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Temporal Fluctuations of Hail in Illinois

by Stanley A. Changnon
Office of Applied Climatology

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Illinois State Water Survey
Atmospheric Sciences Division
Champaign, Illinois

A Division of the Illinois Department of Natural Resources

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INTRODUCTION

This report presents information on the incidence of hail in Illinois during the 1901-1994 period. The emphasis is on the temporal behavior of hail and its implications for understanding and detecting any change in climate conditions that would affect hail incidence. This information should be useful to the hail insurance industry.

The assessment of crop-hail risk over time is best developed using the longest possible period of record. Since hail occurrence, especially in severe dimensions across a large state such as Illinois, is not a frequent event (as compared to rainfall or most other weather conditions), very long records are needed to develop an *adequate sample*. Therefore, this study sought to obtain and develop the longest possible records of hail for purposes of investigation.

This study used hail data from crop-hail insurance losses from 1948 to present and data collected from 1901 to present at weather stations of the U.S. National Weather Service (NWS). The NWS hail day (a day on which hail occurred) records exist for the 1901-1994 period at several weather stations in Illinois, and the crop-hail loss cost data are available for the 1948-1994 period. One objective of this study was to assess the relationship between the annual insurance loss cost values and the annual incidence of NWS hail days during the 1948-1994 period.

This report consists of an introduction, a description of the hail data analyzed in this study, a description of the temporal behavior of the NWS hail-day data for the 1901-1994 period, and a comparative analysis of the insurance loss costs and NWS hail-day data and the results of that study. As part of this study, detailed listings of the hail days at each weather station in Illinois were developed.

DATA EVALUATION

National Weather Service Data

Since 1901 the NWS has maintained about 60 weather stations in Illinois. The two categories of stations include First-Order Stations (FOS) operated by NWS personnel and cooperative weather stations (CWS) operated by volunteers. The FOS in Illinois have been maintained at only a few locations: Chicago, Cairo, Moline, Peoria, Rockford, and Springfield. St. Louis was included in the analysis due to its proximity to Illinois. The Cairo station was closed in 1965, but all other FOS were operated from 1901 to present.

The 55 long-term CWS in Illinois have been operated by volunteer weather observers, and their records represent both a blessing and challenge. They give the spatial detail and definition to hail incidence across the state that the FOS alone cannot provide. But the reporting of hail at CWS is voluntary: some observers over the past 94 years have been faithful in reporting hail, while others have ignored the incidence of hailstorms and reported only what they

had to report, rainfall amount and temperatures. Consequently, it was necessary to carefully assess the historical monthly records of each CWS from 1901 to 1994 to define the quality of the hail data.

The study used a complex scientific technique involving comparison, on a year-by-year basis, of the CWS data with that at nearby FOS, with attention to the name of the weather observer. This technique is described in an article published in a scientific journal (Changnon, 1967). From this assessment, it was possible to define those stations with quality hail records and the periods of these records. For example, the Urbana station had quality hail records from 1903 (when it opened) to 1943, poor records until 1948 when the quality improved, a situation that has continued to the present. Figure 1 shows the 33 CWS with 40 or more years of quality hail-day records during 1901-1994 and the 7 FOS used in this study. The stations provide good regional sampling and coverage across the state. Table 1 lists the names of the stations and the periods of quality hail records.

Insurance Data

The annual loss cost values for Illinois were provided by the National Crop Insurance Services based on data for all crops and all reported hail losses. Each value represents a value that is normalized each year to the amount of liability. Due to the concentration of crop-hail insurance coverage in central and northern Illinois, the Illinois loss costs are considered to represent hail loss conditions in the northern 80 percent of the state (roughly north of a line through St. Louis). In 1994, the amount of liability purchased in the state's southernmost 24 counties was 1.4 percent of the state's total. Thus, the incidence of hail in the southern portion of Illinois had very little influence on the insured hail losses.

HAIL DAY FINDINGS

Average Conditions

The NWS hail-day data were used to define and describe various temporal conditions. The annual average number of hail days is a base line useful for assessing the temporal variability of hail. Table 2 presents averages for the seven stations with records of 90 years or longer. The long-term averages vary only marginally across the state. The lowest hail-day values are 2.0 days at Peoria and 2.1 days at Chicago, and the highest values are in the south where Marion averaged 2.6 days and Springfield averaged 2.4 days. The highest-lowest difference in Illinois (2.0 days versus 2.6 days) represents a 30 percent difference. There is spatial variation in the average numbers of hail incidences in Illinois that creates regional differences in risk of crop and property damage, but the areal variation is not large. The spatial patterns are discussed further in material presented below.

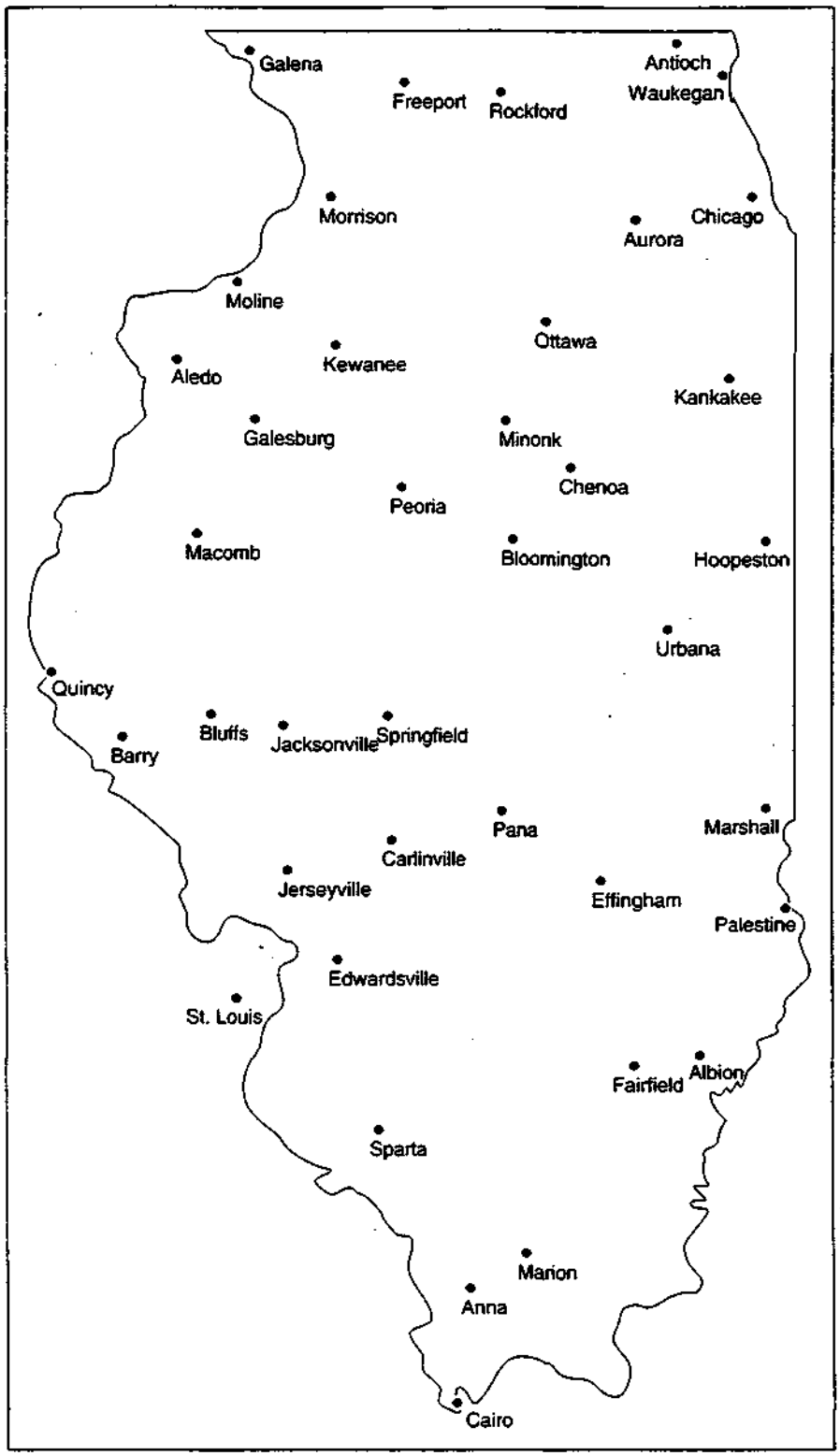

Figure 1. The 40 weather stations with quality hail data for 40 years or more, 1901-1994.

Table 1. Weather stations in Illinois with quality hail-day records and the periods of quality hail data within the 1901-1994 period.

First-Order Stations (FOS)	*Period of Data*
Cairo	1901-1965
Chicago	1901-1994
Moline	1901-1994
Peoria	1905-1994
Rockford (before 1958, this was a CWS)	1903-1914, 1921-1994
St. Louis	1901-1994
Springfield	1901-1994
Cooperative Weather Stations (CWS)	
Aledo	1904-1916, 1937-1963, 1980-1994
Albion	1950-1994
Anna	1916-1925, 1946-1994
Antioch	1903-1920, 1941-1992
Aurora	1902-1940, 1951-1967, 1971-1991
Barry	1940-1979
Bloomington	1932-1937, 1945-1994
Bluffs	1942-1986
Carlinville	1951-1994
Chenoa	1951-1994
Edwardsville	1926-1987
Effingham	1901-1902, 1911-1920, 1951-1994
Fairfield	1951-1994
Freeport	1909-1914, 1931-1988
Galena	1928-1994
Galesburg	1927-1994
Hoopeston	1904-1918, 1951-1994
Jacksonville	1901-1973, 1981-1994
Jerseyville	1948-1994
Kankakee	1923-1937, 1942-1972, 1980-1994
Kewanee	1939-1985
Macomb	1941-1987
Marion (New Burnside prior to 1958)	1901-1994
Marshall (Paris after 1980)	1940-1974, 1981-1994
Minonk	1903-1913, 1950-1994
Morrison	1901-1921, 1927-1980
Ottawa	1925-1994
Palestine	1907-1922, 1933-1985
Pana	1904-1911, 1934-1940, 1950-1994
Quincy	1912-1992
Sparta	1901-1990
Urbana	1903-1943, 1948-1994
Waukegan	1924-1976

Trends

Figure 2 depicts long-term trends and associated variations in the number of hail days at the seven long-term stations. There are no persistent upward or downward trends lasting over the 94-year period at any weather station.

The station's 5-year values are organized in a north-to-south fashion with Chicago at the top and Marion at the bottom. Inspection of these curves, in light of their variations around the long-term averages, illustrates five general findings.

1. *All stations had above average values during the 1946-1965 period,* with this maximization being most pronounced in the central (Springfield) and northern stations, which all experienced their highest 5-year values sometime during this 20-year period.

2. *The central-south stations (Springfield, St. Louis, and Marion) had above average hail incidences during the 1916-1930 period,* but hail incidences elsewhere in Illinois during this period were near to below average.

3. *Most stations had above average hail incidences during 1906-1910.*

4. *All stations in central and northern Illinois show a continuing slow decrease of hail days after the major peaks in the 1950s and early 1960s.* However, the two southernmost stations (Marion and St. Louis) had near normal values since 1960 with no clear trend up or down.

5. *Most stations had their lowest or second lowest 5-year hail-day value during the last 20 years, those since 1975.* This includes Chicago (1981-1985 rank #1), Moline (1981-1985 rank #1), Peoria (1986-1990 rank #1), Urbana (1990-1994 rank #2), Springfield (1981-1985 rank #1), St. Louis (1976-1980 rank #1), and Marion (1976-1980 rank #2).

Interpretation of the above five findings reveals that the temporal behavior of hail is quite similar across the northern 75 percent of the state, but that hail in the southern 25 percent of Illinois is different. *Hail-day frequencies from 1901 to 1994 across the northern 75 percent of Illinois exhibited three major phases of activity over time: 1) near-normal values from 1901 through the mid-1940s, 2) a maximization of incidences from the late 1940s through the mid-1960s, and 3) a general decline in hail days since the 1960s to record low values.*

Had Extremes

Table 2 provides a measure of the maximum numbers of hail days for one year, two consecutive years, and three consecutive years, as identified during the 94-year record. Inspection of these values reveals important aspects about hail maximization. *First, the peak one-year values range from three to five times the annual averages.* The peak values for two consecutive years are two to three times the 2-year averages, and the peak values of three

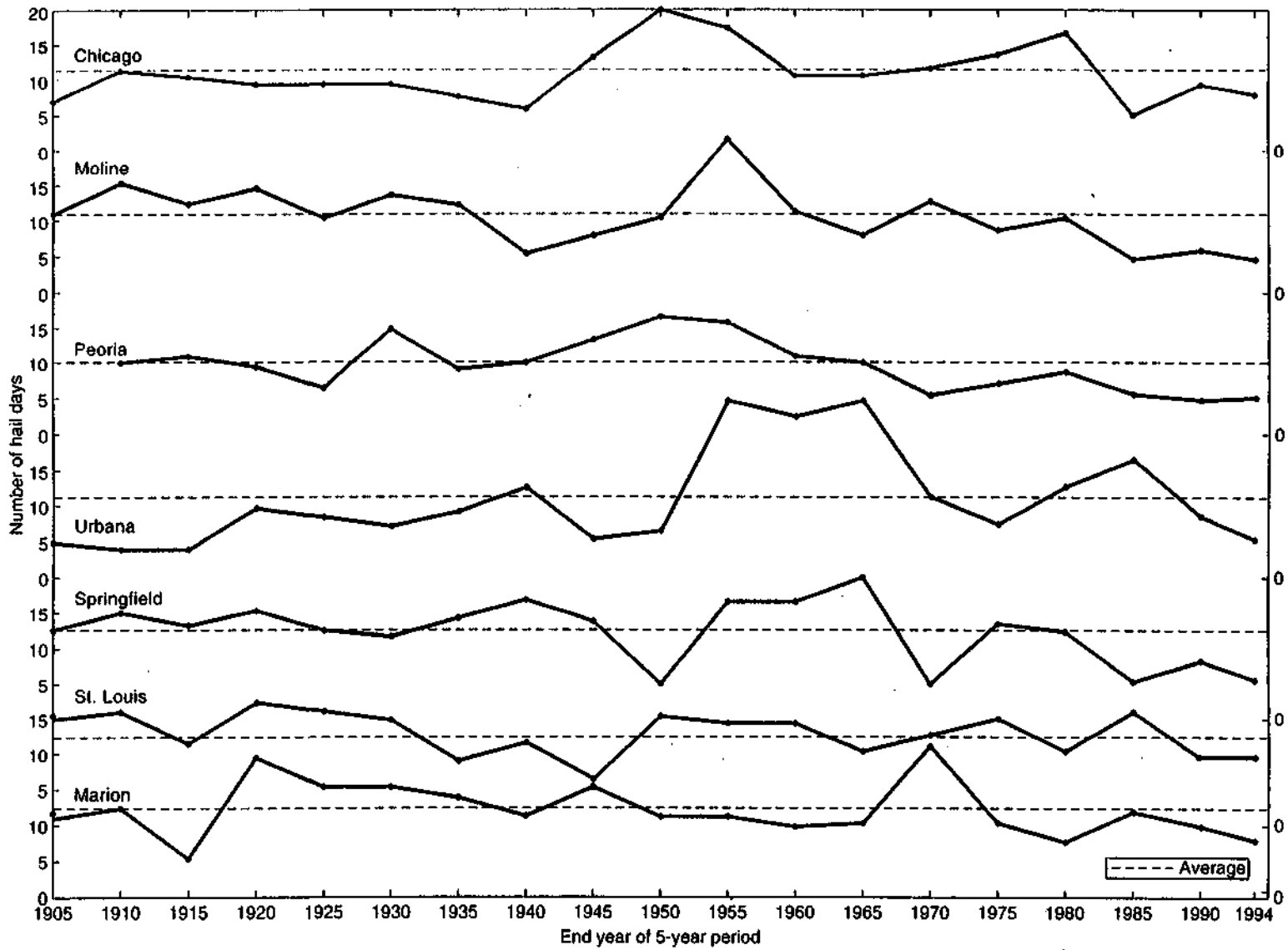

Figure 2. The temporal incidence of hail days from 1901 to 1994 at seven weather stations in Illinois. The values plotted are for 5-year periods (1901-1905,1906-1910, etc.), and the average at each station is shown as a dashed line. The stations are arranged from north at the top (Chicago) to the south at the bottom (Marion).

consecutive years are about twice the 3-year average. The excess diminishes as period length increases, but in all cases, the average versus record maximum difference is quite large.

All stations experienced several years with no hail days. Table 3 presents the frequency of years with no hail at the seven stations with long (94-year) record. Their values range from

Table 2. Average number of hail days and peak values for one, two, or three consecutive years at stations with 94-year records of hail.

		Number of hail days and periods of occurrence		
Station	*Average*	*One year*	*Two years*	*Three years*
Chicago	2.1	10(1947)	12(1947-1948)	14(1947-1949)
Moline	2.3	9(1954)	15(1950-1951, 1953-1954)	20(1953-1955)
Peoria	2.0	7 (1950, 1927, 1954)	11 (1949-1950)	14 (1949-1951, 1952-1954)
Urbana	2.2	9 (1955)	15 (1954-1955)	21 (1953-1955)
Springfield	2.5	8 (1975)	11 (1963-1964)	15 (1962-1964,1975-1977)
St. Louis	2.4	7 (1909)	11 (1909-1910)	15 (1909-1911)
Marion	2.6	7 (1907, 1917,1927, 1945, 1970)	13 (1969-1970)	17 (1916-1918, 1969-1971)

Table 3. Frequency of years with no hail days at weather stations in Illinois.

Stations	*Number of years with no hail*	*Percent of total years*	*Number of times with no hail for 2 years*
Chicago	13	14	3
Moline	16	17	2
Peoria	17	19	3
Urbana	14	15	1
Springfield	13	14	3
St. Louis	11	12	1
Marion	11	12	1

12 to 19 percent of all years with no hail, and there are fewer years with no hail in southern Illinois (Marion and St. Louis) than in northern Illinois. *This can be interpreted that in any given 10-year period at a point in Illinois, there will be one or two years with no hail.* The number of times there were two consecutive years with no hail (shown in table 3) reveals these events occurred very infrequently during the 1901-1994 period.

Expected Extremes

The magnitudes of the maximum values (table 2) are of interest and have application to insurance issues. The one-year maximums range from seven hail days at three stations up to ten days, nearly a 50 percent difference. Since their averages are similar, this suggests that any station could sample up to ten hail days in a year, but most stations have yet to achieve this one-year extreme. *This further reveals that a 94-year period at a point (station) is not adequate to sample the potential extremes that can occur in hail incidence.*

The two-year peaks vary less across the state, with the highest being 11 days at three stations and 15 days at two stations. This difference is 35 percent and again suggests that higher two-year values are apt to occur at several locations, including Springfield, St. Louis, and Peoria. The three-year maximum values also show great differences, from 14 days at Peoria and Chicago to 21 days at Urbana. Such differences out of a series of 94-year point (station) records reveals that *hail in Illinois is highly variable over time, and that much larger numbers than previously sampled are apt to occur at many locations in the future.*

Times of Extreme Hail Values

Another condition of relevance revealed by the peak values of table 2 are the dates of their occurrence. Note that the stations in the northern half of Illinois achieved *their record high 1-, 2-, and 3-year values during the 1947-1956 period, clearly the peak decade of hail activity in this half of the state.* This maximization is also exhibited in the high 5-year values shown on figure 2 for Chicago, Moline, Peoria, and Urbana. The 2-year and 3-year peaks at Springfield came a few years later in the early 1960s. St. Louis peak values were early, 1909-1911, and Marion had a high one-year value in 1907, but then had 2-year and 3-year maximums around 1970. *These record high values further support that the behavior of hail incidences throughout the northern 75 percent of Illinois is similar but quite different than that in southern Illinois.*

Time Periods between Extremes

The number of years between extreme years of hail incidence had value in risk assessment and for applications to the detection of climatic change. Table 4 presents the probability of years between high hail incidence periods, given one high incidence event has occurred. The times between high events was determined for the seven stations with 94-year records. The high one-year values (based on the top five highest values, rated as a frequency of once in 20 years) show that there is a 25 percent chance of a high year occurring within five years after a year with a high value. Note there is a 55 percent (25 + 30) chance of a peak

occurring within ten years after a high year. *The probabilities for high 1-year, 2-year, and 3-year values all show a double preference: either relatively soon (within 10 years) after a peak has occurred, or more than 20 years later. There is only a small probability for another peak to occur 11 to 20 years after a peak.*

Table 4. Probability of a year or multiple year periods with extremely high hail incidences occurring after a high hail event.

Length of period.	*High 1-year*[1]	*High 2-year*[2]	*High 3-year*[2]
1 - 5 years	25%	35%	35%
6 - 10 years	30%	15%	10%
11 - 20 years	15%	10%	5%
21 - 30 years	25%	20%	20%
31-50 years	5%	20%	30%

Note:
[1] based on the five highest values during 1901-1994.
[2] based on the highest three events during 1901-1994.

Hail Patterns and Their Temporal Variations

Figure 3 presents the hail patterns for the four 20-year periods from 1901-1980. Comparison of these allows definition of the major features in the hail pattern of Illinois. Four features, as denoted by study of the H's (highs) and L's (lows) on figure 3, are present in some degree in all four patterns. These include 10 a high in southwestern Illinois between Springfield and St. Louis, 2) a high in northwestern Illinois in and beyond the Galena hill area, 3) a low in hail incidence in southeastern Illinois, and 4) a low in hail incidence in northeastern Illinois. In three of the 20-year periods there was a high in the hills of extreme southern Illinois, but it was not present in 1961-1980. This persistence in the major features of the state's hail patterns suggests there have been no major long-term fluctuations in the primary hail-causing atmospheric conditions.

When considering these persistent high and low incidence areas, it is also important to assess their 20-year magnitudes. For example, the peak of hail activity in the southwestern area had a high of 90 hail days (1901-1920), 60 hail days (1921-1940), 50 hail days (1941-1960), and 55 hail days (1961-1980). *These values again show how much the incidence of hail can vary over time, particularly where the average incidence is high.* This suggests that the hail-producing conditions varied in frequency over time but not in location since the H's and L's stayed in the same locations.

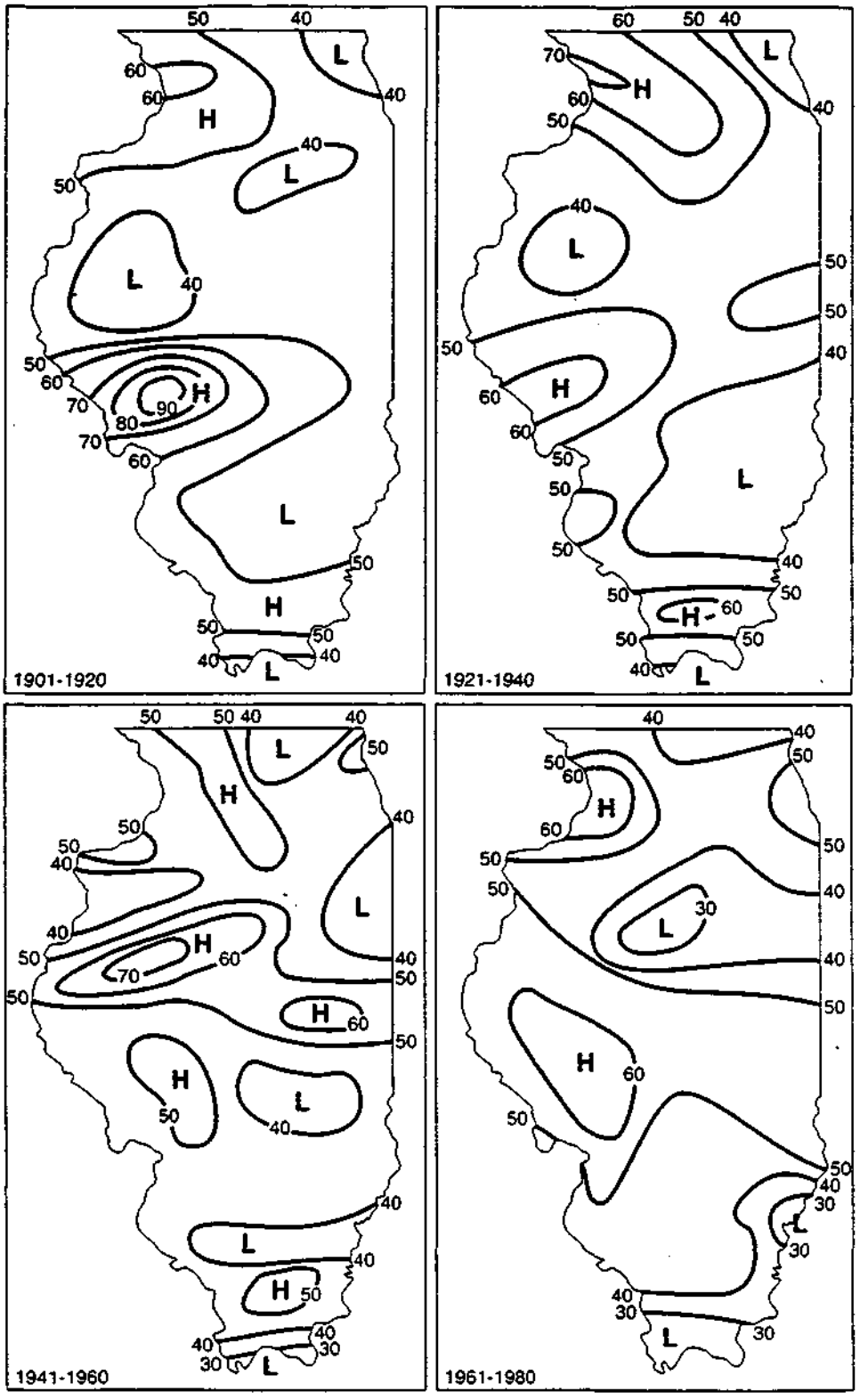

Figure 3. Patterns of hail days for four 20-year periods during 1901-1980.

Areas of low hail incidence in Illinois show less temporal variability. For example, northeastern Illinois had values of 35 to 40 hail days in all four 20-year periods, revealing more temporal stability than exists in the magnitude of the higher incidence areas. *This suggests that the weather conditions that produce hail in Illinois are more variable over the southwestern than northeastern sections of the state.*

The frequency of annual hail days at Springfield was determined for each 20-year period and for 1981-1994, and these values are shown in table 5. Asterisks denote the median and mode values in each period (the mode and median were identical in each period). Examination of their relative placement reveals *a declining frequency of hail since 1940.* The median was three hail days in 1901-1920 and 1921-1940, but it declined to two hail days in 1941-1960 and 1961-1980, and the median was only one hail day per year in the latest period (1981-1994). For the 94-year period, the median (and modal) values of hail days were two days per year. No hail days occurred in 13 years and one year had eight hail days.

Table 5. The frequency distribution of annual hail days at Springfield.

Number of hail days	*Number of annual values per 20-year period*					
	1901-1920	*1921-1940*	*1941-1960*	*1961-1980*	*1981-1994*	*1901-1994*
0	0	2	5	2	4	13
1	3	2	2	3	5*	15
2	4	4	5*	7*	2	22*
3	6*	6*	3	3	2	20
4	5	2	0	1	1	9
5	0	3	4	2	0	9
6	2	1	1	1	0	5
7	0	0	0	0	0	0
8	0	0	0	1	0	1

Note: An asterisk denotes the median and modal values for each period.

Figure 4 depeicts the hail-day pattern based on the 14-year values for 1981-1994. This shows a somewhat different pattern than existed in the four prior 20-year periods (figure 3). The northwestern Illinois high is present but not strong, and the southwestern high has shifted to St. Louis. A high incidence area appeared in east-central Illinois, an area that has generally been a low incidence area in past years. The lows in the southeastern and north-central regions appear as they have in past periods.

The biggest difference between hail during the 1981-1994 period and that in the previous 20-year periods is in the magnitude of hail days. A 14-year period should have lower values than a 20-year period and experience 70 percent of the hail days of a 20-year period. By

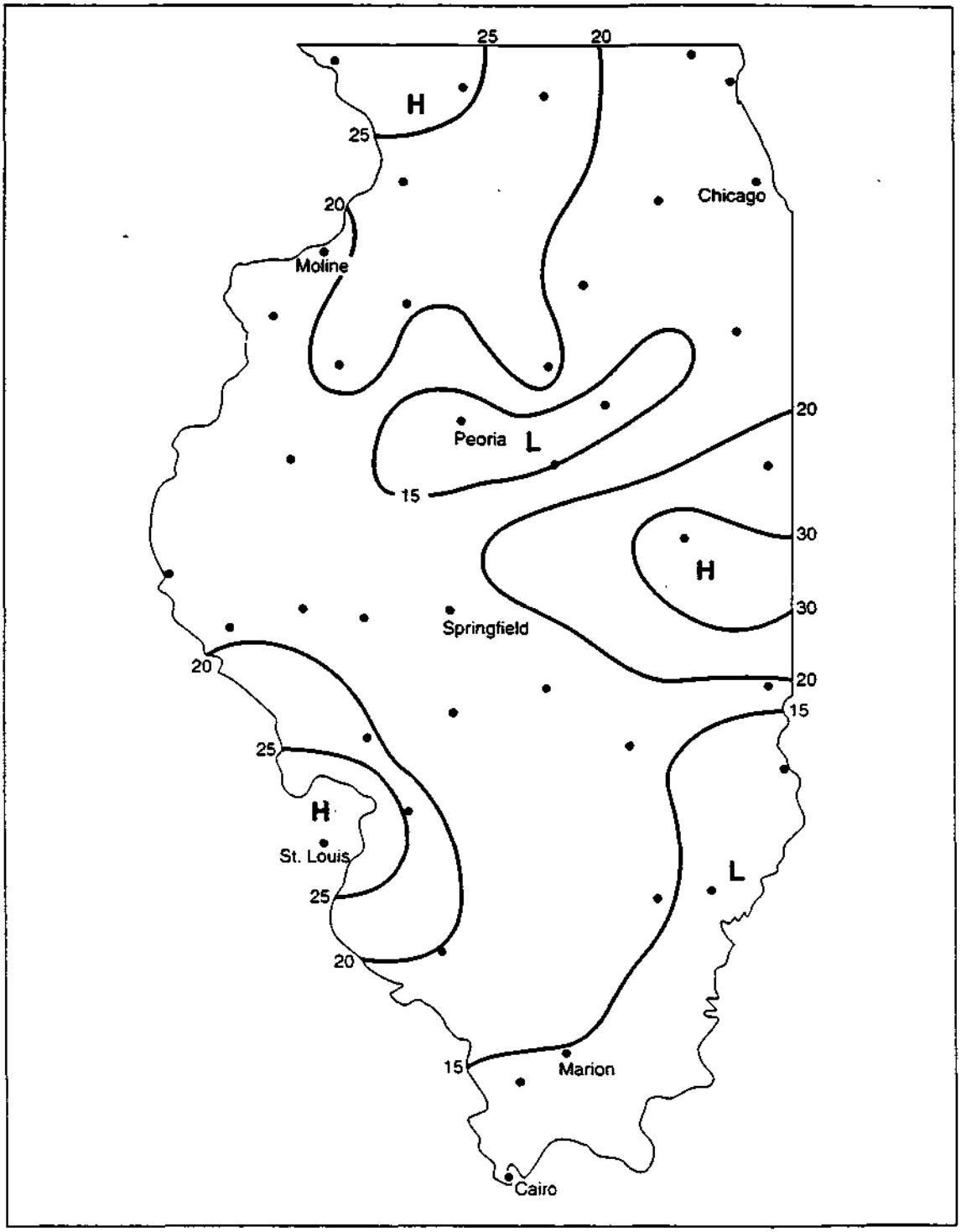

Figure 4. The pattern of hail days during the 1981-1994 period.

converting values of 15 hail days or less in the major lows of 1981-1994 and the values of 25 to 30 hail days in the major highs to 20-year values (multiply by 1.3), the resulting values would be 20 hail days in the lows of 1981-1994 and 30 hail days in the highs. These estimated values are markedly lower than those found in any previous 20-year period (figure 3). This helps reveal that *the occurrence of hail across Illinois in the last 14 years has been uncommonly low.* If the hail-day values of the 1981-2000 period are to match those of past periods, a considerable amount of hail will have to occur during 1995-2000. Interestingly, the hail losses in the High Plains in the last few years have been unusuaully high.

RELATIONSHIP OF CROP-HAIL LOSSES AND NWS HAIL DAYS

Changnon (1960) found a relationship between summer hail-day frequencies in Illinois and annual loss costs in an earlier study of hail done for the Crop-Hail Insurance Actuarial Association. The hypothesis underlying such a relationship was that the number of hail days across Illinois (as reported by the NWS stations) is related to the magnitude of the crop-hail loss each summer. Thus, only the frequency of NWS hail days for summer (June-August) when 98 percent of all reported crop-hail damage occurs in Illinois was that assessed (Stout and Changnon 1967). Various measures of the areal frequency of summer hail days were tested against the annual loss cost. Since most of the insurance coverage is sold in the northern 75 percent of the state, the frequency of hail days was analyzed for this area of Illinois representing 44,200 square miles, the area north of an east-west line through St. Louis.

After extensive statistical testing, the 1960 study found that the strongest relationship existed between the amount of area of Illinois that experienced hail days matching or exceeding the *10-year frequency in a given summer.* That is, the number of hail days expected to occur at a station only once every ten years. This and other return frequencies (5-year and 20-year) were defined in a climatological study of hail (Huff and Changnon 1959). Figure 5 shows the 10-year frequency pattern based on analysis of the historical frequency of hail days at each weather station. For example, the long records at Peoria show a 10-year frequency of slightly less than two days per summer; hence, the area around Peoria shown as "less than 2 hail days." In the high-incidence areas of southwestern and northwestern Illinois, the stations have values in excess of three hail days expected to occur once every ten years. *This earlier analysis (Changnon, 1960) discovered a strong statistical correlation between the summer hail days and the annual loss cost, based on 1948-1959 data.* This relationship meant that the areal extent of summer hail days could be used to predict the loss costs in years before 1948 when no crop-hail data existed.

Figure 6 shows the summer hail-day patterns for a year with extensive summer hail days across most of Illinois (1978) and for a year with practically no summer hail (1988). These maps illustrate the wide contrast in summer hail-day conditions that can exist in different years.

The relationship between annual loss cost values for Illinois and the areal extent of hail days was reanalyzed using the 1948-1994 data. The areal extent of hail across the state was

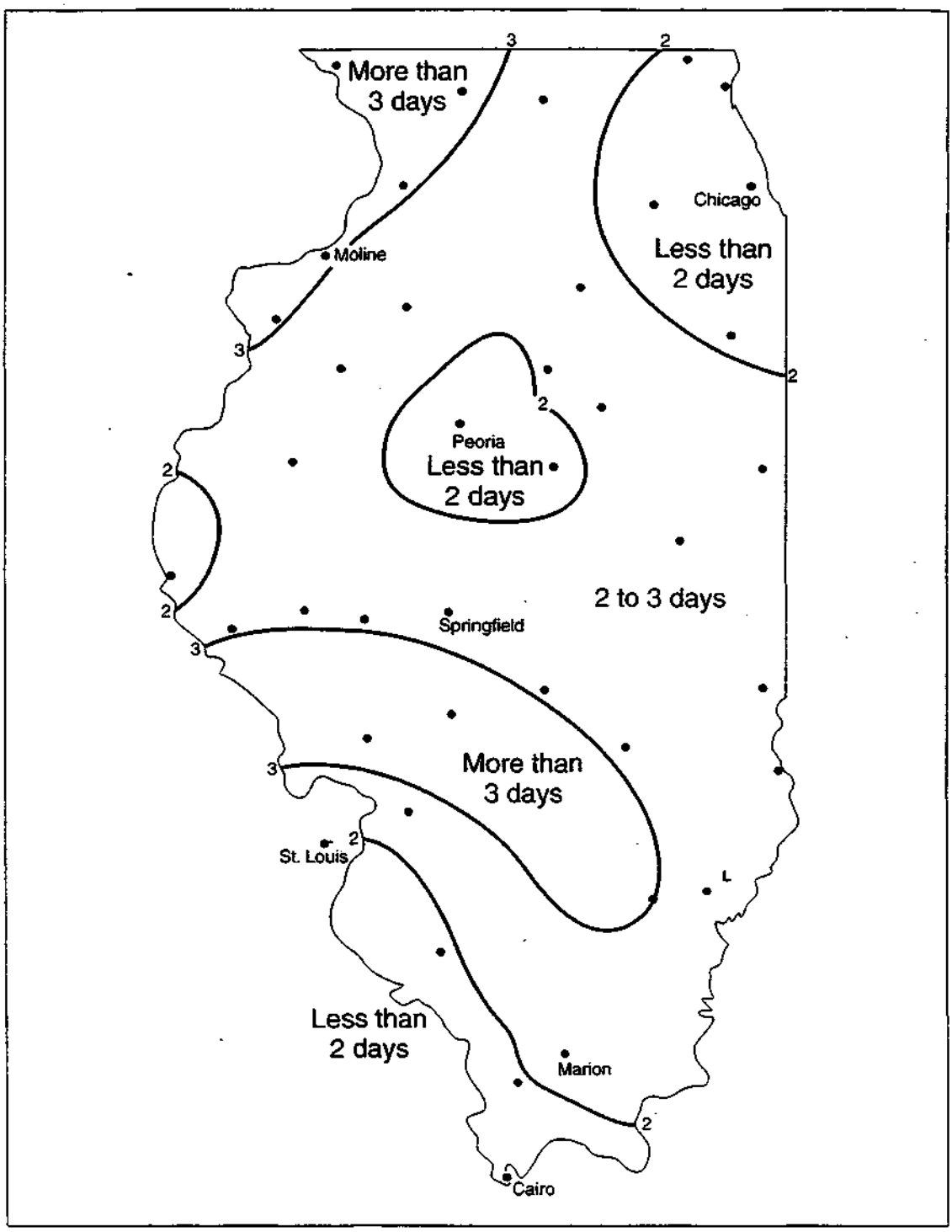

Figure 5. The pattern based on the number of summer (June-August) hail days expected to occur at least once every ten years at a point in Illinois.

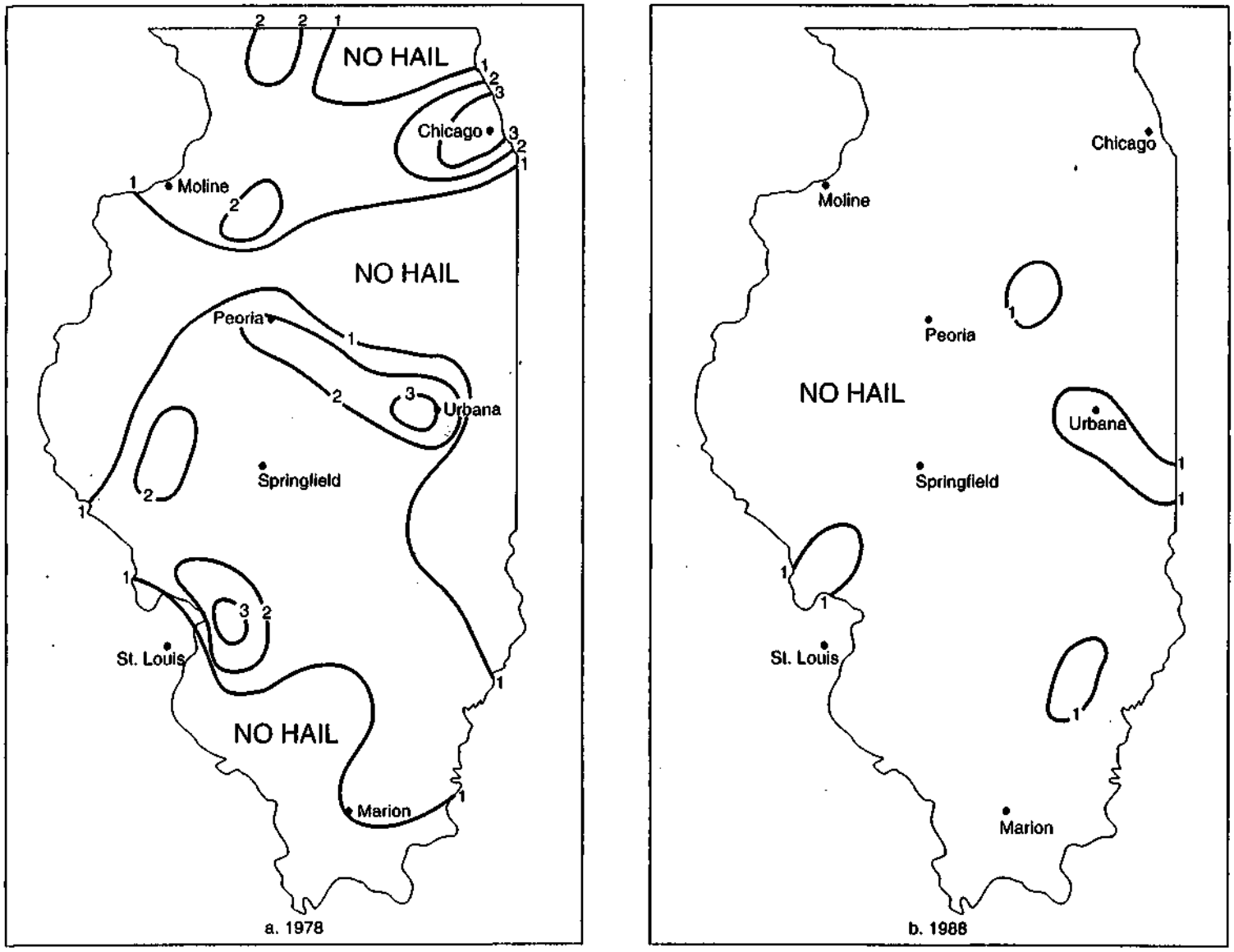

Figure 6. Patterns based on the number of summer (June-August) hail days during 1978 (map a) and 1988 (map b) exhibit major differences.

examined in each summer from 1960-1994 (the years not investigated in the earlier study). This area, expressed as a percent of the total state, was determined based on the number of stations with hail. Also determined was the area with two or more hail days, also expressed as a percent of the state's total area. Figure 7 plots the resulting percentages.

Inspection of the upper curve (percent of Illinois with one or more summer hail days) reveals three interesting temporal regimes. First, the values of the *1960-1970 period* were relatively high, descending slowly, and with little change between years. Second, the values in the *1970-1980 period* showed that the hail extent increased considerably (typically 50 percent or more of the state in many years), and further exhibited considerable year-to-year variation. For example, the 1970 value was 31 percent, rising to 47 percent in 1971, decreasing sharply to 26 percent in 1972, then rising to 54 percent in 1973. Third, the values in the 1981-1994 period were markedly lower than those of the two previous periods, averaging 30 percent. *There has been much year-to-year variability since 1981--note the high of 52 percent in 1987, followed by a low of 12 percent in 1988.*

The lower curve on figure 7 depicts the percent of Illinois experiencing two or more hail days in each summer from 1960 to 1994. This frequency of summer hail days approximates the level found in the earlier study to relate well to the annual loss costs. This important curve shows three quite different periods: a) *1960-1973* with some high values but with hail incidence declining with time from 25 percent to less than 10 percent, b) *1974-1980* with consistently high values of 20 percent to 30 percent of Illinois with two or more hail days, and c) *1981-1994* with consistently low hail area values of 5 percent to 10 percent of the state. These very large temporal shifts, both in areal extent and in the year-to-year variability over time, have meaning for the hail-loss experience for crops in Illinois.

Figure 8 plots hail loss costs for 1948-1994. The curve based on the annual loss cost values shows a remarkable similarity to the lower curve (frequency of two or more summer hail days) in figure 7. This suggests that a good relationship exists.

Using the 47 values (1948-1994) of annual loss costs (all crops) and the summer values for the percent of Illinois (the northern 79 percent) experiencing hail days matching or exceeding the 10-year values, correlation analyses were performed to test the relationship. Areas with a 10-year hail-day frequency were calculated based on mapping the summer (June-August) hail-day pattern for each year, then comparing this pattern with the 10-year frequency pattern (figure 5) . to measure the area matching or exceeding the 10-year values. The areal extent of these extreme areas was calculated to determine what percent of the state this value represented. Values ranged from a low of 0.11 percent in 1986 to a high of 5.94 percent in 1975, and the average was 1.9 percent.

The correlation analysis yielded a correlation coefficient of +0.946, indicating an extremely strong statistical relationship between summer hail days and crop-hail loss costs. The square of this coefficient, 0.90, indicates that the summer frequency of hail days equalling or exceeding the 10-year values explains 90 percent of the variability in the annual loss cost values.

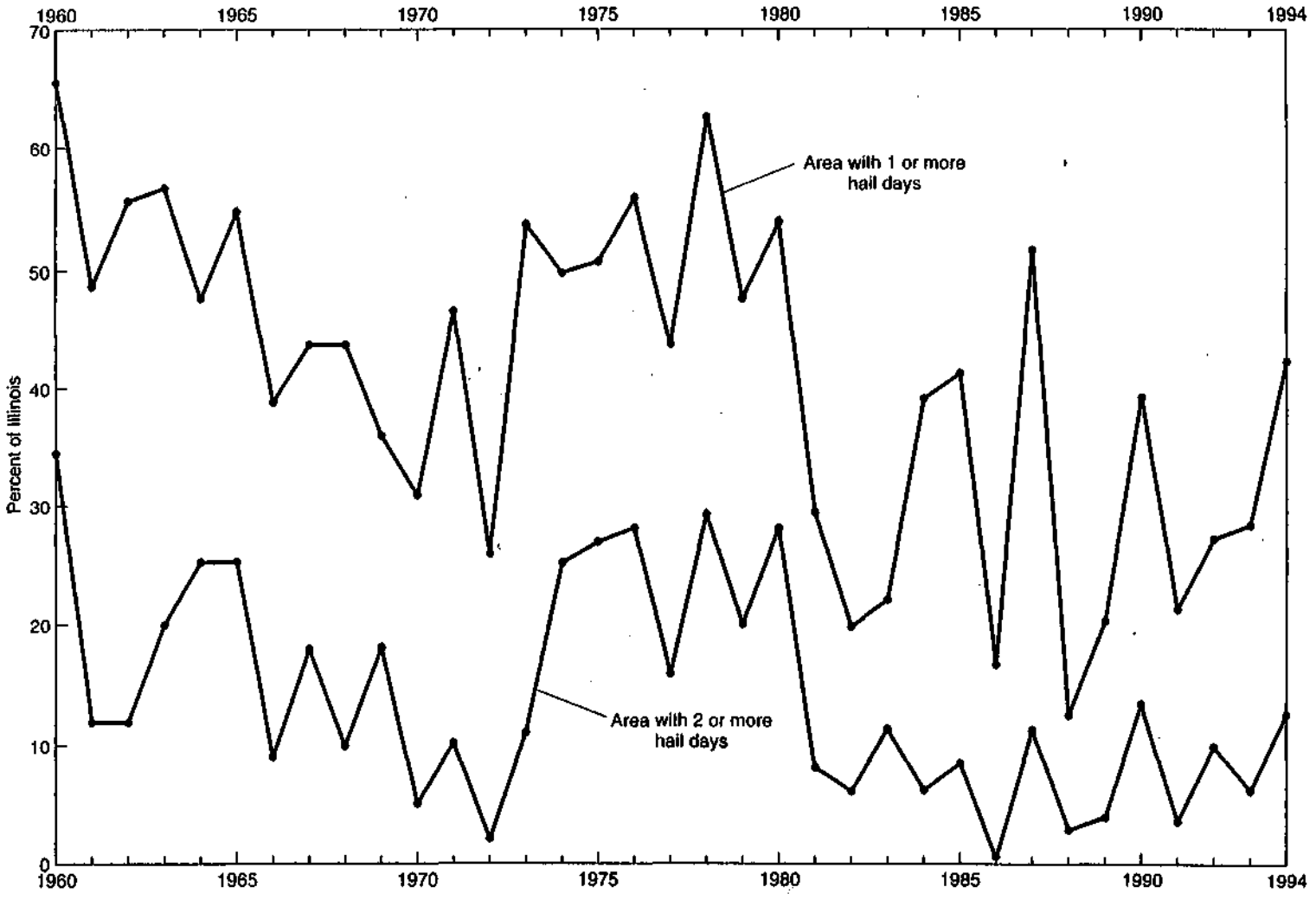

Figure 7. The areal extent of Illinois experiencing one or more hail days in summer (June-August) and two or more summer hail days for each year in the 1960-1994 period. The area is expressed as the percent of the state.

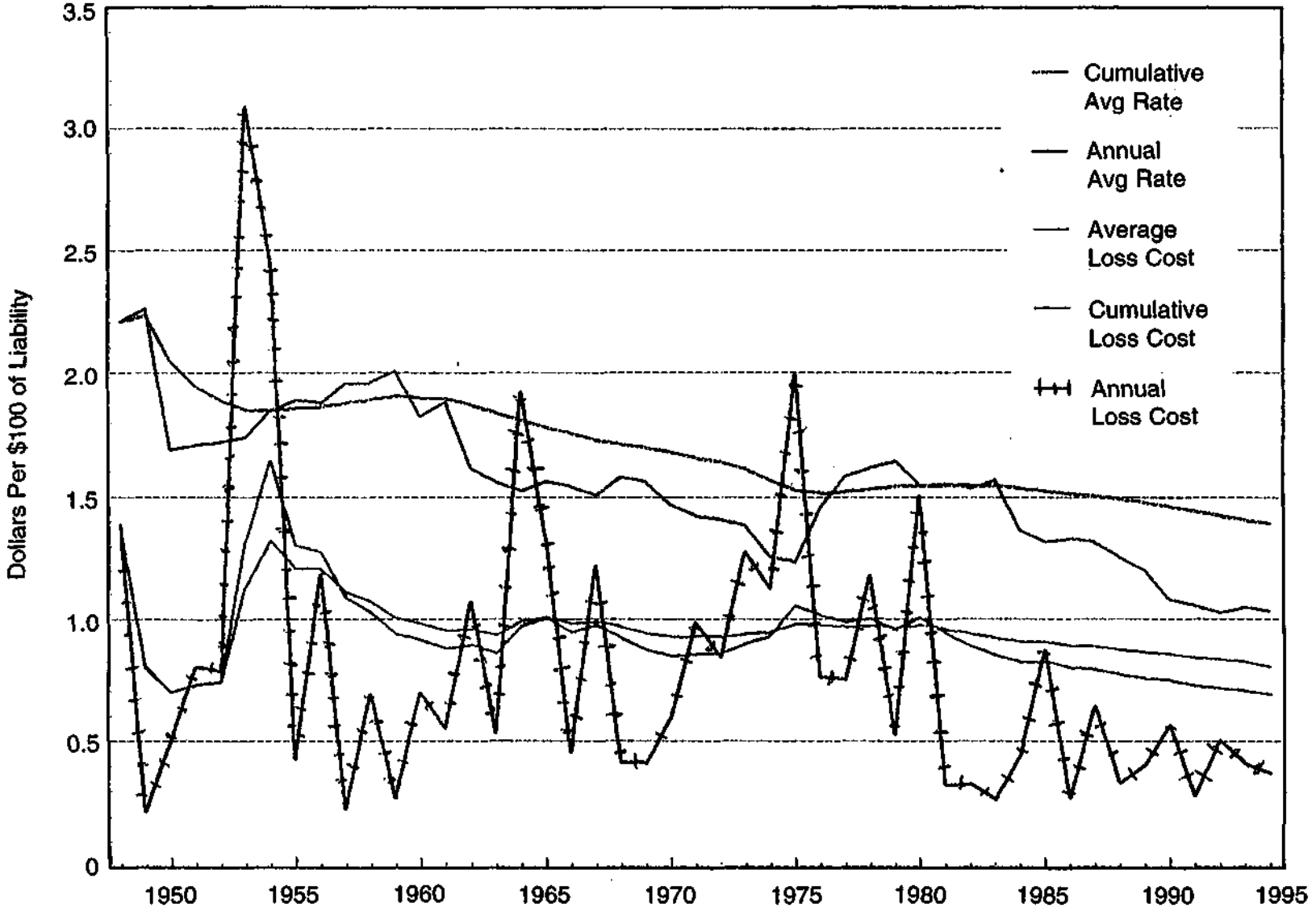

Figure 8. Various expressions of the annual and cumulative crop-hail cost and rate values for the 1948-1994 period in Illinois (courtesy National Crop Insurance Services).

These findings demonstrate the value of NWS hail-days data for representing hail loss and for meaningful indicators of a potential shift in the hail climate of Illinois.

CONCLUSIONS

The long-term hail values for Illinois weather stations exhibit fluctuations during the 1901-1994 period but no long-term trends of decrease or increase. Hail incidence in the northern three-fourths of the state peaked during the 1946-1965 period. Hail incidences have since declined, reaching their its lowest annual values during the 1981-1994 period. The multi-decadal shifts in hail incidence roughly match those found in Midwestern thunder day frequencies (Gabriel and Changnon, 1989). There is no clear evidence of a shift in the hail climate along the lines of that expected due to greenhouse-induced climate change in the Midwest. Global climate models operated with a doubling of carbon dioxide in the atmosphere suggest that summer convection should be enhanced in the central United States, a situation that should increase hail frequency and severity in Illinois.

Past fluctuations of summer hail days are matched by fluctuations in crop-hail insurance loss data. This helps reveal that the frequency of hailstorms over a sizable area is related to the amount of crop-hail loss over a large area. The assessment of hail frequencies over the past 94 years and across the state, indicates a high variability of hail, in both space and time, across Illinois. This indicates that a large systematic shift in hail would have to occur to provide convincing evidence that a climate change affecting convective storms has begun.

Acknowledgments

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