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SUMMARY OF RESEARCH ON HAILSTORMS IN ILLINOIS DURING 1962

by

G. E. Stout
Illinois State Water Survey
Urbana, Illinois

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Crop-Hail Insurance Actuarial Association
209 West Jackson Boulevard
Chicago 6, Illinois

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Introduction

The two specific studies undertaken this year as work being supported by the Crop-Hail Insurance Actuarial Association were completed. Furthermore, several other studies of interest were completed in 1962 which were already in progress or undertaken because additional support was available. Since the results of these other studies should be of interest to the insurance field, these are presented in this report and in another 1962 research report.

One of the two basic studies that was agreed upon for 1962 involved the further study of the 128 most severe hailstorm days in Illinois during the 1910-1959 period. This study was performed in order to determine additional information on storm origins. This research has been completed and is discussed in Crop-Hail Research Report No. 14. The second basic study for 1962 involved investigation of the local and antecedent factors that cause thunderstorms to become hailstorms. This study was completed insofar as funds permitted. Although time did not permit a completion of the study, sufficient knowledge was gained in order to draw preliminary conclusions. The results of this study are presented in this report.

Two other studies were carried on with support from other sources. The first of these was a theoretical study to determine whether or not the explosive forces resulting from lightning could have any bearing on the subsequent precipitation in the thunderstorm. The author's observations and several references found in scientific literature have indicated that violent lightning activity often does not produce hailstones, , while hailstones occasionally fall without observed electrical activity. The second of these studies concerned the frequency of severe weather on various dates in Illinois. These singularities analyses are discussed briefly in this report and the results are presented in detail in Research Report No. 13.

In the appendix, two other 1962 hail studies performed using Association funds are described. First, a field survey was made of hailstorms on May 17, 1962 that occurred in the vicinity of Champaign-Urbana. The second portion of the appendix includes a reprint of "Areal Frequencies of Hail and Thunderstorm Days in Illinois" which was published in the December 1962 issue of the Monthly Weather Review.

Regional Characteristics of Severe Summer Hailstorms in Illinois

Certain regional characteristics of the 128 most severe summer hailstorm days in Illinois during the 1910-1959 period were investigated by S. A. Changnon using U. S. Weather Bureau data for Iowa and Missouri in conjunction with similar data from Illinois. More than 80 percent of these storms were associated with cold front or stationary-warm front conditions, and the cold frontal conditions accounted for nearly 60 percent of the 128 hailstorms.

It was found that 68 percent of the hail areas on these storm days

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originated in Illinois with 25 percent in Iowa and 7 percent in Missouri. Furthermore, 88 percent of these hail areas originated along the confines of the Mississippi River Valley from St. Louis northward to Dubuque, Iowa, More than 75 percent of these originations occurred on the Illinois side of the river.

Approximately 70 percent of all hail reports on the 128 days were from stations located in Illinois, which indicated that the areal extent of these severe Illinois hailstorms was largely restricted to Illinois. On the days prior to the Illinois storm dates, hail was reported in the westernmost areas of Iowa and Missouri on one-half of the 128 storm days. This indicated that the severe hailstorms in Illinois were often storm reformations with a synoptic system that had formed hail several hundred miles west of the state.

The number of hail incidences provided by these 128 hailstorm days at Illinois stations varied from 10 to 58 percent of the total number of hail days that occurred during the 1910-1959 period. In the Decatur and Moline areas more than 50 percent of all hail days that occurred in this 50-year period were severe hail days. Results of this research are described in Research Report No. 14.

EFFECT OF LOCALIZED HEAT AND MOISTURE SOURCES UPON HAILSTORM DEVELOPMENT

A preliminary study of the association between localized heat and moisture sources and hailstorm development in Illinois was made by F. A. Huff. An earlier Water Survey study of mesoscale conditions associated with the development of severe rainstorms indicated that, in some cases, these storms developed in regions of relatively high surface temperature and/or moisture with respect to the surrounding area. These hot and moist spots increase the thermodynamic instability of the atmosphere near the surface which, in turn, favors the development of convective activity. Since hailstorms are the result of strong convective activity in the atmosphere, it was hypothesized that hail might have a tendency to develop or intensify in localized regions of high temperature and/or moisture.

In this preliminary study, data were used for the most widespread and damaging hailstorms in Illinois during the 10-year period, 1951-1960, as determined from U. S. Weather Bureau and CHIAA hail reports. A total of 44 hailstorm days were investigated during this sampling period. The locations of localized regions of high temperature were determined by plotting maps of maximum temperature on each hail day, based upon approximately 95 Weather Bureau stations in Illinois which record temperature data. Moisture zones were determined from over 200 raingage stations of the Weather Bureau in the state. Approximately 80 of the raingage stations have recording gages from which hourly rainfall totals are available in publications of the Weather Bureau.

Two moisture indices were used in the study. The first was a rainfall -map for the day preceding the hailstorm day. The purpose of this map was to determine regions of high surface moisture resulting from the previous day's rain which might be regions of relatively high evaporation on the hailstorm day. The second moisture index was a plot of the 24-hour rainfall ending at noon on the hailstorm day, which was based upon recording gage data only since hourly rainfall amounts were required. Daily totals at Weather Bureau stations are recorded only once daily at about 7 A. M., 6 P.M., or midnight, depending upon the type of station. This second rainfall map was constructed to obtain a moisture index which included an interval of time closer to the beginning of the hailstorms which occurred mostly in the afternoon and evening. As indicated earlier, the maximum temperature on the hailstorm day was used as the heat source index. The locations of hailstorms was plotted on each rainfall and ; temperature map.

This preliminary study of the association betwen localized heat and moisture sources and hailstorm development has not produced significant positive results. Collectively, the 44 hailstorm days did not exhibit a persistent relationship between the location of hailstorms and the location of relatively hot and/or moist regions, although on some days the hailstorms were located primarily near a maximum temperature or an antecedent rainfall center. From the preliminary study, it can only be concluded that a high degree of correlation does not appear to exist between the location of hailstorms and localized heat and moisture zones on days with widespread and heavy crop-damaging hailstorms.

It is quite possible that hailstorm development or intensification is influenced to some extent by local hot or moist spots, but that the preliminary analysis was not sensitive enough to isolate the effect from other factors which define the hailstorm pattern. However, to investigate thoroughly the possible relationship would have required considerably more funds and personnel than could be assigned to this study in 1962. A thorough study would require a much more detailed synoptic analysis of each case to determine the wind movement, atmospheric stability, frontal and/or air mass type associated with the storm, atmospheric precipitable water, and other air mass characteristics. The time of occurrence of the hail storms with respect to the time of maximum temperature and production of moisture centers would have to be evaluated more closely than in the preliminary study. Also, it appears quite likely that the localized heat and moisture sources produce their greatest relative effect in non-frontal hailstorms, that is, those produced strictly by thermal instability in the atmosphere. These cases should then be studied separately. This was attempted in the preliminary study, but there were too few non-frontal storms in the data sample of widespread storms to carry out the analysis. It would be necessary to lower the degree of hailstorm severity to include many more cases of light to moderate damaging storms to evaluate the non-frontal effect. Available time and personnel did not permit this to be done in 1962. Finally, one must realize that even though localized heat and moisture zones do influence hailstorm development or intensification to some degree, the density of temperature and rainfall stations may not be adequate to measure the influence, particularly if the effect is restricted largely to widely scattered, air mass storms which influence only very small areas.

Acoustical Effects on Wet Hailstones

A literature search by H. O. Barthel found insufficient information to determine whether lightning could induce cavitation at appreciable distances from the stroke. Tests are needed, either on lightning or long spark discharges, to find the pressure-distance relationship and to gain a better understanding of the physical processes occurring.

Goyer has reported that explosives have given cavitation results at very close range on artificial hailstones with liquid water centers. This is in contrast to Byers who indicates that tests by List in Switzerland have not shown any effect of concussion waves on stones. Further tests seem necessary and might be done using shock tubes as the energy source. Even if a positive result is obtained in the laboratory, field tests ultimately must determine whether there is any effect on naturally occurring hailstones. These tests are expected to be difficult. However, the annual loss to hailstorms seems to justify such an effort which might control these storms.

Severe Weather Singularities in Illinois

Lengthy climatological records of the dates of occurrence of thunderstorms, heavy rainstorms, tornadoes, and damaging lightning in Illinois were analyzed by S. A. Changnon to ascertain whether singularities, or preferred dates of high or low occurrences, existed in the March-October period. Four semi-objective methods, each based on different statistical criteria, were employed to identify severe weather peak (high frequency) and trough (low frequency) singularities. Testing of the peak and trough singularities identified by two of the methods revealed that these dates had frequencies which were statistically significant.

Three-day periods in which 4 or more of the 5 events had either relatively high or low daily frequencies were defined as composite singularities. Twelve such composite singularities were identified and their dates of occurrence were compared with long-term average daily statewide values of temperature, humidity, sunshine, and pressure. These comparisons revealed that the singularity peaks, such as the one on March 6-7, occurred in periods of relatively low pressure, high maximum temperatures, high humidities, and extensive cloudiness. Conversely, the composite singularity troughs, such as the one during March 9-11, occurred on dates with relatively high pressure, high percentage of possible sunshine, low maximum temperatures, and low humidities. These related weather conditions, which furnish some measure of the stability of the atmosphere, had anomalies in their daily magnitudes which substantiated the dates of the prominent severe weather singularities.

In addition to the trough singularity on March 9-11, other notable composite trough singularity periods when severe weather was infrequent in Illinois occurred on March 22-24, May 5-6, August 24, September 4-6, and October 29-30. In addition to March 6-7, notable peak singularities occurred on March 26-27, May 8-10, June 12-13, August 27-29, and October 10-12. Results of this research are described in Research Report No. 13.

Recommended Research for 1963

The results obtained by Changnon concerning the areal distribution of damaging hailstorms in Illinois (Research Report No. 14) indicated that there were three areas of the state where these storms were particularly frequent. Loss costs in these areas are among the highest in the state. It is recommended that certain damaging hailstorms that occur in the Jacksonville-Decatur area and in the Moline-Monmouth area during 1963 be investigated using radar data from the Water Survey equipment located at Champaign and the radar data from the U. S. Weather Bureau radar sets located in Chicago, St. Louis, and Des Moines, Data on hail incidence on the ground would also be used to relate and identify the hail incidence with the radar echo data. It is envisioned that these studies of a few individual hailstorms in these two areas of high incidence might prove helpful in explaining their occurrences and reasons for such regional intensification. To perform this study, some storm data from adjustors of the member companies would be required. In particular, time of hail occurrence and hail size would be desired from as many locations of loss as possible.

APPENDIX A

HAILSTORMS ON MAY 17, 1962

Stanley A. Changnon, Jr.

One of the programs of the Water Survey is to investigate unusual meteorological conditions such as field surveying and analysis of certain select hailstorms that occur in the vicinity of Champaign-Urbana. An earlier research report dealt with the results of a very detailed survey of a hailstorm that occurred near Decatur on June 22, 1960. (1) A technical paper dealing with this storm and another surveyed hailstorm that occurred in Champaign-Urbana on March 4, 1961, was also prepared. (2) In May 1962 another hailstorm occurred in the Champaign-Urbana area and this storm was surveyed and studied.

During the afternoon of May 17, 1962, a series of hailstorms occurred in the east central Illinois area. Within a radius of 5 miles of Champaign-Urbana, four separate hailstorms occurred in the period from 1225 CST to 1500 CST, and one of these was field surveyed since it occurred in the immediate vicinity of the twin cities. Most of these storms were characterized by: 1) hailstones with diameters 6f generally less than 1/2-inch, 2) relatively short lifetimes ranging from 1 0 to 20 minutes, 3) small areal extent of hail incidence, and 4) a general lack of damage to crops or property.

The thunderstorms which produced these hailstorms were warm air mass instability thundershowers. The Water Survey radar protrayal of these air mass thundershowers indicated that they formed as an east-west line in east-central Illinois and they tended to move along the axis of this line from west to east. These thunderstorms and their resulting hailstorms could not be considered as especially severe hail or thunderstorms.

The third of the four hailstorms in the 1225-1500 CST period passed directly over most of the urban area comprising Champaign-Urbana. This storm caused some minor property damage in Champaign where hailstones measuring 1. 0 inch in diameter fell (Fig. 2). During the two days following this storm a detailed field survey was performed of this hailstorm which produced hail over about 23 square miles (Fig. 1). More than 100 persons at different locations scattered throughout the storm area were interviewed to collect data. Useful, factual information on hail size, time of occurence, storm duration and other pertinent weather conditions including, rainfall amounts was obtained from 58 of those interviewed. Many of those who supplied storm data were professional meteorologists. Most of the locations where useful data were obtained are shown in Figure 2 as observation points. Additional rainfall data in the storm area were obtained from 24 State Water Survey raingages including 10 recording raingages.

In Figure 1, the extent of the hailstorm area is shown in reference to a smoothed urban boundary of Champaign-Urbana. Inasmuch as hailstones that fall at a given location vary in size, diameter measurements of the average size stones and the maximum size stones were obtained if known by the observer. The isodiametric pattern based on the average size hailstones is shown in Figure 1 and the pattern based on the maximum size stones is portrayed in Figure 2. Comparison of similar regions within the hailstorm outlines of Figures 1 and 2 reveals that the diame ters of the maximum size stones were usually 1.5 to 2. 0 times greater than those of the average sizes. This is in agreement with findings for the previous surveyed hailstorms. [2]

Also portrayed in Figure 1 is the isohyetal pattern derived from the rainfall data for the rain that fell during the hailstorm. Note that the three areas of highest rainfall, or cores of rain, fell in or near to the areas where the largest average and maximum sizes of stones fell. Although the rainfall pattern was not completely enclosed, the data shown on Figure 1 suggest that the rainfall area and hail area were nearly coincidental. This close areal relationship had not been noted to occur in the two previous hailstorms similarly surveyed and studied. [1, 2] In the 1960 and 1961 hailstorms, the rain area produced by the individual storm producing the hail was considerably larger than the hail area. This difference in areal relationships may be related to basic differences in the associated synoptic conditions which were frontal for the 1960 and 1961 storms as compared to air mass with this 1962 storm. However, the close areal relationship between rainfall cores and hail cores noted in the 1962 storm was a condition not found with the other two surveyed storms.

Based on the time of occurrence and duration data, maps portraying the areal extent of hail according to stone sizes at each minute during the

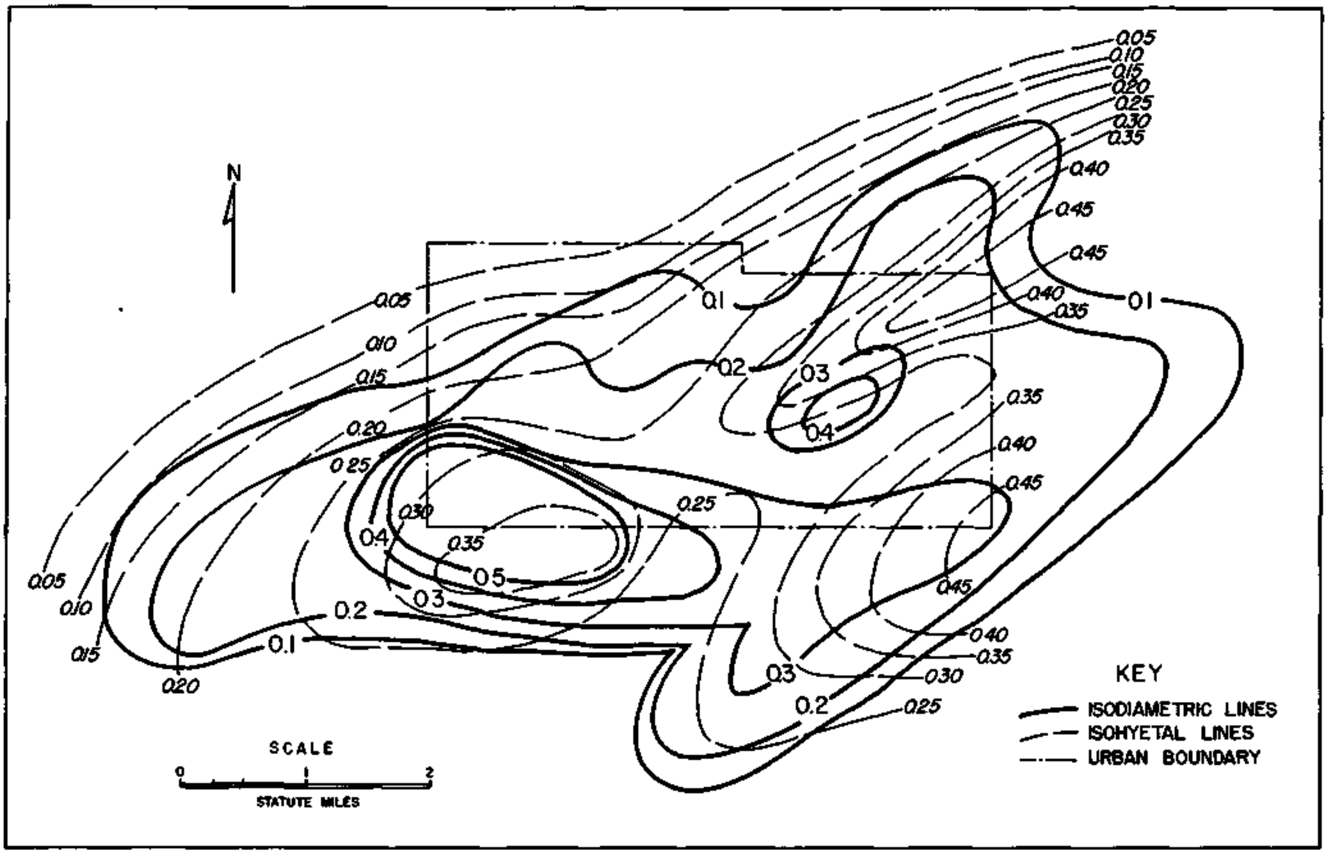

FIG 1 DIAMETERS OF AVERAGE SIZE STONES AND TOTAL STORM RAINFALL. MAY 17, 1962

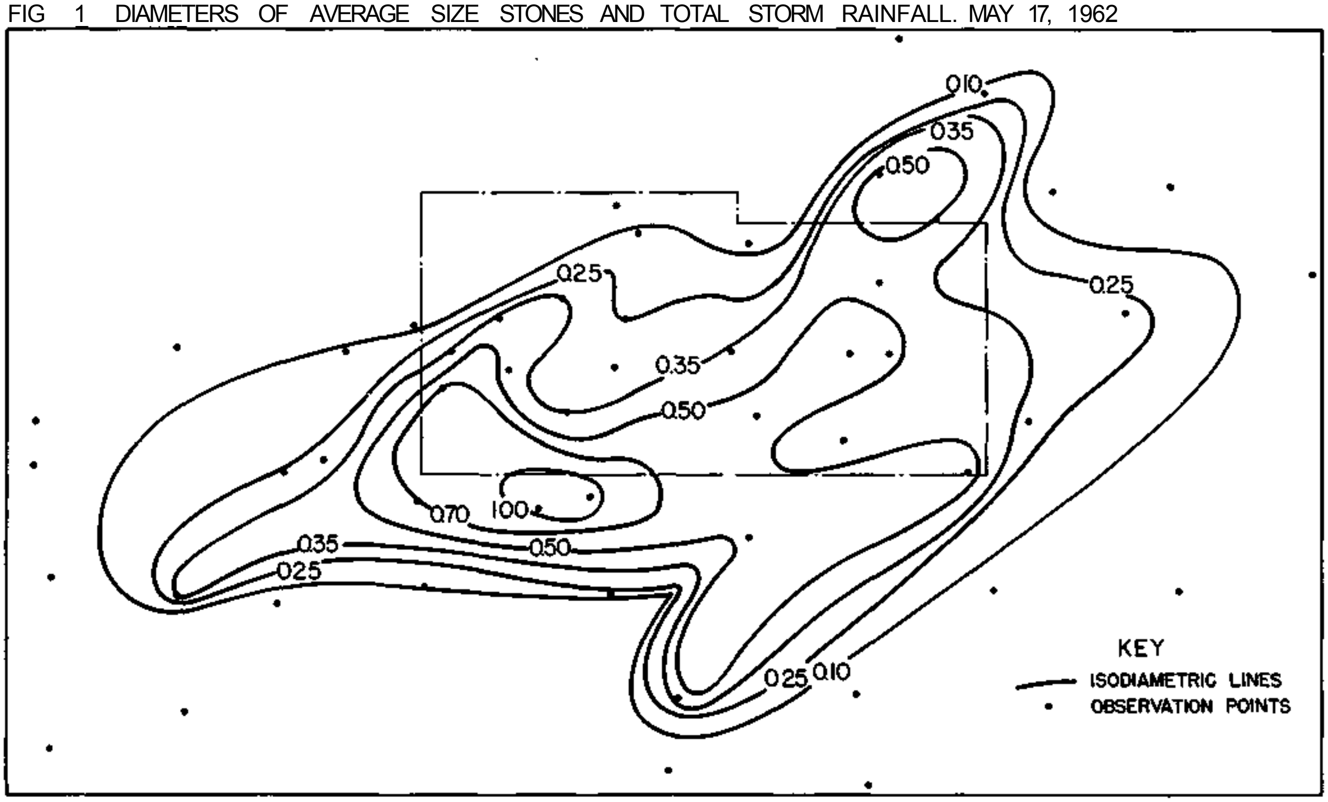

FIG 2 DIAMETERS OF MAXIMUM SIZE STONES, MAY 17, 1962

24 minutes this storm persisted were prepared. This is a technique previcusly utilized to analyze hail cells. [2]

The hail cell initiated at the ground at 1347 CST about 2 miles southwest of the urban boundary (Fig. 3a). Within two minutes the hail cell had become seven times larger, and had also begun to produce 1/2-inch stones (Fig. 3b). After 1349 CST, the cell remained about the same size (1. 5 square miles) until it merged with another cell at 1403 CST. The eastern edge of the hail cell moved to the east at a speed of about 15 mph. Rapid changes in the shape of the cell occurred, but in general the shape was oblate which is similar to the shapes noted in the previous storms. [2] However, the long axis of the oblate-shaped hail area was oriented at a right angle to the direction of movement which is a condition dissimilar to the findings for the previous two hailstorms. [2] In Figure 3h, a map showing the isohyetal pattern and the area that experienced hail during the 1347-1400 CST period is presented. The hail area is a composite of the 1-minute maps for the 14-minute period.

The detailed temporal analysis of this storm revealed that the hailstorm under investigation was actually a composite of two hail cells. The second cell first produced hail at the ground south of the urban area at 1400 CST (Fig. 4a). Within 3 minutes after its formation, this cell had merged with the older cell to form one larger hail cell that enveloped about 10 square miles (Fig. 4b). Both cells had cores of stones with diameters ranging from 0. 5 to 1. 0 inch, and these cores also grew together shortly after the cells merged (Fig. 4).. The northern portion of the older cell began to exhibit renewed growth and rapid forward movement at

1402 CST, and by 1405 CST another small hail core had appeared at the ground within this area of rapid growth. Dissipation of the combined cell began after 1405 CST, and by 1410 CST the hailstorm had ended.

The older cell had been growing, in areal size and stone size, from 1347 to 1354 (7 minutes). Its mature stage lasted for 12 minutes, and the dissipation stage lasted 5 minutes. As had been noted with cells in the June 22, 1960 storm, the core (area of largest stone sizes) of the older hail cell on May 17 occurred in the center and along the forward edge of the cell during the cell's period of formation and early maturity, but during its later stages, the core was located in the rear or near the trailing edge of the cell.

In summary, this detailed analysis of a third Illinois hailstorm reaffirmed many previous findings obtained from field surveying of hailstorms. To accurately reconstruct a hailstorm, surface observations with a density of at least one observation per square mile are required. The May 1962 hailstorm was not a particularly severe hailstorm, but yet at the surface it was a very complex phenomenon. In general, characteristics of this storm including relation of the hail cores to rainfall cores, hail cell size, hail cell shape, relative location of the hail core within the cell, and rapid cell changes with time were in agreement with findings derived for two previous surveyed hailstorms in central Illinois.

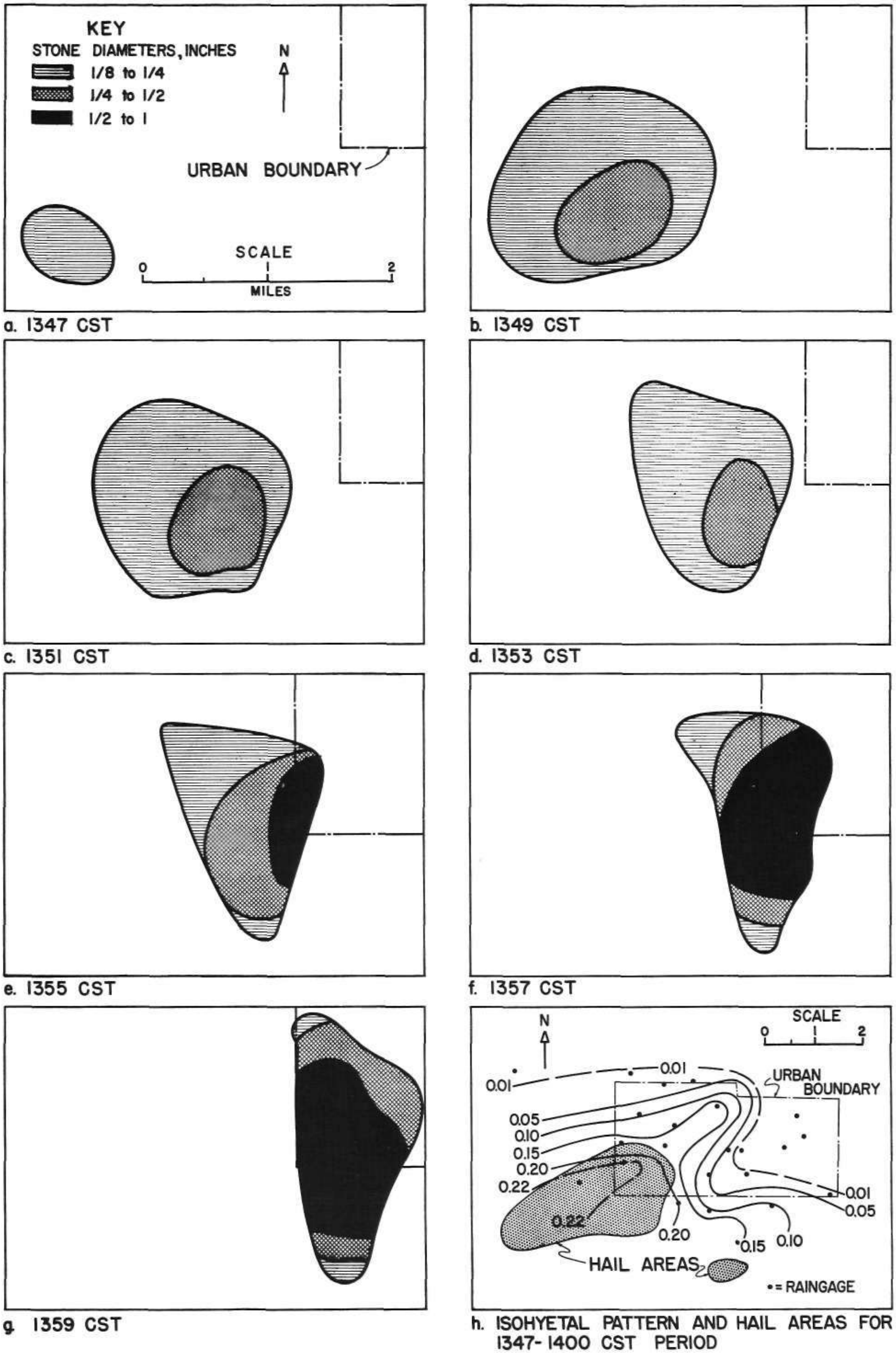

FIG 3 HAIL CELL AND RAINFALL DURING 1347-1400 CST PERIOD, MAY 17, 1962

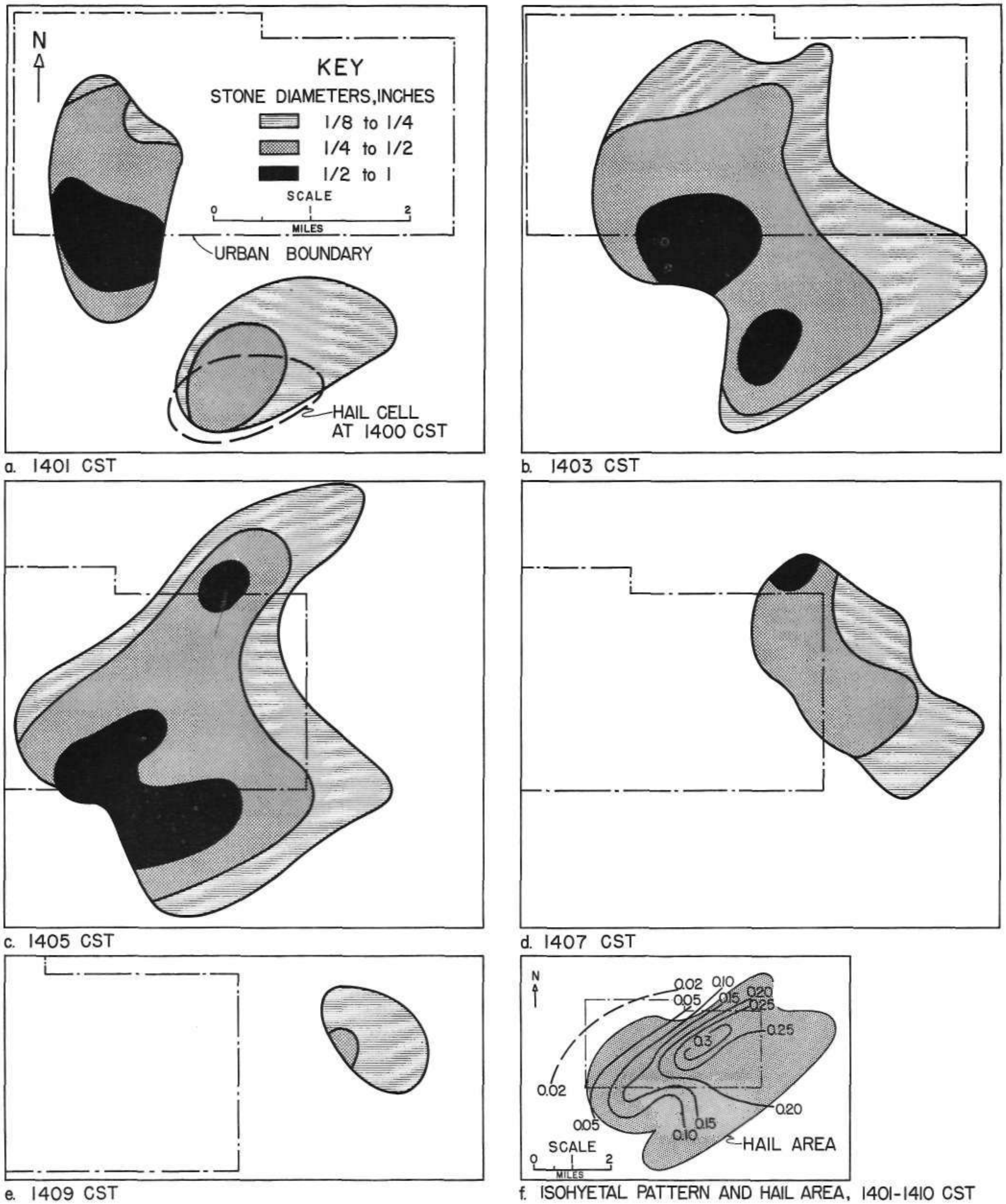

FIG. 4 HAIL CELLS AND RAINFALL DURING 1401-1410 CST PERIOD, MAY 17, 1962

References

1. Changnon, S. A., A Detailed Study of a Severe Illinois Hailstorm on June 22, 1960. CHIAA Research Report No. 6, Chicago, 1960.

2. Changnon, S. A., and G. E. Stout, Details of Surface Characteristics Displayed by Illinois Hailstorms. Paper presented at Amer. Met. Soc. Severe Storm Conference at Norman, Oklahoma, 1962.

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AREAL FREQUENCIES OF HAIL AND THUNDERSTORM DAYS IN ILLINOIS

STANLEY A. CHANGNON, JR.

Illinois State Water Survey, Urbana, Ill.

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ABSTRACT

Hail and thunderstorm statistics for the 1951-60 period obtained from 119 U.S. Weather Bureau stations in Illinois were combined with crop-hail insurance data for this same period for performing a detailed climatological investigation of the frequencies of hail days and thunderstorm days in Illinois. In the crop-growing season thunderstorms occur on 1 out of every 2 days on the average and hail occurs somewhere in Illinois on 4 out of every 10 days. The hail-thunderstorm areal ratio for Illinois is 68 percent as compared with point ratios varying from 3 to 7 percent. It appears that some thunderstorms may not contain hail since 32 percent of all the thunderstorm days had no hail reported at the surface anywhere in Illinois. Thunderstorms on days without hail most frequently occurred in southern Illinois and were associated more frequently with air mass and warm frontal conditions than were the hail-thunderstorms. This research also has shown how "Days With" data from cooperative substations of the Weather Bureau can be used to enlarge our knowledge of regional climatology.

1. INTRODUCTION

In recent years much has been written about the reliability of the commonly referred to hail-thunderstorm ratio, especially since the point observation of thunderstorms represents an areal integration whereas the observation of hail represents occurrence only at the point [10]. Attention also has been given to the question of whether all thunderstorms contain hail aloft during their lifetimes [8]. Hail research in Illinois has produced some information which is pertinent to these issues. This paper summarizes the results derived from a comparative analysis of the simultaneous daily occurrence of hail days and thunderstorm days in Illinois during the March-October period and the mid-May to mid-September period.

One phase of recent Illinois hail studies has been concerned with a basic question concerning the statistical relationship between thunderstorms and hailstorms. This question is: How frequently in the thunderstorm season (March-October) and in the growing season (mid-May to mid-September) do days with thunderstorms in a given area give hail in that area? Since the average areal size of the two events varies [1, 3] and thereby favors thunderstorm frequency, and since the method of recording the two events also favors thunderstorms, any system of incidence comparison requires the integration of occurrence data over a large area in order to obtain true frequencies. To this end, this particular investigation used the State of Illinois as the area of comparison. The frequency of hail days and thunderstorm days was based on occurrence anywhere within the 56,000-square-mile area of the State. In this paper particular attention is given to the data concerning dates which were thunderstorm days but were not hail days.

2. DATA

The analysis utilized a large quantity of data pertaining to the incidence of hail and thunderstorms in Illinois during the 1951-60 period. The principal sources of data included the original records of approximately 110 U.S. Weather Bureau cooperative substations, the records of 9 first-order stations in the Illinois area, and the hail insurance claim records of the Crop-Hail Insurance Actuarial Association. The Weather Bureau records served as the source of thunderstorm data. The Weather Bureau station data and the records of the insurance companies were the sources of the hail data. In central and northern Illinois the insured lands represented approximately 5 percent of the total area, but less than 1 percent of the southern Illinois area.

Before any date was defined as a hail day or a thunderstorm day, its frequency of point reports had to exceed a given number of reports in order to eliminate potential observer errors in the recording of the dates of hail or thunder. In order for a date to be classified as a thunderstorm day at least three stations had to report thunder. The occurrence of three or more station reports of thunder on a single day was selected to define thunderstorm days in order to minimize errors in the reporting of dates with thunder by the cooperative observers. Careful examination of the original records revealed many instances when a date had a large number of station reports of thunder and the ensuing date and/or preceding date had only one or two reports of thunder. Eighty-two percent of the total number of dates with one or two station reports of thunder in the 1951-60 period occurred on either the day preceding or the day following a date with three or more thunder reports. On many of these dates examination of

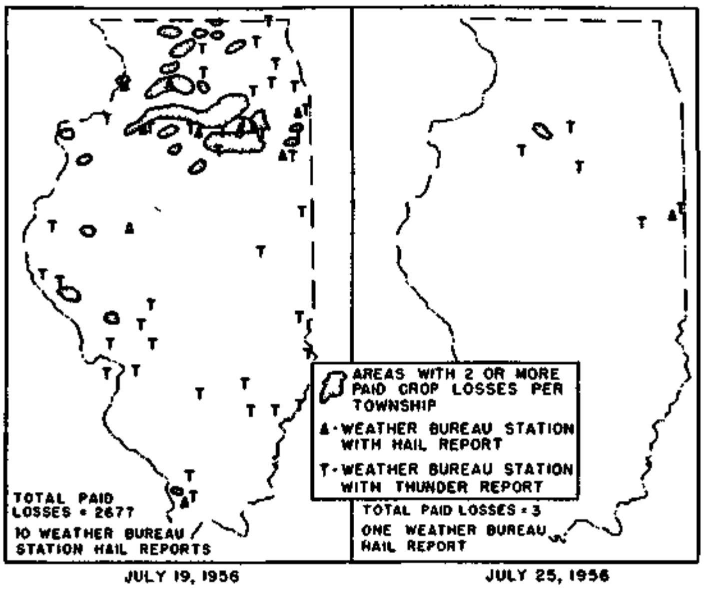

FIGURE 1.—Examples of major (left) and minor (right) hail days in Illinois during 1956.

the hourly rainfall data for the State revealed that no rain had occurred within several hours of the preceding or following day, and therefore, it appeared quite likely that the dates of these thunder reports were erroneous and were a result of either observer error or observer confusion in reporting the actual date of thunder occurrence. For a date to be listed as a hail day there had to be at least three paid hail insurance claims or one or more Weather Bureau station reports of hail. Examples of thunderstorm days with large and small numbers of hail reports and paid crop losses are shown in figure 1. One Weather Bureau station report of hail was selected as an adequate number to define a hail day, as opposed to the requirement of three station reports for a thunderstorm day, because hail is a more infrequent event at a point and it normally receives greater observer attention than does thunder. It is believed that these circumstances eliminate most observer errors in reporting dates of hail incidence.

The adequacy of the thunderstorm day sampling is partially revealed by comparing the frequency of thunderstorm days, as based on the three or more station reports, with the number of thunderstorm days defined using two or more station reports of thunder. The use of one or more station reports to define a thunderstorm day does not provide a satisfactory test of the frequency based on three or more reports because a large number of the single reports are errors by the cooperative observers. In the May 16-September 15 period there are normally 77 thunderstorm days (table 2), as defined by the three or more station reports of thunder. If thunderstorm days are defined by two or more station reports of thunder, the seasonal total increases to 83, which is only an 8 percent increase. The definition based on one or more thunder reports for a thunderstorm day raises the average seasonal number to 94. The hail-thunderstorm ratio for Illinois changes from 68 percent, as based on three or more reports, to 64 percent when based upon two or more station reports. This slight difference indicates adequacy in the thunderstorm day frequency as based upon the definition of the thunderstorm day as a day with three or more stations reporting thunder.

Even with the large amount of hail data employed, it is possible that a few hail days occurred which were not detected. Therefore, the hail statistics presented herein must be considered as a conservative climatological estimate of hail day frequencies. However, two investigations were performed which indicated a nearly complete sampling of hail days.

A hail-reporting network consisting of approximately 1,100 cooperative observers, who were mostly farmers, was operated in east-central Illinois during the thunderstorm seasons of 1959, 1960, and 1961 [16]. These 1,100 observers were quite evenly dispersed throughout a 22,250-square-mile area, and each observer reported the incidence of hail of any size. The dates of hail days in 1959 and 1960, as determined from this reporting network, were compared with the hail dates obtained from the Weather Bureau stations and insurance data in the same years to obtain an estimate of the adequacy of the hail days sampling based upon the Weather Bureau and insurance data.

In the March-October period of 1959 and 1960, the hail network recorded 38 and 36 hail days, respectively, as compared with the Weather Bureau-insurance data listing of 63 and 71 hail days, respectively. Thus, in each of these two years the hail network identified less than 60 percent of the hail days in the State identified by the Weather Bureau-insurance data. Furthermore, the network data did not record any dates of hail which were not identified as hail days by the Weather Bureau and insurance data for the State.

Sampling adequacy for hail days was evaluated also by a statistical investigation which compared the frequency of hail days for different numbers of Weather Bureau stations or data sources. The average number of hail days in the crop-growing season based upon data from the 119 Weather Bureau stations used in this study was 31. Data

TABLE 1.—*Average number of hail days in the crop-growing season derived from data from various numbers of Weather Bureau stations in the 1951-60 period*

Hail reporting stations		Hail days	
Number	Percentage reduction from total	Average number	Percentage reduction from total
119	0	31	0
107	10	30	3
95	20	28	10
83	30	24	23
71	40	20	36
60	50	16	48

from 10 percent of these stations were deleted using a random station selection procedure, and a new average number of hail days was computed based upon the data from the remaining number of stations. This procedure was repeated for 10 percent intervals until only 50 percent of the stations were used to compute an average. Sampling adequacy in the data for hail day frequencies would be indicated by this method if only minor percentage reductions in the number of hail days occurred with the first one or two percentage reductions in the number of stations. The percentages obtained from this procedure are shown in table 1, and these results indicate near adequacy in the sampling based upon data from the 119 Weather Bureau stations.

TABLE 2.—*Average and extreme frequencies of thunderstorm days and hail days during two seasons*

	Thunderstorm season, March-October, 245 days	Crop-growing season, May 16-Sept. 15, 123 days
Thunderstorm days		
Average number of days	123	77
Maximum number of days	159 (1954)	87 (1955)
Minimum number of days	107 (1952)	68 (1953)
Average expressed as percent of total days	50	63
Hail days		
Average number of days	84	53
Maximum number of days	115 (1956)	84 (1956)
Minimum number of days	59 (1951)	36 (1951)
Average expressed as percent of total days	34	43
Percent of thunderstorm days which are not hail days	32	31

3. CLIMATOLOGICAL FINDINGS

The climatological averages and extremes for hail days and thunderstorm days in the thunderstorm season (March-October) and in the crop-growing season (May 16-September 15) are presented in table 2. Thunderstorm days occur in Illinois on 50 percent of the days in the March-October period; this percentage increases in the crop season to 63 percent.

In the March-October period hail occurs, on the average on 84 days, which represents 34 percent of the total possible days. Hail days occur more frequently in the crop-growing period, when 43 percent of all days experience hail somewhere within the State. The average of 53 hail days in Illinois during the growing season represents a significant increase from previously recorded values for the State. Lemons [9] listed an average State value of 16 days; Visher [15] indicated an average of 10 to 15 days; and Stout [13] listed 36 hail days as an average number in Illinois during the growing season. The frequency represented by Stout [13] was based upon insurance data and a hail day was defined as one with 20 or more insurance claims.

Other table 2 values of particular interest are those which express the percentage of Illinois thunderstorm days which were not hail days. Nearly one-third of the thunderstorm days in the 245-day thunderstorm season did not have hail. The frequencies of hail days and thunderstorm days were greater in the crop-growing season, and the percentage of thunderstorm days without hail remained the same. Every hail day during this 10-year period was also a thunderstorm day, although on a few spring days some stations reported hail and no thunder. Changnon [2] has shown that on the long-term average from 5 to 20 percent of the hail days at various locations in Illinois are not thunderstorm days. Shands [11] reported similar findings for Iowa.

4. POINT VS. AREAL HAIL-THUNDERSTORM RATIO

A report on the hailstorm climatology of Illinois by Huff and Changnon [7] contains data that indicate the hail-thunderstorm ratios in Illinois vary from 3 to 7 percent. This finding is based on point averages for the thunderstorm season. Thus, the difference between 97 to 93 percent and 32 percent of the thunderstorm days without hail (table 2), as derived from the State areal ratio, indicates the magnitude of difference between point and areal hail-thunderstorm ratios. Shands' [11] data for the growing season in Iowa, an area almost equal to Illinois, shows that on the average 85 thunderstorm days occur as compared with 33 hail days. Thus, the Iowa areal hail-thunderstorm ratio is 39 percent as compared with 69 percent in Illinois. This difference in ratios is largely the result of differences in the hail day frequencies which were 33 in Iowa and 53 in Illinois (table 2). The hail findings in Iowa were based upon data from all Weather Bureau stations in Iowa; thus, the difference in State frequencies is primarily due to the greater areal sampling of hail incidence in Illinois provided by the insurance data, since all Weather Bureau station data available in Illinois also were employed.

For the entire State the average frequency of hail days in the crop season varies from 100 to 50 times as great as the average frequency at random points within Illinois. For the thunderstorm season the areal-point ratio in Illinois varies from 30:1 to 45:1. Shands [11] using substation data in Iowa expressed a ratio between areal and point frequencies of hail days of 22:1. Harrison and Beckwith [5] indicated that for an area around Denver consisting of about 1,200 square miles the areal frequency of hailstorms was about 11 times as great as the point frequency. For the growing seasons of 1959-61, the central Illinois hail-reporting network [16] averaged 12 hail days per season over 22,250 square miles, and this is an areal-point ratio of about 16 to 1. Therefore, the Colorado, Iowa, and Illinois findings indicate that the hail-thunderstorm ratio is strictly a function of the size of the area investigated and the density of observations within the area.

5. HAIL PRODUCTION BY THUNDERSTORMS

Although the hail-thunderstorm climatological data indicate that not all thunderstorms produce hail at the

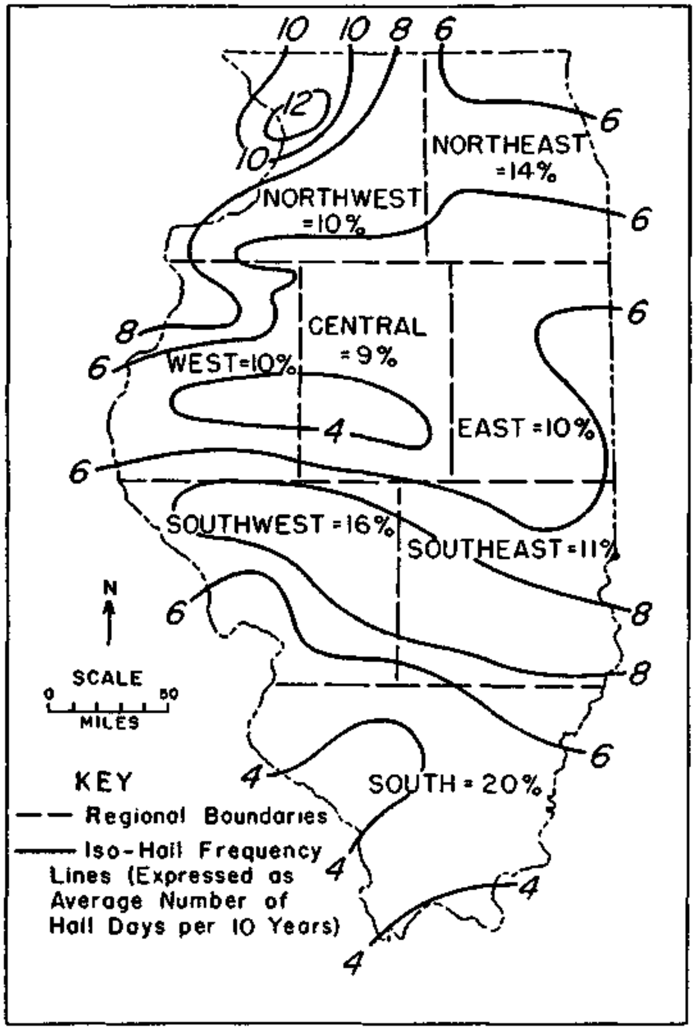

FIGURE 2.—Regional percentages of total thunder reports on no-hail thunderstorm days and summer average hail distribution in Illinois based upon point data.

ground, the findings cannot be construed as proving or disproving whether hail exists aloft in all thunderstorms. However, of the 10-year total of 242 thunderstorms days which were not hail days in the crop-growing season, more than 50 percent had 13 or more stations reporting thunder. By assuming that each of the 119 reporting stations represents about 450 square miles of Illinois, it appears that on 121 days in the 1951-60 period thunderstorms were present over approximately 5,800 square miles, or 10 percent of Illinois, and yet no hail was reported. On 21 days more than 25 percent of all the reporting stations in the State recorded thunder on days with no surface hail occurrences. Practical consideration of these facts makes it appear questionable that each of the many thunderstorms undoubtedly occurring on these days produced hail aloft when no hail appeared anywhere at the surface of such extensive areas.

Recent research by Wilk [17] concerning the detectability of hailstorms in central Illinois using 3-cm. radar revealed that 39 percent of approximately 500 thunderstorm echoes measured during a 3-year period did not contain hail aloft. This percentage of no-hail thunderstorms is in close agreement with the climatological findings for hail at the surface which was 32 percent (table 2).

6. CHARACTERISTICS OF NO-HAIL THUNDERSTORM DAYS

The data associated with the no-hail thunderstorm days in the growing seasons of 1951-60 were analyzed in further detail. One phase of this analysis concerned the regional distribution of stations which reported thunder on the no-hail thunderstorm days, and another concerned the type of synoptic conditions associated with these thunderstorm days.

To measure regional variations, the State was divided approximately along U.S. Weather Bureau [14] climatological boundaries into eight regions (fig. 2), and each region contained about 15 stations reporting thunder and hail. In figure 2 the summer average hail distribution pattern, as described by Stout [12], also has been superimposed. In the 1951-60 period, a total of 3,083 stations reported thunder on the 242 days when no hail occurred. The number of these station reports in each of the eight regions was expressed as a percent of this total, and these percentages appear in their appropriate region in figure 2.

Note that the region of greatest frequency of no-hail thunderstorms is the south which is also the area of lowest summer hail averages. However, the average summer distribution of thunderstorms in Illinois [2] indicates Statewide maximization in the southern region with a secondary maximum along the western State boundary where thunder-report percentages are much lower than in the south. Thus, regional differences in the average thunderstorm distribution cannot serve as an explanation for the regional report percentage differences found in figure 2. Therefore, it appears that the meteorological conditions in southern and possibly northeastern Illinois may differ to some extent from those elsewhere in the State, and that these conditions may limit the production of hail in these two regions.

Synoptically, the thunderstorms on the 242 days with no hail were found to occur most frequently with cold front and air mass conditions. The total and average number of days by synoptic type are shown in table 3.

An examination of the printed *Daily Weather Maps* of the U.S. Weather Bureau for all of the thunderstorm days was performed to determine the one or two basic conditions which were responsible for the thunderstorms in Illinois. A total of 20 different combinations of conditions was found, but these combinations were grouped into six generalized types shown in table 3. For instance, the 79 no-hail days with cold front conditions include 63 cases caused solely by the front, 1 case of cold front with an occlusion, 2 cases with post-frontal over-running, and

TABLE 3.—*Synoptic types associated with thunderstorm days with and without hail during the crop-growing season*

Synoptic types	No-hail thunderstorm days			Hail-thunderstorm days		Average number of days with fronts
	Total days	Season average	Percent of total	Season average	Percent of total	
Cold front	79	8	33	27	51	36
Warm front	20	2	8	3	6	11
Stationary front	48	5	20	15+	28	31
Air mass	55	6−	23	4	8	--------
Low center	32	3	13	3	6	--------
Others	8	1−	3	1−	1	--------
Totals	242	25−	100	53	100	78

13 cases of prc-frontal squall linos. Pro-frontal was defined as being more than 50 miles ahead of the front. Air mass conditions were limited to cases where no front existed within 250 miles of the thunderstorm area on the day of occurrence. The low center typing included transient Lows without fronts, Lows with fronts, waves, and troughs. The category of "other" synoptic types refers to upper troughs and occlusions.

In table 3 the frequencies of no-hail days by synoptic types are also expressed as percentages of the 242 days. Similar percentages for the hail-thunderstorm days in Illinois during the 1951-60 period arc shown for comparison. On a percentage basis, a greater frequency of no-hail thunderstorm days occurred with air mass, low center, and warm front conditions than did hail-thunderstorm days which were more completely associated with cold front and stationary front conditions. Huff [6] derived similar synoptic frequency percentages for 113 thunderstorm days between 1910 and 1960 with widespread hailstorms.

About 50 percent of the thunderstorm days caused by warm fronts, air mass conditions, and low centers did not have hail. However, 25 percent of the thunderstorm days associated with stationary fronts had no hail. Of the 35 thunderstorm days per season caused by cold fronts, on the average only 8, or 23 percent, were not hail days. In a climatological study of synoptic weather, Chiang [4] obtained data on the number of days with fronts occurring in Illinois during the 1945-59 period. Averages compiled for the growing season are presented in table 3 for comparison with the frontal frequencies for hail and no-hail thunderstorm days. Note that 75 percent of all days with cold fronts in Illinois had hail, whereas less than 50 percent of the days with stationary fronts had hail.

Another interesting observation pertaining to the 147 frontal cases associated with no-hail thunderstorm days was the lack of excessive temperature difference across the fronts, which in general indicated that most of these were relatively weak fronts at the surface. For instance, the average temperature difference across the 79 cold fronts was 4.4° F. as compared with 6.8° F. for the 270 cold fronts associated with the hail-thunderstorm days. Huff [6] reported that 50 percent of the cold front cases associated with widespread hailstorm days were pre-frontal in nature, whereas only 17 percent of the 79 cold front cases causing no-hail thunderstorms were prc-frontal. In general, the no-hail thunderstorms appeared to be associated with weaker synoptic systems.

A comparison of the synoptic types with the areas where associated thunderstorm reports were most prevalent revealed that on days witli warm fronts the thunderstorms without hail occurred most frequently in central and northern Illinois. Chiang [4] has shown that warm fronts are most frequently located in central Illinois. Days of low center passages and air mass conditions had the greatest number of thunderstorm reports in the southern and central portions of Illinois. Chiang [4] also revealed that warm-air mass conditions prevail in southern Illinois from 50 to 00 percent of the time in summer as compared with 30 percent of the time in northern Illinois, and that in summer low centers move most frequently across the southeastern and north-central portions of the State. Reports of thunderstorm days caused by either cold fronts or stationary fronts revealed no regional concentration within the State.

7. CONCLUSIONS

During the March-October thunderstorm season in Illinois on the average one-half of the days have thunderstorms and one-third of the days have hailstorms. During the crop-growing season, mid-May to mid-September, 63 percent of all days have thunderstorms and on 70 percent of these days, or 53 days on the average, hailstorms occur somewhere in Illinois. This areal frequency in growing-season hail days in Illinois is more than 50 times greater than the average point frequency of hail, and also is 2 to 5 times greater than any previously recorded areal frequencies for Illinois. The frequently used hail-thunderstorm ratio based on data recorded at a point cannot be considered as an adequate description of the occurrence relationships between hailstorms and thunderstorms.

Nearly one-third of all thunderstorm days in Illinois do not have hail observed at the ground, and during the growing season these no-hail thunderstorms are most frequent in southern Illinois. This ratio plus the fact that these no-hail thunderstorms frequently cover more than 15,000 square miles of Illinois on one day are findings which could be construed as being evidence that many thunderstorms do not produce hail aloft. This receives further support from Wilk's [17] findings and from the fact that the no-hail thunderstorms are associated more frequently with synoptic systems weaker than those associated with hail-thunderstorms.

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REFERENCES

1. H. R. Byers, *The Thunderstorm,* U.S. Weather Bureau, 1949, 287 pp.
2. S. A. Changnon, "Thunderstorm-Precipitation Relations in Illinois," Illinois State Water Survey, *Report of Investigation 34,* Urbana, Ill., 1957, 24 pp.
3. S. A. Cliangnon and G. E. Stout, "Details of Surface Characteristics Displayed by Illinois Hailstorms," paper presented at American Meteorological Society Severe Storm Conference, Feb. 13-15, 1962, 33 pp.
4. I. M. Chiang, "Analysis of Selected Synoptic Elements of the Climatology of Illinois," Masters Thesis, Southern Illinois University, Carbondale, Ill., 1902, 75 pp.
5. H. T. Harrison and W. B. Beckwith, "Studies of the Distribution and Forecasting of Hail in Western United States," *Bulletin of the American Meteorological Society,* vol. 32, No. 4, Apr. 1951, pp. 119-131.
6. F. A. Huff, "Relations Between Summer Hailstorms in Illinois and Associated Synoptic Weather," *Research Report 5,* Crop-Hail Insurance Actuarial Association, Chicago, Ill., 1960, 35 pp.
7. F. A. Huff and S. A. Changnon, "Hail Climatology of Illinois," Illinois State Water Survey, *Report of Investigation 38,* Urbana, Ill., 1959, 40 pp.
S. P. E. Lehr, "The Problem of Forecasting Hail Encounters During Mights through Thunderstorms," *Bulletin of the American Meteorological Society,* vol. 42, No. 5, 1961, pp. 345-348.
9. H. Lemons, "Hail in American Agriculture," *Economic Geography,* vol. 18, No. 4, Oct. 1942, pp. 363-378.
10. H. W. Sansom, "The Occurrence of Hailstorms in British East Africa," *Nubila,* vol. 4, No. 2, 1961, pp. 34-51.
11. A. L. Shands, "The Hail-Thunderstorm Ratio," *Monthly Weather Review,* vol. 72, No. 3, Mar. 1944, pp. 71-72.
12. G. E. Stout, "Summary of Research on Hailstorms in Illinois during 1901,"—Appendix A, *Research Report 11,* Crop-Hail Insurance Actuarial Association, Chicago, Illinois, 1961, pp. 8-15.
13. G. E. Stout, R. B. Blackmer, S. A. Cliangnon, and F. A. Huff, *The Hail Hazard in Illinois,* Illinois State Water Survey, Urbana, Ill., 1959, 33 pp.
14. U.S. Weather Bureau, *Climalological Data for Illinois,* vol. 65, No. 13, 1960, pp. 176-185.
15. S. S. Visher, *Climatic Atlas of the United Stales,* Harvard University Press, Cambridge, Mass., 1954, 403 pp.
16. K. E. Wilk, "Radar Investigations of Illinois Hailstorms," *Scientific Report* No. 1, Contract No. AF19(604)-4940, Illinois State Water Survey, Urbana, Ill., 1961, 42 pp.
17. K. E. Wilk, "Research Concerning Analysis of Severe Thunderstorms," *Final Report* Contract AF19(604)-4940, Illinois State Water Survey, Urbana, Ill., 1961, 68 pp.