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## **DROUGHT EVOLUTION PATTERNS IN THE U.S.A. DURING GREAT PLAINS-CENTERED DROUGHTS**

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**Abstract.** *This study examines the spatial evolution of drought severity within the contiguous United States during the first six months of average Great Plains-centered drought events. It identifies Great Plains-centered drought events from 1895-1989 based on the drought history of the North Central, South Dakota and Low Rolling Plains, Texas climatic divisions. Time series of warm- and cold-season average drought severity based on Great Plains drought for all United States' climatic divisions are calculated and spatially analyzed.*

*Mapped patterns show spatial teleconnections in drought development. Cold-season drought patterns based on the North Central, South Dakota climatic division are clearly in-phase with droughts in the lower Mississippi Valley. Drought patterns based on the Low Rolling Plains, Texas climatic division reveal that droughts are in-phase across the southwestern United States, but are largely out-of-phase with the eastern states.*

Previous studies on Great Plains drought cover a wide range of topics, including examinations of the synoptic meteorological conditions associated with severe drought periods (Namias 1982; Dey 1982, Chang and Wallace 1987), evaluations of the spatial patterns and temporal persistence of drought conditions (Skaggs 1978; McGregor 1985; Oladipo 1986), searches for periodicities (Oladipo 1987), eigenvector analyses (Klugman 1978), historical and dendroclimatic reconstructions of Great Plains drought history (Stockton and Meko 1983; Mock 1991), and examinations of the social aspects of drought (Hecht 1983; Taylor et al. 1987). Other studies focusing on characteristics of drought throughout the United States have helped reinforce the common and substantiated belief that Great Plains' droughts are more tenacious than droughts in other regions of the United States (Walsh et al. 1982; Karl and Koscielny 1982; Diaz 1983; Karl 1983;

Karl et al. 1987; Soulé 1992a). Using the water balance-based Palmer Indices (Palmer 1965), these studies all reached same conclusion: droughts in the interior United States, particularly the Great Plains, are more persistent than in other regions of the country.

A basic aspect of drought characteristics that has not been fully explored in the Great Plains is the spatial evolution of *average* drought conditions, with *average* referring to arithmetic mean values of drought severity (measured monthly by water balance-based indices) across several different drought events. This study examines the spatial development of drought severity patterns within the contiguous United States during the first six months of an average drought event by using the drought history characteristics of two climatic divisions within the Great Plains. Guiding research questions are:

- 1) What are the average national moisture conditions (including drought) at the time droughts are affecting the sample climatic divisions?
- 2) Does the average drought expand into the region from a specific direction, or does the drought tend to develop in place?
- 3) Are there other regions of the United States that tend to be in-phase or out-of-phase with the core areas of greatest drought severity?

## Data

The primary data are monthly values of the Palmer Drought Severity Index (PDSI) for each of the 344 climatic divisions in the contiguous United States for the period January 1895 to April 1989 (National Climatic Data Center 1989). Monthly values of the Palmer Moisture Anomaly Index (ZINX), and the Palmer Hydrologic Drought Index (PHDI) are also used to help determine the starting and ending months for individual drought events. All data are from the National Climatic Data Center's "Time Bias Corrected Divisional Temperature-Precipitation-Drought Index" data set (National Climatic Data Center 1989).

The Palmer Indices (PDSI, PHDI, ZINX) are widely used in examinations of drought characteristics in the United States. The indices are water balance-based, and provide for regionally and temporally standardized measures of moisture. The indices are normalized around zero, or normal moisture conditions, with positive deviations representing wet conditions,

negative deviations representing dry conditions. Of the three, the moisture anomaly or Z-index (ZINX) has the most rapid response to changes in supply (precipitation) or demand (evapotranspiration) of moisture. Since the ZINX responds rapidly, it is appropriately used as a measure of agricultural drought (Sakamoto 1978; Karl 1986). The PDSI is qualitatively referred to as a meteorological drought index as it has an intermediate rate of response to a changed moisture status (Palmer 1965). The PHDI is a modification of the PDSI. The modifications result in an index that more slowly responds to changes in the moisture status of a region, and this slow response is an attempt to emulate actual hydrologic responses in watersheds. Alley (1984) and Karl (1986) outline specific calculation procedures for the Palmer Indices. Limitations of the indices are discussed by Alley (1984) and Heddingshaus and Sabol (1991). Qualitative labels have been attached to various ranges of the indices for the PDSI (Table 1) and the PHDI and ZINX (Table 2).

Seven hundred mb data were examined in map form to help determine the general upper-level flow patterns during drought events (Namias 1979). Since these maps were available only after 1946, quantitative analyses of 700 mb data were not used.

## Methods

Soulé (1990a) used VARIMAX-rotated, S-mode principal components analyses (PCA) to identify spatially homogeneous drought regions in the contiguous United States based on the Palmer indices. For the PDSI analyses, he identified eight significant principal components. For each component he mapped the spatial pattern of the loadings (correlation between a principal component and a variable, with the variables in S-mode PCA being the spatial units) to delimit the generalized boundaries of the drought regions. The maps clearly identify both northern and southern Great Plains drought regions (Soulé 1990a: 76). The two climatic divisions with the highest loadings (strongest relationships) for the principal components delimiting these northern and southern Great Plains drought regions were identified in a separate study and are used here (Soulé 1990b:102). Thus, spatial patterns of average drought severity presented in this study are derived based upon the drought history of the North Central, South Dakota (NCSD) and Low Rolling Plains, Texas (LRPT) Climatic Divisions (Fig. 1).

Analysis began with the identification of all major drought events that occurred at the NCSD climatic division during the study period. A major

TABLE 1  
Severity classes for the PDSI.APPROXIMATE

CUMULATIVE FREQUENCY (%)	PDSI VALUE	SEVERITY CLASS
$\geq 96$	$\geq 4.00$	Extremely wet
91-96	3.00 to 3.99	Very wet
67-90	2.00 to 2.99	Moderately wet
	1.00 to 1.99	Slightly wet
37-66	0.50 to 0.99	Incipient wet spell
	0.49 to -0.49	Near normal
11-36	-0.50 to -0.99	Incipient drought
	-1.00 to -1.99	Mild drought
5-10	-2.00 to -2.99	Moderate drought
	-3.00 to -3.99	Severe drought
$\leq 5$	$\leq -4.00$	Extreme drought

(after Palmer 1965:28)

drought event was defined as any span of six or more consecutive months where values of the PDSI, PHDI, or ZINX were -1.5 or lower (mild drought). This basic scheme follows previous work by Diaz (1983) and Soulé (1992a). Three or more consecutive months with PDSI values of -2.0 or lower (moderate drought) denoted a drought event in the Diaz (1983) definition, and six or more consecutive months were considered a major drought event. Including the faster (ZINX) and slower (PHDI) responding indices and reducing the drought intensity level results in a very liberal drought event definition. Since the ZINX typically responds to moisture deficits before the PDSI or PHDI, this definition insures that the initial months of long drought events are included in the analysis.

Monthly PDSI values corresponding to cold and warm season drought events were extracted from the original data set after all major droughts were

TABLE 2  
Severity classes for the PHDI and ZINX

APPROXIMATE CUMULATIVE FREQUENCY (%)	PHDI VALUE	SEVERITY CLASS	ZINX VALUE
≥ 96	≥ 4.00	Extreme wetness	≥ 3.50
90-95	3.00 to 3.99	Severe wetness	2.50 to 3.49
73-89	1.50 to 2.99	Mild to moderate wetness	1.00 to 2.49
28-72	-1.49 to 1.49	Near normal	-1.24 to 0.99
11-27	-1.50 to -2.99	Mild to moderate drought	-1.25 to -1.99
5-10	-3.00 to -3.99	Severe drought	-2.00 to -2.74
≤ 4	≤ -4.00	Extreme drought	≤ -2.75

(after National Climatic Data Center 1989:4)

identified. The PDSI was used to calculate the arithmetic mean or *average* drought conditions because of its intermediate rate of response to changes in supply and demand for moisture. Droughts beginning in autumn or winter (September through February) were classified as cold-season droughts, while those beginning in spring or summer (March through August) were classified as warm-season droughts. Using data from month one of all major droughts (identified from the climatic history of the NCSD climatic division), an average PDSI value was calculated for each of the 344 climatic divisions. The procedure was repeated for the second through sixth months to produce cold- and warm-season time series of average drought severity.

Isoline maps were used to show the temporal progression of average moisture conditions across the contiguous United States when drought conditions are firmly established in the NCSD region. Variability from the average patterns was also examined using isoline maps of standard deviations. All maps were created by plotting the average drought values and associated standard deviations at the climatic division centroids and then interpolating isolines using a KRIGING algorithm (Golden Software 1989).

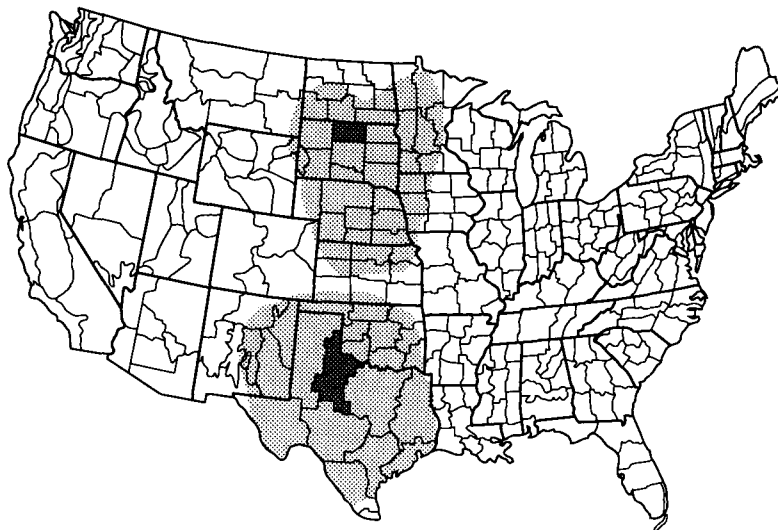


Figure 1. Climatic divisions in the contiguous United States. The North Central, South Dakota and Low Rolling Plains, Texas Climatic Divisions are highlighted with dark shading. The generalized boundary (corresponding to the .60 loading isoline) of spatially homogeneous drought regions in the northern and southern Great Plains is shown using light shading (after Soulé 1990a:76).

Procedures used for the NCSD climatic division were repeated for the LRPT climatic division.

### **North Central, South Dakota-based Droughts**

During the 1,132 month study period there were four major cold-season droughts with an average length of 25 months, and 11 warm-season droughts with an average length of 26.1 months identified in NCSD. According to the definition used, drought conditions were recorded in 34% of all months.

#### **Cold-season**

The progression of mean PDSI values through the first six months of an average drought, defined using the four major cold-season droughts

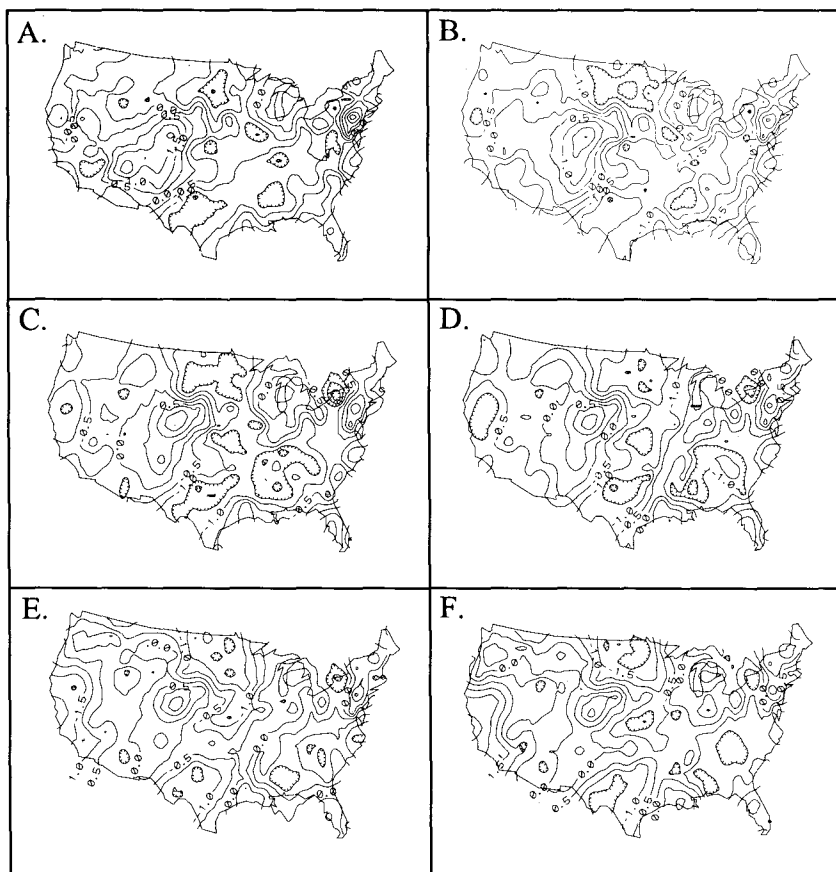


Figure 2. Average PDSI values across the United States during month one (A) to month six (F) for the average cold-season, NCSD-based drought event.

experienced in NCSD, showed that mean moisture conditions were below normal throughout most of the central U.S. during the initial month (Fig. 2). Drought conditions were maximized in the north central Great Plains, southern Great Plains, and the lower Mississippi Valley. Two areas that were out-of-phase with the region surrounding the NCSD division and exhibited above normal moisture conditions include the region extending from the southwest Four Corners area through the central high plains and eastern Rocky Mountains (Colorado), and the middle Atlantic coastal states (Pennsylvania). This pattern changed subtly, as there was a northeastward



shift of the main out-of-phase region in the central high plains, a second in-phase region developed in the extreme west (centered on coastal California) in the later months, and a third out-of-phase region developed in south central Florida. Although the three eastern drought cores remain identifiable in all six months, they nearly merge during month four. There was no major shift in mean drought severity, as the peak values remained largely between -1.5 and -2.0 PDSI units during the six months.

Inter-drought variability was low in many areas, particularly the north central Great Plains, southern Great Plains and high plains, the upper Mississippi Valley, and the extreme southwest (Arizona and California) during the later months (Fig. 3). Inter-drought variability was maximized in a belt stretching from the northern Rocky Mountains southeastward into the south central Great Plains.

The combination of low inter-drought variability and consistent negative moisture deviations in both the north central Great Plains and southern Great Plains/high plains region suggests these two regions were consistently in-phase during cold-season drought periods. Inter-drought variability in the southeastern-core drought region largely was between 2.0 and 2.5 PDSI units, suggesting considerable variability across the four recorded cold-season droughts. However, an opposite positive spatial connection (between southeastern-based droughts and droughts in the northern Great Plains) has been identified by Soulé (1992b).

An examination of 700 mb charts for the initiation phase of the two cold-season droughts beginning in the post World War II era (1947) (one beginning in September 1952, the other November 1987) revealed a similar pattern. During both autumn 1952 and 1987 there was accentuated ridging centered near the Pacific coast and extending to the Arctic. The associated negative vorticity advection and northwesterly flow aloft is consistent with the pattern of developing drought conditions in the northern Great Plains. However, the complexity of the moisture conditions throughout the United States cannot be explained readily from the perspective of mean upper-level flow conditions.

### **Warm-season**

Spatial patterns of average drought severity defined using the 11 major warm-seasons droughts experienced in NCSD during the study period were considerable less complex than those for the cold season (Fig. 4). Two core areas of average drought, one centered around NCSD and a second centered in the central intermountain region but extending through much of the West,

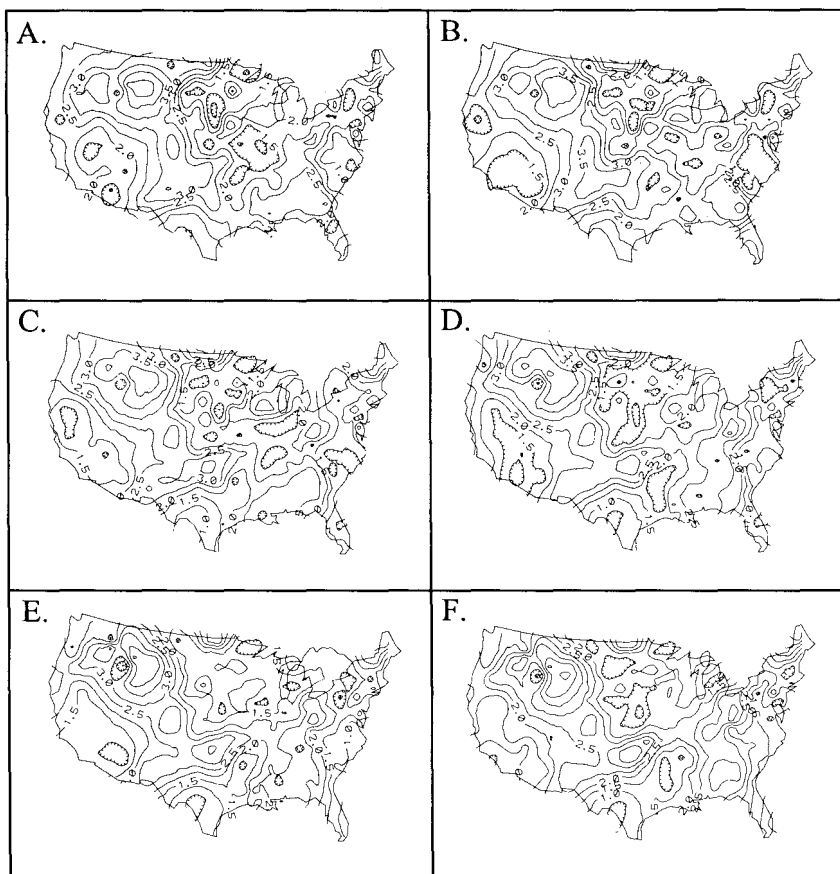


Figure 3. Standard deviation of average PDSI values across the United States during month one (A) to month six (F) for the average cold-season, NCSD-based drought event.

were evident during the initial three months. As the drought progresses, the western core area contracts, with steadily decreasing drought severity through month six. The drought-affected region surrounding NCSD remains stable through the six months, but there was a steady increase in drought severity in the core, with mean PDSI values reaching -2.5 in month five (Fig. 4E). No areas were strongly out-of-phase with the NCSD region, and inter-drought variability was moderate throughout most of the country, with standard deviations generally between 1.5 and 3.0 PDSI units (Fig. 5).

Examination of upper-level flow conditions during spring and summer for the seven warm-season droughts beginning after 1947 (1955, 1959,

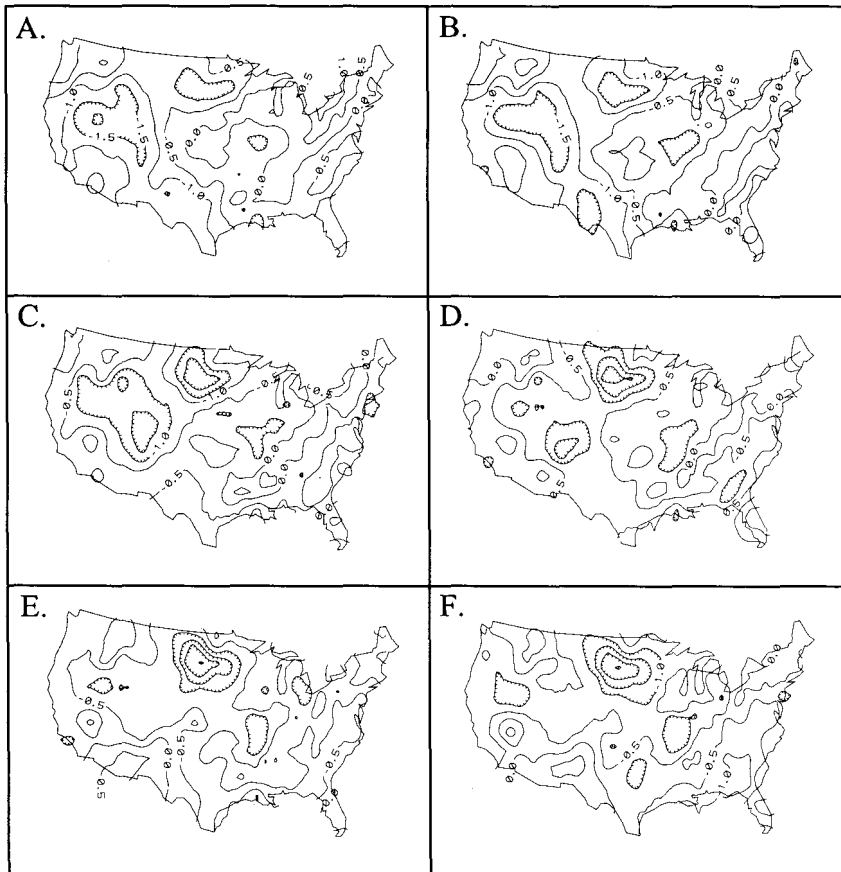


Figure 4. Average PDSI values across the United States during month one (A) to month six (F) for the average warm-season, NCSD-based drought event.

1961, 1974, 1976, 1980) revealed no consistent synoptic patterns. Accentuated ridging upstream of NCSD was evident in 1961 and 1980, but the other five years recorded largely zonal flows across the upper Great Plains during the initial drought months. Accentuated ridging over the continental United States has been linked to drought conditions in the Great Plains (Namias 1983), most recently during the 1980 drought (Karl and Quayle 1981) and the 1988 drought (included in this study as a cold-season drought as it began in November 1987) (Trenberth et al. 1988; Namias 1991). However, Chang and Wallace (1987:1,267) have shown that summer drought conditions in the

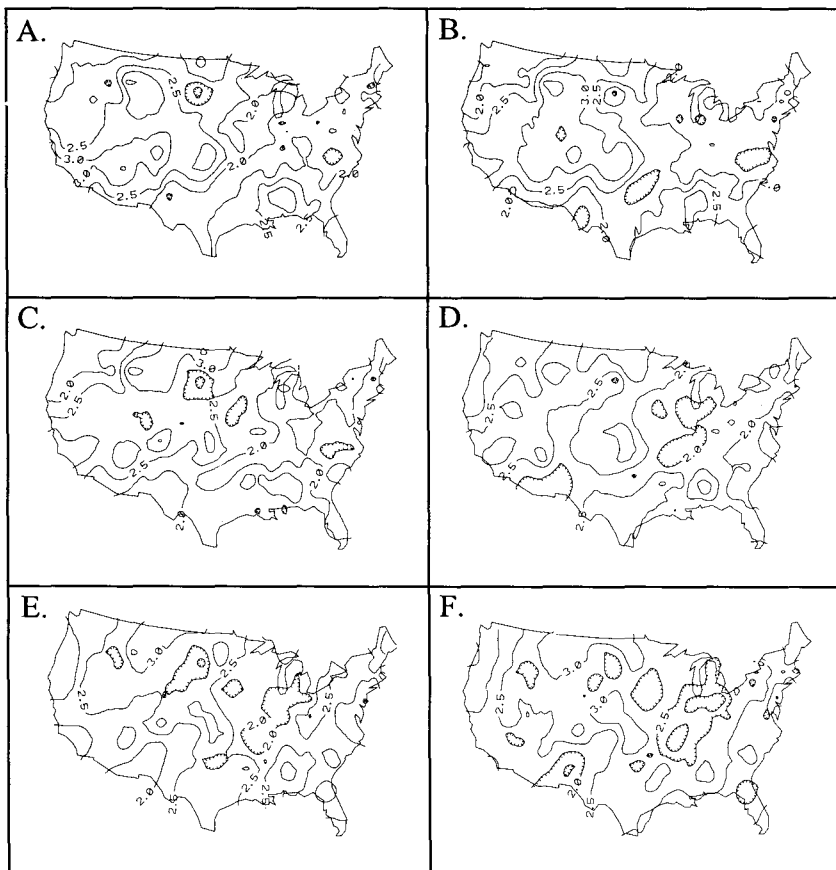


Figure 5. Standard deviation of average PDSI values across the United States during month one (A) to month six (F) for the average warm-season, NCSD-based drought event.

Great Plains can be linked to “an extension of the thermal trough from the southwest desert region into the western Great Plains.” Their explanation loosely matches the predominately zonal upper-level patterns during the initial months of droughts in 1955, 1959, 1974, and 1976, and it is consistent with the spatial connection between the core regions of drought in the Great Basin and the northern Great Plains. Namias (1983, 1991) argues that United States’ droughts can have multiple controlling factors, and that appears to hold true for NCSD-based warm-season droughts.

### **Low Rolling Plains, Texas-based Droughts**

Eight cold-season droughts and ten warm-season droughts were identified in the Low Rolling Plains, Texas Climatic Division. These droughts had a mean length of 22.6 and 14.1 months, respectively. By this study's definition, droughts occurred in 28 percent of the study months.

#### **Cold-season**

Average drought conditions were pervasive throughout most of the central and western states during month one, with drought severity maximized in the Great Basin and the southern Great Plains (Fig. 6). Average moisture conditions were also below normal in the upper Mississippi Valley and the central Atlantic coastal regions. Much of the Tennessee and Ohio Valley region was out-of-phase with LRPT, and moisture conditions were also above normal in a crescent running from the north central Pacific coast through the northern Rocky Mountains and into the Missouri Valley. Although the general moisture patterns change little through the six months, the dichotomy between in- and out-of-phase regions was maximized in month five, with mean PDSI values ranging from -2.5 in the southern Great Plains to 2.5 in the northern Rocky Mountains (Montana). Also evident in months five and six was a return to more normal moisture conditions in the Great Basin and an increase in the drought-affected area in the central Atlantic coastal states.

Inter-drought variability was extremely low in the southern Great Plains drought core, with standard deviations of 0.5 recorded in months one through five (Fig. 7). The combination of low inter-drought variability and a large mean negative moisture deviation suggests that a large area of the southwestern U.S., particularly the southern Great Plains, was consistently in-phase during LRPT-based cold-season droughts. Again, inter-drought variability was maximized in the Rocky Mountain region, particularly the north central Rocky Mountains. The combination of high inter-drought variability and mean moisture conditions near normal suggests there was no tendency for most of the Rocky Mountain region to be in- or out-of-phase with cold-season drought conditions in the southern Great Plains. The one exception was in the extreme northern Rocky Mountains, where positive moisture deviations combined with a moderate degree of inter-drought variability.

Upper level charts were examined for the four LRPT-based cold-season droughts beginning after 1947 (1950, 1966, 1973, 1977). All four droughts

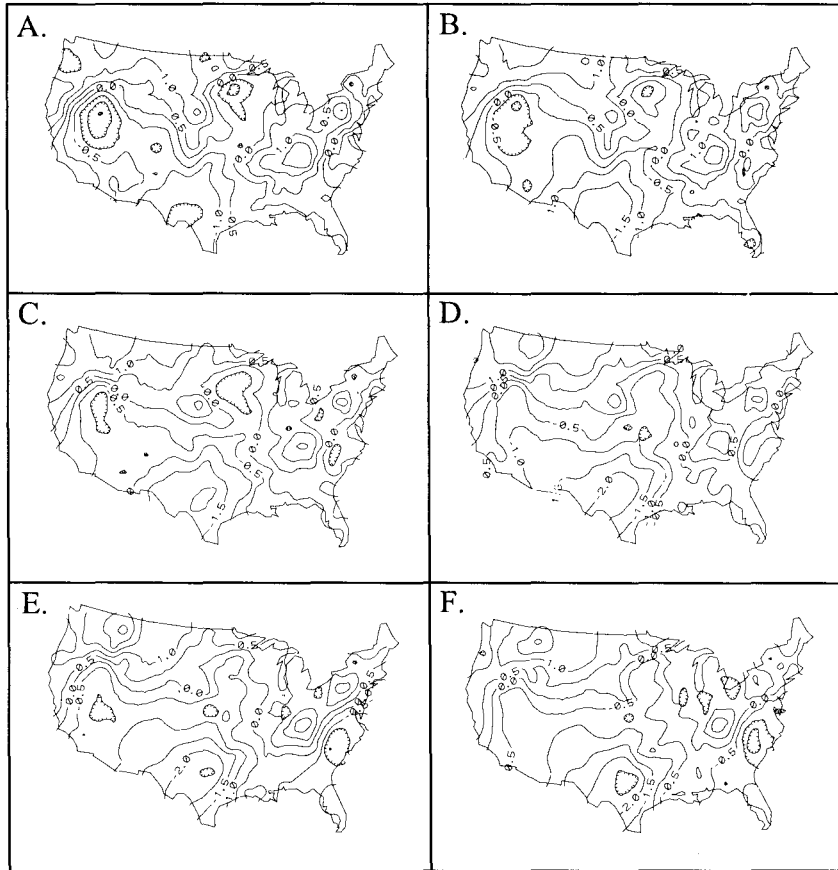


Figure 6. Average PDSI values across the United States during month one (A) to month six (F) for the average cold-season, LRPT-based drought event.

began during Autumn, and a consistent element of the flow pattern was abnormal troughing in the long-wave pattern off the Pacific northwest coast. The trough was particularly accentuated in 1950, 1973, and 1977, and it persisted through the winter months in all four years. Accentuated troughing in the north Pacific results in a southwesterly flow of air, positive vorticity advection, and enhanced cyclogenesis across the north Pacific coast through the northern Rocky Mountains. The pattern of above normal moisture across the northwestern states concurs with this flow regime (Fig. 6). The upper

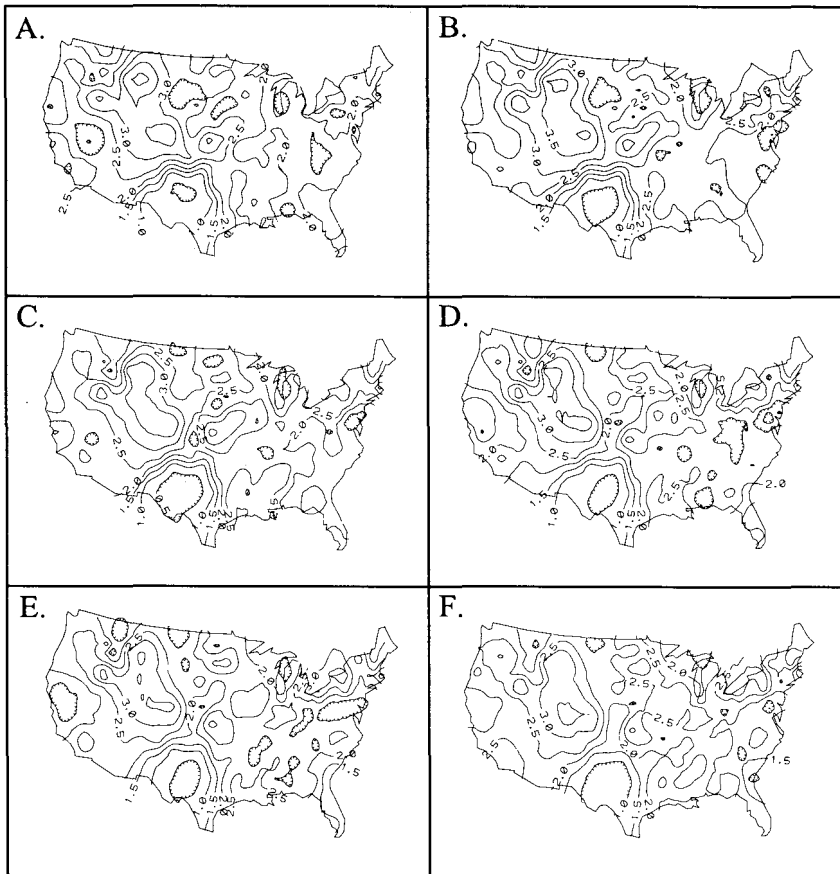


Figure 7. Standard deviation of average PDSI values across the United States during month one (A) to month six (F) for the average cold-season, LRPT-based drought event.

level charts revealed no strong tendency for abnormal ridging across the southwest and central U.S. that would be associated typically with drought conditions. The normal late fall/early winter flow is, however, northwesterly over the southwestern states (Harman 1991). Below normal moisture conditions in the region could be partially linked to abnormal Pacific troughing because most Pacific airstreams and Pacific-spawned cyclonic storms would be directed toward the north, leaving the southwestern states to rely predominately on Gulf moisture for precipitation.

### Warm-season

Patterns for LRPT-based warm season droughts show there was one large core area of average drought centered in the southern Great Plains, with below normal moisture conditions stretching from the desert southwest, through the Great Lakes, and into the northeastern states (Fig. 8). As with the cold-season patterns, there was a consistent out-of-phase region east of the Mississippi. Whereas the out-of-phase region for cold-season droughts was centered in the Ohio Valley, the out-of-phase region in the warm-season extends from the eastern Gulf coast through the southern Atlantic coastal states. The basic pattern changed little during the average drought event, although drought severity increased in the large south central core region through month five. There was also a noticeable shift toward more normal moisture conditions in desert southwest. Average drought conditions were maximized in Arizona during month one at -2.0 PDSI units, but the same area recorded a mean PDSI of 0.00 to -0.05 by month six. There was also a southwestward shift of the core out-of-phase drought region in the southeast through the six months.

Patterns of inter-drought variability revealed a strong southwest to northeast dichotomy (Fig. 9). Inter-drought variability was maximized in the north central intermountain region (Idaho), with standard deviations reaching 5.0 PDSI units in months three, four and five. Variability remained high through the north central Rocky Mountains, north central Great Plains, and upper Mississippi Valley. Conversely, inter-drought variability was much lower (generally under 2.0 PDSI units) from the southern Great Plains eastward and northeastward.

Examination of upper-level charts for the four droughts beginning after 1947 (1963, 1964, 1970, 1984) provided no clues about the possible synoptic conditions responsible for the mapped patterns of average warm-season drought conditions in the southern Great Plains. Flow conditions during the four summers were near normal throughout the contiguous United States.

Synoptic conditions leading to summer droughts in the southern Great Plains have been discussed by both Namias (1955) and Karl and Quayle (1981). The droughts they discussed were either classified as cold-season for this study (e.g., Namias examined drought conditions during the 1950s, and this extended drought began in Autumn of 1950), or were too short in duration to be recorded using this study's drought definition (e.g., Karl and Quayle examined the summer drought of 1980). The regional synoptic



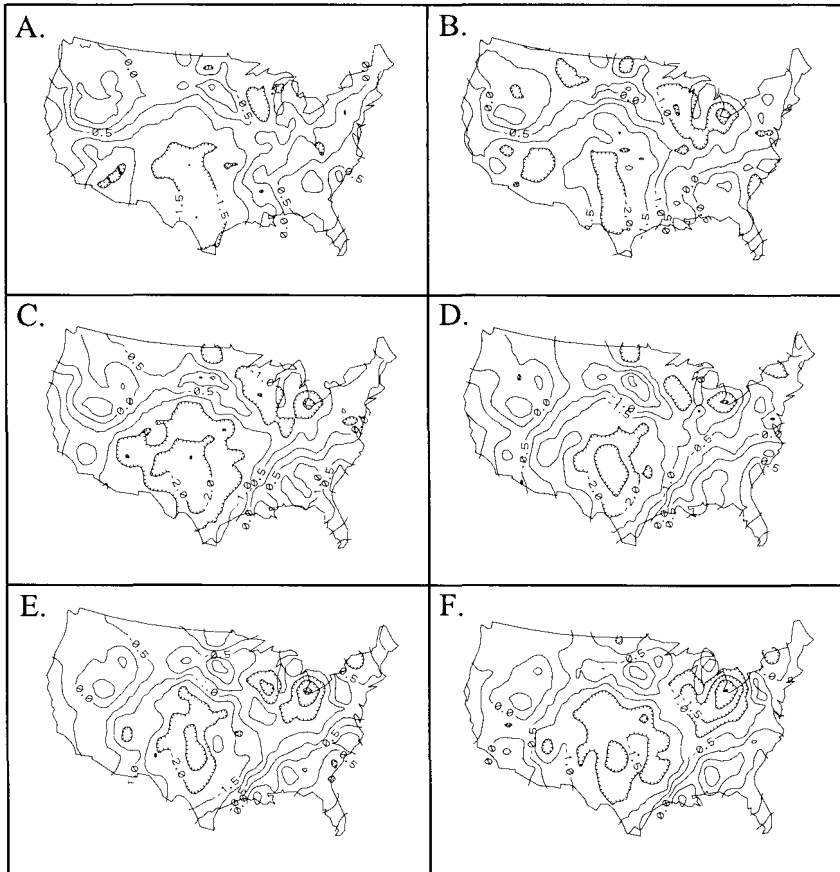


Figure 8. Average PDSI values across the United States during month one (A) to month six (F) for the average warm-season, LRPT-based drought event.

pattern associated with warm-season droughts in the 1950s and 1980 involved abnormal ridging over the lower Mississippi Valley and southern Great Plains (Namias 1955; Karl and Quayle 1981). Accentuated ridging in the southcentral United States during summer would typically result in enhanced subsidence under the ridge, a northward displacement of cyclonic storm tracks, and the closure of the Gulf of Mexico as a moisture source for the southern Great Plains. Although it is a limited sample, the four post-1947 warm-season droughts examined in this study do not fit this pattern, which suggests that other controlling factors may be in operation. Namias (1983)

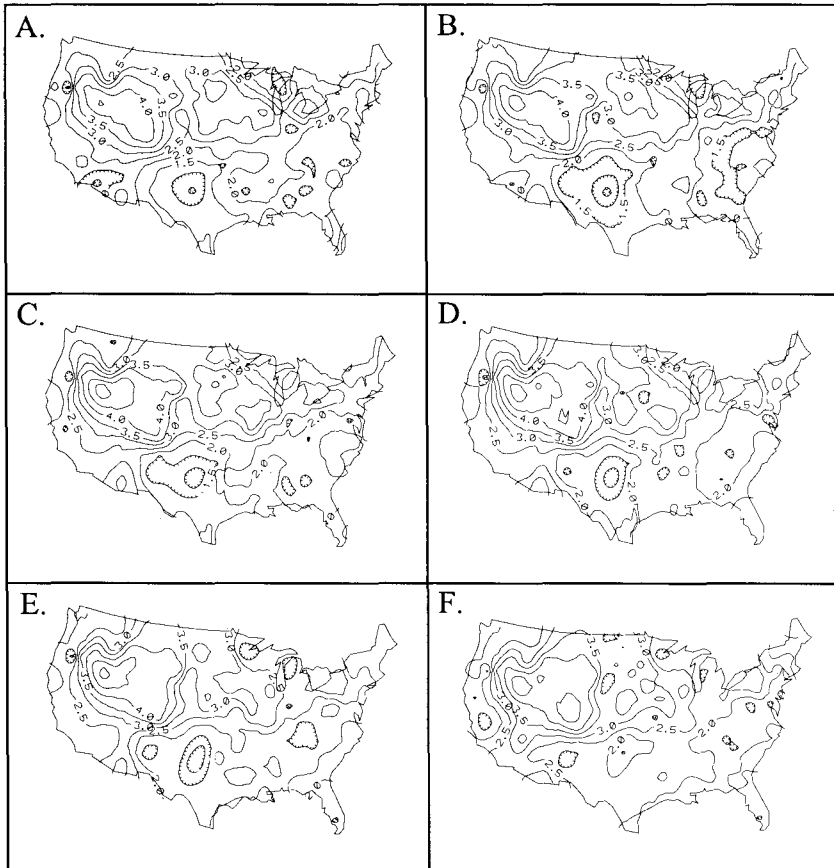


Figure 9. Standard deviation of average PDSI values across the United States during month one (A) to month six (F) for the average warm-season, LRPT-based drought event.

and Chang and Wallace (1987) suggest that positive feedback loops may be in operation for warm-season droughts in the Great Plains, with reduced precipitation causing reduced evapotranspiration causing reduced precipitation. Namias (1991: 54) states there are multiple, interrelated causes of drought that “involve atmospheric teleconnections to and from the Great Plains, interactions between large scale SST anomalies and the atmosphere, and equally important, air-land interactions in the domain of the drought.” These air-land interactions may be particularly strong in the southern Great Plains, as there is a strong negative correlation ( $r = -0.60$  to  $-0.80$ ) between

mean summer temperature and precipitation in the LRPT region (Namias 1983; Chang and Wallace 1987).

### **Conclusions**

This study examined recurring spatial patterns of moisture deviation when drought occurred at climatic divisions in the northern and southern Great Plains. Average cold- and warm-season conditions were examined for both NCSD and LRPT-based droughts. Unique patterns were evident on each series of maps, indicating considerable seasonal and regional variability to the drought history of the Great Plains. Spatial heterogeneity was maximized on the cold-season patterns for NCSD-based droughts, with four distinct drought nodes evident. The least complex pattern was found for NCSD-based droughts in the warm season, with two strong core areas of drought in the initial months yielding to one dominant core surrounding NCSD by month six, and no strong out-of-phase regions. In all cases, the spatial patterns of average moisture showed an intensification of average drought severity in the core region through at least month five. Maximum average drought severity was consistently between -2.00 and -3.00 PDSI units, with average above normal moisture conditions reaching a similar magnitude only during the cold-season.

There is little seasonal agreement in the location and intensity of in- and out-of-phase drought regions when comparing cold- and warm-season maps from the individual climatic division analyses. For example, NCSD-based cold-season drought patterns showed that the central intermountain and Rocky Mountain regions were strongly out-of-phase with the core drought region in the northern Great Plains, while in summer the two regions were consistently in-phase. The lack of agreement between cold- and warm-season patterns is not unexpected because controlling synoptic conditions are seasonally diverse.

Temporal progression of average drought conditions on each series of maps suggests that droughts in the core regions (surrounding the sample climatic division) tend to develop in place, rather than move into the region from another drought core. However, both the cold-season NCSD-based drought patterns and the warm-season LRPT-based patterns show more severe average drought conditions in the central intermountain region during month one, an indication that droughts in the Great Plains are sometimes preceded by drought conditions farther west.

Further analyses are needed to establish whether synoptic conditions associated with severe droughts in the Great Plains consistently recur. The focus of this study was on the spatial patterns of developing droughts through the initial six months. Since drought conditions in the Great Plains often persist through several years (the longest drought identified for this study lasted for 99 months), the analyses of mapped patterns as a function of possible controlling synoptic conditions are only a small part of a much larger, more complex picture. Detailed examination of synoptic conditions during all cold- and warm-seasons when drought conditions are recorded may reveal some consistency in the controlling synoptic conditions through time. Given the economic ramifications of severe, protracted droughts, persons involved in drought contingency planning and the management of on-going droughts (planners, policy makers, and water management personnel) will continue to benefit from analyses that provide details about the drought characteristics of the regions they serve. If consistent spatial and synoptic precursors can be identified for Great Plains droughts, it may be possible to improve drought forecasting. With improved forecasts, decision-makers would be better prepared to plan for and manage water shortages that will accompany future drought events.

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