

DROUGHT IN THE UNITED STATES: 1895-1981

THOMAS R. KARL AND ALBERT J. KOSCIELNY
National Climatic Center, Asheville, NC 28801, U.S.A.

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Statewide averages of temperature and precipitation, from January 1895 to April 1981, were interpolated to a grid and Palmer Drought Severity Indices (PDSI) calculated for each of the grid points. Principal component (PC) analysis was performed on the gridded values of PDSI. By rotating the PC, nine readily identifiable patterns of drought are delineated. Each PC relates to different regions of the country, and is characterized by a distinct annual oscillation of monthly average precipitation. A high degree of confidence is placed in the state gridded data as patterns compare favourably to those derived using smaller averaging areas.

Univariate and multivariate autoregressive spectral estimation procedures together with the traditional spectral estimation techniques were used to investigate the spectra and coherence of the PC scores. No significant cycles were found in the 86-year (1036 months) data set. Coherence was very low (<0.30) for all frequencies between the various patterns depicted by the PC.

Both the spectra of PC scores and drought duration statistics point to the major difference in droughts across the United States; droughts persist much longer in the interior portions of the country than in areas closer to the coasts. Sensitivity tests on the PDSI indicate that this is not directly attributable to the spatially varying available soil water capacity parameter used in the PDSI calculations. This is not to say that soil moisture evaporation does not indirectly influence drought duration, but merely that the differing lengths of droughts in the United States are real and not an artefact of the mechanics in the PDSI calculations.

1. INTRODUCTION

The social, economic, and management planning strategies associated with droughts in the U.S. have been the subject of considerable study in the past few years (Yevjevich *et al.*, 1978; Rosenberg, 1978a, 1978b; Rosenberg *et al.*, 1980). In a study of the dry, hot summer of 1980 Karl and Quayle (1981) suggest that in spite of its technological advances the United States economy is becoming more dependent upon an ample moisture supply. There is a need to understand the spatial and temporal variations of drought for planning purposes, but in addition it also provides direction for research seeking the explanations for the initiation, development, and termination of droughts in the United States. Klugman (1978) addressed the topic of temporal and spatial variations of drought using the Palmer Drought Severity Index (PDSI) in the upper midwest from 1931-1969, and Skaggs (1975) did likewise for the entire United States for the decade of the 1930s. Namias (1955, 1966, 1967) studied the nature and possible causes for the drought in the Northeast during the 1960s, and the early 1950s drought in the southern and central United States. Davis and Rappoport (1974) investigated the statistical predictability of drought in central Ohio using the PDSI. Mitchell *et al.* (1979) used tree ring data to investigate the temporal variations of drought in the western United States from 1700 to 1963.

This study is primarily aimed at determining the spatial patterns and homogeneity of drought, and its temporal behaviour. It differs from previous drought studies in that the entire contiguous United States is examined using precipitation and temperature data over an 86-year period (1036 months). Using these data the spatial patterns of drought are studied by calculating PDSIs for use in a Principal Component (PC) Analysis. Spectral analyses of the PC scores are used to define and delineate time dependent characteristics of the regions depicted by the PC.

2. DATA

Statewide averages of monthly temperature and precipitation were used to calculate Palmer Drought Severity Indices (PDSI) from January 1895 to April 1981 for the 48 contiguous states. The monthly averages of temperature and precipitation have been described elsewhere (Diaz and Quayle, 1978). Palmer (1965) provides a detailed description of the PDSI as well as the logistics involved in the computation. Karl and Quayle (1981) also provide a brief description of the index. The PDSI is a measure of the moisture abnormality over a period of dry, wet, or near-normal weather which may span many months. The longer the spell of dry (wet) weather the lower (higher) the index. PDSI values of 0 to -0.5 are considered near normal, -0.5 to -1 an incipient drought, -1 to -2 a mild drought, -2 to -3 a moderate drought, -3 to -4 a severe drought, and -4 or below an extreme drought. Corresponding categories of moisture excess relate to positive values. The index is standardized which enables direct comparisons of PDSI for such diverse climates as those found in Arizona and Ohio. It is important to note that the PDSI is insensitive to man-made droughts, such as drought created by large scale changes in the local water usage.

In general the probability density distribution for PDSI tends to be bimodal with one peak between -1 and -2 and the other between $+1$ and $+2$. The frequency of PDSI between -0.5 and $+0.5$ (near average conditions) at some locations is as low as half that of the peaks to the right and left, but usually the frequency of occurrence of near average conditions is approximately 75 per cent of the adjacent peaks. Although PC analysis can be applied to non-normal data (Rummel, 1970) the resulting correlation matrix (covariance matrix) can be poorly defined when for example, the data are extremely skewed such that a very few extreme values dominate the resulting correlation coefficients (covariances). In general the skewness of the PDSI used in this study is near zero. The effect of the bimodality of the data on the resulting patterns delineated by the PC analysis is examined in Section 3a. The bimodality is a result of the accounting procedures within the PDSI computations. The severity of dry (or wet) spells is a consequence of the accumulation of successive monthly contributions to drought (wet spell) severity such that near normal months are often assigned a PDSI associated with an ongoing wet or dry spell. This is not an oversight in the calculations, but instead reflects the philosophy that a few months of near normal moisture is usually not sufficient to end a drought (wet spell).

The statewide averages of precipitation and temperature were interpolated to a 60-point grid which closely approximates an equal area grid (Figure 1). The importance of using an equal area grid with geophysical data is demonstrated by Buell (1978) and by Karl *et al.* (1982). The technique of interpolation of the precipitation and temperature data to the grid points is similar to the approach used by the U.S. National Weather Service (1972) for estimating precipitation at a point. The statewide averages of precipitation and temperature are located at the geographical centre of each state, and the precipitation estimate at any grid point is the weighted average of the precipitation from four states, one in each of the quadrants delineated by north-south and east-west lines through the grid point. The weighting factor for precipitation estimates is the reciprocal of the square of the distance ($1/d^2$) between the state centre and grid point whereas for temperature it is simply ($1/d$). If one or more of the quadrants contain no data (as is the case for states bordering oceans or other countries) then the estimation involves only the remaining quadrants. The justification for treating temperature and precipitation differently is provided by Diaz and Fulbright (1981) and Diaz (1981). Using Asymptotic Singular Decomposition (ASD) they find that temperature departures from average in the U.S. have significantly more spatial homogeneity than precipitation departures from average.

The PDSI for the 60-point grid were calculated using the entire 1036 months to establish means. These means were used in the PDSI computations to establish what constitutes an extreme drought, a moderate drought, etc. PDSI are also routinely calculated and archived by the U.S. National Climatic Centre for approximately 350 climatic divisions in the contiguous United States. These PDSI are based on 1931 to 1960 means. Figure 2 depicts those divisions which were used in the PC analysis for comparison with the results of the PC analysis using the state gridded data to make certain the state averages and the gridding procedures were not altering important regional patterns. There is one climatic division that corresponds to each of the 60 grid points in Figure 1.

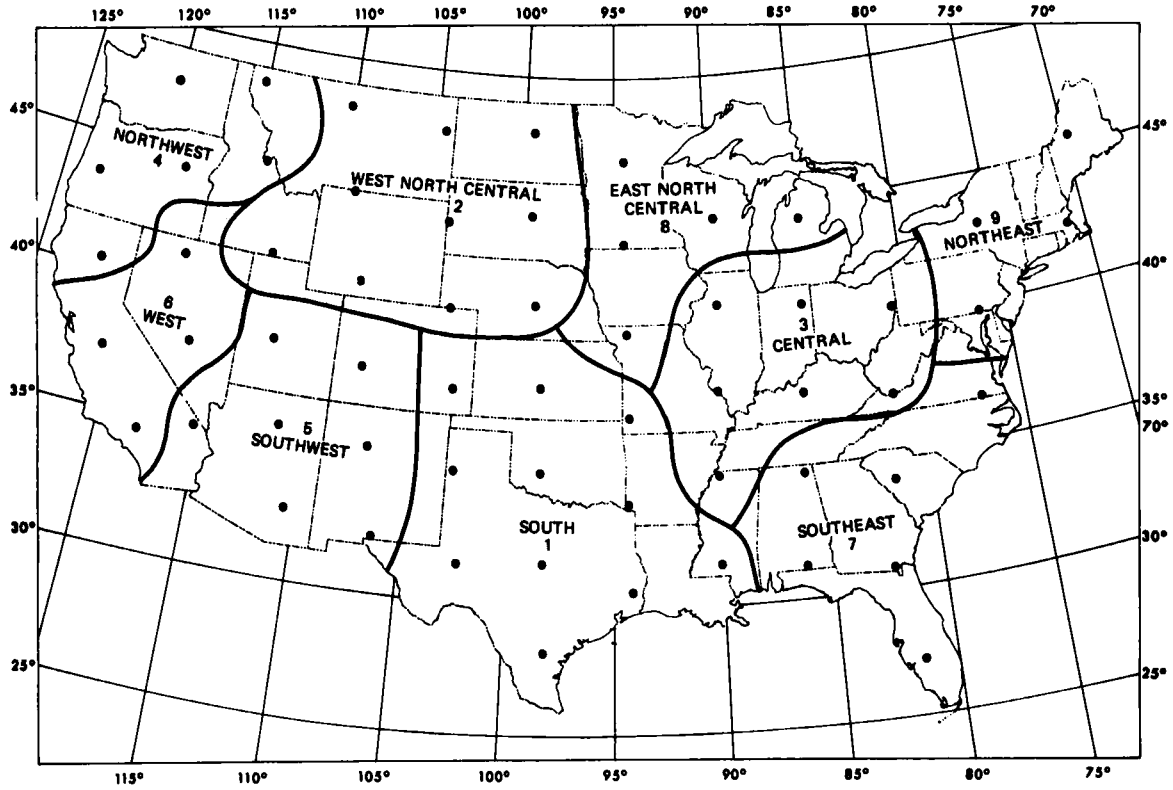


Figure 1. Grid points which were used for the principal component analysis, and the principal components to which they are best related

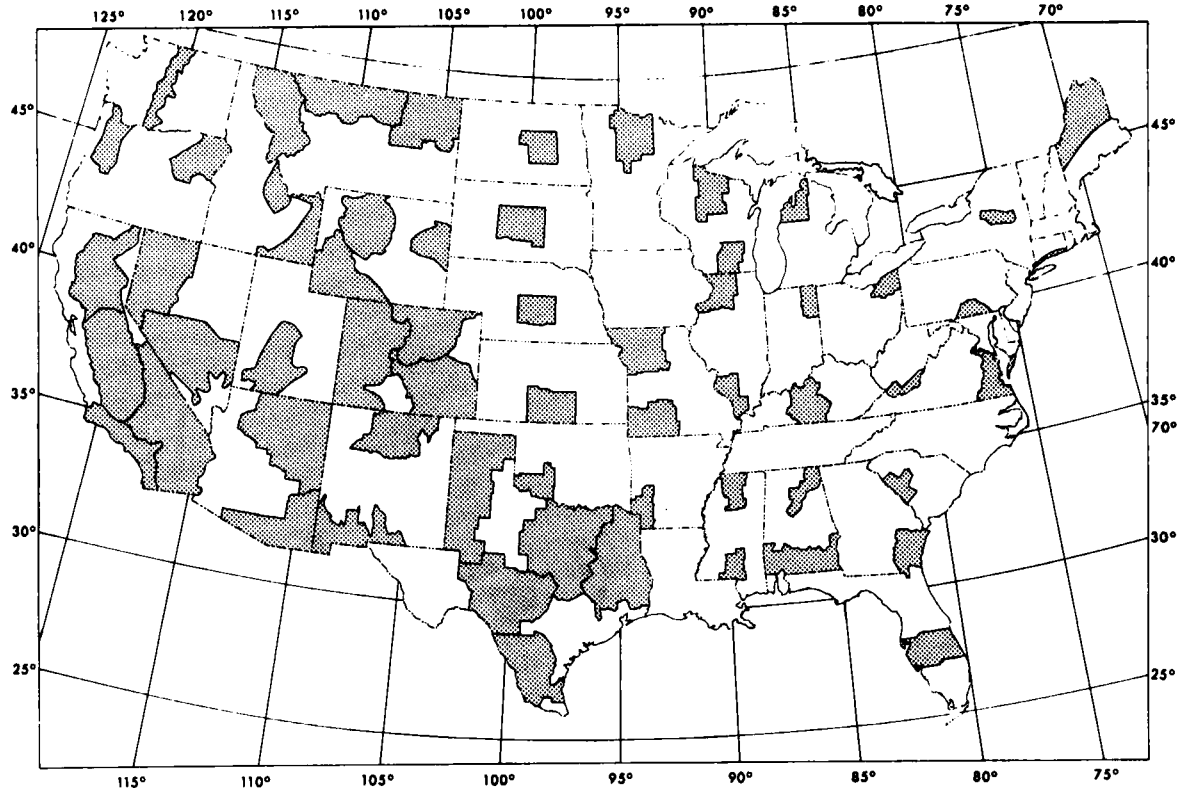


Figure 2. Climatic divisions corresponding to the 60 grid points

3. RESULTS

(a) *Drought patterns*

In the past two decades PC analysis (or similarly, empirical orthogonal function analysis) has been widely used in climate studies, i.e. Kutzbach (1967); Christensen and Bryson, (1966); Klugman (1978); Trenberth and Paolino, (1981). Rummel (1970) and Johnston (1978) provide the reader with a general appreciation of the methods for application of PC analysis. Traditionally (except for the Christensen and Bryson article) the approach has been to present the unrotated PC. Figure 3 depicts the unrotated PC based on the correlation matrix of the 60 grid points. The variance explained by each component is indicated in each panel, i.e. D_1 —29.8 per cent implies that nearly 30 per cent of the variance in the data set is explained by the first component. Since the patterns are based on the correlation matrix the isopleths in Figure 3 depicting the PC can be regarded as the loadings or the correlation coefficients of the grid points with the specific PC. Areas where approximately half (49 per cent) the variance is explained by each component are shaded. The first PC is the 'general component', that is the tendency of the entire United States to have either a drought or moisture excesses. However, the interpretation of the PC is not as easy in subsequent PC, and is quite complex after the first few. As described by Walsh and Richman (1981) and Richman (1981), unrotated PC are usually not the most realistic representation of the modes of spatial variability (see Appendix). They are efficient for data compaction, but can be quite misleading when used for interpretational purposes. Since one of the objectives of this study was to identify spatially homogeneous areas of drought, the PC were rotated to satisfy the varimax criterion of Kaiser (1958) as described by Walsh and Richman (1981) and Richman (1981). Figure 4 depicts the

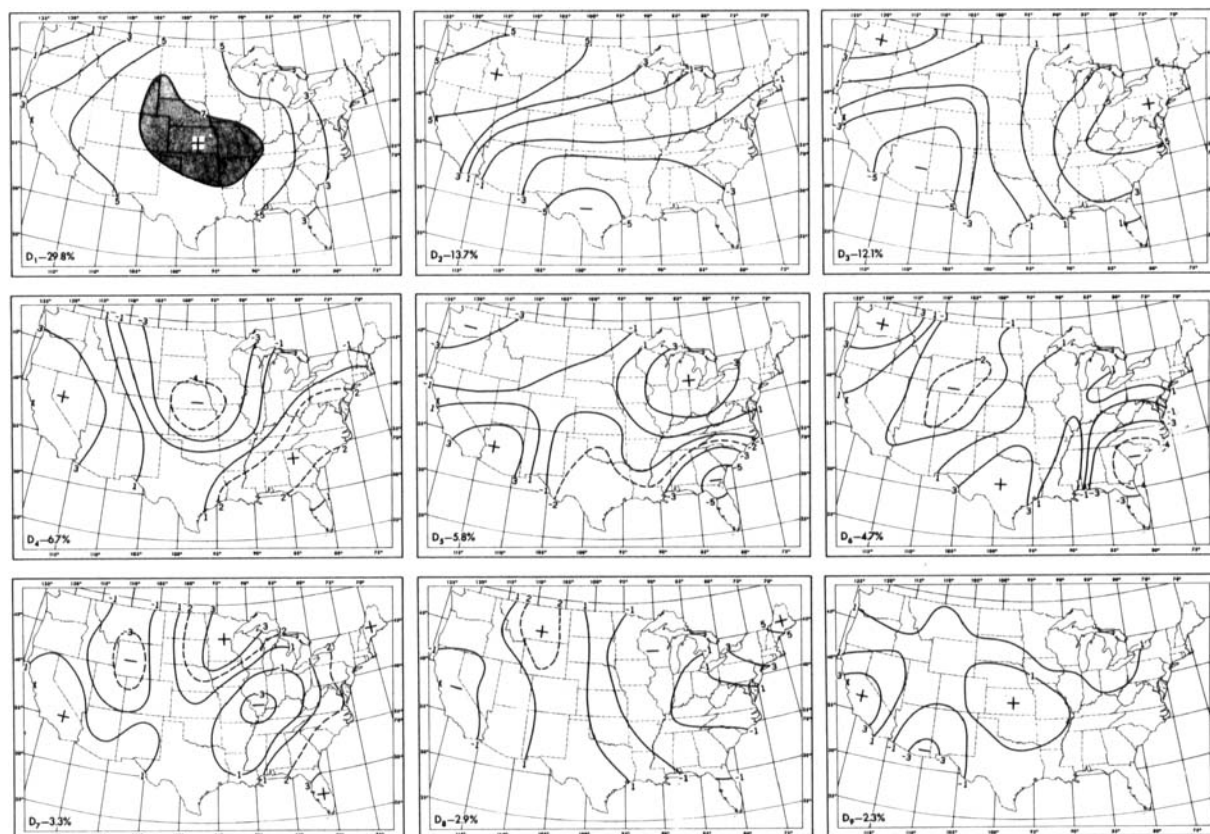


Figure 3. The first nine unrotated principal components loadings ($\times 100$) for PDSI using 1895–1981 data

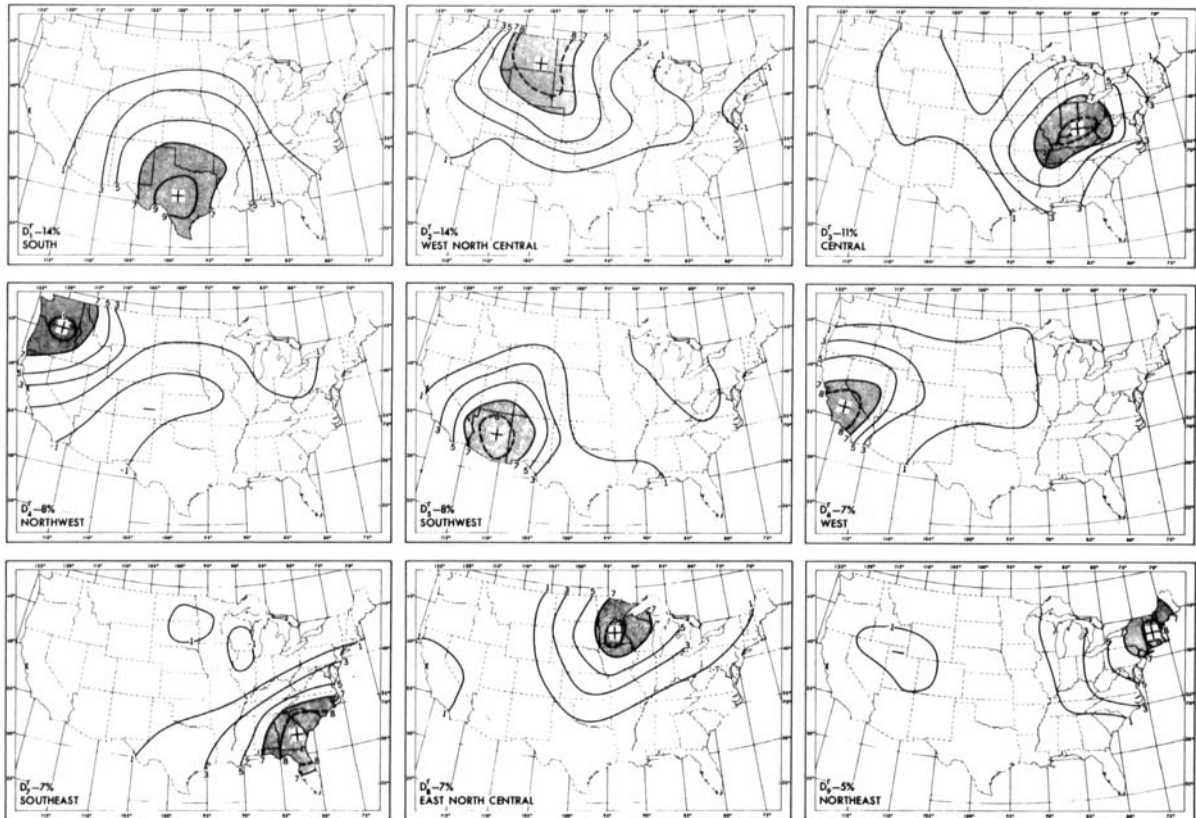


Figure 4. The first nine orthogonally rotated principal components loadings ($\times 100$) for PDSI using 1895–1981 data

nine orthogonally rotated PC. Each PC is easily interpreted as representing various areas of the United States. Figure 1 outlines those grid points which loaded most highly on each of the nine PC. Geographical names are attached to each of the PC. Nine PC were retained based on the resolution of the original data set (state averages). Additional PC merely split the patterns in Figure 4 into smaller areas.

The orthogonality constraint was relaxed to test if the same homogeneous regions, as depicted in Figure 4, would remain. The direct quartimin method of rotation (Jennrich and Sampson, 1966) was used for this purpose. This rotation minimizes the simplicity criterion, G , (Harman, 1967) such that:

$$G = \sum_{i \neq j} \left[\sum_{k=1}^p a_{ki}^2 a_{kj}^2 - \frac{\Gamma}{p} \left(\sum_{k=1}^p a_{ki}^2 \right) \left(\sum_{k=1}^p a_{kj}^2 \right) \right] \quad (1)$$

where, i and j vary from 1 to m , m is the number of factors (components), p is the number of variables (grid points), and a is the matrix of factor loadings. In equation (1) Γ was set to 0.25 based upon an intensive Monte Carlo study to test the goodness-of-fit between rotated factors and known input structure (Richman, 1982). Squared multiple correlation coefficients were used as communality estimates in the principal diagonal of the correlation matrix. This is a factor analysis approach, and essentially eliminates the unique variance of each grid point and considers only the shared variance of all grid points in the subsequent factor loadings. The factors in the oblique solution highlight the same regions as do the orthogonal PC (Figure 5). This being the case the simpler orthogonal solution was chosen for subsequent time series analysis.

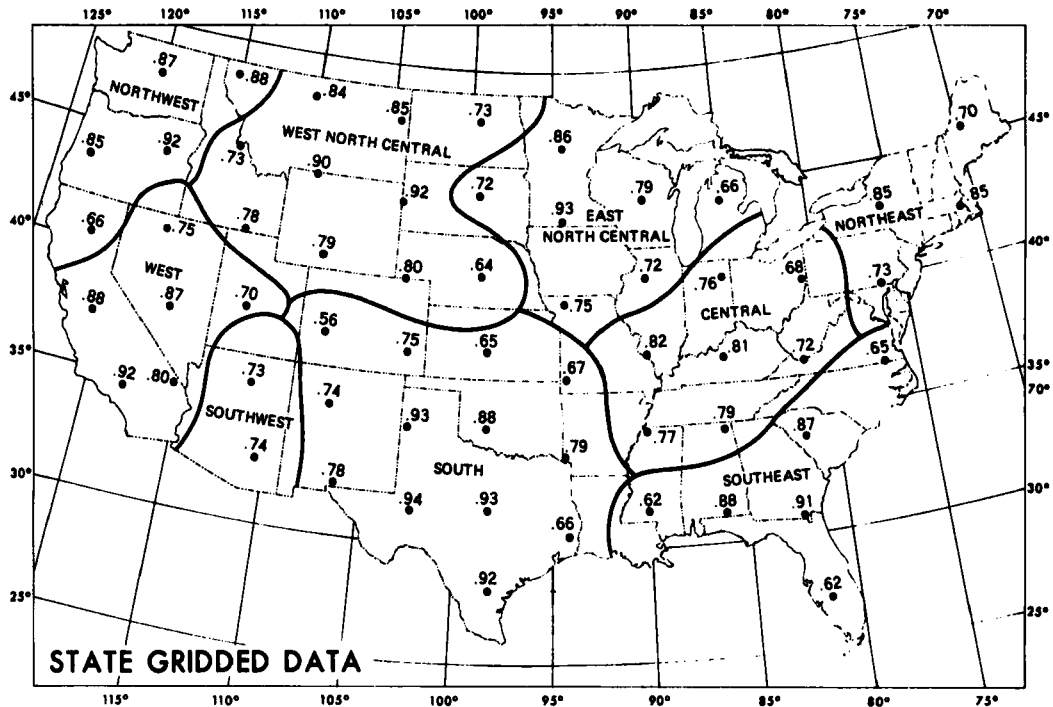


Figure 5. Grid points which are best related to the first nine obliquely rotated factors using 1895–1981 data. Loadings (derived from the structure matrix) with respect to a specific factor are depicted for each grid point

The patterns produced by using state gridded data were compared to PC based on divisional data (Figure 2). Since the nine PC in Figure 4 explain approximately 80 per cent of the variance in the data set, orthogonally rotated PC from a subset (1931–1979) of the 86-year state gridded data set, which matched the years of record of the divisional data, were extracted until they explained no more than 80 per cent of the variance. By the eighth PC of the state gridded data, approximately 80 per cent of the variance was explained. For this reason eight PC from the divisional data (1931–1979) were compared to eight PC of the state gridded data (1931–1979). Figures 6 and 7 depict the highest loadings and the PC to which they correspond for each grid point and division (also represented by grid points). In spite of the fact that the eight PC from the divisional data explain approximately 20 per cent less of the total variance than the eight PC of the state gridded data, the locations of the PC compare quite favourably. The major difference is the size of the PC representing the northern Plains–Rockies. This can be attributed to the extreme drought conditions there during the 1930s. The divisional PDSI data set is based on 1931–1960 means and as a result the importance of this regional event is not captured. By using the entire 86 years of data this decade-long drought is put into a broader perspective. The increase in variance explained by the eight PC of the state gridded data contrasted to the divisional data is undoubtedly due to the loss of detail in the state averaging process. More importantly however, the consistency of the two sets of PC indicates that the regional characteristics of the PDSI are being correctly depicted in the state average gridded data set.

Julian (1970) indicates that when using covariance or correlation coefficients there is an implicit assumption that positive and negative departures from the mean can be treated as identical. Since most factor or PC analyses begin with a correlation or covariance matrix this ‘flip-flop’ feature of correlation coefficients works its way into the resulting spatial factors or components. The bimodality of the PDSI data dictate further examination of this feature. A correlation matrix was calculated using only PDSIs less than -0.5 at one or both of the cross correlated grid points. Nine PC and factors were derived from this matrix and compared to the patterns and regions delineated by using the entire data set. The results remained unchanged. The regions delineated on Figures 4 and 5 remained stable.

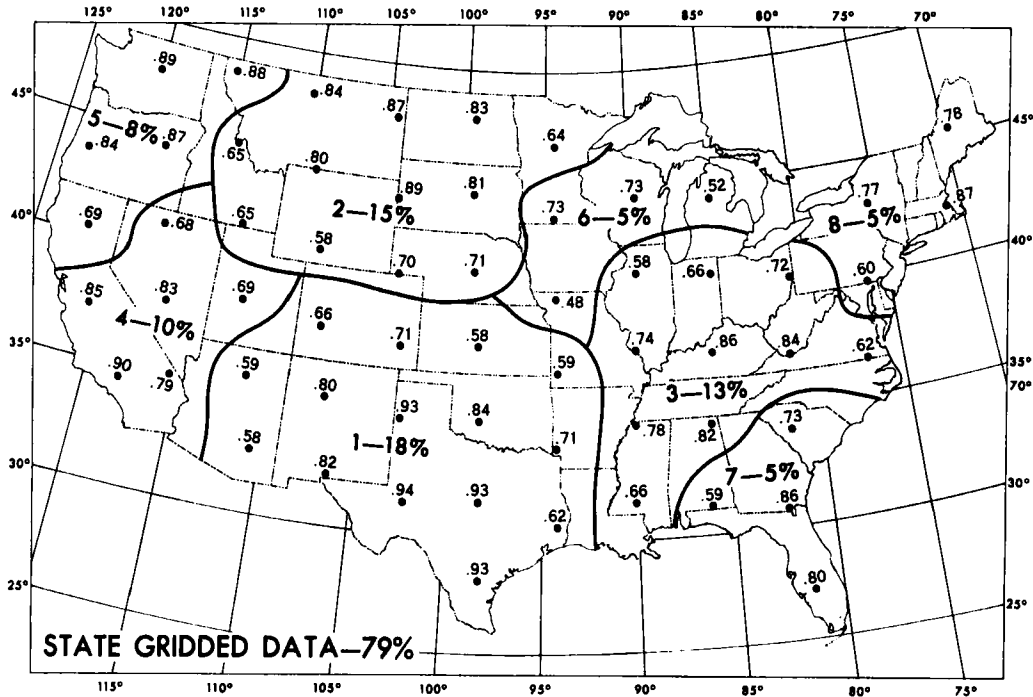


Figure 6. Grid points which are best related to the first eight rotated principal components using 1931 to 1979 data. Loadings with respect to a specific component are depicted for each grid point

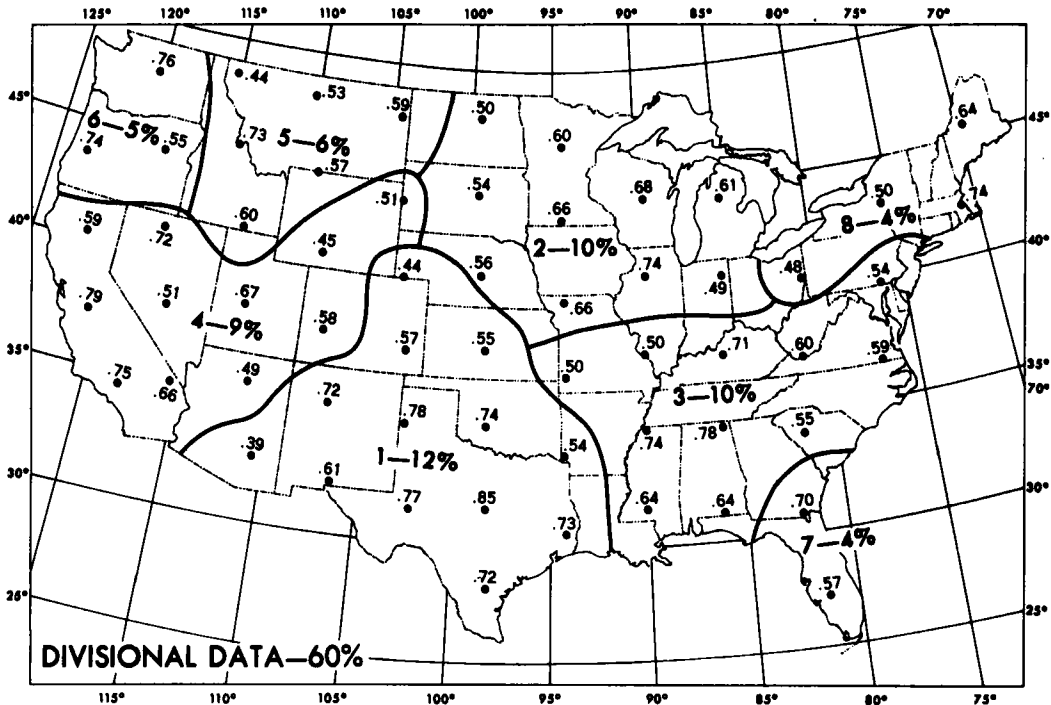


Figure 7. Divisions (depicted by grid points) which are best related to the first eight rotated principal components using 1931 to 1979 data. Loadings with respect to a specific component are depicted for each division

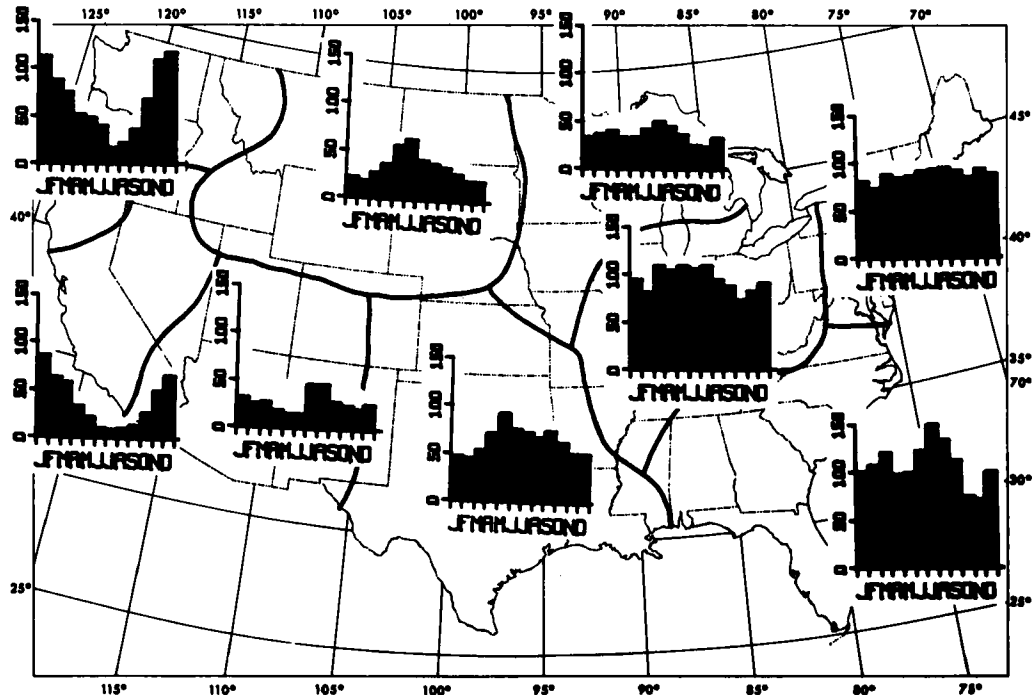


Figure 8. Monthly average precipitation (mm) in each of the nine regions delineated by the principal

The distinctions between the nine PC depicted in Figure 4 are further characterized by the intra-annual variation of precipitation in each of the regions (Figure 8). The monthly averages in Figure 8 are derived from the grid points within the shaded regions of Figure 4. There is a clear distinction between the single late spring–early summer maximum of precipitation in the West North Central Region and the bimodal spring–autumn maximum in the South Region. The Southwest is differentiated from the South Region by the primary late summer and secondary winter peaks. In the West there is no late summer peak, but it is differentiated from the Northwest by the broad spring–summer–autumn precipitation minimum as opposed to a sharp troughed minimum during midsummer. In the Central Region precipitation is fairly evenly distributed through the year, but there is a distinct double maximum which occurs during the spring and early summer and again during mid-winter. This is contrasted to the primary mid-summer peak and secondary early spring peak in the East North Central Region. The annual oscillation of monthly precipitation in the Southeast is similar to the East North Central Region, but the monthly variation is considerably amplified. The Northeast has a very even distribution of precipitation throughout the year.

Since the PDSI does not have an annual oscillation these differences between regions are by no means an artefact of the properties of the index. The obvious explanation for the differences within each of the nine regions characterized by the PC is simply that each region has a unique synoptic climatology which controls the precipitation regimes. It would be surprising if the synoptic patterns, which inhibit or enhance the normal oscillatory progression of seasonal rainfall for each of the nine regions were not also responsible for drought initiation, development and termination. Even the nine oblique factors have rather weak correlations with each other (Table I). These correlations are equivalent to the correlations between the factor scores of the various factors. Cross correlations of the nine factors in Table I indicate small positive correlations between adjacent regions with the two highest correlations between the West North Central Region and the East North Central Region, and the West North Central Region and the Southwest Region. There is only a small positive correlation between the West North Central Region and the South (northern versus southern plains), and even a slight negative correlation between the Southwest and the West North Central Region. Contrary to what could be surmised from the first unrotated PC (Figure 3), overall there are not very strong correlations between

Table I. Cross correlations of the obliquely rotated factor patterns of Figure 5. Correlations in excess of 0.20 are underlined

	South	W.N. Central	West	Northwest	E.N. Central	Southeast	Central	Northeast	Southwest
South	1.00								
W.N. Central	<u>0.22</u>	1.00							
West	<u>0.25</u>	<u>0.44</u>	1.00						
Northwest	<u>-0.22</u>	0.11	0.06	1.00					
E.N. Central	<u>0.25</u>	<u>0.40</u>	<u>0.21</u>	0.09	1.00				
Southeast	<u>0.29</u>	0.09	<u>-0.02</u>	0.06	0.12	1.00			
Central	<u>0.21</u>	0.12	0.09	0.08	<u>0.24</u>	<u>0.24</u>	1.00		
Northeast	<u>-0.04</u>	<u>-0.03</u>	<u>-0.14</u>	0.11	<u>0.26</u>	0.19	<u>0.29</u>	1.00	
Southwest	0.10	<u>-0.06</u>	<u>0.24</u>	<u>-0.08</u>	<u>-0.08</u>	0.09	0.09	<u>-0.04</u>	1.00

various portions of the United States. This suggests that the effect of changes of circulation must be considered for space scales as small as those depicted in Figure 4 and 5. The timing of the circulation changes should have a different effect on the precipitation, and consequently the droughts in each of these regions. Trewartha (1961) addresses this topic in some detail, and in fact subjectively types regional rainfall patterns which delineate many of the regions depicted in Figure 4. Walsh *et al.* (1982) also retain nine rotated components calculated from monthly precipitation data (1900 to 1977) for 60 stations in the U.S. Their components delineate regions quite similar to those in Figure 1 and 5.

(b) *Temporal variations of drought patterns*

PC scores (PC_s) are computed by the following equation:

$$PC_s = AR^{-1}Z \quad (2)$$

where, A is the 9×60 orthogonally rotated PC loading matrix, R is the 60×60 correlation matrix of the grid points, Z is the 60×1036 matrix of standardized 'Z-scores', and PC_s is the 9×1036 matrix of standardized component scores. These scores indicate the relative importance of each PC for each of the 1036 months of data.

The drought-stricken years of the 1930s are evident by the very low scores (nearly four standard deviations below normal) in the West North Central PC (Figure 9). The droughts in the mid 50s, mid 70s, and late 70s and early 80s are mild by comparison. In the South the 1950 to 1970 period is quite interesting with an abrupt change from extreme drought to very wet conditions in 1957, and a sudden return to drought in 1963. The Central PC contains three extreme drought episodes, 1930-1931, 1941, and 1953-1954. Notice the shorter duration of these episodes as compared to the South or West North Central PC. In the Northwest there are no single instances of extreme conditions such as occurred in the South or West North Central PC scores, but there are numerous occasions when the PC scores were more than two standard deviations from the mean. From 1901 to 1905 the Southwest experienced a sustained period of unprecedented drought which has not been repeated in subsequent years. It is noteworthy that during this identical period the scores for the PC of the West were near or slightly above normal. The PC scores in the West were at their lowest during 1976 and 1977. Other notable drought periods occurred during 1924 and again in 1959 and 1960. In the Southeast very low scores were common during the late 1920s and early 1930s. Unlike some of the PC in the interior portions of the U.S. (West North Central, South, Southwest) these low scores were not continuous over several years, but were interrupted by intervening high component scores. The East North Central PC, similar to the West, recently had its lowest scores during the 1976-1977 drought years. The scores for the Northeast PC are characterized by a lack of persistence when compared to some of the other PC scores. This lack of persistence accentuates the relatively long drought of the mid 1960s. Visual inspection of the scores across the nine regions indicates that if there are any long term trends in the data they are rather small, and are not likely to be statistically significant.

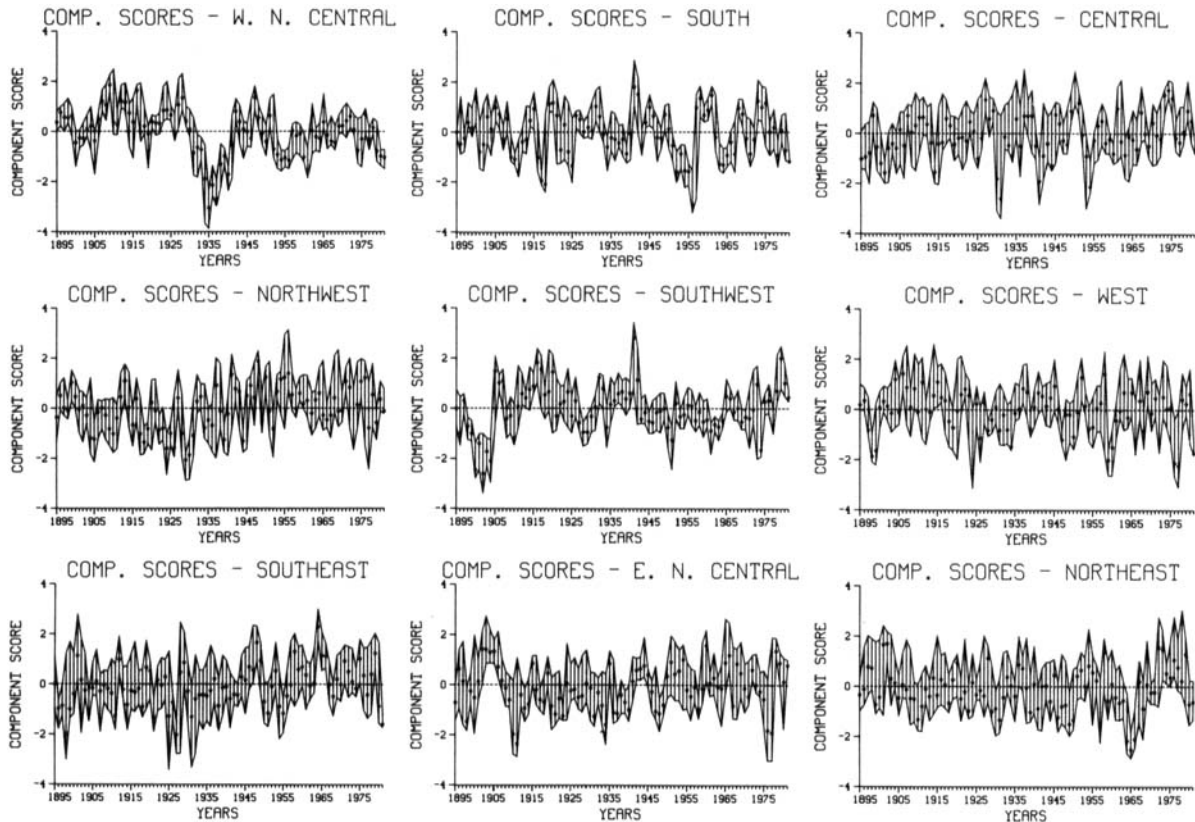


Figure 9. Standardized component scores for the rotated principal components. Maximum, minimum and median scores for each year (based on monthly data) are plotted

(c) Spectra and coherence of drought patterns

Both autoregressive and traditional lagged product spectral methods were used to estimate the spectra of the component scores. Conventional spectral methods, where the spectrum is estimated by convolving a window function with the true spectrum, has a number of shortcomings associated with its spectral estimates, i.e. a tradeoff between bias and variance, and leakage from variance peaks. Autoregressive (AR) spectral techniques do not have these problems and the spectral estimate is unbiased and not subject to leakage. The Akaike criterion was used to select the appropriate order of the AR model. The use of the Akaike criterion has been shown to work very well when analysing data from the physical sciences (Ulrych and Bishop, 1975; Jones, 1974; Goerss, 1978). Theoretical development of the technique is provided by Ulrych and Bishop (1975) and Goerss (1978). As described by Jones (1974) the autoregressive estimate helps meteorologists avoid interpreting peaks in the classical estimates as real. Since it is possible in the lagged product technique to produce peaks almost anywhere in the spectrum by simply narrowing the bandwidth of the spectral window, the AR spectral estimates are very valuable in interpreting the spectra estimated by the traditional technique. In addition, for the purposes of cross spectral analysis, Goerss (1978) demonstrates through a Monte Carlo study that AR coherence estimates are indeed superior to traditional estimates.

The univariate AR spectral estimates (Figure 10) do not contain any spectral peaks other than those expected for a simple (first order) red noise process. This is not surprising considering that the lag one correlations of the PC scores are between 0.83 and 0.94. Such high lag one correlations are attributed to the fact that the PDSI for any month in an established wet or dry spell is calculated from the PDSI of the previous month as well as the current month's moisture anomaly value. A high pass difference filter (Jenkins and Watts, 1968) was applied to the component scores before applying the AR techniques in

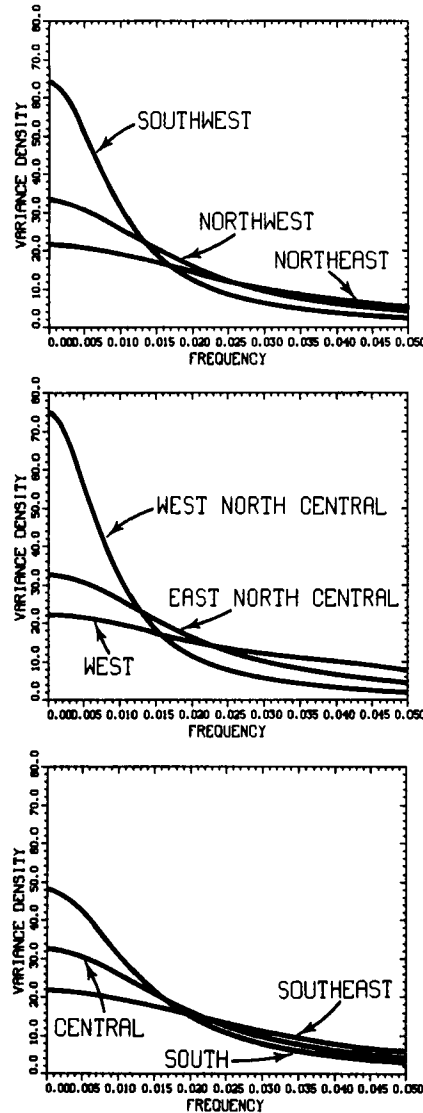


Figure 10. Univariate autoregressive spectra of the rotated principal component scores

order to determine if details were being missed in the spectra. This was deemed appropriate since the series have very high lag one correlations (Jenkins and Watts, 1968, Chapter 9). The spectra of the filtered scores did not reveal any spectral peaks.

Multivariate AR spectral estimates produce spectra nearly identical to those in Figure 10. One advantage of using the multivariate AR model to estimate the spectrum is that the AR model can express current values of a series as the sum of linear combinations of past values of the series and also of related series. Thus, the coherence and phase can be calculated directly from the variance density matrix. The coherence estimates from both the original component scores and the filtered scores were quite low. Figure 11 depicts the coherences for two of the more highly related PC. The low values of the coherence do not warrant any physical interpretation.

The traditional spectral estimates using a Turkey window are presented in Figure 12. As the spectral window width decreases numerous peaks appear in the spectra. However, based on the data, these peaks are likely to be due to sampling fluctuations (Jenkins and Watts, 1968, Chapter 7). This result is contrary to the investigations of Mitchell *et al.* (1979). However, they analysed a series of reconstructed drought indices over a very large area, the entire western United States, and did not consider whether

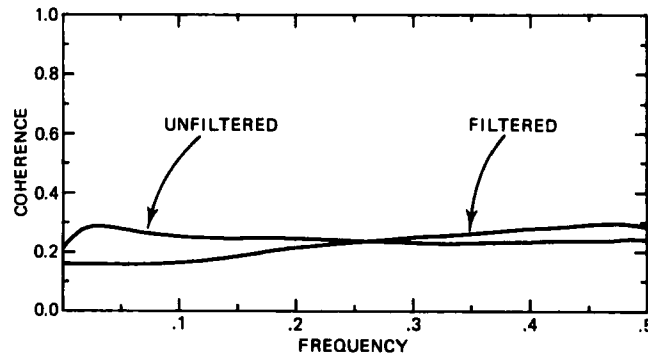


Figure 11. Coherence between the principal component scores of the Southwest and West for high pass filtered data and unfiltered data

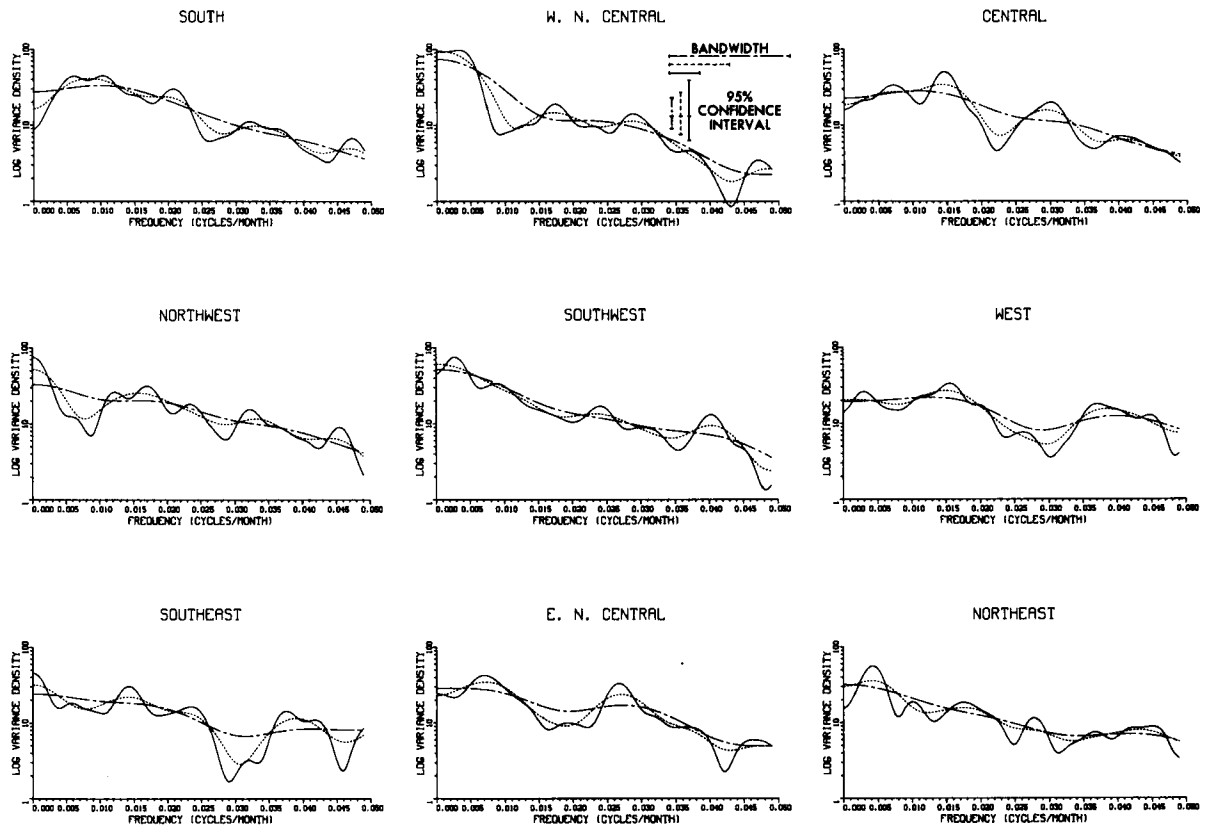


Figure 12. Lagged product estimates of the spectra of the rotated principal component scores. For solid curves lags = 320, dash curves lags = 160, and chain dashed curves lags = 80. Confidence intervals and bandwidths for all nine spectra are given in the W. N. Central spectrum

drought regions were contiguous or respond similarly to circulation changes. In addition, they treat 350 years of data ending in 1963 as opposed to the most recent 86 $\frac{1}{3}$ years (1895–1981).

(d) Drought duration

One of the more interesting aspects of Figures 10 and 12 is the greater proportion of variance explained at the low frequencies for the PC located in the interior portions of the United States as opposed to those along the coasts. This is interpreted to mean that droughts last longer in the interior

Table II. Cumulative percentages and associated number of occurrences (not necessarily consecutive) of the duration of PDSI $\leq X$ (where $X = -0.5, -1, -2, -3, -4, -5,$ and -6) within drought episodes (a drought episode consists of consecutive months of PDSI ≤ -0.5)

(a) Georgia: January 1895-April 1981 (1036 months)

Months \ PDSI	1	2	3	4	5	6	7	8	9	10	11	12	13-18	19-24	25-36	37-60	61+	Max. no.
≤ -0.5	28	34	50	55	62	70	77	78	84	84	88	88	95	96	99	100	100	38
≤ -1	21	4	12	4	5	6	5	1	4	0	3	0	5	1	2	1	0	37
≤ -2	12	29	39	51	57	67	69	78	80	84	84	84	92	94	98	100	100	30
≤ -3	6	8	5	6	3	5	1	4	1	2	0	0	4	1	2	1	0	16
≤ -4	18	43	54	54	61	64	79	82	86	86	89	89	93	93	100	100	100	9
≤ -5	5	7	3	0	2	1	4	1	1	0	1	0	1	0	2	0	0	3
≤ -6	10	40	50	60	70	70	70	80	80	80	80	80	100	100	100	100	100	1
	1	3	1	1	1	0	0	1	0	0	0	0	2	0	0	0	0	
	25	50	50	50	50	75	75	75	100	100	100	100	100	100	100	100	100	
	1	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	
	50	50	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	
	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	
	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

(b) California: January 1895-April 1981 (1036 months)

Months \ PDSI	1	2	3	4	5	6	7	8	9	10	11	12	13-18	19-24	25-36	37-60	61+	Max. no.
≤ -0.5	22	41	55	62	68	71	75	77	82	86	88	90	96	96	99	100	100	40
≤ -1	16	14	10	5	5	2	3	1	4	3	1	2	4	0	2	1	0	39
≤ -2	18	39	45	55	61	65	71	73	78	84	90	90	94	96	98	100	100	30
≤ -3	9	10	3	5	3	2	3	1	2	3	3	0	2	1	1	1	0	21
≤ -4	31	42	46	50	50	65	77	81	85	88	88	88	88	92	100	100	100	14
≤ -5	8	3	1	1	0	4	3	1	1	1	0	0	0	1	2	0	0	9
≤ -6	36	45	55	55	55	64	64	73	73	73	82	82	82	100	100	100	100	
	4	1	1	0	0	1	0	1	0	0	1	0	0	2	0	0	0	
	0	25	25	25	25	25	25	50	50	50	50	50	75	100	100	100	100	
	0	1	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	
	0	0	0	0	33	33	33	33	33	33	67	67	100	100	100	100	100	
	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	0	
	0	0	0	33	67	67	67	67	100	100	100	100	100	100	100	100	100	
	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	

(c) Wyoming: January 1895-April 1981 (1036 months)

Months \ PDSI	1	2	3	4	5	6	7	8	9	10	11	12	13-18	19-24	25-36	37-60	61+	Max. no.
≤ -0.5	32	46	56	61	63	71	71	73	76	76	78	78	80	88	90	98	100	80
≤ -1	13	6	4	2	1	3	0	1	1	0	1	0	1	3	1	3	1	79
≤ -2	17	29	37	46	50	54	58	58	58	62	62	62	75	83	83	96	100	73
≤ -3	4	3	2	2	1	1	1	0	0	1	0	0	3	2	0	3	1	51
≤ -4	17	17	17	17	25	33	33	33	33	42	42	42	58	67	67	92	100	39
≤ -5	2	0	0	0	1	1	0	0	0	1	0	0	2	1	0	3	1	19
≤ -6	0	11	11	22	22	22	33	33	33	33	33	44	56	56	67	100	100	
	0	1	0	1	0	0	1	0	0	0	0	1	1	0	1	3	0	
	14	29	43	43	43	43	43	43	43	43	43	43	43	57	71	100	100	
	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	2	0	
	0	0	0	0	0	0	0	0	0	0	0	25	50	50	100	100	100	
	0	0	0	0	0	0	0	0	0	0	0	1	1	0	2	0	0	
	0	0	0	0	0	0	0	0	25	25	25	50	75	100	100	100	100	
	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0	0	0	

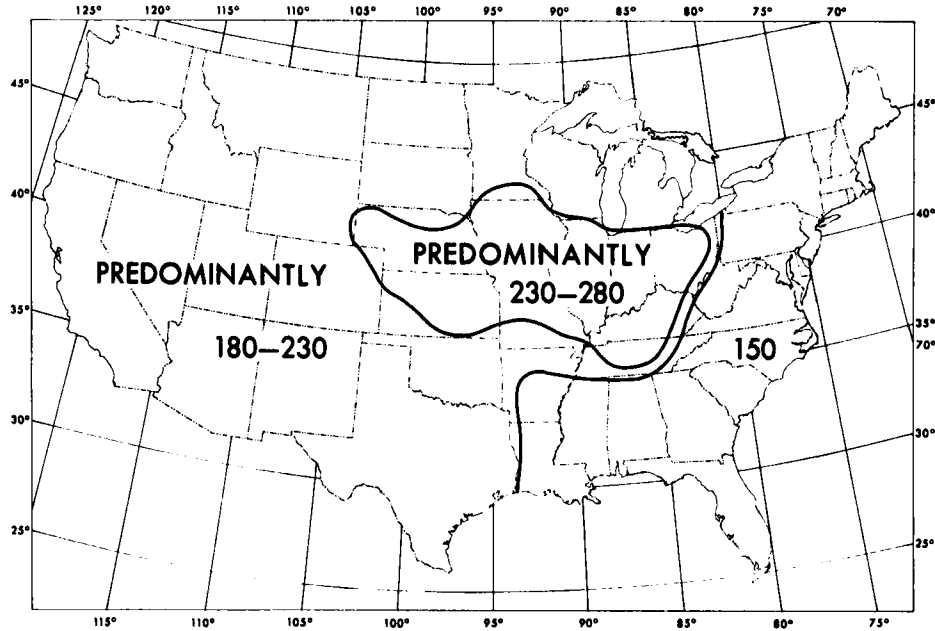


Figure 13. Available soil water capacity (mm) for PDSI calculations recommended by Palmer (1965)

portions of the United States as opposed to coastal areas. This has been verified by tables produced for each state similar to Table II. The states in Table II are those states which had (correlated) most highly with the Southeast (Georgia), West North Central (Wyoming), and West (California) PC. The longest drought in each of the PDSI categories is at least twice as long in Wyoming compared with California or Georgia.

From Figure 13 it is unclear whether the soil water capacity parameter used in the PDSI calculations is indeed responsible for the increased length of droughts in the interior United States. Sensitivity tests were performed with the PDSI to determine if changes in the duration of droughts across the United States could be detected by varying the soil water capacity parameter. PDSI were calculated using 79 years of data from the Asheville, North Carolina city station. Three different values of available soil water capacities (AWC) were used in the calculations: (1) 100 mm, (2) 150 mm, and (3) 250 mm. Palmer (1965) performed a similar test using data from Dover, Maryland. He indicated that droughts have lower (more negative) PDSI for higher values of AWC. Palmer (1965) attributes this to the generalization that an area which lacks an adequate capability for storing water is not as affected by prolonged dry weather as is an adjoining area which has this capability, i.e., areas with low AWC are accustomed to low water availability. Palmer (1965) did not mention what effect variable AWC had on the length of droughts ($PDSI \leq -0.5$). The Asheville AWC sensitivity tests indicate that the changes in AWC as depicted in Figure 13 have no effect on the duration of droughts. They confirm Palmer's Dover, Maryland experiments, and indicate that the change of the soil's AWC across the United States can decrease the drought index by as much as 1.5 points i.e. -4.0 to -5.5 for some of the lowest PDSI. The index remains virtually unchanged for small negative values i.e. -0.1 to -1.0 . The decrease in the duration of droughts from the interior to the coastal portions of the United States is real and is not an artefact of the mechanics in the PDSI calculations.

4. CONCLUSIONS

A rotated principal component approach to PDSI has delineated spatially homogeneous areas of drought. Overall, each area is not very highly correlated with other areas. The synoptic climatology for

each of these areas must be significantly different. An in depth study of the circulation features associated with drought must address circulation features down to scales as small as 500 to 1000 km.

Autoregressive and the classical lagged product spectral techniques did not indicate any statistically significant cycles of drought during the past 86 years. By treating spatially homogeneous regions of the United States, cycles such as the 22-year rhythm of drought found by Mitchell *et al.* (1979), using over 350 years of tree ring data, cannot be found in our twentieth century data set. Assuming the reality of a physical mechanism for such a cycle its weak response in distinct portions of the United States during the past century awaits explanation.

Droughts have been found to persist nearly twice as long in interior portions of the United States as opposed to areas closer to major moisture sources. This is not attributable to soil characteristics in the PDSI calculations. It is a characteristic feature of the climate of drought in the United States.

APPENDIX

The correlation coefficient between two variables can be represented by a pair of vectors in two dimensional space. The cosine of the angle between the vectors represents the correlation coefficient between the two variables. A correlation of 0.0 is represented by an angle of 90 degrees, -1.0 by 180 degrees, 1.0 by 0 degrees etc. Johnston (1978) gives further details. A technique of positioning PC which can be visualized in terms of geometrical relations is called the centroid method. Although it is not always accurate (if there are many positive and negative correlations amongst the variables) it is very useful in illustrating the concepts behind positioning and rotation PC.

In Figure 14 the correlation matrix of six variables is represented by the angles between vectors X_1 to X_6 (always measuring the angle between the vectors as the smallest angular distance between the two).

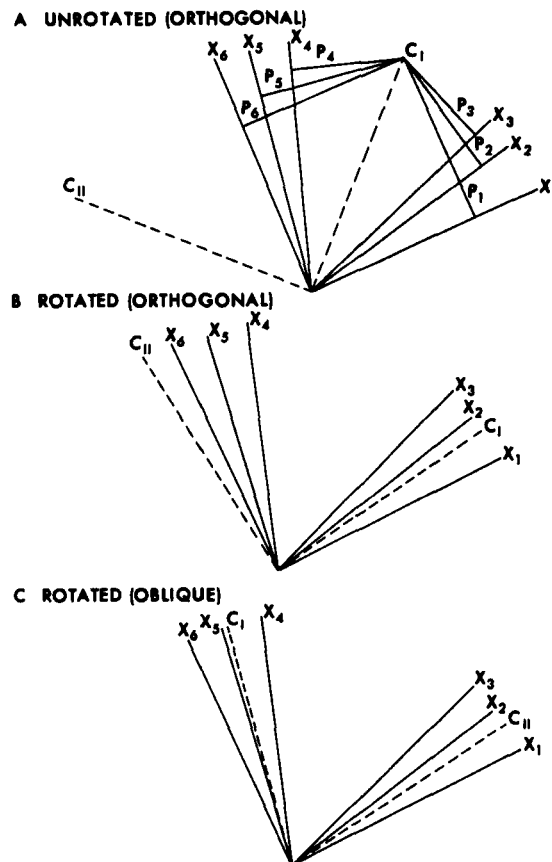


Figure 14. Geometrical representations of unrotated, orthogonally rotated, and obliquely rotated principal components

Each variable is given equal weight by assigning a unit length to each vector. The first PC is positioned by the vector addition of all the vectors and it is assigned a unit length (Figure 14(a)). The variance explained by the first PC on each vector (or variable) is obtained by drawing a perpendicular bisector from each vector to the end point of the first PC (P_1 to P_6 in Figure 14(a)). The distance from the origin of each vector to the perpendicular bisector is the variance explained by the first PC on that variable. This is subtracted from the length of the vector (X_1 to X_6 in Figure 14(a)) before positioning the second PC. At this point the vectors are of unequal lengths (unless of course the first PC explains an equal amount of variance on two of the vectors). Vector addition is again used to locate the second PC, but once found it is only used to indicate whether the PC is to the right or left of the first PC, since it is constrained to be orthogonal (90°) to the first PC. The variance explained by the second PC on each vector (variable) is determined as described for the first PC. Subsequent PC are located in a similar manner. Unrotated PC as just described are depicted in Figure 14(a).

As is rather typical of unrotated PC the PC do not clearly indicate that there are two distinct patterns or groups of variables (Figure 14(a)). If there are numerous groupings or patterns the problem is compounded even further. Figure 14(b) shows the results of an orthogonal rotation of the two PC in Figure 14(a). The position of each rotated PC can be determined by introducing a hypothetical relation between the PC and the vectors such that each vector coincides with a PC or is either 90 or 180 degrees from the PC. The actual relation between the orthogonally rotated PC and the vectors is obtained by coming as close as possible to this ideal while maintaining the orthogonality constraint (Figure 14(b)).

Obliquely rotated PC (Figure 14(c)) are positioned in the same manner as orthogonal rotations except they are not constrained to be separated by 90 degrees. Obviously, the solutions to the rotated PC are dependent upon the initial number of PC extracted. It is readily apparent that the rotated PC depict the groupings or patterns of the variables much clearer than the unrotated PC. In practice the obliquely rotated solution can be quite similar to the orthogonally rotated solution if there is little correlation between patterns or groups, but will better represent the patterns or groupings if they are significantly correlated.

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