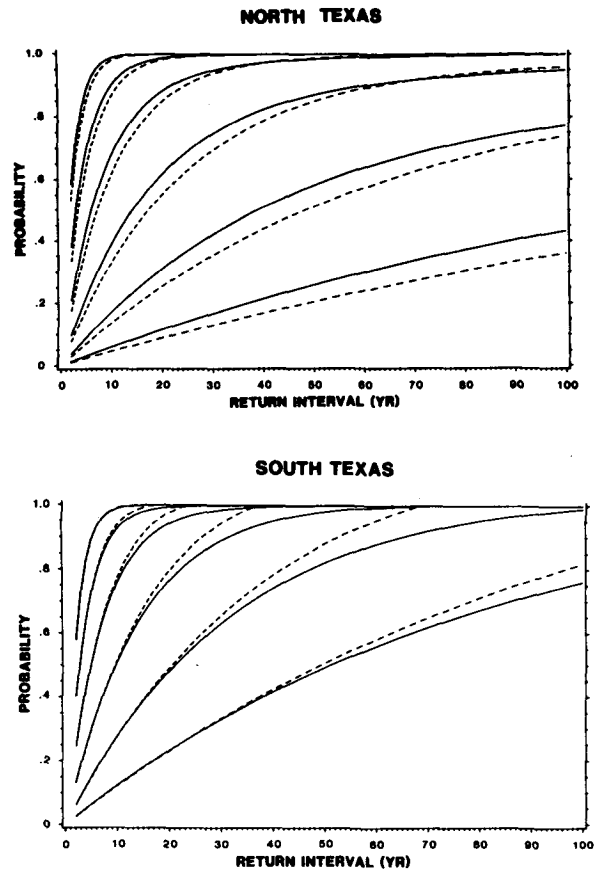


FIG. 4. The adjusted return time probabilities are plotted for six levels of drought (solid lines) and wetness (dashed lines) in north and south Texas (June PDSI levels are ±1.0 to ±6.0 from top left to bottom right). The estimated return curves are based on the 283 yr reconstructions, but were first multiplied by the ratio of observed-to-reconstructed probabilities from 1931 to 1980 because the reconstructions underestimate actual moisture extremes. The +1.0 and -1.0 curves for south Texas are nearly identical.

occurrence of an extreme drought every 15 years in north Texas and every 10 years in south Texas (June PDSI  $\leq -4.0$ , Fig. 4). As these figures indicate, the recurrence probabilities for drought and wetness anomalies are higher in south Texas, particularly at the most severe levels (Fig. 4). The higher risk for moisture extremes in south Texas is also suggested by the variance statistics in Table 3 and is consistent with the return probabilities calculated for the actual June PDSI data used for calibration in north and south Texas. Unlike south Texas, however, the return probabilities for wet anomalies are uniformly lower than the dry risk in north Texas, and may reflect the greater distance to moisture sources in the Gulf of Mexico.

Interpretation of the return curves in Fig. 4 should be qualified by several points. Return time analysis assumes independence of the June PDSI values, but the interannual persistence discussed above suggests that this assumption may be violated in the case of moisture extremes. The high probabilities for the return of dry or wet conditions over very short intervals may therefore reflect in part development of interannual moisture regimes such as the historic drought of the 1950s, so the true return intervals between such regimes might be lower. However, the return curves could be underestimating the intervals between damaging droughts simply because the dryness levels specified by Palmer (1965) and used in Fig. 4 are arbitrary threshold values. The dry conditions indicated by PDSI values slightly above a given threshold may produce essentially the same negative impact, particularly when nonclimatic variables such as the strength of the agricultural economy or the buffering capacity of the water supply system are considered.

Finally, the return curves are strictly applicable only to the large north and south Texas regions investigated. Calculations based on the individual climatic divisions, however, do not indicate any major differences compared to the return probabilities based on the larger regional averages. The South Central division has the highest recurrence probabilities for June moisture extremes, and the North Central division has the lowest of the four Texas climate divisions investigated.

## 9. Spectral analysis

Spectral analyses (Jenkins and Watts, 1968) indicate that the tree-ring reconstructions of June PDSI contain marginally significant spectral peaks at frequencies near the quasi-biennial pulse and the lunar nodal tide. While these results are in general agreement with certain quasi-periodicities identified in western droughts (Stockton et al., 1983; Currie, 1981, 1984) and eastern air temperatures in North America (Currie, 1984), they do not represent an a priori hypothesis test and can only be regarded as inconclusive statistical results (e.g., Pittock, 1983).

Cross-spectral analyses between the observed and reconstructed June PDSI series during the calibration period indicate that the tree-ring reconstructions faithfully reproduce the frequency domain properties of the actual June PDSI data. The estimated power spectra of the observed and reconstructed series for the 1931–80 period are plotted in Fig. 5a, and broad spectral peaks with periods between 3 and 4 yr, and 12 to 24 yr are present in all series. These similarities in the low-frequency variance of June PDSI in north and south Texas are certainly to be expected given the shared regional climate (Pittock, 1983).

The squared coherency remains well above the 95% confidence level and demonstrates the highly significant agreement between the observed and reconstructed series at all frequencies in both north and south Texas (Fig. 5b). The observed and reconstructed series in both regions are in phase at all frequencies, and the lack of pronounced slope in the gain spectra indicates that both reconstructions represent unbiased estimates of the actual June PDSI series in the frequency domain (Fig. 5c).

The notable consistency between the actual and reconstructed PDSI records during the calibration period indicates that the reconstructions should provide reliable estimates of any low-frequency or quasi-periodic components in growing season droughts over the past 283 yr in Texas. Significant spectral peaks ( $P < 0.05$ ) are present in the power spectra for both long-term June PDSI reconstructions at 2.3 and between 14 and 18.67 yr, explaining 4% and 16% of the reconstructed variance, respectively (bandwidth = 0.045 cpy, Fig. 6). The power spectra presented in Figs. 5 and 6 were computed using a Hamming window (IMSL Inc., 1982). The weak red noise persistence component observed in the actual PDSI data was added to the serially random tree-ring reconstructions, so the statistical significance of the spectral peaks identified in both types of data were evaluated assuming a first-order autoregressive null continuum.

The apparent concentration of low-frequency variance near 2.3 yr may be related to the quasi-biennial pulse often present in meteorological data (Barry and Perry, 1973), although this frequency component is not prominent in the observed or reconstructed data from 1931 to 1980 (Fig. 5a). The broad spectral peak between 14 and 18.67 yr resolves to a significant peak between 17.5 and 20 yr at the narrowest bandwidth (BW = 0.18 cpy;  $P < 0.01$  for the 17.5-yr peak in south Texas;  $P < 0.05$  for the 20-yr peak in south Texas, and for the 17.5 and 20-yr peaks in northern Texas). At this level of spectral resolution, the broad spectral peak includes the 18.6-yr period in the lunar nodal tide (Currie, 1981; Currie and Fairbridge, 1985). Other tree-ring studies of drought in the Great Plains have found quasi-periodicities in this frequency range that are temporally and spatially complex, but may be related

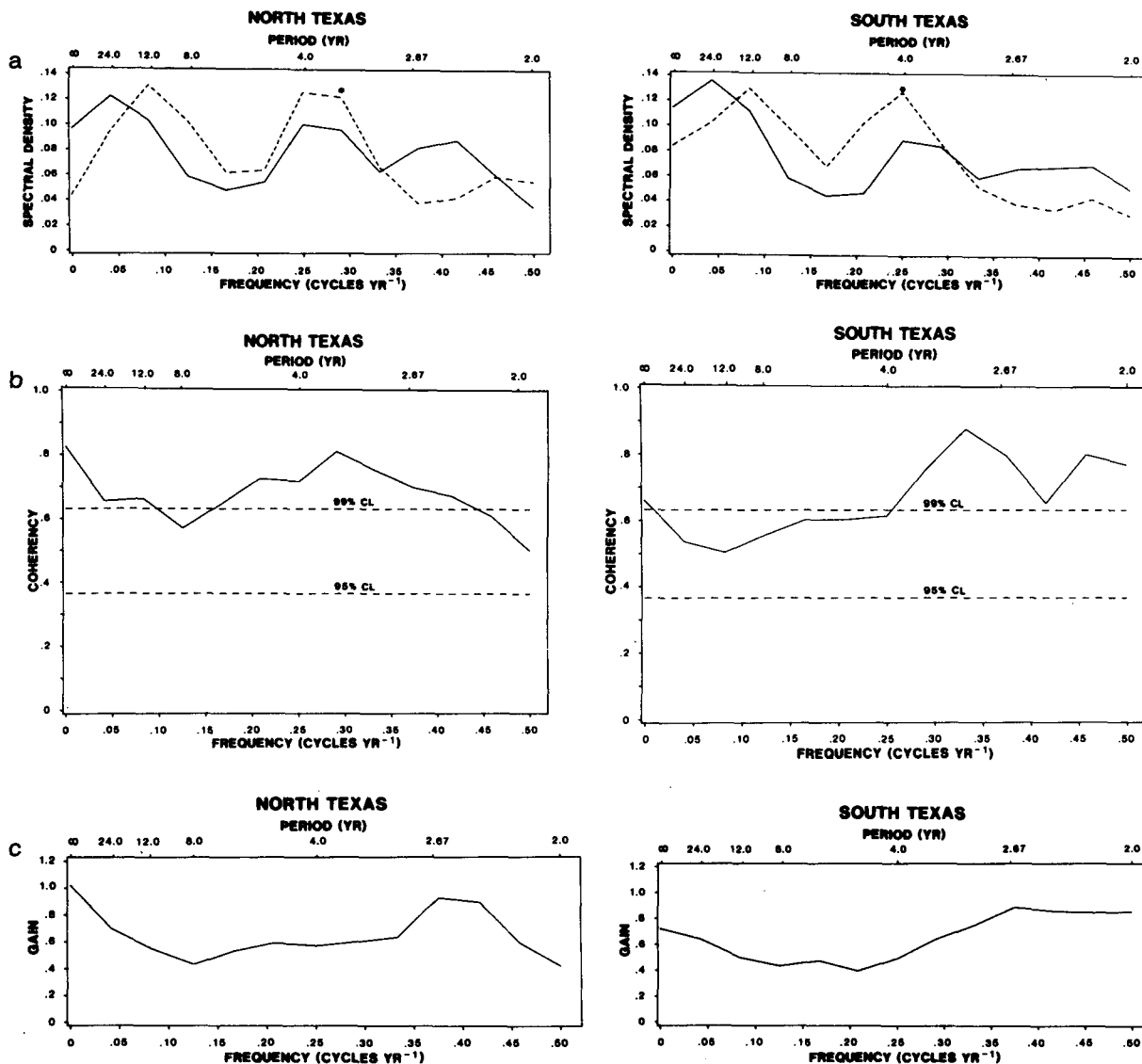


FIG. 5. Cross-spectral analysis between observed and reconstructed June PDSI for north and south Texas, 1931-80. (a) Relative spectral density for observed (dashed lines) and reconstructed (solid lines) June PDSI calculated using a Hamming window with 12 lags, resulting in 10 deg of freedom and bandwidth of 0.105 cycles per year (asterisk represents  $P < 0.05$ ); (b) squared coherency between observed and reconstructed June PDSI along with the 95% and 99% confidence limits; (c) gain spectra for observed and reconstructed June PDSI.

to solar and/or lunar influences (Stockton et al., 1983; Meko et al., 1985).

A *t*-test for differences between means of reconstructed June PDSI for the 9 years of lunar nodal maxima and nine minima since 1800 (Currie, 1984) indicates a marginally significant difference in moisture regimes for north Texas ( $P < 0.10$ ), but no significant difference in south Texas ( $P < 0.23$ ). The true significance of the apparent low-frequency signal in Texas June PDSI remains obscure in the absence of an a priori model predicting periodicities at specific frequencies (Mitchell et al., 1966), and because the spectral peak

is not significant when tested between 1870 and 1980. The analyses of western droughts and eastern air temperatures reviewed by Pittcock (1983), however, also indicate a breakdown in oscillations between periods of approximately 18.6 and 22 yr in the late nineteenth century.

The spectral analysis of long-term June PDSI is adequate to suggest that the search for possible lunar nodal tidal influences on climate might be expanded into Texas, which is certainly not unreasonable considering the general spatial coherence of climate across the central and southwestern United States where these

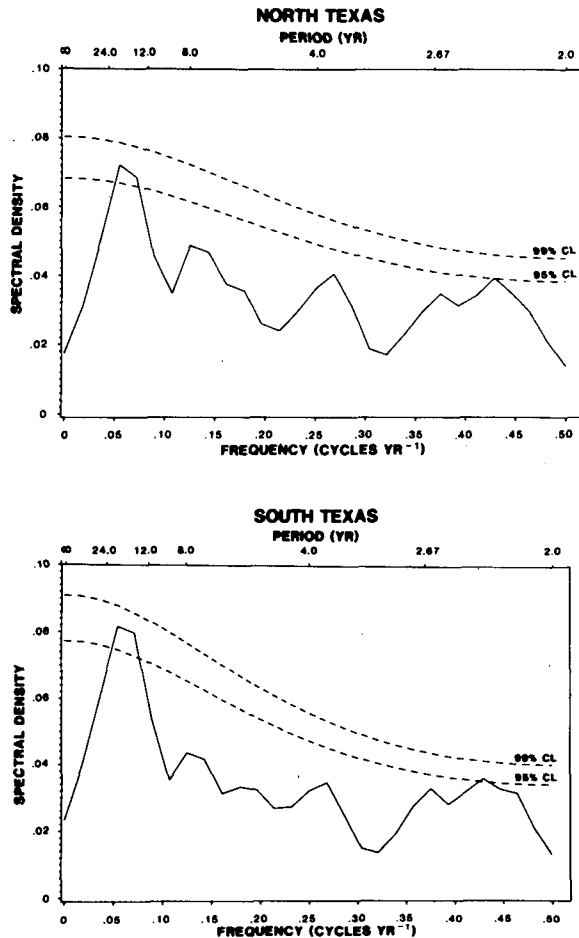


FIG. 6. Relative spectral density estimated for the 283-yr reconstructions for north and south Texas (1698–1980). The spectral estimates were calculated using a Hamming window with 28 lags, resulting in 25 degrees of freedom and bandwidth of 0.045 cpy. The 95% and 99% confidence limits were based on a first-order autoregressive null continuum. Spectral peaks significant at the 95% level are present in both reconstructions at 2.3 and between 14 and 18.67 yr.

possible effects have previously been identified. The detection of lunar influences over Texas would also appear to be generally consistent with Currie's (1981, 1984) hypothesized mechanism for orographic modulation of an 18.6-yr quasi-standing atmospheric wave by the Rocky Mountains. Whatever physical or stochastic mechanisms might be responsible for the apparent low-frequency component of reconstructed June PDSI in Texas, it is probably not due to recurrent infestation of the sample trees by 17-yr periodical cicadas (*Magicalada* spp.) because the nine prairie-border post oak sites appear to be well outside of the known distribution of this species (Simon, 1979).

## 10. Summary and conclusions

Nine climate-sensitive post oak chronologies have been used to reconstruct the June PDSI in northern

and southern Texas. The well-verified reconstructions explain some 60% of the June PDSI variance during the calibration period (1931–80) and indicate that the multiyear drought of the 1950s was the most severe continuous drought episode since 1698. The three driest decades by rank appear to have been 1855–64, 1950–59, and 1772–81. The 50 years of meteorological observations from 1931–80 are generally representative of the mean, variance, and recurrence probabilities of June PDSI over the past 283 years, but significant changes in average June PDSI appear to have occurred in Texas over time intervals shorter and longer than 50 years. Significant interannual persistence of June moisture extremes indicates that the drought hazard may increase in the summer following a moderate-or-worse June drought. June wetness extremes exhibit similar persistence, but to a lesser degree. The low frequency variation in June PDSI indicated by the broad spectral peak between 14 and 18.67 yr in the two reconstructions may be weakly related to periods of maxima and minima in the lunar nodal tide in northern Texas.

Considering the profound economic and environmental impact of the record drought from 1951 to 1956 (Griffiths and Ainsworth, 1981; Karl and Quayle, 1981), it is reassuring to conclude that the severity of this prolonged drought has evidently not been exceeded in Texas since 1698. It is also fortunate from a long-term planning perspective that the period of meteorological observations from 1931 to 1980 appears to have been representative of growing season climate conditions over the past 283 years, because the historical expectations of rainfall and streamflow in Texas are largely based on this time period. The estimated occurrence of the three driest decades in the 1770s, 1860s, and 1950s very loosely suggests that the approximate frequency of these extreme episodes of prolonged drought may be about once per century.

The interannual persistence of June moisture extremes in Texas is evident in the actual statewide temperature, precipitation, and PDSI data available from 1888 to 1982, but this relatively short record may be biased by the prolonged drought of the 1950s. The long tree-ring reconstructions reported here substantiate this apparent interannual persistence and suggest a near 65% risk for below average June moisture conditions in Texas for the summer following a moderate June drought. Persistence in tree-ring data has usually been treated as a problematical function of internal tree physiology and stand dynamics, but the autoregressive modeling approach suggested by Meko (1981) has permitted the recovery of evidence concerning the interannual persistence of climate in Texas that may have some modest forecast value.

Annual resolution and the potential for direct quantitative reconstruction of monthly, seasonal, or annual climate variables are the principal virtues of proxy tree-ring data. The lack of widespread spatial arrays of tree-

ring data, however, has been a severe practical limitation confronting dendroclimatic applications to large-scale climatic problems. This study extends the network of high quality, climate-sensitive tree-ring chronologies in the southern Great Plains. The coupling of these new tree-ring data with the expanding geographic array for the Northern Hemisphere (Stockton et al., 1985) has the potential to increase understanding of the climate system.

*Acknowledgments.* This research was supported by the Climate Dynamics Program of the National Science Foundation, grants ATM-8006964, ATM-8120615, ATM-8412912 and ATM-8612343. The expert advice and assistance of Edward R. Cook have considerably improved this research, and Colm O’Cinneide helped us assess the statistical significance of interannual persistence. We also thank Rita C. Berg, T. J. Blasing, Randall S. Cerveny, James E. Dunn, Glenn L. Evans, Thomas P. Harlan, Graham G. Hawks, John G. Hehr, and Robert Mauermann for their help, and the following landowners for permission to collect tree-ring samples from their property: Mr. Herman Leifeste, Dr. Dwight Nichols, Wichita Mountains National Wildlife Refuge, Chickasaw National Recreation Area, U.S. Army Corps of Engineers, and the Corpus Christi Power and Light Company.

APPENDIX

Significance Test of Runs

The statistical significance of interannual persistence was tested by comparing it with the expected runs of two drought categories in a random normal distribution (O’Cinneide, personal communication, 1987) as follows:

$$E_0(T) = \frac{M(M - 1)}{N} \tag{A1}$$

where  $E_0$  is the expectation in a random normal distribution,  $T$  the number of runs of a category (PDSI  $\leq -2.0$  following  $\leq -2.0$ , or PDSI  $\geq +2.0$  following  $\geq +2.0$ ),  $M$  the total number of occurrences of a category in a series, and  $N$  the number of years in the series.

$$V_0(T) = \frac{M(M - 1)}{N} \times \left[ 1 + \frac{(M - 1)(M - 2)}{N - 1} - \frac{M(M - 1)}{N} \right] \tag{A2}$$

where  $V_0$  is the variance of expected occurrences in the number of runs ( $T$ ), and all other variables are as described above.

The significance test is

$$z_a = \frac{T - E_0(T)}{\sqrt{V_0(T)}} \tag{A3}$$

where  $z_a$  is the z-score, the variables are as described

above, and the null hypothesis is that given the number of occurrences of a condition in a period, the times of occurrence are completely random.

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