MINNESOTA DROUGHT

Special Report 15

RODNEY R. SWERMAN
DONALD G. BAKER
Soil Science Dept.

RICHARD H. SKAGGS
Geography Dept.

WATER RESOURCEES RESEARCH CENTER
UNIVERSITY OF MINNESOTA
ST. PAUL, MN 55108
JUNE 1987

MINNESOTA DROUGHT

Rodney R. Swerman
Donald G. Baker
Richard Skaggs

ABSTRACT

Drought is an ordinary and expected part of the climate of any location. However, there are few measures of drought and often it is difficult to recognize when a drought has begun and when it has ended. In the United States, the Palmer Drought Severity Index (PDSI) is the most commonly employed measure of drought. Examination of the averages and variability of the PDSI is needed to draw conclusions about the temporal and geographic patterns of drought over Minnesota to be drawn.

There is a consistent gradient in the duration and severity drought occurrence from southwest to northeast across the state. The droughts in the southwest are more intense and have the longest duration. Toward the north and east, the droughts become much less severe and much shorter in average duration, although there is a tendency for more frequent short and mild droughts in the north and east.

The persistence of drought is its most outstanding characteristic. Once a drought has become established, it tends to persist for several weeks to several months. The persistence is much stronger in the southern and western portions of the state.

In the southern and western areas of the state a drought established by the beginning of the growing season has a likelihood of 50 percent or greater of continuing through the end of the growing season in August. Thus, it is important to have a near real time monitoring system for drought during the late spring and early summer.

The frequency, severity, and duration of drought is not constant in time. In the early part of this century, from the early 1920's through the 1930's, much of Minnesota became progressively drier as measured by the PDSI. After 1940, precipitation increased substantially and drought was much less frequent and persistent. Much of the famous 1950's drought on the Great Plains did not affect Minnesota. The past five years or so have been among the wettest on record. However, it cannot be concluded that favorable moisture conditions and infrequent drought are likely in the future. A return to the drier conditions of the early part of this century with persistent droughts should be expected sometime in the future. The question, which cannot be answered, is when these more drought conditions will reoccur.

MINNESOTA DROUGHT

RODNEY R. SWERMAN
DONALD G. BAKER
RICHARD H. SKAGGS

INTRODUCTION

Drought is an elusive and difficult condition to define because the requirements for water vary so widely. For example, drought for a crop commences when the soil is deficient in supplying moisture for particular physiologic stages. Thus, drought is not uniform for different crops nor even within areas as small as a farm or a single field. For the urban dweller a drought commences when the reservoir or water source is low and restrictions in the use of water are required. This may occur even with near normal precipitation if the normal demand exceeds the normal supply. It is apparent that a drought is not simply an interval of limited precipitation. A satisfactory definition requires that a demand for water exists and that the demand be greater than the amount supplied at a particular time. A more specific definition of drought rests upon what condition, crop, profession, or citizen is affected. Thus, there can be crop or agricultural droughts, forest droughts, engineering droughts, urban droughts, and economic droughts.

An early definition given by the American Meteorological Society (1959) is a prolonged and abnormal moisture deficiency. This definition, while not specific, does emphasize two key notions -- a long time period and precipitation below the expected. Palmer (1965) attempted to make more explicit these key notions. Palmer's quantification of a drought rests upon the normal water budget for a location. His method took the realistic view that over time the local economy, made up of all the local interests, agricultural and non-agricultural, is built upon certain water supply expectations or normals. When these expectations are not fulfilled, a drought has commenced. The intensity of drought is defined by the degree to which the normal or expected precipitation for that area has failed to be met. Palmer's method recognizes that regions may differ appreciably in terms of the amount of water required to meet expectations. The same notion of the expected precipitation can be applied to different times of the year. Palmer's index scales departures of precipitation from the expected and permits comparisons between locations and times of the year.

This study provides historical and statistical analyses of drought in Minnesota using the Palmer Drought Severity Index (PDSI). The objective is to explicate areal and temporal differences in the distribution, frequency, intensity, and duration of drought across the state.

DATA

The analyzed record consists of monthly PDSIs calculated for the nine climatic divisions of the state. The record starts in 1895, but due to the need to start the index at zero, the first five years of record were used to allow the index to come into equilibrium. The record analyzed in most of this study was the 84 years, 1900 to 1983. For selected portions of the study the record was extended to include values for 1984 through 1986.

The PDSI is a measure of meteorologic drought. It measures drought by calculating the moisture anomaly from the difference between the precipitation calculated to be climatically appropriate for existing conditions (CAFEC) and observed precipitation. The CAFEC value is an expected precipitation calculated for each climatic division. The observed precipitation is the average precipitation of stations within the climatic division. Thus, a PDSI value of -3.0 in Georgia, for example, is equal in severity to a -3.0 in western Kansas. A -3.0 in Georgia might be a 6 inch precipitation deficit while a -3.0 in western Kansas might be only a 2 inch precipitation deficit. However, both imply the same relative effect on the native vegetation, crops, and local economy of the affected areas.

Palmer (1965) defined four levels of drought intensity: <= - 1.0 (mild), <= -2.0 (moderate), <= -3.0 (severe), and <= -4.0 (extreme). These are based on the response of the native vegetation to the moisture condition. According to Palmer the following are conditions typical of each value.

Mild. Some of the native vegetation almost ceases to grow.
Moderate. The least tolerant species of the native plant community begin to die and be replaced by more xerophytic species.
Severe. Only the most xerophytic species of native vegetation continue to grow. Vegetal cover decreases.
Extreme. Drought resistant species gradually give way to bare soil.

These threshold values were used in the study of the Minnesota drought record. A value of <= -1.0 was taken to be the threshold of a drought period. Palmer also defined four corresponding levels of wet spell intensity but gave no description of responses by the native vegetation.

Minnesota is divided into 9 climatic divisions (Figure 1). A PDSI value is calculated for each division based on the average precipitation and temperature for the division. The state is also divided by what is known as an ecological ecotone. This zone of floristic transition, sometimes referred to as the "tension zone", between the humid east and the more arid west, is about 50 miles wide and separates the original areas dominated by prairie and forest vegetation from each other (Figure 1). Of particular interest is the fact that this transition zone lies more or less between climatic divisions 1 and 2 in the northwest and between 8 and 9 in the southeast, but cuts directly through division 5, the central division.

RESULTS AND DISCUSSION

TREND OF THE PDSI

The year by year, and a smoothed version (using a normal curve smoothing function of 2 sigma = 5 years) of the July PDSI values for divisions 1 - 9 and the state average, for the period 1900 - 1985, are shown in Figures 2 to 11. There are some features common to all divisions. One is the severe drought of the 1930's. Another is the general declining trend of the PDSI values from 1900 to the 1930's. Within this declining trend there are large swings in the values indicating that substantial variability was experienced at this time. Another common feature is the rapid recovery in the PDSI values in the 1940's. However, no long-term trend is discernible since the early 1940s. All divisions except 3 (Figure 4) show a recent upturn in the values beginning about 1975, a reflection of the wet period that much of Minnesota and several northern states are currently experiencing.

Divisions 3 and 9, the northeastern and southeastern corners of the state (Figures 4 and 10) exhibit the least variability of the nine divisions. The greatest variability in the first half of the record was experienced in divisions 4 and 5 (Figures 5 and 6). In the latter half of the record the largest variability seems to have occurred in division 7 (Figure 8).

The average summer (months of June - August) observed and smoothed (2 sigma = 5 yrs) PDSI values for divisions 1 through 9 and the state average, 1900 to 1985, are shown in Figures 12 to 21. From these figures no long term trend in the PDSI is evident. If one looks at shorter periods of the record, two trends are identifiable. For all divisions there was a general decline in the PDSI values from about 1905 to the mid 1930's. From the mid 1930's to the mid 1940's all divisions show a strong upward trend in the PDSI. For the period of record since the mid 1940's the PDSI has shown no trend but has fluctuated above and below the zero value several times in each division. In the past 5 to 6 years there has been a rather strong upward trend in the index for the state as a whole.

In recent years many of the divisions have been very wet, though this is just now showing up on the smoothed curves for the divisions. To give some idea of how abnormally wet the past few years have been, in divisions 7, 8, and 9, the averages of the summer season PDSI values for 1983 and 1984 are the highest 2 year averages in the record, (Figures 18 to 20). Also the years of 1983, 1984, and 1985 are the three wettest consecutive summers in division 5 (Figure 16).

Divisions 2, 3, 6, and 9 (Figures 13, 14, 17, and 20) show the least fluctuation in summer PDSI values. This is likely due to the less variable climate in the eastern and northern parts of the state. Those divisions south and west do not necessarily receive less precipitation than those north and east, but do have a greater variability of precipitation and higher evapotranspiration demand during the critical months of June through August.

RANGE IN DROUGHT VALUES, MEANS, AND MEDIANS

Through 1983 the highest PDSI value in the Minnesota record was 6.5 in division 7 for February, 1969. In the past year (1986) divisions 4, 5, and 7 exceeded that value, with division 7 having a value of 8.1 for September. The lowest value in the record is -9.9 in division 4 for July and August, 1934, and division 5 for July, 1934. Table 1 gives the maximum and minimum values and respective dates of occurrence of the PDSI for each division from 1900 to 1983. During 1986, 6 of the 9 divisions set new record high values, and these are also listed in Table 1.

In Minnesota the range in the PDSI is slightly asymmetrical with lower minimums than higher maximums. Several reasons for this have been suggested. Perhaps it is due to a negative skewness of the distribution of monthly precipitation totals. Or perhaps it reflects climatic differences between Minnesota and the test area, western Kansas, from which Palmer (1965) developed his drought index. Another possible reason is a greater persistence of drought because of "positive feedback" or self-reinforcement of the dry conditions. Some studies have demonstrated that precipitation decreases as the amount of evapotranspiration decreases even though all other conditions are kept the same. Thus, it is possible that a drought, once established, can perpetuate itself. If this hypothesis is confirmed in the future, "real time" monitoring of drought conditions will be even more crucial in water management schemes.

There are some differences between divisions in the months of minimum and maximum PDSI. Divisions 4, 5, 7, 8, and 9 have the lowest minimums from May through August. Divisions 2, 3, and 6 generally show the lowest minimums from February through May. This pattern is largely the result of the extreme drought of 1976 - 1977 in the latter divisions. This drought reached maximum cumulative intensity during March and April of 1977, after which it rapidly abated. Seasonality of the maximums is less pronounced. All divisions generally show the highest maximums in the autumn and early winter. June, 1984, was very wet in division 7, setting a maximum which stands out. In 1986 new maximums were established for September and October, again making autumn the season of highest maximums in division 7.

The monthly means for each division, 1900 - 1985, are depicted in Figure 22. Several interesting features appear in the means across the state. One is the strongly positive values in divisions 1 and 2. The mean of division 1 is nearly statistically significantly different from zero (probability of about 0.1). Palmer categorized all values from +.5 to -.5 as being a near normal moisture condition. The largest absolute value of a mean (October, Div. 1, +.49) is within this range. In all divisions there is a rise in the mean values from August through October, showing that the autumn rains are important to the annual moisture balance. The other interesting feature is the shift in the seasonality of lowest monthly means. In the northeast division they occur in late winter and early spring, while in the southwest division they occur in mid to late summer. The other divisions show a smooth transition across the state between these two divisions.

The monthly medians for each division, 1900 - 1985, are shown in Figure 23. An advantage of the median over the mean is that it always divides the distribution equally. The high medians of divisions 1 and 2 are most noticeable. Several months in these two divisions have medians greater than +1.0, that is, in fifty percent of the years those months indicated at least a slightly wet condition. All divisions, except 4 and 5, show an increase in the median values from August through October, again indicating the general improvement is the moisture condition in autumn. The pattern of the medians trending toward a zero value through the winter months is prominent. The winter season seems to be acting as a moderator, returning moisture surpluses or deficits accumulated the previous season to a more nearly normal condition.

FREQUENCY, TIMING, AND DURATION OF DROUGHT

Divisional Frequency

The frequency of drought in Minnesota is not constant across the state. The frequency is expressed as the percentage of months during the 84 years that the index was less than or equal to a particular PDSI value (Table 2). Divisions 5 and 7 had the highest frequency of drought. Division 3 had the lowest frequency, although division 9 was nearly as drought-free as division 3. The frequency differences across the state may involve the variability of precipitation. The standard deviations of the divisional averages have been calculated (NCDC, 1981). In divisions 3, 4, and 7 one standard deviation equals 13.7%, 20.4%, and 20.0% of the annual precipitation, respectively. The percentages in the remaining divisions fall between divisions 3 and 7. The greater variation in precipitation in the southern and western portions of the state may contribute to the higher frequency of drought.

Early work on drought and moisture stress in Minnesota by Blake, et al., (1960) indicated that roughly divisions 4, 5, and 7 have the highest probability of moisture stress and drought days. Drought days and moisture stress were determined using evapotranspiration estimates based on the Penman method, crop rooting depths, and soil AWC. Basically it was a water budgeting of the soil similar to Palmer's method of calculating the drought index. The pattern of drought frequency using the Palmer index corresponds very well with the earlier calculations by Blake, et al. Divisions 3 and 9 have the lowest probability (frequency) of drought and divisions 4, 5, and 7 have the highest probability.

Annual, Seasonal, and Monthly Frequency

The twelve monthly PDSI values in the calendar years 1900 - 1985 were averaged (Figure 24), e.g., in 22 years division 2 the annual average PDSI was +.5 to +1.49. The southern and western divisions have greater dispersion of the PDSI values, and there is a relative absence of high annual averages (=> + 3.5) in divisions 2, 3 and 6. The values appear to be normally distributed for a sample size of 86.

The May through August PDSIs for all divisions for 1900 - 1985 were averaged because sufficient moisture during these months is critical to all major crops grown in Minnesota (Figure 25). The 4-month averages do not appear normally distributed; in most divisions the distributions are bimodal. The method by which the PDSI is calculated induces serial correlation. The value of the index in April or May influences the value in August. Seldom does a value far from zero in May reverse its sign by August to give a seasonal average of zero. This persistence is characteristic of drought and is expected. However, the bimodal nature of the curves (Figure 25) also identifies a tendency for years to be either "dry" or "wet" relative to "normal", a condition that rarely occurs.

Frequencies of drought for May to September (the growing season), 1900 - 1983, were calculated for divisions 3 and 7 (Table 3). These two divisions were chosen as representing the two extremes of the nine divisions. The frequencies are the percent of months in the May to September period in which the PDSI was less than or equal to the indicated values. These values were plotted to give two curves that represent the maximum and minimum frequencies of growing season droughts of varying intensities across Minnesota (Figure 26).

The frequencies of drought by division for the month of July, 1900 - 1983, are shown in Figure 27. July was chosen because it is ordinarily the month when moisture stress on major crops and vegetation reaches a maximum. Values shown are the percent of the time that the July PDSI values were less than or equal to the indicated value during the period. Divisions 4 and 7 have the highest frequency of July droughts, while divisions 2, 3, 6, and 9 generally have the lowest frequencies for each given index value. These values were plotted for divisions 3 and 7 to give two curves that indicate the maximum and minimum frequencies of July droughts across Minnesota (Figure 28).

The distributions of July PDSI values, 1900 - 1985, are presented in Figure 29. The monthly distributions are not normally distributed. Several are positively skewed or bimodal. There is strong serial correlation from one month to the next that may be significant to as long as one year. Dry or wet spells are an accumulation of the condition over time. Therefore, a particular month quite frequently is within one of these periods and the PDSI will reflect a condition that has accumulated during the previous several months. Usually an index value near zero occurs during the transitions between dry and wet periods.

January distributions (Figure 30) are not very different from those for July. The skewness and bimodalism still appear. The distribution for division 3 appears nearly normal in both January and July. Droughts or wet periods are shorter in division 3, allowing for more frequent occurrences of monthly values near zero.

The accumulation of months with a PDSI less than or equal to -1.0 for divisions 3 and 7, 1900 - 1984, were calculated (Figure 31). A steep gradient indicates a period of at least mild drought, and horizontal line segments indicate periods of near normal or wet conditions. The decades of the 1920's and 1930's stand out as a very droughty period of the record. Divisions 3 and 7 were again chosen as representing the extremes across the state. Accumulations for the other divisions can be expected to lie between these two.

The historical accumulations of months with a PDSI value less than or equal to -3.0 for divisions 3 and 7, 1900 - 1984, are depicted in Figure 32. These two divisions were again taken to be the extremes across the state. A non-horizontal portion of the graph indicates a period of at least severe drought. It is apparent that a value of less than or equal to -3.0 is twice as likely in division 7 as in division 3. Also it is apparent that dry and wet periods alternate, although it is difficult to isolate any periodicity. About 80% of the severe drought months in division 7 and about 65% of the severe drought months in division 3 occurred in the first half of the record. This demonstrates the almost radical difference in the moisture climate between the first and last half of the record. Again, the period of the 1920's and 1930's stands out as very droughty.

Seasonality of Drought

The seasonality of drought is defined here as the number of times in 84 years (1900 - 1983) that each month had a PDSI value less than or equal to the critical values for mild, moderate, severe, and extreme drought for divisions 3, 5, 6, and 7. At a level of mild drought, the months of November, December, and January tend to have the highest frequencies. The seasonality at is intensity of drought is not exceptionally pronounced. This slight degree of seasonality is likely due to accumulation of moisture deficits beginning sometime during the summer months. On occasion the index does not become <=-1.0 until late autumn or early winter. The precipitation falling in November and December is often insufficient to alleviate a moisture deficit which may have accumulated during the summer and early autumn months. An increase in drought frequency at this time is not critical as vegetation is dormant and the soil has usually frozen.

At the moderate drought intensity (values <= -2.0) stronger seasonality appears. Divisions 3 and 6 show the strongest seasonality, with late autumn and early winter the driest and early spring the least. In divisions 5 and 7 the peak of seasonal occurrence of moderate drought is in the summer months with the minimum in September and October.

The seasonality of severe drought (values <= -3.0) is more pronounced than that of moderate drought. All 4 divisions show a marked change in drought occurrence throughout the year. Again divisions 5 and 7 peak in summer and divisions 3 and 6 peak in late autumn and winter. The minimums for divisions 5 and 7 occur in winter and in divisions 3 and 6 they occur in spring.

Extreme drought (values <= -4.0) shows a seasonality that is not as pronounced as at the severe level. At this intensity the four divisions act rather independently of each other. Division 3 peaks in late summer and early autumn, with a minimum in late spring. Division 6 peaks in late autumn and winter, with a minimum in summer. Division 5 peaks in late summer, with a minimum in late winter and spring, while division 7 peaks in mid to late spring, with a minimum in winter and early spring.

In general, at all intensity levels, late summer through mid-winter is the peak period of drought occurrence with late winter to early summer the minimum period of drought occurrence. At the moderate, severe, and extreme intensity levels a decrease in the occurrence of drought is noticeable from January to April and May.

Runs of Drought

The longest runs of continuous drought can be summarized by month and by division for the period 1900 - 1983 (Figure 33). This was done for PDSI values ranging from -1.0 to -4.0. With the exception of the mild drought intensity, division 4 has the longest drought period for each intensity. In general, the southwest, west central, and central divisions have the longest runs of drought. A subscript of 2 in the figure indicates that two runs of the same intensity and maximum length occurred.

The mean lengths (in months) of runs of drought with intensities less than or equal to -1.0, -2.0, -3.0, and -4.0 were computed for each division (Figure 34). The number of consecutive months for each indicated severity level that occurred are the third number within each division. The southwest, west central and central divisions have the highest mean length of drought periods. Of interest at the -4.0 intensity is division 7, having the 2nd lowest mean. Although of shorter mean length, division 7 has a greater number of these extreme droughts.

The median length of drought periods of intensities less than or equal to -1.0 through -4.0 for each division, 1900 - 1983, are shown as the second number in Figure 34. The median is the 50% probability value, i.e., one-half of the droughts of a given intensity are shorter than and one-half are longer than the median length. The separation of the mean and median values shows that the length of droughts is not normally distributed. It does show that one-half of the droughts of any intensity last less than 2 to 6 or 7 months. Again, the number of consecutive months of the indicated severity that occurred are the third number within each division. Figure 34 demonstrates that those few drought periods that lasted for months, even years, have separated the means from the medians, skewing the distributions of drought duration. This is most pronounced in the south and west divisions.

Commencement and Termination of Drought

A summary of the beginning and ending of drought periods with a PDSI value of <= -1.0 for each month in each division, 1900 - 1983, is shown in Figure 35. For example, for January in division 1, drought periods began in 3 different years and ended in 2 different years, giving a total of 5 out of 84 years that a drought period began or ended in January. These maps are not meant to be used as a comparison among divisions but as a comparison of months to each other. The months of April through September are the most active months for the beginning and ending of droughts.

Length vs. Severity of Drought

The length versus severity of drought periods was summarized for each division for the period 1900 to 1983 (Table 4). The values summarized are the number of times a drought with a PDSI value less than or equal to the given intensity has lasted as long, or longer than the given length. For example, in division 7 there have been 16 drought periods with an intensity of <= -2.0 and a minimum length of 6 months. It is clear that there is an inverse relationship between length and severity as expected. There is a gradient from northeast to southwest across the state with the shorter and less intense droughts dominant in the northeast and longer and more intense droughts more common in the south and west. Table 4 can be used to estimate the likelihood of lengths and intensities of drought.

The data on length and severity of drought illustrate the persistent nature of drought. This persistence is most crucial during the growing season. To assess the importance of drought during the growing season, the frequency of May PDSI values in the drought categories of mild, moderate, severe, and extreme were tabulated along with the percentages of subsequent Junes, Julys, and Augusts that experience the same or greater intensity of drought (Table 5). The data clearly demonstrate that if a drought is established at the beginning of the growing season the probability is quite high that it will persist through the growing season. If the May drought intensity is in the severe or extreme categories, those most likely to cause substantial economic loss, the chances are fifty percent or better that severe or extreme drought will continue to be indicated by the PDSI through August in divisions 1, 4, 5, 7, and 9. In division 2, 3, and 6, mild and moderate drought is likely to persist through the growing season, but the chances are less than fifty percent that severe and extreme drought will continue to be indicated throughout the entire growing season. Thus, it seems useful to monitor the PDSI in the spring because, based on Table 5, it is possible to estimate the likelihood that drought conditions will continue through the summer.

SUMMARY

From about 1905 to the mid 1930's there was a general decline in the July and summer, (June - August) PDSI for each division and the state as a whole. From the mid 1930's to the mid 1940's there was a rapid recovery to a rather large positive anomaly (wet condition). Although much of the state has, throughout the 1980s, been in a very wet period, no long-term trend in the PDSI for the 9 divisions or the state as a whole can be detected.

The range of the PDSI in Minnesota is asymmetrical, with the absolute value of the extreme minimums greater than the maximums. Division 7 in the past year (1986) has become asymmetrical on the positive side with a value of +8.1 compared with -7.2 for the minimum. In 1986, 6 of the 9 divisions set new record maximums, reducing the asymmetry for the state as a whole and illustrating the very wet nature of the past few years.

The mean and median of monthly PDSI values show a high positive anomaly in divisions 1 and 2, which would indicate that more frequently than not these divisions have adequate to surplus moisture. The means show an increase from August to October in all divisions. The medians show an increase during the same months in all divisions but 4 and 5. The season of lowest monthly means shows a smooth transition across the state, from January through March in division

3, to June through August in division 7. The median values in all divisions show a general trend toward zero through the winter. The winter season acts to moderate extreme moisture conditions that may have developed the previous growing season.

The duration of droughts tends to be longest in west-central, central, and southwestern Minnesota. The variation of the mean length of drought periods across the state is large. For a moderate drought (PDSI <= -2.0) the average length ranges from greater than 11 months in the southwestern division to less than 5 months in the northeastern division. The median lengths of drought periods show no real trend across the state, varying from 2 to as long as 7 months. When looking at moderate or more intense droughts, the southwestern division has higher mean and median values, but the number of drought periods in the sample is less in this division than in the other divisions.

Generally, a drought that has become established by May is persistent through the following summer. This relationship, which may have prognostic value, is strongest in the southern and western divisions. Those divisions north and east of the "tension zone" tend to have a higher frequency of precipitation amounts sufficient to quickly end a drought as well as support the forest cover. More work could be done with wet Aprils and Mays, separately or in combination, using the results to establish the probabilities of wet summers.

No work was done with wet periods in the record. Wet periods in some respects are capable of causing as much hardship as drought periods. Whether they behave like drought periods, as far as probabilities, duration, and any prognostic value are concerned, has yet to be determined.

LITERATURE CITED

Baker, D. G., W. W. Nelson, and E. L. Kuehnast, 1979, *Climate of Minnesota, Part XII - The Hydrologic Cycle and Soil Water*, Tech. Bull. 322. University of Minn. Ag. Exp. Station.

Blake, G. R., E. R. Allred, C. H. M. van Bavel, and F. D. Whisler, 1960, *Agricultural Drought and Moisture Excess in Minnesota*, Tech. Bull. 235. University of Minn. Ag. Exp. Station, in Cooperation with ARS, USDA.

Huschke, R. E., ed., 1959, *Glossary of Meteorology*, American Meteorological Society, Boston, Mass., 638 pp.

Palmer, Wayne C. 1965, *Meteorological Drought*, Research paper no. 45, U.S. Department of Commerce, Weather Bureau, Washington, DC.

U.S. Dept. of Commerce, 1981, *Climatography of the U.S.*, no. 85. Divisional Normals and Standard Deviations of Temp and Precipitation 1931 - 80. NOAA - EDIS - NCDC, Asheville, N.C.

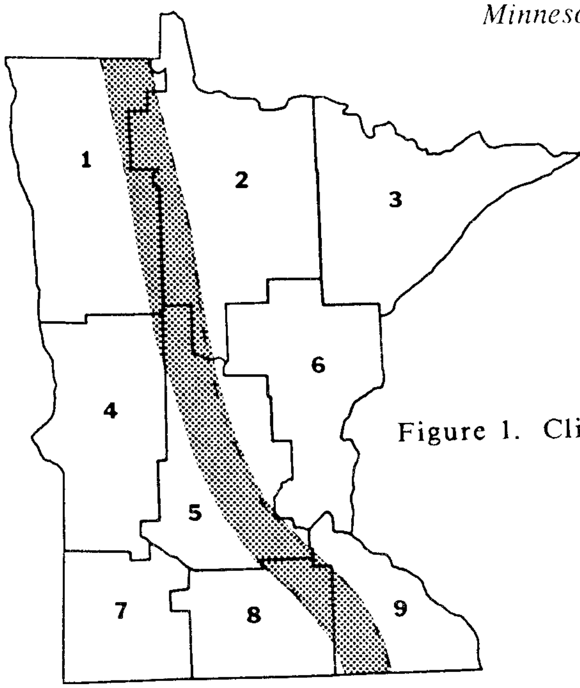


Figure 1. Climatological Divisions of Minnesota.

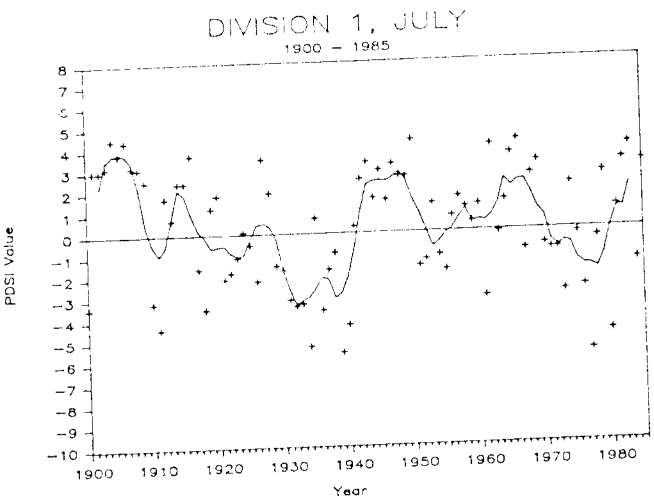


Figure 2. July observed and smoothed PDSI

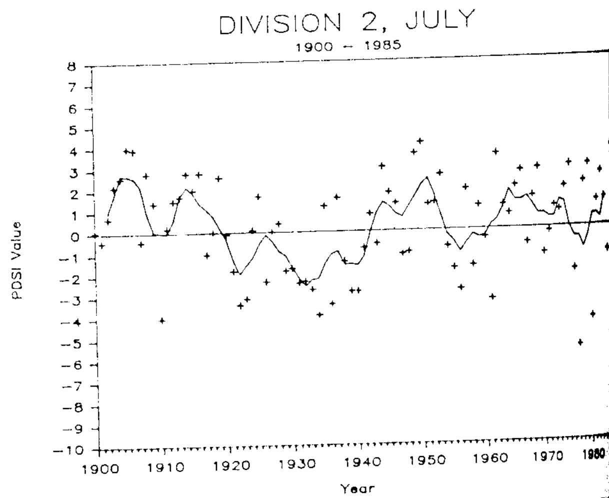


Figure 3. July observed and smoothed PDSI

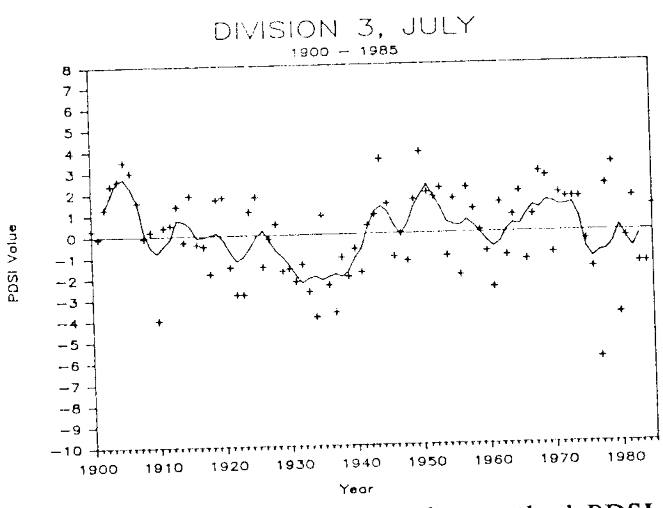


Figure 4. July observed and smoothed PDSI

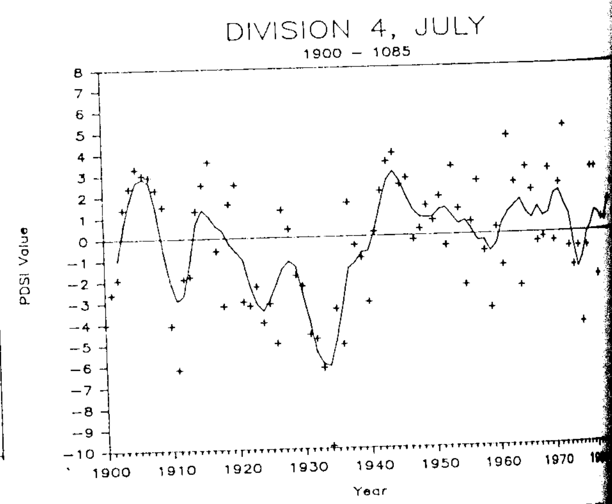


Figure 5. July observed and smoothed PDSI

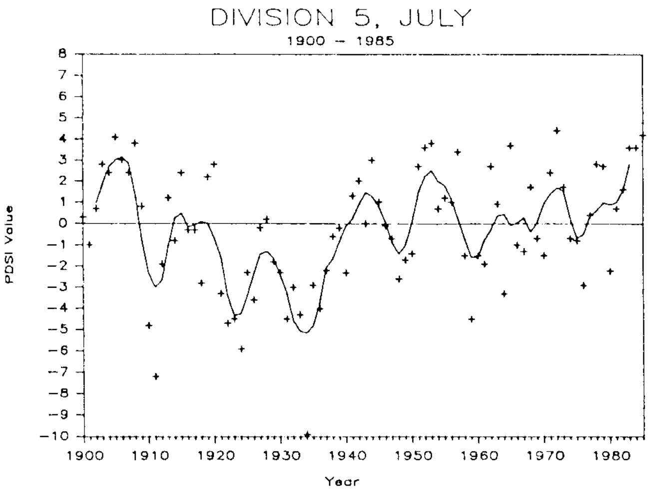


Figure 6. July observed and smoothed PDSI

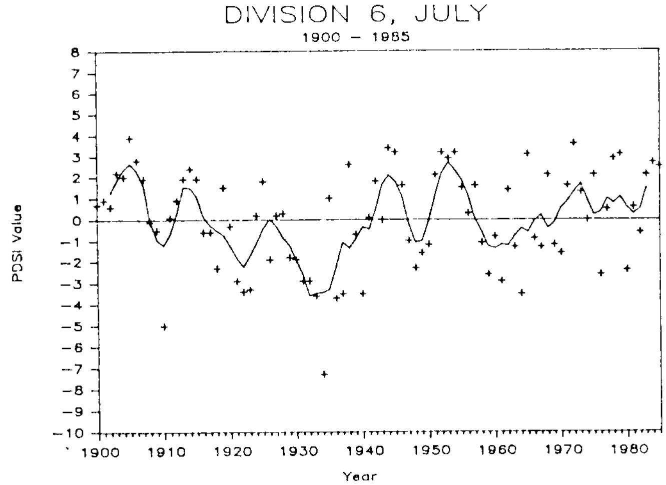


Figure 7. July observed and smoothed PDSI

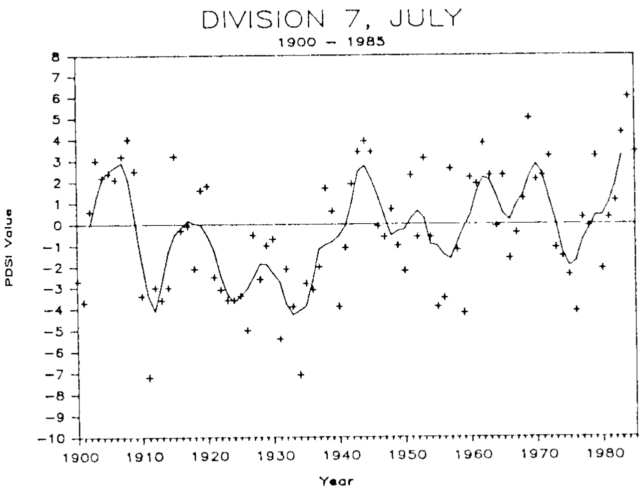


Figure 8. July observed and smoothed PDSI

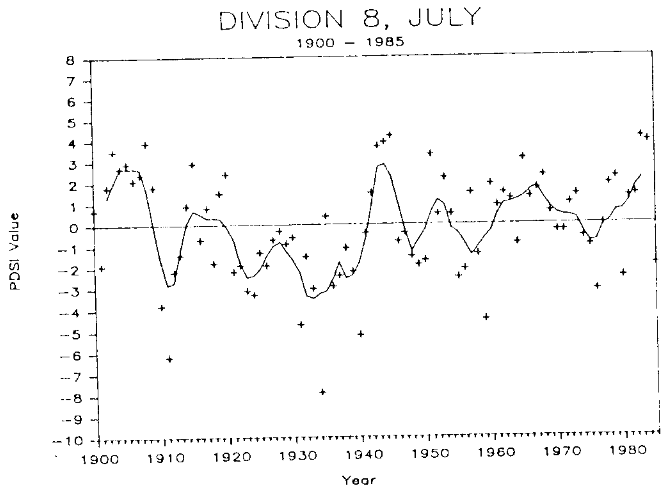


Figure 9. July observed and smoothed PDSI

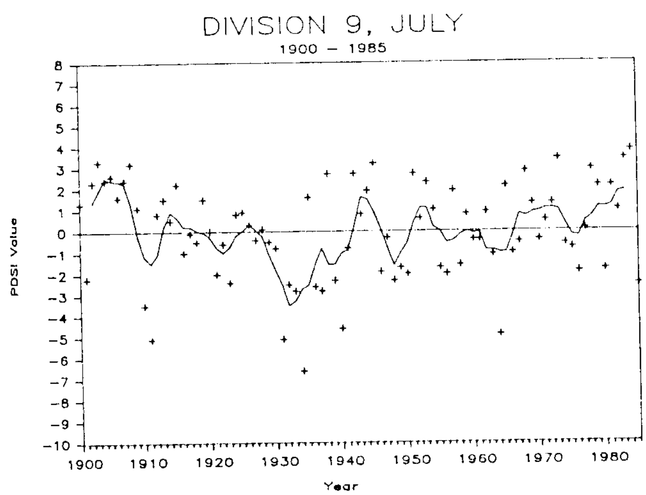


Figure 10. July observed and smoothed PDSI

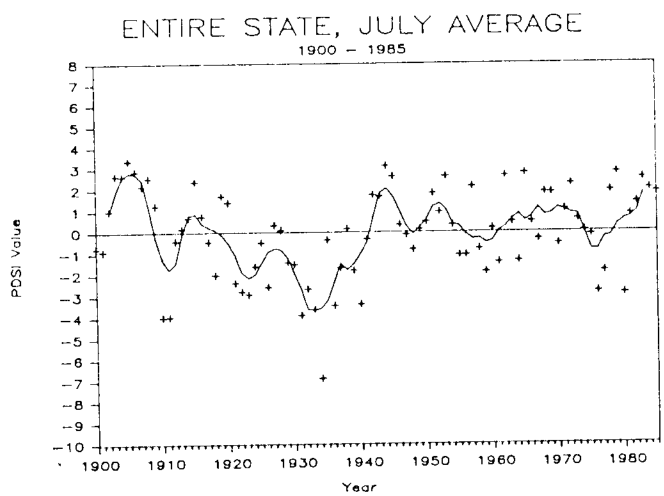


Figure 11. July observed and smoothed PDSI

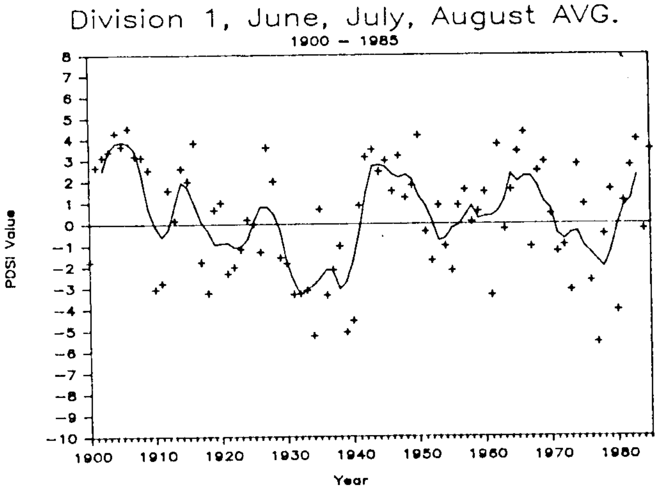


Figure 12. Summer observed and smoothed PDSI

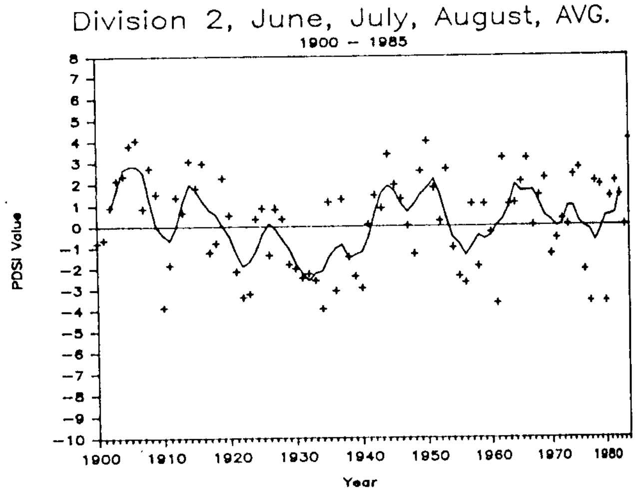


Figure 13. Summer observed and smoothed PDSI

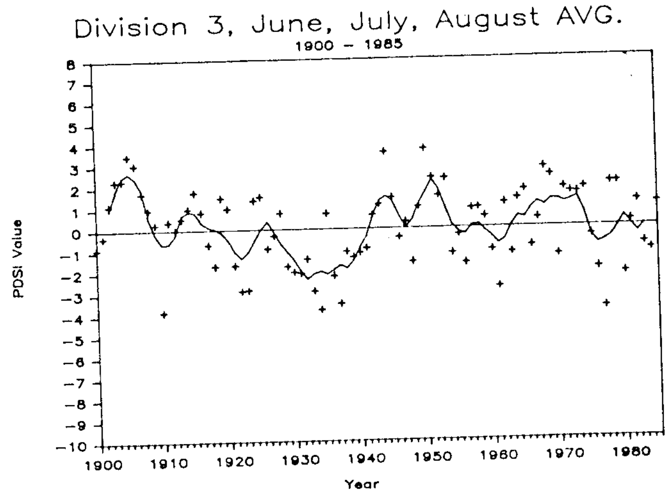


Figure 14. Summer observed and smoothed PDSI

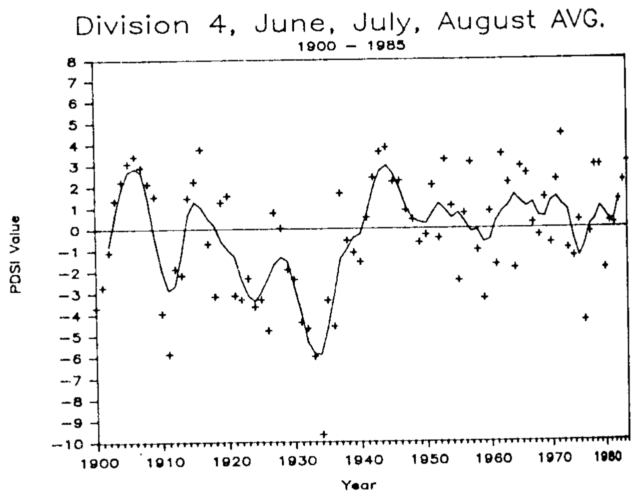


Figure 15. Summer observed and smoothed PDSI

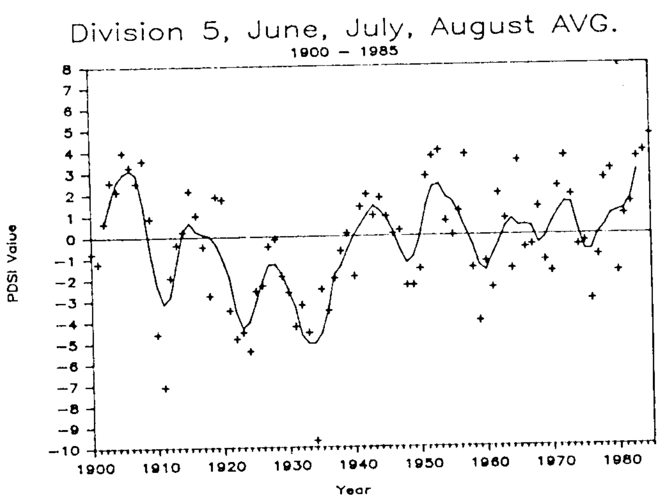


Figure 16. Summer observed and smoothed PDSI

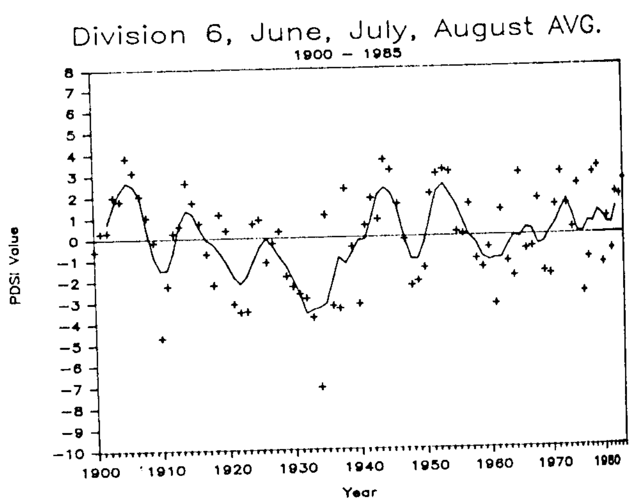


Figure 17. Summer observed and smoothed PD

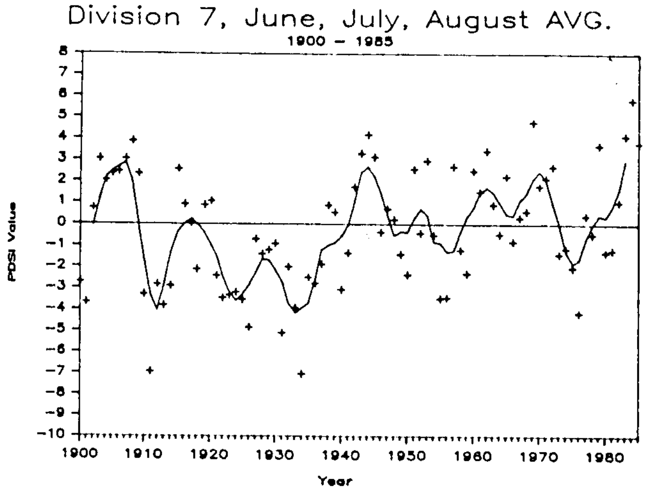


Figure 18. Summer observed and smoothed PDSI

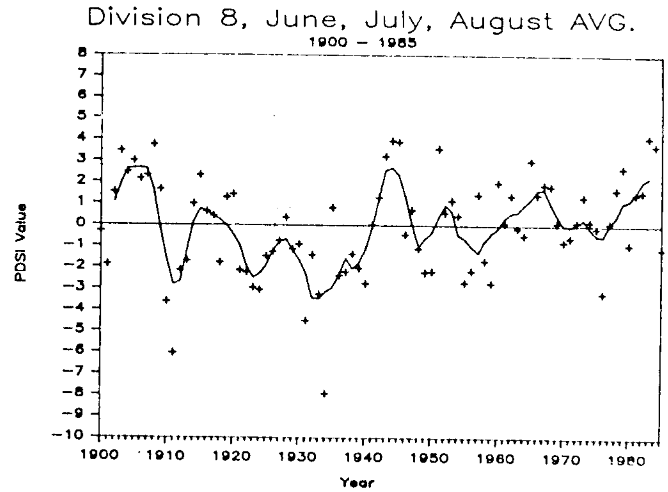


Figure 19. Summer observed and smoothed PDSI

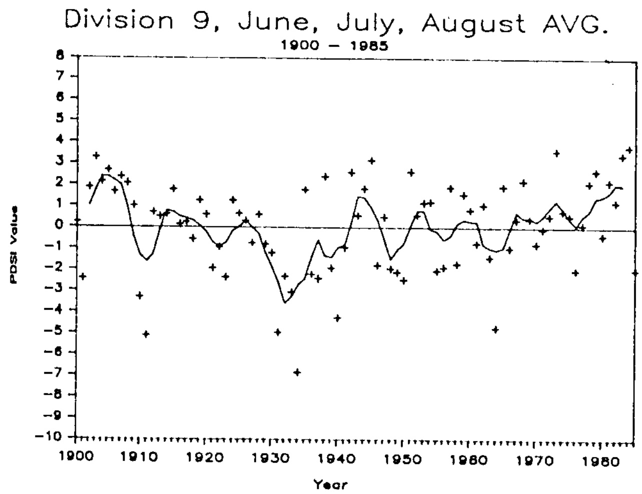


Figure 20. Summer observed and smoothed PDSI

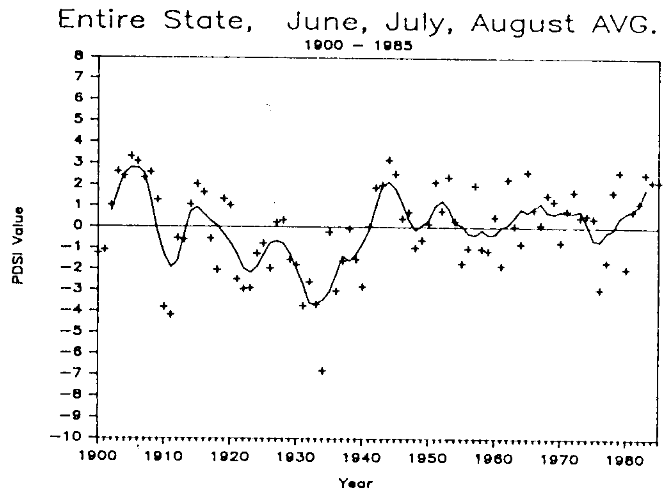


Figure 21. Summer observed and smoothed PDSI

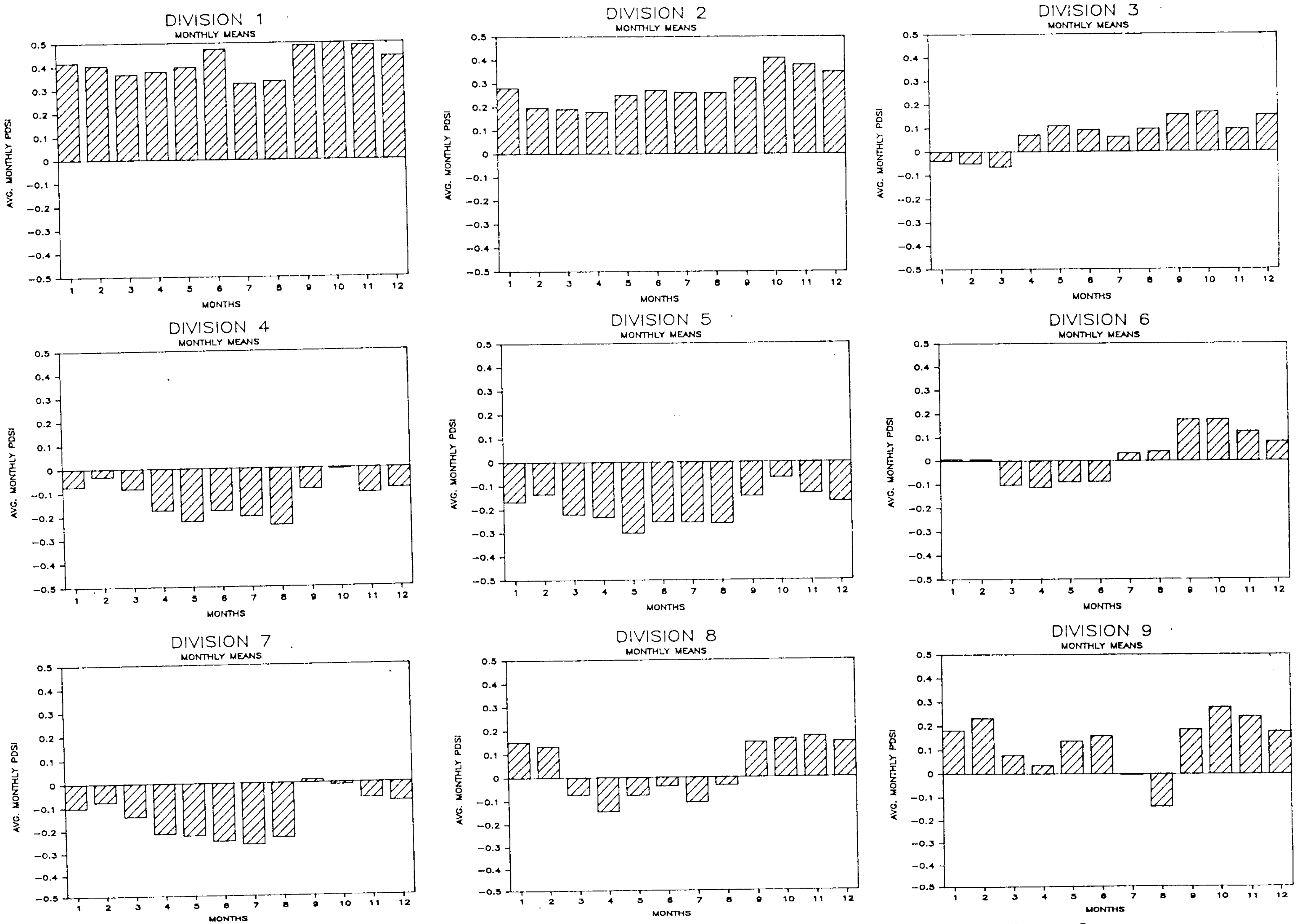


Figure 22. Monthly mean PDSI values, 1900 - 1985. The vertical axis is scaled from -.5 to +.5. The horizontal axis is months from January (1) to December (12).

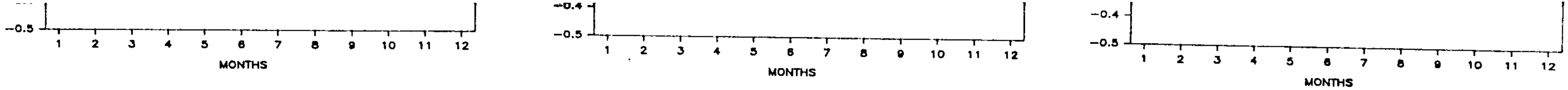


Figure 22. Monthly mean PDSI values, 1900 - 1985. The vertical axis is scaled from -.5 to +.5. The horizontal axis is months from January (1) to December (12).

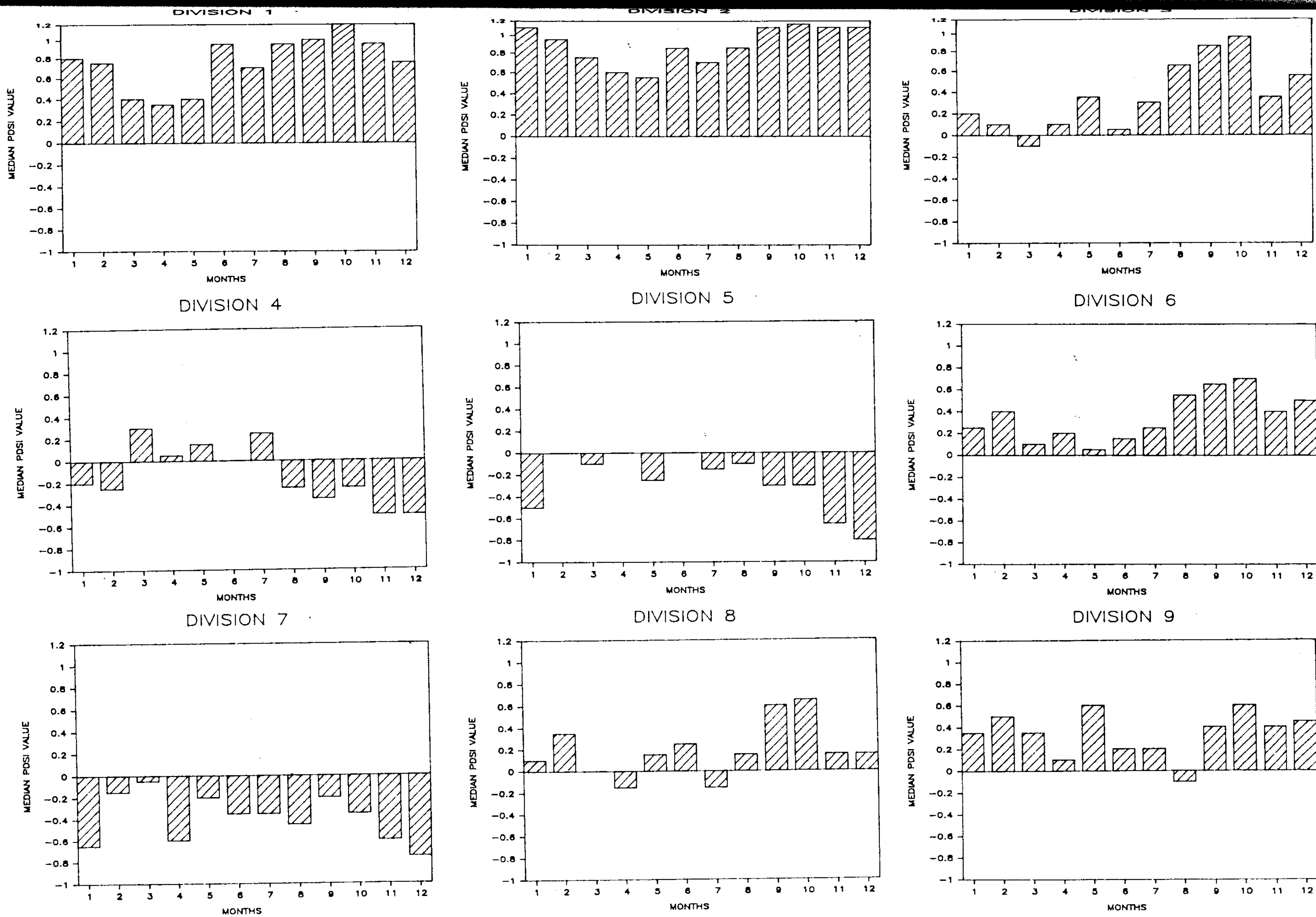


Figure 23. Monthly median PDSI values, 1900 - 1985. The vertical axis is scaled from -.5 to +.5. The horizontal axis is months from January (1) to December (12).

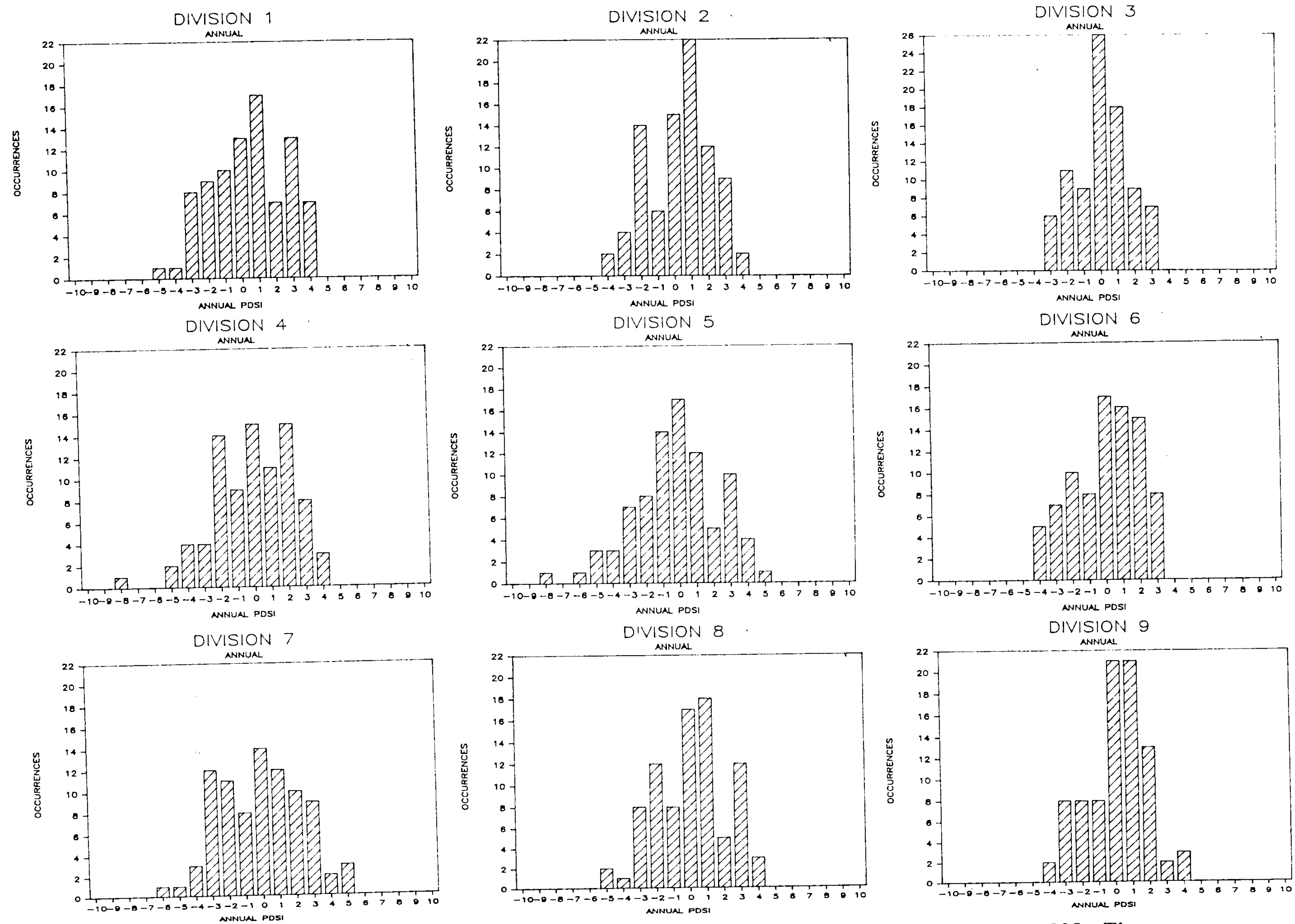


Figure 24. The frequency distributions of average annual PDSI values, 1900 - 1985. The

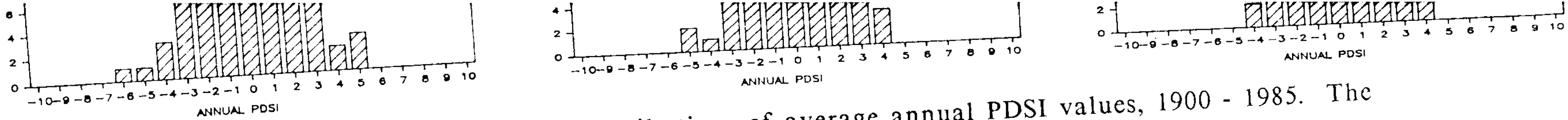


Figure 24. The frequency distributions of average annual PDSI values, 1900 - 1985. The vertical axis is scaled 0 to 22, except for division 3.

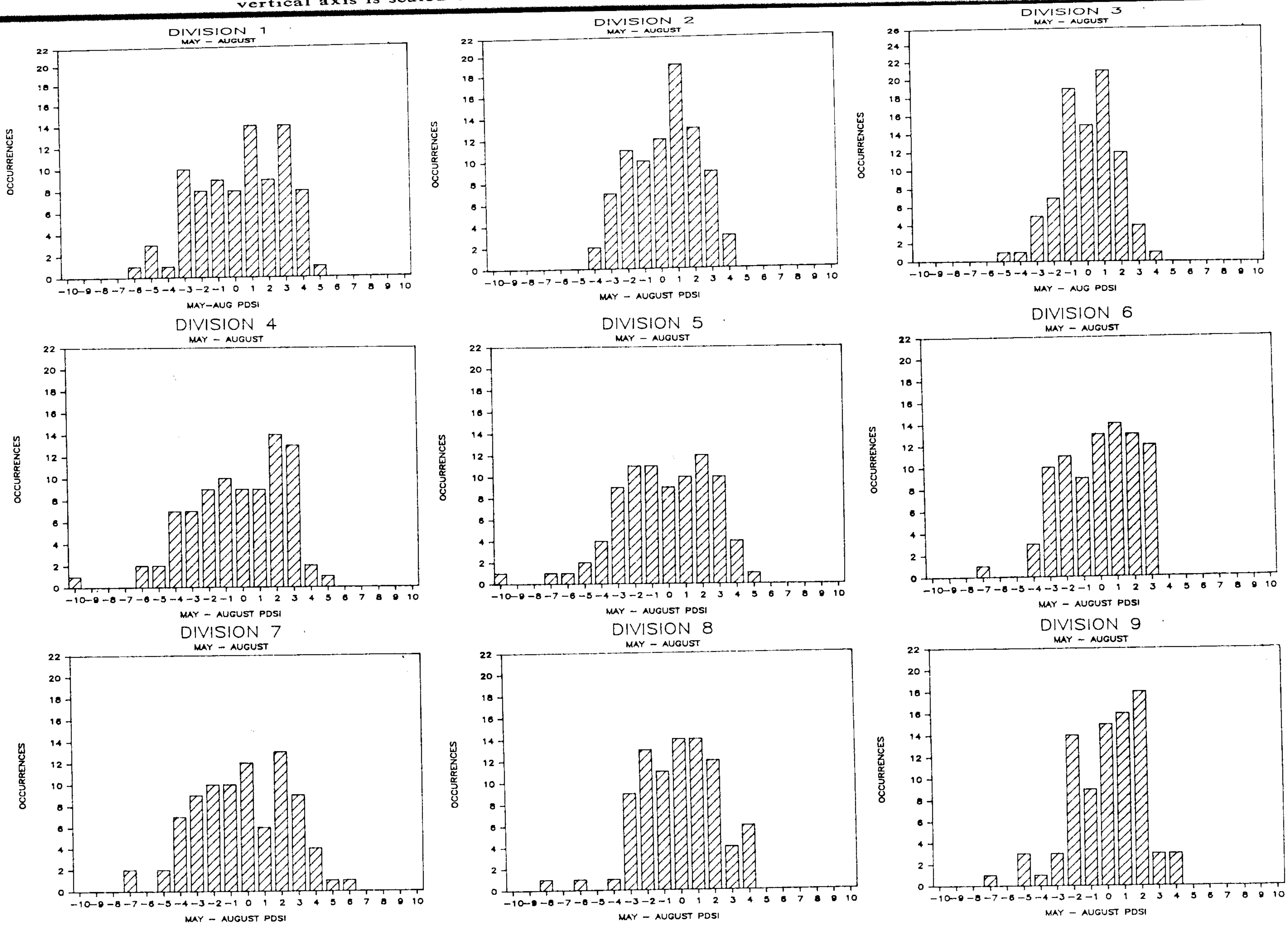


Figure 25. The frequency distributions of May through August PDSI values, 1900 - 1985. The vertical axis is scaled 0 to 22.

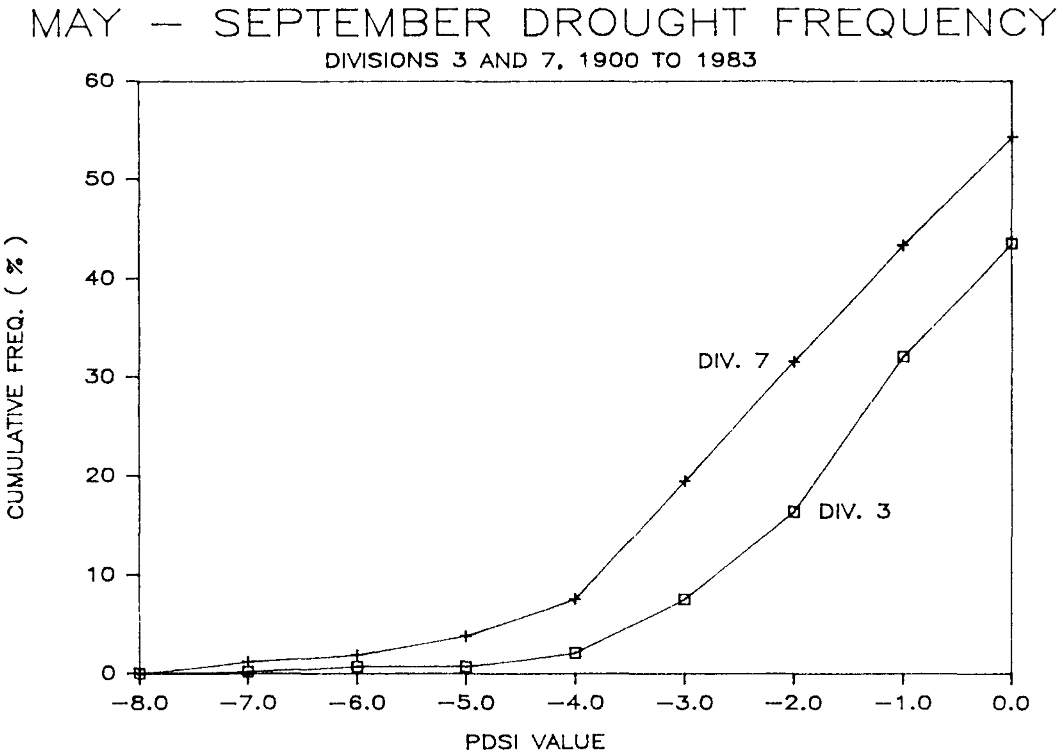


Figure 26. Cumulative percentage of May to September PDSI values for divisions 3 and 7, 1900 - 1983 .

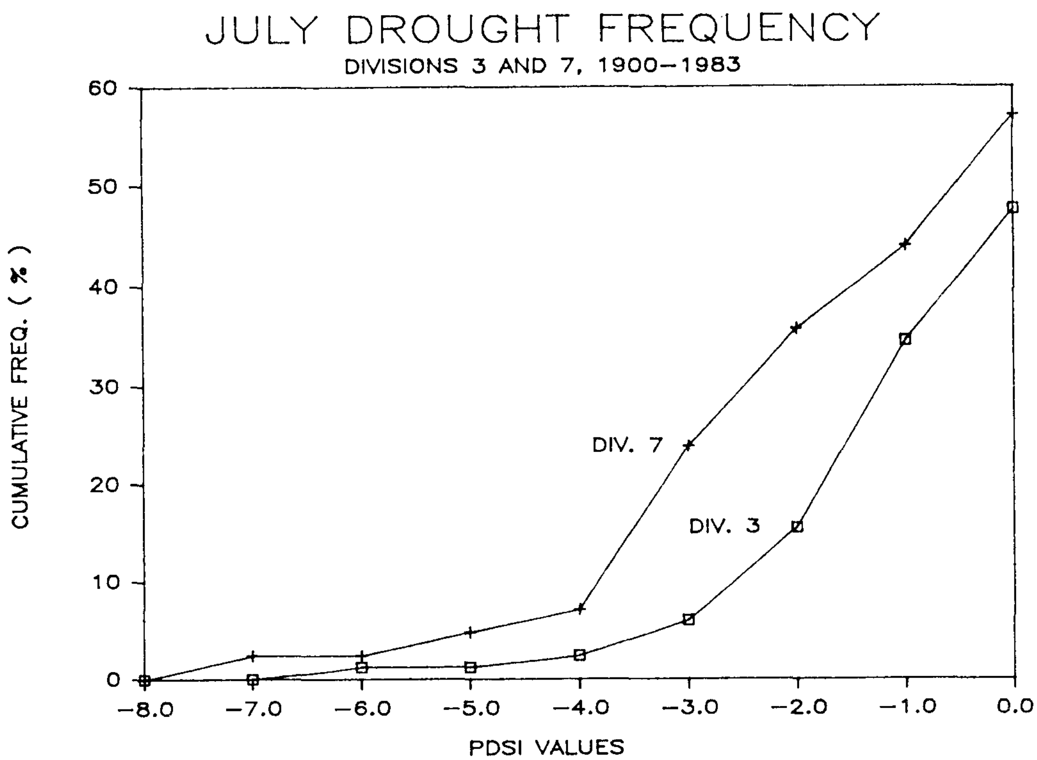
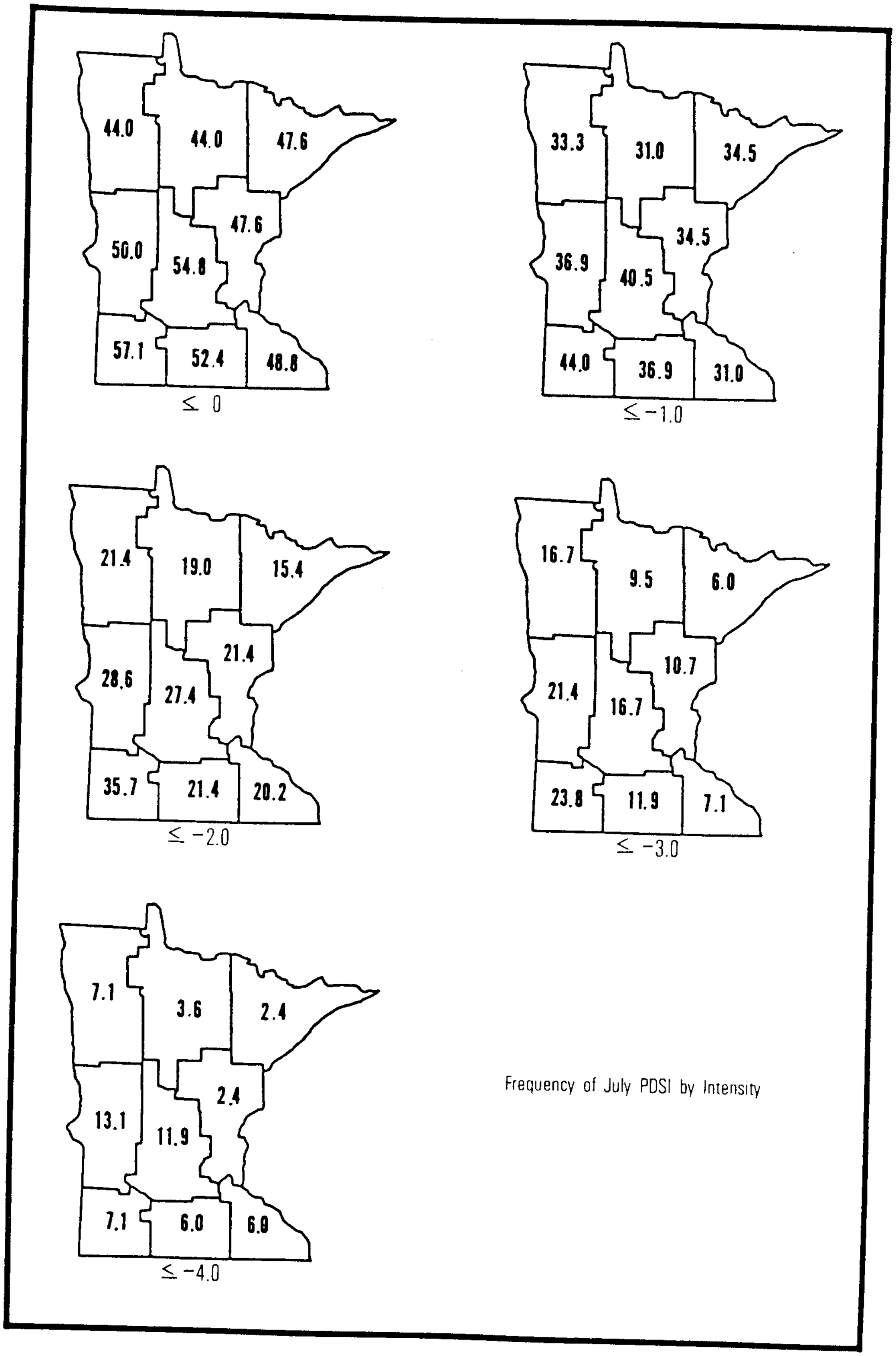


Figure 28. Cumulative percentage of July PDSI values for divisions 3 and 7, 1900 - 1983 .

and 7,

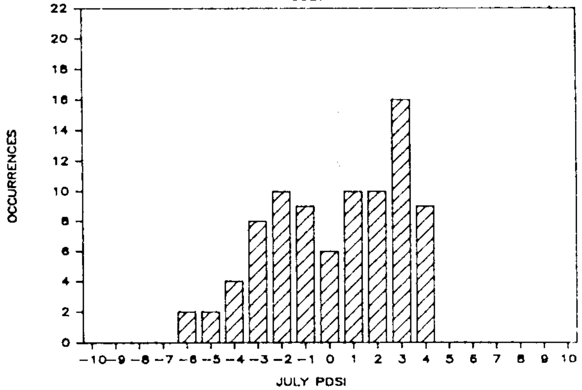


Frequency of July PDSI by Intensity

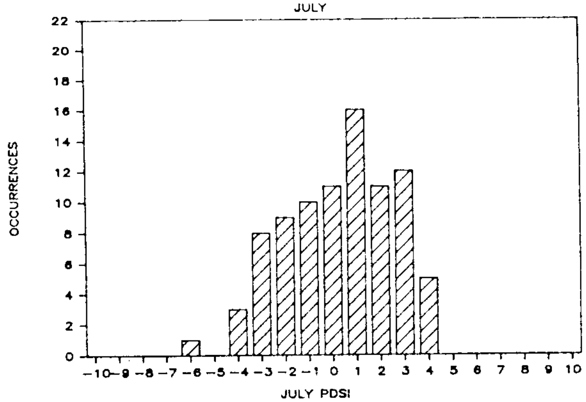
Figure 27.

13 .

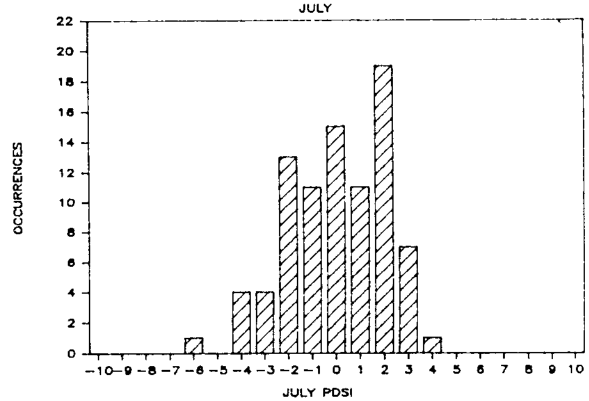
DIVISION 1
JULY



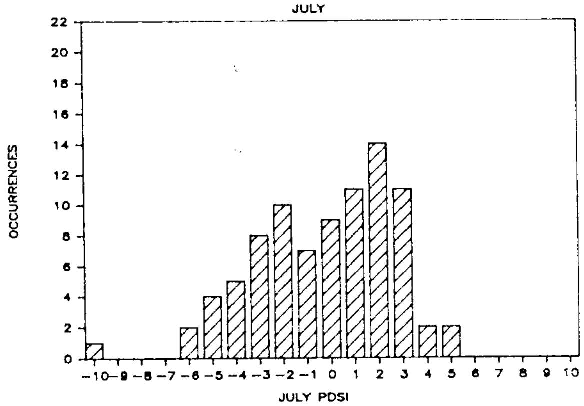
DIVISION 2
JULY



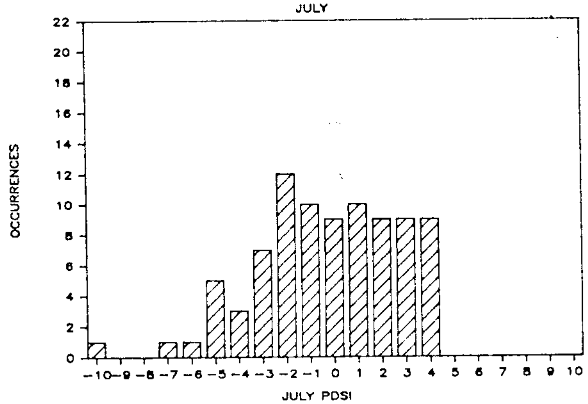
DIVISION 3
JULY



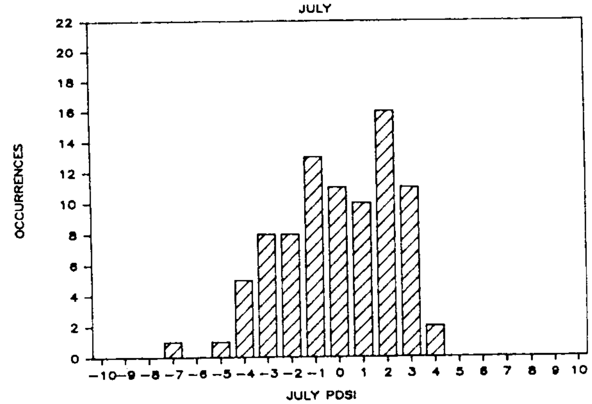
DIVISION 4
JULY



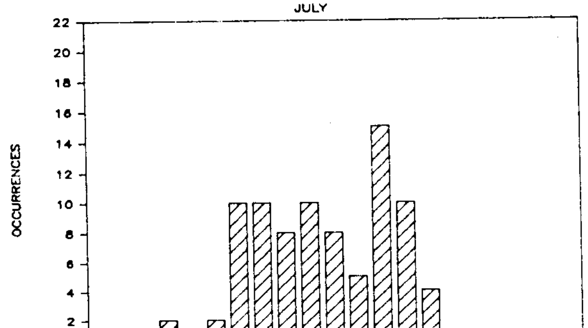
DIVISION 5
JULY



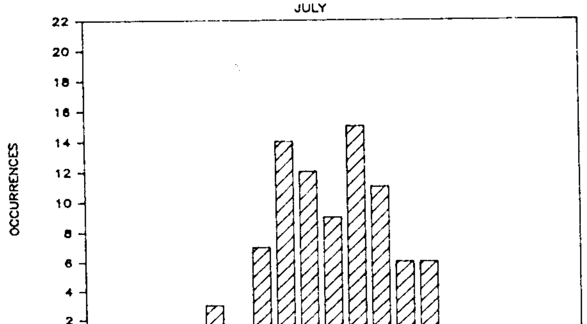
DIVISION 6
JULY



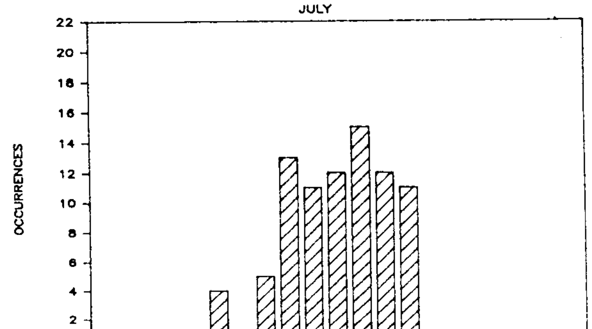
DIVISION 7
JULY



DIVISION 8
JULY



DIVISION 9
JULY



JULY PDSI JULY PDSI JULY PDSI

Figure 29. The frequency distributions of July PDSI values, 1900 - 1985. The vertical axis is scaled 0 to 22.

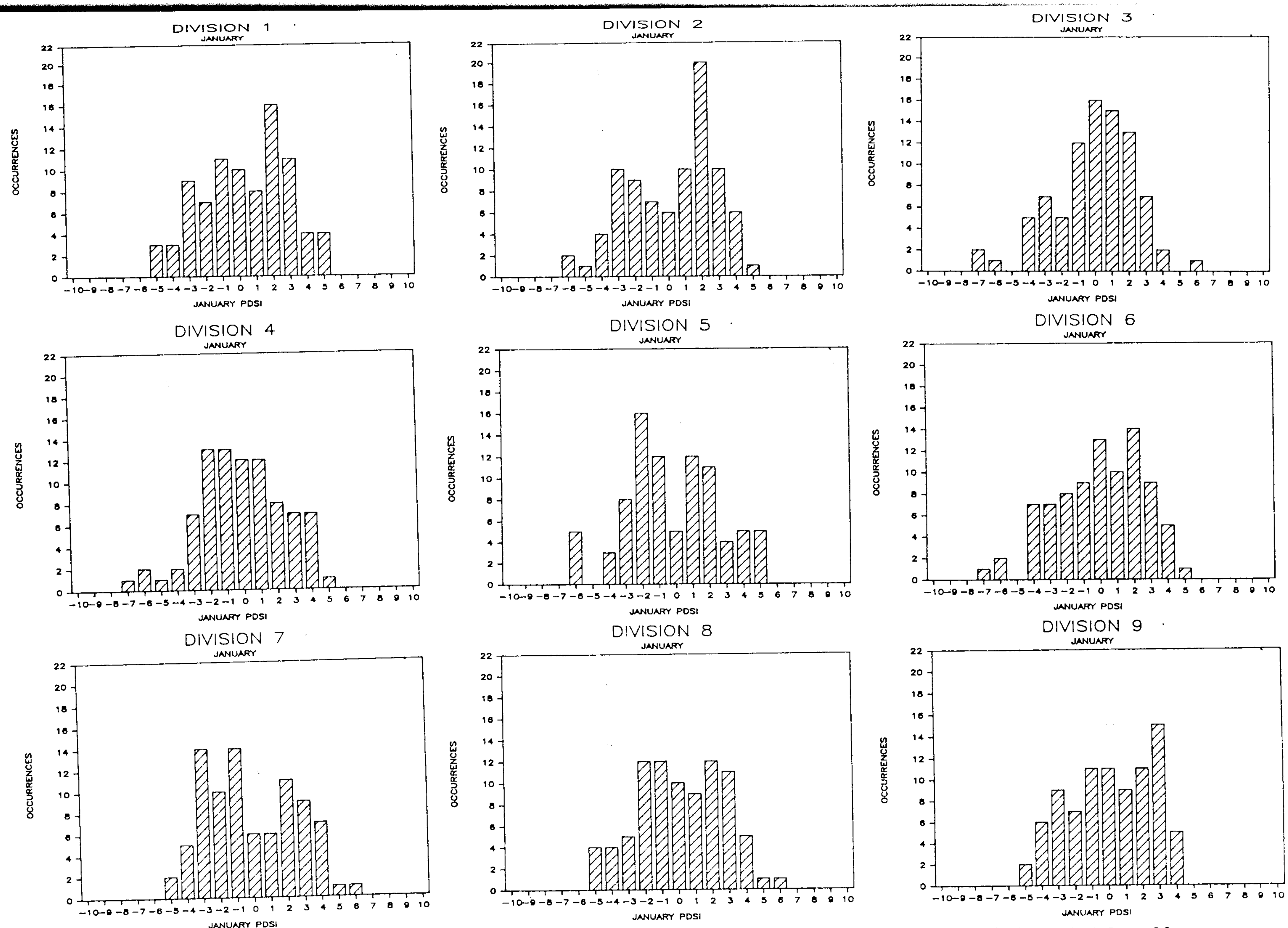


Figure 30. The frequency distributions of January PDSI values, 1900 - 1985. The vertical axis is scaled 0 to 22.

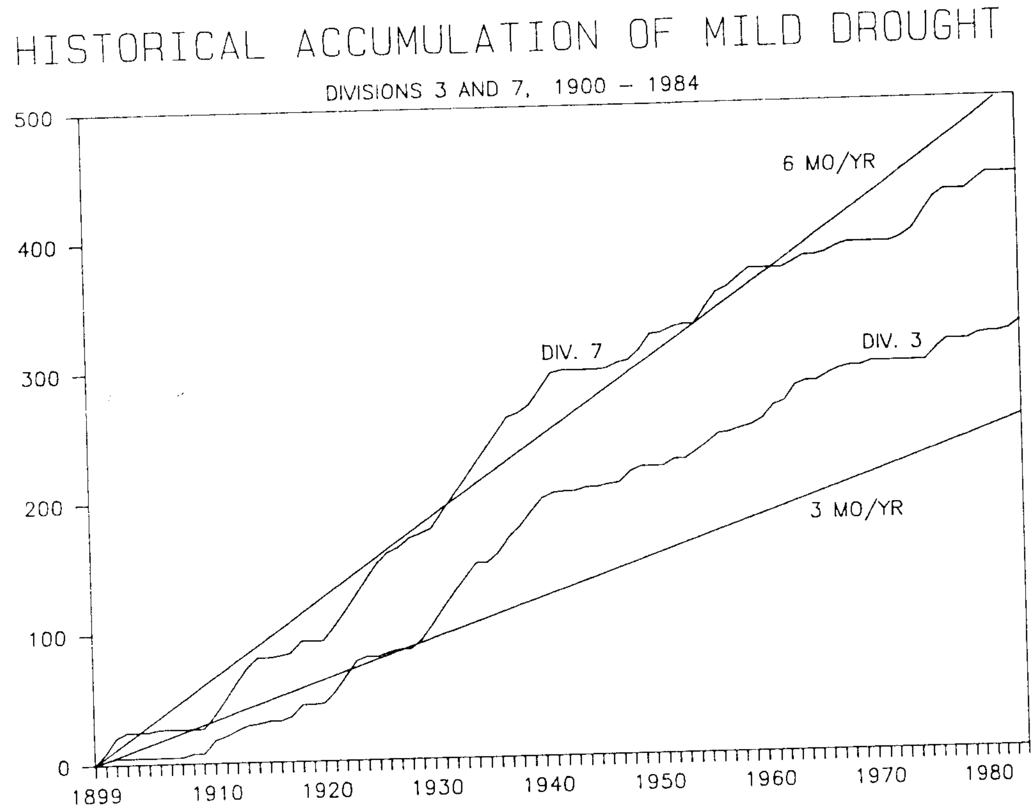


Figure 31. The historical accumulation of months with at least mild drought, divisions 3 and 7, 1900 - 1984. The constant accumulation rates of 6 months and 3 months per year are included for reference.

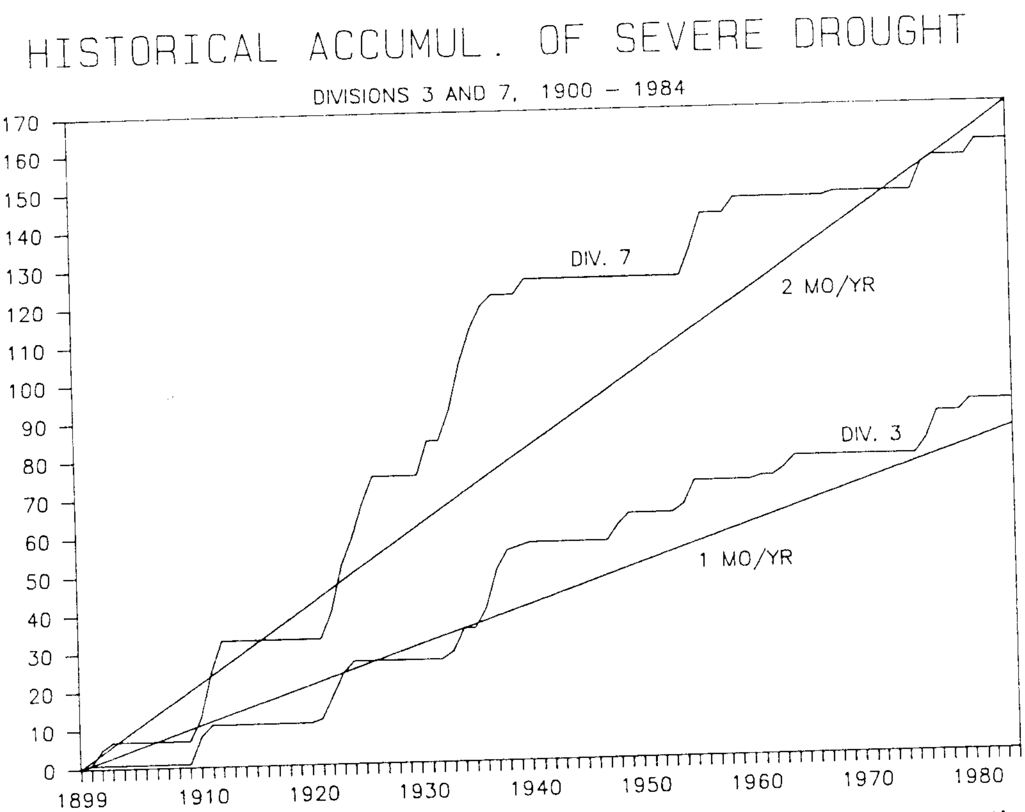


Figure 32. The historical accumulation of months with at least severe drought, divisions 3 and 7, 1900 - 1984. The constant accumulation rates of 6 months and 3 months per year are included for reference.

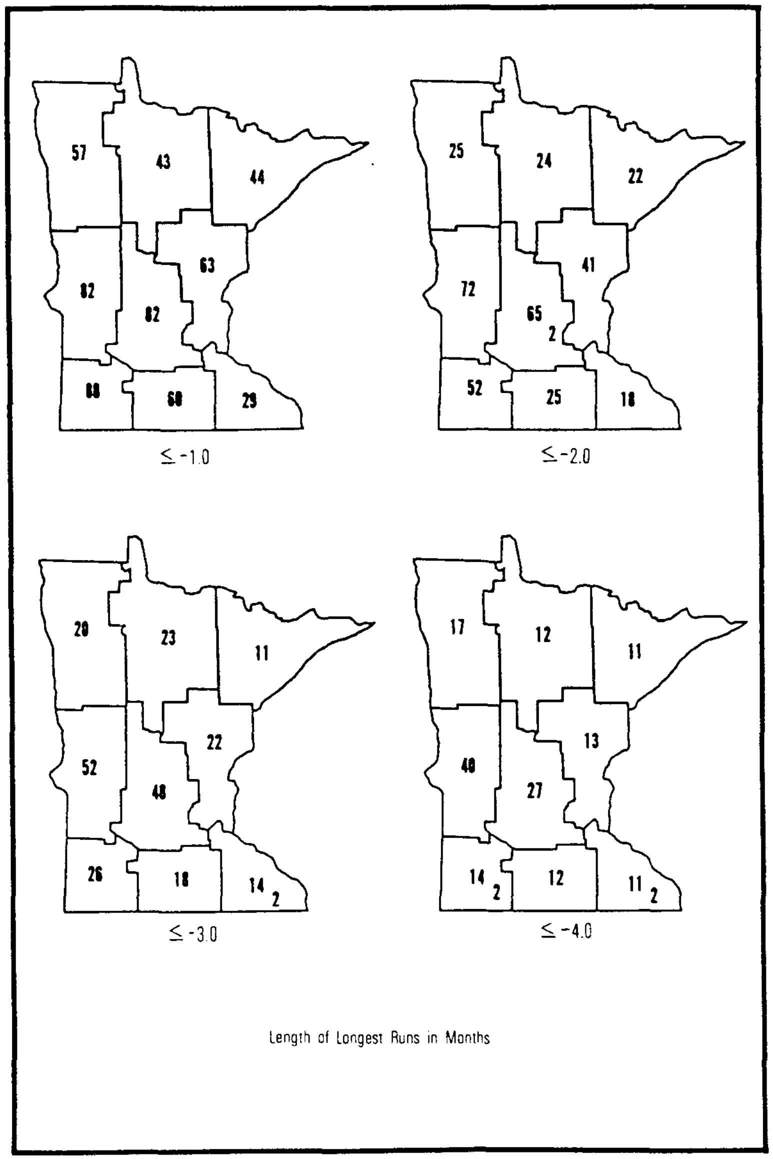


Figure 33.

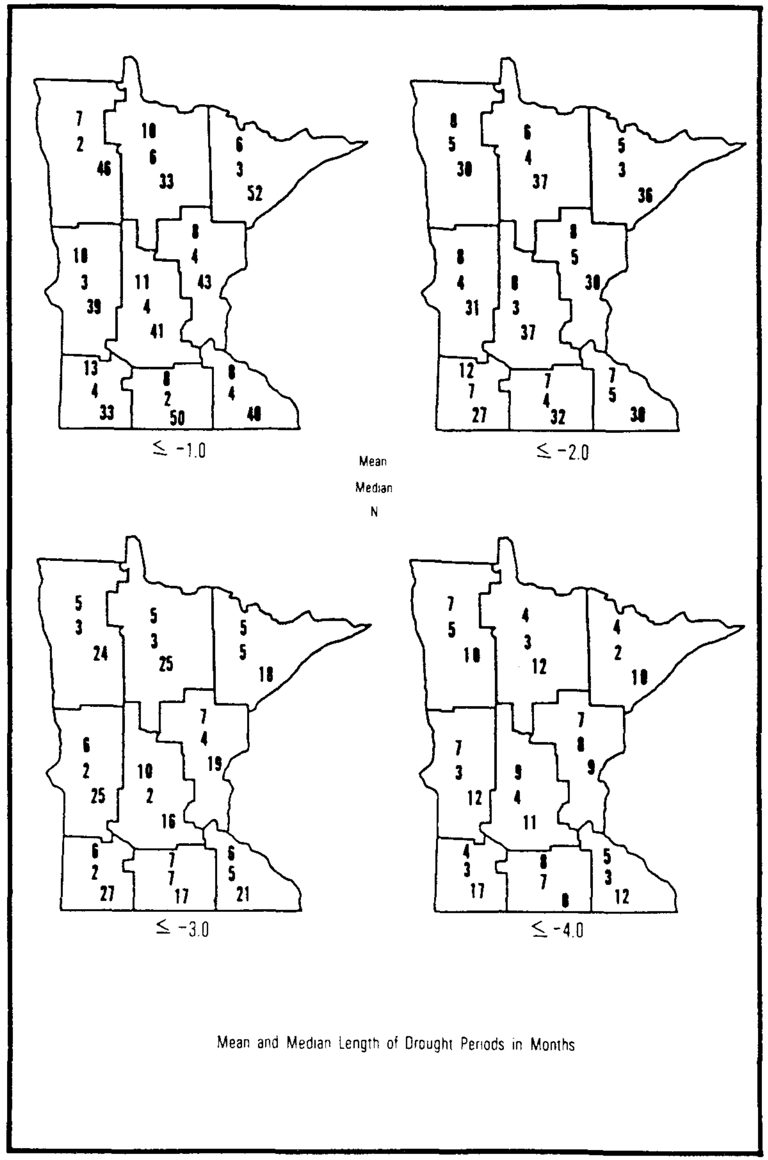


Figure 34.

Beginning and Ending Months of Drought Periods

Figure 35.

TABLE 1: MAXIMA AND MINIMA OF THE PALMER DROUGHT SERVERITY INDEX

CLIMATIC DIVISION	MAXIMUM	MO/YR	MO/YR	MO/YR	MINIMUM	MO/YR
1	5.9	10/03			-6.0	9/34
2	5.6	11/05			-7.0	3-4/11
3	5.7	1/69			-7.8	2/77
4	5.2*	9/65	5/72		-9.9	7-8/34
5	5.2*	9/65			-9.9	7/34
6	4.9*	11/05	12/65	1/69	-8.0	4/11
7	6.5*	2/69			-7.2	7/11
8	5.8*	1/69			-8.0	8/34
9	4.8*	10/03			-7.1	6/34
* 4)	7.0	9/86				
* 5)	7.0	9/86				
* 6)	6.3	9/86				
* 7)	8.1	9/86				
* 8)	6.1	10/86				
* 9)	4.9	9/86				

* indicates PDSI values for 1986 that were not part of the anlaysis exceeded the maximum values during the analysis period.

TABLE 2: ANNUAL PROBABILITY OF DROUGHT BY SEVERITY

Frequency of months with occurrences exceeding the indicated values.

SEVERITY	CLIMATIC DIVISION 1	2	3	4	5	6	7	8	9
-1.0	33.0	32.3	31.9	38.5	42.9	34.4	43.7	37.6	31.3
-2.0	22.1	23.1	17.6	25.6	29.9	23.7	31.1	20.9	20.4
-3.0	12.5	12.4	9.1	14.5	15.4	13.2	17.3	12.1	12.4
-4.0	6.5	5.2	3.8	8.7	9.4	6.2	7.2	6.5	5.4

TABLE 3: PERCENTAGE AND CUMULATIVE PERCENTAGE OF PDSI MONTHS BY LEVEL OF SEVERITY: MINNESOTA CSD 3 AND 7, MAY THROUGH SEPTEMBER

PDSI VALUE RANGE	DIVISION 3 %	DIVISION 3 CUM. %	DIVISION 7 %	DIVISION 7 CUM. %
-8.9 to -8.0	0.0	0.0	0.0	0.0
-7.9 to -7.0	0.2	0.2	1.2	1.2
-6.9 to -6.0	0.5	0.7	0.7	1.9
-5.9 to -5.0	0.0	0.7	1.9	3.8
-4.9 to -4.0	1.4	2.1	3.8	7.6
-3.9 to -3.0	5.5	7.6	11.9	19.5
-2.9 to -2.0	8.8	16.4	12.1	31.6
-1.9 to -1.0	15.7	32.1	11.7	43.3
- .9 to - .1	11.4	43.5	11.0	54.3

Table 4. FREQUENCY OF DROUGHT BY SEVERITY AND DURATION FOR MINNESOTA CLIMATOLOGICAL SUBDIVISIONS

DIV. 1

			SEVERITY					
		MO	0	-1	-2	-3	-4	-5
M	L	1	33	46	30	24	10	9
I	E	2	31	30	25	17	7	6
N	N	3	27	23	23	14	6	6
	G	6	22	18	14	6	5	0
	T	9	19	12	9	*	*	*
	H	12	15	10	8	4	2	*
		18	9	5	*	*	*	*

DIV. 2

			SEVERITY					
		MO	0	-1	-	-3	-4	-5
M	L	1	40	33	37	25	12	5
I	E	2	36	25	31	16	6	4
N	N	3	32	22	25	13	6	3
	G	6	24	17	16	7	4	2
	T	9	15	13	9	*	*	*
	H	12	13	11	7	3	1	*
		18	6	5	*	*	*	*

DIV. 3

			SEVERITY					
		MO	0	-1	-2	-3	-4	-5
M	L	1	50	52	36	18	10	3
I	E	2	43	37	26	14	6	3
N	N	3	40	28	21	12	5	3
	G	6	28	16	11	9	3	2
	T	9	17	11	5	*	*	*
	H	12	14	10	3	0	0	*
		18	8	4	*	*	*	*

DIV. 4

			SEVERITY					
		MO	0	-1	-	-3	-4	-5
M	L	1	40	39	31	25	12	6
I	E	2	37	30	22	17	10	4
N	N	3	32	23	18	12	7	4
	G	6	23	14	11	7	4	3
	T	9	16	11	7	*	*	*
	H	12	13	10	3	2	2	*
		18	7	5	*	*	*	*

DIV. 5

			SEVERITY					
		MO	0	-1	-2	-3	-4	-5
M	L	1	37	41	37	16	11	8
I	E	2	34	31	28	9	9	6
N	N	3	28	26	21	8	7	5
	G	6	27	17	13	7	5	3
	T	9	17	13	6	*	*	*
	H	12	13	8	6	4	3	*
		18	6	6	*	*	*	*

DIV. 6

			SEVERITY					
		MO	0	-1	-	-3	-4	-5
M	L	1	50	43	30	19	9	6
I	E	2	42	33	26	15	8	4
N	N	3	38	24	17	12	6	4
	G	6	26	17	15	8	5	4
	T	9	16	13	11	*	*	*
	H	12	13	11	9	4	2	*
		18	10	3	*	*	*	*

DIV. 7

			SEVERITY					
		MO	0	-1	-2	-3	-4	-5
M	L	1	39	33	27	27	17	7
I	E	2	34	27	24	19	10	4
N	N	3	28	22	23	13	9	4
	G	6	21	14	16	10	4	2
	T	9	16	12	11	*	*	*
	H	12	12	9	8	5	2	*
		18	8	8	*	*	*	*

DIV. 8

			SEVERITY					
		MO	0	-1	-	-3	-4	-5
M	L	1	45	50	32	17	8	6
I	E	2	38	32	25	13	8	5
N	N	3	31	·24	17	11	8	4
	G	6	23	14	14	10	7	2
	T	9	13	12	11	*	*	*
	H	12	11	10	8	3	2	*
		18	8	7	*	*	*	*

DIV. 9

			SEVERITY					
		MO	0	-1	-2	-3	-4	-5
M	L	1	49	40	30	21	12	6
I	E	2	45	28	20	16	9	5
N	N	3	39	26	19	15	8	3
	G	6	27	18	15	9	5	0
	T	9	16	12	12	*	*	*
	H	12	12	12	7	4	0	*
		18	9	8	*	*	*	*

Table 5. Persistence of May PDSI values

DIV. 1

PDSI	# OF MAYS	JUNE %	JULY %	AUG. %
-1	28	82	82	76
-2	18	83	67	61
-3	8	75	75	50
-4	6	83	83	67

DIV. 2

PDSI	# OF MAYS	JUNE %	JULY %	AUG. %
-1	29	90	66	59
-2	17	83	53	53
-3	6	75	50	33
-4	4	83	25	25

DIV. 3

PDSI	# OF MAYS	JUNE %	JULY %	AUG. %
-1	23	87	74	56
-2	12	58	58	42
-3	3	100	67	0
-4	1	100	100	0

DIV. 4

PDSI	# OF MAYS	JUNE %	JULY %	AUG. %
-1	33	91	85	82
-2	27	85	81	74
-3	12	83	75	67
-4	9	67	67	56

DIV. 5

PDSI	# OF MAYS	JUNE %	JULY %	AUG. %
-1	38	89	79	71
-2	28	96	71	61
-3	12	83	75	67
-4	6	83	67	67

DIV. 6

PDSI	# OF MAYS	JUNE %	JULY %	AUG. %
-1	29	93	76	59
-2	18	94	72	67
-3	8	88	63	38
-4	3	100	33	33

DIV. 7

PDSI	# OF MAYS	JUNE %	JULY %	AUG. %
-1	34	97	91	85
-2	26	92	96	88
-3	14	79	86	71
-4	7	71	43	43

DIV. 8

PDSI	# OF MAYS	JUNE %	JULY %	AUG. %
-1	32	84	81	72
-2	16	81	75	63
-3	9	78	78	44
-4	7	57	57	29

DIV. 9

PDSI	# OF MAYS	JUNE %	JULY %	AUG. %
-1	23	87	83	83
-2	12	67	75	67
-3	7	71	71	71
-4	5	80	80	60