DROUGHT IN THE UNITED STATES

Some Aspects of Major Dry and Wet Periods in the Contiguous United States, 1895–1981

HENRY F. DIAZ[1]

National Climatic Center, Asheville, NC 28801

(Manuscript received 30 April 1982, in final form 1 October 1982)

ABSTRACT

Using state monthly values of the Palmer Drought Index from January 1895 through April 1981, the spatial and temporal features of dry and wet episodes over the contiguous United States were analyzed. The variance spectrum of the area under both drought and wet spells in the western United States (17 westernmost states) was also investigated.

The main results are as follows. Consistent with the findings of previous investigators, the interior and western portions of the United States are found to be more drought-prone than other parts of the country. By contrast, the likelihood of drought occurrence in states near coastal areas is considerably less. Prolonged moisture abnormalities also tend to occur over the more drought-prone states indicating a tendency toward bimodality (either "too dry" or "too wet").

The variance spectrum of the area under drought in the western United States exhibits a red-type spectrum, whereas the wet spell area exhibits relatively greater variance at the highest and intermediate frequencies (2 and 3–9 years). In a few regions of the United States, the initiation and termination of drought episodes tend to occur more often at certain times of the year. For most regions, however, this preference is only marginal or non-existent.

1. Introduction

Droughts in North America have been a recurrent event throughout the period of instrumental measurements, and evidence from tree rings indicates that they have occurred for many centuries in the past (Fritts, 1965; Landsberg, 1975; Mitchell *et al.*, 1979).

Although drought appears to be a "normal" part of the climate of North America (Borchert, 1950), its impact on the people who are affected can be devastating. The consequences of drought are felt across a wide spectrum of societal activities—agriculture, water supply, hydropower generation, etc.

Bark (1978) presents a table listing major drought periods from the 13th century to the 1950's deduced from tree rings in Nebraska. Twelve droughts lasting 10 years or more are shown; three lasted 20 years or longer. The longest drought, lasting 38 years, is inferred to have occurred toward the end of the 13th century (by contrast, the "Dust Bowl" drought lasted approximately 10 years). Bark states that "it is staggering to contemplate what effect such a drought would have today." Indeed it is, and because significant changes in global climate are possible during the next century as a consequence of CO_2 warming, the possibility of a drought lasting as long or longer than that of the 1930's should clearly be taken seriously. (For a topical discussion of the economic impact of drought on the American economy, social and political implications, technological options and other topics, see Chapters 3–9 in Rosenberg, 1978.)

Anomalously wet spells can be thought of as the extreme opposite of the drought phenomenon. Prolonged periods of above normal wetness can be just as devastating as their dry counterparts—harvests can be ruined, fields can be flooded, rivers can overflow their banks, etc.

This paper is the third in a series of drought studies supported by the National Climatic Center's Historical Climatology Project (cf. Karl and Quayle, 1981; Karl and Koscielny, 1982). The purpose of this study is two-fold. First, to identify the major wet and dry periods since 1895 in the contiguous United States; and second, to depict their spatial and temporal variation with the aim of determining whether any consistent patterns are discernible in the timing of the onset and disappearance of dry and wet episodes, and of the spatial coherence of these events. The measures of dryness or wetness are explained in the following section.

2. Data description

The basic index of dryness and wetness used in this study is the Palmer Index (PI) (Palmer, 1965) developed during the early 1960's to establish in a more quantitative fashion what was then, and to some ex-

[1] Present affiliation: NOAA, ERL, Boulder, CO 80303.

tent still is, a somewhat qualitative phenomenon (Gibbs, 1975). However, the reader is referred to Landsberg (1975, p. 62) for a list of other measures of drought.

Using state averages of monthly temperature and precipitation (Diaz and Quayle, 1978, 1980), and the formulas developed by Palmer, an index was calculated for each of the 48 contiguous United States. Palmer called it the drought severity index, but it is shortened here to PI because it applies to both moisture surpluses as well as deficits. Thus, it reflects the balance between the moisture demand and supply (Karl and Quayle, 1981).

PI values between -2 and $+2$ are considered normal; values of -2 to -3 are indicative of "moderate" drought, -3 to -4 are in the severe category and values below -4 are considered indicative of "extreme" drought conditions. Similarly, positive values reflecting an excess of moisture are used to describe the magnitude of a wet spell. Monthly PI values from January 1895 through April 1981 for each of the 48 contiguous states were used to develop various measures of the temporal and spatial variability of wet and dry spells.

3. Analysis

a. *Spatial and temporal characteristics*

Initially, the state series of PI were used to identify the major dry and wet periods. The procedure used was as follows. A drought sequence was taken to be the occurrence of three or more consecutive months with a PI value $\leqslant -2.0$. The end of a drought sequence was taken as the last month in the run where the PI retained a value $\leqslant -2.0$. A wet spell was similarly defined, except that it refers to a value of the PI $\geqslant +2.0$. The occurrence of six or more consecutive months of dryness or wetness (as defined above) constituted a "major" dry or wet episode. The length of time chosen is arbitrary. However, because it encompasses the passage of at least two seasons, it was thought to represent the occurrence of a fairly long-lasting phenomena.

A representative sample of a state-by-state summary of these "major" events is given in Table 1. A somewhat different criterion was used in producing Fig. 1. In the figure, the occurrence of at least two consecutive months with a PI $\leqslant -3.0$ (moderate or worse drought) was taken as a drought event and all such periods were tabulated for each state (see Warrick, 1980). A comparison of Fig. 1 and Table 1 shows that both criteria are regionally indicative of the same major dry episodes. In Fig. 1, the states were grouped by "homogeneous" regions according to the results of Karl and Koscielny (1982). However, results for the traditional nine regions plus a national index (see Diaz and Quayle, 1978) are shown at the bottom of Fig. 1 for comparison.

A few observations can be made regarding these figures. First, the drought of the 1930's was both long-lived and widespread. An excellent study of the 1930's drought by Skaggs (1975) showed that there were at least a couple of "waves" of drought occurring during the decade. Second, the areas affected by each subsequent drought episode were not the same in each instance. A later study of drought in the Midwest by Klugman (1978) which included subsequent decades showed similar features. Fig. 2 gives examples of the different spatial arrangements during a portion of two major (1930's and 1950's) and one moderate (1970's) drought episodes in this century.

As noted in the introduction, part of the motivation for this study was a desire to understand the "climatology" of drought and wet spell events during the period of available instrumental records. By climatology of droughts and wet spells is meant the spatial and temporal behavior of some of the major meteorological anomalies (the PI being a measure of more than just precipitation excess or deficit) of the past 86 years.

To determine whether certain portions of the country were more likely to experience one type of phenomenon over the other (dryness *versus* wetness), the duration (months) of droughts and wet spells lasting $\geqslant$6 months and $\geqslant$12 months was tabulated for each state. The ratios of drought duration to wet spell duration for both criteria were calculated and are shown in Fig. 3, according to whether this ratio was $\geqslant$1 ($>$ symbol) or $<$1 ($<$ symbol). Also, the ratio of the longest drought event to the longest wet spell event is included, in terms of whether this ratio was $\geqslant$1($>$) or $<$1($<$).

The following features are evident. For most of the contiguous United States, the longest drought in the past 86 years exceeded in time duration the longest wet spell. Regardless of whether a 6-month or 12-month criterion was used to define a drought episode, drought lasted longer than wet spells over the major portion of the contiguous United States. The southern Gulf Coast states and Michigan were the only areas in which a wet-type regime predominates.

The ratio of the combined total number of months under dry or wet episodes to the total number of months on record (1036) may be taken as an indicator of the degree of recurrence of periods of abnormal moisture conditions (regardless of sign), as well as some measure of the dispersion about the climatological norm. The map shown as Fig. 4 indicates that from the eastern Great Plains ($\sim$95°W), westward to the Pacific coastal ranges, the development of frequent moisture abnormalities both in the positive and negative sides is a relatively common feature of the regional climate. Karl and Koscielny (1982) noted this in their study. They also noted that, as Fig. 4 indicates, the lowest values of this ratio occur near all the coastal zones, implying a lesser degree of variability in these areas.

Arizona

Dry Period	Duration (mo)	Wet Period	Duration (mo)
3/1896 - 8/1896	6	2/1905 - 10/1907	33
9/1898 - 12/1904	76	1/1915 - 11/1917	35
5/1928 - 3/1929	11	7/1919 - 10/1920	16
3/1934 - 10/1934	8	8/1931 - 7/1933	24
5/1943 - 11/1943	7	12/1940 - 12/1941	13
3/1947 - 1/1948	11	12/1965 - 9/1966	10
8/1950 - 7/1951	12	10/1972 - 8/1972	10
9/1953 - 2/1954	6	3/1978 - 6/1980	28
1/1956 - 7/1957	19		
2/1961 - 7/1961	6		
2/1971 - 7/1971	6		
3/1972 - 9/1972	7		
Total	175		169

Arkansas

Dry Period	Duration (mo)	Wet Period	Duration (mo)
7/1896 - 2/1897	8	8/1905 - 3/1906	9
6/1901 - 5/1902	12	8/1906 - 2/1907	8
8/1916 - 2/1917	7	12/1926 - 1/1928	14
2/1918 - 8/1918	7	2/1945 - 5/1946	16
10/1924 - 8/1925	11	1/1950 - 2/1951	14
3/1936 - 9/1936	7	4/1957 - 11/1958	20
7/1943 - 1/1944	7	8/1961 - 2/1962	7
9/1953 - 1/1956	29	11/1972 - 9/1975	35
7/1956 - 12/1956	6	2/1979 - 11/1979	10
2/1963 - 3/1964	14		
Total	108		133

California

Dry Period	Duration (mo)	Wet Period	Duration (mo)
11/1897 - 9/1899	23	3/1906 - 3/1907	13
6/1910 - 12/1910	7	1/1911 - 7/1911	7
12/1917 - 8/1918	9	6/1912 - 1/1913	8
12/1923 - 9/1924	10	12/1913 - 10/1914	11
2/1931 - 9/1931	8	1/1915 - 2/1917	26
3/1934 - 9/1934	7	2/1927 - 7/1927	6
10/1949 - 4/1950	7	2/1941 - 9/1942	20
3/1959 - 10/1960	20	2/1958 - 9/1958	8
1/1961 - 7/1961	7	4/1967 - 9/1967	6
5/1966 - 10/1966	6		
3/1972 - 8/1972	6		
1/1976 - 11/1977	23		
Total	133		105

Colorado

Dry Period	Duration (mo)	Wet Period	Duration (mo)
8/1900 - 4/1904	45	6/1895 - 4/1896	11
9/1932 - 2/1938	66	6/1897 - 1/1898	8
7/1939 - 8/1940	14	9/1906 - 9/1907	13
5/1950 - 9/1951	17	10/1908 - 2/1910	17
1/1953 - 7/1953	7	10/1911 - 10/1917	73
9/1953 - 3/1957	43	11/1919 - 8/1922	34
8/1960 - 7/1961	12	5/1923 - 5/1924	13
11/1962 - 10/1964	24	3/1926 - 9/1926	7
8/1974 - 1/1975	6	6/1927 - 11/1930	42
1/1977 - 10/1978	22	6/1941 - 4/1942	11
9/1980 - 4/1981	8	5/1947 - 3/1948	11
		5/1957 - 4/1958	12
		7/1965 - 2/1966	8
		10/1969 - 7/1970	10
		4/1973 - 9/1973	6
Total	264		276

Georgia

Dry Period	Duration (mo)	Wet Period	Duration (mo)
4/1896 - 10/1896	7	8/1898 - 2/1899	7
12/1897 - 6/1898	7	1/1912 - 1/1913	13
7/1899 - 1/1900	6	6/1928 - 1/1930	20
2/1911 - 9/1911	8	11/1947 - 6/1949	20
4/1925 - 2/1926	11	2/1964 - 8/1965	19
1/1927 - 11/1927	11	4/1975 - 1/1976	10
6/1931 - 4/1932	11		
11/1933 - 5/1934	7		
12/1934 - 6/1935	7		
1/1950 - 6/1950	6		
4/1954 - 8/1956	29		
8/1980 - 4/1981	8		
Total	118		89

Illinois

Dry Period	Duration (mo)	Wet Period	Duration (mo)
7/1901 - 5/1902	11	3/1898 - 11/1898	9
7/1913 - 4/1915	22	7/1902 - 4/1903	10
10/1920 - 7/1921	10	7/1907 - 12/1907	6
8/1922 - 7/1923	12	7/1915 - 1/1916	7
6/1930 - 7/1931	14	9/1926 - 8/1928	24
8/1933 - 8/1934	13	10/1928 - 1/1930	16
11/1939 - 6/1941	22	9/1945 - 2/1946	6
8/1953 - 12/1954	17	1/1950 - 11/1950	11
10/1956 - 3/1957	6	6/1951 - 3/1952	10
9/1963 - 12/1964	16	9/1961 - 3/1962	7
		9/1972 - 9/1975	37
Total	143		43

Kansas

Dry Period	Duration (mo)	Wet Period	Duration (mo)
7/1901 - 4/1902	10	8/1902 - 12/1904	29
4/1911 - 11/1911	8	8/1906 - 3/1907	8
12/1916 - 8/1918	21	6/1908 - 3/1909	10
2/1933 - 10/1940	93	5/1915 - 6/1916	14
7/1952 - 2/1957	44	10/1923 - 3/1924	6
5/1963 - 10/1965	18	6/1927 - 12/1927	7
10/1966 - 5/1967	8	6/1928 - 8/1929	15
7/1980 - 4/1981	10	9/1941 - 6/1943	10
		4/1944 - 9/1945	18
		1/1949 - 10/1949	10
		5/1951 - 4/1952	12
		3/1958 - 12/1958	10
		10/1959 - 8/1960	11
		5/1961 - 9/1962	17
		9/1965 - 2/1966	6
		10/1968 - 4/1970	19
		11/1972 - 5/1974	20
		10/1974 - 6/1975	9
Total	212		231

Maine

Dry Period	Duration (mo)	Wet Period	Duration (mo)
4/1941 - 9/1941	6	11/1897 - 7/1898	9
1/1944 - 8/1944	8	2/1900 - 1/1901	12
10/1947 - 3/1950	30	3/1901 - 10/1901	8
5/1950 - 10/1950	6	12/1901 - 3/1903	16
9/1955 - 4/1956	8	9/1907 - 5/1908	9
1/1957 - 10/1957	10	4/1920 - 12/1920	9
3/1965 - 10/1965	8	4/1928 - 10/1928	7
12/1965 - 9/1966	10	7/1954 - 3/1955	9
Total	86		80

Montana

Dry Period	Duration (mo)	Wet Period	Duration (mo)
9/1904 - 4/1906	20	7/1903 - 3/1904	9
12/1930 - 3/1933	28	12/1906 - 6/1910	43
4/1934 - 7/1941	88	5/1911 - 4/1914	36
6/1949 - 6/1950	12	7/1915 - 5/1917	23
9/1952 - 3/1953	7	6/1923 - 4/1924	11
11/1953 - 7/1954	9	2/1927 - 8/1928	19
9/1960 - 4/1962	20	10/1946 - 4/1947	7
9/1979 - 4/1981	20	8/1951 - 3/1952	8
		4/1965 - 9/1965	6
		12/1968 - 7/1969	8
		4/1975 - 8/1976	17
		5/1978 - 4/1979	12
Total	204		199

Nebraska

Dry Period	Duration (mo)	Wet Period	Duration (mo)
10/1910 - 7/1911	10	1/1897 - 6/1897	6
7/1922 - 4/1923	10	7/1902 - 9/1907	63
10/1933 - 8/1941	95	6/1908 - 3/1909	10
9/1953 - 4/1957	44	4/1915 - 2/1916	11
10/1974 - 3/1975	6	4/1919 - 2/1921	23
8/1976 - 2/1977	7	8/1923 - 3/1924	8
9/1980 - 4/1981	8	2/1927 - 9/1927	8
		4/1944 - 9/1944	6
		10/1946 - 6/1947	9
		4/1951 - 5/1952	14
		9/1965 - 2/1966	6
		12/1972 - 7/1973	8
		8/1977 - 8/1978	13
		10/1979 - 3/1980	6
Total	180		191

New York

Dry Period	Duration (mo)	Wet Period	Duration (mo)
6/1899 - 11/1899	6	11/1927 - 8/1928	10
9/1908 - 2/1909	6	6/1972 - 9/1972	15
7/1923 - 12/1923	6	5/1974 - 3/1975	11
9/1930 - 6/1931	10	8/1975 - 4/1977	21
8/1939 - 1/1940	6	8/1977 - 10/1978	15
4/1941 - 4/1942	13		
6/1964 - 2/1966	21		
4/1966 - 10/1966	7		
Total	75		72

North Dakota

Dry Period	Duration (mo)	Wet Period	Duration (mo)
11/1897 - 9/1898	11	4/1896 - 7/1896	16
6/1910 - 7/1911	14	9/1900 - 4/1901	8
7/1917 - 1/1919	19	6/1901 - 2/1903	21
12/1930 - 3/1932	16	9/1903 - 6/1904	11
8/1933 - 3/1941	92	4/1912 - 5/1913	14
9/1952 - 3/1953	7	11/1915 - 4/1917	16
10/1953 - 5/1954	8	2/1922 - 7/1922	6
1/1961 - 4/1962	16	11/1922 - 11/1923	13
11/1963 - 5/1964	7	5/1927 - 4/1928	12
7/1967 - 5/1968	11	6/1928 - 5/1929	12
7/1976 - 6/1977	12	9/1941 - 8/1943	24
12/1979 - 10/1980	11	11/1944 - 4/1945	6
		10/1951 - 3/1952	6
		7/1965 - 10/1966	16
		10/1971 - 11/1972	13
		11/1977 - 9/1978	11
Total	224		195

Ohio

Dry Period	Duration (mo)	Wet Period	Duration (mo)
5/1895 - 5/1896	13	1/1907 - 5/1908	17
4/1900 - 5/1901	14	10/1911 - 5/1912	8
7/1901 - 5/1902	11	8/1915 - 6/1916	11
6/1930 - 11/1931	18	9/1926 - 8/1927	12
11/1933 - 4/1935	18	9/1950 - 3/1951	7
7/1944 - 1/1945	7	8/1975 - 2/1976	7
11/1952 - 7/1954	19	8/1979 - 3/1980	8
10/1963 - 3/1964	6	6/1980 - 12/1980	7
5/1964 - 1/1965	9		
Total	115		77

Tennessee

Dry Period	Duration (mo)	Wet Period	Duration (mo)
9/1899 - 5/1900	9	4/1912 - 10/1912	7
9/1904 - 4/1905	8	4/1920 - 9/1920	6
8/1913 - 12/1914	17	12/1926 - 6/1927	7
3/1925 - 10/1925	8	6/1928 - 11/1928	6
12/1925 - 5/1926	6	3/1929 - 11/1929	9
7/1930 - 11/1931	17	10/1949 - 4/1951	19
11/1939 - 7/1940	9	7/1967 - 12/1967	6
9/1940 - 7/1942	23	10/1972 - 4/1976	42
6/1952 - 2/1953	9	4/1979 - 11/1979	8
8/1953 - 1/1955	18		
Total	124		110

Texas

Dry Period	Duration (mo)	Wet Period	Duration (mo)
6/1901 - 8/1902	15	6/1895 - 2/1896	9
2/1909 - 11/1911	22	4/1900 - 10/1900	7
3/1916 - 9/1918	31	2/1903 - 10/1903	9
11/1924 - 8/1925	10	4/1905 - 11/1906	20
6/1934 - 4/1935	11	11/1907 - 9/1908	11
5/1939 - 3/1940	11	10/1913 - 9/1915	24
12/1950 - 2/1957	75	1/1919 - 7/1921	31
2/1963 - 1/1965	24	12/1923 - 5/1924	6
1/1967 - 8/1967	8	3/1926 - 12/1926	10
1/1971 - 7/1971	7	6/1935 - 1/1936	8
		12/1940 - 10/1942	23
		12/1944 - 10/1945	11
		7/1949 - 12/1949	6
		4/1957 - 12/1958	21
		10/1960 - 4/1961	7
		6/1961 - 11/1961	6
		3/1968 - 7/1969	17
		3/1973 - 10/1973	8
		9/1974 - 9/1975	13
		10/1976 - 4/1977	7
Total	214		254

Utah

Dry Period	Duration (mo)	Wet Period	Duration (mo)
11/1899 - 8/1905	70	5/1906 - 2/1908	22
5/1924 - 10/1924	6	9/1908 - 2/1910	18
6/1926 - 1/1927	8	10/1916 - 9/1917	12
3/1931 - 10/1931	8	4/1920 - 10/1923	43
1/1934 - 1/1936	25	1/1937 - 12/1937	12
10/1950 - 4/1951	7	3/1938 - 2/1939	12
12/1953 - 12/1955	25	2/1941 - 7/1942	19
3/1956 - 3/1957	13	6/1947 - 8/1948	15
12/1958 - 7/1961	32	12/1948 - 10/1949	11
12/1962 - 8/1963	9	12/1951 - 8/1952	9
3/1972 - 8/1972	6	5/1957 - 4/1958	12
6/1974 - 2/1975	9	5/1965 - 12/1965	8
11/1976 - 12/1977	14	10/1972 - 1/1974	16
		1/1979 - 8/1979	8
		1/1980 - 10/1980	10
Total	232		226

Virginia

Dry Period	Duration (mo)	Wet Period	Duration (mo)
10/1900 - 3/1901	6	5/1901 - 2/1902	10
5/1925 - 1/1926	9	5/1908 - 10/1908	6
4/1930 - 7/1931	16	6/1937 - 11/1937	6
9/1931 - 9/1932	13	12/1957 - 8/1958	9
9/1941 - 4/1942	8	5/1972 - 8/1973	16
10/1953 - 9/1954	12	3/1975 - 1/1976	11
7/1963 - 12/1963	6	11/1977 - 8/1978	10
11/1965 - 8/1966	10	1/1979 - 4/1980	16
9/1980 - 4/1981	8		
Total	88		84

Washington

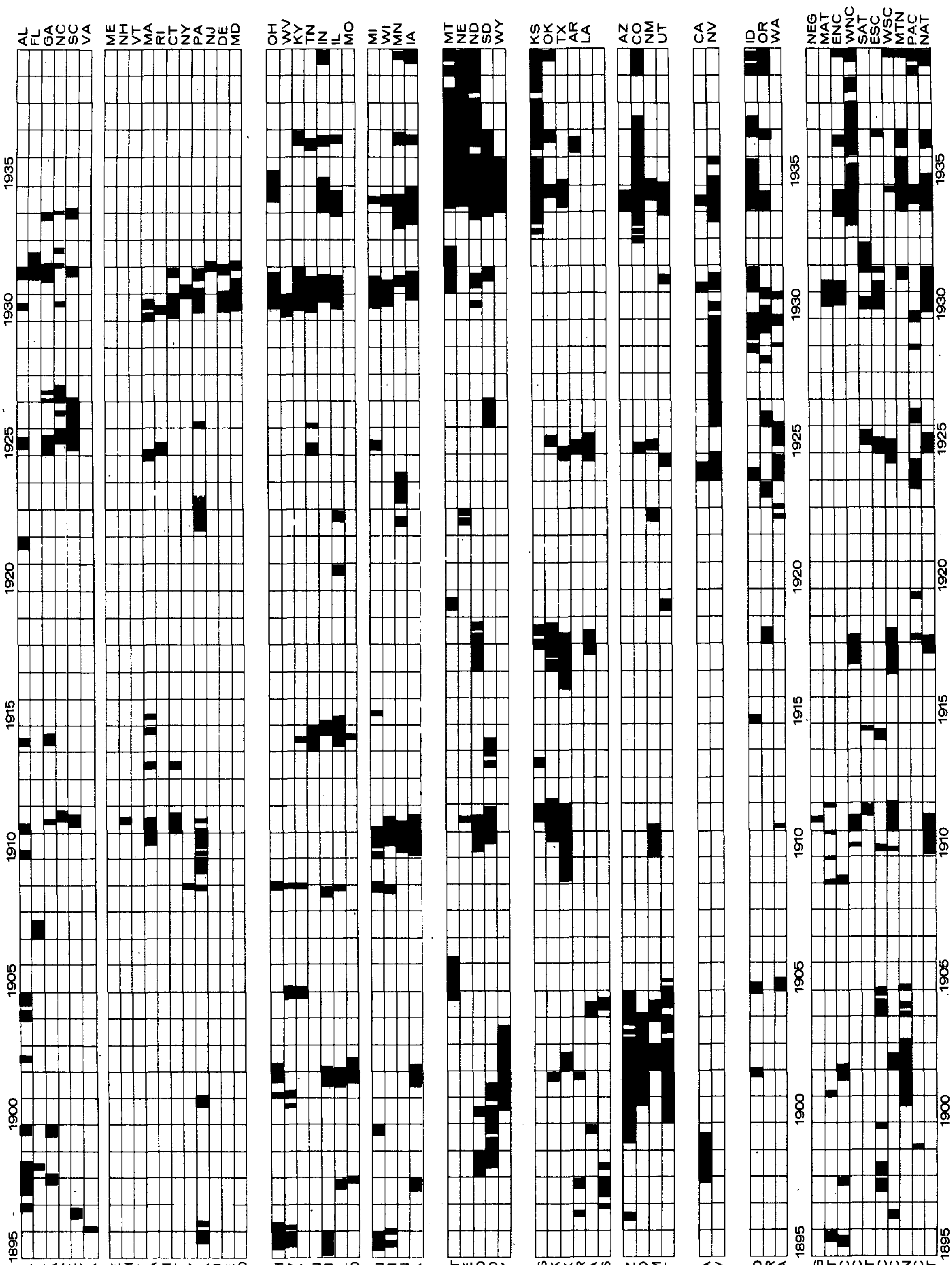
Dry Period	Duration (mo)	Wet Period	Duration (mo)
10/1904 - 8/1905	11	11/1896 - 4/1897	6
1/1911 - 8/1911	8	4/1899 - 12/1899	9
6/1922 - 6/1923	13	4/1948 - 12/1948	9
11/1923 - 7/1926	33	3/1950 - 8/1950	6
12/1928 - 5/1929	6	10/1950 - 3/1951	6
9/1929 - 2/1931	18	10/1955 - 3/1956	6
8/1938 - 1/1940	19	3/1960 - 8/1960	6
12/1943 - 1/1945	14	8/1968 - 1/1969	6
11/1976 - 4/1977	6	12/1971 - 9/1972	10
		12/1973 - 7/1974	8
		10/1975 - 8/1976	11
Total	128		83

Wisconsin

Dry Period	Duration (mo)	Wet Period	Duration (mo)
6/1895 - 3/1896	10	6/1905 - 3/1906	10
5/1910 - 6/1911	14	7/1912 - 12/1912	6
8/1930 - 10/1931	15	1/1916 - 6/1916	6
8/1933 - 8/1934	13	9/1926 - 2/1927	6
6/1948 - 6/1949	13	10/1928 - 4/1929	7
10/1953 - 3/1954	6	5/1938 - 2/1939	10
6/1963 - 8/1964	15	7/1951 - 3/1952	9
7/1976 - 6/1977	12	9/1959 - 2/1960	6
		4/1960 - 11/1960	8
		9/1965 - 3/1966	7
		6/1968 - 1/1969	8
		8/1972 - 5/1973	10
		7/1978 - 8/1979	14
Total	98		107

TABLE 1. Beginning and ending dates of the major dry and wet periods for selected states since 1895.

Summarized in Table 2 is the frequency of occurrence of short (<1 year) and long (≥1 year) dry and wet episodes by state. States such as Colorado, New Mexico, South Dakota and Wyoming have experienced seven drought events of one year or greater duration during the past 86 years. Somewhat unexpected is the fact that Illinois also has experienced seven dry sequences of a year or more during this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1895 1900 1905 1910 1915 1920 1925 1930 1935

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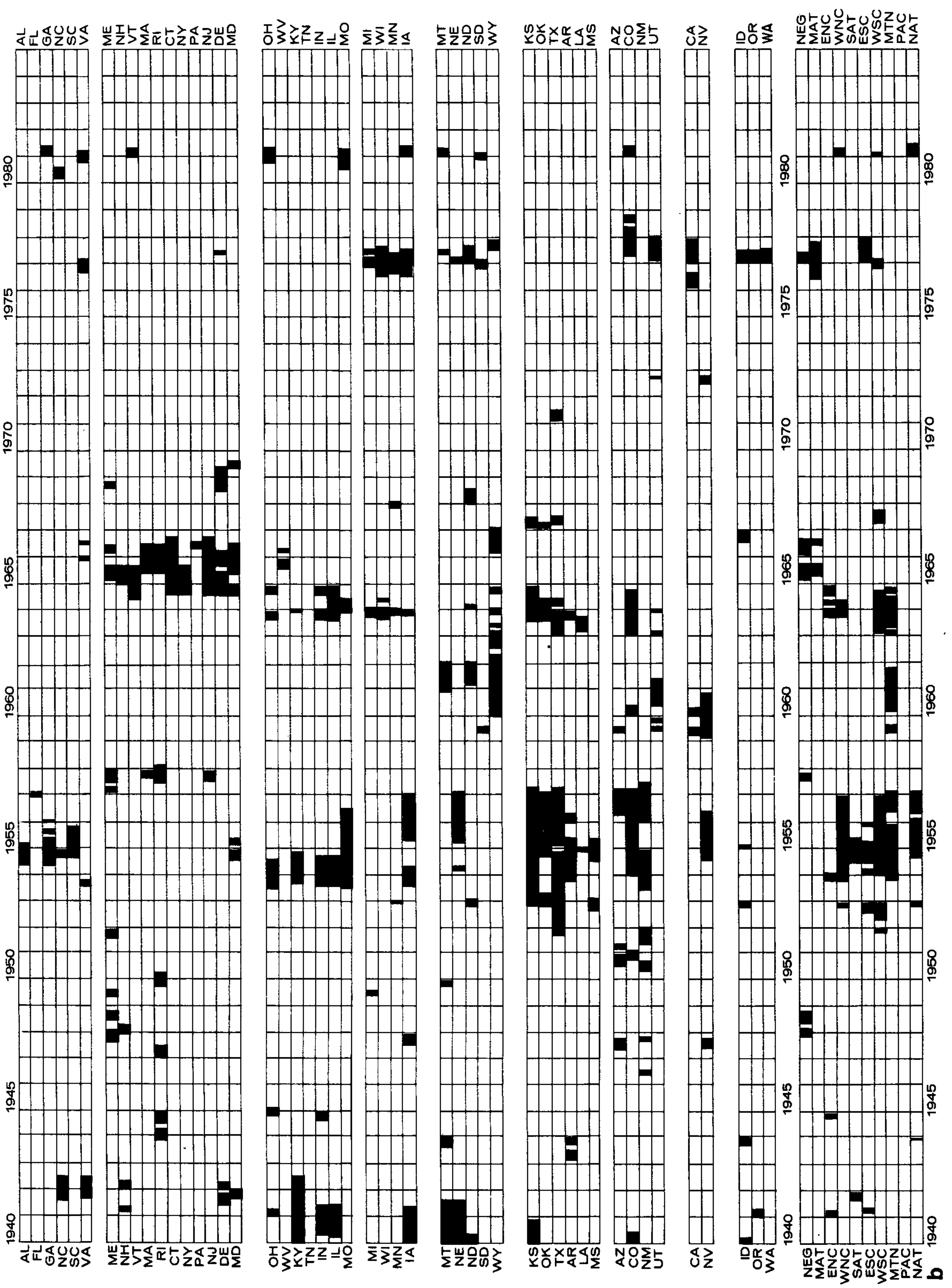

FIG. 1. Distribution of moderate to extreme drought in (a) 1895–1939; (b) 1940–1981; arranged by homogeneous state regions (see text).

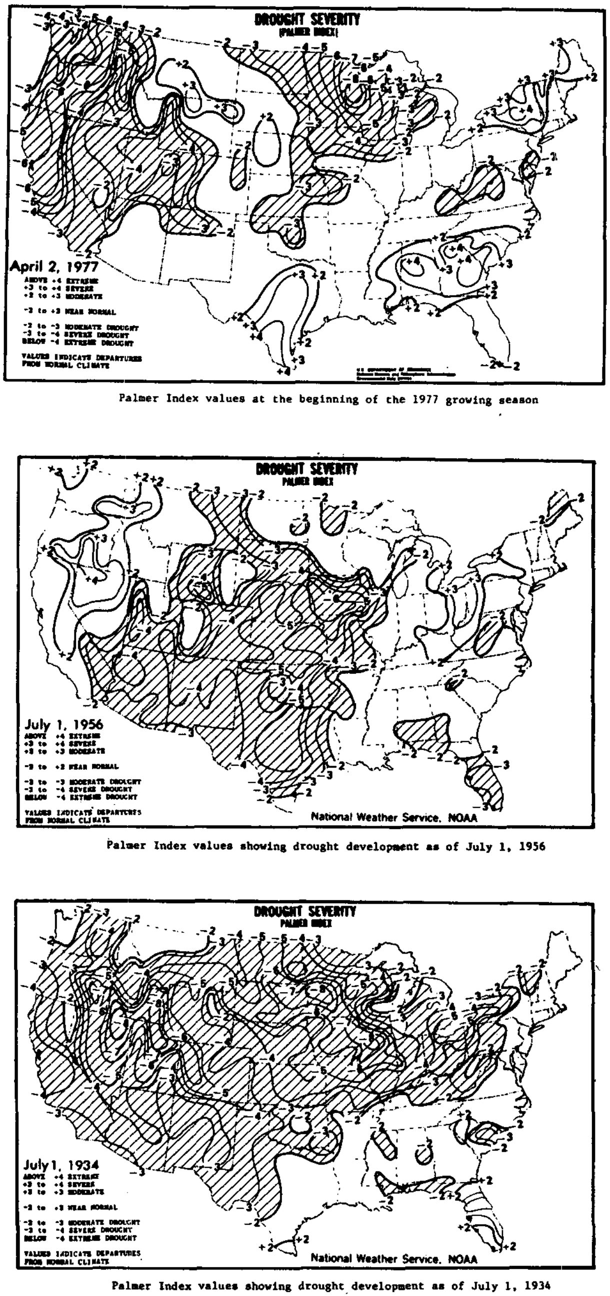

FIG. 2. Spatial character of three severe drought periods. Top, Spring 1977; middle, Summer 1956; bottom, Summer 1934. From *Weekly Weather and Crop Bulletin.*, NOAA).

time. Conversely, Colorado, Kansas, North Dakota, Utah, and Wyoming have experienced seven or more wet spell episodes of a year or longer.

Table 3a gives the duration of the ten longest dry and wet episodes on record and the states where they occurred. All of the longest droughts have occurred in the western United States (Great Plains included). However, while some of the longest wet spells have occurred in the eastern United States, most have occurred in the West. We can conclude, then, that the climate of much of the western United States is one in which the occurrence of prolonged periods of "abnormal" moisture conditions is part of the natural climatic "landscape"; whereas, for the eastern United States, such prolonged departures from the mean state are much less common. The tendency in the West for either "too wet" or "too dry" conditions is further illustrated in Table 3b which lists the ten states having the greatest number of months in each of the dry (PI ≤ -2.0) or wet (PI ≥ 2.0) categories (see also Fig. 4).

In order to analyze the time variation of drought events, the fractional area under drought (PI ≤ -2) or wet spell (PI ≥ 2) in the region encompassing the western 17 states (North Dakota to Texas, westward) was calculated for each month of record. The resulting monthly values represent an index of the total area affected by drought (DAI), or wet spell (WSAI) conditions in this region.

The results, presented in Fig. 5, appear to indicate a tendency for the percentage area under drought to undergo "periodic" fluctuations until the 1950's; becoming less consistent thereafter. Note that the 1930's drought developed in at least three distinctive episodes (see Skaggs, 1975). The suggestion of a rhythmic recurrence of drought affecting the Great Plains and the western United States led Borchert (1971) to suggest that a similar episode of widespread drought was likely to occur during the 1970's. The 1970's drought, however, was relatively short-lived (Figs. 5a, d) and affected primarily the western third of the contiguous United States (Fig. 2), although the north-central states were also extremely dry by the spring of 1977. Hot and dry weather also affected the central United States in the summer of 1980 (Karl and Quayle, 1981).

Wet periods appear to have a shorter time-scale of recurrence, on the order of 3–5 years. In order to explore the apparent rhythmic behavior of both the DAI and the WSAI (Fig. 5) in a quantitative manner, spectral analysis was performed; the results are presented in the next section.

b. Variance spectrum of DAI and WSAI

Smoothed spectral estimates of the DAI and WSAI series for the 17 western states were calculated by Fourier transformation of the autocovariance function employing a Tukey spectral window (Jenkins and Watts, 1968). The spectrum was computed separately for each calendar month and the annual mean series. Statistical significance was calculated separately for selected months following Gilman *et al.* (1963).

Fig. 6 shows the 13 sets of spectral plots together with their respective 95% confidence limits. The monthly and annual DAI and WSAI spectra are shown together in order to point out differences in

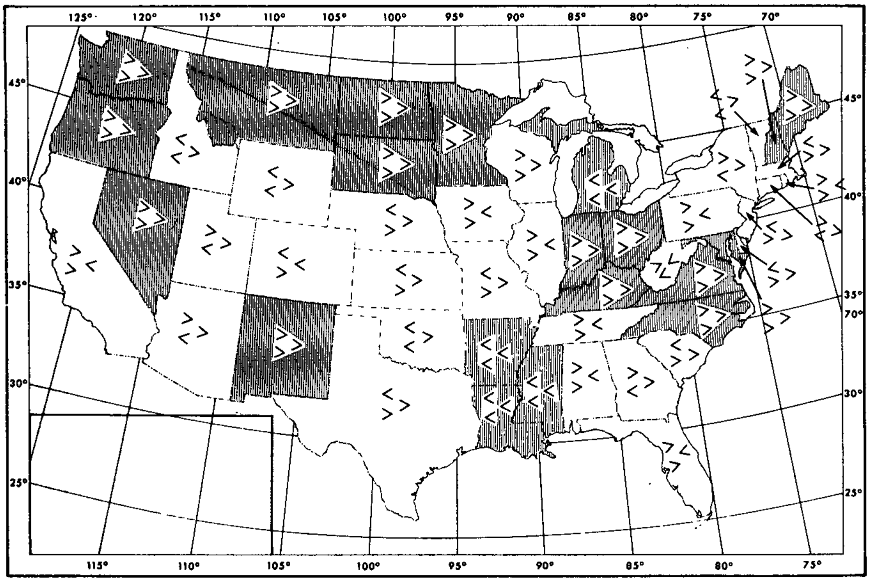

FIG. 3. Ratio characteristics of drought duration to wet spell duration. > indicates ratio ⩾ 1; < indicates ratio < 1. Left symbols refer to ratio of total drought to wet spell duration based on a six-month (top symbol) or a 12-month (bottom) criterion. Right symbol refers to the ratio of the longest drought to wet spell duration.

the shape of their spectrum. A close inspection of Fig. 6 reveals the following features. The DAI tends to be concentrated at lower frequencies [period $P > 10$ years], whereas there is a tendency for the WSAI to have a greater proportion of the variance in the frequency interval $3 < P < 6$ years. The monthly spectral traces vary among each other, but a few groups of months can be identified which possess similar spectral shapes. These are, November–February, March–April, June–July, and August–September. The months of May and October were not classifiable into any one group. The spectral curves for the annual series differ mainly at the high frequency end of the spectrum, where the WSAI has a peak in the neighborhood of two years; the DAI exhibits essentially a "red noise" spectrum.

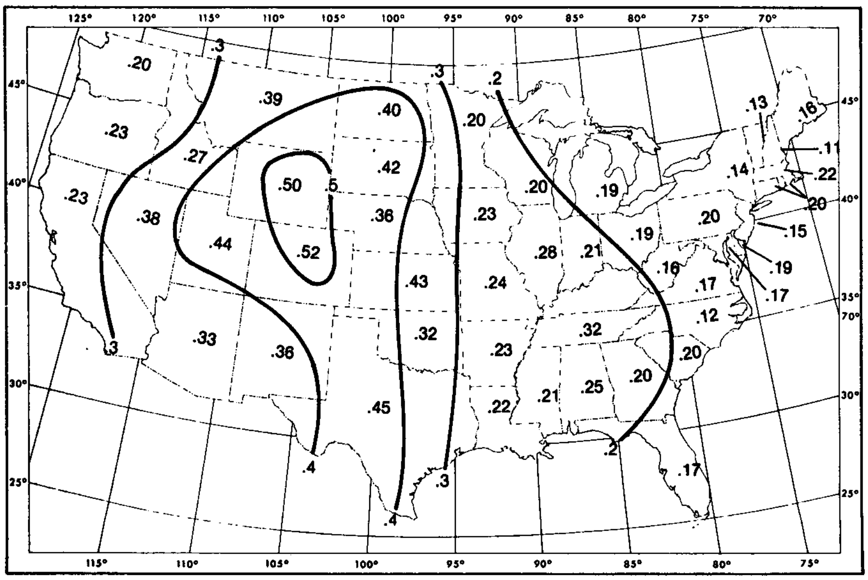

FIG. 4. Ratio of the total number of months under drought and wet spells (|PI| ⩾ 2; six month or longer events) to the record length.

TABLE 2a. Relative frequency of drought duration (PI ≤ −2).

State	Number of occurrences <1 year	Number of occurrences ≥1 year	State	Number of occurrences <1 year	Number of occurrences ≥1 year
AL	6	5	NE	5	2
AZ	9	3	NV	6	6
AR	7	3	NH	3	2
CA	9	3	NJ	4	2
CO	3	8	NM	3	7
CT	5	3	NY	5	2
DE	5	2	NC	2	4
FL	8	2	ND	6	6
GA	11	1	OH	4	5
ID	5	4	OK	6	5
IL	3	7	OR	6	3
IN	3	6	PA	3	4
IA	11	5	RI	5	4
KS	4	4	SC	4	3
KY	4	4	SD	4	7
LA	6	4	TN	6	4
ME	7	1	TX	5	5
MD	3	3	UT	7	6
MA	4	5	VT	3	2
MI	5	2	VA	6	3
MN	5	4	WA	4	5
MS	8	3	WV	7	2
MO	4	4	WI	2	6
MT	2	6	WY	1	7

TABLE 2b. Relative frequency of wet spell duration (PI ≥ 2).

State	Number of occurrences <1 year	Number of occurrences ≥1 year	State	Number of occurrences <1 year	Number of occurrences ≥1 year
AL	8	2	NE	10	4
AZ	2	6	NV	10	5
AR	4	5	NH	4	2
CA	6	3	NJ	6	2
CO	8	7	NM	5	6
CT	3	5	NY	2	3
DE	10	3	NC	4	0
FL	4	3	ND	6	10
GA	2	4	OH	5	2
ID	8	4	OK	6	7
IL	8	3	OR	5	5
IN	8	2	PA	3	2
IA	9	4	RI	7	2
KS	10	8	SC	6	3
KY	5	4	SD	9	7
LA	6	4	TN	7	2
ME	6	2	TX	13	7
MD	9	1	UT	5	10
MA	8	2	VT	4	2
MI	6	4	VA	6	2
MN	8	3	WA	11	0
MS	5	4	WV	4	3
MO	7	4	WI	12	1
MT	6	6	WY	1	9

It should be noted that in June and July there is a strong WSAI signal in the neighborhood of the quasi-biennial pulse. Other authors (*e.g.*, Sellers, 1960; Engelen, 1972; Bradley, 1976) have also noted a significant quasi-biennial signal in the summer precipitation record of many stations in the western United States.

Although the January DAI spectrum and the January and December WSAI spectrum appear to have statistically significant periods, a test of significance showed this not to be the case when compared to a "red noise" null hypothesis.

The work of Mitchell *et al.* (1979) and Bhalme and Mooley (1980, 1981) identified statistically significant power present at ~22 years in the drought area over the western United States in the former study, and in the flood area over India in the latter ones. Furthermore, these authors showed, by means of a harmonic dial analysis, that the peak in both the drought and flood area indices tended to occur shortly after the double sunspot minimum. It is noted that the rhythmic uniformity of the approximately 22-year oscillation in the area with PI ≤ −2 became less distinct after the mid 1800's (Mitchell *et al.*, 1979, Fig. 2). Since the data used in this study dates from 1895, it is not surprising that no statistically significant cycle of ~22 years was found [Karl and Koscielny (1982) also found no significant periods in the PI series from each region]. Fig. 7 shows the Hale sunspot cycle plotted against the annual percentage area of the western United States under drought as previously defined. The association between the two curves, with

TABLE 3a. The ten longest dry (PI ≤ −2) and wet periods (PI ≥ 2).

State	Dry (months)	State	Wet (months)
1. NE	95	CO	73
2. KS	93	NE	63
3. ND	92	AL	50
4. MT	88	WY	50
5. AZ	76	PA	47
6. TX	75	MT	43
7. WY	73	UT	43
8. UT	70	CO	42
9. CO	66	TN	42
10. NM	61	MA	37

TABLE 3b. The ten states with the most months under dry or wet spells.

State	Dry (months)	State	Wet (months)
1. CO	264	CO	276
2. WY	247	WY	271
3. UT	232	TX	254
4. SD	225	KS	231
5. ND	224	UT	226
6. NV	221	SD	213
7. TX	214	MT	199
8. KS	212	ND	195
9. MT	204	OK	187
10. NM	200	NM	176

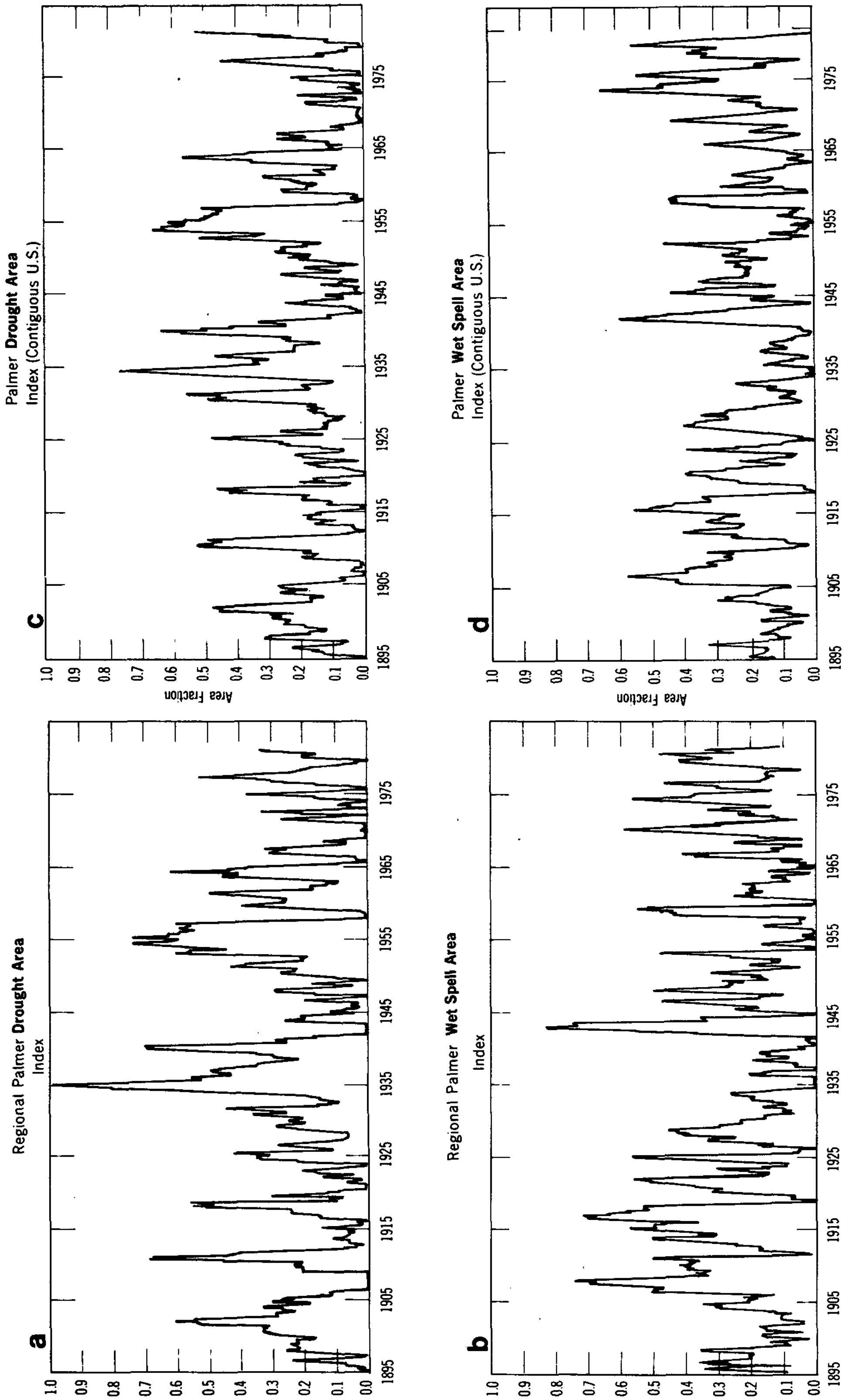

FIG. 5. Five month running means of monthly drought area index (DAI) and wet spell area index (WSAI). Left panels (a) and (b) show mean values for the 17 western states and right panels (c) and (d) show values for the contiguous 48 states.

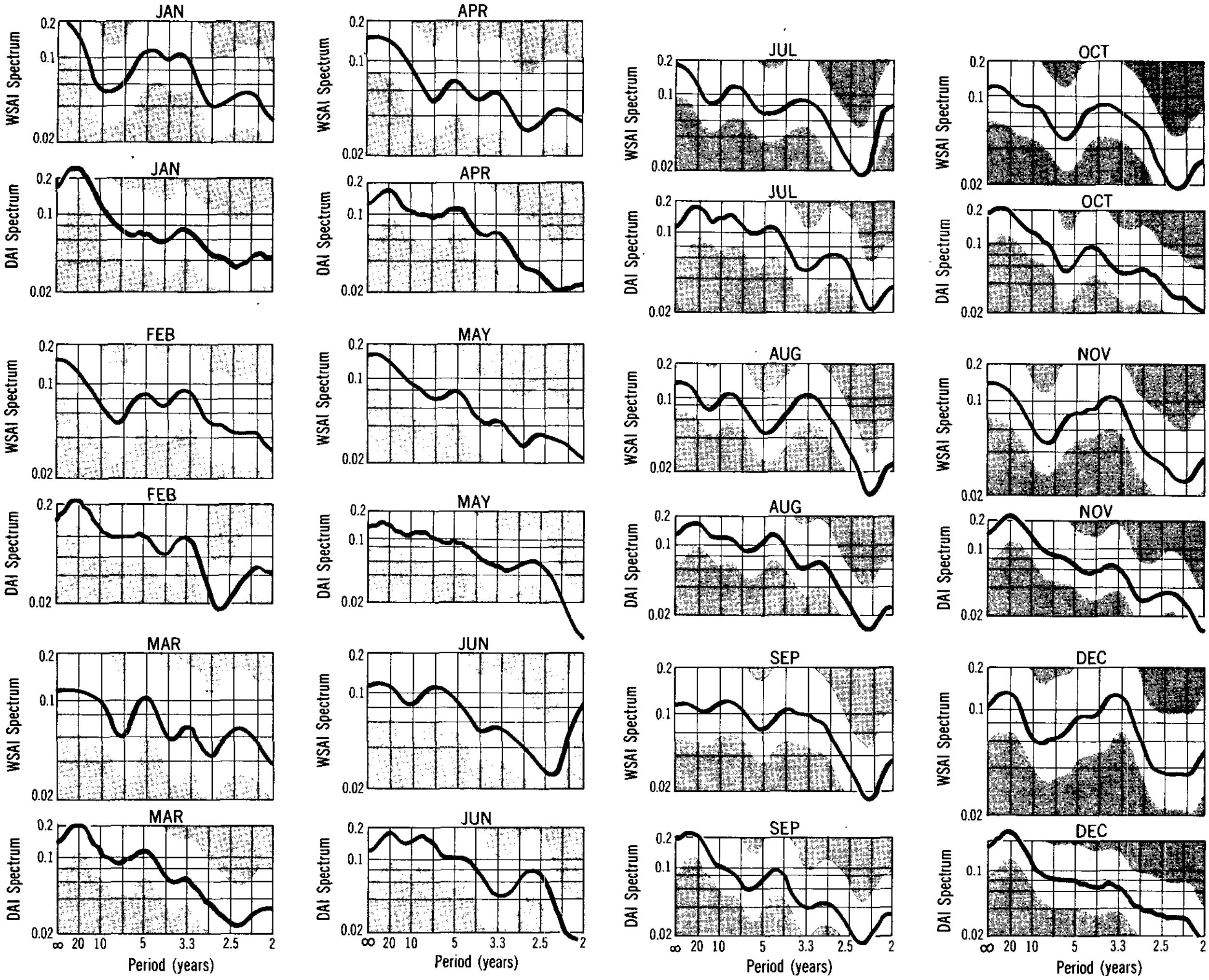

FIG. 6. Power spectral densities for each calendar month and annual mean values of DAI and WSAI. Unshaded region indicates 95% confidence limits.

a minimum of area under drought in the rising phase of the Hale cycle and a minimum in the declining phase, comes primarily from the drought episodes of the 1930's and 1950's. This underscores the problem

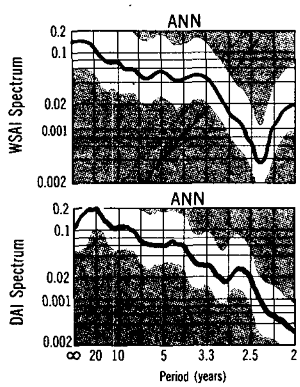

FIG. 6. (*Continued*)

of statistical relationships found within a certain period of time not retaining their validity in subsequent periods (see Landsberg, 1982).

Some studies have also found a significant 11-year peak in the variance spectrum of precipitation (*e.g.*, Mori, 1981). As Fig. 8 shows, there also appears to be an association between drought area and the 11-year sunspot cycle. Drought area for both the western and contiguous United States tends to be near maximum during and in the year immediately after the 11-year sunspot minimum. However, there is no statistically significant peak in the spectrum of the annual DAI in the frequency range 8–12 years. By comparison, the WSAI tends to maximize 3–4 years before and after the year of the 11-year sunspot minimum.

To ascertain whether drought episodes tended to begin or end at a preferred time of the year (which would imply a certain degree of conditional predictability), the months of the year when a significant

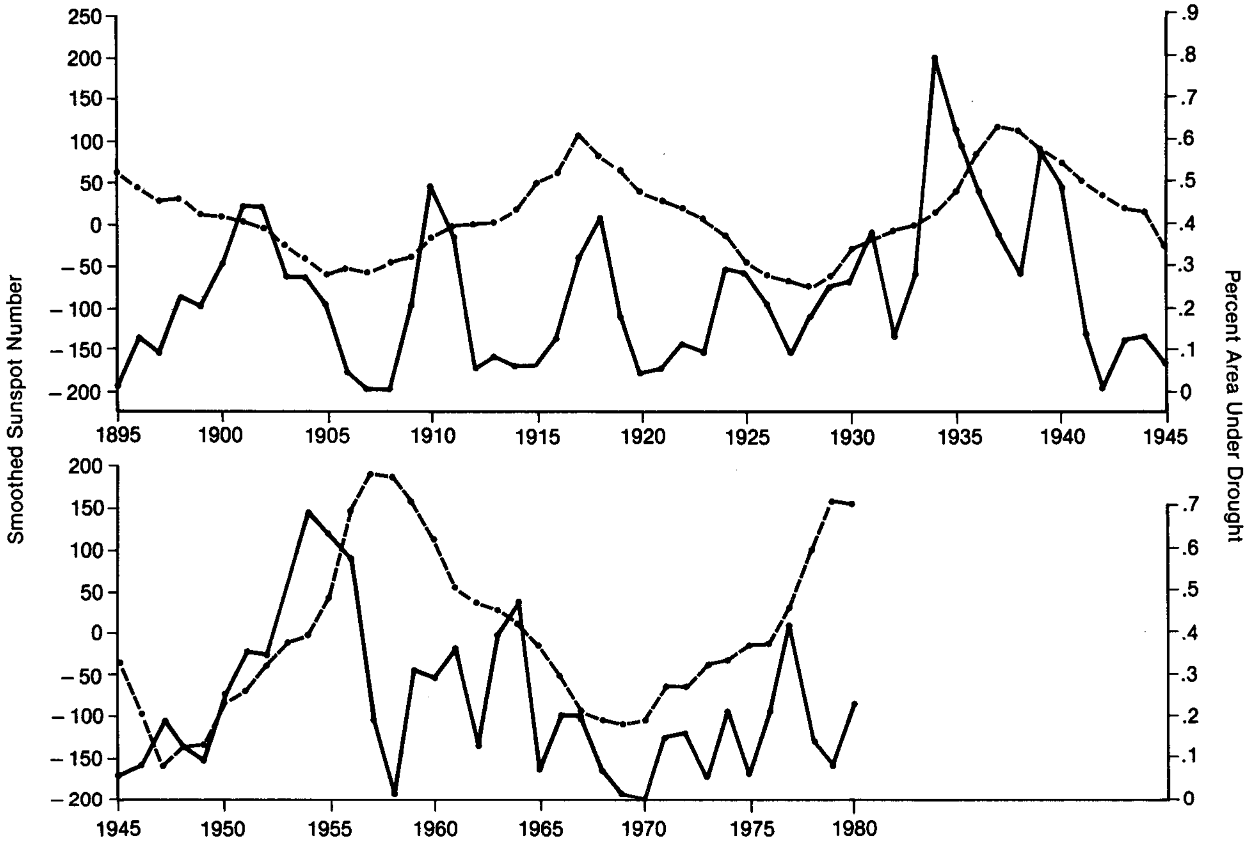

FIG. 7. Smoothed annual values (12-month means) of the Hale Sunspot Cycle (dashed line) versus annual mean percentage area under drought in the western United States.

percentage of droughts began and ended were tabulated and stratified by drought regions [The regions, based on the results of Karl and Koscielny (1982), are similar to the ones found by Walsh *et al.* (1982).] based on principal component analysis of precipitation from a network of stations. Fig. 9 gives the percent frequency of occurrence by calendar month and region of the beginning (first of at least three consecutive months with PI ≤ -2.0) and ending (first month with PI > -2.0 following a drought sequence) of all drought episodes in the contiguous United States.

The results indicate some regionally dependent preference for the onset and ending of drought to occur at certain times of the year. For example, in the Southwest, droughts are more likely to start during the winter season (December–March) and more likely to end during mid to late summer (July–September). In the West (California and Nevada), a spring preference for the onset of drought (March–May) is followed by a fall preference for their demise (September–November). A late spring/early summer and fall preference for drought initiation in the central United States (Central and East North Central regions) is in agreement with previous findings (Lawson *et al.*, 1978); however, the termination frequency shows a more even distribution throughout the year. In contrast, the Northeast region shows no significant preference for either onset or termination, reflecting the more even distribution of monthly precipitation present in this part of the country. In the Southeast, only an April maximum for initiation and a weak summer/fall termination preference is evident.

As the percentage figures indicate, these are generally weak associations. There are only a few regions, mostly located in the western United States, where the percentages are large enough (slightly over 20% of all cases) to be useful as possible indicators of the likelihood of the establishment of a drought, given that a period of deficient precipitation has occurred prior to a key month.

A possible link (weak as it might be) of the WSAI with Southern Oscillation/El Niño type events is suggested by the shape of the WSAI spectrum (which, it has been shown, differs markedly from that of the DAI). A considerable fraction of the variance is present in the winter half-year months over a frequency range of 0.325–0.2 cycles per year (3–9 year periods). Interestingly, in a comprehensive survey of El Niño phenomena by Quinn *et al.* (1978), a mean recurrence interval of 3–7 years for El Niño occurrences,

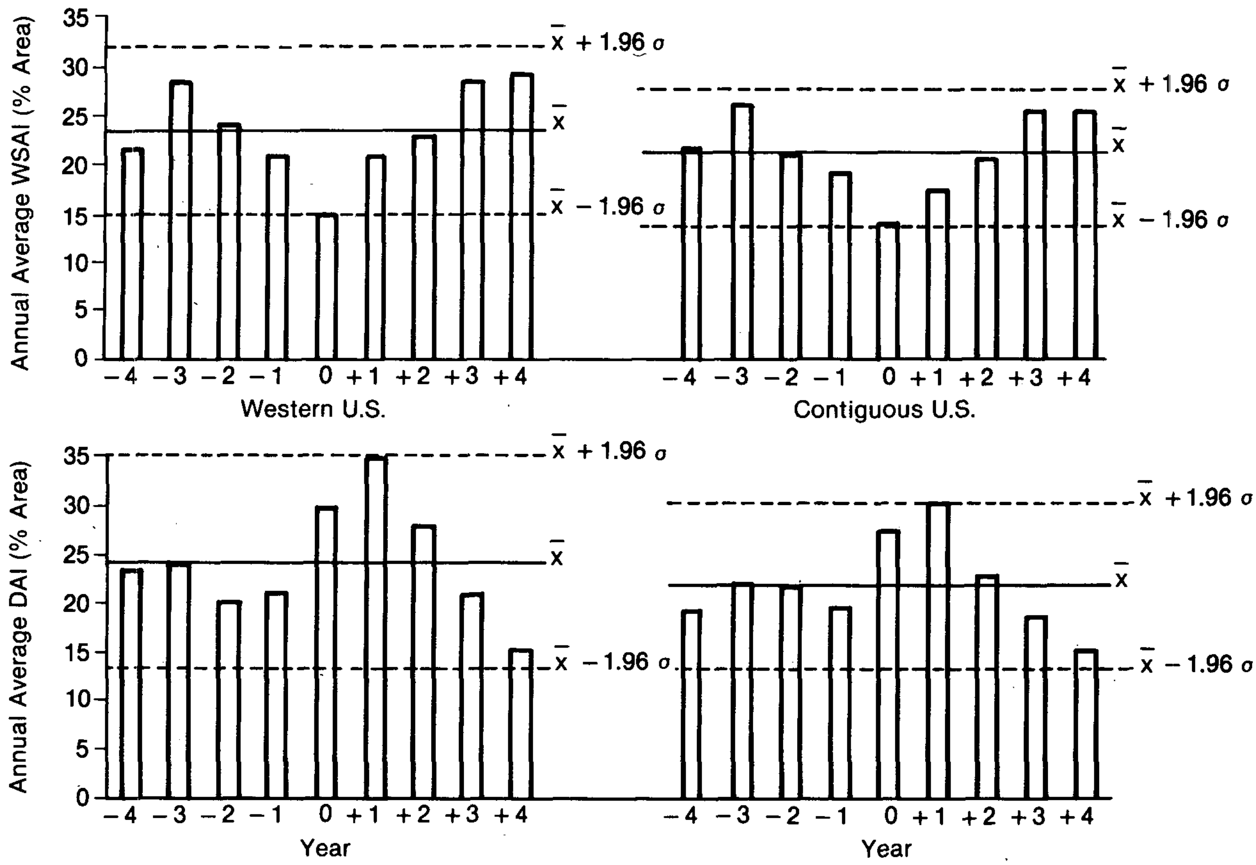

FIG. 8. Superposed epoch analysis of mean percentage area under drought for the western (left) and coterminous (right) United States. Key date is the year of the 11-year sunspot minimum.

regardless of strength, was determined for ~120 years of record. Trenberth (1976) found a maximum in the coherence spectra of sea level pressure in the South Pacific in the frequency range 2–10 years. Julian and Chervin (1978) and Wright (1977) have also shown, in studies of Southern Oscillation indices, a frequency spectrum exhibiting the same range of principal time scales.

Douglas and Englehart (1981) noted a teleconnection between autumn rainfall in the central equatorial Pacific and subsequent season precipitation in Florida. The authors suggest the correlation arises from the differences in the position and strength of the major troughs in the westerlies between years with low and high central equatorial Pacific rainfall (see Horel and Wallace, 1981). van Loon and Madden (1981) performed a comprehensive analysis of the statistical association between a measure of the Southern Oscillation (SO) and sea level pressure and temperature throughout both Southern and Northern Hemispheres for northern winter (December–February). They showed the SO to be statistically correlated with both pressure and temperature over large areas of both hemispheres and concluded that the phenomenon exerts a noticeable influence on the atmospheric circulation. The results shown here support the existence of a modulation of precipitation over the United States, particularly in the West with a time scale of the order of the SO/El Niño phenomena.

4. Summary

Using Palmer Indices developed for each of the 48 contiguous United States, the spatial and temporal patterns of variation of dry and wet spells in the contiguous United States have been analyzed. In concurrence with other studies, it was found that the interior and western areas of the United States are more likely to endure protracted periods of dry weather. However, long periods of abnormally high moisture are also likely to occur in the interior and western regions of the country, as well as in a few eastern states (see Table 3a). "Abnormally high" should not be confused with high precipitation in an absolute sense. The Palmer Index is a measure of moisture deficit or surplus relative to the average climate and soil conditions in the region.

The variance characteristics of the dry and wet indices differ measurably from each other. Drought

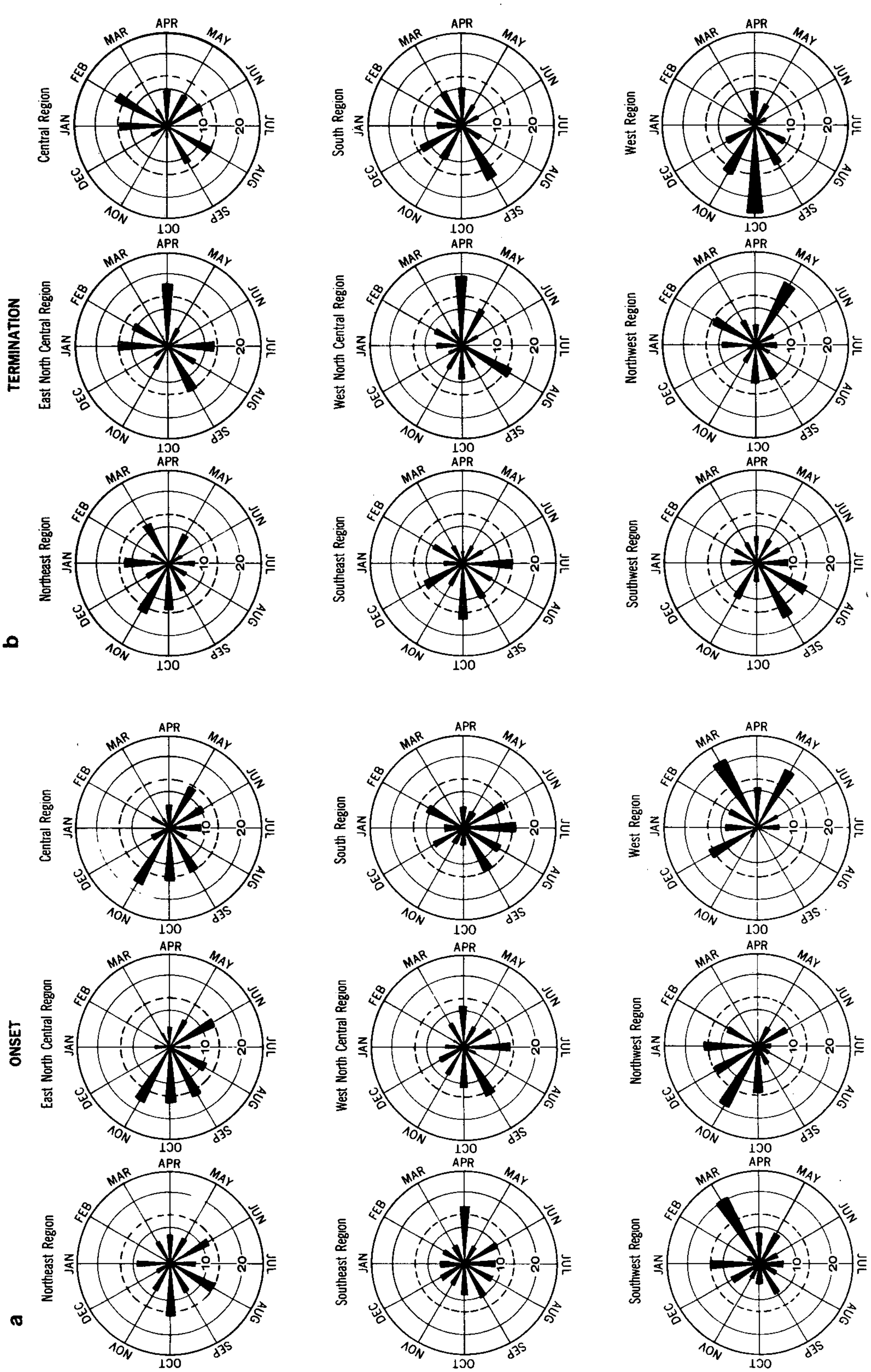

FIG. 9. Regional percent frequency of (a) drought onset and (b) drought termination by month. Dashed circle delimits the 5% significance level against the alternative of random occurrence.

tends to have a "redder" spectrum, whereas wet spells occur with higher frequency. Nevertheless, no one statistically significant period (at the 95% level with respect to both a "red" or "white" noise continuum) was found in the 86-year record. There is greater variance in the spectra of the DAI at ~20 years, and more in the WSAI at ~3–9 years, but it is not sufficiently strong to depend on.

In some regions of the country, the onset and termination of dry episodes tend to occur preferentially at certain times of the year. However, except in a few states, this association can only be regarded as marginal.

Acknowledgments. I would like to thank Ralph Slutz, Robert Quayle, Tom Karl and Kirby Hanson for their helpful suggestions.

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