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Spatial patterns of multiple drought types in the contiguous United States: a seasonal comparison

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ABSTRACT: The impacts of severe droughts on human activities, terrestrial ecosystems, and hydrologic systems are wide ranging and easily discernible. Because these impacts are felt at different times by water users, various forms of drought are recognized (e.g. agricultural, hydrological). The purpose of this study is to examine spatial patterns of drought in the contiguous United States on a seasonal basis using 4 measures of drought severity. Data used include the Palmer Moisture Anomaly Index (ZINX), Palmer Drought Severity Index (PDSI), Palmer Hydrologic Drought Index (PHDI), and standardized scores of monthly precipitation (PREZ) for the 344 climatic divisions in the contiguous United States, by month, for the period 1931 to 1985. Principal Components Analysis and a VARIMAX rotation are used to search for spatially coherent drought regions, i.e. clusters of climatic divisions that experienced similar moisture conditions during the study period. Regional drought patterns are presented using isoline maps of principal component loadings. Within a given season, the location, size and orientation of most drought regions is largely consistent across the drought types represented by the PREZ, ZINX, PDSI, and PHDI. Although the fast responding index (ZINX, PREZ) patterns are more discrete (i.e. the drought regions are smaller and more numerous), the general location and orientation of the regions conform to those for the more slowly responding indices (PDSI, PHDI). For the fast responding indices there is a considerable amount of interseasonal variability in the regional drought patterns. The amount of variability decreases for both PDSI and PHDI, with most PHDI drought regions remaining stable throughout the year.

INTRODUCTION

Drought is a recurring component of climate in the continental United States. The negative impacts of a severe, protracted drought on human activities and the landscape are wide ranging and easily discernible. However, since droughts often last for months or years, these impacts are not uniformly experienced. The selection of appropriate measures, or definitions, of drought is thus complicated by the variable nature of drought impacts. At present, no universally acceptable definition of drought exists, except perhaps the general concept – 'lack of rain'. Instead, numerous definitions and measures of drought intensity geared to specific aspects of drought are used. The drought types recognized by climatologists, geographers, and others involved in drought research include, among others: agricultural, meteorological, hydrological, forest-fire potential, municipal water supply, and recreational.

The diverse nature of drought analyses can be partially attributed to the absence of unifying definitions and measures of drought. Analysis of the behavior (duration, severity, etc.) of individual drought types (e.g. agricultural drought) is common: however, the concurrent behavior of more than one drought type is not generally examined (Yevjevich et al. 1978, Dracup et al. 1980). Thus, the base of knowledge about drought is skewed toward individual drought types.

Much of the work in geographical climatology centers on the identification of regions that exhibit similar characteristics in response to meteorological fluctuations (e.g. Kutzbach 1967, Horel 1981, Karl & Koscielny 1982, Barring 1987, Ehrendorfer 1987). Walsh et al. (1982) claim that the accuracy of long-range (monthly to seasonal) precipitation forecasts should be greatest within spatially coherent precipitation regions. This argument could be applied to the forecasting of drought events, especially on a seasonal basis. Further justification for identifying spatially homogeneous, drought-type specific regions is that the different types of drought can vary both temporally and spatially in their impacts on human activities. Separate forecasting, drought planning, and water management schemes may need to be developed if the spatial properties (size,

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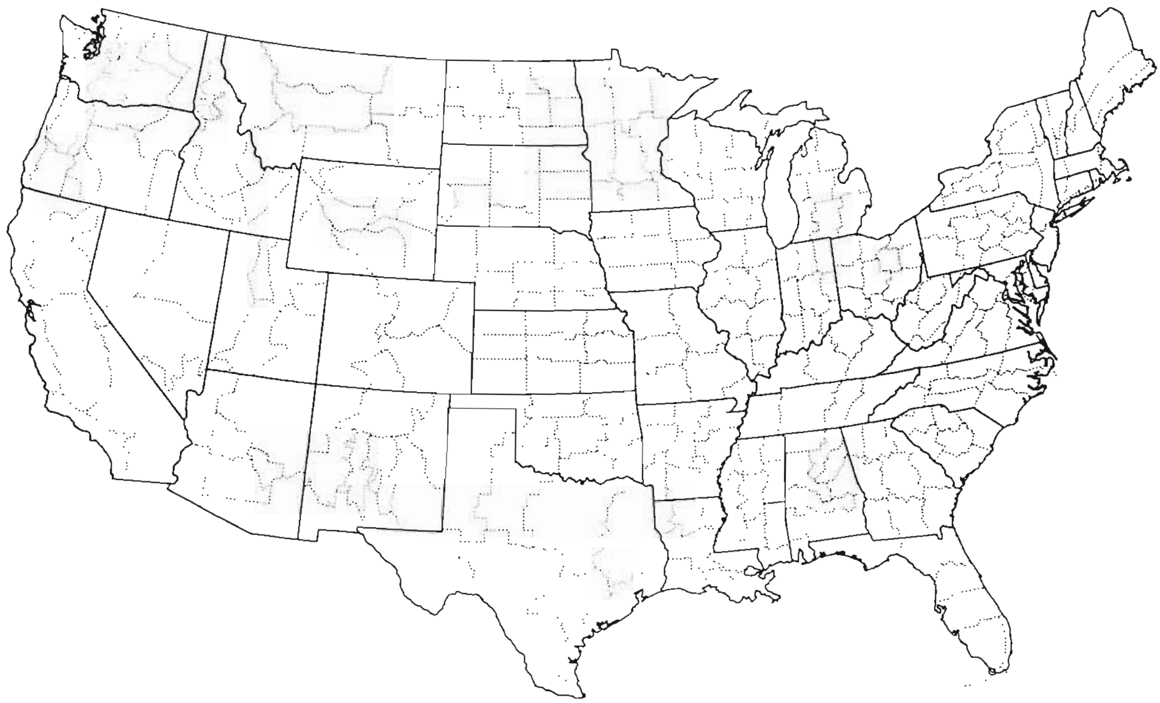

Fig. 1. The 344 climatic divisions in the contiguous United States

shape, location) of drought regions are highly variable among different drought types over the climatic record.

In this study spatial patterns of drought in the coterminous United States are examined on a seasonal basis using 4 measures of drought severity. The primary objectives are: (1) to identify spatially homogeneous drought regions in the contiguous United States on a seasonal basis, (2) to determine if the identified regions are consistent across the drought types represented, and (3) to examine the degree of season-to-season persistence of these regions.

DATA

All data used in this study are obtained from the 1986 version of the National Climatic Data Center's (NCDC) magnetic tape file TD9640 (NCDC 1986). Items directly extracted from this file include monthly values of the Palmer Moisture Anomaly Index (ZINX), the Palmer Drought Severity Index (PDSI) (Palmer 1965), and the Palmer Hydrologic Drought Severity Index (PHDI) (Karl & Knight 1985) for the 344 climatic divisions in the contiguous United States for the period 1931 to 1985 (Fig. 1). The calibration period for all indices is 1931 to 1985.

The Palmer indices are derived through manipulations of various water-balance variables. They incorporate both current and antecedent moisture conditions so that a long period of drought or wetness produces large absolute values of the indices. Although there is no upper or lower limit, the indices generally range from +7 to −7, with positive values representing moisture conditions above normal, negative values conditions below normal (i.e. a drought). The indices are also standardized so that drought (moisture) conditions can be compared across dissimilar climatic regimes and through time. Alley (1984), Karl & Knight (1985), and Karl (1986) provide detailed descriptions of the procedures used to calculate the Palmer indices.

The ZINX measures the departure of the moisture status in an area from normal in a given month. It is the most sensitive of the 3 Palmer indices. Large deviations in supply (precipitation) or demand (evapotranspiration) of moisture within a given month will cause large changes in index values. Because of this trait, the ZINX is often positive for 1 or 2 mo during long periods of meteorological or hydrological drought (e.g. several months with negative PDSI or PHDI values). In terms of drought types, the ZINX is most appropriately used as a measure of agricultural or forest-fire potential drought (Karl 1986).

The PDSI is usually presented as a measure of meteorological drought intensity. Palmer (1965) designed the index to represent general moisture conditions during periods or spells of abnormally dry or wet weather. It responds too slowly to be useful as a measure of agricultural drought (Steila 1972) and too rapidly to assess conditions of hydrological drought (streamflow, ground-water levels) accurately (Alley 1985).

Hydrologic conditions are generally not representative of moisture departures for other uses during the early stages of a drought. The PHDI, a measure of hydrological drought, expresses this by lagging behind both the ZINX and PDSI during the initial months of a drought. Also, since streamflow and reservoir levels are often well below normal long after a meteorological drought has ended, values of the PHDI tend to remain negative for up to several months after PDSI values have returned to normal levels.

Besides the Palmer indices, standardized scores (z-scores) of monthly precipitation (PREZ) were calculated for each climatic division using data for the entire study period (1931 to 1985). The PREZ provides for a measure of drought intensity based solely on the deviation of precipitation from normal.

METHODS

The technique used to help aid in the identification of spatially homogeneous drought regions is Principal Components Analysis (PCA). The use of PCA to identify clusters of stations or spatial units that behave similarly with respect to a particular climatic variable is well established by the work of, among others, Dyer (1975), Barring (1987), Ehrendorfer (1987), for the spatial coherence of precipitation patterns, Horel (1981) and Richman (1981) for atmospheric pressure patterns, and Karl & Koscielny (1982) and Eder et al. (1987) for spatial patterns of meteorological drought.

This study employs S-mode PCA, one of the 6 basic modes of PCA described by Richman (1986). For each of the 4 drought indices (PREZ, ZINX, PDSI, PHDI), the original data matrix has 344 variables (columns) and 165 observations (rows). The variables are the 344 climatic divisions in the contiguous United States while the observations are collected over the 165 mo contained in each season during the 55 yr study period. Karl et al. (1982) point out that potential biases can result when using an irregularly spaced data set in an S-mode PCA. However, regularly spaced data sets are not always employed when analyzing climatic variables with PCA (e.g. Goossens 1986, Eder et al. 1987). The alternate options of interpolating the raw data to an equal-area grid or selecting only climatic divisions corresponding to an equal-area grid were not used in this study because of the potential for loss of information during the data reduction process, and the need to preserve the loadings for each variable (344 climatic divisions) for further analyses. The physical interpretations of the drought regions may suffer somewhat, but the primary goals of this study are unhindered by using all available data.

The first step in the PCA procedure was the computation of a 344 × 344 Pearson product-moment correlation matrix for each drought index. The correlation matrix was then input into the procedure to extract the principal components (PCs or eigenvectors) and the associated eigenvalues of the unrotated solution. All PCAs were completed using the FACTOR procedure of SAS (SAS 1985).

In an S-mode PCA, the loadings can be mapped to show the spatial pattern of the characteristic under investigation. Mapping the loadings pattern from the unrotated PCA generally does not yield physically interpretable patterns when dealing with meteorological or climatological data (Richman 1981, 1986). Thus, results from the unrotated PCAs were used only to determine the number of factors to retain for rotation.

By rigidly rotating a predetermined number of PCs toward *simple structure*, clusters of climatic divisions that behave similarly with respect to the various drought types were identified. A *simple structure* solution is obtained when the number of near-zero loadings is maximized (Thurstone 1947). The VARIMAX orthogonal rotation was used in this study. A VARIMAX solution strives for *simple structure* by increasing the value of large component loadings and decreasing the value of small loadings, i.e. the variance is maximized (Richman 1986). VARIMAX is a commonly used rotational method for meteorological map typing (e.g. Horel 1981, Karl & Koscielny 1982, Ehrendorfer 1987).

For this study a 2-stage approach was used to determine the number of components to retain for rotation. The first stage employed the use of a scree test (Cattell 1966). Plots of eigenvalues for sequentially extracted components (scree plots) from the unrotated PCAs were used to identify a range of components to retain. For all indices, the scree plots suggested that a minimum of 6 PCs be retained for rotation.

For each data set, the second stage began with retention of 6 components, rotation of the solution toward simple structure, and examination of the resulting loading matrix. The process was repeated with 7, 8, etc. components for rotation. To select the final number of components a critical loading value of 0.70 was used. If the maximum loading on the last PC extracted was below 0.70, the analysis proceeded using the results from the previous step. For example, if after rotation of 9 PCs, the maximum loading on the ninth PC was 0.45, then the results from the 8 PC solutions were used (providing that solution fulfilled the criteria). Loadings ≥0.70 indicate that ca 50 % or more of the variance in a variable is explained by a PC. By using a loading of 0.70 as a cut-off point, the amount of overlap in mid-level loadings is minimized. Thus, mutually exclusive drought regions are identified and the possibility of identifying non-meaningful drought regions is diminished. After determining the appropriate rotated solution to use, the PC loadings were extracted to aid in the identification of spatially homogeneous drought regions.

The centroids of each climatic division were located and digitized to provide x-y coordinate pairs. These pairs were then merged with the corresponding loadings, which served as the z coordinate. The x-y-z data were converted to a uniformly spaced grid with the kriging algorithm of Golden Software's SURFER program (Golden Software 1986). The SURFER program was then used to fit isolines to the grid and draft a map for each PC. For each index, the series of maps was overlaid to produce the final map of the regional drought patterns. To aid in interpretation the loadings were multiplied by 10 before the gridding procedure. To make the maps more readable, isolines were drawn only for values ≥6 using an interval of one.

RESULTS

Spatially homogeneous drought regions were identified for the PREZ (Fig. 2), ZINX (Fig. 3), PDSI (Fig. 4), and PHDI (Fig. 5) on a seasonal basis. Those areas enclosed by the 0.60 loading isoline represent the core areas of the drought regions. In some instances no 0.70 loading isolines were drafted (e.g. PC7 for the PREZ in autumn) because the gridding algorithm failed to assign loading values ≥0.70 in the creation of the uniformly spaced grid.

A general trend across all the analyses is that more PCs are needed to explain the variance in the data set using the faster responding indices (PREZ and ZINX) (Table 1). This is not surprising since conditions of hydrological drought generally begin and end slowly whereas agricultural drought conditions often exhibit large variations from month to month. Thus, the more slowly responding indices are less temporally volatile and the PCA can account for a larger portion of the

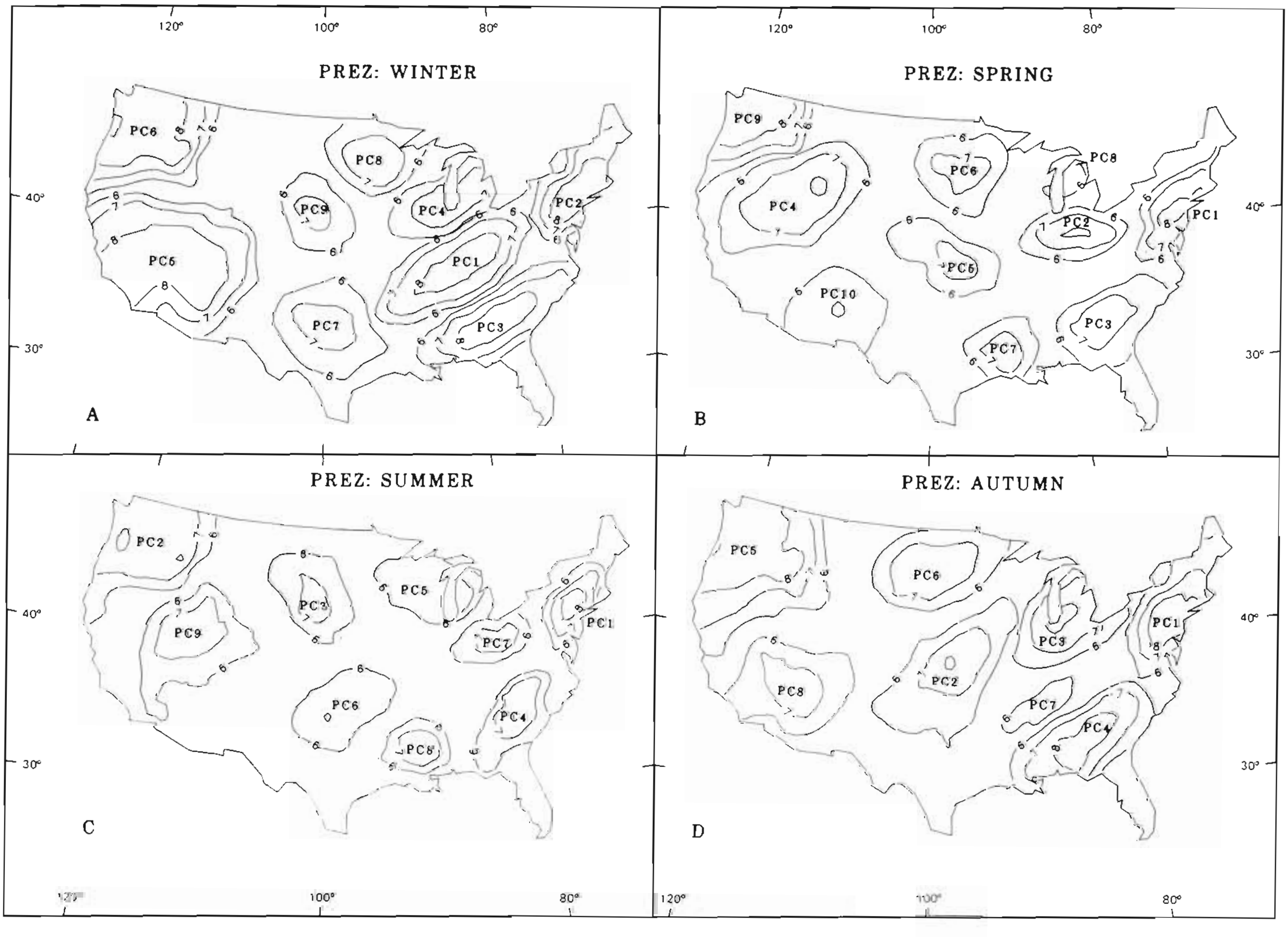

Fig. 2. Isoline maps of the VARIMAX orthogonally rotated PC loadings (× 10) for winter (A), spring (B), summer (C), and autumn (D) for the PREZ PCAs. Drought regions are labeled according to the PC they are aligned with

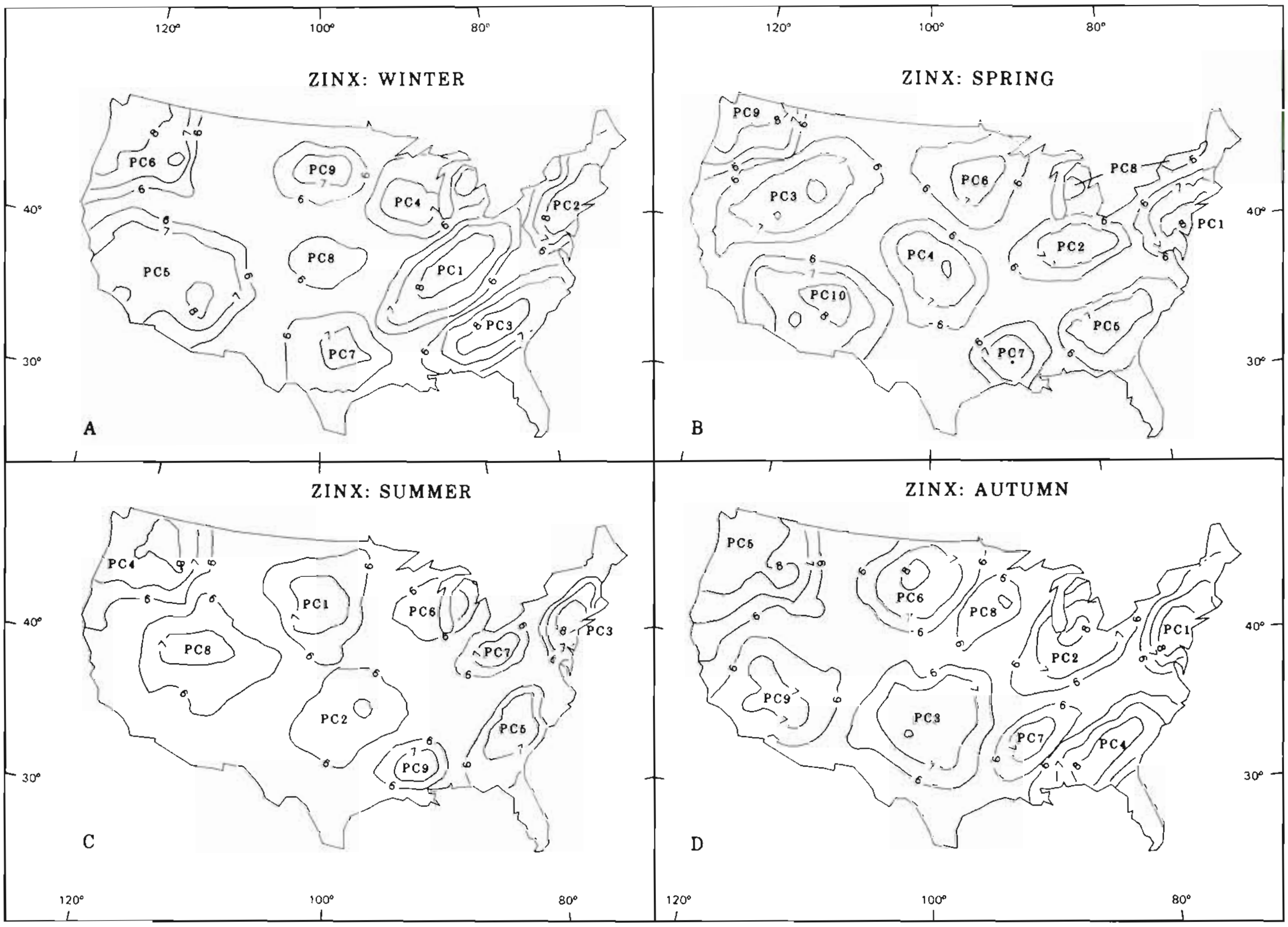

Fig. 3. As in Fig. 2, for the ZINX

Table 1. Summary of PCs retained and percent variance explained for the seasonal PCAs

Index	Season	No. PC retained	% Variance explained
PREZ	Winter	9	67
	Spring	10	60
	Summer	9	53
	Autumn	8	64
ZINX	Winter	9	67
	Spring	10	63
	Summer	9	56
	Autumn	9	67
PDSI	Winter	8	65
	Spring	10	68
	Summer	8	60
	Autumn	7	60
PHDI	Winter	7	65
	Spring	7	64
	Summer	7	60
	Autumn	7	62

variance in these data sets with fewer PCs. The climatic implications of this comparison are also consistent. A greater degree of spatial homogeneity is expected with the PHDI drought regions (i.e. fewer, but larger regions) because it takes a greater deviation from normal synoptic conditions to elicit changes in hydrologic conditions (estimated by the PHDI) than it does to elicit the same magnitude of change in agricultural drought conditions (estimated by the ZINX). Because agricultural drought severity is more tightly coupled with localized synoptic variability (e.g. convectional activity), agricultural drought regions will tend to be smaller and more numerous. Conversely, synoptic anomalies responsible for severe hydrologic droughts will tend to be more broad-scale in nature (e.g. persistent anticyclonic activity), resulting in more widespread deviations from normal moisture conditions.

On average, the greatest amount of explained variance is in winter (66 %), the least in summer (57 %). This seasonal difference reflects the fact that cyclonic storms tend to follow recurring tracks during winter,

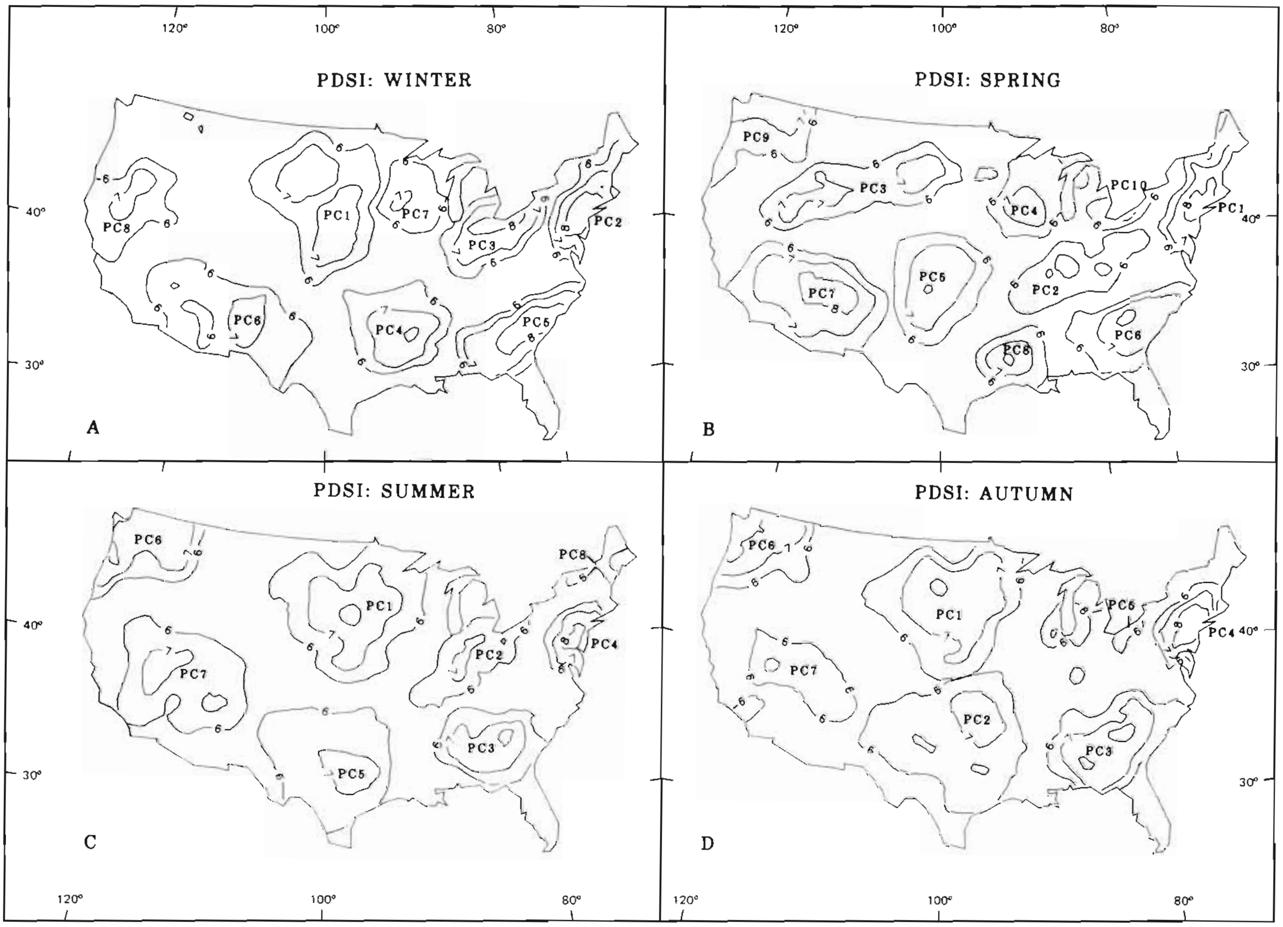

Fig. 4. As in Fig. 2, for the PDSI

bringing homogeneous temperature and precipitation conditions over large regions. Thus, neighboring climatic divisions will tend to experience similar drought (moisture) conditions during winter and the PCA can more easily sort out the patterns. In summer, the spatially erratic nature of convectional precipitation patterns results in increased heterogeneity among climatic divisions and the PCA cannot easily distinguish regional clusters.

Mapped patterns for the PREZ and ZINX

For the PREZ (Fig. 2), the greatest degree of seasonal persistence in the drought regions is in the Middle Atlantic/Northeast, the Pacific Coast/Northern Intermountain, and the Southeast. This persistence is likely a reflection of more homogeneous air mass conditions in these regions. For the remainder of the country there is a considerable amount of inter-seasonal variability in terms of the size, shape, and alignment of drought regions. Progressing from winter to summer, the drought regions become increasingly more compact, an indication of the increased complexity in precipitation patterns.

Seasonal drought patterns for the ZINX (Fig. 3) are almost identical with those for the PREZ. Although thermal conditions are included in the Palmer model (i.e. through evapotranspiration), the agreement in mapped patterns shows that precipitation is the dominant variable in the ZINX. The only substantive differences occur in autumn, where an extra drought region is identified by the ZINX in the upper Mississippi valley, and in winter, when the southern, central, and northern Great Plains drought regions are more closely aligned north to south.

The regional drought patterns for both the ZINX and PREZ match closely with seasonal shifts in synoptic patterns. The January cyclone trajectory map of Bryson & Hare (1974, their Fig. 26), shows 3 principle storm paths in the contiguous United States and one just north of the Canadian border. If this map is super-

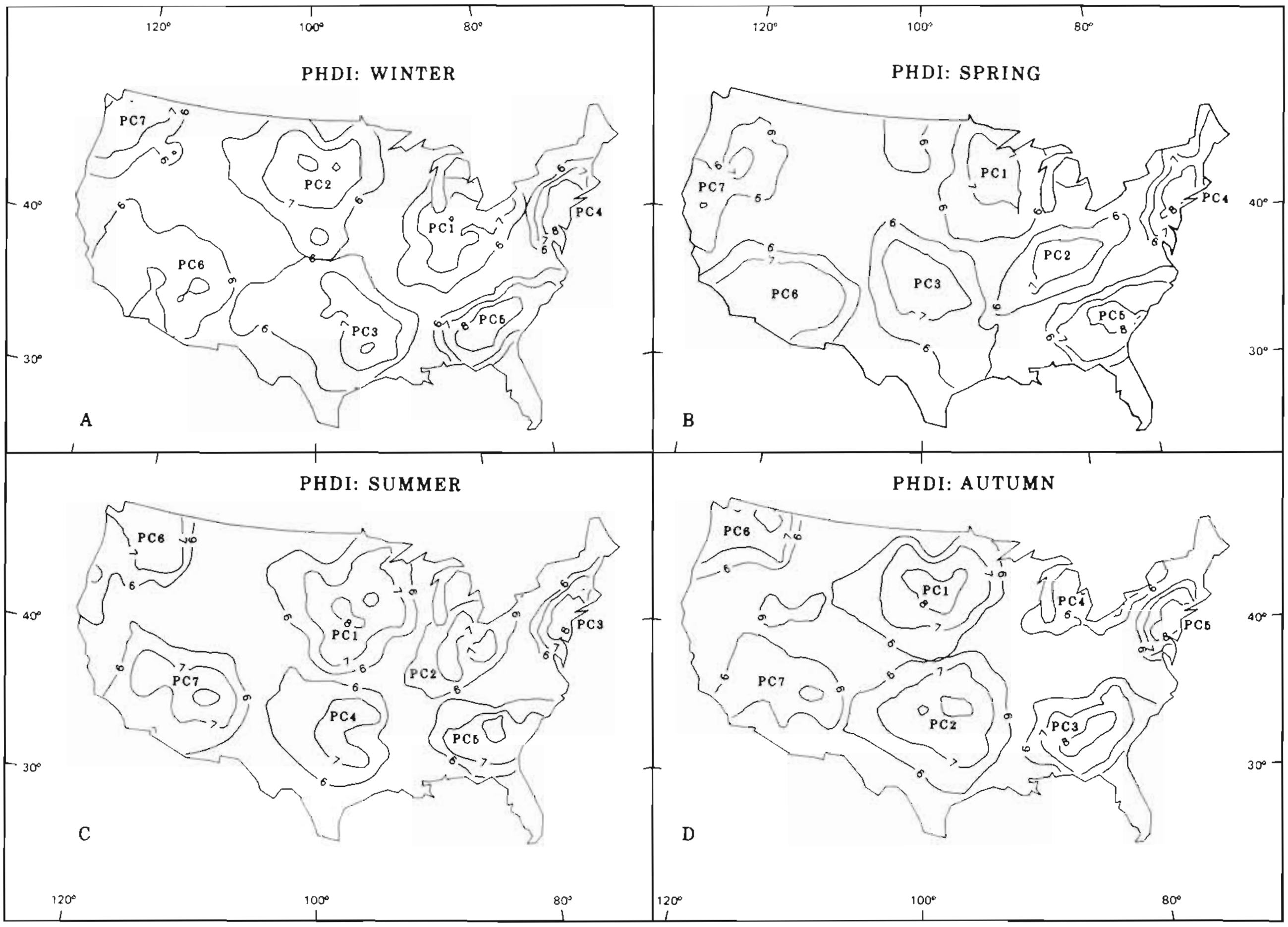

Fig. 5. As in Fig. 2, for the PHDI

imposed on the regional drought map for the PREZ in winter (Fig. 2a), the trajectories pass directly through the principle axes of 4 drought regions (PCs 9, 4, 1, and 3), and are parallel to 2 others (PCs 2 and 8). Walsh et al. (1982) had similar findings when comparing spatially coherent precipitation regions in the United States to cyclone trajectories. The precipitation received from cyclones along these trajectories, or lack of rainfall when cyclones failed to follow these normal paths, appears to influence the location, size, and orientation of winter drought regions.

The PREZ drought region maps for spring, summer and autumn (Fig. 2b, c, d) were compared to the mid-season cyclone and anticyclone trajectory maps of Klein (1957). Although the match-ups are not as numerous or distinct as in winter, the orientation and location of certain drought regions do correspond with cyclone paths in all seasons. The general trend from a more meridional alignment of most drought regions in winter, to a zonal alignment in summer, followed by a return to a meridional alignment in autumn is also evident in the maps of both mean cyclone and anticyclone paths.

The split in drought regions along the Gulf Coast from winter to spring/summer is intriguing. This split seems related to the shift from a dominance of cyclonic to convectional precipitation. The lower Mississippi valley has a definite winter maximum of precipitation related to the Gulf Atlantic storm track (Trewartha 1981). In the southeastern coastal states precipitation is usually more evenly distributed throughout the year, with cold-season cyclonic precipitation matching warm-season convectional precipitation. While the climatic differences between these 2 regions are arguably subtle, they appear to be reflected in the PREZ and ZINX drought regionalizations.

The regional drought patterns for the PREZ and ZINX also may reflect distinct seasonal variations in normal precipitation for other areas of the country. For example, PC10 for the PREZ in spring appears to pick up a Sonoran desert climatic pattern, where precipitation amounts are generally very small through April, May, and June due to persistent subsidence from the Pacific anticyclone. Conversely, within the central Inter-mountain drought region on the same map (PC4) the spring climate is dominated by a southwesterly flow of maritime polar air around an upper level trough, resulting in a late spring maximum of precipitation (Trewartha 1981). A lack of inter-annual variability in precipitation also may influence the drought patterns, as illustrated by the stability of the Middle Atlantic/Northeast drought region in all seasons.

Mapped patterns for the PDSI and PHDI

Because the PDSI of any given month is strongly controlled by moisture conditions in the previous months, linking the PDSI patterns to intra-seasonal synoptic controls of climate is more difficult than with the PREZ or ZINX. Overall, there is considerable seasonal variability in the derived patterns for the PDSI (Fig. 4). As with the ZINX and PREZ, the greatest amount of seasonal persistence is found in the Middle Atlantic/Northeast and Southeast drought regions. The lack of a drought region centered in the Pacific Northwest in winter is unusual. This is a consistent region in nearly all other instances. The more southerly location of PC Region 8 in winter (Fig. 4a) is possibly related to the timing of maximum yearly rainfall. The maximum rainfall generally occurs in late autumn (November) north of this region and in early winter (January) to the south of this region (Trewartha 1981). Because of the lag effect built into the PDSI, this region may be more representative of moisture conditions in December, when maximum precipitation is expected. PC Region 3 in spring (Fig. 4b) is also unusual because it extends from the central Inter-mountain region, across the Rocky Mountains, and into the northern Great Plains. The Rocky Mountains are generally not aligned with any drought region; they serve as a transition zone between the Pacific Coast and Great Plains drought regions. The large area enclosed by the 0.60 loading isolines for the southern and northern Great Plains drought regions in summer and autumn (Fig. 4c, d) shows that a large number of climatic divisions experienced similar drought conditions during these seasons over the climatic record.

Despite the unusual location of some drought regions, the overall PDSI patterns are consistent with synoptic knowledge, e.g. a southwest-northeast alignment of drought regions in the eastern United States during winter and spring, and a more zonal alignment in summer. In addition, when the seasonal PDSI maps are overlaid on the seasonal ZINX maps, the core areas for the majority of regions match closely.

As a measure of hydrologic drought, the PHDI responds slowly to changes in moisture supply and demand. Thus, it exhibits less temporal variability than the other 3 drought measures and produces more persistent inter-seasonal drought patterns (Fig. 5). In all seasons, 7 regions are identified, with very little difference in the total amount of explained variance (Table 1). Particularly striking is the excellent match between summer and winter patterns. The greatest inter-seasonal variability is in the Northern Great Plains and Ohio Valley regions, while the least variability occurs in the southeast and Middle Atlantic/Northeast regions. As with the PDSI, the Northern and Southern Great Plains drought regions include a large number of climatic divisions in summer and autumn, indicating homogeneous hydrologic drought history characteristics in these areas during these seasons.

CONCLUSIONS

There is a high degree of inter-regional variability in drought characteristics (e.g. frequency, duration, intensity, spatial coverage) within the contiguous United States (Diaz 1983, Karl 1983). This variability makes it difficult to develop drought contingency and water management plans that are applicable across the country. Results from this study show that the degree of intra-regional variability in drought characteristics over the climatic record is small enough to allow for the identification of certain clusters of climatic divisions as spatially homogeneous, drought-type specific regions on a seasonal basis. Below, above, and normal moisture conditions were predominately in-phase (seasonally) over the course of the study period for each of these regions. Within a given season, the location, size and orientation of most drought regions is largely consistent across the drought types represented by the PREZ, ZINX, PDSI, and PHDI. Although the fast responding index (ZINX, PREZ) patterns are more discrete (i.e. the drought regions are smaller and more numerous), the general location and orientation of the regions conform to those for the more slowly responding indices (PDSI, PHDI). For the fast responding indices there is a considerable amount of inter-seasonal variability in the regional drought patterns. The amount of variability decreases for both the PDSI and PHDI, with most PHDI drought regions remaining stable throughout the year. While the location and alignment of drought regions can be circumstantially related to certain aspects of mesoscale synoptic meteorological patterns (e.g. cyclone trajectories), further analyses are needed to authenticate or refute these suspected causal links.

Planning and water management efforts designed to alleviate the negative impacts of drought are generally region specific (Yevjevich et al. 1978). A logical step to help improve drought contingency planning efforts would be to base the boundaries of administrative regions on climatically-based regionalization schemes, such as those developed in this study. Since the spatial characteristics of most drought types are intra-seasonally stable across the drought types , an administrative regionalization scheme based on the PDSI, with its intermediate rate of response to changes in supply and demand of moisture, would likely be appropriate in most situations.

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