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SUMMARY OP 1966 HAIL RESEARCH IN ILLINOIS

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ABSTRACT

Research on hail in Illinois performed during 1966 involved three different studies. The first study concerned determination of the probabilities for the areal extent of damaging hail in fixed areas of 1000 and 3000 square miles. Information on the likelihood for various amounts of damaging hail in fixed areas is important in an understanding of hail production in Illinois, and also has relevance in making decisions about the amount of liability that should be assumed in an area.

The second hail study accomplished was a detailed investigation of damaging hailstorms in central Illinois during the early morning of 11 July 1966. This study was concerned primarily with the surface characteristics of the hail and the causes for these unusual nocturnal hailstorms. A principal objective was to determine whether surface data on hail provided by routine insurance records of claims and field adjustments of loss for damaging hailstorms were adequate to allow a detailed reconstruction of the storm characteristics and their patterns.

The third hail study in 1966 concerned the collection and analysis of historical hail records from 225 U. S. Weather Bureau stations in Indiana, Michigan, and Wisconsin. The data were analyzed to develop mean seasonal and annual patterns of hail for these three states, and to show the relation of these patterns to those previously established for Illinois. The availability of these patterns for surrounding states allows a more accurate evaluation of the Illinois hail patterns and the causes for the areal variability of hail.

PROBABILITIES FOR AREAL EXTENT OF DAMAGING HAIL IN FIXED AREAS

Introduction

To perform a study of the areal extent of hail damage in areas of 1000 and 3000 square miles within Illinois, climatological data from U. S. Weather Bureau stations and data from insurance records in Illinois were employed. However, these records did not furnish all desired data, and certain assumptions had to be made to derive the desired statistics.

The climatological hail-days data for the 1934-1963 period served as the basis for determining the probabilities for several hail criteria. Included among these were the regional numbers of hail days in summer, point numbers of hail days per summer, and the areal extent (number of stations reporting hail) on summer hail days. Long-term climatological records of hail-day incidences at several points within each area were assumed to sample most hail days in the area. This assumption was proven correct by tests using sequential deletion of data by stations.

The climatological records of hail days contained no information on the areal extent of hail per station report, and this information is vital to any study of the probabilities for loss areas. Two sources of obtaining at least an estimate of the mean areal extent of hail per report of hail were available. Research (1) has shown that the average areal extent of a hail streak in Illinois is 36 square miles (3 x 12), and it could be assumed that each station report of a hail day represented a hailfall covering approximately 36 square miles. However, it has been found in every field investigation of hailstreaks that more than one hailstreak occurred in a relatively small area, and that these streaks often partially overlapped (2, 3). Thus, the use of 36 square miles to represent the areal extent of damaging hail for each station's report of hail appeared to be an underestimation of mean areal extent of hail.

Insurance statistics for individual days with hail in Illinois during the 1953-1959 period (4) were analyzed, and the median number of square miles with crop damage per storm day in Illinois was found to be 105 square miles. This area with damage normally was rectangular with a long east-west axis of about 20 miles and a short north-south axis of about 5 miles. Since the minimum distance between stations in both the 1000- and 3000-sq-mi areas (figure 1) was 25 to 30 miles, it appeared reasonable to let each climatological-station report of a hail day represent the incidence of damage over 105 square miles. If two stations reported hail in a test area on a given day, it was assumed that 210 square miles had been damaged. If the same station had two dates of hail in a season, it was assumed that the associated damage areas completely overlapped. The use of the value of 105 square miles can only be considered as an approximate approach since the insurance data do not represent the entire hail area, and the statistics on extent of damage are dependent on the varying amount and density of insurance coverage during the 1953-1959 period.

Hail-Day Frequencies

The 1000- and 3000-sq-mi areas chosen for analysis are depicted in figure 1. Hall data for the larger area were derived from the eight stations within that area, and data for the 1000-sq-mi area came from the five stations within its perimeter. Hail-days data for the summer season, June-August, were chosen for the analysis since this season closely matches the crop-damage season in Illinois (5).

Figure 2 shows the frequency distribution of summer hail days in each area. Once in 25 years the 3000-sq-mi area will have 10 or more days with hail, whereas once in 10 years the 1000-sq-mi area will have 5 or more hail days. Also shown are curves for selected stations which illustrate that point frequencies of hail do not vary considerably in the test areas. Comparison of the values of the station and area curves at any selected recurrence interval furnishes a measure of the point-area relationship between hail occurrences in Illinois. For a given recurrence interval, the 3000-sq-mi area experiences about three times more hail days than occur at a point.

Areal Extent of Damaging Hail

Determination of the probabilities for the areal extent of damaging hail was the primary goal of this research, and this study is closely related to activities on a project currently being supported by the National Science Foundation. The first step in obtaining these probabilities was the identification of the frequency of occurrence of different numbers of hail days in summer.

The frequencies for the 1000- and 3000-sq-mi areas are shown in table 1 expressed as a percentage of the total number of summers, 30. These percentage frequencies were plotted on probability scales and the resulting curves are shown on figure 3. The probabilities for each number of hail days in summer, hereafter referred to as the summer hail type, derived from the graph are listed below the frequency values in table 1. Use of the curves in figure 3 reveals that 90 percent of the time the 1000-sq-mi area can expect 4 or fewer hail days in summer, whereas the 3000-sq-mi area will have 5 or fewer hail days.

Table 1. Frequency and Probability of Summer Hall Days as Percentages

Area, sq mi	0 days	1 day	2 days	3 days	4 days	5 days	6 days	7 days	8 days	9 or more days
1000										
Frequency,%	20	13	20	20	18	3	3	0	3	0
Probability,%	17	17	22	20	14	7	2	0.8	0.2	
3000										
Frequency,%	10	3	27	13	25	10	3	3	3	3
Probability,%	7	10	15	19	19	14	9	5	1.4	0.6

The second step in obtaining the desired areal extent probabilities was to calculate the areal extent of damaging hail in different years and to relate these values to a likelihood of occurrence. The establishment of the probabilities of summer hail days in the 1000- and 3000-sq-mi areas proffered a means to achieve the desired likelihoods for areal extent, but only if the summer hail types (1-day, 2-day, 3-day, ..n-day types) could be expressed or translated into numbers of miles of damage.

As explained earlier, each station report of a hail day was assumed to be representative of 105 square miles of damage. Thus, the areal extent of hail in each summer type was dependent on the number of station reports. The data from the individual calendar years for each summer hail type was averaged to "model" the extent, or number of reports, of hail. For instance, there were seven years in the 3000-sq-mi area that were the 4-hail day type (4 dates with hail in summer), and averaging of these years showed that: l) two different stations reported 1 day with hail per summer, 2) one station had 2 reports of hail, and 3) occasionally (1 year out of 3) one station had 3 hail days. These averages, or models of each season, were multiplied by the assigned 105 square miles of damage per hail report to get a total damage area. The values for cases of 2 or 3 hail reports per station were calculated as 210 or 315 square miles of damage, respectively, but on the assumption that these were geographically fixed 105-sq-mi areas with damage repeated over the same miles.

3000-Square-Mile Area. The resulting values for the 3000-sq-mi area appear in table 2. For the 4-hail-day summer type there are 210 square miles damaged once by hail,' another 105 square miles damaged twice (which can be interpreted as 210 total miles of hail damage), and 45 square miles damaged three times for a total of

135 damaged miles (3 x 45). The upper-row totals in table 2 represent the actual geographical extent of hail damage regardless of the number of times each mile was damaged. The lower totals represent the total accumulated square miles of damage including those which experienced repeated damages. To obtain these lower totals the square-mile value listed for the 2-damage occurrences was multiplied by 2, those for 3 occurrences by 3, those for 4 by 4, and the resulting products were summed along with the total miles listed for the 1-hail occurrence.

In the final phase of the probability analysis for the annual extent of damaging hail in the 3000-sq-mi area, the probability values derived for each hail season type, as shown in table 1, were used with their matching total accumulated miles with damage (table 2) to plot the probability curve shown in figure 4. Interpretation of the upper curve shows that 1 percent of the time hail damage will occur to 1050 or more square miles, whereas 70 percent of the time the damage area will exceed 280 square miles. Also shown on figure 4 are probability curves for the number of miles damaged as a result of repeated hailfalls on the same area. Thirty percent of the time 270 miles or more will be damaged as a result of 2 or more days with hailfalls on the same area, and 100 miles or more of damage will result from 3 or more days of hail at the same location.

Another way to express the probabilities for the areal extent of crop damage in the 3000-sq-mi area during one season is by the

Table 2. Areal Extent and Total Number of Square Miles Damaged by Hail for Each Summer Hail Day Type in 3000-Square-Mile Area

Number of times damage occurred to area	Number of square miles per season for given summer hail type									
	0 days	1 day	2 days	3 days	4 days	5 days	6 days	7 days	8 days	9 days
1	0	105	310	315	210	210	210	105	105	105
2	0	0	0	50	105	105	105	210	0	0
3	0	0	0	0	45	70	105	105	315	105
4	0	0	0	0	0	0	0	0	0	210
Total affected miles	0	105	310	365	360	385	420	420	420	420
Total accumulated miles	0	105	310	415	555	630	735	840	1050	1260

use of the probability values in table 1 and the associated damage area values in table 2. For instance, the 3-day summer hail type has a probability of occurrence of 19 percent (one year in five), and the values in table 2 for the 3-day type show that 315 square miles of area will be damaged one time and another 50 miles will be damaged twice. Thus, in one year out of five, a 3000-sq-mi area can expect crop-hail damage to 365 square miles of its area, and damage will occur to a total of 415 miles because 50 miles of the 365 will experience damage twice.

An expression of the areal extent of damaging hail also was obtained for 5-year periods. In the 30-year sampling period (1934-1963) 102 summer hail days occurred in the 3000-sq-mi area and this represents an average of 3.4 days per summer. In an average 5-year period, there would be 17 hail days in the 3000-sq-mi area. Fourteen of these days would produce hail at only one station, two days would have hail at two stations, and one day would have hail at three stations. Thus, in an average 5-year period, the total number of miles damaged by hail would be a sum of 1470 miles (14 single day reports times 105 miles), 420 miles (2 hail reports on 2 days times 105), and 315 miles (3 hail reports on 1 day times 105), which combined produce a total of 2205 square miles of damage.

Five-year running totals of summer hail days for the 3000-sq-mi area based on the 1934-1963 period were calculated to produce 26 different 5-year values of hail days. The highest number was 27 days (1942-1946 period); the lowest was 8 days (1936-1940); and the median number was 16 hail days, one day lower than the average number. For each 5-year total, the number of square miles of damage was computed by assigning 105 square miles of damage to each report. The lowest 5-year value was 945 square miles in 1936-1940 (6 percent of total miles), and the highest was 3675 miles in 1942-1946 (25 percent of possible miles). A probability curve based on the 26 five-year values of miles damaged is shown in figure 5. Fifty percent of the time the area damaged by hail in a 5-year period will be 2000 square miles or more.

<u>1000-Square-Mile Area</u>. Analyses for data on the 1000-sq-mi area were performed in the same probability manner as that employed for the 3000-sq-mi area. Table 3 shows the expected number of miles damaged for each summer type (table 1) in the 1000-sq-mi area. For the 3-day type there are 210 square miles damaged once during a season and 74 miles damaged twice for a total of 148

miles (2 x 74). The lower totals in table 3 represent the accumulated miles of damage including those which experienced damage more than once.

Table 3. Areal Extent and Total Number of Square Miles Damaged by Hail for Each Summer Hail Day Type in 1000-Square-Mlle Area

Number of times damage occurred to area	Number of square miles per season for given summer hail type							
	0 days	1 day	2 days	3 days	4 days	5 days	6 days	8 days
1	0	105	137	210	84	105	210	105
2	0	0	73	74	63	105	105	0
3	0	0	0	0	84	105	105	315
Total affected miles	0	105	200	284	241	315	420	420
Total accumulated miles	0	105	283	358	462	630	735	1050

The probability values derived for each hail season in the 1000-sq-mi area, as shown in table 1, were matched with their accumulated totals of miles (table 3) to plot the probability curves shown in figure 6. These curves show for the 20 percent probability level (2 years out of 10) that 400 square miles or more will be damaged by one or more storms, a total of 260 square miles or more will be damaged by 2 or more storms, and 30 square miles or more will be damaged by 3 or more storms.

An expression of the frequency of damaged square miles for a period of years was obtained for the 1000-sq-mi area. In the 1934-1963 period there were 73 hail days in the summer season, which is an average of 2.4 days per summer, or 12 hail days in an average 5-year period for 1000 square miles. On 10 of these days hail occurs at only one station in the 1000-sq-mi area and on 2 days hail occurs at two stations out of the five in the area. Thus, in an average 5-year period, the total number of miles damaged by hail, which is a combination of 1050 miles (10 single-day reports times 105 miles) and 420 miles (2 hail reports on 2 days time 105), is 1470 square miles.

Five-year running totals of summer hail days for the 1000-sq-mi area were computed for the 30-year period, resulting in 26 different 5-year values of hail days. The highest number was 25 days (1942-1946); the lowest was 6 hail days (1936-1940, 1948-1952, and 1955-1959); and the median number was 11 days, one less than the calculated average value. For each 5-year total, the number of square miles of damage was computed by assigning 105 square miles of damage to each station report of hail. The lowest 5-year value was 630 square miles in 1936-1940 and 1948-1952, and the highest was 3360 square miles in 1942-1946. The probabilities for various areal extents of crop-hail damage in a 1000-sq-mi area during 5-year periods can be determined from the curve shown on figure 7.

Sampling Adequacy

A test of the sampling adequacy of the eight stations in the 3000-sq-mi area was made by a process of data deletion. Using various numbers and combinations of stations ranging from 1 to 8 in the area, the average number of summer hail days was calculated for each number of stations, as summarized in table 4. The 8-station average for the area was 17 days, and the deletion of one station created an average of 15-9, or 1 hail day less in 5 years. With each subsequent deletion of a station the averages dropped more rapidly (the difference between averages based on 2 and 3 stations was 2.5 hail days). The diminishing difference in the hail-day averages as stations increased suggested that the eight stations were providing a reasonably good sample of the total hail day occurrences over the 3000-sq-mi area.

Table 4. Average Number of Summer Hail Days in 3000-Square-Mile Area Determined from Different Numbers of Stations

	Number of stations in area							
	1	2	3	4	5	6	7	8
Seasonal average number of days	2.7	5.3	7.3	10.1	12.3	14.3	15.9	17.0

Comparison of the numbers of stations with their averages indicated a curvilinear trend, and therefore the following equation was derived from these data: $Y = -0.6921 + 3.2746X - 0.1321X^2$, where Y is the average areal number of hail days and X is the number of stations in the area. Solution of this equation for different numbers of stations above the eight available stations furnished estimates of 1) the total or "true" average number of summer hail days, and 2) the number of stations that would provide this true average. The maximum average number of hail days predicted by the equation is 19+ days which would be achieved by 12 stations in the area. This is only 2 days, or 12 percent, more than the number of days based on 8 stations. These results indicate that the data from the eight stations in the 3000-sq-mi area provide an excellent sample of the hail conditions within the area over a 30-year period.

HAILSTORMS ON 11 JULY 1966

Introduction

A series of damaging hailstorms that occurred in a relatively small portion of central Illinois during the early morning of 11 July 1966 were analyzed for two reasons. The first was to learn whether hail insurance data, collected under routine company operations, could provide information adequate for a detailed mapping of surface hailfalls. The damage adjustors were personally contacted by a former adjustor to obtain additional information they might have casually collected concerning stone sizes, the exact times of hailfall, and other storm characteristics. Their reports, both these oral interviews and their routine written forms, plus the hail claims to the insurance companies were the basis for the surface analysis of the hailfall.

A second reason for this study was to analyze the causes for these nocturnal hailstorms. Damaging hailfalls at night in Illinois are quite unusual (6), and additional knowledge of such storms is quite meaningful.

This portion of the 1966 report consists of one section devoted to a description of surface hailfalls and a second section treating storm morphology and synoptic weather conditions. Several persons aided in the study of this storm. Mr. Glenn E. Stout had the foresight to initiate the investigation and the collection of data pertaining to this storm. Mr. John Hornaday contacted many insurance personnel and collected information from their written reports and through personal conversations. Mr. Ashton Peyrefltte assisted in the synoptic weather analysis and aided in the plotting of various data.

Surface Characteristics of the Hall

In the hallfall area outlined on figure 8, there were nearly 300 individual claims of damage. Approximately 60 percent of these were closed by a financial settlement, and the rest were released, or not paid. Paid losses for the hail damages on 11 July totaled almost $100,000 which does not make this an exceptionally damaging storm (7).

The various forms of insurance data were used to plot the maps portrayed on figure 8.. The outer extent of hallfall was defined as that region included in hail claims filed by insurees. Absolute proof that hail actually fell throughout all of this enveloped area is lacking. However, it is reasonable to conclude that those filing claims for which no payment was made thought that hail fell at their farms or at nearby locations, and thus the areal extent of hailfall shown is likely a reasonable approximation of the hail area on 11 July.

The "work sheets" of the adjustors, which indicate the amount of crop loss in percent for each insured field, were used to construct the pattern depicted on figure 8A. These isopercentile lines were drawn for losses measured to soybean crops. The major loss area was near Piper City where damages rated in excess of 60 percent. Other isolated areas with 1 to 20 percent losses are shown throughout the hailfall area. Again, based on these measures of loss, this series of hailstorms is not to be considered as particularly damaging.

There are no data to suggest that there were repeated hailfalls on the same area, and this has been shown to be the situation normally necessary to produce extreme damages to crops in Illinois (8). Of interest is the fact that the extent of the area with paid losses, that inside the isopercentile lines, is considerably less than the hail area with unpaid claims of damage (extent of hailfall). Such data from several storms might provide a useful measure of the relationship between the areal extent of nondamaging hail and the areal extent of damaging hail.

Photographs of damaged corn and soybean plants in the storm area near Piper City are presented in figure 9. These photographs reveal the defoliation and the type of stalk and stem damage produced by wind-blown hail. Bruising of stalks and stems of these two crops is very detrimental to their ensuing growth and final yield.

Information presented in figure SB for time of hail occurrence, storm movement, and stone sizes was constructed from all available data. In general, the reports from the adjustors did not contain the data on time of hail needed for an accurate reconstruction of the history of the hailstreaks. However, time data were sufficient to allow a generalized interpretation of forward motion of storms, but these are gross estimates that do not reveal the details of motion of the many hailstreaks which likely occurred in this area.

The 16 separate measurements of stone sizes were insufficient to permit the development of any reliable stone-size patterns. In general, the largest stones, 3/4 to 1-1/4 inch in diameter, fell near Piper City where damages were greatest. This area also had very heavy rain, 1.0 to 2.5 inches, in a relatively short time (1 hour), and this probably added to the crop damages. The largest hailstones measured in one portion of the area where 60 percent losses to soybeans occurred were only 3/4-inch in diameter, but the high winds, estimated locally to be 80 mph, were a major contributing factor in producing the hail damage. The winds bent the plants over so that more of the vulnerable stalks or stems were exposed to hail, and the wind blew the stones at low angles where they had a better chance to intercept stalks and stems (figure 9). The small area of 5-percent loss shown located 8 miles northeast of Gibson City was produced by stones measuring only 1/4-inch in diameter, also revealing that wind-blown hail of any size can be damaging to crops. In general, the results from this storm indicate that the amount of crop damage is slightly related to stone sizes, but the simultaneous occurrence of high-speed winds is the key factor in the occurrence and amount of crop damage attributed to hail. The adjusted loss data were adequate to prepare detailed maps of the areal extent and patterns of damages. However, if the desired goal of surface hail data is to provide information that will allow detailed reconstruction, in time and space, of individual hailstreaks or hailstorms, then the present insurance data alone do not appear adequate.

Storm Morphology and Synoptic Analysis

A description of the major features of the system that produced the central Illinois hailstorms on 11 July was developed using radar data from the 10-cm WSR-57 in Chicago, surface weather data, and synoptic weather data of the U. S. **Weather Bureau.** The description is set forth in chronological **order to reveal** the changing character of the system and the **apparent reasons** for the changes. The Illinois hailstorms were associated with **a** fast-moving squall line that had developed in south-central Minnesota 8 hours before the hailstorms occurred.

Scattered thunderstorm activity occurred during the morning of 10 July in central Minnesota, northeast of where an east-west stationary front intersected a cold front in a small low pressure system in the South Dakota-Minnesota region. Air and dew point temperatures just north of the stationary front were quite high and not significantly different from values south of the front. This stationary front was positioned eastward across northeastern Iowa and extreme northern Illinois, and remained in this position from early on 10 July until mid-day of 11 July. Low-level convergence into central Minnesota and a high-level jet stream across this region were instrumental in the development of the thunderstorms and their subsequent organization into a squall line.

As the thunderstorms in south-central Minnesota became organized into a NE-SW oriented line in late afternoon on 10 July, they began moving at 35 mph to the southeast. This movement followed the position of the jet stream which extended southeasterly from central Minnesota across Wisconsin and northern Indiana. The squall line was also moving in and along a NNW-SSE oriented moist tongue (more than 1.5 inches of precipitable water).

Severe weather alerts had been issued by the U. S. Weather Bureau for areas in southern Wisconsin ahead of this squall line. The Chicago radar report at 2145 CST, when the line was in south-central Wisconsin (figure 10), gave measured echo tops as high as 62,000 feet.

The line began moving faster, 45 to 50 mph, as it approached the frontal zone in northern Illinois at 2300 CST on 10 July (figure 10). The flow aloft (above 25,000 feet) in this area was from 40 to 55 mph from the northwest and was obviously the guiding force for this squall line. Stability indices south of the front in Illinois were -3, and all conditions necessary for enhancing convection were present.

As the line entered Illinois and began to pass through the stationary front (figure 10), two things happened. The middle section of the NE-SW oriented line continued to move forward very rapidly (50 mph), but the end elements of the line slowed.. Lake Michigan apparently caused a definite diminishment of convection, and thus a decrease in the strength and movement of the northeast portion of the line, and the western elements of the squall line seemed to slow as they entered the frontal zone.

Also simultaneous with the passage of the squall line through the frontal zone was the initiation of widespread damaging surface winds (50 to 80 mph). The line had moved into a warmer, moister, and certainly more unstable area, and radar photographs show the center of the line to be a nearly solid echo without any cellular pattern (figure 11). This rapidly advancing solid rain area produced damaging surface winds at most places along a path 60 miles wide beginning in northern Illinois at 0000 CST and extending into central Illinois where they ceased at 0230 CST. Thus, an area about 60 by 150 miles (9000 square miles) experienced the extremely strong downdraft or gust front that continuously advanced ahead of this massive storm. Rainfall in Illinois produced by the squall line varied from 0.75 to 1.5 inches at points all along the center of the line with lesser amounts where the weaker western and eastern elements of the line passed.

At about the time the storm passed Chicago (0050 CST), two thunderstorms developed 40 miles ahead of the line. These unusual nocturnal thunderstorms, labeled 1 and 2 on figure 12A, could have been produced by the instability of the stationary front or by air ascending because of descending air immediately ahead of the squall line. Eighteen minutes later (figure 12B) a third storm, labeled number 3, had developed ahead of the rapidly advancing center portion of the squall line.

The first hail in Illinois began at 0115 CST, occurring just after the leading edge of the squall line merged with echo number 3 (figure 12C). As the squall line approached the large thunderstorm, labeled 1-2 (figure 12D), which was a merger of earlier storms 1 and 2 another hailstorm or series of storms began in the center portion of the hailfall area. The final hailstorms on 11 July, which began around 0200 CST, developed along the forward edge of the squall line where echo 1-2 had been enveloped (figure 12E). Hail production from the squall line ended by 0215, and no further hail occurred in Illinois. The squall line continued its rapid southward movement until 0350 CST (figure 10), after which it dissipated rapidly. Dissipation came about as the line moved away from the area of excessive frontal instability and moved to the anticyclonic side of the jet stream.

In a situation of obviously widespread instability and very strong convection, such as that exemplified by the large squall line on 10-11 July, the causes for a very restricted amount of hail are extremely interesting and pertinent in furthering knowledge of hail formation. The squall line, as massive as it was, was incapable of producing surface hailfalls until it merged with the rather uncommon nocturnal thunderstorms. Mergers of thunderstorms have been noted as the cause of severe weather (9), and obviously the dynamic interactions between two convective systems thrust together resulted in the type of vertical motions and liquid water content necessary to produce surface hail.

AVERAGE HAIL PATTERNS IN INDIANA, MICHIGAN, AND WISCONSIN

Introduction

As a part of a study of the effect of Lake Michigan on precipitation systems sponsored by the Department of Interior (10), data on hail were collected for three states bordering the lake. Hail data from Illinois have been analyzed in previous research (11, 12). These hail data allow the compilation of many climatological measurements of hail. Important among these are the average monthly, seasonal, and. annual patterns of hail days. Such patterns have been used in the development of crop-hail risk maps (5), and they also provide useful knowledge on the formation of hail.

The data obtained for Indiana, Michigan, and Wisconsin consisted of first-order station and cooperative substation records of hail-day incidences during the 1901-1965 period. Historical records were obtained from 225 stations in this 3-state area. The records from the substations were evaluated by a lengthy process (6) to ascertain which stations had quality records. This was necessary since substations are operated by volunteer observers who may or may not accurately report hail occurrences. In the 3-state area 158 stations had quality records of 10-year length or more and as shown in table 5, most of these covered periods of 20 years or longer.

Table 5. Number of Stations with Quality Hail Records

	Number of stations sorted by length or records, years			
	10-19	20-39	≥ 40	Total
Indiana	3	23	8	39
Michigan	18	36	16	70
Wisconsin	12	28	9	49

Results

In figure 13 the average patterns of hail for the three primary seasons of hail activity are presented. These patterns are based on all available quality data in the 3-state region plus that from Illinois. Most of the discussion concerns the patterns and their major features in Indiana, Michigan, and Wisconsin.

In the spring season (figure 13a) several areas of high and low occurrences are present. Notable among the higher hail incidence areas are two east-west ridges, one across southern portions of Illinois and Indiana, and another across the central sections of these two states. In lower Michigan low incidences occur along Lake Michigan, whereas in upper Michigan a ridge of high frequency appears. Spring hail incidences in Wisconsin are highest in the southwestern hill area, and are least in the northwest corner of the state.

In summer (figure 13b) the number of hail days in most locations is lower than in spring, except in northwestern Wisconsin. Many high incidence areas apparent on the spring map also appear in summer. The ridges across southern and central Illinois and

Indiana are again apparent along with a localized high in northwestern Indiana. A moderate high incidence area again appears in east-central lower Michigan. A low incidence area related to lake effects stretches across the southern end of lower Michigan, and another low occurs in the northern end of Michigan. A moderate east-west ridge of high incidence again appears in the upper peninsula and a high is repeated in southwestern Wisconsin.

In the fall (figure 13c) the mean pattern has many features not present in the other two seasons. Certain areas in upper and lower Michigan have more hail days, on the average, in fall than in any other season. Notable among the fall pattern features are the lake-induced high incidence areas along western lower Michigan. High occurrences again appear in northwestern Indiana and in the upper peninsula, although the high is more pronounced (90 days per 20 years at Munsing, Michigan) than in the other seasons. Both of these appear to be results of lake effects. The ridge across southern Illinois again appears in the fall season.

The pattern based on the total number of hail days expected during an average 20-year period is shown in figure 13d. The salient features of the three seasonal maps appear, including 1) the ridge across southern Illinois and Indiana, 2) the small high in northwestern Indiana, 3) the low in lower Michigan along the lake, 4) the low over and around upper Lake Michigan, 5) the ridge along the upper peninsula, and 6) the high in southwestern Wisconsin.

The pattern shown for Wisconsin agrees favorably with that posed by Burley (13) based on a 10-year sample of data. However, 3urley's pattern does not indicate the high (50 days or more) incidence area shown in figure 13d for north-central Wisconsin. Sampling errors associated with a 10-year record of hail days are the likely explanation for this difference.

A generalized interpretation of the varied pattern in figure 13d reveals five major zones of hail incidence. Hail occurrences along the Ohio River are generally lower than those in a wide band oriented SW-NE across the southern half of Illinois, central Indiana, and southeastern lower Michigan. A trough parallel to this broad ridge extends from western Illinois northeastward across Lake Michigan and into Canada, although it is interrupted by a lake-induced high in western lower Michigan. Highs in northwestern Illinois connect to the high extending into southern Wisconsin, but this semi-ridge diminishes in northeastern Wisconsin. The fifth major feature is a ridge that begins in northern Wisconsin and extends eastward across the upper peninsula of Michigan. These major features are likely the result of broad-scale variations in the synoptic climatological patterns (14) plus localized effects produced by hill areas and the Great Lakes.

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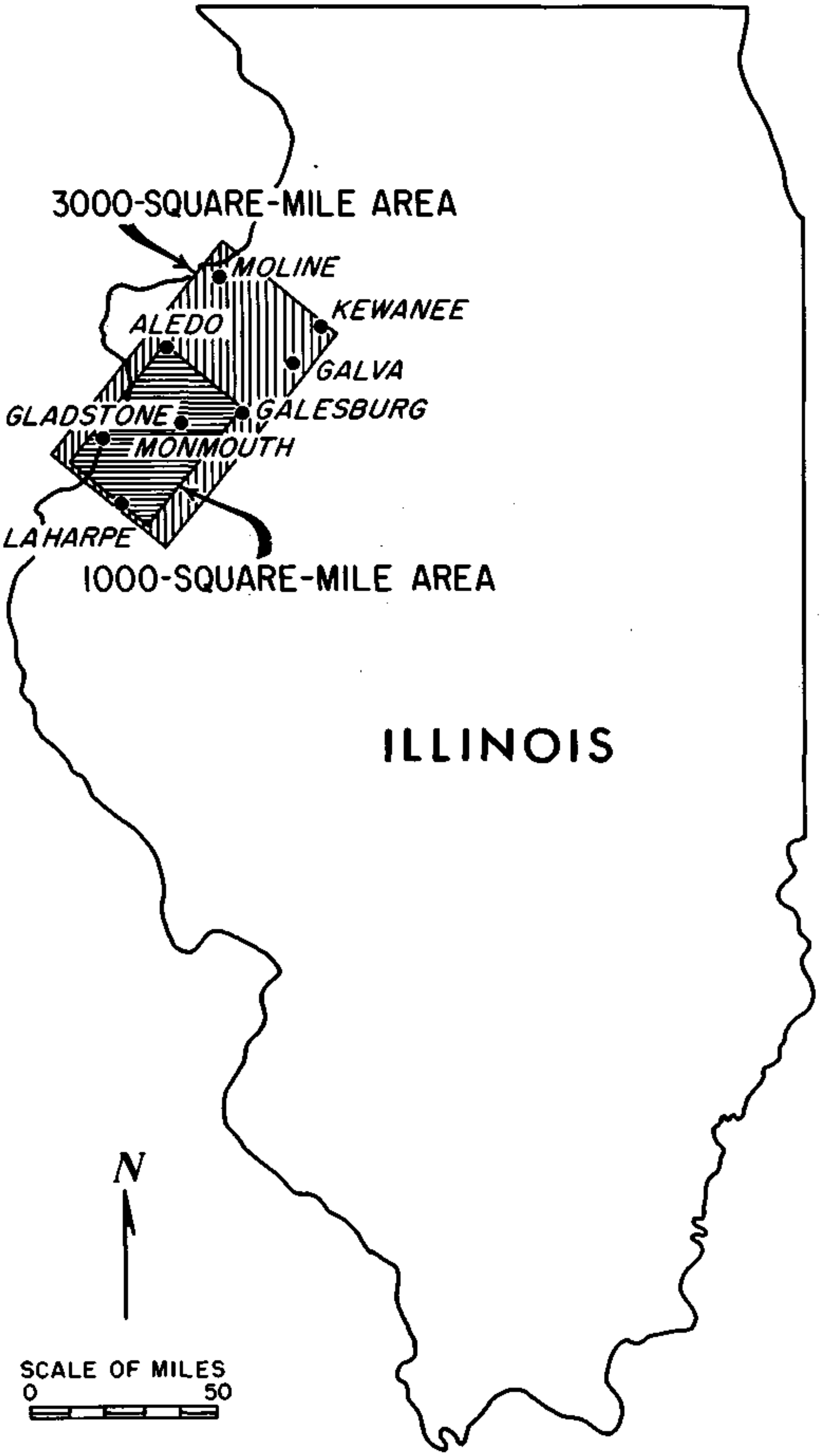


Fig.I 1000- AND 3000-SQUARE-MILE STUDY AREAS AND STATIONS WITH HAIL DATA

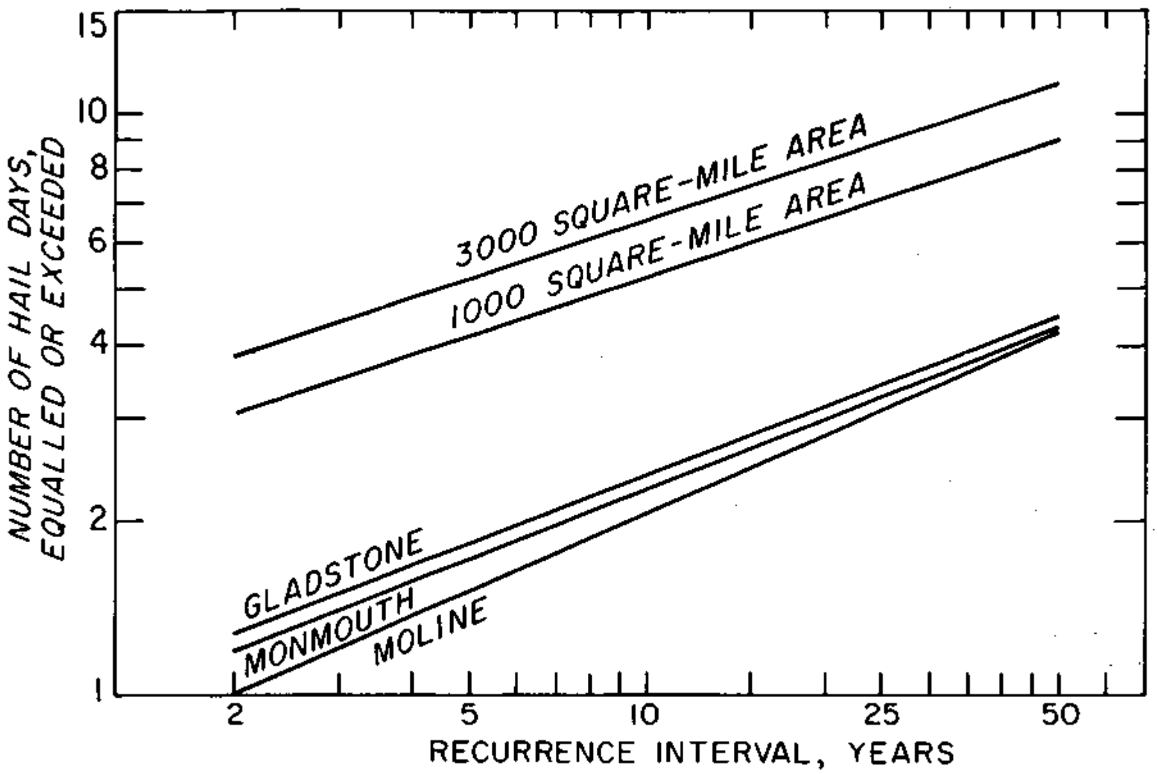


Fig. 2 FREQUENCY DISTRIBUTION OF SUMMER HAIL DAYS

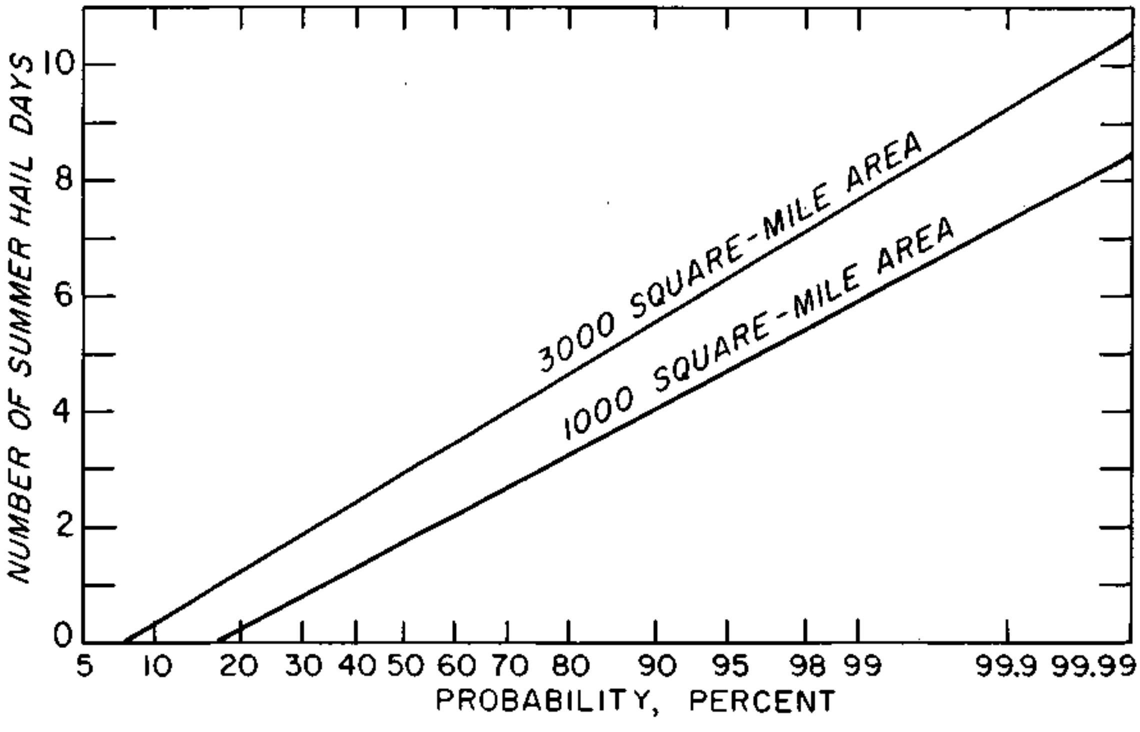


Fig. 3 PROBABILITY OF AREAL FREQUENCY OF SUMMER HAIL DAYS

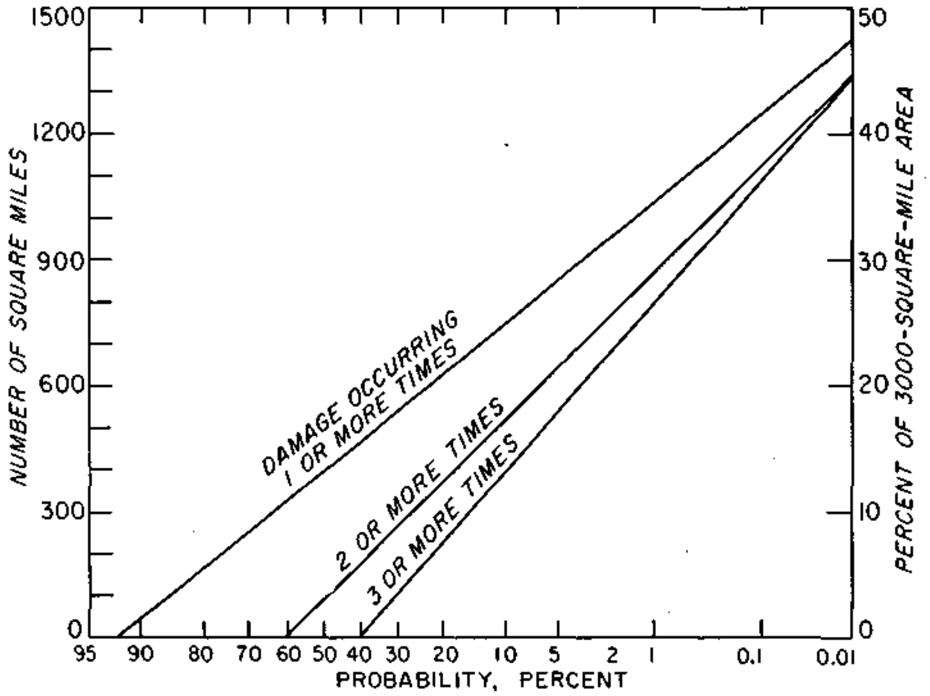


Fig. 4 PROBABILITY OF CROP DAMAGE WITHIN A 3000-SQUARE-MILE AREA DURING ONE YEAR

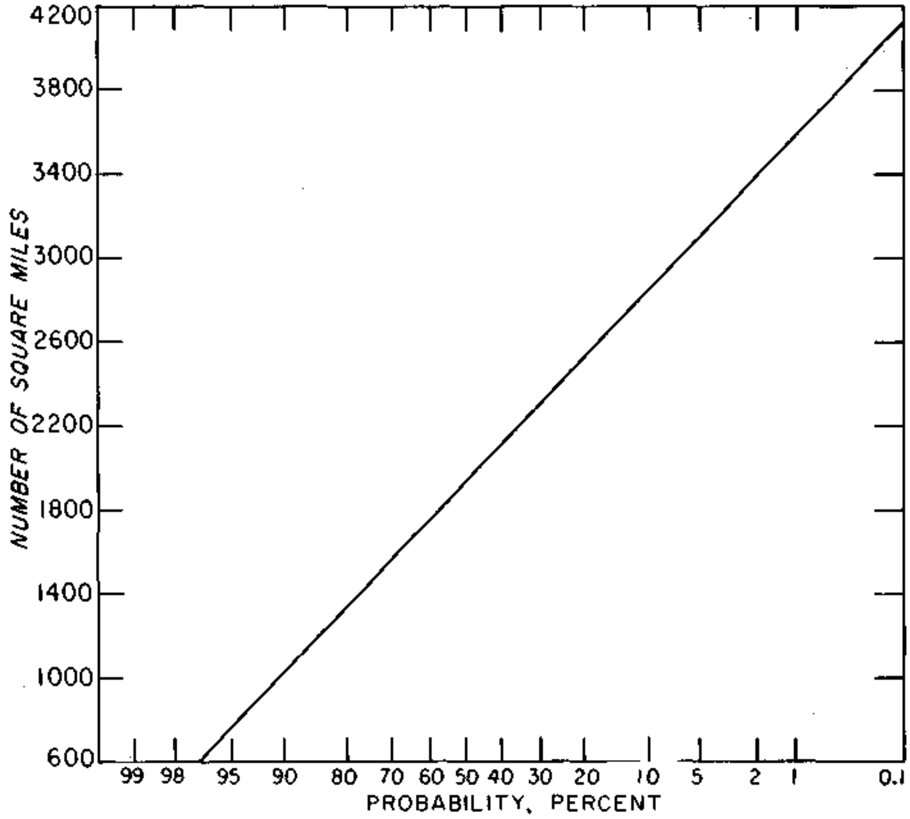


Fig. 5 PROBABILITY OF CROP DAMAGE WITHIN A 3000-SQUARE-MILE AREA DURING A 5-YEAR PERIOD

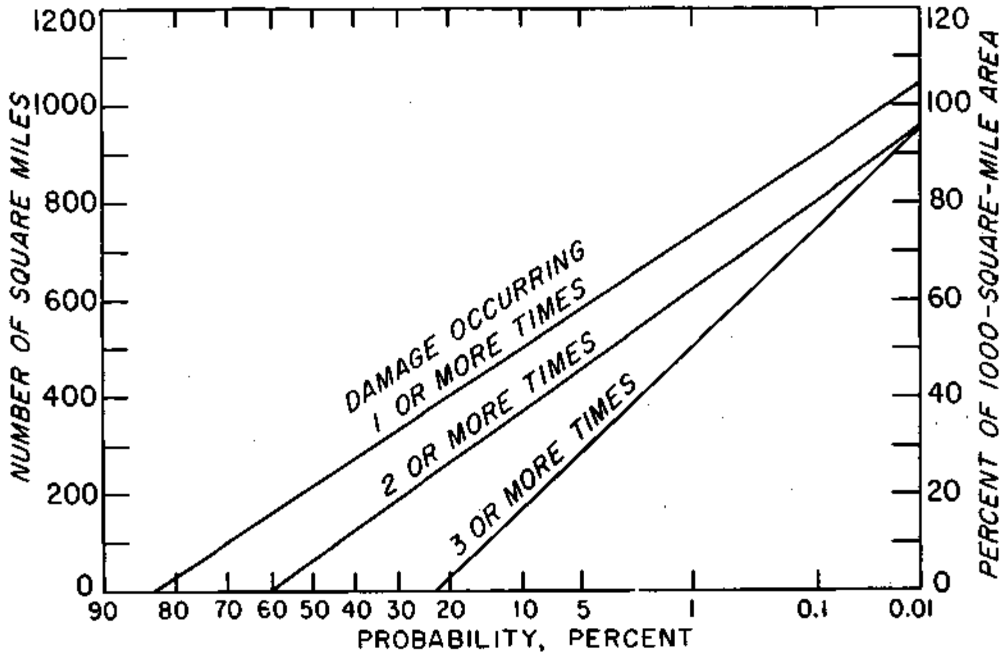


Fig. 6 PROBABILITY OF CROP DAMAGE WITHIN A IOOO-SQUARE-MILE AREA DURING ONE YEAR

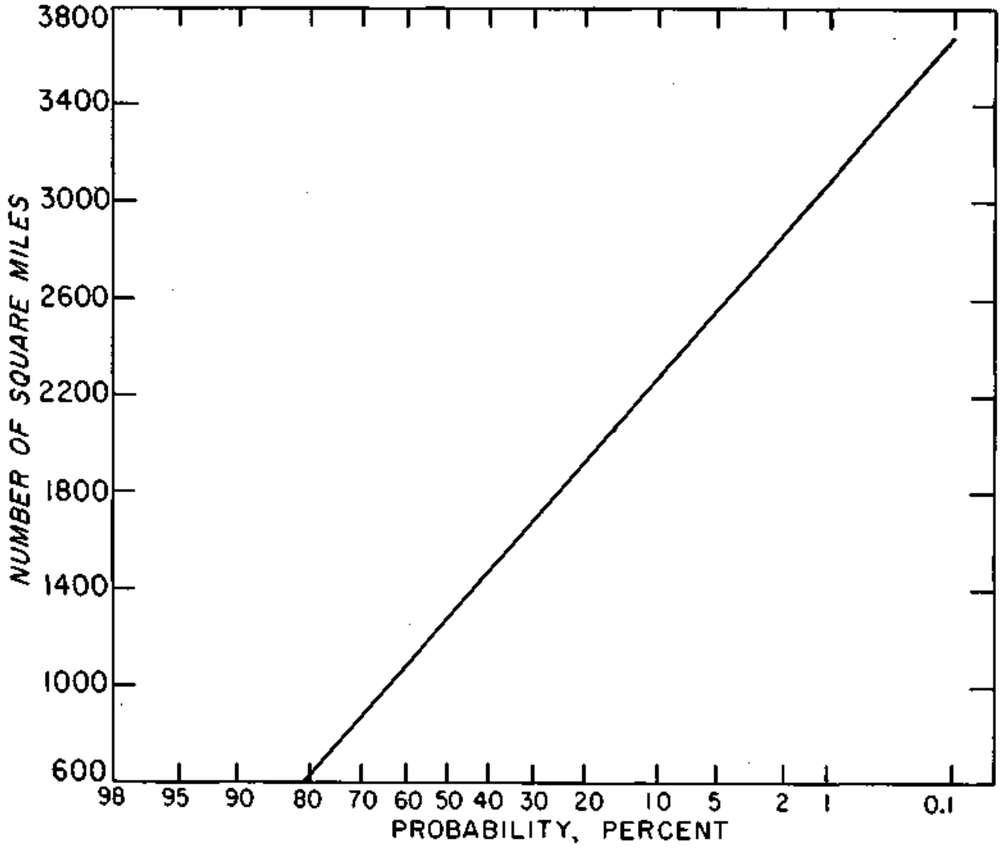


Fig. 7 PROBABILITY OF CROP DAMAGE WITHIN A IOOO-SQUARE-MILE AREA DURING A 5-YEAR PERIOD

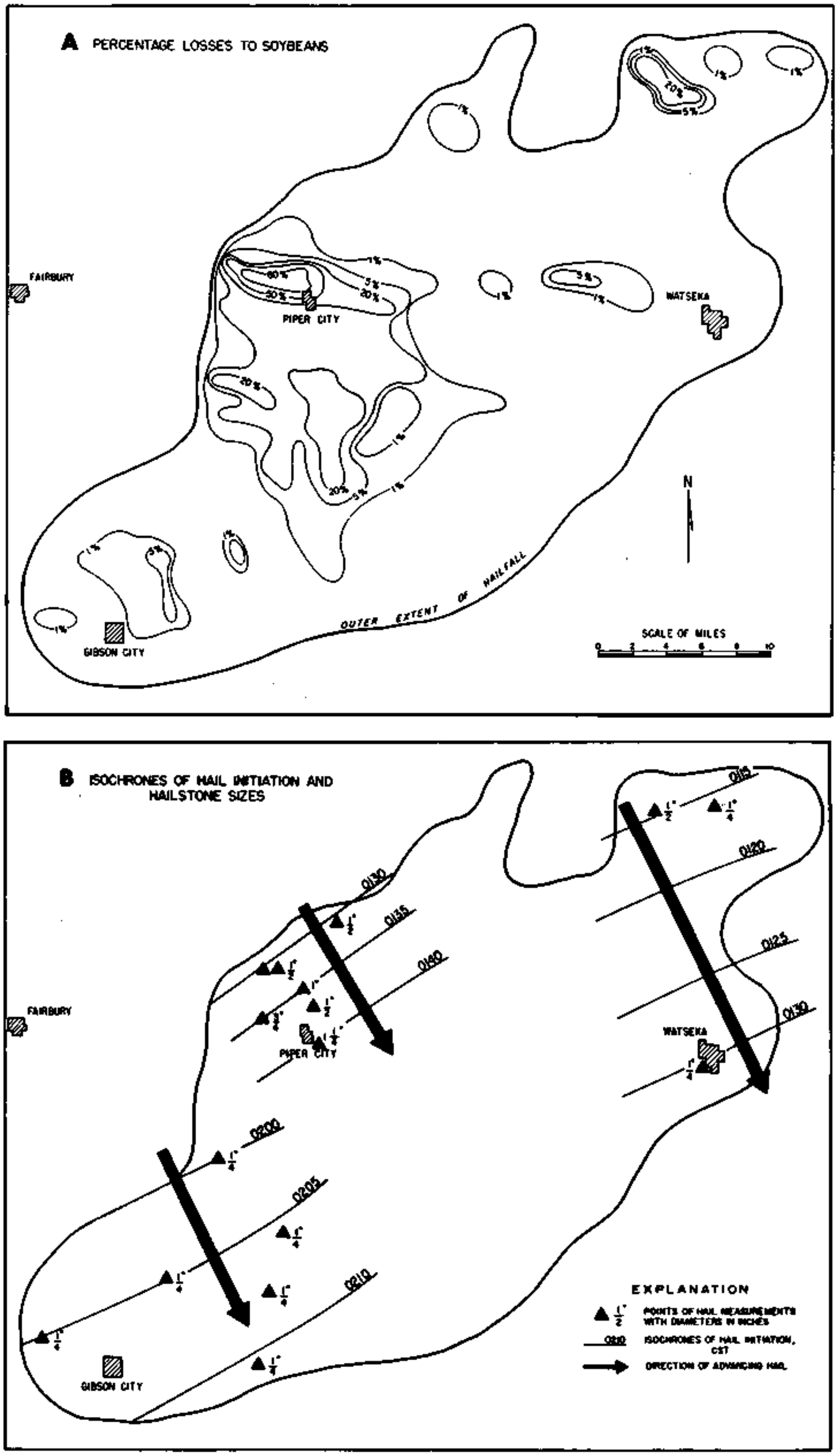


Fig. 8 CROP LOSS PATTERN AND MOVEMENTS OF HAILSTORMS ON JULY 11, 1966

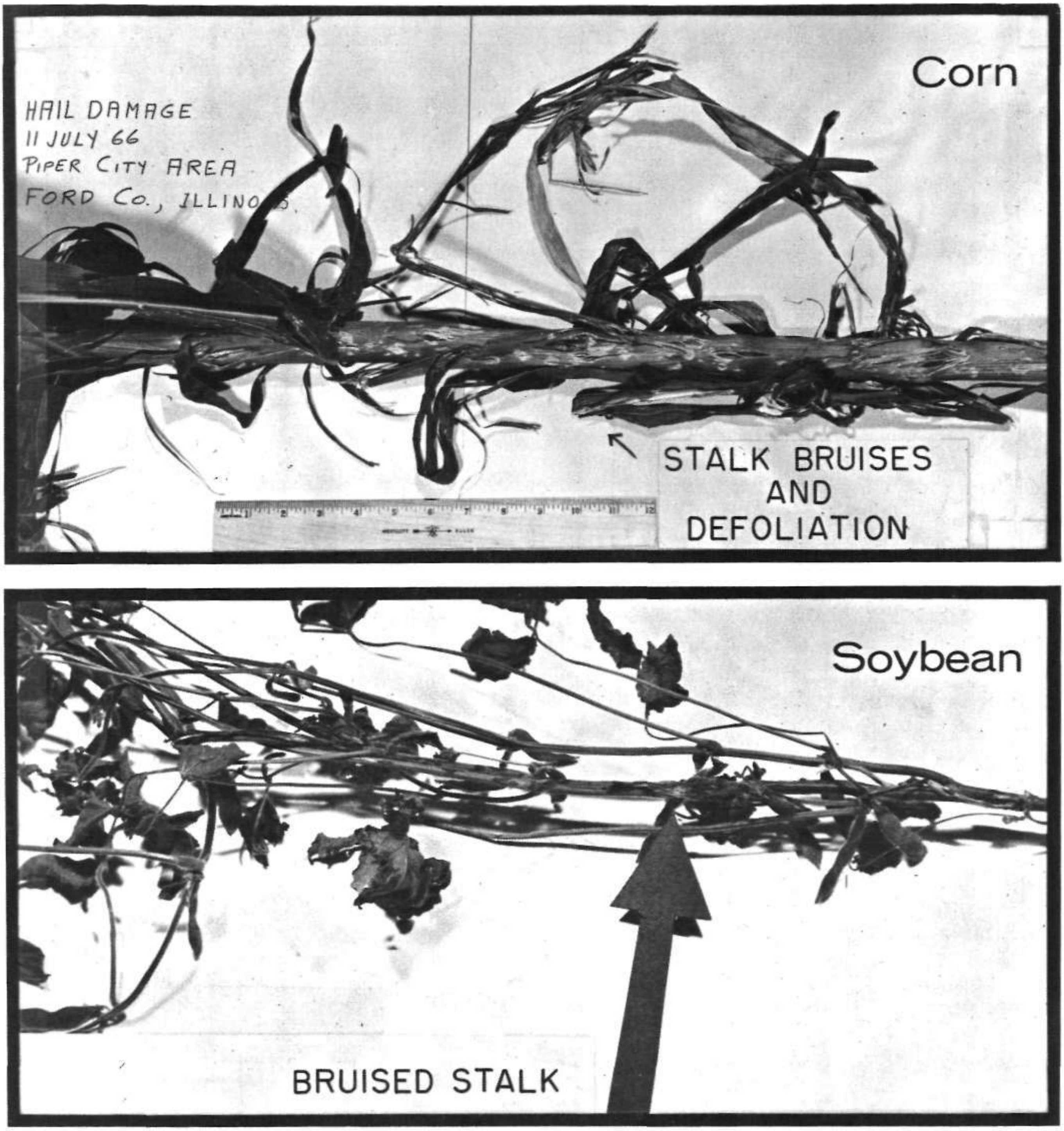


Fig. 9 CORN AND SOYBEAN PLANTS DAMAGED BY HAILSTORMS ON II JULY 1966

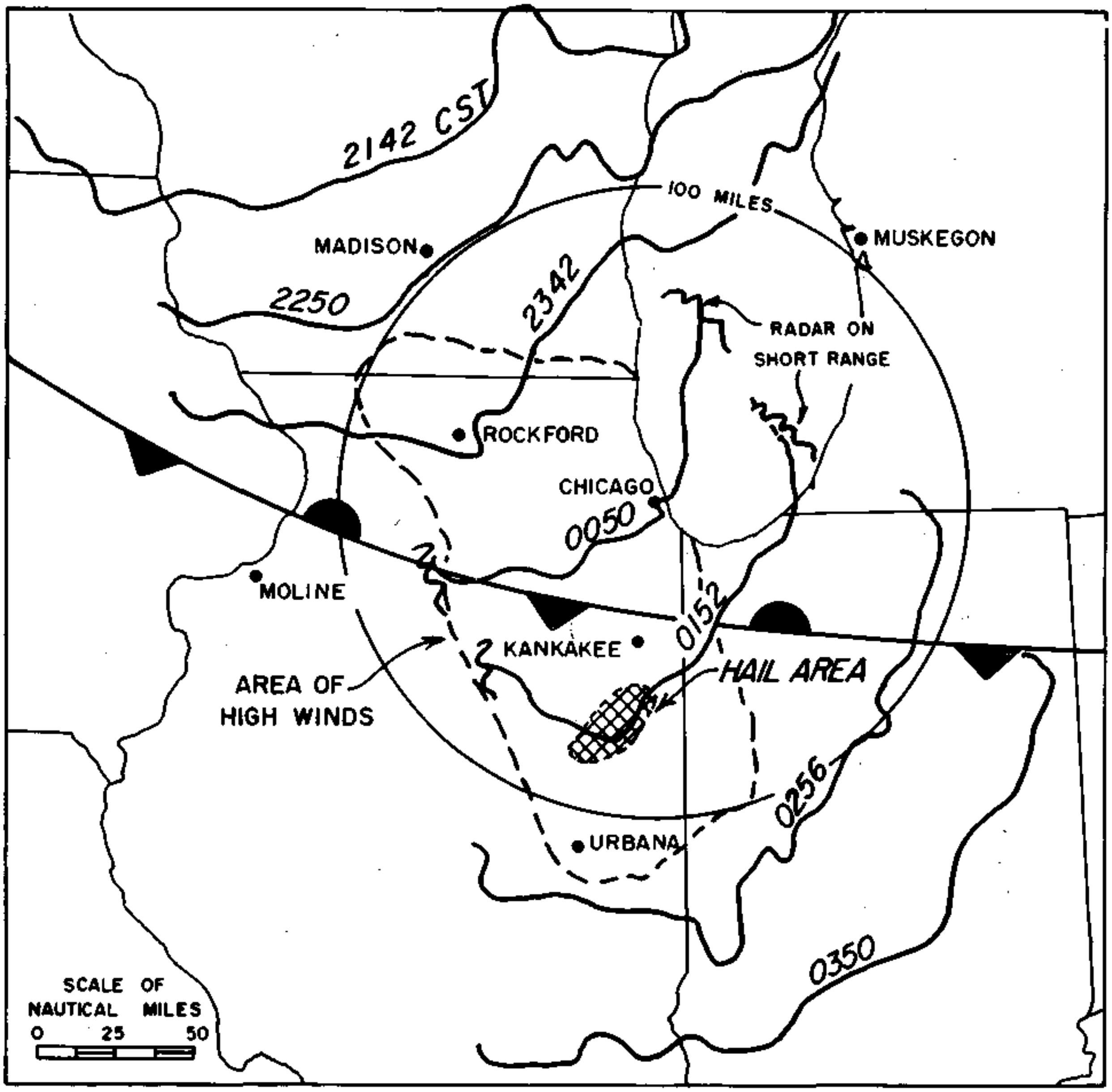


Fig. 10 POSITIONS OF LEADING EDGE OF SQUALL LINE ECHOES ON 10-11 JULY 1966

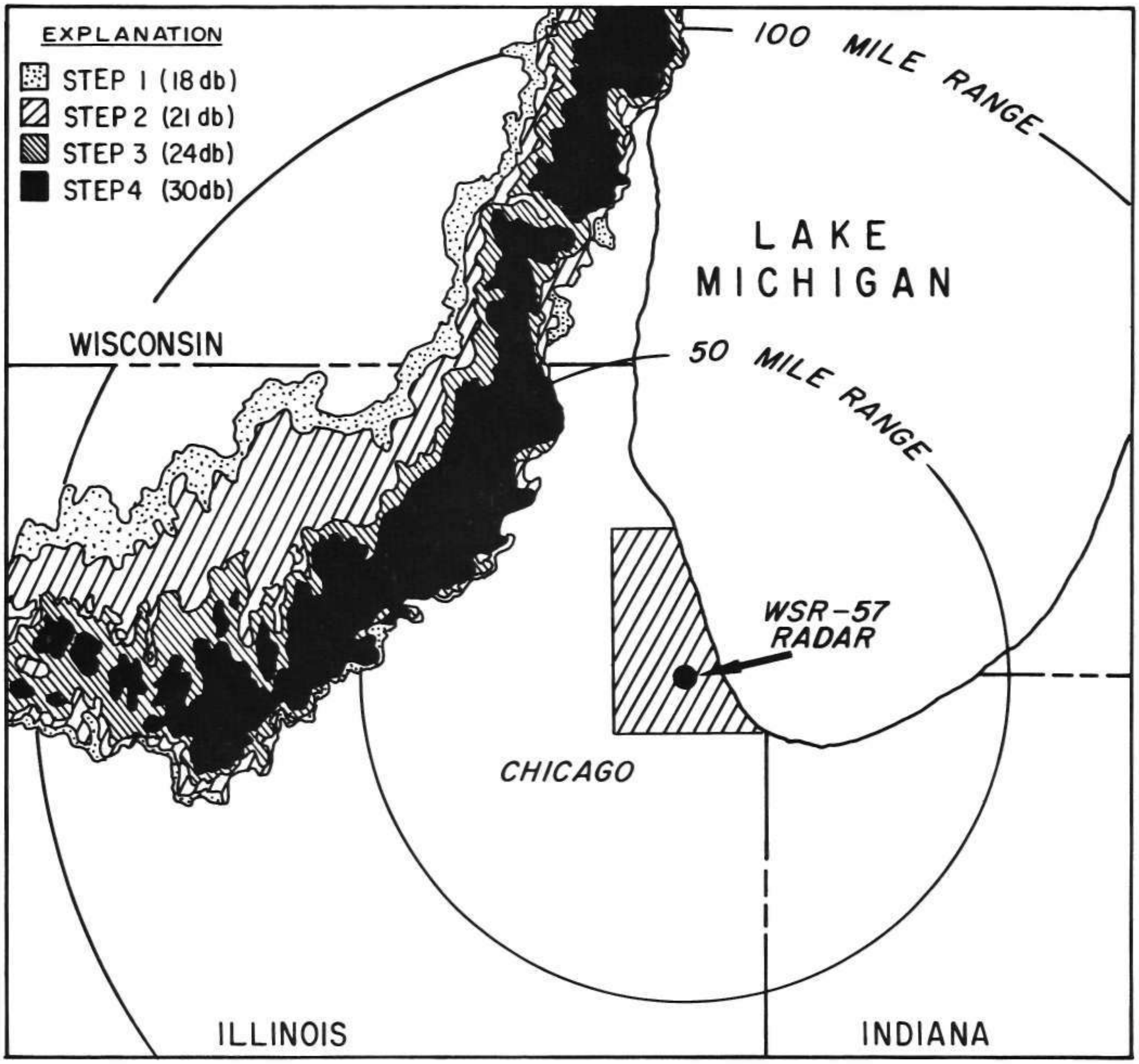
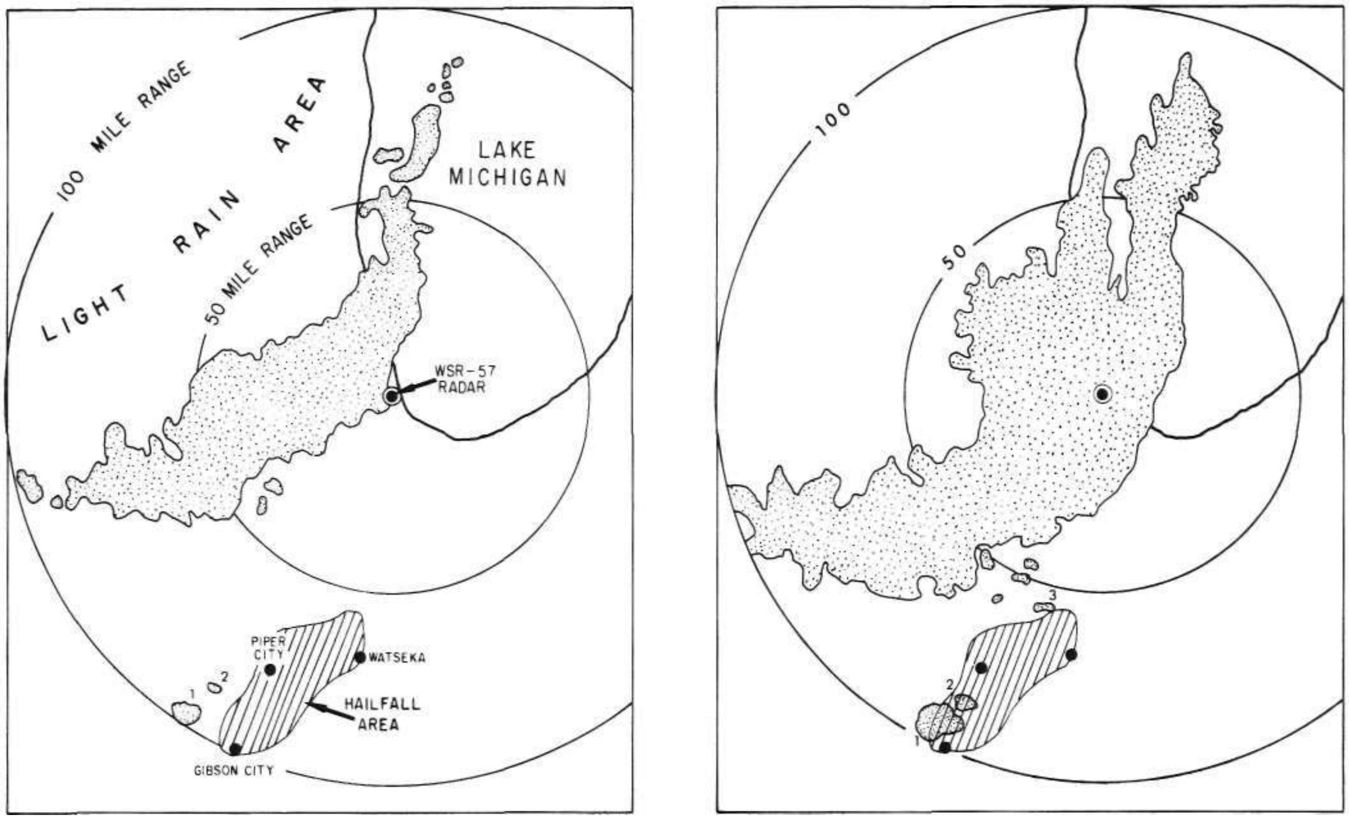
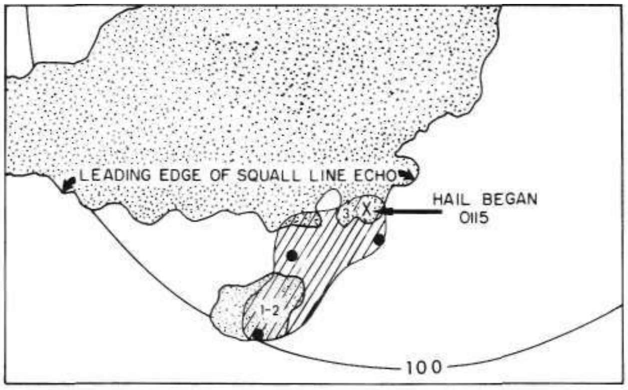


Fig. II RADAR-DEPICTED OUTLINES OF SQUALL LINE PRECIPITATION AT 0013 CST ON II JULY 1966 BASED ON FOUR REDUCED GAIN-STEP LEVELS

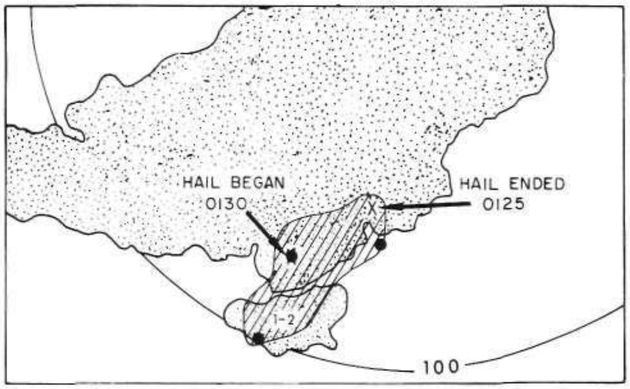


A. 0050 CST, MAXIMUM SENSITIVITY, 10° TILT

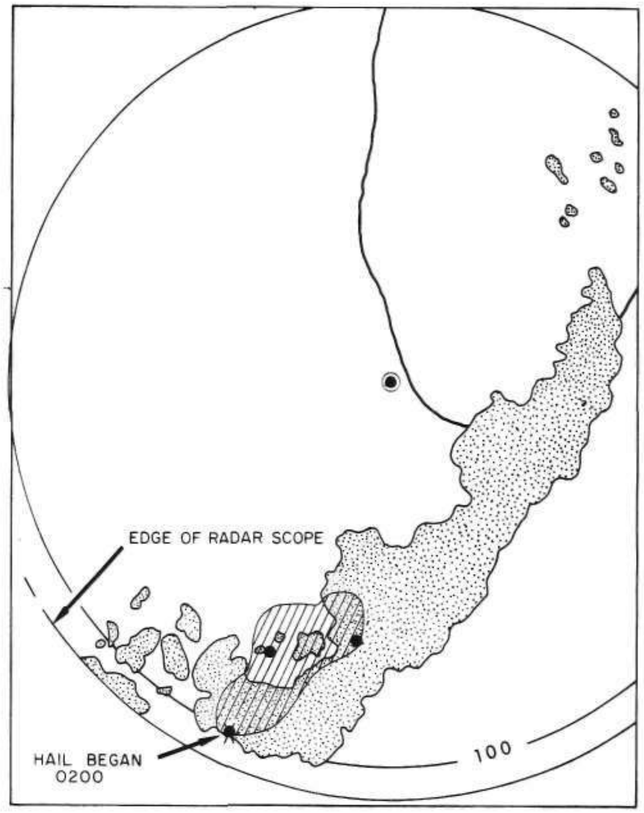
B. 0108 CST, REDUCED GAIN (-21 db) 0° TILT



C. 0117 CST, MAXIMUM SENSITIVITY, 0° TILT

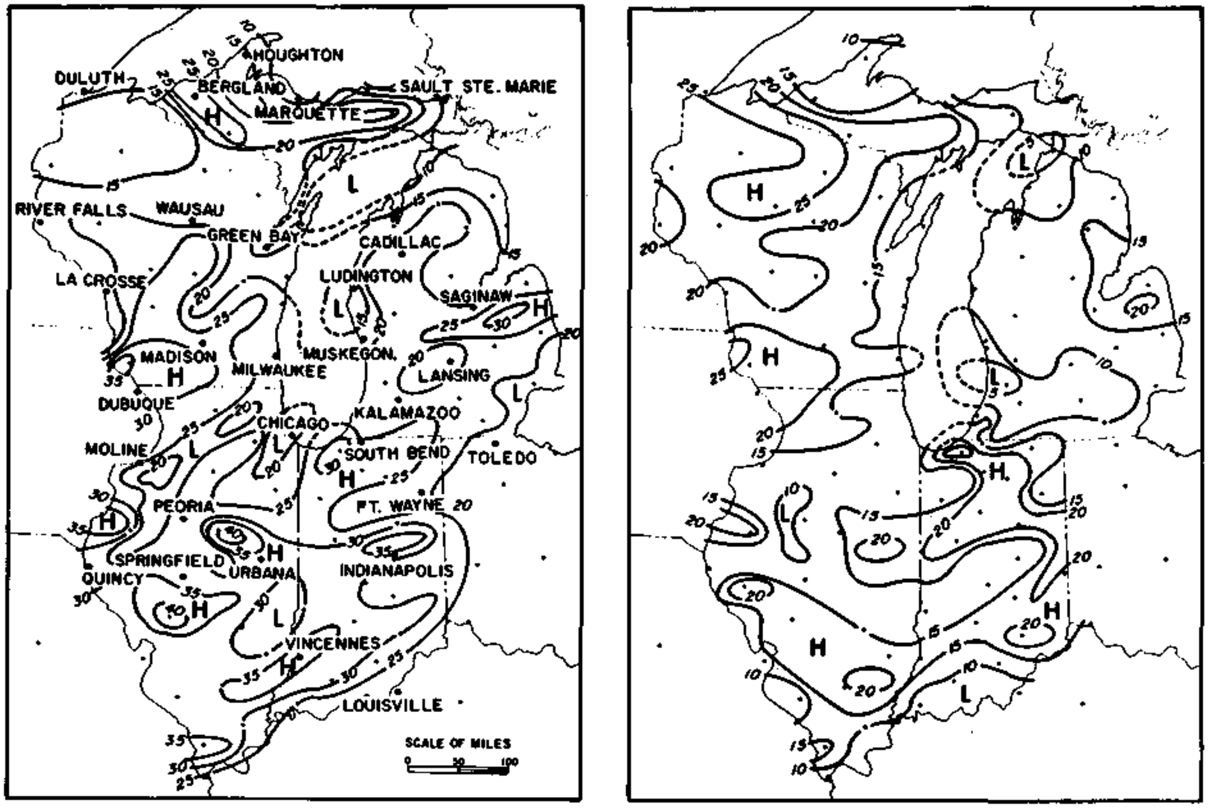


D. 0129 CST, MAXIMUM SENSITIVITY, 0° TILT



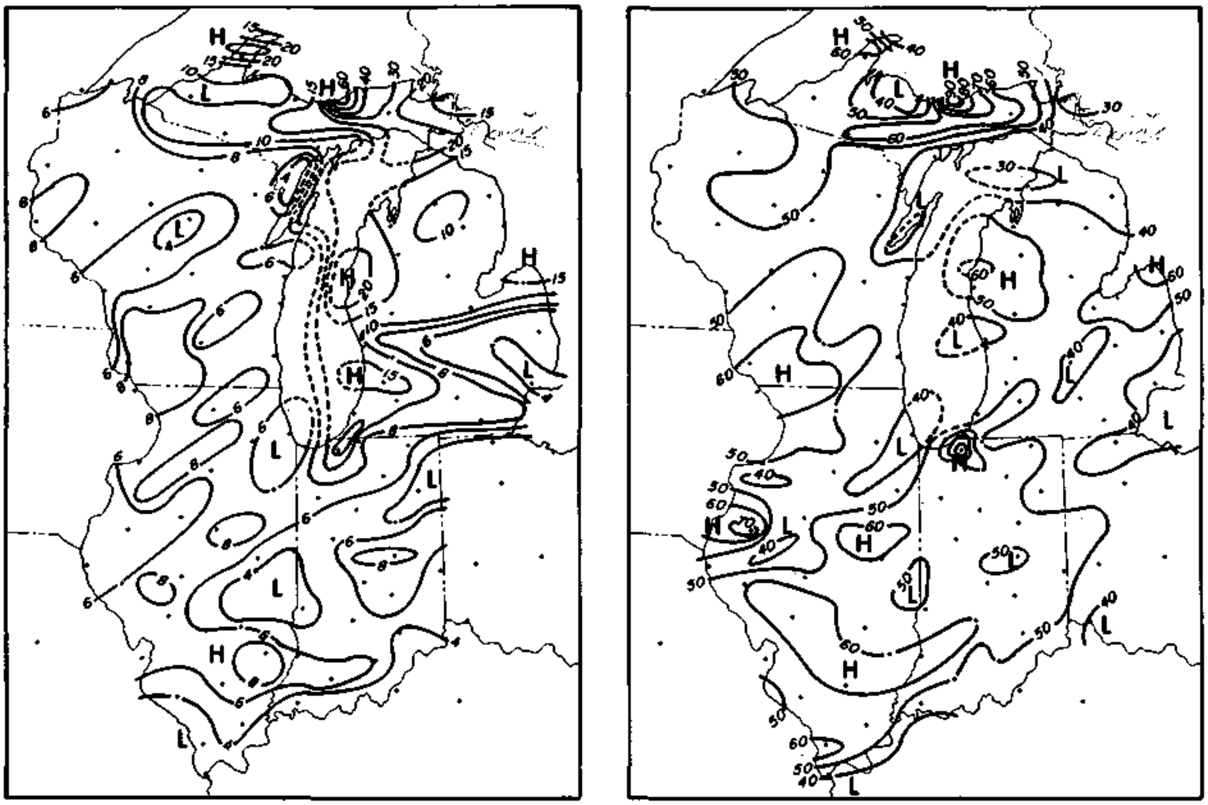
E. 0152 CST, REDUCED GAIN (-27 db),0° TILT

Fig. 12 ASSOCIATION BETWEEN RADAR ECHOES AND HAILFALLS ON II JULY 1966



a. SPRING (MARCH-MAY)

b. SUMMER (JUNE-AUGUST)



C. FALL (SEPTEMBER-NOVEMBER)

d. TOTAL NUMBER OF HAIL DAYS IN AN AVERAGE 20-YEAR PERIOD

Fig. 13 NUMBER OF HAIL DAYS IN AVERAGE 20-YEAR PERIOD