Mausam, (1992), **43**, 1, 43-50

551.577.38(73)

Concurrent and lagged relationships among various drought indices in the United States

PETER T. SOULE

Dept. of Geography, Univ. of Alabama,

Tuscaloosa, Alabama 35487-0322 *U.S.A.*

(*Received 14 November 1990*)

सार — इस अध्ययन का उद्देश्य अनावृष्टि तीव्रता के लिए विशिष्ट प्रकार के विभिन्न उपायों के मध्य संगामी तथा पश्चता संबंधों की प्रकृति की जांच करना है। संयुक्त राज्य अमेरिका में 1931 – 1985 की अवधि के लिए औसत तापमान, कुल वर्षण, पामर आर्द्रता असंगति सूचक, पामर अनावृष्टि तीव्रता सूचक, पामर जल अनावृष्टि तीव्रता सूचक का परीक्षण जलवायवी खण्डों के नमूने से किया गया। साधारण सह संबंधों के प्रयोग द्वारा दो स्तरों पर संबंधों की जांच की गई है। स्तर एक में संपूर्ण अध्ययन अवधि से आंकड़ों का उपयोग किया गया है। स्तर दो में सूखे की चुनी हुई घटनाओं से आंकड़ों का प्रयोग किया गया है ।

परिणाम यह बताता है कि प्रबल संबंध, अनावृष्टि सूचकों के साथ अनुक्रिया की समान दरों से आर्द्रता की आपूर्ति तथा मांग के परिवर्तनों के मध्य हैं। सहसंबंध यह भी दर्शाते हैं कि तीव्र-अनुक्रिया अनावृष्टि सूचकों का पश्चता मूल्य अधिक प्रबलता से संगामी मूल्यों की तुलना में मंद-अनुक्रिया पामर आर्द्रता असंगति सूचक से सहसंबंधित है। सूचकों के सहसंबंधित युग्मों के मध्य अंतः स्थानीय विभिन्नताएं सामान्यतः कम हैं और एक स्तर तथा दो स्तर के विश्लेषणों के लिए नमूनों के अतिरिक्त संगत प्रवृत्तियों का पालन करती हैं। सहसंबंधित सूचकों के कुछ युग्मों के लिए अंतः स्थानीय विभिन्नताएं अधिक हैं, जो यह दर्शाती है कि प्रत्येक अनावृष्टि के अभिलक्षण औसत या सामान्य परिस्थितियों से बहुत अधिक विचलित हो सकते हैं।

ABSTRACT. The purpose of this study is to examine the nature of the concurrent and lagged relationships among various drought type-specific measures of drought severity. Monthly values of average temperature (TEMPZ), total precipitation (PREZ), the Palmer moisture anomaly index (ZINX), the Palmer drought severity index (PDSI), and the Palmer hydrologic drought severity index (PHDI) were examined from a sample of climatic divisions in the United States for the period 1931-1985. The relationships are examined at two levels through the use of simple correlations. Level one utilizes data from the entire study period. Data from selected drought events are employed in level two.

The results show that the strongest relationships are between drought indices with similar rates of response to changes in moisture supply and demand. The correlations also show that lagged values of fast-response drought indices (ZINX, PREZ) are more strongly correlated with the slow-response PHDI than concurrent values. Inter-site differences between correlated pairs of indices are generally small and follow consistent trends across the sample for both level one and level two analyses. Intra-site differences are large for some pairs of correlated indices, indicating that characteristics of individual droughts can deviate substantially from average or normal conditions.

Key words — Drought, Palmer indices, Concurrent relationships, Lagged relationships, Correlation.

1. Introduction

The phenomenon of drought has inspired large and diversified research efforts. Much of the work has involved the use of climatic indices to examine the main components of drought : intensity, duration, length, and spatial coverage. The largest number of drought indices are based upon various manipulations of water balance variables. Since the effects of droughts are felt by water users at different times, response times of the various water balance-based indices range from rapid to slow. Soil moisture deficiencies detrimental to agricultural activities can develop in time spans of a month or less. Thus, agricultural drought severity indices must be tightly coupled with precipitation and surface soil moisture. Conversely, conditions of hydrologic drought typically take months to develop. Hydrologic drought indices must be designed to respond slowly to changes in supply (precipitation) and demand (evapotranspiration) of moisture throughout entire hydrologic systems.

The most popular and widely used drought index based on water balance variables is the Palmer drought severity index (PDSI) (Palmer 1965). The PDSI is considered to be a meteorological drought index in that it measures the moisture abnormality for a place or an area through spells of dry or wet weather. The index incorporates current and antecedent moisture conditions so that a long period of drought or wetness produces large absolute values of the index (negative values relate to dry conditions, positive to wet). Also, the index is standardized so that drought conditions can be compared across dissimilar climatic regimes and through time. Although it has been applied in other countries (*e.g.*, Sakamoto 1978, Bhalme and Mooley 1979), the PDSI has been used most often to study drought at a variety of scales within the United States.

Although the PDSI is the dominant drought index in the United States, other water balance-based indices are frequently used in the study of drought. One index which is commonly used outside the United States is Thornthwaite's Index of Aridity (I_a) (Thornthwaite 1948). Standard departures of the I_a from mean yearly values (Krishnan 1979), median yearly values (Subrahmanyam and Sastri 1969), and median monthly values (Sastri 1984) have all been used to categorize drought intensities for spatial and temporal analyses in India. Another popular index uses the ratio of actual to potential evapotranspiration as a measure of agricultural drought (Sastri *et. al.* 1981, 1982, Mohan *et al.* 1984). This index has been shown to be strongly related with crop yield (Chang *et al.* 1963).

Most descriptions of hydrologic drought severity are based upon direct measures such as departures from normal streamflow, lake levels, or water table levels (Williams 1954, Changnon *et al.* 1982, Carter 1983). However, some water balance-based indices have been used to measure hydrologic drought, with varying degrees of success (*e.g.*, Alley 1985, Shelton 1982, 1984, Soule and Shankman 1990).

The existing knowledge of drought characteristics is largely focused on specific types of drought (*e.g.*, agricultural or hydrologic). The primary objective of this paper is to determine the strength of simultaneous and lagged relationships among various drought type-specific measures of drought severity. Guiding research questions include : (i) what is the statistical relationship among measures of drought severity with different moisture-response times, (ii) do the relationships (among indices) computed exclusively during established drought events vary from relationships computed using all available data (thus including droughts, wet spells, and normal conditions), and (iii) what is the degree of spatial variability in these relationships within the contiguous United States.

2. Data and methods

All data used in this study were obtained from the 1986 version of the National Climatic Data Center's (NCDC) magnetic tape file TD9640 (NCDC 1986). Monthly values of average temperature, total precipitation, the Palmer moisture anomaly index (ZINX), the Palmer drought severity index (PDSI) and the Palmer hydrologic drought Severity index (PHDI) were examined from a sample of climatic divisions in the United States for the period 1931-1985.

The three Palmer indices were chosen because of their wide acceptance by climatologists as representative measures of drought conditions. A complete

TABLE 1

Severity classes for the PHDI and ZINX

Approx. cum freq. (%)	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 –0.09
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 NCDC 1986, p.3

explanation of the indices' calculation procedures is beyond the scope of this paper.

The methods used to calculate the PHDI are largely the same as those for the PDSI. The main difference in the procedures involves the identification of the month in which a drought or wet spell ends. For the PHDI a drought (wet spell) is not considered to have ended until P_e (probability of ending a wet or drought spell) equals 100%, resulting in a more slowly responding index. Complete explanations of the procedures used to calculate the indices are given by Alley (1984), Karl and Knight (1985) and Karl (1986).

The indices are designed so that negative values indicate dry spells or droughts, positive values indicate wet spells, and values near zero represent normal moisture conditions. Descriptions of drought (wet spell) severity assigned to different ranges of the PDSI by Palmer (1965) are well known. Similar descriptions are provided for the ZINX and PHDI (Table 1).

The ZINX measures the departure of the moisture status in an area from normal in a given month. Large deviations in supply (precipitation) or demand (evapotranspiration) of moisture can elicit large responses in index values. Because of this trait, the ZINX is often positive for one or two months during long periods of meteorological or hydrological drought. In terms of drought sub-types, the ZINX is most appropriately used as a measure of agricultural drought intensity (Karl 1986). Sakamoto (1978) found the ZINX to be closely correlated with monthly wheat yields in Australia. Karl (1986) feels that the ZINX is a better measure of agricultural drought than the more commonly used crop moisture index (Palmer 1968).

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

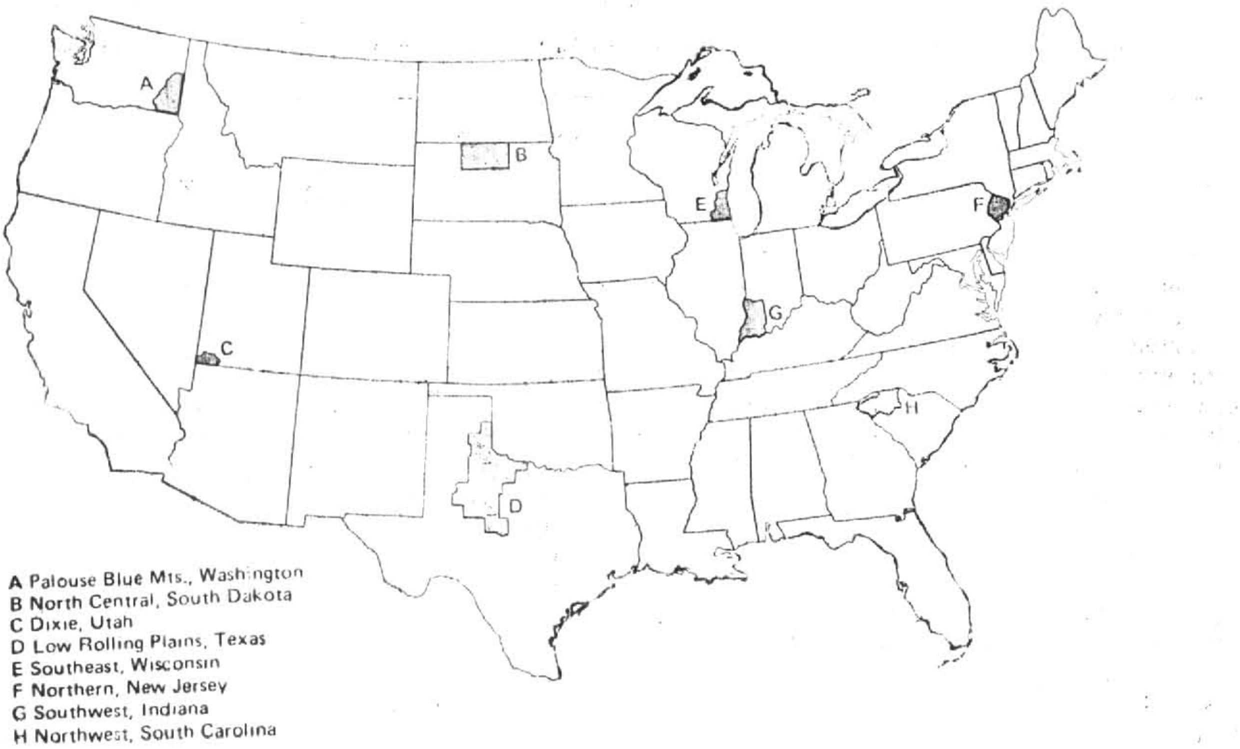

Fig. 1. Locations of the sample climatic divisions

Hydrologic conditions are generally not representative of moisture departures for other uses during the early stages of a drought. The PHDI expresses this by lagging behind both the ZINX and PDSI during the initial months of a drought. Also, to reflect the fact that 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 or above normal levels. In addition to the Palmer indices, standardized scores (z-scores) of monthly precipitation (PREZ) and average temperature (TEMPZ) were calculated using the Standard procedure of the statistical analysis system (SAS) (SAS Institute 1985).

Concurrent and lagged relationships among the four drought sub-types were examined based on the drought histories (as measured by the PREZ, ZINX, PDSI and PHDI) of eight climatic divisions in the contiguous United States (Fig. 1). These divisions represent the core areas of spatially-homogeneous meteorological drought regions (Soulè and Meentemeyer 1989). Although the northern New Jersey, northwest South Carolina, southwest Indiana, and Low Rolling Plains Texas divisions all have climates classified as humid sub-tropical (Köppen Cfa), there is considerable climatic variability among these four locations. Potential natural vegetation ranges from tall-grass prairie in Texas, to broadleaf deciduous forest in Indiana. The northcentral south Dakota and southeast Wisconsin divisions have climates classified as humid continental (Köppen Dfa). Potential natural vegetation in South Dakota in short-grass prairie, while Wisconsin supports a mixture of grasses and oak-hickory forests. The two western divisions are located in mountainous regions and are considerably more arid. The Dixie Utah division has a cold steppe climate (Köppen BSk). Despite the low mean annual rainfall (45 cm), the Palouse Blue Mountain Washington division classifies as a marine west coast climate (Köppen Csb).

For this study a major drought event was defined as any span of six or more consecutive months with any of the Palmer indices $\leqslant -1.0$. Diaz (1983) gives a similar definition in which a string of three or more months with PDSI values $\leqslant -2.0$ is considered a drought event and six or more consecutive months a major drought. Including the fast responding ZINX and slowly responding PHDI in the definition insures that the beginning and ending periods of long drought events are included in the analysis.

To determine the nature of the concurrent relationships among the various drought sub-types, Pearson product moment correlation coefficients were calculated at two levels for all possible combinations of the Palmer indices, precipitation z-scores, and temperature z-scores. First level analyses included all monthly values for the entire study period. Correlation analyses in the second level were performed using sub-sets of the full data set. Thus, each period identified as a major drought event was analyzed separately. To examine the nature of the lagged relationships among the drought sub-types, simple correlations were computed for all possible combinations of the four drought indices, temperature z-scores, and one, two and three month lagged values of the same. All correlations were completed using the CORR procedure of SAS (SAS 1985a).

3. Results and discussion

Concurrent and lagged relationships among the four drought sub-types and temperatures are presented from the two levels of analyses : full data set and major

TABLE 2

Simple correlations among drought severity index values using the full data set at the eight sample climatic divisions

Varriables correlated	Climatic division abbreviation								Mean*	Range**
	SW IND	N NJ	NW SC	SE WISC	NCEN SD	LRP TX	DIXIE UTAH	PBM WASH		
PHDI/PHDILAG1	0.91	0.92	—0.90	0.91	*0.97*	0.94	0.95	0.95	(0.91)	0.07
PHDI/PHDILAG2	0.86	0.82	—0.79	0.85	*0.92*	0.86	0.88	0.87	(0.86)	0.13
PHDI/PDSI	0.89	—0.88	0.89	0.89	*0.97*	0.92	0.90	—0.88	(0.90)	0.07
PHDI/PDSILAG1	0.90	—0.88	—0.88	0.90	*0.94*	0.93	0.91	0.90	(0.91)	0.06
PHDI/PDSILAG2	0.87	0.84	—0.83	0.88	*0.92*	0.90	0.88	0.88	(0.88)	0.09
PHDI/ZINX	0.52	0.51	—0.50	0.53	*0.55*	0.54	0.53	0.55	(0.53)	0.06
PHDI/ZINXLAG1	0.55	0.52	—0.49	0.58	0.58	0.60	0.57	*0.61*	(0.56)	0.12
PHDI/ZINXLAG2	0.52	0.49	—0.46	0.59	0.58	0.59	0.56	*0.62*	(0.55)	0.16
PHDI/ZINXLAG3	0.49	—0.42	—0.42	0.56	0.55	0.56	0.54	*0.60*	(0.52)	0.18
PHDI/PREZ	0.38	*0.43*	0.39	0.33	0.30	0.28	0.27	—0.26	(0.33)	0.17
PHDI/PREZLAG1	0.40	*0.44*	0.39	0.39	—0.32	0.36	—0.32	0.33	(0.37)	0.12
PHDI/PREZLAG2	0.38	*0.43*	0.37	0.40	—0.32	0.37	—0.32	0.35	(0.37)	0.11
PHDI/PREZLAG3	0.37	0.37	0.34	*0.38*	—0.31	0.36	0.33	0.35	(0.35)	0.07
PDSI/PDSILAG1	0.97	0.87	—0.85	0.90	*0.95*	0.92	0.91	0.91	(0.90)	0.10
PDSI/PDSILAG2	0.80	0.75	—0.73	0.79	*0.89*	0.83	0.82	0.81	(0.80)	0.16
PDSI/ZINX	0.65	0.64	0.63	0.67	0.62	0.66	0.66	*0.69*	(0.65)	0.07
PDSI/ZINXLAG1	0.55	0.53	0.49	0.62	0.59	0.61	0.62	*0.65*	(0.58)	0.16
PDSI/ZINXLAG2	0.47	0.44	0.39	0.55	0.56	0.56	0.55	*0.59*	(0.51)	0.20
PDSI/PREZ	0.51	*0.56*	0.53	0.48	—0.38	0.43	0.39	0.41	(0.46)	0.18
PDSI/PREZLAG1	0.43	*0.47*	0.40	0.45	—0.36	0.39	0.38	0.40	(0.41)	0.11
PDSI/PREZLAG2	0.37	*0.40*	—0.32	0.39	0.33	0.38	0.34	0.38	(0.36)	0.08
PDSI/TMPZ	—0.17	—0.08	—0.22	—0.16	—0.28	*—0.40*	—0.28	—0.21	(—0.23)	0.32
PDSI/TMPZLAG1	—0.17	—0.04	—0.21	—0.11	—0.27	*—0.36*	—0.27	—0.20	(—0.20)	0.32
PDSI/TMPZLAG2	—0.13	—0.01	—0.16	—0.08	—0.26	*—0.35*	—0.24	—0.18	(—0.18)	0.34
ZINX/ZINXLAG1	0.25	0.18	—0.09	0.36	0.32	0.33	0.30	*0.41*	(0.28)	0.32
ZINX/PREZ	0.96	0.97	*0.97*	0.92	0.87	0.90	—0.86	0.87	(0.92)	0.11
ZINX/PREZLAG1	0.21	0.17	—0.06	0.28	0.18	0.26	0.21	*0.29*	(0.21)	0.23
ZINX/TMPZ	—0.15	—0.15	—0.26	—0.18	—0.42	*—0.51*	—0.32	—0.28	(—0.28)	0.36
ZINX/TMPZLAG1	—0.07	—0.01	—0.11	—0.02	—0.18	*—0.18*	—0.11	—0.08	(—0.10)	0.17

* Average of the correlation values across the climatic divisions, ** Difference between the strongest and weakest correlation, regardless of sign, Strongest correlation is italicized.

drought events. Simple correlations (r-values) among selected combinations of drought severity indices and temperature z-scores based on the full data set are presented for the eight sample climatic divisions (Table 2).

The average of the r-values across the climatic divisions gives a good indication of the general relationships among the drought sub-types and temperature. The strong correlation between the PHDI and PDSI is not surprising since these two indices will be identical during the mid-portions of long droughts and wet spells. The impact of the moisture conditions in the preceding months on hydrological and meteorological moisture conditions in the current month is illustrated by the strong correlations between current and one and two month lagged values of the PHDI and PDSI.

Lagged values of the faster responding ZINX tend to be more strongly related to the PHDI than concurrent values. In light of the design of the indices, this is an expected result. Well above or below normal hydrological moisture conditions generally only develop with sustained deviations of moisture supply and demand. Several consecutive months with below normal moisture supplies will eventually cause hydrologic conditions to fall below normal. However, PHDI values will generally remain negative, indicating continued hydrological drought, for up to several months after moisture supplies have returned to normal or above normal. The greater lagged correlations confirm that the indices are behaving in the expected fashion.

Although the ZINX and PREZ are highly related to each other (average $r > 0.90$), the PREZ is not utilized in the calculation procedures for either the PHDI or PDSI. The correlations between concurrent and lagged values of the PREZ and the PHDI are thus lower than the equivalent ZINX correlations, but they do follow the same trend in that the lagged relationships are stronger than the concurrent relationships.

The PDSI calculation procedures allow it to respond more quickly to monthly changes in supply and demand for moisture in comparison to the PHDI. As a result, *r*-values for the PDSI/ZINX and PDSI/PREZ correlations are higher than their PHDI counterparts. The concurrent relationships (PDSI/ZINX, PDSI/PREZ) are slightly stronger than the lagged relationships, suggesting that while there is a one to three month "buffer" for hydrological drought conditions (*i.e.* there is generally no immediate response to large deviations from normal moisture supply and demand), meteorological or average drought conditions (indicated by the PDSI) are more closely linked to weather conditions of the current month.

It is generally accepted that some drought events (particularly summer droughts) exhibit the characteristics of a positive feedback system (Namias 1983, Chang and Wallace 1987). Once a drought becomes established the soil moisture will be depleted, reducing evapotranspiration and hence convectional precipitation, which prevents the soil moisture from being recharged. If this is true the ZINX, which is only indirectly influenced by its previous month's value, should be positively correlated with lagged values of itself and the PREZ. Although the one month lagged correlations (ZINX/ZINX and ZINX/PREZ) are positive, two and three month lagged correlations (not shown) were consistently near zero, indicating that monthly moisture anomalies (and thus positive feedbacks) are only persistent in the short term.

On average, during the summer months there is a negative relationship between temperature and precipitation in most of the contiguous United States, although the strength of the relationship is spatially variable (Namias 1983, Chang and Wallace 1987). Measures of continentality match up closely with the strength of this relationship (*i.e.*, temperature is more inversely related with precipitation in the continental interior) (Barry and Chorley 1987). The overall negative correlation between TEMPZ and the PDSI and ZINX, both concurrent and lagged, as well as the spatial variability in the strength of these relationships, conform to these previous findings. In particular, both this study and those of Namias (1983) and Chang & Wallace (1987) found the strongest negative relationships in the southern Great Plains.

As illustrated by the difference between the strongest and weakest correlation, the overall relationships (both concurrent and lagged) between the drought sub-types are largely homogeneous across the United States. While no one climatic division consistently has the strongest or weakest correlations across all the variable pairs, certain trends are evident. The strongest relationships between the PHDI and PDSI (concurrent and lagged) all occur at the northcentral South Dakota climatic division. This is likely a reflection of the tendency for both droughts and wet spells to persist for long periods (six or more months) in the northern Great Plains (Diaz 1983). The majority of weakest correlations among the drought indices occur for the northwest South Carolina climatic division. The sporadic nature of summertime convectional rainfall receipt in this region is the most likely cause of this variability. The northeren New Jersey climatic division has the majority of the strongest correlations between the Palmer indices and PREZ, coupled with the weakest relationships with TEMPZ. This combination of factors supports the Namias (1966) finding that droughts in the middle Atlantic/northeast region are more weakly related to persistent anticyclonic activity than in other areas.

TABLE 3

Minimum, maximum and median values of simple correlations from fourteen major drought events, Low rolling plains, Texas climatic division

Variables correlated	Median	Min	Max
PHDI/PHDILAG1	0.80	0.34	0.95
PHDI/PHDILAG2	0.61	—0.29	0.85
PHDI/PDSI	0.67	0.45	1.00
DI/PDSILAG1	0.79	0.65	0.96
PHDI/PDSILAG2	0.69	0.08	0.89
PHDI/ZINX	0.20	—0.44	0.45
PHDI/ZINXLAG1	0.46	0.28	0.91
PHDI/ZINXLAG2	0.55	—0.02	0.84
PHDI/ZINXLAG3	0.38	—0.06	0.79
PHDI/PREZ	0.08	—0.45	0.35
PHDI/PREZLAG1	0.26	—0.18	0.79
PHDI/PREZLAG2	0.36	—0.15	0.72
PHDI/PREZLAG3	0.32	0.06	0.77
PDSI/PDSILAG1	0.54	0.04	0.82
PDSI/PDSILAG2	0.24	—0.24	0.62
PDSI/ZINX	0.62	0.03	0.89
PDSI/ZINXLAG1	0.42	0.27	0.87
PDSI/ZINXLAG2	0.31	—0.06	0.81
PDSI/PREZ	0.51	0.00	0.77
PDSI/PREZLAG1	0.31	—0.05	0.89
PDSI/PREZLAG2	0.28	—0.08	0.82
PDSI/TEMPZ	—0.33	—0.84	0.18
PDSI/TEMPZLAG1	—0.25	—0.65	0.58
PDSI/TEMPZLAG2	—0.11	—0.71	0.27
ZINX/ZINXLAG1	0.08	—0.23	0.54
ZINX/PREZ	0.94	0.75	0.98
ZINX/PREZLAG1	0.23	—0.28	0.79
ZINX/TEMPZ	—0.57	—0.86	0.09
ZINX/TEMPZLAG1	—0.10	—0.53	0.75

TABLE 4

Median values of simple correlations from all major drought events at the eight sample climatic divisions

Variables correlated	SW IND (11)	N NJ (13)	NW SC (15)	SE WISC (17)	NCEN SD (8)	LRP TX (14)	DIXIE UTAH (18)	PBM WASH (15)	Mean*	Range**
	Climatic division abbreviation									
PHDI/PHDILAG1	0.85	0.78	0.82	*0.86*	−0.73	0.80	0.80	0.83	(0.81)	0.13
PHDI/PHDILAG2	0.66	0.60	0.63	0.67	−0.57	0.61	0.59	*0.70*	(0.63)	0.13
PHDI/PDSI	0.78	0.76	−0.57	0.60	*0.87*	0.67	0.79	0.68	(0.71)	0.30
PHDI/PDSILAG1	0.74	0.72	*0.84*	0.79	0.78	0.79	0.77	−0.66	(0.76)	0.18
PHDI/PDSILAG2	0.66	0.66	0.67	0.68	−0.64	*0.69*	−0.64	*0.69*	(0.67)	0.05
PHDI/ZINX	0.35	0.22	−0.04	0.09	*0.43*	0.20	0.25	0.30	(0.23)	0.39
PHDI/ZINXLAG1	0.49	−0.37	0.39	0.41	0.38	0.46	*0.52*	0.46	(0.43)	0.15
PHDI/ZINXLAG2	0.42	0.43	0.50	0.47	0.45	*0.55*	−0.41	0.41	(0.46)	0.14
PHDI/ZINXLAG3	0.36	−0.35	0.42	*0.58*	0.44	0.38	0.37	0.43	(0.42)	0.23
PHDI/PREZ	0.20	0.10	−0.06	−0.17	*0.27*	0.08	0.14	0.03	(0.07)	0.44
PHDI/PREZLAG1	*0.40*	0.26	0.30	0.29	−0.22	0.26	0.23	0.27	(0.28)	0.18
PHDI/PREZLAG2	0.32	0.33	*0.40*	0.27	0.36	0.36	−0.24	0.26	(0.32)	0.16
PHDI/PREZLAG3	0.28	0.29	0.41	*0.46*	0.36	0.32	−0.17	0.31	(0.32)	0.29
PDSI/PDSILAG1	0.67	0.57	0.55	*0.68*	0.57	0.54	−0.52	0.58	(0.58)	0.16
PDSI/PDSILAG2	*0.46*	0.30	−0.20	0.28	0.20	0.24	0.30	0.40	(0.30)	0.26
PDSI/ZINX	0.54	−0.53	0.60	0.57	0.59	0.62	*0.67*	0.65	(0.60)	0.14
PDSI/ZINXLAG1	0.48	0.42	0.42	*0.54*	−0.35	0.42	0.36	*0.54*	(0.44)	0.19
PDSI/ZINXLAG2	0.35	0.37	0.33	0.37	0.32	−0.31	−0.31	*0.43*	(0.35)	0.12
PDSI/PREZ	0.41	0.47	0.39	−0.34	*0.57*	0.51	0.46	0.46	(0.45)	0.23
PDSI/PREZLAG1	0.36	0.34	0.32	0.43	0.35	0.31	−0.30	*0.44*	(0.36)	0.14
PDSI/PREZLAG2	0.30	0.29	0.24	0.31	0.30	0.28	−0.21	*0.36*	(0.29)	0.15
PDSI/TMPZ	−0.08	−0.11	−0.17	−0.23	−0.09	−0.33	*−0.36*	−0.02	(−0.17)	0.34
PDSI/TMPZLAG1	−0.05	−0.11	−0.20	−0.15	−0.21	*−0.25*	−0.15	−0.07	(−0.15)	0.20
PDSI/TMPZLAG2	0.06	−0.08	−0.14	0.03	0.04	−0.11	*−0.24*	−0.09	(−0.07)	0.30
ZINX/ZINXLAG1	0.02	0.01	0.06	0.12	0.11	0.08	−0.04	*0.19*	(0.07)	0.23
ZINX/PREZ	0.94	*0.97*	0.96	0.91	0.93	0.94	0.86	0.92	(0.93)	0.11
ZINX/PREZLAG1	0.05	−0.02	0.05	0.15	0.21	*0.23*	−0.01	0.19	(0.11)	0.25
ZINX/TMPZ	−0.05	−0.33	−0.37	−0.17	−0.36	*−0.57*	−0.45	−0.36	(−0.33)	0.52
ZINX/TMPZLAG1	0.01	0.01	−0.09	−0.01	0.04	*0.10*	0.05	−0.07	(0.01)	0.19

Values in parenthesis above show the No. of major drought events, 1931-1985. * Average of the median values across the climatic divisions ** Difference between the strongest and weakest correlation, regardless of sign. Strongest correlation is italicized.

Correlations between all possible combinations of concurrent and lagged index values were examined from each major drought event at the eight sample climatic divisions. Both concurrent and lagged relationships among the index pairs can be highly variable from one major drought event to the next. To illustrate this, the minimum, maximum and median correlations between selected pairs of indices from the fourteen major drought events at the Low Rolling Plains, Texas climatic division are presented (Table 3). Comparing the median r-values from this analysis to their counterparts on the full data set analysis (Table 2) shows that the general trends among the indices are the same, even though only time periods with below normal moisture conditions are now being examined. However, it is clear that the relationships are not always stable from one drought event to another. Namias(1983) has shown that the causes of drought can vary greatly, both spatially and temporally, within the contiguous United States. It is highly probable that the extreme cases of variability in drought sub-type relationships (from one event to the next) result because these drought events are caused by vastly different sets of synoptic controls.

The median values from the correlation analysis of major droughts for each climatic division are presented to provide an overall impression of the concurrent and lagged relationships among the indices during major drought events (Table 4). Although average correlations across the eight divisions are consistently weaker than their counterparts for the full data set analysis (Table 2), the relationship between the averages is strongly linear (r=0.94), an indication that the indices behave similarly during droughts, wet spells and spells of normal weather.

The results reveal both inter and intra-site variability in the temporal relationships among the drought sub-types, as expressed through the drought severity and temperature indices. The high degree of intra-site variability supports the notion that each drought event is related to a unique mix of synoptic conditions. However, over the climatic record the general synoptic conditions causing one drought in a given area are likely to recur several times, and this recurrence will be reflected in the general relationships among drought sub-types, temperature and precipitation.

4. Conclusions

This study focused on the statistical relationships among four main drought types (as measured by the Palmer drought indices and precipitation z-scores), the relationship between drought severity and temperature, and the spatial variability of these relationships in the United States. The primary findings are : (1) the strongest relationships (all positive) are consistently between drought indices with similar rates of response to changes in supply for moisture (*e.g.*, PHDI/PDSI), (2) there are stronger relationships between lagged values of the fast-response indices (ZINX, PREZ) and the PHDI than concurrent values, (3) on average there is a negative relationship between temperature and precipitation (measured through ZINX); however the magnitude of this relationship varies spatially, (4) intersite differences between correlated pairs of indices are generally small and follow consistent trends across the sample for both the full data set and major drought event analyses, and (5) intra-site differences (as measured by the range between minimum and maximum r-values for all major drought events) were large for some index pairs, indicating that the characteristics of individual drought events can deviate substantially from average or normal conditions.

References

Alley, W.M., 1984, "The Palmer Drought Severity Index : Limited tions and Assumptions", *J. Clim. Appl. Met.*, **23,** 1100-1109.

Alley, W.M., 1985, "The Palmer Drought Severity Index as a measure of Hydrologic Drought", *Water Res. Bull.*, **21,** 104-114.

Barry, R.G. and Chorley, R.J., 1987, *Atmosphere, Weather and Climate,* London : Methuen & Co. Ltd.

Bhalme, H.N. and Mooley, D.A., 1979, "On the Performance of a Modified Palmer Index", *Arch. Met. Geoph. Blocl.*, Ser. **B, 27,** 281-295.

Carter, R.F., 1983, "Effects of the Drought of 1930-1981 on Stream flow and on Ground-Water Levels in Georgia", Doraville : Georgia Department of Natural Resources.

Chang, F.C. and Wallace, J., 1987 ,"Meteorological Conditions During Heat Waves and Droughts in the United States Great Plains", *Mon. Weath. Rev.*, **115,** 1253-1269.

Chang, J., Campbell, R. and Robinson, F., 1963, "On the Relation-ship Between Water and Sugar Cane Yield in Hawaii *Agron. J.*, **55.** 450-453.

Changnon, S.A., Achtemeir, G.L., Hilberg, S.D., Knapp, H.V. Olson, R.D., Roberts, W.J. and Vinzani, P., 1982, "The 1980-1981 Drought in Illinois : Causes, Dimensions and Impacts", Champaign : Illinois State Water Survey.

Diaz, H.F., 1983, "Some Aspects of Major Dry and Wet Periods in the Contiguous United States, 1895-1981", *J. Clim. Appl. Met.*, **22,** 3-16.

Karl, T.R., 1986, "The Sensitivity of the Palmer Drought Severity Index and Palmer's Z-index to their Calibration Coefficients Including Potential Evapotranspiration", *J. Clim. Appl. Met.*, **25,** 77-86.

Karl, T.R. and Knight, R.W., 1985, *Atlas of Monthly Palme Hydrologic Drought Indices,* 1931-1983, *for the Contiguous United States,* Asheville : National Climatic Data Center.

Krishnan, A., 1979, "Key Paper on Definition of Droughts and Factors Relevant to Specification of Agricultural and Hydrologic Droughts", In : *Hydrological Aspects of Droughts* : International Symp. Proc. New Delhi : The Indian Institute of Technology, 67-102.

Mohan, H.S.R., Stanislaus, M.J., and Valsala, P., 1984, "An agroclimatic approach to the assessment of tropical droughts", *Mausam,* **35,** 291-294.

Namias, J., 1966, "Nature and Possible Causes of the Northeastern United States Drought During 1962-1965, *Mon. Weath. Rev.*, **94,**, 543-554.

Namias, J., 1983, "Some Causes of United States Drought" *J. Clim. Appl. Met.*, **22,** 30-39.

National Climatic Data Center, 1986, Time Bias Corrected Divisional Temp-Precip-Drought Index : TD 9640 Tape Documentation. Asheville, N.C. : National Climatic Data Center.

Palmer, W.C., 1965, "Meteorological Drought", Res. Pap. No. 45, U.S. Weath. Bur.

Palmer, W.C., 1968, "Keeping Track of Crop Moisture Conditions, Nationwide: The New Crop Moisture Index", *Weatherwise,* **21,** 156-161.

Sakamoto, C.M., 1978, "The Z-index as a Variable for Crop Yield Estimation", *Agric. Met.*, **19,** 305-313.

SAS Institute, 1985, *SAS User's Guide : Basics*, Version 5 Edition. Cary, N.C. : SAS Institute, Inc., 1290 pp.

SAS Institute, 1985 a, *SAS User's Guide. Statistics*, Version 5 Edition. SAS Institute, Inc.

Sastri, A.S.R.A.S., Krishna, Y.S.R. and Rao, B.V.R., 1981, "A New Method for Classification of Agricultural Droughts", *Arch. Met. Geoph. Boicl.* Ser. B, **29**, 293-297.

Sastri, A.S.R.A.S., Rao, B.V.R., Krishna, Y.S.R. and Rao, G.G.S.N., 1982, "Agricultural Droughts and Crop Production in the Indian Arid Zone", *Arch. Met. Geoph. Biocl.*, Ser. **B**, **31**, 405-411.

Sastri, C.V.S., 1984, "The Drought Year of 1979—A critical appraisal with reference to the semi-arid region of Delhi", *Mausam*, **35**, 273-276.

Shelton, M.L., 1982, "Spatial Characteristics of Severe Drought in the Sacramento River Basin", In : *International Symp. on Hydromet.* Ivan Johnson and Robert Clark, Eds. Bethesda: American Water Resources Association, pp. 355-360.

Shelton, M.L., 1984, Hydroclimatic Analysis of Severe Drought in the Sacramento River Basin, California, *Phys. Geo.*, **5**, 262-286.

Soulé, P.T. and Meentemeyer, V., 1989, The Drought of 1988, Historical Rank and Recurrence Interval, *Southeast. Geo.*, **29**, 17-25.

Soulé, P.T. and Shankman, D., 1990, "The Relationships of Palmer's Drought Indices to River Stage inWestern Tennessee", *Phys. Geo.*, **11**, 206-219.

Steila, D., 1972 : Drought in Arizona. Tucson : University of Arizona, Division of Economic and Business Research.

Subrahmanyam, V.P. and Sastri, C.V.S., 1969, "Some Aspects of Drought Climatology of the Dry Subhumid Zones of South India", *J. Met. Soc. Japan*, **47**, 239-244.

Thornthwaite, C.W., 1948, "An Approach Toward a Rational Classification of Climate", *Geo., Rev.*, **38**, 55-94.

Williams, D., 1954, "Water Table Level as an Indicator of Drought Conditions", *Forestry chron.*, **30**, 411-416.