Temporal and Spatial Variations in Hail in the Upper Great Plains and Midwest

STANLEY A. CHANGNON, JR.

Illinois State Water Survey, Champaign, IL 61820

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ABSTRACT

The distribution of hail days during 1961–80 in the northern Great Plains-Midwest was evaluated on a temporal and spatial basis to help interpret crop-hail losses. Comparisons with earlier (1901–60) hail day data revealed the seven-state study area contained eight permanent areas of high and low incidences found in any 5-year or longer period. The high hail incidence areas were related either to major topographic features or to areas of frequent frontal occurrences. Certain other areas of high or low hail incidence appeared at random locales, lasted 5 to 20 years, and disappeared. The annual and July incidences of hail increased sporadically but steadily from 1901 to 1980 in the Dakotas, Nebraska and Minnesota, reaching a peak during 1961–80. This has led to relatively more crop damage in recent years. In Montana, eastern Iowa, and Illinois, hail has decreased to a low in 1961–80. During the 1961–80 period, hail maximized in 1961–65, being 30% more frequent than in any subsequent 5-year period.

1. Introduction

This research assessed the temporal and spatial variations of hail days in the upper Midwest and Great Plains during 1901–80, with particular attention to conditions during 1961–80. The study was partly motivated by hail insurance concerns about how the crop losses experienced during 1961–80 compared with losses over longer periods. Major hail losses occurred during the 1961–80 period within the study area, raising questions as to 1) the distribution of hail within the 20-year period, and 2) how the 1961–80 hail frequencies compared with those in other 20-year periods. Most quality hail insurance loss records began in the study area only during the late 1940s; hence, an adequate temporal assessment of the 1961–80 losses could not be accomplished with the insurance data. Thus, the study focused on use of the hail-day data available in the records of the National Weather Service and predecessor agencies back to the turn of the century. (A hail day is a day when hail falls at a station.) The study was facilitated because the states investigated were in the north central region (Fig. 1) and the extensive hail data required could be provided by the State Climatologists, cooperating with the Illinois State Water Survey as part of the activities of the North Central Regional Climate Center Office.

The study had three phases: The first involved data acquisition and evaluation. The second step was analysis of the annual hail day frequencies and those for July (the prime month of crop hail loss). Assessment focused on a) the temporal distribution of 10 yr point values during 1901–80; and b) discrete 20-year patterns of hail during 1901–80. The final step involved evaluation of the 1961–80 hail conditions through study of 5-year periods. This study (Changnon and Hsu, 1984) was a part of a long-term climatic research effort dealing with severe local storms (Changnon, 1978). This research used data from cooperative substations and first-order stations, evaluation of substation data, descriptions of the space and time variations found, and explanations of the various fluctuations.

2. Data acquisition and evaluation

Hail-day records, which indicate only whether or not hail fell on a given day, do not convey all the agricultural or meteorological information desired by insurance companies and atmospheric researchers. However, these data offer a set of unbiased long records dating back to 1900 for studies of hail in periods before hail insurance records began in the 1940s. This insurance need for pre-1950 information led to extensive research involving 26 states in the 1960s. At that time, all available quality data from first-order stations and cooperative substations of the U.S. Weather Bureau (now the National Weather Service) were utilized to define the average monthly and annual patterns of hail days during 1901–60 (Stout and Changnon, 1968). The insurance industry then used these average frequencies, along with other seasonal insurance statistics (Changnon and Stout, 1967), to develop crop risk indices to help establish state rates (Changnon and Fosse, 1981). These earlier studies of hail-day frequencies provided the data for the 1901–60 period needed in this present study.

The important part of the 1961–80 data acquisition

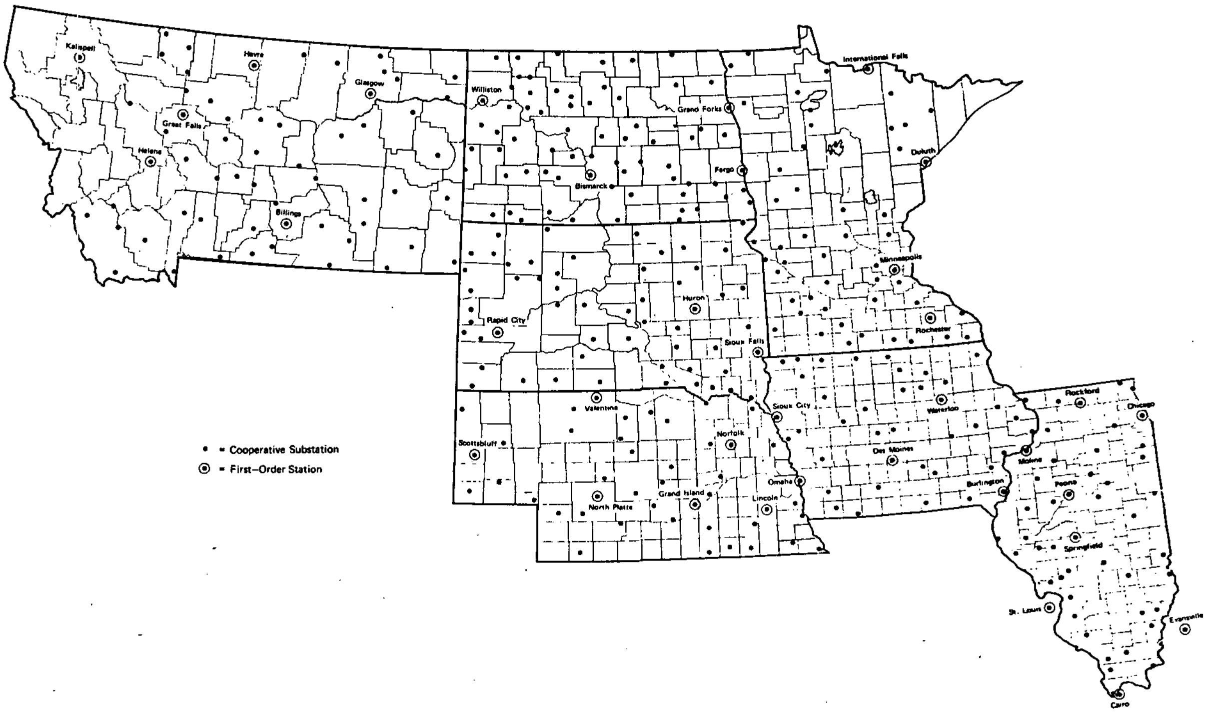

FIG. 1. Stations with quality hail-day data during 1961–80.

concerned the identification of the quality hail-day records from the cooperative substations. This evaluation was done in a series of steps, according to the method described by Changnon (1967). First, the monthly and annual values for each year in a substation record were compared with those of nearby continuously manned first-order stations that were assumed to be correct. At some substations, the total lack of reporting of hail quickly identified useless records or periods of poor records within the 1961–80 study period. In the evaluation, careful attention was paid to the names of the volunteer observers so that those with an interest in reporting hail and other storm phenomena could be detected and their records more carefully assessed. Once it appeared that the hail records of a substation might be of good quality, average monthly and annual hail frequencies were calculated and plotted on base maps, and these values were compared with those of nearby first-order stations. Such analyses quickly revealed substations that had extremely high or low (unrealistic) values for certain months; the records of these stations were then deleted as poor quality.

For every substation, quality records were found for only portions of the 20-year period. No substation record was included in the study if it had fewer than 10 years of quality data. The substations assessed as providing quality hail data for at least 10 years during the 1901–60 period are identified in the report by Stout and Changnon (1968).

Quality substation data identified in that study were used to help select substations for evaluation in the study of the 1961–80 hail data. Within the seven-state area under study, data were acquired for 690 cooperative substations which were believed to potentially have quality data during the 1961–80 period. These substations also provided reasonably uniform coverage across each state. The evaluation of these substations, using data from 37 first-order stations in and around the seven-state area, indicated that 335 cooperative substations had quality hail-day data for at least 10 years during the 20-year period. Table 1 identifies the number of quality stations in the study area (335 substations and 37 first-order stations) and their areal representativeness. As shown, the study-

TABLE 1. Number of quality hail stations in study area.

State	Number of quality stations	Average number of km^2 per station	Number of first-order stations
Montana	60	5,030	6
North Dakota	69	2,638	4
South Dakota	56	3,571	3
Nebraska	46	4,348	7
Minnesota	53	4,113	4
Iowa	39	3,774	5
Illinois	49	2,980	8
Total	372	3,660	37

area average is one station per 3660 km^2, with higher station densities in North Dakota and Illinois and the lowest density in Montana, mainly because of the infrequency of substations in large parts of that state. Montana was not totally investigated; the area investigated was primarily the area east of the northern Rocky Mountains, representing approximately two-thirds of the state. The distribution of the substations with quality data in 1961–80 is shown in Fig. 1, along with the locations of the first-order stations. A reasonably uniform distribution existed across the study area.

3. Evaluation of the representativeness of 1961–80 hail days

a. Annual data: decadal values

Three analyses were made of the annual hail data. First, the data from all 37 first-order stations were combined into 5 yr and decadal (1901–10, 1911–20, etc.) values and analyzed. Representative illustrations of decadal values are presented in Figs. 2a and 2b. For each of the first-order stations, the decades with the maximum and minimum values during 1901–80 were determined, plotted, and compared. The curves in Fig. 2 help to illustrate the considerable interregional variability. Even within regions of general homogeneity in decades of maximum and minimum values, different outcomes were found. For example, the stations in the central part of the region including Bismarck, Rapid City, Sioux City, Rochester, Duluth, and Fargo (note locations in Fig. 1) all reveal a general increase from their lowest decadal values (either in 1901–10 or 1911–20) to peak values in 1961–70 or 1971–80. However, within this 3-state region (ND, SD, MN), is one station, Huron, which achieved its maximum 10 yr value in 1921–30, or relatively early, and its lowest 10 yr value in 1951–60, a downtrend amidst stations with uptrends. Major differences in hail trends in various states have been noted previously (Changnon, 1978).

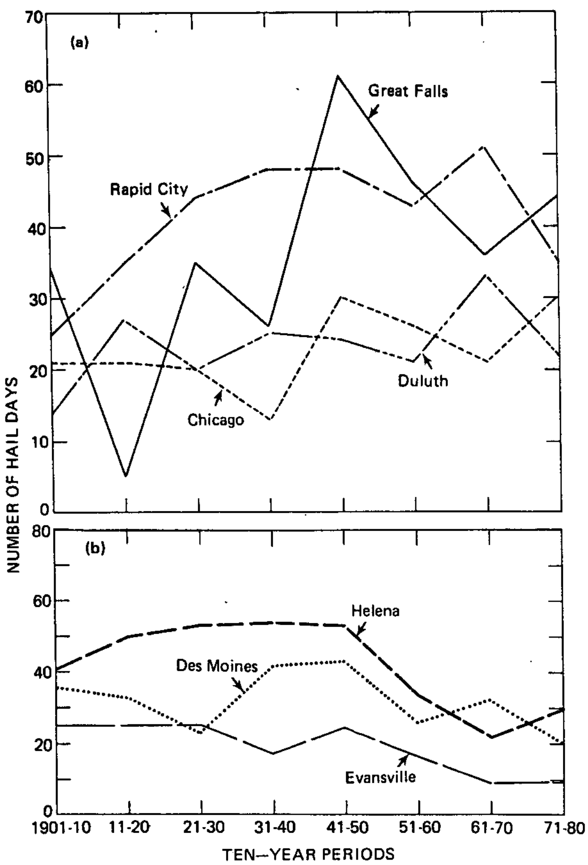

FIG. 2. Decadal frequencies of hail days at selected first-order stations.

A qualitative analysis was made to determine whether, over the 80-year period, there was an uptrend in hail frequencies, a general downtrend, or essentially no trend. This analysis led to the conclusion that most of the Dakotas, Minnesota, northern Illinois, northern Iowa, and northern Nebraska (including North Platte and Grand Island; see Fig. 1) were in an area of general uptrends in hail-day frequencies during most of the 80-year study period. Several of these upward trends are shown in the curves displayed in Fig. 2a. Some of the stations peaked in 1951–60 and others peaked in the more recent two decades, but, in general, lower values occurred in the earliest 30 years of the study period and larger values in the last 30 years. On the other hand, general downtrends over most of the 80-year period were found in two areas, and some stations with downtrends are shown in Fig. 2b. The stations with downtrends included stations in the southern two-thirds of Illinois and southeastern Iowa, plus the stations in western Montana.

In the broadest sense, the central portion of the study area had increasing frequencies of hail days over time, whereas the western and southeastern extremities of the study region had general downtrends. In a recent study of thunderstorm frequencies in North America, Changnon and Hsu (1984) found that the north central United States (generally approximating the area uptrends found in this hail study) and most of Canada showed a general uptrend in thunder-day frequencies from 1901 through 1980. The thunder-day research also revealed that the stations in the southeastern United States, including those in southern Illinois, had long-term downtrends beginning after the 1920s, which is in close agreement with the hail results (Fig. 2b). Thus, the results of this hail study are in good agreement with the thunder-day temporal distributions for 1901–80.

b. Annual data: 20-year patterns

A second assessment of the 1961–80 hail frequencies involved an assessment of spatial hail patterns, particularly the major high and low incidence areas during this 20-year period. The patterns for 1961–80 and the three prior 20-yr periods (1901–20, 1921–40, and 1941–60) are shown in figures 3, 4, 5, and 6. Inspection of these patterns leads to the conclusion that there are large variations with most locales experiencing 35 to 60 days of hail for 20 years. Furthermore, implanted on these patterns are localized high incidence areas, defined by frequencies above 60 hail days per 20-year periods and lows defined by fewer than 30 hail-days.

High hail incidence zones in this area of the United States could be related to the orographic influences of mountains and high hills, or to synoptic-scale features which tend to recur in the same area and cause a greater incidence or intensification of thunderstorms in certain regions. For example, Huff (1964) found that the major high hail incidence zones in Illinois were related to areas where frontal frequencies were highest. Synoptic-scale factors causing high hail incidences would be expected to produce broader-scale highs than those due to mountains, at least in the study area which is largely flatlands.

Comparison of the generally higher hail incidence areas in each of the 20-year maps (Figs. 3–6) leads to the identification of ten major high hail incidence areas, present in at least three of the 20-year periods. Beginning in the west, the first major high area is found in the Rocky Mountains of southwestern Montana, with another smaller high in north central Montana. Both of these are clearly related to orographic influences on storm initiation.

The third major high area is formed by a series of highs in western North Dakota. These result from synoptic-scale factors leading both to storm initiation and intensification in that region (Frisby, 1963). The high hail frequency areas in western North Dakota exist in an area where cold fronts maximize in June and July (Morgan *et al.,* 1975) and where July cyclone frequencies are high (Zishka and Smith, 1980). Thus, it appears to relate to synoptic weather conditions. For example, in the Junes during 1961–70, areas of 9360 km^2 in the western third of North Dakota average 65 cold fronts, whereas such areas in the eastern half of the state averaged 50 to 55. This is an area of low hail frequency, as described later.

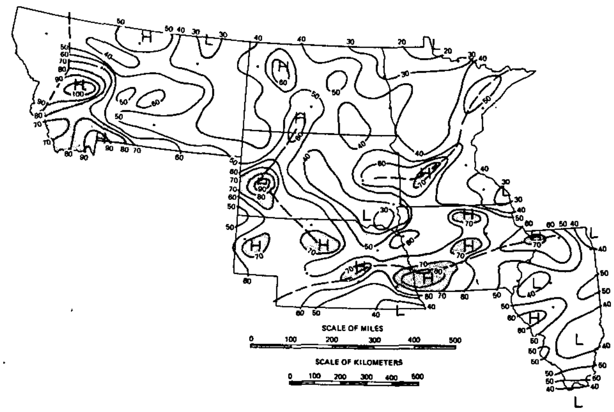

FIG. 4. Number of hail days in 1921–1940.

The fourth high, in western South Dakota, is centered in the Black Hills. The high in the Black Hills is likely related to orographic influences (Koscielski, 1967), and no other hail-producing weather conditions. The average frequency of cold fronts (Morgan *et al.,* 1975) in the summer (Jun–Aug) months shows a maximum in the Black Hills with an increase in frontal frequencies extending into southern North Dakota. Extending northeast and southeast from this Black Hills high are hail highs into southern North Dakota and north central Nebraska. These ridges of high incidence, which are denoted by dashed lines on Figs. 3–6, are considered to be related to initiation and intensification of hailstorm conditions in the Black Hills, as well as frequent frontal activity.

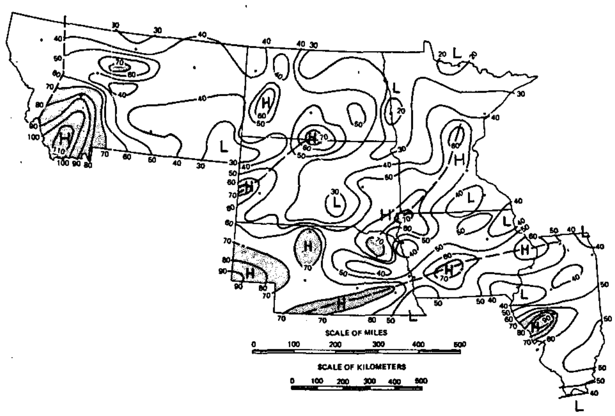

FIG. 3. Number of hail days in 1901–1920.

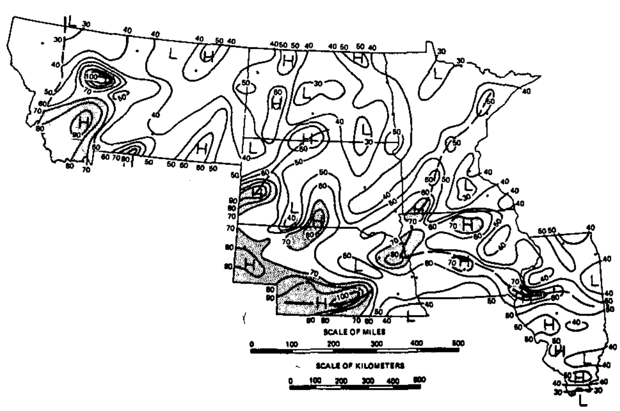

FIG. 5. Number of hail days in 1941–1960.

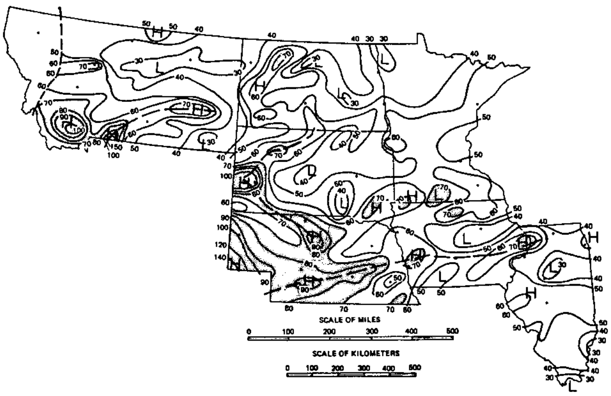

FIG. 6. Number of hail days in 1961–1980.

A high in western Nebraska is related to mountain-induced storms from Colorado and Wyoming (Musil and Dennis, 1968), although the area is in a region of peak cold frontal frequency in August (Morgan *et al.*, 1975) when hail is very frequent. A major high extends northeastward from southeastern South Dakota and northwestern Iowa across most of Minnesota, and this is considered a result of synoptic-scale weather factors. This is a zone of frequent cold frontal activity in July and frequent stationary frontal activity in August (Morgan *et al.*, 1975). Another high begins in Nebraska and extends across Nebraska, Iowa, and into northern Illinois. There are isolated hail highs of greater frequency scattered along this ridge of high hail incidence, but this ridge is present in all four 20-year periods. This elongated high is an area where a variety of hail-producing synoptic weather variables maximize. Morgan *et al.* present results that show this is an area of high frequency of cold fronts and squall lines in June, of many warm fronts in July, and of stationary fronts. Crow (1969) also indicated this to be an area traversed by storms originating in the mountains of northeastern Colorado, at least in certain situations. A small high in north central Iowa is seen in most of the periods; this is an area of frequent cold fronts in May and June (Morgan *et al.*). A synoptic scale hail-high extends across central Illinois, an area where cold and stationary frontal occurrences are frequent in May and June, the peak hail months (Morgan *et al.*). Another hail maximum is located in extreme southern Illinois which is potentially related to the influence of an isolated hill area located there (Changnon *et al.*, 1975). Thus, in the study area, we have identified ten major highs and five of these are related to orographic features (two in Montana, the Black Hills, western Nebraska, and extreme southern Illinois).

Seven major highs caused by both sets of factors were further studied as to changes in their extents and magnitudes. Table 2 shows the areal extent values and point maximum of each high for each 20-year period. Inspection of the areal values of each high reveals considerable changes between 20-year periods. The larger southwestern Montana high area decreased continually from 54 600 km^2 in 1901–20 to 38 500 km^2 in 1961–80, a 29 percent decrease. Conversely, the Black Hills high increased from 14 600 km^2 in 1941–60 to 41 300 km^2, or nearly 300 percent, in the next 20 years. Several highs did peak in areal

TABLE 2. Changes in 20-year periods in the extent and percent magnitude of hail in permanent high-hail incidence areas.

Major highs largely related to topographic influences

	Montana SW		Black Hills		Western Nebraska	
Period	Area[1]	Max[2]	Area[1]	Max	Area[3]	Max
1901–20	54.6	116	15.6	73	28.6	91
1921–40	48.1	105	18.2	91	6.5	76
1941–60	42.3	93	14.6	94	25.2	93
1961–80	38.5	101	41.3	110	45.8	141

Major highs largely related to synoptic weather conditions

	Western North Dakota		NW Iowa-Minnesota		Nebraska-Iowa-NW Illinois		SC Illinois	
	Area[3]	Max	Area[3]	Max	Area[3]	Max	Area[3]	Max
1901–20	4.7	65	33.4	78	73.6	77	22.9	91
1921–40	5.2	67	27.3	75	99.1	84	4.7	63
1941–60	2.0	61	58.5	82	87.1	101	0	57
1961–80	14.1	73	35.6	76	102.7	98	3.9	64

[1] Area in thousands of km^2 where 70 or more days of hail occurred.
[2] Maximum number of hail days at any point in high.
[3] Area in thousands of km^2 where 60 or more days of hail occurred.

extent in 1961–80, including the highs in the Black Hills, western Nebraska, and western North Dakota, and the extensive Nebraska-Iowa-Illinois high. The size of the Iowa-Nebraska high peaked in 1941–60, and the Illinois and Montana highs peaked in 1901–20. No high hail area was extensive in 1921–40. The point maximums also revealed considerable variability varying between 10 to 40 percent between periods.

Inspection of Figs. 3, 4, 5, and 6 also reveals the presence of notable low hail frequency areas, generally defined as having fewer than 30 hail days per 20-year period, due either to fewer storm incidences or lesser storm intensification related to the infrequency of synoptic weather features leading to hail. The study area has a general latitudinal gradient with fewer convective storms in the north than in the south. Hence the lower hail incidence areas identified across northern North Dakota, Minnesota, and Montana are essentially related to latitudinal decreases in frontal frequencies (Morgan *et al.*, 1975). Major other low hail incidence areas include one in central Montana and a major one in southeastern Montana and northwestern South Dakota. A sizable low incidence area extends from central South Dakota into northern Nebraska where cold fronts are infrequent in June and July (Morgan *et al.*). Another low is found in northeastern South Dakota, and there is another in southeastern Nebraska. A low hail incidence area is found in northeastern Iowa and southern Minnesota, and another is found in southeastern Iowa and western Illinois. Two other smaller low incidence areas are found in northeastern and south-central Illinois. Thus ten major low incidence areas are displayed in the patterns of all four 20-year periods, suggesting that they are permanent features in the hail distribution of this 7-state area. These lows are all areas of relatively infrequent frontal occurrences in the May-August period (Morgan *et al.*).

Comparison of the 1961–80 pattern (Fig. 6) with those in the prior three 20-year periods also indicates the presence of certain recent high and low incidence areas not present in prior periods. For example, in east central Minnesota a low was present where there had been highs in prior periods. However, major low hail incidences were not present over northern North Dakota, and the area of more than 50 hail days in the southeast was much larger than in prior periods. In South Dakota the 1961–80 pattern was not too different from others, but the frequency of hail in the high incidence areas of the Black Hills and the southeast was much greater than in the prior periods. The low in northeastern Iowa was much larger in 1961–80, stretching into west central Iowa. In Montana, the 1961–80 pattern (Fig. 6) was markedly different from that in prior 20-year periods. For example, there was a major east-west low in the northeast and a high in south central Montana that were not found in prior periods. In some areas, the 1961–80 pattern was quite different from the 1941–60 pattern and was more similar to the 1921–40 period. In Illinois, Nebraska, South Dakota, and North Dakota the 1961–80 patterns were not very different from those in prior years.

c. *Annual data: 1961–80 compared to average of 1901–60*

A third assessment of hail during the 1961–80 period focused on a comparison with the average frequency of hail days in earlier years. This was accomplished by comparing the 1961–80 frequency with the 20 yr average based on the 1901–60 data period. This comparison allowed an assessment of whether the frequency of all hail days in the latest 20 years was more, less, or similar to that in the prior 60 years.

The sets of values for 21 first-order stations scattered throughout the area are presented in Table 3. Eight stations had less hail in the last 20 years, 12 had more, and one had about the same amount. These distributions suggest that most of the total area had more hail during 1961–80 than the 60 yr average would have predicted. Inspection of where the negative, or lower, values occurred in the most recent 20 years reveals that the stations were concentrated in an area in the eastern Iowa–southern Illinois region and in parts of Montana.

The frequencies of hail at all 372 stations for the 1961–80 period were compared with the 20 yr averages based on the prior 60 years. The resulting comparison is presented in Fig. 7. Areas of lower

TABLE 3. Comparison of 1961–1980 hail days with the 20-yr averages based on 1901–1960 at selected first-order stations.

First-order stations	1961–1980 total	20-yr averages, 1901–1960	Difference (recent − early)
Great Falls MT	40	34	+6
Havre MT	20	23	−3
Helena MT	26	47	−21
Williston ND	20	20	0
Bismarck ND	28	25	+3
Fargo ND	25	18	+7
Rapid City SD	43	41	+2
Huron SD	23	27	−4
North Platte NE	43	35	+8
Grand Island NE	42	40	+2
Omaha NE	37	35	+2
Sioux City IA	33	32	+1
Des Moines IA	26	33	−7
Duluth MN	27	22	+5
Minneapolis MN	27	24	+3
Rochester MN	31	21	+10
Moline IL	23	26	−3
Chicago IL	26	21	+5
Springfield IL	27	28	−1
Evansville IN	9	22	−13
St. Louis MO	22	25	−3

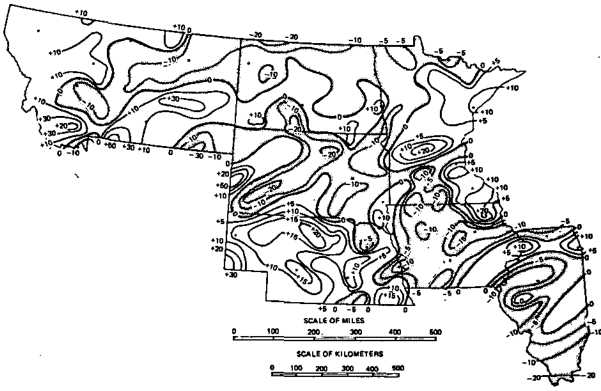

FIG. 7. Differences in the number of hail days in 1961–1980 minus those in the average of 1901–1960.

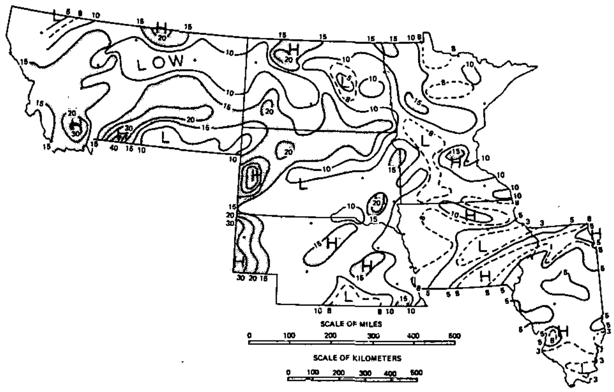

FIG. 8. Number of hail days in Julys of 1961–1980.

values in the last 20 years are shaded. These reveal that a greater than average incidence of hail occurred in 1961–80 over large portions of Montana and in most of Nebraska and Minnesota. The area of greater frequency that begins in southwestern Montana extends eastward across North Dakota. In certain areas, such as southwestern Montana, eastern Montana, western South Dakota, and western Nebraska, the recent hail frequencies were 30 or more days above the long-term average. Sizable positive departures, ranging from 10 to 20 days or more, occurred elsewhere throughout the hail increase zone (Fig. 7). The areas of less hail during 1961–80 compared to the average included large portions of North and South Dakota and most of Illinois. In these areas, the number of hail days ranged from 10 to 20 days fewer than the 1901–60 average would have predicted.

Fifty-eight percent of the entire study area had more hail days in the 1961–80 period than the long-term 1901–60 average would have predicted. Many of the major positive departures occurred in the areas of persistent average high incidence. These included southwestern Montana, western North Dakota, western South Dakota, and western Nebraska.

d. July data

Particular attention was paid to the patterns of hail days in July since that is the prime month of crop loss produced by hail throughout the 7-state area (Changnon and Stout, 1967). Seasonal intensity indices calculated from hail insurance loss data for each month (Changnon and Stout) reveal that the susceptibility of a given crop varies from month to month. These studies revealed that hail in July is much more damaging to the principal crops in the 7-state study area than is hail in any other month. For example, the average daily hail loss values for wheat in Minnesota in July are four times the average daily values for June and August. Similarly, the average July daily hail loss values for corn in Illinois are three times the averages in June and August.

Figure 8 presents the 1961–80 July hail-day patterns, and Fig. 9 shows the average 20-year July pattern based on the longer term data, 1901–60. Comparison of the two July hail patterns reveals a considerable difference in the magnitude of hail over most of the 7-state area. There are also certain pattern features that are quite different, particularly in Montana and the Dakotas. There was more hail in the month of July during 1961–80 than in the average 20-year period in most areas except for the northern half of North Dakota, northeastern Montana, south central South Dakota, southwestern Montana, and most of the eastern two-thirds of Iowa–northwestern Illinois. Except for a few other small areas of less hail in recent years, 81% of the study area had more hail in July in the recent 20-year period than the 60 yr average would have predicted. Most of Montana, Minnesota, Nebraska, and Illinois had more hail in the month of July in 1961–80 than the longer-term average would have predicted. The tendency towards more July hail in the most recent 20 years is partially

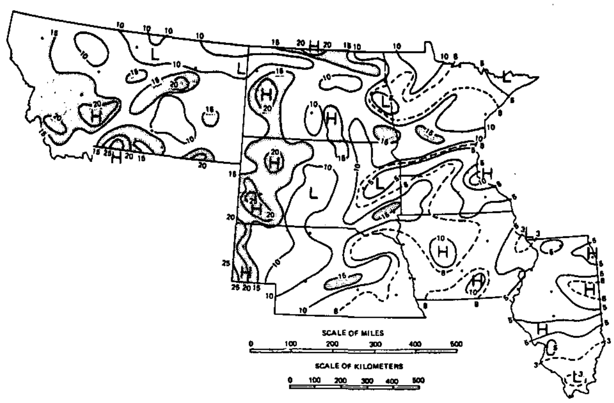

FIG. 9. Average number of hail days in July, based on 1901–1960 data.

counter to the results for total hail days (Fig. 7), which showed generally less hail recently in the Montana and Illinois areas. Elsewhere, the temporal shifts are in agreement in that the latest period is one of above-average hail incidences.

Translation of the July hail-day findings into an assessment of crop loss in the area indicates that during the 1961–80 period there was a greater hail threat to wheat, corn, and soybean crops over most of the region than the average of the earlier 60 years. Areas of potentially greater crop loss due to hail during 1961–80 include 1) most of Montana, 2) the southern two-thirds of North Dakota, 3) the northern half of South Dakota, 4) most of Nebraska, 5) half of Iowa (southwest, north, and southeast), 6) most of southern and eastern Minnesota, and 7) most of northern Illinois.

This agrees well with hail insurance loss cost values (losses divided by liability multiplied by 100) for the 7 states. The pre-1960 loss cost value and the 1961–80 value (shown in parentheses) for states with more July and total hail days in 1961–80 are as follows: North Dakota = $4.08 ($4.54); South Dakota = $3.51 ($3.73); Minnesota = $2.97 ($3.31); and Nebraska = $3.43 ($3.61). Iowa and Montana values showed no temporal difference, but Illinois decreased from $1.13 to $0.92.

4. Assessment of hail frequencies during 1961–80

The distribution of hail days during the 1961–80 period was investigated using hail frequencies in four discrete 5-year periods: 1961–65, 1966–70, 1971–75, and 1976–80. The patterns of hail days in each of these 5-year periods appear in Figs. 10–13. Comparison of the major high- and low-incidence areas in these periods helped assess pattern similarities and differences. In all four periods, major highs are found in 1) southwestern Montana, 2) western Nebraska, 3) the Black Hills (with extensions to the northeast), 4) central and southern Nebraska, 5) an area from South

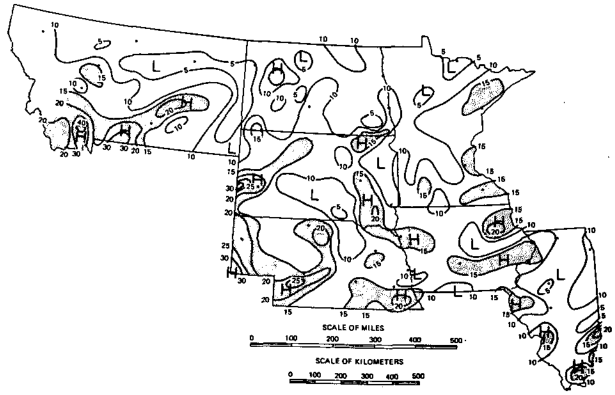

FIG. 11. Number of hail days in 1966–1970.

Dakota northeast across Minnesota, 6) an area across south central Iowa and northern Illinois, 7) northeastern Illinois, and 8) southwestern Illinois. Most are high incidence areas found in the 20-year periods (Figs. 3–6). However, some preferred high-incidence areas found in the 20 yr patterns were not present in most of the 5-year periods during 1961–80. For example, there is no high connecting the Black Hills high to the one in north central Nebraska, and the northeastern Illinois high found in the recent 20 years was a low in prior periods. Also, a major high along the Yellowstone River Valley of central Montana is found in 3 of the 5 yr patterns but was not present in the prior 20-year periods (Figs. 3, 4, and 5). Also the elongated, east–west ridge from southwestern Nebraska across Iowa is not well defined in many of the 5-year periods and is absent in 1971–75.

Certain low-incidence areas are found in at least three of the 5-year patterns shown in Figs. 10–13. These include a general east-west oriented area of low incidence in northern Montana and parts of northern North Dakota and Minnesota. A second major low-incidence area includes southeastern Montana and northwestern South Dakota. Other frequent

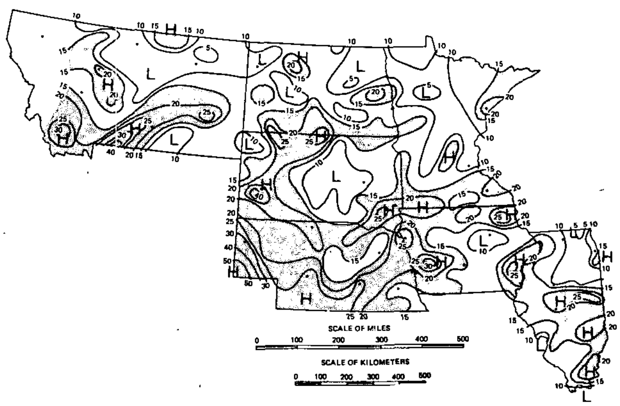

FIG. 10. Number of hail days in 1961–1965.

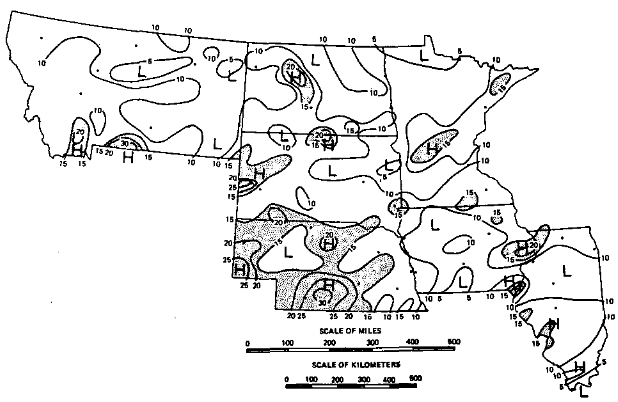

FIG. 12. Number of hail days in 1971–1975.

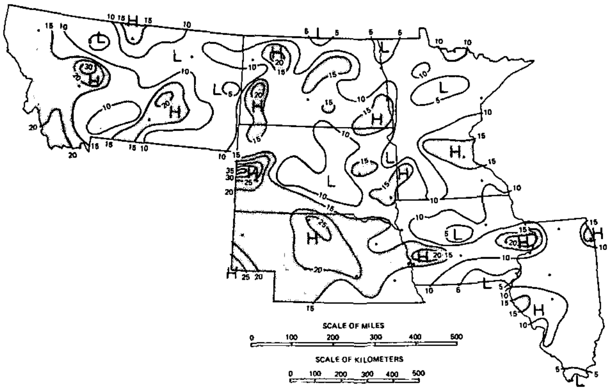

FIG. 13. Number of hail days in 1976–1980.

lows are found in central and northeastern South Dakota, north central Iowa, and northwestern and southern Illinois. Several of the semi-permanent low-incidence areas found in the 20 yr patterns appeared in most of the 5-year periods of 1961–80.

The frequency of hail during 1961–80 was examined by comparing the 5 yr area average values. For each period, the point frequencies of hail days in each state were combined to develop a statewide average and these are shown in Table 4. The areal mean values reveal that hail frequencies in 1961–65 were much greater than those in any of the following periods. The 1961–65 values in all seven states ranked highest among the values for the four periods. In the more westerly areas including Montana, North Dakota, and Nebraska, the lowest 5-yr values occurred in the next period, 1966–70, followed by a slow increase to 1980. In South Dakota and Iowa the lowest 5 yr values occurred in 1971–75, and in the more easterly locations (Illinois and Minnesota) the lowest 5 yr values occurred in 1976–80. Thus the temporal distributions based on the area frequencies of hail days revealed a sharp decrease from the early high value in 1961–65 in the western portion of the study area, followed by a slow increase, but in the easterly portions of the area there was a general downtrend from 1961 through 1980.

5. Conclusions

The study of various hail-day patterns for the upper Midwest and Great Plains revealed certain semi-permanent climatic features in the patterns. These include both high and low hail incidence areas that occurred in the same general location and were present in any discrete 5- or 20-year period in the 1901–80 period of study. These high- and low-incidence areas shifted somewhat in location and varied considerably in size and the magnitude of their incidences changed considerably between periods of varying lengths, but they were always present in the patterns.

There were eight permanent high hail incidence areas found in the 5 and 20 yr patterns. These included four related to orographic influences: two in Montana, one in the Black Hills, and one in western Nebraska. The four other permanent high hail incidence areas are apparently related to areas of frequent storm initiation and/or intensification which, in turn, are related to the frequent presence of synoptic-scale weather conditions that produce hail. These include a high incidence area in western North Dakota, one extending from northwestern Iowa across central Minnesota, a third extending from southwestern Nebraska across central Iowa into northwestern Illinois, and a fourth across south-central Illinois.

In a similar fashion, permanent climatic low hail incidence areas were found in seven general locations. Generally, low hail incidence across the northern portions of Montana, North Dakota and Minnesota is related to the general northward decrease in hail in North America (Lemons, 1942). The other major low incidence areas were southeast Montana–northwest South Dakota, central South Dakota, northeast South Dakota, northeast Iowa–southeast Minnesota, southeast Iowa–western Illinois, and extreme southern Illinois. These were all in areas of relatively low frontal occurrences.

In addition to these permanent highs and lows, a second important aspect found in the patterns of both 5 and 20 yr time scales was the fact that major high and low incidence areas appeared for time periods of 5 up to 20 years and then disappeared. For example, in the 1961–80 period, a high hail incidence area appeared in south central Montana for the only time during the 80-year study period. Conditions leading to localized or high hail incidences apparently occur in a random fashion representing the random noise in the occurrence of hail.

A second major objective of this study concerned the temporal variations in the frequency of hail days during 1901–80. Not unexpectedly, the frequency of hail days, whether for a major hail month like July

TABLE 4. State average hail-day values for 5-year periods in 1961–1980.

	5-year period			
State	1961–65	1966–70	1971–75	1976–80
Montana	14*	9**	10	11
North Dakota	12*	9**	10	11
South Dakota	15*	13	12**	13
Nebraska	14*	10**	11	12
Iowa	17*	11	9**	11
Minnesota	12*	10	11	10**
Illinois	14*	11	10	9**
Area mean	14.0	10.4	10.4	11.0

* Highest 5 yr value.
** Lowest 5 yr value.

or for annual totals, varied greatly between periods of 5 up to 60 years.

Decadal values of first-order stations in the central part of the region indicate a zone of general uptrends in hail days from the early part of the century until the latest 20 years. Other stations in Illinois and Montana indicated general downward trends in hail since 1930.

Comparison of the number of hail days during 1961–80 with the 20 yr average values, based on the period 1901–60, revealed that much of the central portion of the study area had more hail days in the recent 20 years than would have been expected based on the long-term historical average. Only portions of Montana, southeastern Iowa, and most of Illinois had fewer hail days in the last 20 years than the long-term averages. Differences in the number of hail days were often 10 to 30 days per 20-year period, reflecting increases or decreases of 10 to 50% in the last 20 years.

Comparison of the hail frequencies in the month of July in 1961–80 with the July average of 1901–60 revealed that recent July hail incidences were much greater over most of the study area in the last 20 years. Only northern portions of North Dakota and central and eastern Iowa had substantially fewer July hail days in recent years than in earlier years.

Thus, the assessment of the 1961–80 hail frequencies with respect to the earlier hail-day data revealed that 1961–80 had a pattern that was generally similar to the patterns of earlier years, but it was a period of greater hail activity, both on an annual and a July basis. The greater hail frequencies in the last 20 years were particularly notable in the central portions of the study area, reflecting a long-term upward trend in hail days found at several stations in the Dakotas and Minnesota. The long-term trends in hail days for 1901–80 were found to be similar to those from studies of trends in thunder days. The 1961–80 period had certain major pattern differences from those in other earlier years, including a major high in south central Montana, one extending from the Black Hills to northern Nebraska, and a new high in northeastern Illinois.

Within the 1961–80 period, hail incidences in 1961–65 were considerably greater (30 to 40% higher) than those in the other 5-year periods. The study region averages reveal that the 5 yr hail-day frequencies from 1966 to 1980 were generally uniform. The period of minimum values varied systematically across the area. The 1976–80 period had the lowest frequency in the eastern sections, including Illinois and Minnesota, whereas 1966–70 had the lowest in the western portions of the study area (the Dakotas and Montana).

Hail-day frequencies have large interannual variations (Changnon and Schickedanz, 1969). Maximum point annual values are typically triple the average point value and the annual maximum is zero days at all locales in the U.S. This great variability makes it important to distinguish between true climatic features in hail incidence and random fluctuations. The permanent high and low incidence areas discussed in this study, and the up or down trends persisting more than 20 years are seen as major climatic features in the 7-state area. The 20 yr or shorter term fluctuations resulting in unusual highs and lows in the hail pattern are random events due to short sequences of unusual weather conditions. This randomness is also an important facet of the hail climate of the region, but in an insurance context should be treated as random statistical variability at a point or over a region.

These findings have clear applications to the crop-hail insurance industry. They also improve our general knowledge of the climate of severe storms and are valuable to interpretations of prior efforts to suppress hail (Changnon and Schickedanz, 1969). Hail suppression projects were conducted in the Dakotas during the 1961–80 period and hail days offer one means to assess these projects. For example, hail incidences were relatively high in North Dakota in 1961–80, but this study shows that the higher incidence there was a multi-state condition.

For the insurance industry, it has been important to learn that certain major high and low hail incidence areas are permanent climatic features and thus should be taken into account in rate structures. The transitory highs and lows, such as the highs in central Montana, northern Nebraska, and northern Iowa during 1961–80, also must be recognized and dealt with as random events. Another finding of relevance to the insurance industry relates to the frequency of hail. Those familiar with hail appreciate the considerable year-to-year variability; however, this study provides a measure of longer-term, 5 to 20 yr temporal aberrations that can be experienced in the region. Of particular importance to insurance interests is that most of the region had more hail days in 1961–80 than prior averages would predict. This is particularly true for the frequency of hail days in July, the prime month of crop-hail damages. Insured hail losses over much of the region during the 1961–80 period were greater than those in prior years (back to the 1940s). The findings based on hail days basically substantiated the loss experience in the 7-state area; i.e., abnormally high losses in the Dakotas, Nebraska, Iowa, and Minnesota during the 1961–80 period, and lower crop-hail losses in Montana and Illinois.

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