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Temporal Distribution of Midwestern Precipitation during the 20th Century

by
Stanley A. Changnon
Atmospheric Environment Section

Illinois State Water Survey
A Division of the Illinois Department of Natural Resources

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Stanley A. Changnon

Midwestern Regional Climate Center
Illinois State Water Survey
Champaign, IL

Abstract

Temporal fluctuations in the annual and summer precipitation across the Midwest during the 1898-2002 period are defined and described. Precipitation amounts were assessed for 15-year periods to show how patterns of precipitation have shifted spatially over the 20th Century. The early part of the century featured near average precipitation conditions, followed by predominately dry conditions from 1928 through 1957. For example, during 1928-1942, 96 percent of the Midwest had below average precipitation. After 15 years with near average conditions from 1958 to 1972, extremely wet conditions developed during 1973-2002, with 91 percent of the Midwest experiencing above average precipitation. Extreme precipitation values sampled during each 15-year period revealed temporal differences with much more extreme amounts during wet and dry periods than during near average periods. Annual totals reflected the long-term variations in summer rainfall, revealing the importance of summer rainfall in determining annual amounts. Regionally, amounts were below average more frequently in the southern Midwest than in the central and northern Midwest. Values were above average more frequently in the northern Midwest than in the central and southern Midwest. The results provide information that should be useful for hydrologic and agricultural planning and assessments.

Contents

Acknowledgments

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Introduction

This study presents various measures of the fluctuations in the annual and summer precipitation amounts across the Midwest during the 20th Century. The measures are designed for easy interpretation and applications in hydrology, agriculture, and engineering design. The results describe the past fluctuations on a regional basis, offering perspectives on past hydrologic conditions such as runoff and droughts, and crop yields. The findings also serve as guidance for potential future outcomes.

Summer rainfall also was examined because of its importance to both agriculture and water resources. The magnitude of Midwestern corn and soybean crop yields correlates well with the amount of summer rainfall (Thompson, 1975). Long-term shifts in corn yields in Illinois were found to be aligned closely with shifting summer rainfall conditions (Changnon and Winstanley, 1999). A study of the impacts of seasonal precipitation amounts on surface water and groundwater supplies and quality in Illinois using 1901-1997 data found that the major seasonal effects occurred in summer (Winstanley and Changnon, 1999).

Design and operation of water management and supply systems in the Midwest depend upon precipitation information. Inputs typically include the average and extreme annual precipitation values. Extremes include heavy rainfall events and prolonged wet periods, droughts, and prolonged drier-than-average periods. Typically, the time distributions of heavy precipitation frequencies have been treated statistically as random events, and often no information is available on how extremes have been distributed over time and space.

Recent studies have found multi-decadal increases in annual precipitation across the Midwest since the 1940s (Karl and Knight, 1998). Huff and Angel (1990) assessed the temporal distribution of 1- and 2-day heavy rainfall frequencies (2-year events) in the Midwest for 1901-1940 and 1941-1980, finding 10 to 20 percent increases over time across most of Iowa, Missouri, and Illinois, and in parts of Indiana, lower Michigan, Ohio, and Wisconsin. Using 304 weather stations across the Midwest, Angel and Huff (1997) examined the time distributions of 5.1-centimeter (cm) rain days for 1901-1994, finding 20 percent increases since the 1940s.

As a result of these recent findings about precipitation increases in the Midwest, water and agricultural interests have posed questions, such as:

1. Have such long-term (30- to 50-year) precipitation increases occurred before?
2. When will the current ongoing increases end?
3. What conditions may follow when the increases end?

Some recent studies have addressed possible temporal changes in Midwestern streamflows resulting from the precipitation shifts. Lins (1997) found that streamflow in the United States is organized in coherent regional modes of temporal variability that have distinct patterns in the Midwest, including the upper Mississippi River, central Mississippi River, Ohio River, and Great Lakes basin. Knapp (1994) assessed the 1901-1990 flows of rivers and precipitation of the upper Mississippi River basin and found that temporal trends in the average flows and even flooding strongly correlated with changes in the average annual precipitation. He noted that the basin's streamflows during 1965-1990 were higher than in any earlier period.

Lettenmaier et al. (1994) analyzed streamflow data for 1948-1988 across the nation and concluded that most areas of the Midwest had temporal increases. In a more comprehensive study of the national flow records extending back to 1934, Lins and Slack (1999a) determined that Midwestern increases occurred during 1934-1993 in only the annual minimum (not maximum) daily flows. They further found no systematic large-scale increases in the frequency of Midwestern floods for the 20th Century (Lins and Slack, 1999b), noting that precipitation increases over time were largely in summer rainfall that had little direct effect on floods because summer is when low flows typically occur. Changnon and Kunkel (1995) assessed Midwestern floods during 1921-1985, and found increased flooding in the cold and warm seasons over time in Iowa, Minnesota, northern Illinois, and parts of Wisconsin. Differences in the findings of these various studies relate to different analytical approaches and different periods analyzed.

This report presents multi-year precipitation data for 105 years for the 75 climate districts that comprise the Midwest. For each area, and regional combinations of areas, the timing and duration of periods with increasing or decreasing precipitation were determined, as well as the timing and duration of relatively extreme precipitation conditions. Such spatial assessment is particularly important for assessing runoff into the major river basins and the basins of the Great Lakes.

This study was based upon precipitation data collected during 1898-2002. Information is presented based on precipitation conditions in seven discrete 15-year periods during the 105-year period of study: 1898-1912, 1913-1927, 1928-1942, 1943-1957, 1958-1972, 1973-1987, and 1988-2002. Past research on fluctuations in Illinois precipitation and temperature conditions has revealed that 10- to 15-year periods dominate the cyclical behavior of the precipitation and temperature (Neill, 1980; Lamb and Changnon, 1982; Easterling et al., 1990). Neill and Hsu (1981) performed a harmonic spectral analysis of historic Midwestern precipitation data for 1901-1980, and found the most significant wavelengths were between 10 and 18 years in length.

The area of study embraced the nine Midwestern states including Minnesota, Iowa, and Missouri on the west; Illinois, Indiana, and Wisconsin in the central portion; and Michigan, Ohio, and Kentucky on the east and south. Precipitation data assessed were the regional mean values as determined for the climate districts in each state. Most Midwestern states have nine such districts, although Missouri has six districts and Kentucky has four districts. Ohio and Michigan each have ten climate districts. District values for a given year or a season are the averages of the values for all weather stations operating in a particular district (see Figure 1 for district boundaries).

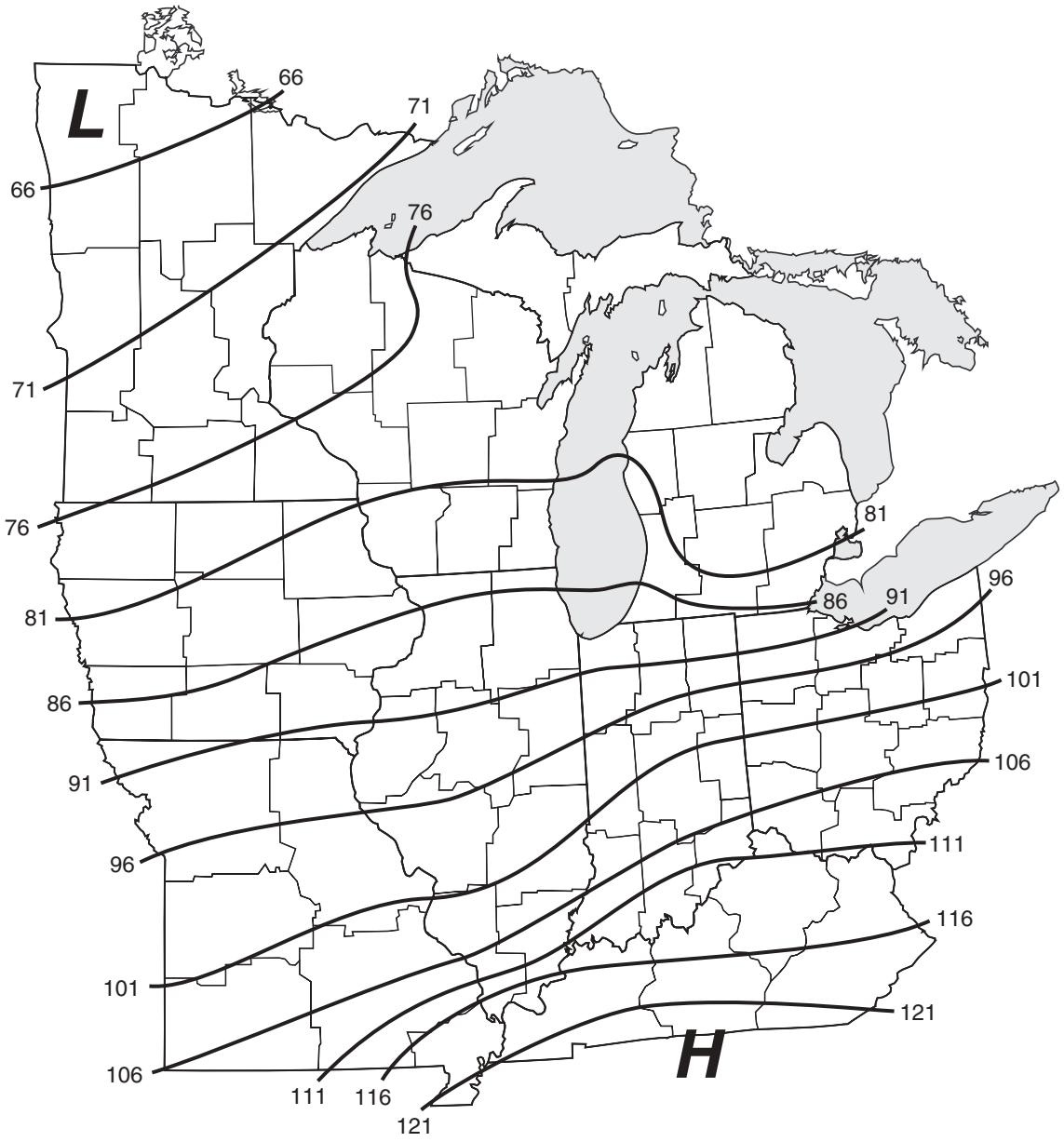


Figure 1. Pattern depicting average annual precipitation (cm) based on 1898-2002 data for the Midwest

Data and Analysis

Maps based on the average precipitation amounts for annual and summer periods in the climate districts for individual 15-year periods were developed. The nine-state area includes 75 climate districts defined by the National Climatic Data Center. District precipitation values were corrected for time of observation (Karl et al., 1986). Each 15-year precipitation value was expressed as a percent of the district's 105-year average. Thus, these percentages measure the departures in each period from the long-term mean.

A second analysis involved cartographic presentations based on the frequency of years in each 15-year period with above average, near average, or below average precipitation. The 105 precipitation amounts for each climate district for the 1898-2002 period were ranked and then divided into three groups with 35 values each: above average, near average, and below average. Maps were developed for each 15-year period with patterns based on the frequency of above, near, and below average precipitation years during the 15 years.

Each combination of years, based on the ranks of the frequencies of above, near, and below average for each district, formed a "climate type," and six climate types were defined as shown in Table 1, with type 1 being the wettest and type 6 being the driest. Type 1, in the order of most to least frequent kind of precipitation years, was a sequence of above average, near average, and below average. For example, a 15-year period with 7 years of above average, 5 years of near average, and 3 years of below average amounts was a climate type 1. If a district had a period with a tie among two of the three values, such as six years above and six years near average, the district type was determined based on the predominating surrounding district values, becoming either type 1 or type 3 in this example.

Analysis of the precipitation patterns, based on the percentage of long-term mean values, allowed definition of when, where, and how much precipitation departed from average in each of the seven 15-year periods. Patterns of the frequencies of climate types, based on years with above, near, and below average amounts in each 15-year period, help reveal the cause of the pattern departures. For example, above average precipitation during a 15-year period could result from many years of above average amounts and several slightly below average years, or from only a few excessively above average years and numerous near average values. This analysis helps explain the 15-year departures as well as how wet, near average, and dry years fluctuated over time.

Table 1. Climate Types Based on Frequencies of Years with Above, Near, and Below Average Precipitation during a 15-year Period

Climate type	*Rank order*
1	Above average, near average, and below average
2	Above average, below average, and near average
3	Near average, above average, and below average
4	Near average, below average, and above average
5	Below average, above average, and near average
6	Below average, near average, and above average

Annual Precipitation

Precipitation Patterns

The average annual precipitation across the Midwest has a distinct latitudinal distribution (Figure 1). Amounts are lowest in the north and highest in extreme southern parts of the region. Annual average precipitation in northern Minnesota is 25 inches (63.8 centimeter or cm), compared to 49 inches (125 cm) in southern Kentucky. Note that the highest average is almost double the lowest one. Average isohyetal lines between the extremes are oriented west-east, becoming closer together to the south (Figure 1). Slight irregularities in the pattern occur around Lake Michigan and Lake Superior. Figure 2 illustrates the percentage patterns based on the annual precipitation in the seven periods.

The 1898-1912 Period

Figure 2a (1898-1912) exhibits very minor extremes with little spatial variability across the Midwest except in the northern sections. The predominating above average area is in extreme northern Minnesota. Values in Table 2 reveal more districts with below average values than with above average values, and 17 districts with values of ~100 percent (99.6-100.5%), defined as average. District values of 101.6 percent or higher were classified as above average in Table 2, and values of 99.5 percent or lower were classified as below average.

The highest percentage among the 75 climate districts was 106 percent in Minnesota, and the lowest was 96 percent in Michigan, as shown in Table 3. Values in Table 3 also show that 60 percent of the 75 districts had values ranging from 99 to 101 percent of average, reflecting the small amount of variability from average precipitation during this period.

The 1913-1927 Period

The second 15-year period, 1913-1927, had district values exhibiting greater differences and more spatial variability (Figure 2b) than occurred in 1898-1912. The range of district values embracing 60 percent of the Midwestern climate districts was 97 to 103 percent (Table 3), a much greater range than in 1898-1912. Extreme district values ranged from a low of 93 percent in lower Michigan and in Minnesota to 107 percent in southern Ohio.

Table 2. Number of Midwestern Climate Districts in Each 15-year Period during 1898-2002 with Above Average (101% or Higher), Below Average (99% or Lower), and Average (100%) Annual Amounts

	Number of districts		
Period	*Above*	*Below*	*Average*
1898-1912	28	30	17
1913-1927	29	39	7
1928-1942	0	72	3
1943-1957	36	29	10
1958-1972	25	38	12
1973-1987	73	1	1
1988-2002	68	6	1

Table 3. Range of Precipitation Departures, in Percent of Average Annual Precipitation, Found among 75 Midwestern Climate Districts during Each 15-year Period

Period	District extremes (%) Maximum	Minimum	Range embracing 60% of District values closest to average
1898-1912	106	96	99 - 101
1913-1927	107	93	97 - 103
1928-1942	100	89	96 - 100
1943-1957	108	93	96 - 102
1958-1972	107	92	97 - 103
1973-1987	115	97	103 - 108
1988-2002	112	97	102 - 106

The 1913-1927 precipitation pattern features a west-east-oriented area of above average values across the southern Midwest, plus another above average area in Wisconsin. In this isolated area, there were more near average years than dry or wet years (see 1913-1927 map on Figure 3), but there were more wet years than dry years. Typical district values of above, near, and below average years were 5-7-3, 4-8-3, or 5-6-4. Most of the upper two-thirds of the Midwest had below average precipitation, and two major low areas occurred, one in Minnesota and another in Michigan. The main precipitation feature of this period was widespread below average values (39 of 75 districts, Table 2). There were 10 more climate districts with below average values than above average ones.

The 1928-1942 Period

The 1928-1942 period included the famous droughts of the 1930s, and the dryness of the period is revealed in Figure 2c. All Midwestern climate districts had values that were at or below the long-term average, the only 15-year period with such an extreme frequency of below average occurrences (Table 2). The highest district values were 100 percent (average) found in Wisconsin districts where there were five above average years, four years with near average amounts, and six years below average years: climate type 5. The lowest district values were 89 percent in western Minnesota, reflecting the severity of the 1930s droughts in the adjacent High Plains. The range of 60 percent of the 75 district values was small, 96-100 percent (Table 3).

The 1943-1957 Period

Precipitation during the 1943-1957 period formed quite a different pattern than found in previous periods. Four zones were oriented southwest-northeast across the Midwest with considerable spatial variability in the pattern (Figure 2d). The westernmost of the four zones was an area of above average values extending across most of Minnesota. To the immediate east was a zone of below average values across western Missouri, Iowa, and Wisconsin that reflected a series of severe droughts in this area during the 1950s. An area of above average values included eastern Illinois, Indiana, and lower Michigan. Located further east was another area of below average values in Kentucky and Ohio. The period's highest value was 108 percent in Minnesota

(the highest value achieved up to this time), and the lowest value was 93 percent in Wisconsin (Table 3). Values in Table 2 show that this period had slightly more above average district values than below average values for the first time in 60 years.

The 1958-1972 Period

The precipitation pattern for 1958-1972 (Figure 2e) shows much of the northern and western Midwest had values above average. In contrast, the southeastern half of the Midwest had below average precipitation. The pattern also reveals numerous small areas of high and low values.

The highest district departure in this period was 107 percent in Iowa, and the lowest was 92 percent in Missouri, the lowest value reached during the entire 105 years (Table 3). A range of 97 to 103 percent included 60 percent of the district values nearest to average. More districts had below average than above average values, with 12 climate districts having 100 percent (average) values (Table 2).

The 1973-1987 Period

The 1973-1987 period represented a shift to relatively widespread wet conditions. Most (73) climate districts had above average values. This period was essentially the opposite of the dry 1928-1942 period. The highest departure was 115 percent in Michigan, the highest departure found during the 105-year sample. The lowest district value was 97 percent in southern Ohio (Table 3) where one district had four above average years, five near average years, and six below average years: climate type 6 (Table 1).

Areas with the greatest positive precipitation departures were in the upper Midwest, with the highest values (>108 percent) found in a belt across Iowa, Minnesota, northern Illinois, and lower Michigan (Figure 2f). Streamflows and floods have increased significantly in this area over time (Changnon and Kunkel, 1995).

The 1988-2002 Period

The 1988-2002 period (Figure 2g) also had numerous districts with above average annual precipitation, continuing the wet trend found in 1973-1987. The greatest positive departures were in Minnesota, Iowa, and lower Michigan where values exceeded 106 percent of average. The highest district value was 112 percent in lower Michigan, and the lowest value was 97 percent in upper Michigan (Table 3). The 60 percent range of the 45 district values closest to average was low, 102 to 106 percent, reflecting consistently above average values across much of the Midwest. The only areas with average or below amounts were in the extreme northern and southern portions of the Midwest. The century's last two wet periods, coupled with a dry 1928-1942 period, reveals why investigators have found upward time trends in annual precipitation since the 1930s (Karl and Knight, 1998).

Summary

Fluctuations in annual precipitation conditions over time were assessed for various parts of the Midwest. State conditions were measured for each 15-year period, and the frequencies of periods with above, near, and below average precipitation appear for selected states in Table 4. Minnesota had four periods with above average, one near average, and only two periods with below average values. In contrast, Kentucky had two periods with above average values, two

Table 4. Frequency of Different Levels of Precipitation in the Seven 15-year Periods for Selected States and Basins of Lake Superior and Lake Michigan, 1898-2002

	Precipitation levels		
Location	*Above average*	*Near average*	*Below average*
Minnesota	4	1	2
Iowa	3	3	1
Illinois	2	3	2
Kentucky	2	2	3
Ohio	3	2	2
Lake Superior basin	4	1	2
Lake Michigan basin	2	2	3

periods near average, and three periods with below average precipitation. Even Iowa, which is adjacent to Minnesota, had a quite different distribution of conditions than experienced in Minnesota. The state values shown in Table 4 reflect considerable intra-regional differences. The recent shift to above average amounts occurred sooner and was more pronounced in Minnesota-Iowa than in Illinois, Kentucky, and Ohio, further reflecting the upward trend in streamflow and flooding found in the Minnesota and Iowa River basins (Changnon and Kunkel, 1995).

Precipitation in the drainage basins of Lake Superior and Lake Michigan also was classified, as shown in Table 4, and their precipitation conditions were quite different. Lake Superior experienced four 15-year periods with above average precipitation, compared to only two such periods for Lake Michigan. Values for each of the seven periods were compared. Both lakes had below average amounts in 1913-1927 and 1928-1942, and above average amounts in 1958-1972, but they differed in the four other periods.

Climate Types: Frequency of Wet, Near Average, and Dry Years

Annual precipitation values in each climate district were sorted into one of three classes: above, near, or below average. This approach to measuring annual precipitation variability relied on the frequency of above, near, and below average annual amounts in each 15-year period and climate district. The rank order based on the frequency of each precipitation class was ascertained for each 15-year period, and these ranked sequences formed six climate types (Table 1). The maps for each 15-year period indicate the climate types for each of the 75 districts, based on the rank order (high to low) of years with above, near, and below average amounts. This array also defined the regions where above average, near average, or below average years were most frequently present in each period.

The 1898-1912 Period

The climate type pattern for 1898-1912 (Figure 3a) shows that 40 of the 75 climate districts had more near average years than above or below average years, and these near average districts cover a wide portion of the Midwest. Type 3, the wetter version of the two near average types, prevailed in Missouri, Illinois, and Indiana, whereas type 4 prevailed in Michigan. As shown in Table 5, above average years were most frequent in 21 districts, and below average

Table 5. Number of Midwestern Climate Districts with Above Average, Near Average, or Below Average Prevailing Precipitation Amounts for 15-year Periods, 1898-2002

Period	*Above average*	*Near average*	*Below average*
1898-1912	21	40	14
1913-1927	14	43	18
1928-1942	10	8	57
1943-1957	28	15	32
1958-1972	23	31	21
1973-1987	69	5	1
1988-2002	57	17	1

Note:
The 105 annual amounts for each of the 75 climate districts were sorted into three equal groups with the 35 highest classed as the above average values, the middle 35 as the near average values, and the 35 lowest as below average values. The counts in this table are based on these classifications.

years predominated in 14 districts. Below average years prevailed in three relatively small areas. Most such districts experienced type 5, not the driest possible type outcome.

Other than the large above average area in the northwest, this period was dominated by years with near average precipitation. Many areas with slightly below average (98-100%) 15-year precipitation totals (Iowa, Illinois, Indiana, and lower Michigan, see Figure 2a) were in this preferred near average area shown on Figure 3a. Examination of the number of above and below average years in area districts revealed comparable frequencies, but with much greater precipitation departures in the few dry years than in the few wet years.

Three small areas of disagreement between precipitation values and climate types existed during 1898-1912. Precipitation values were 100 percent in southeast Iowa, but the districts were dry (type 5). Examination of their 15-year frequencies revealed six dry years and five wet years (four years were near average). The wet year amounts were sufficiently high to compensate for the deficits of the six dry years. A similar explanation existed for Ohio and eastern Indiana where precipitation values were 98-100 percent, and yet dry type 5 occurred. The third anomalous area was in southwestern Minnesota where precipitation was 98 percent, but the district climate types were wet type 2. This was explained by district yearly values revealing that the five dry year amounts were greater departures below average than were the surpluses of the six wet years (four years were near average).

A large area of prevailing wet types existed in Minnesota and Wisconsin. All climate districts in this region had more years with above average values than years with near or below average values. Most districts were type 1, the wettest possible combination of years. The three Minnesota districts where the number of above average years equaled or exceeded eight years, more than half of the 15-year period, also are denoted.

The 1913-1927 Period

Figure 3b presents the pattern based on most frequent types of years during 1913-1927. As in 1898-1912, near average years (types 3 and 4) prevailed in many of the districts (43 total). As shown in Table 5, below average years were most frequent in 18 districts (mainly in Illinois and lower Michigan), and most were type 6, the driest possible combination. Above average years occurred in only 14 districts, all in the southern section of the Midwest where the 15-year precipitation totals also were above average (see Figure 2b).

An anomaly exists in Wisconsin: 15-year amounts were above average (Figure 2b), but near average years were most common (Figure 3b). In this area, all districts were type 3, with many more above average years, the wetter of the two near average types, than below average years. Another anomaly, or apparent difference between pattern values in Figures 2b and 3b, existed in central Illinois where precipitation values were 98-100 percent, but four districts were climate types 5 or 6, both indicative of dry conditions. Examination of the 15-year distributions of precipitation years revealed all districts experienced six dry years, five wet years, and four near average years. With only one less wet year than dry years, precipitation amounts were sufficient to overcome the lower values from the six dry years, thus attaining 15-year values near 100 percent.

The 1928-1942 Period

The 1928-1942 period included the extreme droughts of the 1930s, which led to a high frequency of dry climate types. As shown in Table 5, 57 of the 75 districts were either type 5 or 6. Figure 3c shows that climate districts with below average years were most common in all nine states. Major high frequencies (districts with >8 dry years) were in Minnesota-western Wisconsin, western Missouri, and Indiana-lower Michigan. Six of the eight districts where near average years prevailed were type 4, a drier sequence than type 3.

Two small areas were type 1 or 2 (southwestern Illinois-Missouri and southwestern Michigan), denoting more above average years than other levels. These types occurred where the 15-year total precipitation was only slightly below average, 99 percent of average (Figure 2c). However, a greater disparity between totals and types existed in southern Missouri where amounts were 98 percent and dry types 5 and 6 occurred. This anomaly occurred because these districts had eight dry years and six wet years, and the precipitation produced in the six wet years was considerably greater than the deficits produced in the eight dry years. Similarly, two Wisconsin districts had 98-100 percent precipitation values but were classed as type 5. Both districts had five wet years and six dry years, but the wet year amounts were large enough to overcome the departures during the six dry years.

The 1943-1957 Period

The 1943-1957 pattern of climate types (Figure 3d) reveals that below average years prevailed across the region's southern extremes, in large portions of Wisconsin-Iowa-Michigan, and in southeastern Ohio. This agreed well with the pattern based on departures of the 15-year precipitation totals for 1943-1957 (Figure 2d). However, disagreements between amounts and types existed in two small areas. Districts in southern Illinois and southwestern Indiana had amounts from 102 to 104 percent of average but were dry climate types 5. District values showed many wet years with some districts having distributions of seven wet years and eight dry years

(none near average). In similar fashion, western Minnesota amounts rated as 104 to 106 percent were type 3, not the expected wet types 1 or 2. In both cases, precipitation in wet years was relatively high, exceeding that in the dry or near average years.

Table 5 shows that 32 districts had more below average years than the other two types, reflecting the impact of the southwestern droughts during the 1950s. A large number of dry years, more than eight per district, occurred in central Wisconsin where precipitation amounts were 94 to 95 percent of average. An extensive area of prevailing dry years also occurred in the southern Midwest.

Many districts in the eastern Midwest (Michigan-northern Indiana-Ohio) were wet type 2, and six districts had more than eight years with above average amounts. This is where 15-year amounts were 106 and 107 percent of average. An interesting feature of the pattern is numerous locations where wet types 1 and 2 occurred adjacent to dry types 5 and 6.

The 1958-1972 Period

The number of districts where wet, near average, or dry years were most frequent during the 1958-1972 period had a distribution similar to those in the first two 15-year periods (1898-1912 and 1913-1927). Near average types predominated in all three periods.

Near average years prevailed in 31 districts, above average years were most common in 23 districts, and below average years prevailed in 21 districts. The resulting Midwestern pattern (Figure 3e) shows two large areas of near average precipitation conditions, the northern sections of Minnesota-Wisconsin and the southern sections of Illinois and Indiana, including parts of Ohio and Kentucky. Close agreement existed between climate type distributions in the Midwest and the total precipitation pattern (Figure 2e). For example, the area of prevailing near average years in Illinois and Indiana, types 3 and 4, occurred where the total precipitation was 98 to 100 percent of average.

Most districts with more dry years, types 5 and 6, were distributed in isolated regions, including Missouri, and parts of Illinois, Wisconsin, Indiana, Michigan, Ohio, and Kentucky. Areas where above average years prevailed, Iowa-western Minnesota, and upper Michigan, also had 15-year precipitation totals well above average (Figure 2e).

The 1973-1987 Period

The pattern based on the most frequent annual precipitation classes for 1973-1987 (Figure 3f) shows that most of the Midwest had many more above average years than the two other classes. Table 5 reveals that 69 of the 75 climate districts were climate types 1 or 2, and 44 districts rated as type 1, the wettest possible climate type.

Areas with eight or more above average years occurred in a total of 48 districts, or 64 percent of the Midwest: Minnesota (5), Missouri (3), Iowa (5), Wisconsin (7), Illinois (6), Ohio (5), Michigan (9), Indiana (5), and Kentucky (3). Ten districts with 10 or more years with above average precipitation occurred in Minnesota, Wisconsin, Illinois, lower Michigan, and northeastern Ohio. Districts with 10 or more years of above average precipitation had total precipitation values of 108 percent or more of average.

Near average years prevailed in three districts of southern Ohio, and dry years were most common in one Ohio district. The pattern of preferred years (Figure 3f) closely resembles that for total precipitation (Figure 2f).

The 1988-2002 Period

The 1988-2002 period in the Midwest continued the 1973-1987 trend with a large region where years with above average precipitation prevailed (Figure 3g). As shown in Table 5, 57 climate districts were type 1 or type 2 during this period. Furthermore, 26 of the type 1 or 2 districts had eight or more years of above average amounts.

Fifteen districts scattered across several states were type 3 or 4, prevailing near average amounts, and these included several southern sections where precipitation totals were 98 to 102 percent of average (Figure 2g). Northern Michigan had a district with most frequent dry years (type 5). There was good agreement between the prevailing year pattern and the percent of average precipitation pattern (Figure 2g).

Variations in Extreme Annual Amounts

A third measure of the temporal variability of annual precipitation was based on the annual number of climate districts with the top 25 percent (wettest) and bottom 25 percent (driest) precipitation values during 105 years, 1896-2000. This period began and ended two years before the data period used in the other parts of this study. That is, for each of the 75 climate districts in the Midwest, the top 25 percent (26 values) and bottom 25 percent of the 105-year amounts were identified for each year, 1896-2000. These counts from the 75 districts were summed for each year, and the resulting distributions are depicted in Figures 4 and 5.

The temporal distribution of the drier districts (Figure 4) shows about 25 districts or less in most years. The major droughts of the 1930s created 66 dry districts in 1933 and 67 districts in 1935, the two highest annual counts. The droughts of the 1950s created three years with high counts, 1952 with 56 districts, 1955 with 54 districts, and 1958 with 50 districts. Other isolated years with large counts of dry districts included 1901, 1910, 1925, and 1988. Other than the 1987, 1988, and 1989 values, the last 20 years, 1981-2000, were devoid of dry districts, This period was similar to the 1901-1920 period.

The 105-year distribution based on annual numbers of wet districts (Figure 5) is quite different than the dry district distribution. No annual counts above 47 districts per year occurred during the 1896-1944 period with most years having 20 wet districts or fewer. The highest annual values include 75 districts in 1978, 74 districts in 1951, 72 districts in 1977, 72 districts in 1945, and 66 districts in 1993. Inspection of Figure 5 also shows eight years in the 1980s with high values (50-60 districts). Clearly, the most widespread wet years occurred during 1975-2000 when there were few dry districts (Figure 4).

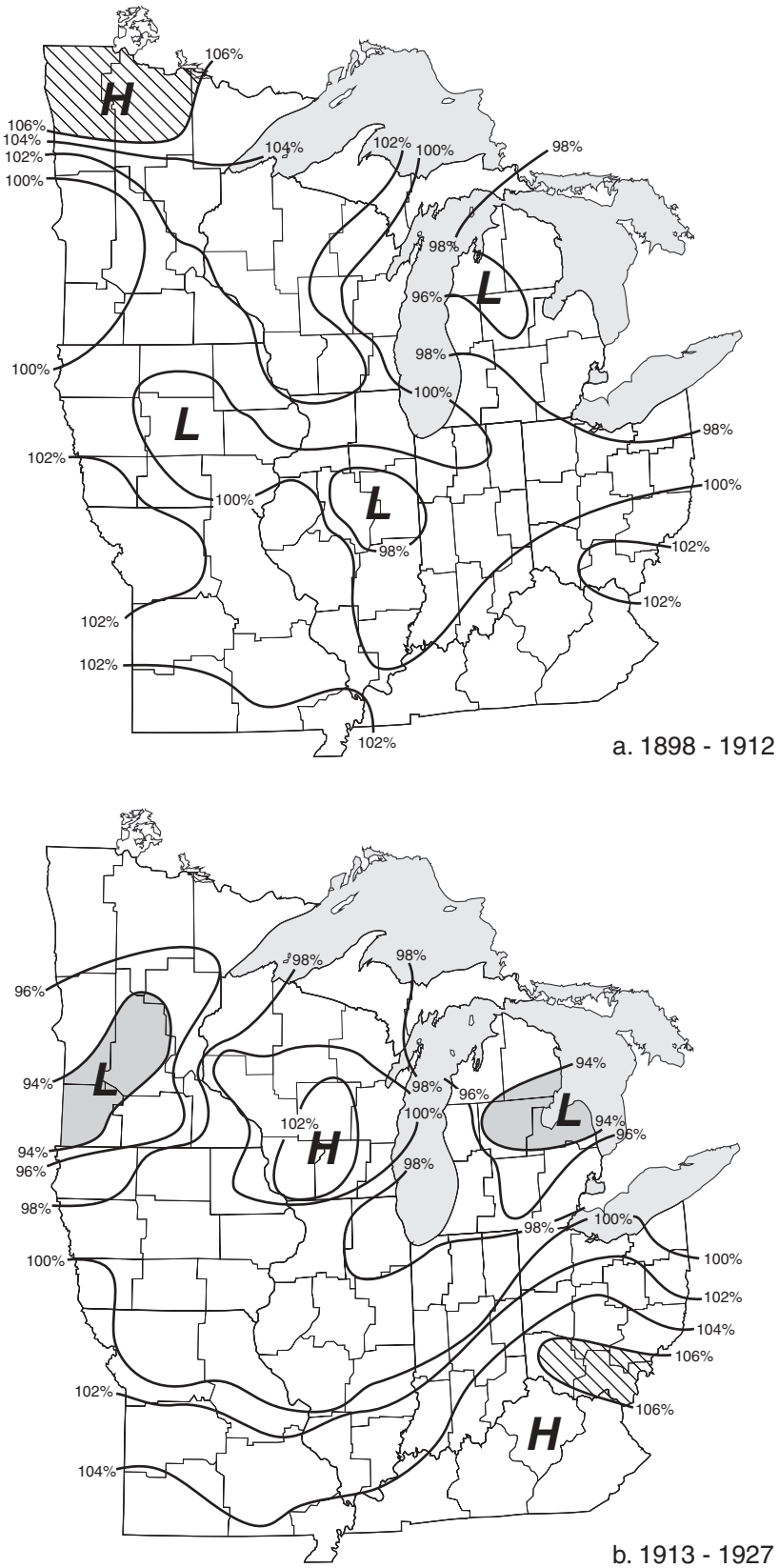
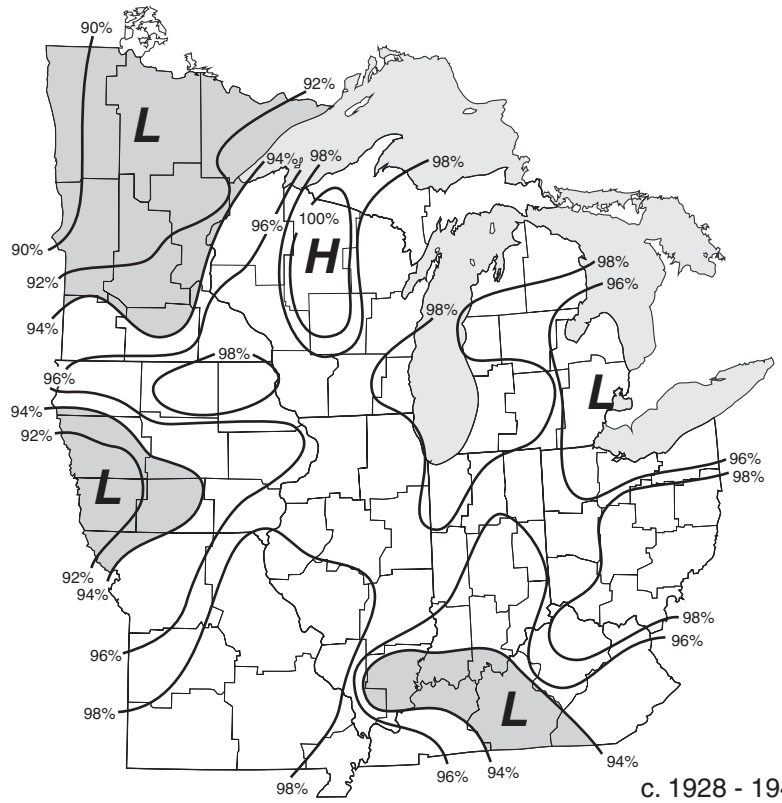
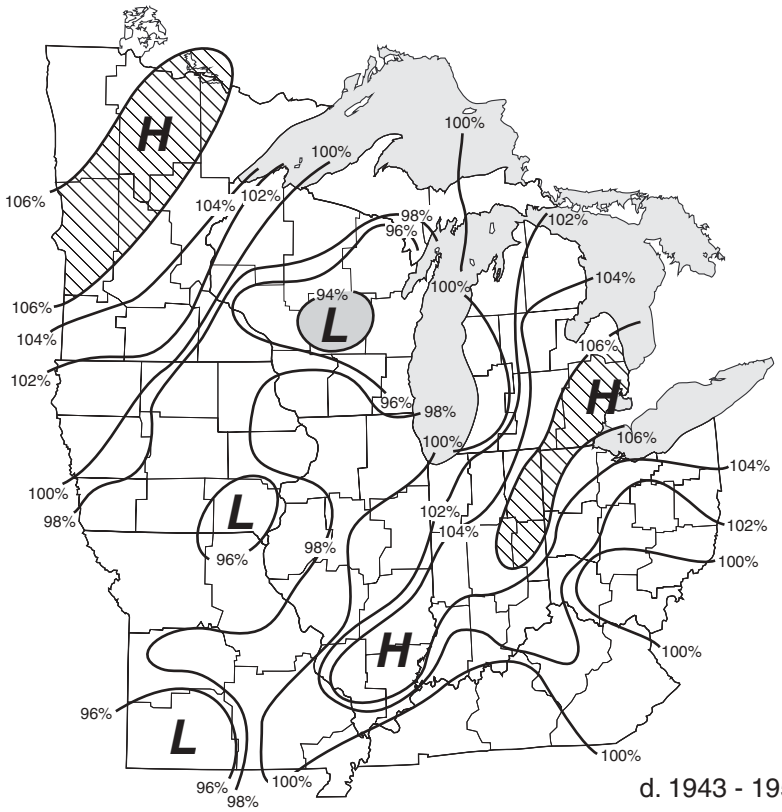


Figure 2. Pattern based on the percent of average annual precipitation during a. 1898-1912, b.1913-1927, c.1928-1942, d. 1943-1957, e. 1958-1972, f. 1973-1987, and g. 1988-2002

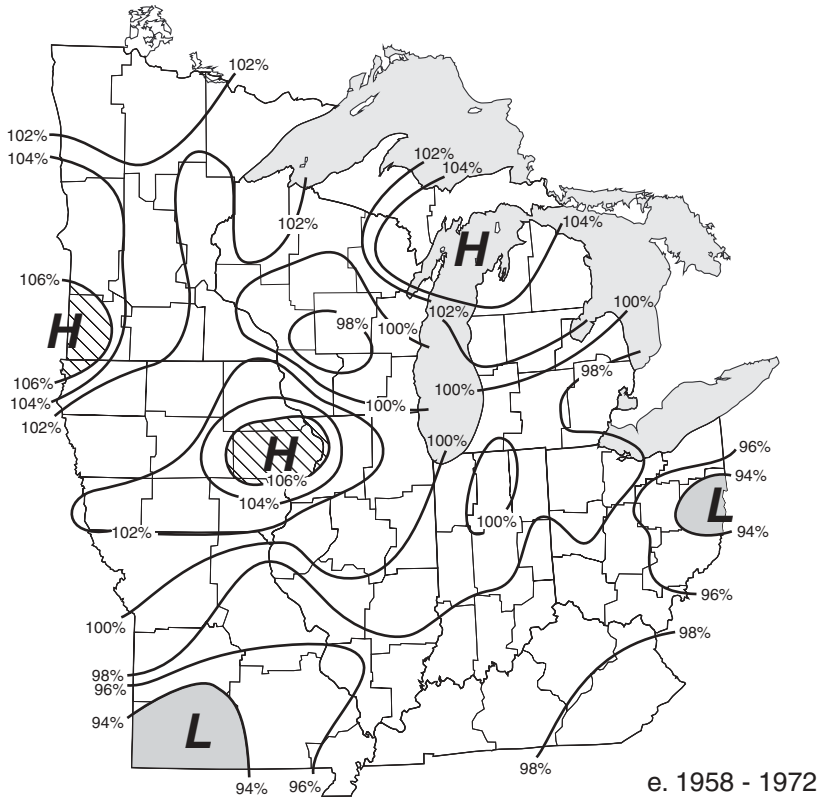


c. 1928 - 1942

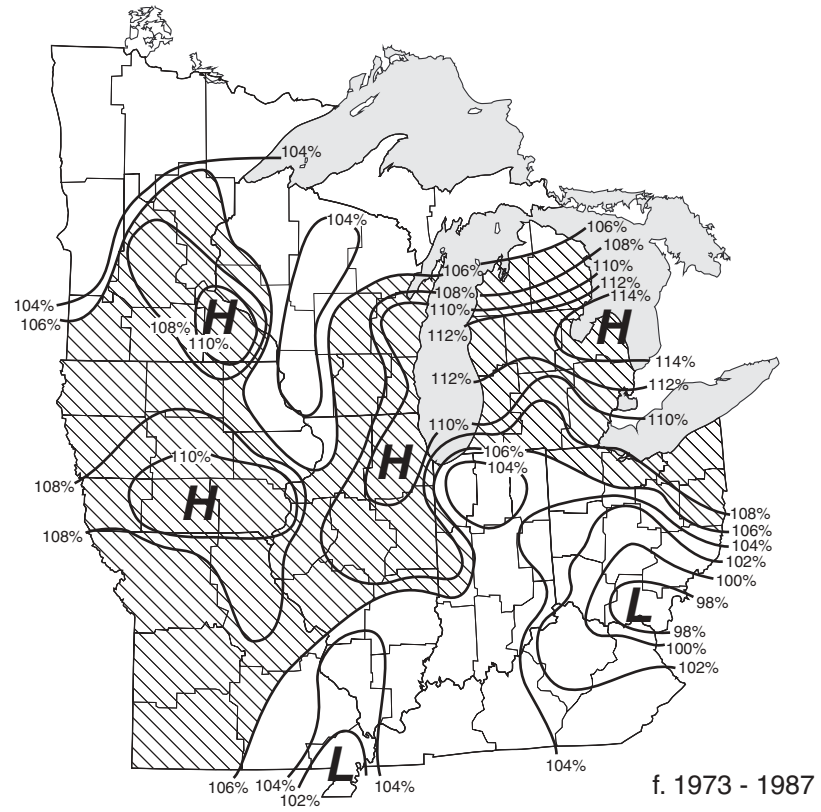


d. 1943 - 1957

Figure 2. Continued



e. 1958 - 1972



f. 1973 - 1987

Figure 2. Continued

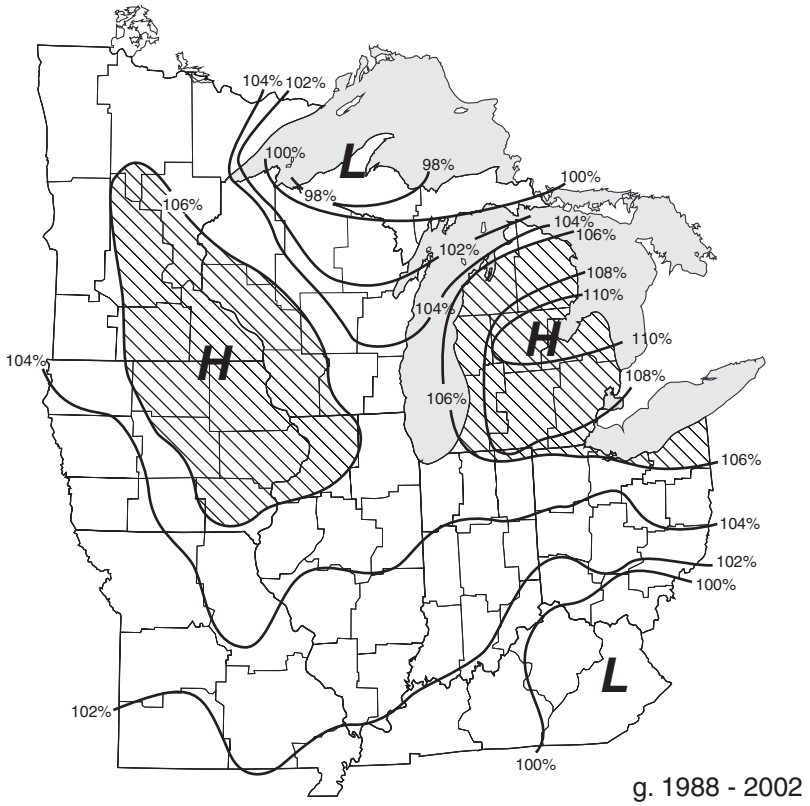


Figure 2. Concluded

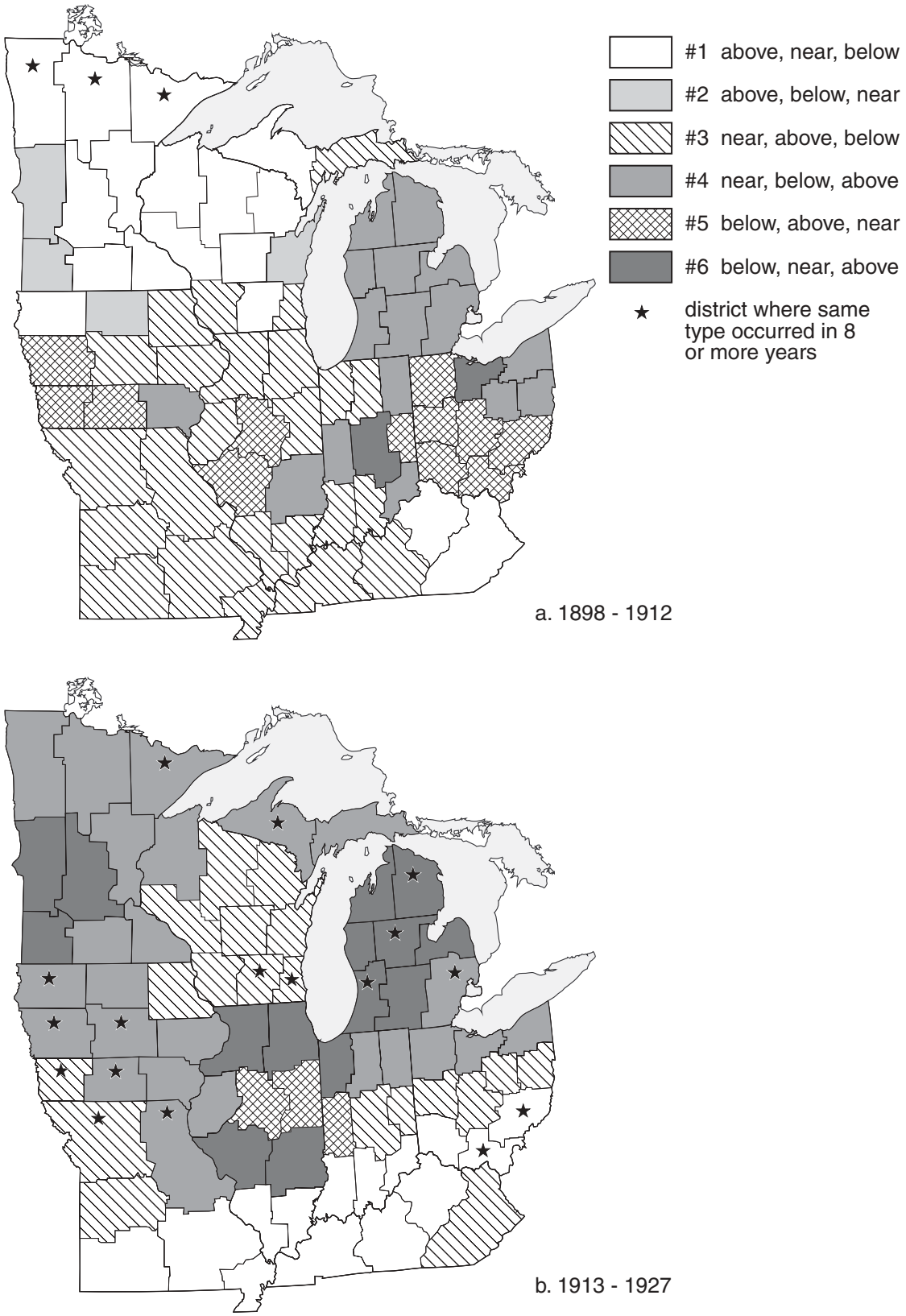
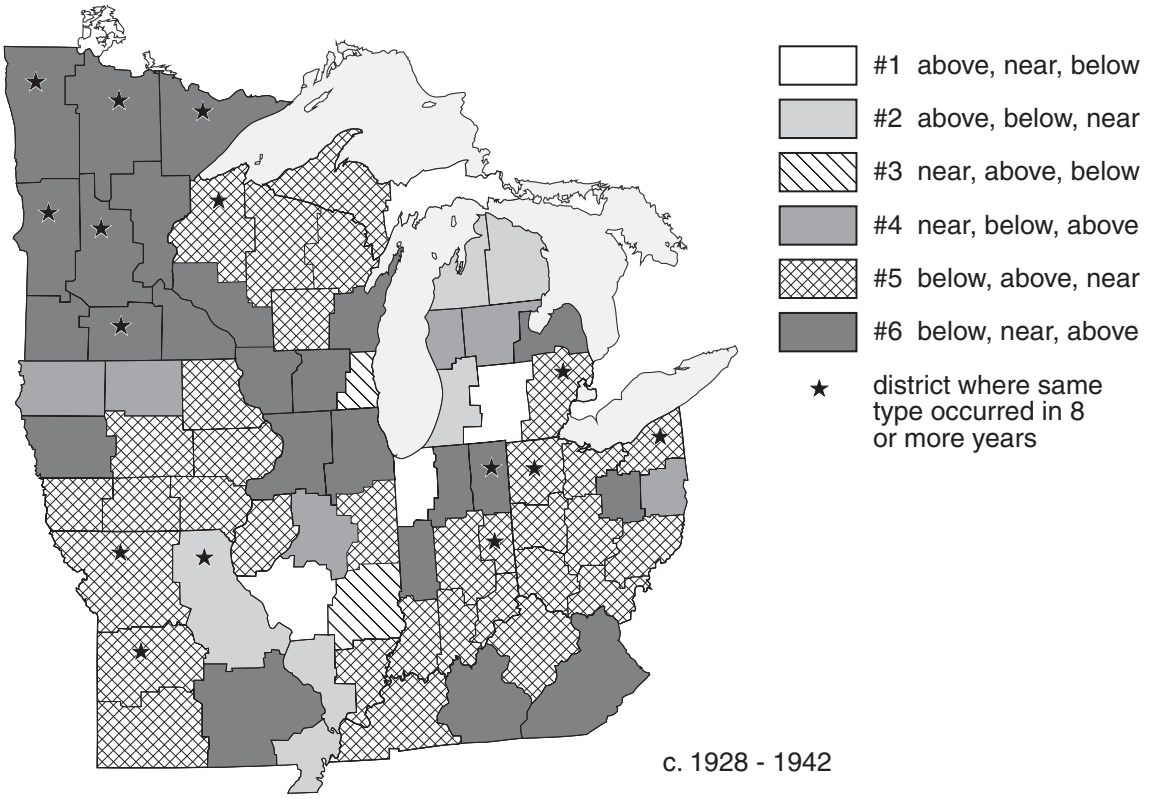
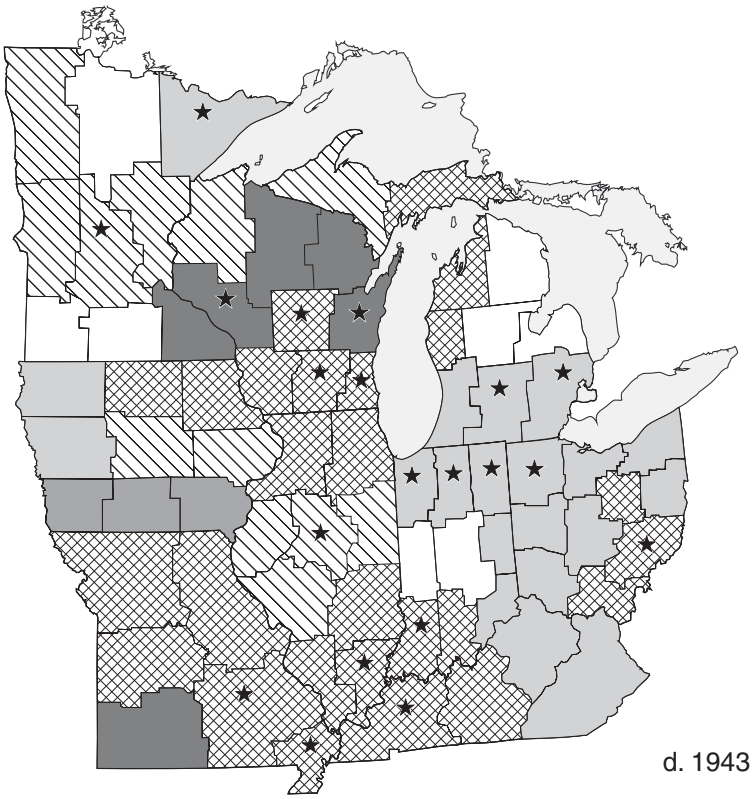


Figure 3. Climate types sampled during a. 1898-1912, b. 1913-1927, c. 1928-1942, d. 1943-1957, e. 1958-1972, f. 1973-1987, and g. 1988-2002

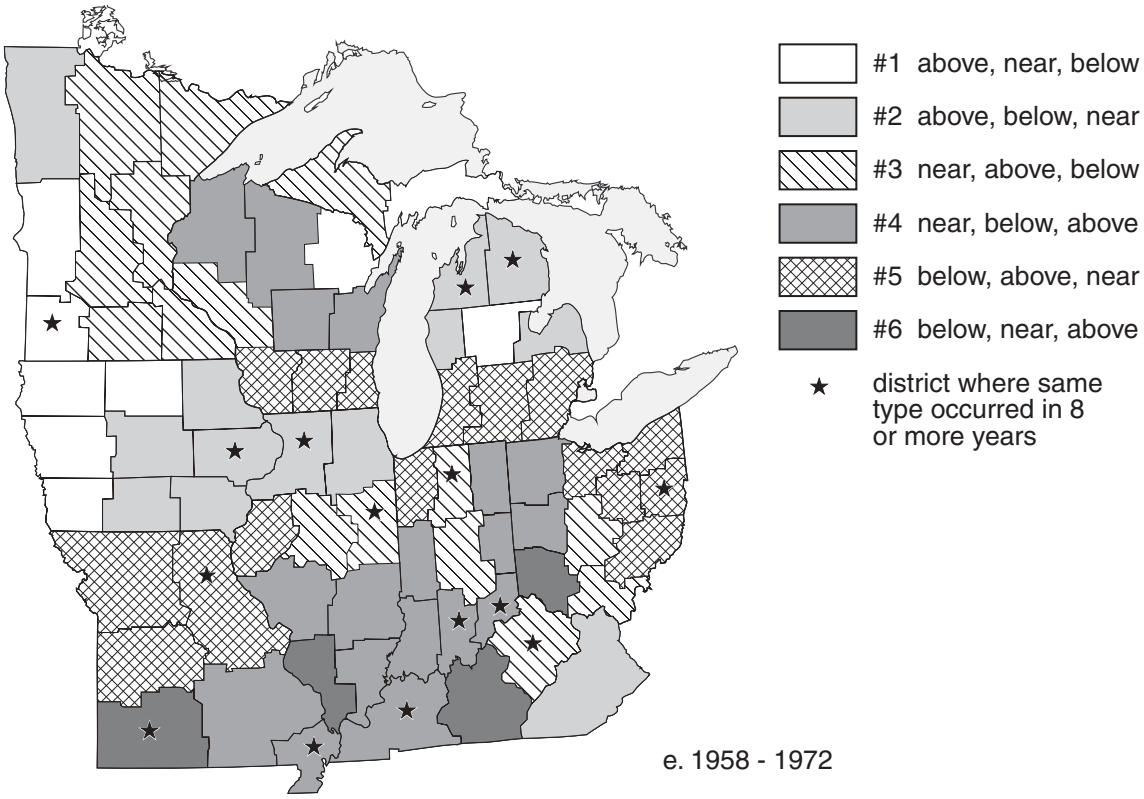


c. 1928 - 1942

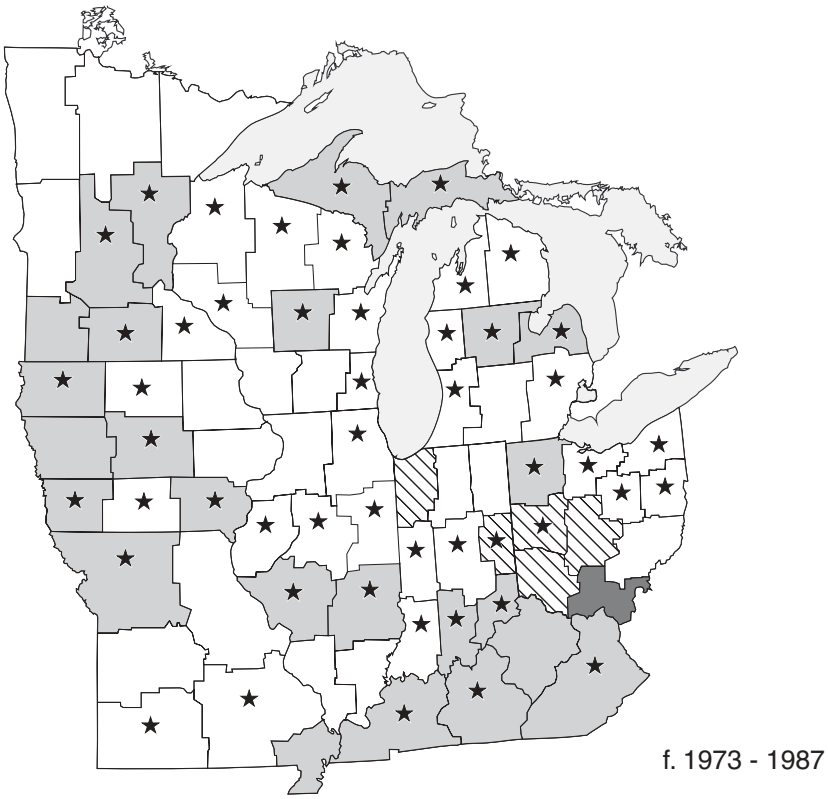


d. 1943 - 1957

Figure 3. Continued

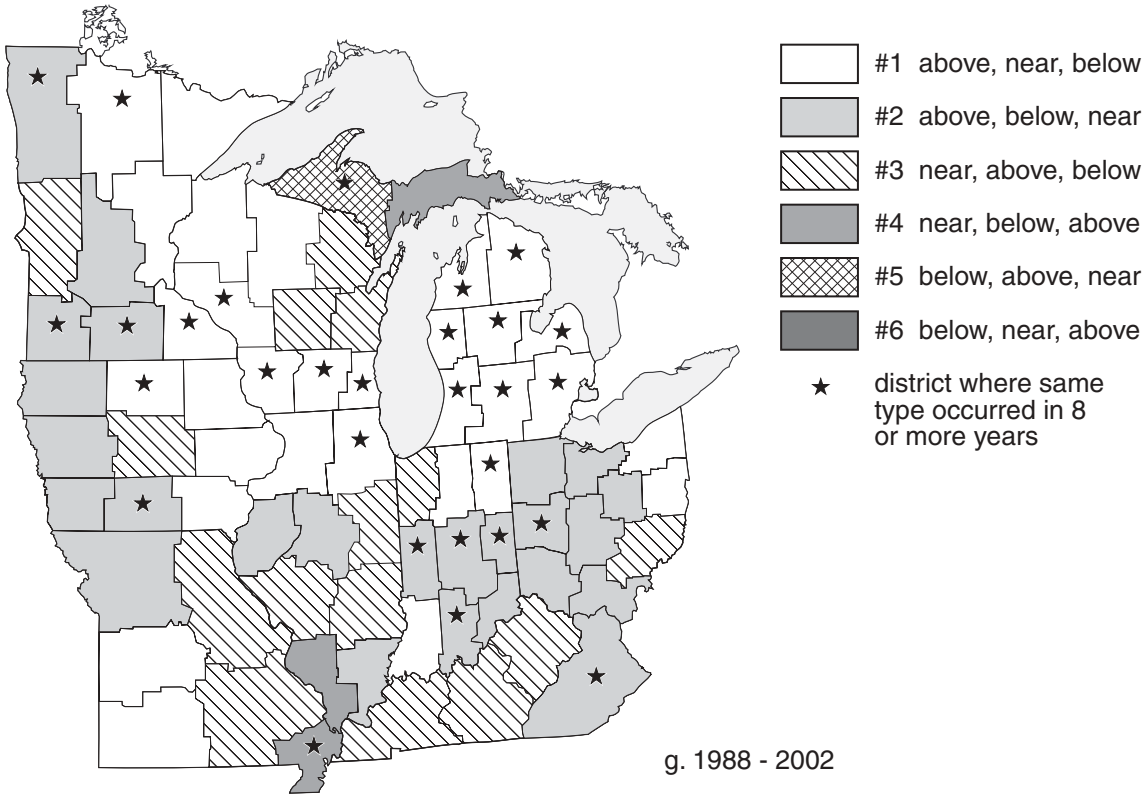


e. 1958 - 1972



f. 1973 - 1987

Figure 3. Continued



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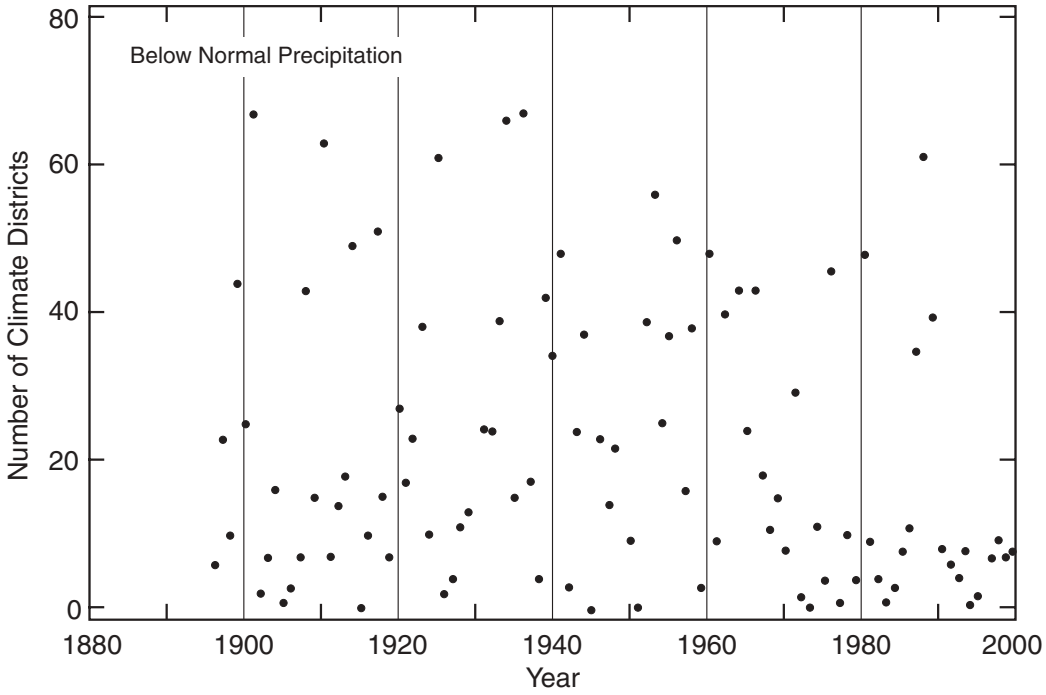


Figure 4. For each climate district among the 75 total districts in the Midwest, the lowest 25 percent of the 105-year amounts (26 values) were identified by year from 1896 to 2000. These counts for the 75 districts were summed for each year. The resulting distribution of dry districts is depicted.

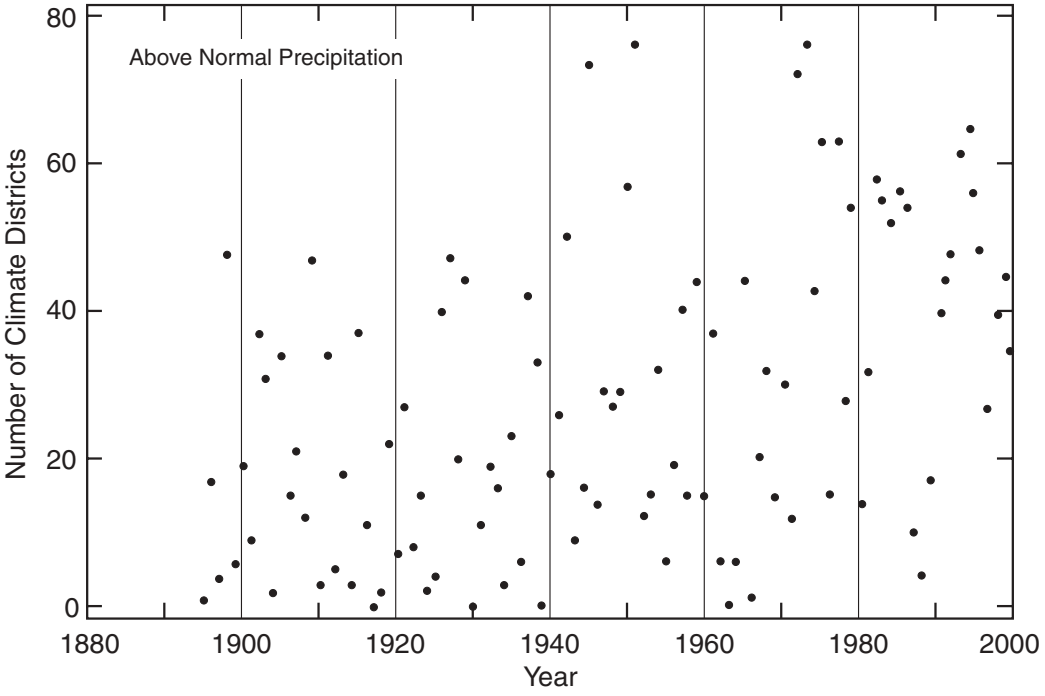


Figure 5. For each climate district among the 75 total districts in the Midwest, the highest 25 percent of the 105-year amounts (26 values) were identified by year from 1896 to 2000. These counts for the 75 districts were summed for each year. The resulting distribution of wet districts is depicted.

Summer Rainfall

Average summer rainfall (June-August) is the highest of all four seasons in many parts of the Midwest, and is the most critical seasonal rainfall for both agriculture and hydrologic considerations. Crop yields depend on summer rainfall (Changnon and Winstanley, 2000). Ninety percent of all flash floods occur as a result of high rainfall in summer months (Changnon et al., 2001), and water-short communities typically experience their greatest shortages in summer (Changnon and Easterling, 1989). Hence, a temporal analysis was made of summer rainfall in the Midwest.

The average summer rainfall pattern for 1898-2002 (Figure 6) shows a decrease from west to east. The highest amounts (>30 cm) are in the west-southwest (Iowa-Missouri), and amounts decrease rapidly to the northeast, becoming least (<22.5 cm) in Michigan. The only divergence from this pattern is the higher rainfall found in eastern Kentucky and southeastern Ohio. The pattern reflects the important role of thunderstorms, which also decrease west to east across the Midwest, and produce 70 to 80 percent of the region's summer rainfall (Changnon, 2001). The temporal analysis of the summer rainfall was based on conditions during the seven 15-year periods, and amounts in each climate district were expressed as a percent of their 1898-2002 average.

The 1898-1912 Period

The precipitation pattern for 1898-1912 (Figure 7a) is dominated by wetter than average values in the western Midwest and less than average values in the eastern half of the Midwest. The highest district value was 111 percent of average rainfall in Missouri, and the lowest district value was 89 percent of average rainfall in lower Michigan. As shown in Table 6, an almost equal number of districts were above average (35) and below average (31), and 9 districts had exactly average values. Very few district values exceeded 94 or 106 percent of average, revealing a lack of variability around the average.

Table 6. Various Statistical Measures of Midwestern Summer Rainfall, Expressed as Departures from 105-year Averages for the Region's 75 Climate Districts and the 1898-2002 Period

	Number of districts			*Extremes*			
Period	*Above average*	*Average*	*Below average*	*>106%*	*<94%*	*Highest value,%*	*Lowest value,%*
1898-1912	35	9	31	5	4	111	89
1913-1927	7	5	63	0	19	104	88
1928-1942	10	3	62	1	27	107	84
1943-1957	45	6	24	24	6	116	91
1958-1972	32	5	38	9	3	110	90
1973-1987	65	5	5	43	0	121	95
1988-2002	57	5	13	47	1	118	94

The 1913-1927 Period

The ensuing 15-year period, 1913-1927, had a distinctly different pattern of summer rainfall dominated by 63 districts with below average rainfall (Figure 7b), or 84 percent of the 75 total Midwestern districts (Table 6). The only areas with slightly above average amounts were in isolated portions of Missouri, Wisconsin, and Ohio. The highest district value was 104 percent in Missouri, and the lowest value was 89 percent in lower Michigan, the same states with high and low extremes in the previous period. Table 6 shows that 19 districts had values 94 percent or more below average.

The 1928-1942 Period

The third period, 1928-1942, continued from 1913-1927 the predominance of districts with below average amounts (Figure 7c). Table 6 shows 62 dry districts, with above average values in only 10 districts in the southeast (Kentucky and Ohio). Areas with substantial below average amounts, the 27 districts with less than 94 percent, were found across Minnesota and Michigan, and in portions of Missouri, Illinois, and Wisconsin. The lowest single district value was 84 percent in central Minnesota, and the highest district value was 107 percent in Kentucky. The 1912-1941 period in Illinois accounted for 60 percent of the years during 1901-1997 with major water resource problems (Winstanley and Changnon, 1999).

The 1943-1957 Period

Dry conditions during the two prior summer 15-year periods were ended during 1943-1957 as 45 of the Midwest's climate districts, 60 percent, experienced above average summer rainfall (Table 6). The pattern of Figure 7d shows that above average rainfall predominated in the northern two-thirds of the Midwest, peaking at greater than 110 percent of average over most of Minnesota and parts of Iowa, Wisconsin, and Michigan. The peak district departure was 116 percent in central Minnesota, reversing the conditions there in 1928-1942. Below average values occurred in 24 districts along the Midwest's southern extremities (Kentucky and Ohio). The lowest single district value was 91 percent in Kentucky. In many respects, the precipitation pattern of this period is the opposite of the one that preceded it, likely reflecting the severe drought of 1952-1955.

The 1958-1972 Period

The fifth 15-year period, 1958-1972, brought a highly variable pattern with sharp spatial differences between areas of above and below average summer rainfall (Figure 7e). However, as shown in Table 6, very few districts had values greater than 106 percent or less than 94 percent. The largest area of above average values extends across Iowa and into the northern half of Illinois (Figure 7e), into Michigan, and southward across most of Indiana. All of Missouri and Ohio had below average summer rainfall values, as did most of Minnesota and Wisconsin. Values were below average in 38 climate districts, above average in 32 districts, and average in 5 districts. The highest single district value was 110 percent in Iowa, and the lowest value was 90 percent in Ohio. Only three districts had values less than 94 percent as compared to six districts in the previous period.

The 1973-1987 Period

A 30-year period with widespread and frequent above average summer rainfall began in 1973. As shown in Table 6, 43 climate districts had more than 106 percent of average rainfall, and 65 districts (87% of total) had above average rainfall in 1973-1987. Only five climate districts had below average amounts and these were in the Missouri-Iowa area (Figure 7f). The peak single district value of 121 percent of average was the highest value experienced during 1898-2002 (Table 6). Above average rainfall covered most of the Midwest, and the heavier amounts (>110%) were found in Illinois, Indiana, Michigan, and Ohio.

The 1988-2002 Period

The 1988-2002 period continued the wet summers of the previous period. The pattern (Figure 7g) shows the heaviest amounts (>110%) extended across Iowa, portions of Minnesota and Wisconsin, and most of Michigan and Indiana. Values in Table 6 show that 57 climate districts had above average rainfall values, including 47 districts with values above 106 percent, a number greater than in the prior 15-year period. Below average amounts were restricted to the lower Mississippi River valley and to southeastern Ohio. The peak single district value was 118 percent in Michigan, and the lowest value was 94 percent in Illinois.

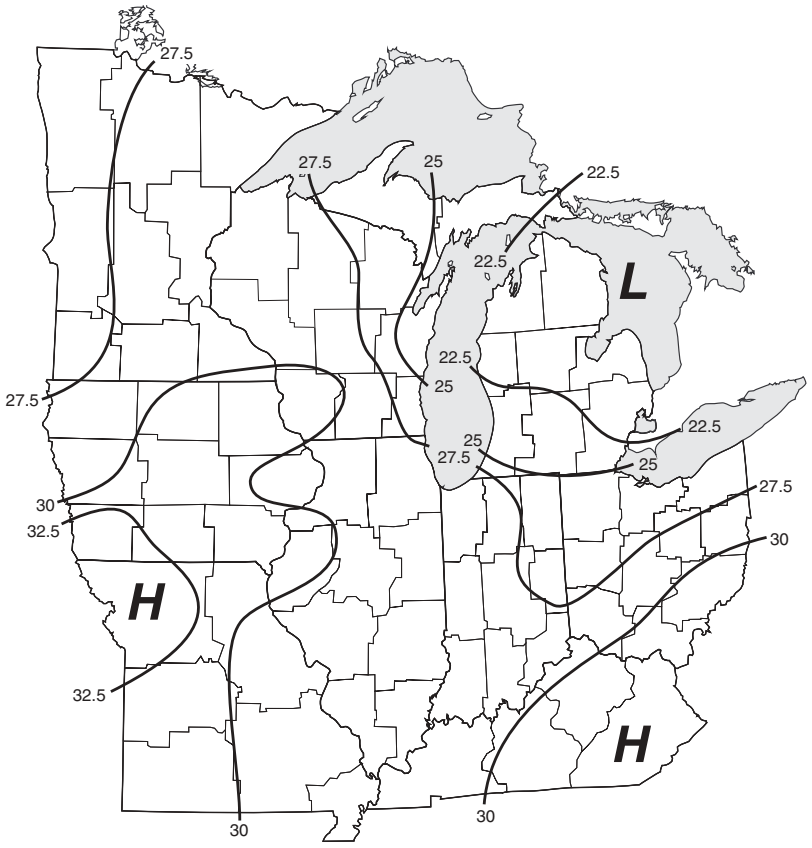


Figure 6. Pattern of the average summer rainfall, cm, based on 1898-2002 data

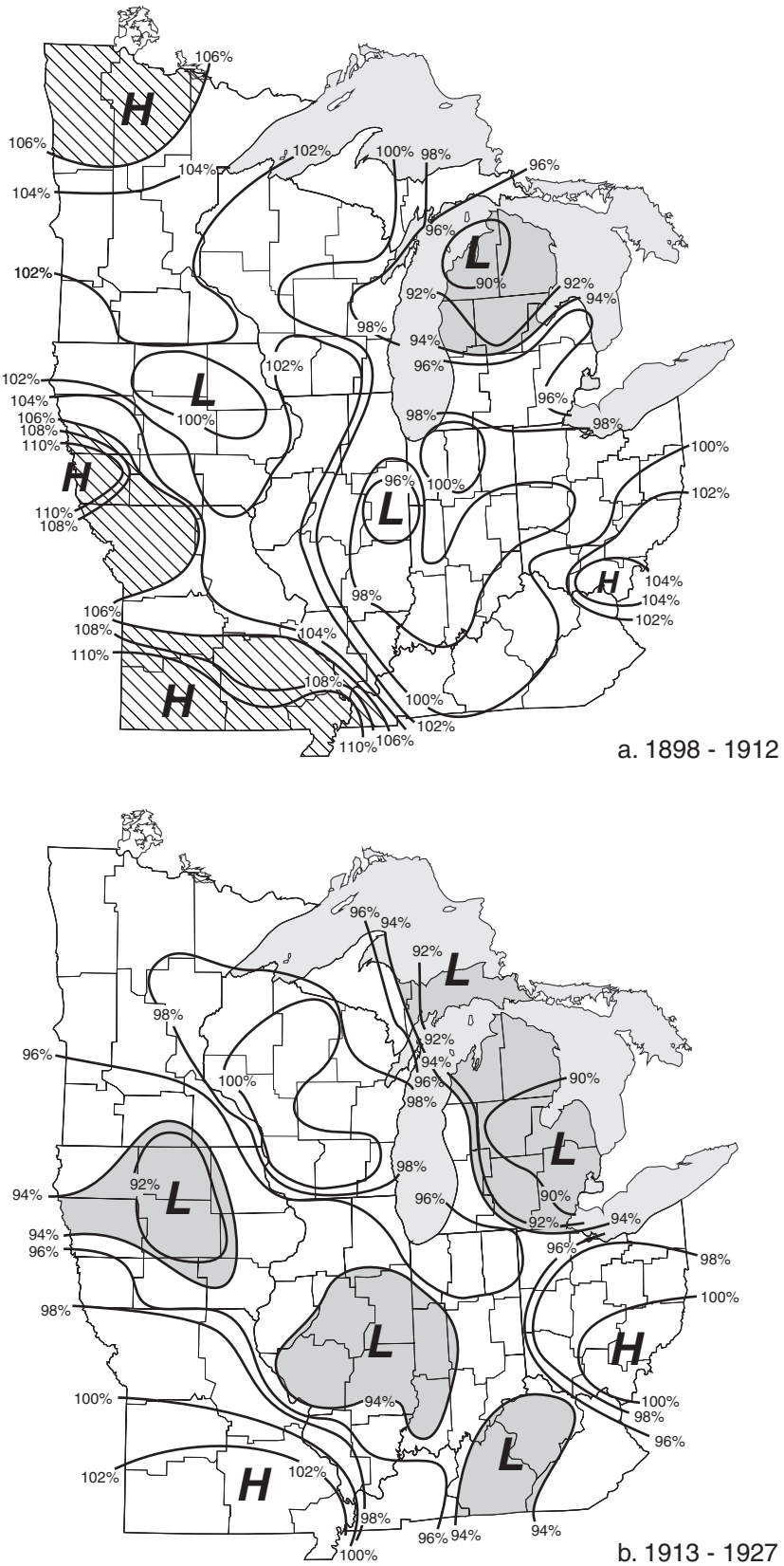
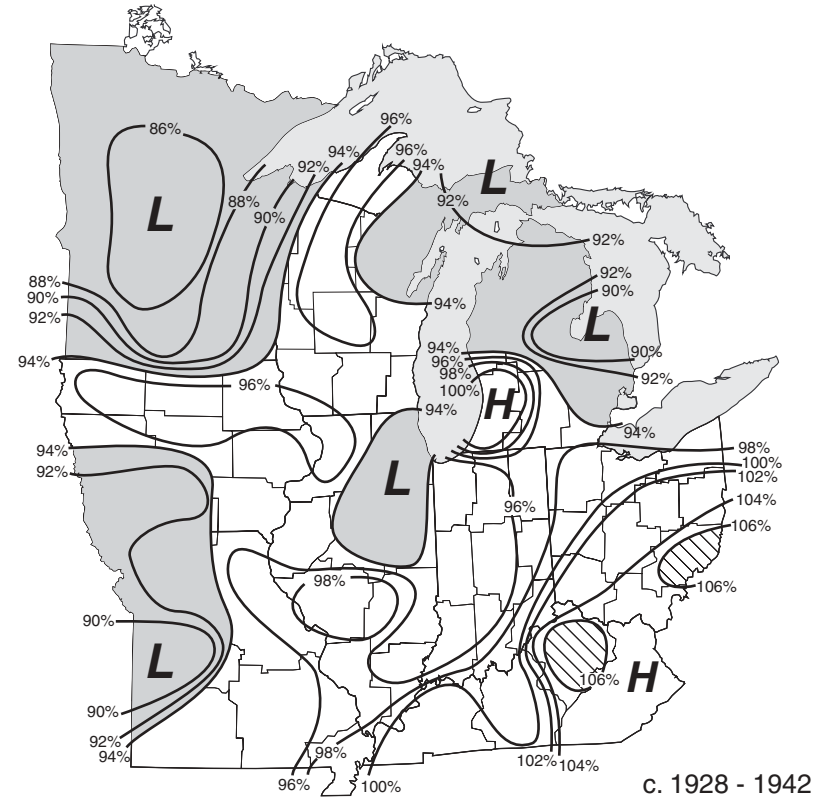


Figure 7. Pattern based on percent of average summer rainfall for a. 1898-1912, b. 1913-1927, c. 1928-1942, d. 1943-1957, e. 1958-1972, f. 1973-1987, and g. 1988-2002



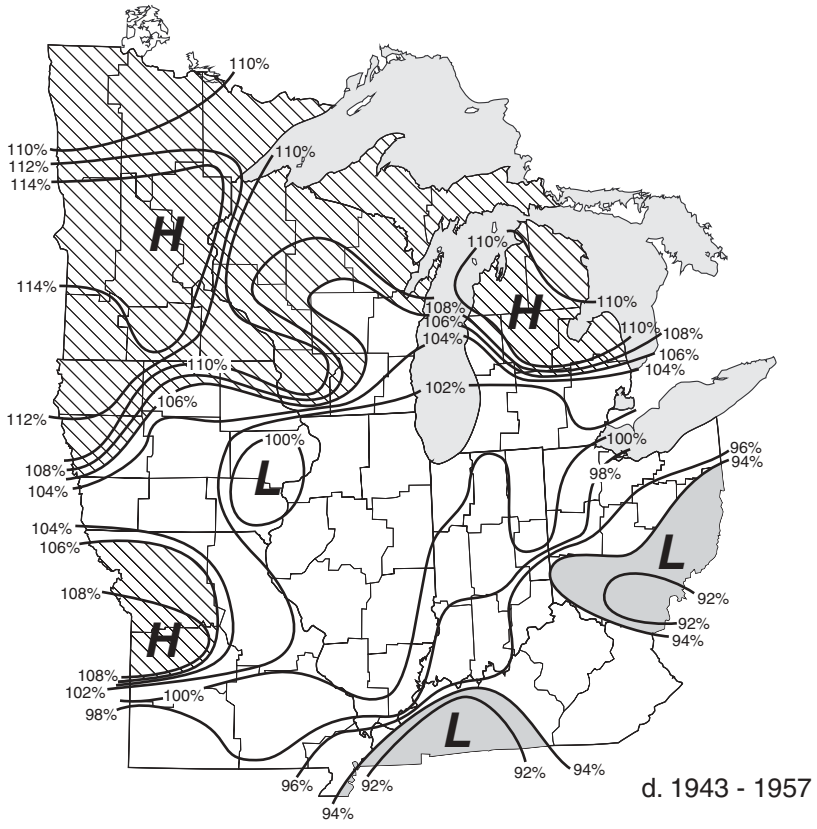
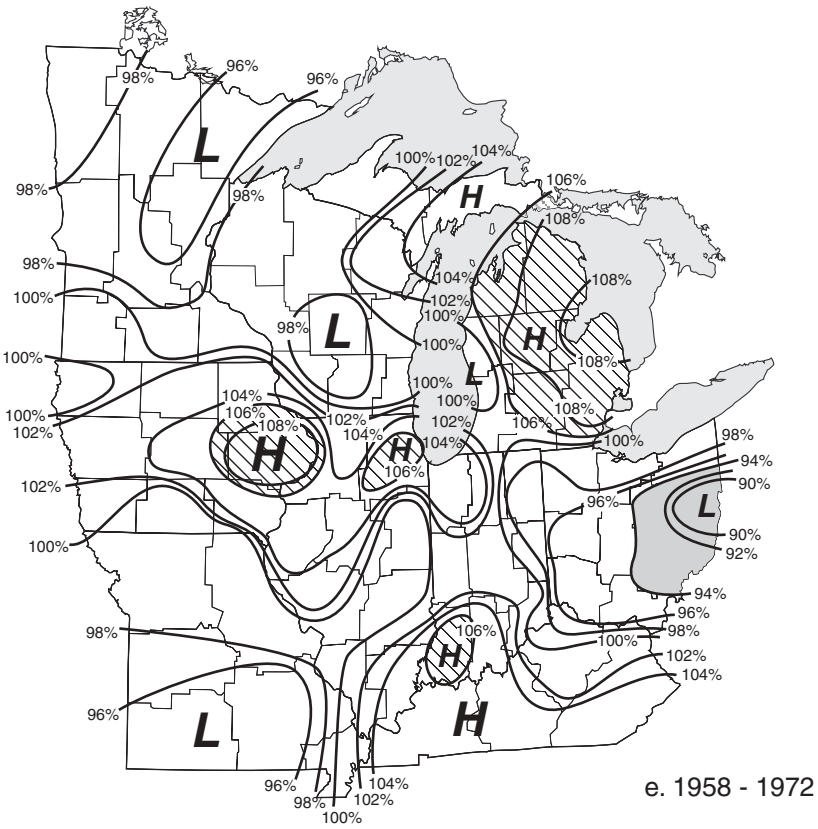
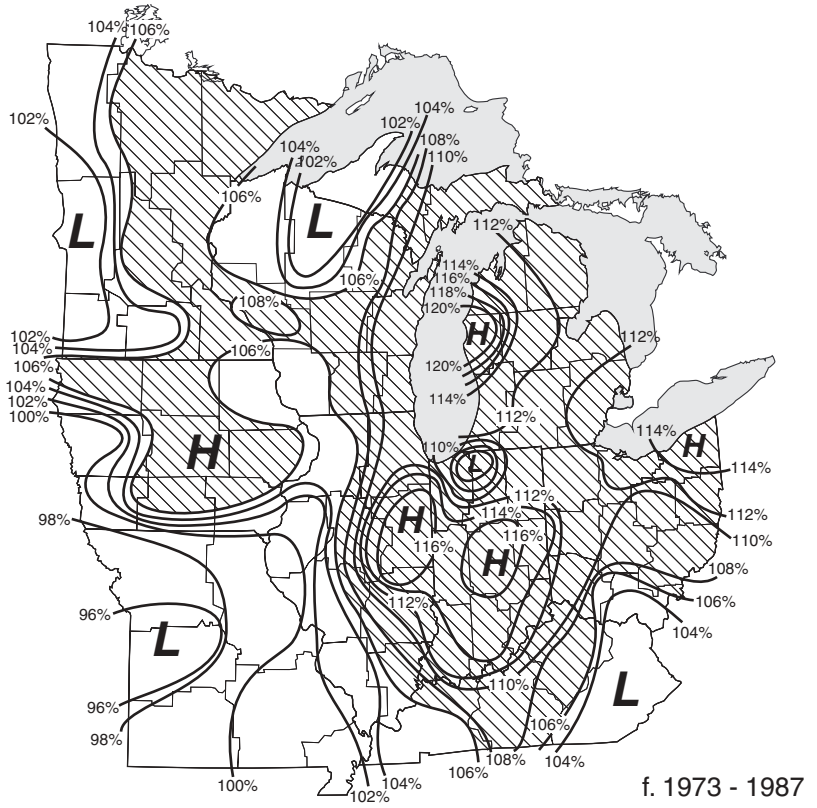


Figure 7. Continued



e. 1958 - 1972



f. 1973 - 1987

Figure 7. Continued

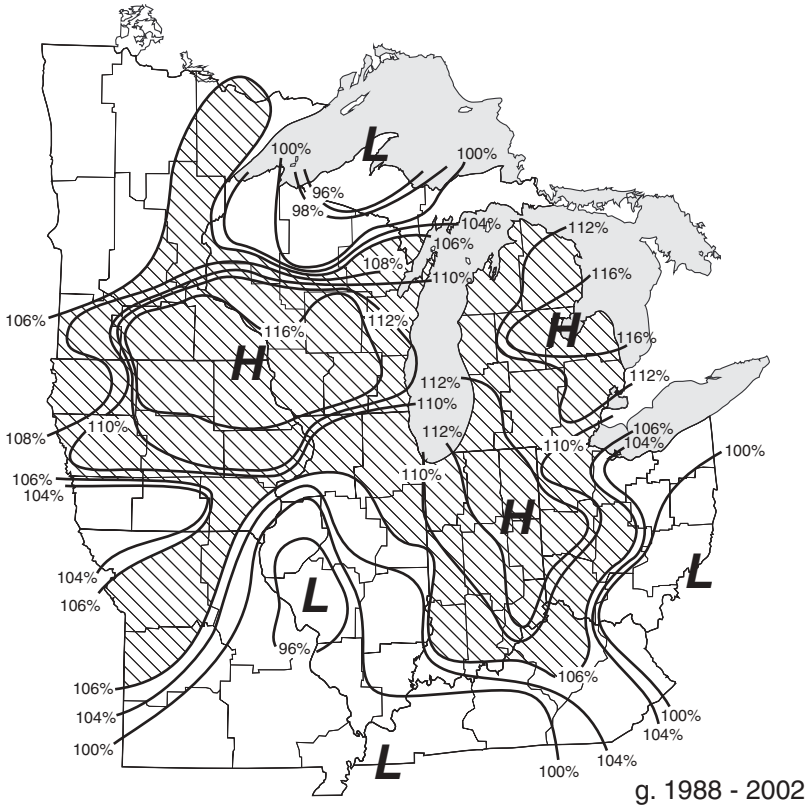


Figure 7. Concluded

Summary

Annual Precipitation

The 105-year study period sampled a wide range of annual precipitation conditions across the Midwest, and three types of conditions occurred. The first two 15-year periods, 1898-1912 and 1913-1927, had prevailing near average conditions, with few extremes and minor spatial variability. In the next two periods, 1928-1942 and 1943-1957, below average precipitation conditions prevailed, and considerable spatial variability in total precipitation was evident. The fifth period, 1958-1972, had near average conditions like the first two periods, but with more spatial variability than exhibited during the first two 15-year periods. The last two periods encompassing 1973-2002 were shaped by above average precipitation, reflecting trends noted elsewhere that indicated ever wetter Midwestern conditions since the 1930s (Karl and Knight, 1998; Kunkel et al., 1993). Both 1973-1987 and 1988-2002 also exhibited considerable spatial variability in total precipitation. The seven-period sequence was as follows: two near average periods followed by two below average periods, another near average period, and two above average periods.

The 1898-2002 distribution of prevailing precipitation conditions also reveals why various recent studies of total precipitation, heavy rainfall events, and streamflow have all detected upward trends for large parts of the Midwest beginning during the 1930s and 1940s. During the 1928-1942 period, 72 of the 75 climate districts had below average precipitation, followed by a balance between above and below average conditions during 1943-1957, and then a high frequency (68 of 75 districts) of above average precipitation conditions during 1973-1987 and 1988-2002.

Annual precipitation values, expressed as a percent of the long-term averages, displayed varying extremes over time. Extreme departures in climate district values sampled in the two early periods differed by 13 percent or less, whereas extreme values in the drier and wetter periods differed by 15 to 18 percent. Locations where extreme district values occurred revealed regional preferences. During the 105-year period there were 14 extreme high and low values (7 periods each with a high and low value): five extremes occurred in Michigan, four extremes in Minnesota, and two extremes in Wisconsin (one each in Illinois, Missouri, and Ohio). This reveals a propensity for extreme high and low values to be greatest in the northern Midwest where the lowest annual average precipitation occurs.

Patterns based on the total annual precipitation departures were compared with those based on years with the most frequent precipitation class, as defined by six climate types. This analysis showed good agreement in the four 15-year periods when precipitation was either relatively high or low: 1928-1942, 1943-1957, 1973-1987, and 1988-2002. In two periods when near average conditions prevailed, 1898-1912 and 1913-1927, there were small regional differences. For example, an area with districts having 98 to 102 percent of average annual precipitation occasionally was associated with below average climate types (climate type 5 or 6). Inspection of such anomalies revealed only one less wet year than dry years, and the precipitation in the wet years was sufficiently high to equal or exceed deficient amounts in the dry years.

In some 15-year periods, there were districts with excessive numbers in 8 or more years (more than half the period) with one type of precipitation class, either above average or below average, and precipitation values associated with these districts were assessed. When 8 or more

years were type 1 or 2, wet or above average years, the 15-year precipitation departures were 106 percent or greater. Conversely, when 8 or more years were type 5 or 6, dry conditions, the 15-year precipitation values were 96 percent or lower.

Examination of the general features of the seven precipitation patterns reveals that southern portions of the Midwest had values below average, and lower than those elsewhere, in five of the seven periods. Only the 30 years beginning in 1898, 1898-1927, had above average values in the south. Northern sections of the Midwest frequently had above average precipitation conditions in the five periods. Only the 1913-1927 and 1928-1942 periods had notably low values across the area's northern sections. The east-west section across the central Midwest experienced all types of conditions, with two periods having below average values, three periods with near average values, and two periods with above average values.

The analysis of the number of climate district precipitation amounts rated as being in the higher and lower 25 percent of each district's 105 values for the 1896-2000 period revealed important temporal shifts over time. The largest number of wet districts occurred in 1977-1978, the only such pair of high years during 1896-2000. The years with the two highest counts of dry years were 1933 and 1935. However, most years with extremely high counts of wet or dry districts were isolated in time. Temporal distributions based on the annual number of wet and dry districts showed three distinct eras during the 1896-2000 period. Most years in 1896-1930 had only 20 or fewer dry and wet districts with a few isolated years having large counts of dry districts. For 1931-1965, there were periods in the 1930s and 1950s with exceptionally large numbers of dry districts and a few years with high counts of wet districts (1945 and 1951). This reflected a 35-year period of great precipitation variability and major extremes. The third era, 1966-2000, was one with most years of low counts of dry districts and many years after 1975 with large numbers of wet districts.

Summer Rainfall

Summer rainfall values (percent of average) for the seven periods revealed two periods with widespread below average amounts (1913-1927 and 1928-1942), and two periods with widespread above average amounts (1973-1987 and 1988-2002). Interestingly, these formed two 30-year periods of extremes, one being essentially dry (1913-1942), and one being wet (1973-2002). The 15-year periods in the dry or wet regimes each had 57 or more districts, more than 75 percent of the entire Midwest, in the below or above average category. The two wet periods had large numbers of climate districts with values greater than 106 percent, with totals representing 60 percent of the Midwest. The two dry periods did not experience comparable numbers of climate districts with values less than 94 percent.

Summer rainfall in three other 15-year periods during 1898-2002 reflected a mixture of below and above average values. Two periods had one large area of above average values and one large area of below average values. In 1898-1912, rainfall in the western half of the Midwest was above average and eastern half below average, whereas in 1943-1957, the southern third of the Midwest was below average and northern portions were above average. The pattern of the remaining period, 1958-1972, exhibited less regional consistency with three separate areas of below average values and two distinct areas of above average values. Notably, this period had only nine districts with rainfall greater than106 percent and only three districts with less than 94 percent, revealing precipitation in most districts was near average.

Comparison of the percent of average patterns for the annual precipitation and summer rainfall for the seven 15-year periods revealed strong agreement in five of the seven periods. Only in 1913-1927 and 1943-1957 were there notable pattern differences, but their major locations of high and low values agreed. This reveals the considerable impact of summer rainfall distribution in the Midwest on the annual precipitation patterns.

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