Drought in the Upper Midwest, 1931–1969

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ABSTRACT

Monthly Palmer Drought Index values for the periods 1931–40, 1941–50, 1951–60 and 1961–69 were subjected to eigenvector analysis. Patterns and periods of variable moisture conditions resulted which fit well the patterns found in drought studies of areas east and west of the upper Midwest. The 1930's and 1950's included years of severe drought but the patterns of drought were not identical. The 1930's drought spread from the west; the 1950's drought spread from the south and southwest. The 1940's and 1960's were wetter than normal in the upper Midwest.

1. Introduction

Droughts periodically affect large portions of the United States. Most studies of droughts have dealt with the most severely affected regions. Droughts in major agricultural areas such as the Great Plains' droughts in the 1930's and 1950's and droughts in highly populated regions such as the drought in the Northeast in the 1960's have been well publicized. The upper Midwest was affected by droughts during the period 1931–69, although these droughts have received less attention. The purpose of this paper is twofold: 1) to describe and examine spatial and temporal drought patterns in the upper Midwest for the period 1931–69 and 2) to determine the manner and degree to which this area was affected by continental scale droughts.

Eigenvector analysis[1] was applied to 39 years of monthly drought data for the upper Midwest to produce patterns of moisture variability and to determine time periods when the various patterns occurred. The results are compared to patterns and periods for the Great Plains and the Northeast which were derived in previous drought studies (Borchert, 1950, 1971; Namias, 1955, 1966, 1967; Skaggs, 1975).

2. Data

Drought has been defined subjectively by describing its effects on residents of afflicted areas or by analyzing changes in the economy of such regions. Comparative regional analyses of such subjective measures would be difficult and could lead to uninterpretable results. Precipitation data and departures from normal are unacceptable measures of drought because a departure of 10–20 mm in a humid area is not as serious a problem as an equal departure from normal in a semi-arid area. Even if this regional aspect is incorporated into a statistic, the land use of an area must also be considered because a crop such as corn needs more moisture than grassland does, for example. In this analysis, Palmer Drought Index (PDI) values (Palmer, 1965) are used to describe drought; this is the system currently used to classify and measure drought severity by the Environmental Data Service and the National Weather Service. Man-made drought, a demand created by economic development for more water than is normally available in an area, is not considered in these index values. Positive values indicate that the amount of precipitation during a particular month was more than necessary for normal conditions and negative values signify drier than normal conditions.

The data for this analysis are monthly PDI values for climatological divisions (relatively homogeneous climatic areas of states) in the upper Midwest. The upper Midwest is defined as North Dakota, South Dakota, northern Nebraska, Minnesota, Iowa, the northern peninsula of Michigan, Wisconsin and northern Illinois, and contains 53 climatological divisions. The data were partitioned into the four groups: 1931–40, 1941–50, 1951–60 and 1961–69, to facilitate comparisons of drought in the upper Midwest to droughts in the Great Plains and the Northeast.

An analysis of variance was conducted to determine whether the partitioning of the data produced samples

[1] This method has been used to determine precipitation patterns in Nevada (Stidd, 1967); patterns of sea level pressure, temperature and precipitation over North America (Kutzbach, 1967); anomalous precipitation patterns for the western United States (Sellers, 1968); patterns of circulation variability over the Northern Hemisphere (Kutzbach, 1970); and patterns and periods of drought for the United States for 1931–40 (Skaggs, 1975).

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TABLE 1. Analysis of variance.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F ratio
Between groups	6580.978	3	2193.659	
Within groups	21616.802	4208	5.139	427.025*
Total	28197.780	4211		

* Significant at the $\alpha=0.01$ level.

from the same or different populations. The state of Minnesota was chosen as a sample area for this analysis because of its location and its extent both in the east–west and north–south directions. The F statistic was significant at the $\alpha=0.01$ level (Table 1). The Scheffé test (Kerlinger and Pedhazur, 1973) was then used to determine which decades were different from one another (Table 2). The four means were arranged in order from largest to smallest and differences (D) were taken between adjoining means, i.e.,

$$D=C_i\bar{X}_i+C_j\bar{X}_j,$$

where $C_i=1$ and $C_j=-1$. The absolute values of these differences were compared to the statistic S which is computed from

$$S=[(p-1)F_\alpha(p-1,N-p)]^{\frac{1}{2}}[\text{MSR}\,\Sigma\,(C_j)^2/n_j]^{\frac{1}{2}},$$

where p is the number of categories, $F_\alpha(p-1,N-p)$ the tabled value of F with $p-1$ and $N-p$ degrees of freedom at a prescribed α level, N the number of individuals, MSR the mean square error from the analysis of variance, C_j the coefficient by which the mean of category j is multiplied, and n_j the number of individuals in category j. Only if $|D|>S$ are the two means being tested different at the α significance level.

The difference between the means of the periods 1941–50 and 1961–69 was not significant at the $\alpha=0.01$ level. It is, however, significant at the $\alpha=0.109$ level. The other two differences are significant at the $\alpha=0.01$ level. Even though the means for 1941–50 and 1961–69 are similar, the two periods are analyzed separately to determine if the same patterns of drought and wet conditions would result from both data sets.

TABLE 2. Comparisons using Scheffé method.

Ordered means	Calculated differences $\|D\|$
1941–50; $\bar{X}_2=1.4822$	
1961–69; $\bar{X}_4=1.2355$	$\|\bar{X}_2-\bar{X}_4\|=0.2467$
1951–60; $\bar{X}_3=0.5083$	$\|\bar{X}_4-\bar{X}_3\|=0.7272$*
1931–40; $\bar{X}_1=-1.6704$	$\|\bar{X}_3-\bar{X}_1\|=2.1787$*

* Significant at the $\alpha=0.01$ level.

TABLE 3. Variance explained (%).

Years	Eigenvector 1	Eigenvector 2	Eigenvector 3	Total
1931–40	57.4	16.2	6.0	79.6
1941–50	50.6	10.9	9.1	70.6
1951–60	41.0	15.6	13.0	69.6
1961–69	45.1	15.8	10.5	71.4

3. Results

The data matrices (120×53 for the first three decades and 108×53 for 1961–69) contain monthly PDI values for each of the 53 climatological divisions. Eigenvectors for each of the four periods are computed from a 53×53 matrix of sums of squares and cross products. The first eigenvector has the highest resemblance to all the observation vectors simultaneously, the second eigenvector has the second highest resemblance to all the observation vectors simultaneously, and so on. In most cases a large portion of the variance in the data can be accounted for by retaining only the first few eigenvectors. In each of the four time periods identified here, the first three eigenvectors accounted for approximately 70% of the variance (Table 3). In each case, eigenvectors 4–53 accounted for a relatively small amount of the remaining variance (<5%) and were therefore not interpreted.

Each element in an eigenvector corresponds to a particular climatic division. When plotted on maps, values of the three eigenvectors for each time period show patterns of moisture conditions. Entries with large absolute values (>0.25) indicate a more severe anomaly in an area than entries with small absolute values (<0.05 is considered as near normal).

Each eigenvector also has an associated vector of coefficients which can be plotted as a time series. The values of the coefficients indicate how closely the associated pattern fits the actual moisture conditions for a particular month. High positive values indicate that the associated pattern explains the moisture conditions well, high negative values indicate that almost the inverse pattern explains well, and values near zero indicate that the associated pattern explains little for the particular time period. In this particular analysis, coefficients with absolute values greater than 10 are considered indicative of anomalous moisture conditions. Coefficients of ±10 lie about one standard deviation from the mean with approximately 25% of the coefficients lying outside this range.

a. 1931–40

The 1930's were predominantly dry in the upper Midwest. The elements of the first eigenvector are all negative, indicating that the pattern (Fig. 1b) was predominantly one of drought. The large coefficients, which are all positive (Fig. 1a), indicate that

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the pattern fits the actual moisture data well at four distinct times: 1) mid-1931, 2) mid-1933 through mid-1935, 3) mid-1936 through mid-1938, and 4) mid-1939 through late 1940. The values of the coefficients are greatest during the second period, indicating the pattern of eigenvector 1 explains the actual moisture conditions better during that time than during any of the other time periods. The drought was worst in the western portion of the study area; in fact, the values of the eigenvector for most of the region west of a line through western Minnesota and Iowa are below −0.15. The largest negative entry of this eigenvector is associated with the Black Hills region of South Dakota. Keeping in mind that the PDI values are dependent upon departures from normal precipitation amounts, we cannot conclude that this region was the driest in an absolute sense, but only that it exhibited the greatest departure from the norm. Southeastern Wisconsin has values near −0.05 during these same periods indicating that area was near normal.

The pattern of the second eigenvector also has a west-to-east gradient (Fig. 1c). Coefficients having large absolute values are associated with five time periods: 1) mid-1931, 2) mid-1934, 3) late 1934 through early 1935, 4) mid-1938 through early 1939, and 5) early 1940 (Fig. 1a). In the first two periods the coefficients are near +10 indicating that during mid-1931 and mid-1934 the intense drought spread into the eastern half of the upper Midwest states, while it remained dry in the western half. The rapid change to negative coefficients in late 1934 through early 1935 implies that the extremely dry conditions retreated rapidly from the eastern half of the region, while drought remained intense in the western half. In mid-1938 dry conditions reintensified after a brief respite, first in the western half (negative second eigenvector coefficients along with rising positive first eigenvector coefficients) and then in the east for a short time in early 1940 (positive second eigenvector coefficients). This late resurgence of the 1930's drought continued through late 1940.

Eigenvector 3 is of minor importance for the broad-scale pattern of drought. Western Minnesota and eastern South Dakota apparently experienced minor dry conditions in late 1931 through 1932, before the onset of the main 1930's drought (Figs. 1a and 1d).

The most important 1930's moisture anomalies in the upper Midwest are shown in the maps of the first three eigenvectors and in the associated coefficients. There was a serious drought in the western portion of the study area for a portion of 1931 (eigenvector 1, Figs. 1a and 1b); in late 1931 and 1932 this drought spread into Minnesota (eigenvector 3, Figs. 1a and 1d). From mid-1933 through the end of 1934 and from mid-1936 through mid-1940 the drought was worst in the west (eigenvectors 1 and 2, Figs. 1a.

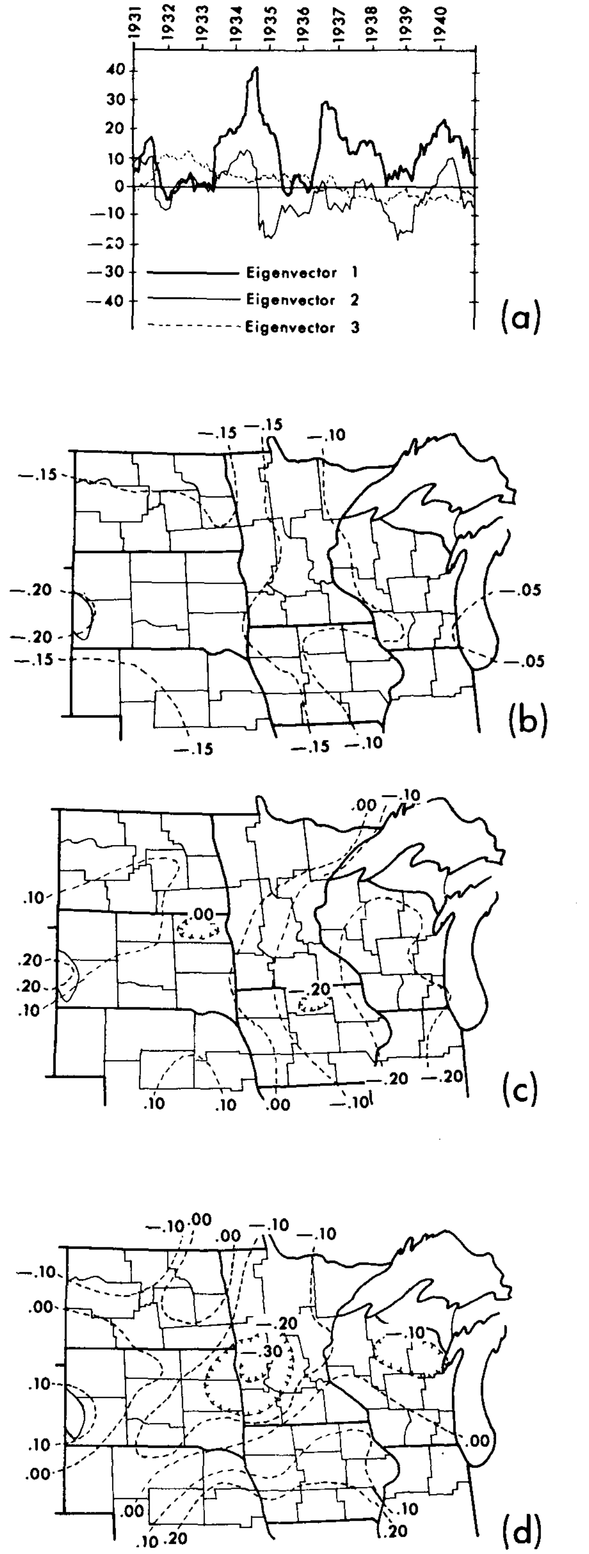

Fig. 1. (a) Coefficients of eigenvectors 1, 2 and 3 for the period 1931–40, (b) map of eigenvector 1 for the period 1931–40, (c) map of eigenvector 2 for the period 1931–40, (d) map of eigenvector 3 for the period 1931–40.

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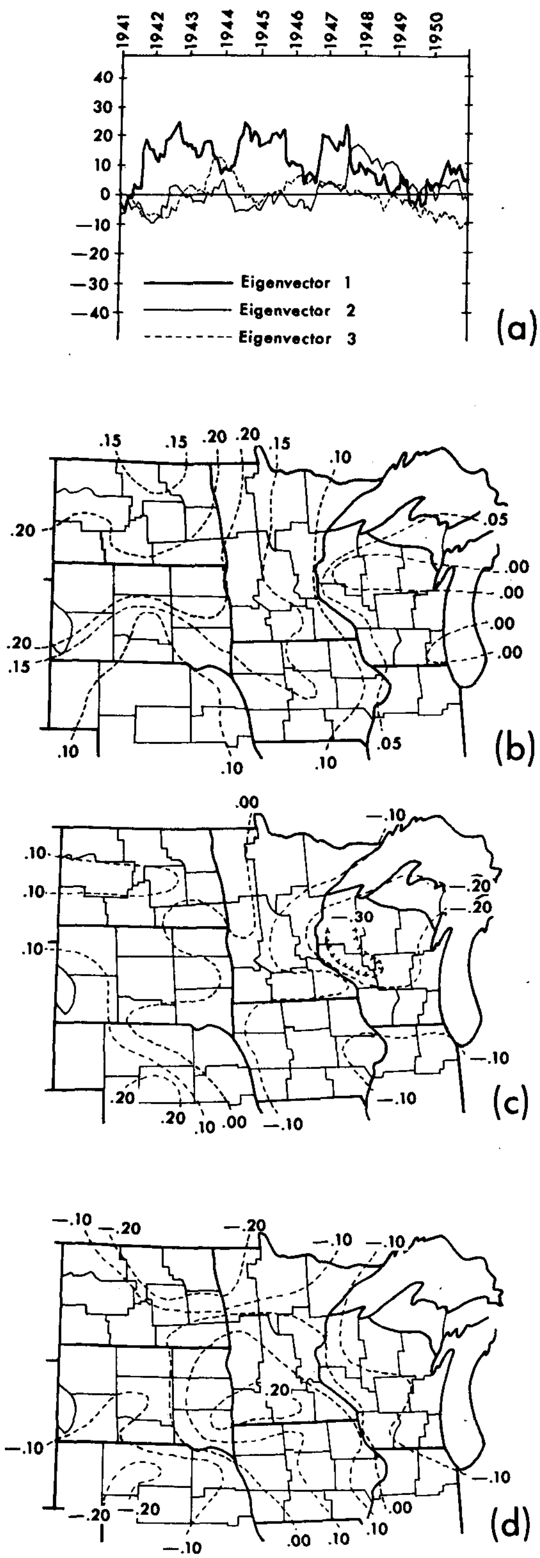

FIG. 2. As in Fig. 1 except for the period 1941–50.

1b and 1c). Almost the entire United States was dry during the drought periods associated with eigenvector 1. A west-to-east moisture gradient existed across the United States, an exception being an area from west-central Illinois to central Ohio; there the drought was as severe as the drought in the eastern Great Plains (Skaggs, 1975). These descriptions agree with Borchert's (1950, 1971) conclusions: the most extreme drought occurred in the years 1933, 1934 and 1936 and was centered in the west, affecting virtually the entire Great Plains and extending eastward across Illinois, Indiana, and into Ohio.

b. 1941–50

The 1940's were wetter than the preceding ten years in the upper Midwest and throughout most of the United States. The dominant pattern was one of above normal moisture over the entire upper Midwest; it was relatively wetter in the west than in the east (eigenvector 1, Fig. 2b). This pattern has four periods of importance: 1) late 1941 through late 1943, 2) mid-1944 through late 1945, 3) late 1946 through mid-1947 and 4) mid-1950 (Fig. 2a).

The second eigenvector for the 1940's is important only during one period, mid-1947 through late 1948 (Fig. 2a). The pattern shows a general west-to-east gradient; the west was wet and the east dry. The wet region was centered in southwestern Nebraska and the dry region in west-central Wisconsin (Fig. 2c).

The large coefficients of eigenvector 3 are associated with the periods late 1943 through early 1944 and late 1950 (Fig. 2a). The pattern is intricate, but generally the northern, western and eastern portions of the area were dry; the central area was wetter than normal during the first period and the inverse of this pattern occurred in late 1950. Southwestern Minnesota was the center of the wet area; dry conditions were most severe in north-central Nebraska and north-central and northeast North Dakota in late 1943 through early 1944 (Fig. 2d).

When the three eigenvectors are combined the overall pattern for the decade emerges. Late 1941 through late 1943 was generally wetter than normal in the west to near normal in the east (eigenvector 1, Figs. 2a and 2b). The west and east were drier than normal and the central area was wet during the period from late 1943 through early 1944 (eigenvector 3, Figs. 2a and 2d). The west was wet and the east near normal to dry from mid-1944 through late 1945, from late 1946 through mid-1948, and again in the second half of 1950 (eigenvectors 1, 2 and 3, Figs. 2a–2d). On the whole, this decade was much wetter than the previous one and in an absolute sense in the western and central thirds of the area, but in the eastern third (Wisconsin and northern Michigan) normal to slightly below normal moisture conditions must have prevailed.

c. 1951–60

Another serious drought occurred in the mid 1950's. A comparison of the 1930's and the 1950's shows

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major differences in the drought patterns. The values of the first eigenvector of the 1950's are negative as in the 1930's, but while the 1930's pattern indicated a west-to-east gradient (west dry, east wet), in the 1950's there was a south-to-north gradient (Fig. 3b). There are four periods when this pattern describes the moisture conditions well: 1) early 1951 through mid-1952, 2) early 1953, 3) mid-1955 through mid-1957 and 4) mid-1960 (Fig. 3a). From early 1951 through mid-1952 and in early 1953 the south was wet and there was a drying trend toward the north. The mid-1950's were dry, but the drought was centered to the southwest of the study area rather than in the west and in the study area as had been the case in the 1930's. In fact, the 1950's drought was a relatively minor episode in much of the upper Midwest. The area was peripheral to the center of drought and the major drought pattern was much less persistent, lasting from mid-1955 through mid-1957. Furthermore, the coefficients on this pattern have a much smaller magnitude than the coefficients associated with the 1930's pattern which also indicates a relatively less severe drought episode. There were local areas of decade-average dry conditions as well as local areas of decade-average moist conditions. These patterns must be deduced, however, from the second and third eigenvectors.

The second eigenvector is important during two short periods: 1) the second half of 1952 and 2) mid-1957 through early 1958 (Fig. 3a). During 1952 the pattern shows moist conditions in the south-central area and dry conditions predominantly in the northwest; the reverse of this pattern occurred from mid-1957 through early 1958 (Fig. 3c). The second eigenvector for the 1930's had a west-to-east (dry west, wet east) trend, the second eigenvector for the 1950's trends south-central to northwest (dry to wet) during the late 1950's. In the 1930's, drought dominated much of the decade; the 1950's drought lasted for a comparatively short period and was preceded and followed by wet spells.

The third eigenvector shows a south-to-north gradient (south dry, central and north wet, and extreme north-central dry) (Fig. 3d). Southeastern South Dakota and west-central Wisconsin were the wettest areas, southern Iowa was the driest. The coefficients indicate that the third eigenvector is only important during mid-1953 and early 1954 (Fig. 3a).

The drought of the 1950's spread from a different direction and was not as severe as that of the 1930's. The early 1951 through mid-1952 period was wetter than normal with moist conditions centered in the south (eigenvector 1, Figs. 3a and 3b), and by mid-1953 this area of wet conditions had moved northward (eigenvector 3, Figs. 3a and 3d). The wetter than normal conditions in the upper Midwest during 1952–54, compared to dry conditions over most of the United States, were also observed by Namias

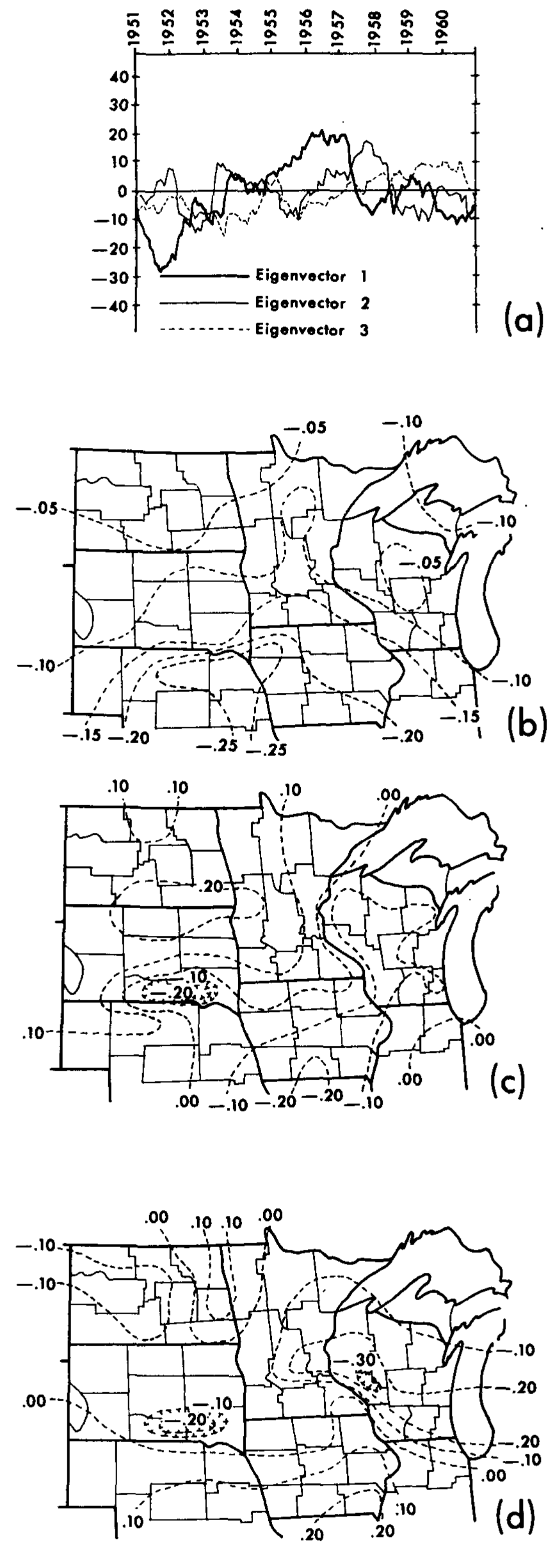

Fig. 3. As in Fig. 1 except for the period 1951–60.

(1955). The drought of mid-1955 through early 1958 was centered in the south and was less severe to the north (eigenvectors 1 and 2, Figs. 3a–3c).

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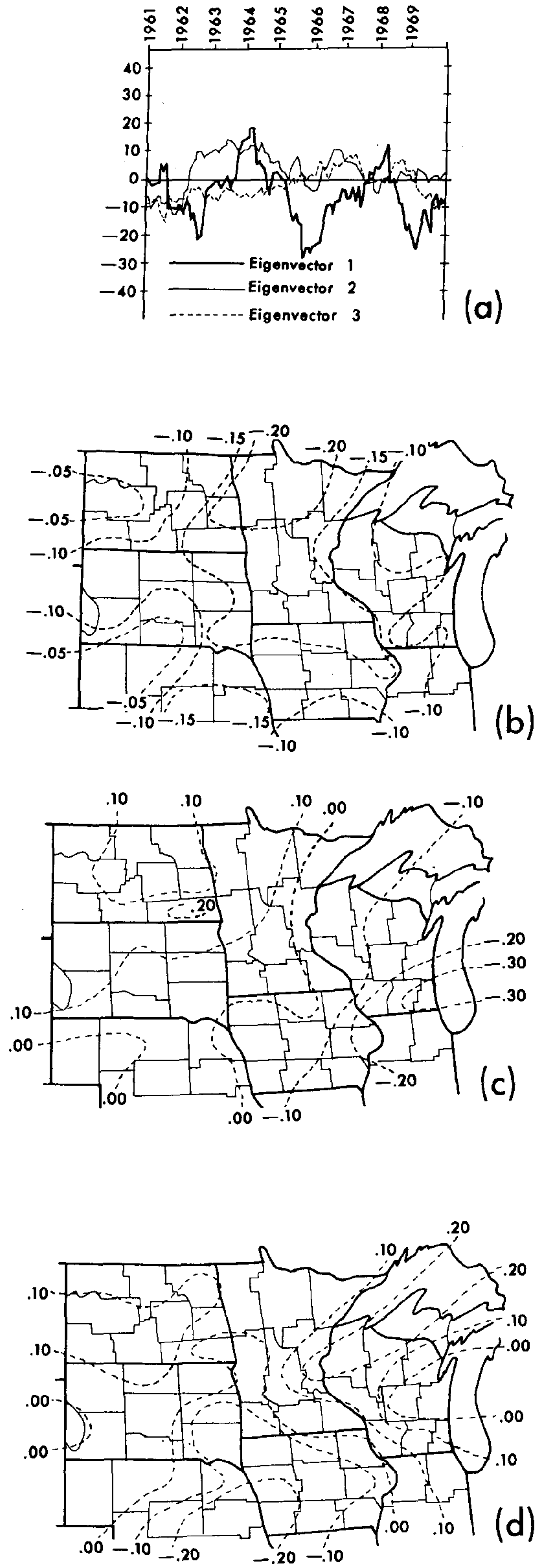

FIG. 4. As in Fig. 1 except for the period 1961–69.

d. 1961–69

This period was wetter than normal for the upper Midwest. The values of the first eigenvector are negative over the entire area, the north-central having the highest negative values with a gradual decrease in all directions (Fig. 4b). The coefficients indicate six short periods during which this eigenvector is important: 1) late 1961, 2) mid-1962, 3) mid-1963 through mid-1964, 4) mid-1965 through early 1966, 5) early 1968, and 6) late 1968 through mid-1969 (Fig. 4a). Of the six periods, mid-1963 through mid-1964 and early 1968 were the only dry spells, the other periods were wetter than normal; the north-central section was the center of both the wet and dry conditions.

A "ridge" of negative values extended across northern South Dakota and southern North Dakota to the Black Hills. Much smaller first eigenvector values occurred in northwest North Dakota and in northern Nebraska into south-central South Dakota on either side of this ridge. The result is relatively dry conditions in the northwest and southwest portions of the region with above normal moisture conditions between.

The second eigenvector is important from early 1963 through mid-1964 and in late 1966 (Fig. 4a). The pattern shows dry east and wet west with the driest conditions in the southern tier of divisions in Wisconsin (Fig. 4c). Since the coefficients on the second eigenvector were mostly negative through the decade, southern and southeastern Wisconsin experienced decade-long drier than normal conditions which can be considered an extension of the Northeast dry conditions.

The third eigenvector tends to enforce wet conditions in eastern Nebraska and to lead to drier conditions from the northern peninsula of Michigan westward through northern Wisconsin and into east-central Minnesota. In the former area the eigenvector is negative and in the latter it is positive, but the significant coefficients in mid-1961 and mid-1969 for the third eigenvector are negative and the pattern is reversed (Figs. 4a and 4d).

The period 1961–69 was generally wetter than normal for the north-central portion of the United States. For a short time during 1961 and again in 1969, the northern portion of the area was dry and the south was wetter than normal (eigenvector 3, Figs. 4a and 4d). From early 1963 through mid-1964 the eastern portion was drier than normal, the remaining area was near or above normal (eigenvector 2, Figs. 4a and 4c). The patterns show that the upper Midwest was influenced both by the wet conditions to the west of this area and by the drought east of this area.

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4. Discussion

The data and interpretation given here provide a detailed picture of wet and dry conditions in the upper Midwest from 1931 through 1969. The results are a mixture of broad-scale (continental) patterns and local variations, some of which are quite large. The continental drought of the 1930's severely affected most of the region; indeed, the western third of the upper Midwest can be considered the heart of the drought region. Recovery in the first half of the 1940's proceeded more slowly than farther south on the Great Plains and farther west. Yet the eastern third (Wisconsin and northern Michigan) was, comparatively, little affected. The 1950's drought was quite intense, but it was short-lived and centered to the south and southwest of the upper Midwest. Only a few parts of the region were seriously impacted for any length of time. Sharp gradients of wetness and dryness occurred which are indicative of the fringe location of the region with respect to the 1950's drought.

The 1940's in the upper Midwest were, as in much of the country, quite moist. Again the eastern third of the area behaved somewhat differently. Wisconsin and northern Michigan were slightly wet to slightly dry rather than wet to very wet on a decade basis as in the western and southwestern portions of the area. The 1960's were more varied with the northwest, southwest, northeast and southeast near normal to dry while the central portion was wet to very wet.

The patterns of moisture status are reasonably clear, but the causes for the patterns are not. This is a difficulty when empirical orthogonal functions are used to clarify the observed data. Causal hypotheses for the broad-scale patterns range from persistent westerly surface flow in a zonal circulation period during the 1930's (Borchert, 1950), to persistent upper level anticyclones in the 1950's (Namias, 1955), to persistent anomalous northwesterly flow in the 1950's (Skaggs and Hokenstrom, 1975), to persistent zonal or meridional flow (Dzerdzeevskii, 1969). Persistence is the common thread in these hypotheses, but the source of persistence is obscure. The explanations range from linkages between circulation and solar cycles to the natural evolution of a stochastic process (e.g., Currey, 1962; Lorenz, 1965; Hasselmann, 1976) to self-perpetuation of a random or man-made perturbation (e.g., Charney *et al.*, 1977). In any case, the explanations are yet to be discovered.

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