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INSURANCE-RELATED HAIL RESEARCH IN ILLINOIS DURING 1968

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CONTENTS

ABSTRACT

The primary research effort in 1968 concerned continuation of the surface hail studies in a 1600-square-mile area containing 557 points for hail measurement, In 1968 this large area experienced hail on 19 days with crop damage on 9 days. Exceptional areal variability in point hailfalls was noted with many points having no hail and others as many as 10. Night hailfalls had significantly shorter durations than those in the daytime, and the longest point durations of hail occurred in the 1600-1800 CDT period when hail also was most frequent. The detailed rain-hail analysis performed on each of the 265 hailstreaks in 1968 is illustrated by the results for the 20 streaks that occurred on 23 September.

A major storm day (15 May) produced 110 hailstreaks in a 14-hour period. One was a "super" hailstreak covering 788 square miles and lasting 90 minutes. Although occurring early in the crop season, the 110 streaks produced 175 paid losses which was 78% of the total losses for 1968 in the study area.

Percentage crop losses for damaged crops adjacent to hailpads operated in 1967-1968 were used to investigate the relationship between hailfall parameters and actual loss. Hailstone size showed no relationship to loss, but the number of stones larger than 0. 25 inch per square foot showed a definite relationship to loss in wheat and corn crops. Soybean losses did not relate well to stone frequency, but were related to energy imparted by the hailfall.

Study of the increases in hail occurrences 30 miles downwind of the Chicago-Gary area shows a recent increase that can be related to the urban-industrial effects in the atmosphere. These increases also are apparent in the crop-hail losses in northwestern Indiana, thus indicating that urban-produced hail can occur downwind of large urban-industrial complexes and may increase future losses.

The detailed field studies of 16 very damaging hailstorms in Illinois during the 1959-1968 period were used to model the surface characteristics of hailstones. The hail area at any given time during the storm was generally elliptical (being shallowest along the axis of storm motion), and inside the heavy rain core. The hail area tends to move to the right during its life and the larger stones generally fall in the right-rear portion of the hail area.

Hail-day frequencies, as defined by reports from U.S. Weather Bureau stations located in an area of 1000 square miles, were compared with crop-loss day frequencies defined from insurance data in an area of 1500 square miles that partially overlapped the 1000-square-mile area. These two sets of hail occurrences showed a high correlation (+0. 86), indicating that hail-day frequencies for county-sized areas are closely related to hail loss day frequencies for comparable areas.

INTRODUCTION

The prime research activities during 1968 concerned the operation of a dense surface hail network in central Illinois and the varying analyses of the resulting data. Other research activities included a comparison of crop losses with hailfall measurements, consideration of the possibilities that large urban-industrial complexes affect hail frequency, the study and summarization into models of 16 severe hailstorms which had been carefully field surveyed in the past 10 years, and the investigation of the relationship between the frequency of Weather Bureau regional hail days and regional crop-loss days. Many of these research activities were intimately related to hail research activities being performed as part of three National Science Foundation projects (NSF GA-482, NSF GA-1520, and NSF GA-4618), and that being supported by the state of Illinois.

The studies performed for the Crop-Hail Insurance Actuarial Association were a part of a long range program aimed at obtaining a better understanding of various surface hail conditions and how these conditions relate to the spatial and temporal variations in hail damage to crops.

This report describes the various research results and illustrates certain of the pertinent findings. Results of prior research performed as part of the CHIAA program are presented in the form of reprints of two papers published during 1968 in national scientific journals.

SURFACE HAIL RESEARCH

The 1968 program for studying surface hail conditions was concentrated in a 1600-square-mile area in central Illinois. In the spring of 1968 the Illinois State Water Survey enlarged its recording raingage network, which previously contained 49 recording raingages in 400 square miles, to 196 recording raingages in 1600 square miles and named in the Central Illinois Network (Fig. 1). In this study area 100, 1-square-foot hailpads were installed at 100 of the raingage sites, and another 96 pads were installed in a 100-square-mile area (one pad per mi^2) near Farmer City (Fig. 1) during the June-September period. This became the most concentrated hail network ever operated in Illinois and the second most dense network operated anywhere in the world (Changnon, 1968a). Hail data also were secured from 261 cooperative hail observers in the network (Fig. 1). Another 182 observers reported hail in the three counties upwind of the network. Additional useful hail data were furnished by the various hail insurance companies who supplied the adjustors' worksheets for all paid claims in the four counties totally or partially enveloped by the network (Dewitt, McLean, Macon, and Piatt) and two to the west (Logan and Tazewell).

These data sources within the network study area furnished 1166 hail reports in the May-September period of 1968. The 443 cooperative observers supplied 313 hail reports and 218 no-hail reports. Individual paid losses for hail damage totaled 223, hail incidences at the raingage-hailpad sites totaled 527, and the dense hailpad network indicated 103 point incidences of hail.

Hail occurred in the network on 19 days in the May-September period with damaging hail at two or more farms on nine of these days. Various statistics relating to the network hail in 1968 are presented in Table 1. The total number of hailstreaks (areas of continuous hail related in time) was 265, and although larger than the 171 in 1967, the number was not proportionately larger since the network size had quadrupled from 1967 to 1968. The 1968 total area of hail was 2318 square miles, and this figure includes several repeated hailfalls on the same area of the network.

Selected Hailfall Statistics

The total number of hailfalls at each of the 196 raingage sites were used to construct Fig. 2. Some areas in the northwest and southwest had no hailfalls in 1968, whereas others near Farmer City had eight or more. One gage north of Farmer City had 10 hailfalls and a gage eight miles southeast of it had only one in 1968.

Another look at the extreme areal variability of hailfalls is provided by the 4-month period of data from the very dense hailpad network (Fig. 1).

Table 1. Characteristics of Hailstorms in Central Illinois Network in 1968

Date	Square miles with hail	Number of hailstreaks	Maximum hailstone diameter, inches	Crop damages
5/ 8	54.4	3	0. 75	No
5/15	1393.1	110	2.25	Yes
5/18	17.7	17	0.50	No
5/20	0.9	1	0.25	No
5/23	64.2	18	0.50	No
5/28	49.9	6	0.70	No
6/14	220.5	33	0.75	Yes
7/ 1	161.9	20	0. 50	Yes
7/8	27.4	3	0.40	Yes
7/ 9	99.6	11	1.00	Yes
7/15	11.6	4	0.42	Yes
8/ 4	19.0	2	0. 25	No
8/ 8	11.2	5	0. 65	Yes
8/9	1. 5	1	0. 25	No
8/18	10.0	3	0.55	Yes
8/31	2.7	2	0.55	No
9/1	7.5	3	0.52	Yes
9/17	18.1	4	0.46	No
9/23	146.6	19	1.31	No

Since time of hail cannot be derived from the hailpad data, the point frequencies for these 96 pads were expressed as the number of days with hail (Fig. 3). It is likely that several of these hailpads had two or more hailfalls on certain of the days. However, short distance variability on this scale is quite obvious with point frequencies varying from four hail days to none across distances of one mile.

The number of hail reports per hour, as derived from the observer reports containing time of hail and from the 527 raingage-indicated hail times, were used to construct the solid curve shown on Fig. 4. The principal maximum was in the 1700-2100 CDT period with a secondary maximum at 1100. The 1967metwork data had indicated maxima at the 1600-1900 and the 0000-0100 CDT periods (Changnon, 1968d) which reveals that data from one year of hail sampling in networks of this size likely do not describe the true climatological diurnal distribution of hail. The 1000-1100 maximum (Fig. 4) in 1968 was largely the result of many hailfalls from a series of hailstorms on one day, 15 May 1968. Thus, in areas of 400 to 1600 square miles a 1- or 2- year sample may be inadequate to describe the average of certain hail conditions.

Also shown on Fig. 4 are curves for the average point durations of hailfall for each hour. The duration data from the cooperative observers were analyzed separately from that of the recording raingages since both sets of data may contain bias. For instance, examination of the observer data indicated a tendency to "round" the hailfall duration to the nearest five minutes. Since most Illinois hailfalls are less than five minutes, this tends to furnish over-estimates in the average durations. Conversely, the hail-mdications on the recording raingage chart have been noted to be unresponsive to small (<0. 25-inch diameter) hailstones, and durations calculated from these may tend to be slight underestimates of point hailfall duration. Comparison of the hourly average durations shows that the gage duration values were less than the observer values in all but two hours (1400 and 2200 CDT). Both data sets indicate the longest durations for hailfall in the hours ending at 1700 and 1800, but the observer averages at this time are 14-15 minutes and that of the gages is 3 to 5 minutes. The gage average durations show much less temporal variability than do the observer averages, but both sets show that nocturnal hailfalls are considerably shorter than those in the daytime. No gage-indicated hailfalls occurred in the 0200-1000 period, hence the "no data" label for durations on Fig, 4.

The square miles in the network where losses to crops were paid by insurance companies in 1968 are depicted according to date of loss in Fig. 5. No losses occurred in the northern portion of the network, and a few square miles had losses on two days. Most of the losses came from hail on 15 May, and this outstanding storm day is under intensive study with selected results presented in a later section of this report. There is no great correlation between the loss pattern of 1968 (Fig. 5) and the point frequency of hail for 1968 (Fig. 2). Most of the losses occurred in areas with 2 to 4 hailfalls, but areas with 2 to 4 hailfalls elsewhere in the network had no losses. In this instance, there seems to be little relationship between the seasonal number of hailfall occurrences and the frequency of loss at a point.

Hailstreak-Rain Cell Studies

The basic analysis performed on all hail days in 1968 included difficult, time-consuming, and detailed definition of the 265 individual hailstreaks and their related rain cells. The hail time and no-hail data were used to delineate the hailstreak boundaries. The recording raingages furnished the time of hail (and duration) and time and amount of rainfall that occurred with the rain cell that produced the hailstreak. The hailpads furnished data on the number of stones, sizes of stones, and energy imparted by the total hailfall. Data from the cooperative hail observers also gave time of hail, duration, hailstone sizes, number per square foot, and other pertinent information. Crop-hail losses also indicated locations and thus areal extent of hail.

Examples of the products of this laborious research are shown in Figs 6 and 7. Fig 6 A-D depict the hailstreak and rain cell patterns that occurred on 23 September. There were 19 rain cells in the 0940-1320 CDT period, and 18 of these produced hailstreaks with rain cells 5 and 14 both producing two hailstreaks.

The analysis of the rain cells on this data was less complicated than that required on. many hail days. Most of the rain cells were semi-isolated, fast-moving small thunderstorms of the air mass variety and only five produced point amounts of 0. 2 inch or more. Inspection of the hailstreak positions within their associated rain cells reveals that most were "centered" along the core of the cell with a few (in rain cells 3, 6, 14, and 15) in the right side of the cell. Some of the streaks occurred at or near the start of the ram cells (numbers 2, 5, 9, 11, and 17), most during the mature (heaviest rain) stage (numbers 3, 4, 6, 7, 8, 10, 14, 15, 16, 17, and 18), and a few during the dissipation stage (numbers 5, 12, 13, and 19). Analysis of the ISOchrones based on the start of the rainfall shows that the rain cells moved forward at speeds ranging from 48 mph (cell 19) to 10 mph (cell 6), and that some moved forward unevenly with one side advancing faster than the other (cells 3, 4, 16, and 19).

Other temporal data depicted on Fig. 6 are the time differences between the start of rain and the start of hail. At many locations the rain and hail Started together (a 0 difference) and most, differences were two minutes or less. The increasing time differences during the life of the hailstreaks in cells 3 and 17 indicate that the hailfall area was advancing more slowly than the rain shaft. Another interesting aspect noted in the many hailstreaks is seen in rain cells 5, 6, 8, and 15 where the hailstreak orientation does not parallel that of the cell, indicating tangential movement (left to right) across the main axis of the rain cell motion.

More detailed hail information available for the hailstreaks is presented in Fig. 7. For instance, examination of the streak data with cell 3 shows that the hailfall durations (at points with available data) were 5 to 6 minutes and that the maximum stone diameters at the start were 0. 5 inch, diminishing to less than 0. 2 inch in one mile, and then dramatically increasing to 1. 31 inches near the streak's end. Numbers of stones per square foot were relatively high at the beginning and diminished to a low of two stones in mid-streak. Energy values for the streak reveal a tremendous (10) range, from 0. 0001 foot-pounds per square foot to a high of 1. 0568.

The Water Survey rain-hail network, which is unique in its size and instrumental density, allows the development of such new and pertinent hail information heretofore unavailable.

A Major Hail Day-15 May 1968

The single most extensive and severe hail day in the network during 1968 was 15 May when 175 of the 223 total paid losses of 1968 occurred. Losses would have been much greater had the 110 hailstreaks on this date occurred later in the crop season.

A detailed reconstruction of the 110 hailstreaks and rainfall patterns during the 14-hour storm period is shown in Fig. 8. The morning period of nine major thunderstorms produced 47 hailstreaks with some damaging hail. The second phase of the storm period started at 1600 CDT as a giant, steady-state storm passed across the network (Fig. 8B). This storm produced 22 hailstreaks and the one labeled as number 2 produced hail over 788 square miles (see Fig 9) with rainfall amounts over five inches. A series of "feeder" thunderstorms for the giant storm followed it (Fig. 8C), and these produced 27 additional hailstreaks in the 1800-2045 CDT period. Before this phase had passed from the network, the fourth phase, a squall line, entered the network from the southwest. This series of three major thunderstorm cells produced 14 more hailstreaks (Fig 8D). A detailed analysis of the 15 May storm is the subject of a research paper (Changnon and Stout, 1969), and will be the subject of an extensive research report.

More detailed data on the super hailstreak of the 15 May storm are presented in Fig. 9. The size of the next largest hailstreak measured in the two years of network operation was 62 square miles. The super hail=streak produced hail for 40 minutes in one 40-square-mile area, produced stones with diameters of 2. 25 inches, produced as many as 1050 stones per square foot in one area, and resulted in energy values exceeding 15 foot-pounds per foot over large areas.

The total number of distinct hailfalls per point, as measured at the 100 raingage-hailpad sites centered in a 1100-square-mile area around Farmer City, on 15 May is depicted in Fig. 10. Two sites north of Farmer City had five different hailfalls (which contributed significantly to the seasonal maximum in that area shown on Fig. 2), and only one small area in the south had no hail.

Fortunately, the severe, repeated hailstreaks on May 15 occurred well before the corn and soybean crops were in their maximum susceptibility-to-damage periods (Changnon, 1967a) but 175 paid losses occurred. The percentage losses from paid claims appear in Fig. 11 and are symbolized by crop type. Several 100 percent losses to wheat crops occurred near Clinton, and these were largely a result of the super hailstreak which produced a large volume of hailstones and large sized stones in this area (Fig. 9). Although the bean and corn plants had just emerged by 15 May, several losses in the 10 to 25 percent levels are shown on Fig. 11.

COMPARISON OF CROP-LOSS MEASUREMENTS AND HAILPAD MEASUREMENTS

One of the long-range goals of the hail research program has been to ascertain which of several hailfall conditions (hailstone size, number of stones per unit area, energy, wind) was most directly related to crop-hail damage. Prior research using the cooperative observer data (Changnon, 1967a) had indicated that neither stone size nor frequency were closely related to damage, but the data were too qualitative to be totally conclusive. There is a need to establish the hailfall conditions that closely relate to crop loss so that equipment can be designed to objectively measure losses in areas without crops or where crops are uninsured.

The operation of 49 hailpads in 1967 and the 196 during 1968 has finally provided some useful quantitative data for studying this problem. In the 2-year period 29 different wheat losses ranging from 2 to 100 percent occurred within 100 feet of a hailpad. Hailpads were this near to 17 different corn losses, although unfortunately the maximum loss measured close to a hailpad was only 25 percent. Hailpads also were close to 16 different soybean losses that ranged from 2 to 100 percent. The percentage losses have been compared with various data from their nearby hailpads, and the most promising results are shown by the graphs in Fig. 12. The sizes of the stones, considered for several categories, showed no relationship to the amount of loss. The results for total hailfall energy and total number of stones with diameters larger than 0. 25 inch are presented (Fig. 12) for the three crops with the individual values designated by month so that any-seasonal changes in the crop (as a target) could be assessed.

Wheat losses show little relationship to hailfall energy with energies of 10. 0 foot-pounds per square foot being associated with losses ranging from 4 to 100 percent. However, the plot of wheat losses against the number of stones per square foot (a measure of the total volume of ice that fell), shows a fairly good relationship.

Similarly, corn losses show a poor relationship to energy but a marked relationship with the number of stones. However, two stone-number relationships seen to exist as noted by the two lines drawn in the lower graph for corn in Fig. 12. The curve based on May data indicates that it takes more ice (stones) then than in July-August to realize a corn loss. This agrees with the susceptibility-to-damage results obtained for corn in earlier research (Changnon, 1966b).

The results for soybean losses do not agree with those for corn and wheat in that stone frequency (lower graph) does not relate well to loss and that hailfall energy does relate to soybean loss. Three curves have been constructed for the soybean energy-loss data to conform to three apparently different seasonal relationships. The June data (and possibly the one August data point) appear to fit a curve that indicates much less energy is needed in June to produce a 10-percent loss than is needed in May or July. This agrees with previous findings (Changnon, 1966b) which show that soybeans have periods with greater susceptibility to loss in late June and early August than exist in May or July.

These results presented in Fig. 12 are interesting and need to be corroborated and expanded with more data. It is hoped that network operations in 1969 will provide more useful data, particularly on higher corn losses near hailpads.

INCREASED CROP-HAIL LOSSES FROM INADVERTENT WEATHER MODIFICATION

A recent study of the precipitation anomaly discovered at La Porte, Indiana (Changnon, 1968c), has interest and possible importance for hail insurance groups. The historical weather records at La Porte showed sizeable increases since the mid-1930's in the amount of rain (in the warm season), the number of days with moderate rainfall, the number of thunderstorm days, and in the number of hail days. In the 1952-1957 period La Porte experienced more hail days than any other location in the United States.

The extensive study of this localized anomaly led to the conclusion that the increases were largely related to man's inadvertent modification of the atmosphere. The large Chicago-Gary urban area and related industrial complex located 25 to 30 miles upwind of La Porte are producing many effects that could act to induce or enhance precipitation and, as a consequence, lead to increased thunderstorms and hail. These effects include sizeable additions of freezing and condensation nuclei (particles for droplets to grow on), added heat and surface roughness (to produce vertical motions in the atmosphere), and added water vapor.

The number of hail days at La Porte in the 1951-1965 period was 246 percent greater than the average number at the surrounding stations which was considerably larger than the 31 percent increase shown for annual precipitation, 34 percent in rain days, and 38 percent in thunderstorms. This significant increase in hail at La Porte, which began in 1950 (Fig. 13), has at least two items of importance for the hail insurance industry. One is that areas downwind of major cities may expect to experience more hail loss than other nearby rural areas, and secondly, that the urban-induced hail increase may occur rapidly and, be marked by sharp year-to-year fluctuations.

On Fig. 13 the 5-year moving average curves of Chicago, South Bend, and Ogden Dunes, all stations with reliable hail records and relatively close to La Porte, are presented for comparison with that at La Porte. The dramatic increase in hail days at La Porte began in the 5-year period ending in 1952, a peak being reached for the 5 years ending in 1956-1957. After a recession for the 1956-1960 period, a second peak was reached with 52 hail days in the 1961-1965 period.

The hail data at La Porte and surrounding stations available in the 1901-1965 period were used to develop the average pattern of hail days shown in Fig. 14. Although La Porte did not experience exceptionally large numbers of hail days prior to 1950, the very large numbers experienced since then create a relatively high incidence area (82 days) for an average 20-year period within the 1901-1965 base period. Other stations northeast and southeast of La Porte had relatively high hail-day averages substantiating the reality of the La Porte high value. The careful research of the 30 days in the 1951-1965 period when La Porte had hail and none occurred elsewhere in the surrounding 4-state area revealed that hail on these "solo" days 1) occurred largely in the summer, and 2) occurred largely at night between midnight and noon, normally a period of low hail incidence (Changnon, 1968e).

The question of the validity of the La Porte hail-day increase was investigated thoroughly. One means of investigation was to inspect and compare the La Porte data with the hail insurance data for the counties in the La Porte area. Annual loss cost data from La Porte County and three other nearby counties (Fig. 15) that could be suspected of experiencing man-made hail effects were used to calculate regional annual average loss costs. To provide a meaningful measure of hail loss, only years with a 4-county liability of $100, 000 or more were used in this analysis, and only years after

1942 had this much liability. Five-year moving totals of the 4-county average loss costs were used to make a temporal graph (Fig. 15) that would be comparable withthat for Weather Bureau hail days in Fig. 13. The La Porte hail day curve also was replotted on the Fig. 15, and a remarkable association is indicated. This indicates that 1) a good relationship exists between hail days and amount of annual loss, 2) the urban-produced increase in hail days at La Porte are substantiated and thus real, and 3) sizeable man-made increases in hail loss have been experienced.

The average loss frequency (number of years with loss divided by the number of years with liability) of the four counties, as based on 34 years of data in each county (1933-1966), was 43 percent. That for the two counties east of La Porte and Starke Counties was only 30 percent, indicating a greater frequency of hail losses in the area that apparently related to the urban-produced hail.

A recent paper reviewing research into urban-industrial effects on precipitation (Changnon, 1969) suggested that localized high hail incidence areas in and around Kansas City and Omaha might be related to urban effects. Kansas City and environs were shown to average 14 percent more hail days than did rural areas to the west or east, and the Omaha average hail day frequency was eight percent higher than those in the surrounding rural areas.

The Chicago urban-industrial complex has led to significant increases in hail days and hail losses in the area adjacent and out to 40 miles downwind of it. Other evidence points to similar but less significant increases in hail days in the Kansas City and Omaha urban areas. Thus, there appears to be rather good evidence that man has inadvertently produced hail with a frequency and a quantity sufficient to produce increased crop-hail damages. The rapid increase in losses in the La Porte area also suggests this may occur rather suddenly.

SURFACE MODELS OF HAILSTORMS

The accumulation of a large amount of surface data in and around 16 hailstreaks (areas of continuous hail) in Illinois during an 8-year period has allowed a detailed analysis of the instantaneous patterns of hail (hail areas) during all stages of the hailstreak lifetimes. These instantaneous (1-minute) hail area maps portray the areal distribution of different sizes of stones, size and shape of hail area, rotation, relations between hail areas and rainfall, and lightning associated with hail.

All 16 hailstreaks produced damages to crops and/or property, and 1-inch or larger stones (Table 2). Eleven streaks occurred in summer (June-August) and five occurred in the spring season (March-May). Data from additional hailstreaks would make these results more meaningful, but collection of adequate data is very difficult. In-storm measurements are hazardous and difficult and to model hailstorms we are forced to study detailed, although limited surface hail data.

Table 2. Characteristics of 16 Damaging Hailstreaks

			Synoptic		Motion			Max.	Max.	Max.
Date	CST	Duration, minute	weather condition	Rain data	Dir., deg.	Speed, mph	Size, mi^2	length, mi	width, mi.	stone diam., in
6/22/60	1848	50	sta. fnt.	no	288	21	57	17.0	3.9	2.0
6/22/60	1853	30	sta. fnt.	no	302	23	29	11.5	3.0	2.2
6/22/60	1853	16	sta. fnt.	no	285	24	12	6.5	2.2	0.9
6/22/60	1864	43	sta. fnt.	no	304	14	36	10.0	4.1	2.5
6/22/60	1903	33	sta. fnt.	no	265	12	19	6.3	3.0	2.5
6/22/60	1911	25	sta. fnt.	no	248	16	11	6.6	2.1	3.3
3/ 4/61	1730	14	squallline	yes	269	31	21	10.1	2.0	2.0
5/17/62	1347	21	warm fnt.	yes	252	24	18	9.2	3.0	1. 2
5/17/62	1400	10	warm fnt.	yes	233	36	6	6.0	1.5	1.0
8/ 8/63	1600	26	air mass	yes	38	18	17	7.9	2.9	-1.3
3/12/67	1635	28	squallline	yes	258	31	36	13.8	3.1	3.3
3/12/67	1641	26	squallline	yes	254	37	37	15.0	3.0	1.5
7/31/67	1640	37	air mass	yes	300	26	47	16.3	4.6	2.5
8/ 3/67	1200	25	squallline	no	287	28	51	11.1	6.0	1.2
8/ 3/67	1200	16	squallline	no	312	22	13	6.0	2.0	0.8
8/ 3/67	1206	22	squallline	no	296	32	43	10.6	5.5	1.1
Averages for 16		26.4			281	24.7	28.3	10.2	3.2	1.8
Averages for 171 non damaging streaks		8.5			268	43.1	8.1	5.8	1.4	0.3

Average values for certain characteristics of the 16 streaks are listed for comparison with those based on 171 non damaging hailstreaks in Illinois (Changnon, 1968d). The damaging streaks have much larger values of duration, size, length, and width than do the non damaging streaks, but slower speeds and more northwesterly motions. The hail-producing synoptic weather conditions in the five spring storms and 11 summer storms are those found to be prevalent in the production of damaging storms in Illinois (Changnon, 1961).

Data

Meteorological teams canvassed the storm areas to provide much of the data. The streaks occurred in densley settled rural areas (4 to 6 farms per square mile) or in urban areas, and in most instances at least one rather detailed time measurement for different stone sizes was collected for each square mile. Other data such as stone structures, number per square foot, and angle of fall were also collected when available, but were too sparse for a detailed analysis. Additional hail data for seven storms were obtained in dense networks of recording raingages modified to record hail (Changnon, 1966a), and the detailed rainfall data also allowed a meso scale rain-hail analysis for these seven storms. Additional hail data for 10 storms were furnished by cooperative hail observers in existing hail networks.

Analysis

The many point measurements of hail size and time were used to construct 1 - minute maps of hailfall (hail areas) for the entire lifetime of each hailstreak. A schematic example of these maps illustrating the kind of data and the terminology used in this paper is shown in Fig. 16. Quality data on stone types, number per unit area, and angle of fall were generally too sparse to allow a comparable analysis of these features.

The conditions exhibited on the 1-minute maps near the beginning of the streak (first 1-5% of duration), at the time 20% of the duration had elapsed, at 40%, at 60%, at 80%, and at 95-100% of the total duration (near streak termination) were summarized for all 16 streaks. This normalization method for six fixed time periods was the basis for comparing and modeling the hail-area characteristics of streaks with different durations. Although the sample was small, the data for the 11 summer (June-August) storms were grouped and analyzed, as were the data for the five spring (March-May) storms, and seasonal values are presented where they differed.

The computations made for each of the six fixed percent-time intervals included ' 1) the areal shape, including the length of the width and depth (Fig. 16) and the difference in the orientations of the storm motion and width axis, 2) the size of area of small stones (diameter 0. 2-0. 5 inch), moderate stones (0.5-1.0 inch), and large stones (> 1.0 inch), 3) areal positioning of stone size classes in nine zones (Fig. 16), 4) motion in distance and azimuth of the front and back centers of the hail area, and 5) relations with associated rainfall including the placement and distances between the hail area and the rainfall core and cell edges, the maximum rainfall rate in the hail area, and the stage of the ram cell. Analysis of lightning included the type and direction associated with different stone sizes.

Individual Characteristics

Hail Area Shape. Most hail areas had somewhat irregular shapes, being generally elliptical (Fig. 17) with the major axis (width) generally oriented normal to the hail area motion. The width and depth averages (Table 3) reveal that the spring hail areas were not as elliptical as those in summer. In the first three intervals, the spring depth averages exceeded the width, whereas summer area widths were greater than depths at all intervals. Ratios of width to depth for all hailstreaks increase with duration, from 1. 2:1 at 1% to 1. 4:1 at the 80% interval. The widths frequently exceeded the depths at most times (Table 3) except at 40% when only 9 of the 16 areas had widths greater than depths.

The orientation differences between the width axis and the hail area motion reveal (Table 4) that the spring streaks were oriented more nearly at right angles than were those of summer streaks. Rotation of the 16 hail areas, as measured by changes in the width orientation between intervals, was nearly evenly divided between anticyclonic and cyclonic at the time intervals between 20% and 80%. However, 12 hail areas (75%) had anticyclonic rotation during the 1-20% period, and 11 had cyclonic rotation during the 80-100% period.

Hail Area Size. Median size values of the hail area and the three stone-size regions within it were presented rather than averages because a few large values (Table 5) in two streaks made the averages unrealistically large. Regions for each stone size in summer streaks exceed those of spring streaks at most time intervals. The hail areas maximized at the 60% interval. The graphed values for all streaks (Fig. 18) compare the extent of the three size regions. The average times of beginning and ending of the moderate and large stones (Table 6) were derived from the 1-mmute maps. The bigger stones began and ended later in the spring streaks than in summer streaks. The begin-end extremes show that in some streaks the bigger stones occurred at all times (1-100%) in the streak duration.

Distribution of Stone Size Regions in Hail Area. The seasonal values for positioning were alike and only results for all streaks are presented (Fig. 19). Initially (Fig. 19) small stones prevail in all zones with moderate sizes assuming predominance in the 20-40% time intervals. In the 60 and 80% intervals large stones predominate in the right-rear zones (replacing the moderate), and this distribution is not unlike that in a schematic model by Browning (1964). The diagram in Fig. 19 show that the location of greatest frequency for each size has ia motion. Moderate and large stone centers move cyclonically which agrees with the sorting expected in a hailstorm model of Bates (1963).

Table 3. Comparison of Hail Area Widths and Depths at Time Intervals During Hailstreak

Average length, mi, at percent time intervals in streak duration

	1-5%		20%		40%		60%		80%		95-100%	
	Wid	Dep	Wid	Dep	Wid	Dep	Wid	Dep	Wid	Dep	Wid	Dep
Spring	0.9	1.2	1.5	1.9	1.9	2.2	2.5	2.2	2.4	2.2	1.2	1.0
Summer	1.8	1.0	2.9	2.0	3.4	3.0	3.6	2.8	3.3	2.1	1.8	1.2
All	1.5	1.1	2.5	2.0	2.9	2.7	3.3	2.6	3.0	2.2	1.6	1.2

Ratio of Average width to average depth

	1 - 5%	20%	40%	60%	80%	95-100%
Spring	0.7 1	0.8 1	0.9 1	1.11	1.11	1.2 1
Summer	1.8 1	1.4 1	1.11	1.3 1	1.6 1	1.5 1
Total	1.2 1	1.2 1	1.11	1.3 1	1.4 1	1.3 1

Number of times width exceeded depth

	Total	1-5%	20%	40%	60%	80%	95-100%
Spring	5	2	2	3	3	3	3
Summer	11	11	9	6	8	9	10
Total	16	13	11	9	11	12	13

Table 4. Comparison of Orientations of Hail Area Width and Those of Storm Motion During Hailstreak

Average difference, degrees, in orientations (measured clockwise from storm orientation) at percent time intervals in streak duration

	1 - 5%	20%	40%	60%	80%	95 - 100%
Spring	87	90	92	94	102	108
Summer	108	113	109	110	108	103
Total	101	105	103	105	107	105

Number of times each hail width axis rotated between percent time interval

	5 to 20% period	20 to 40% period	40 to 60% period	60 to 80% period	80 to 95% period
Anti-cyclonic	12	9	9	7	5
Cyclonic	4	7	7	9	11

Table 5. Median Sizes of Hail Areas and Stone Regions

	Area, mi^2, at percent time intervals in streak duration					
	1-5%	20%	40%	60%	80%	95-100%
Small-stone region						
Spring streaks	1.0	1.5	1.8	1.2	1.5	0.8
Summer streaks	1.1	2.6	2.2	2.3	1.7	1.1
All streaks	1.1	2.0	1.9	1.8	1.7	1.1
Moderate-stone region						
Spring	0	0.6	1.6	2.0	2.2	0.5
Summer	0	1.0	2.4	2.2	1.7	0.3
All	0	0.8	1.9	2.2	1.9	0.3
Large-stone region						
Spring	0	0	0.4	1.4	1.3	0
Summer	0	0	1.0	1.7	1.4	0
All	0	0	0.5	1.7	1.3	0
Hail area						
Spring	1.0	2.1	3.8	4.6	5.0	1.3
Summer	1.1	3.6	5.6	6.2	4.8	1.4
All	1.1	2.8	4.3	5.7	4.9	1.4
Maximum	7.8	16.3	17.2	14.1	10.6	6.2
Minimum	0.3	0.9	1.6	1.5	1.6	0.4

Table 6. Time of Beginning and Ending of Bigger Hailstones

	Time percent of streak duration			
	Moderate-size stones		Large-size stones	
	Begin	End	Begin	End
Spring average	27%	97%	43%	86%
Summer average	14	93	31	84
Total streaks average	18	95	36	84
Earliest	1	58	9	60
Latest	39	100	57	100

Motion of Hail Area. The direction and amount of motion were measured using the front and back center points (Fig. 16). Table 7 presents average directional values indicating 1) spring areas moved from the WSW, whereas the summer ones moved from the NW, and 2) the in-motion changes during spring streaks are less than those in summer streaks. The frequencies of direction change in Table 7 show that right turns prevailed in early and late stages of streaks, whereas left turns were more prevalent in middle stages..

The seasonal values of distance moved showed little difference and only values for all streaks are presented (Table 8). Average front motion (and speed) is uniform until after the 80% interval, whereas the motion of the back center continually increases during 1-80% period. The differences in the 1-40% period show that the greatest motion, and thus growth, occurs on the front of the hail shaft. However, the increasing motion of the back exceeds that of the front in the 40-100% period, revealing that dissipation of hail occurs in the back of the hail shaft. Front motion exceeded back motion in all 16 streaks in the 1-20% period, in 12 streaks in the 20-40% period, 10 in the 40-60%, 4 in the 60-80%, and in only 1 in the 80-100% period.

Rain-Hail Relations. The locations and distances of the centers of the hail area and the large-stone region were referenced from the rain core center (Fig. 16) for the seven streaks with rain data. The centers of the hail areas were concentrated in the rain core at all time intervals, but with some dispersion into most surrounding zones after the 40% interval. Average distances (Table 9) between centers of hail areas and rain cores increase with time but none are great. The large stone centers generally positioned in the right center, right rear, and back center zones around the core, which agrees with Schleusener's (1962) results for Colorado. The lalrge hail centers are all about one mile out from the center of the rain core, also indicating close proximity between heavy rain and large hail. At most intervals the average distances between the hail area center and the front and back edges of the rain cell (Table 9) were equivalent.

The stage of rain cell life (growth, maturity, or dissipation) at each interval of hailstreak duration was determined using the pattern and amount of rain. Damaging hail fell in each stage of some streaks but most often occurred as a rain cell was going from the growth to the maturity stage. The averages of the maximum rainfall rates measured inside the hail area increased with time (Table 10) peaking at 60%. The hail at all intervals occurred in areas of relatively heavy rainfall.

The average direction of motion of the seven rain cores and their hail areas was determined at each interval. Their differences (Table 10) are consistent indicating that both were moving as a unit.

Table 7. Direction of Motion of Front Center of Hail Areas During Hailstreaks

	Percent time periods of hailstreak duration					
	1-20%	20-40%	40-60%	60-80%	80-100%	Duration Mean
Average direction, degrees						
Spring streaks	253°	250	250	252	261	253
Summer streaks	294	301	299	291	307	298
All streaks	281	285	283	278	292	284
Direction change from prior period						
Spring streaks	---	-3°	± o	+2	+9	
Summer streaks	---	+7	-2	-8	+16	
All streaks	---	+4	-2	-5	+14	
Frequency of direction change from prior period						
Right	---	9	6	6	12	
Left	---	5	8	10	4	
No change	---	2	2	0	0	
Average direction change, degrees						
With right turns	---	18	8	17	12	
With left turns	---	19°	9	18	8	

*KEY: + = right turn
- = left turn

Table 8. Movement of Front and Back Centers of Hail Areas During Hailstreaks

	Distance, miles, during percent time periods of hailstreak duration				
	1-20%	20-40%	40-60%	60-80%	80-100%
Front Center					
Average	1.9	1.9	1.7	2.0	1.3
Maximum	4.0	5.7	2.9	4.1	3.9
Minimum	0.8	0.6	0.8	0.7	0.2
Back Center					
Average	1.2	1.6	1.8	2.4	2.0
Maximum	2.2	4.2	4.7	4.3	3.7
Minimum	0.2	0.2	0.5	0.8	0.5
Average difference, FC - BC	+0.7	+0.3	-0.1	-0.4	-0.7

Table 9. Average Distances between Centers of Hail Areas and Core and Edges of Rain Cell During Hailstreaks

	Distance, mi, at percent time intervals of streak duration					
	1-5%	20%	40%	60%	80%	95-100%
Rain core center to hail area center	0.2	0.3	0.6	1.0	0.8	0.9
Ram core center to large hail region	---	0.8	1.0	1.3	1.4	0.7
Hail area center and rain cell front	2.4	2.8	3.0	3.1	3.1	2.9
Hail area center and rain cell back	2.6	2.9	3.0	3.3	2.9	2.7

Table 10. Characteristics of Rainfall During Hailstreaks

	Percent time interval during hailstreak duration					
	1-5%	20%	40%	60%	80%	95-100%
Maximum rainfall rate in hail area, in/hr						
Average	2.1	2.4	2.8	3.2	2.9	2.3
Highest	4.8	5.0	5.0	5.8	5.5	5.3
Frequency of ram cell stages						
Growth stage	6	5	4	2	2	0
Maturity stage	12		3	5	4	4
Dissipation stage	0	0	0	0		13
Average direction of motion, degrees						
Ram cores	270	276	272	274	281	283
Hail areas	280	284	280	279	275	284
Difference, RL-HA	-10	-8	-8	-5	+6	-1

Table 11. Direction and Type of Lightning

	Percent of total report		
	Small	Moderate	Large
Predominate type			
Cloud-to-cloud	33	30	25
Cloud-to-ground	56	60	70
Both	11	10	5
Primary direction			
North	27	22	4
East	6	10	30
South	31	34	31
West	20	14	7
Overhead	16	20	28

Lightning with Hail. Direction and type of nearby lightning (within 2 miles) at points in small, moderate, and large hail regions were known for 10 storms. The cloud-to-ground reports (Table 11) represented 56% of the small-size reports, 60% of the moderate, and 70% of the large-stone reports. Cloud-to-cloud frequency decreased with increasing stones sizes. The direction to nearby lightning from points where large hail occurred showed much greater percentages to the east and overhead than did those with the small and moderate stones (Table 11). The plot of these directional values (Fig. 20) in their preferred locations shown at the 60% interval (Fig. 19) suggests that lightning activity was most frequently positioned in and to the south of the moderate- and large-stone regions.

Models of Hailstorms

As noted in a recent hail model report (Orville et al. , 1966), similarities in hailstorm features need to be identified to understand hail physics. Although the 16 damaging hailstreaks differed in many ways, certain characteristics were quite similar in all streaks. For instance, all made right turns in their early and late stages, and their motions always closely agreed with those of the rain core. The center of the hail area was always in or very near to the rain core and often positioned midway between the front and back of the rain cell. The hail area was almost always elliptical with the width 1. 3 times greater than the depth oriented normal to the storm motion, and rotating anticyclonically early and cyclomcally later in life. In the streak's early stages, all stones were small and large stones never fell in the left center or front of a hail area. In all streaks, the motion (growth) of the front of the hail area exceeded that of the back side during the first 40% of life. Certain motion, size, and shape features based on all 16 streaks are modeled in Fig. 21 (with other features in Figs. 18 and 19).

This study suggests there is a Midwest spring hailstorm model and a summer one. The hail area of the spring model is smaller at most times, continues to grow over a longer period, is more nearly circular, has a width oriented more normal to motion, and experiences the beginning and end of larger stone sizes later in the streak life than do the summer streaks. These results are also presented in another publication (Changnon, 1968b).

RELATIONS BETWEEN WEATHER BUREAU HAIL DAYS AND INSURANCE HAIL LOSS DAYS

In an earlier study of hail data for the, 1948-1959 period, Changnon (1960b) found a good relationship between the statewide frequency of summer hail days, as defined from U. S. Weather Bureau data, and the annual loss cost in Illinois. The amount of area in north-central Illinois with summer hail-day frequencies exceeding those expected once in 10 years was highly correlated (+0. 96) with the annual loss costs. This relationship has served as the rationale for using the long records of Weather Bureau stations 1) to synthetically develop annual loss cost experience in Illinois for the 47 years prior to 1948 (Roth, 1960), and 2) more importantly, to develop insurance rate regions within the Illinois stations. Since the Weather Bureau hail records include all dates of hail and many of these are non damaging days, there is still a need to establish for areas much smaller than the state the relationship between insurance loss-day frequencies and the Weather Bureau hail-day frequencies if the hail-days data are to be used in "expanding" the insurance experience on a county basis.

Study of the Kansas average hail day patterns and the statewide loss cost and loss frequency patterns (Stout and Changnon,, 1967) showed correlation coefficients of +0. 61 between the average June haiL-day patterns and insurance loss costs. The coefficient for loss frequency (number of years of loss in 1924-1964 divided by number of years with liability) and average hail days was +0. 52.

Recent NSF-sponsored hail research (NSF GA-482) included the determination of regional hail-day frequencies for five small areas in Illinois (see Fig. 4 in CHIAA Research Report 39). These frequencies were calculated on a seasonal and annual basis for the 1934-1963 period using all the Weather Bureau stations in each area. Another part of this research involved using county crop-hail loss data for the 1948-1966 period also to develop small area (see Fig. 5 in CHIAA Research Report 39) statistics including regional hail-loss-day frequencies.

One 1000-square-mile area defined by five Weather Bureau stations was located in east-central Illinois, and it partially overlapped one of the 1500-square-mile areas (composed of Livingston and Ford counties) developed as one of the four insurance data areas. Both areas had hail data for the period 1948-1963 (16 years), and correlations were performed using data from this period. The results (Table 12) are very encouraging for the relationship between annual hail-day frequencies and total loss days. The +0. 86 coefficient indicates that the Weather Bureau annual hail-day frequency in a small area explained 74% of the variation in the number of loss days. However, the annual hail days explained only 42% of the variation in large loss days, and the summer hail-day frequencies are not as well correlated with loss days as are the annual days. This is to be expected since the loss days occur in six months (May-October) rather than solely from the three summer months (June-August). Considering the fact that the two areas are not totally coincident (only 20% overlapping), the correlations are remarkably high and indicate that Weather Bureau hail-day frequencies for small county areas are well related to insurance loss day frequencies for similar sized areas that are geographically juxtaposed. However, the results shown

Table 12. Correlation Coefficients Between Summer and Annual Weather Bureau Hail-Day Frequencies in 1000-mi^2 Area and Annual Loss Day Frequencies in 1500-mi Area for 1948-1963 Period

	Correlation coefficients		
	Summer hail days (Weather Bureau)	Annual hail days (Weather Bureau)	Average number of days
Total loss days	+0.63	+0.86	15
Total loss days with lost> $4000*	+0.46	+0.65	2
Average number of days	4-	12	--

*Based on 1966 dollar value

in Figs. 2 and 5 of this report, and similar network data for 1967, do suggest that there is a poor relationship in any given year between the number of hail days at a point and the number of loss days at that point.

ACKNOWLEDGMENTS

This research has been performed under the general direction of Glenn E. Stout, Head of the Atmospheric Sciences Section of the Illinois State Water Survey. Survey staff members who materially assisted in the 1968 field program and the analysis of the resulting raingage and hailpad data included Oscar Anderson, Eberhard Brieschke, Dan Watson, Edna Anderson, and Pamela Collins. Help in performing required computer analysis was given by Paul T. Schickedanz, and John Brother performed much of the drafting required for this report. The advice and assistance of E. Ray Fosse and other members of the CHIAA staff in supplying large volumes of useful hail insurance data are appreciated. Thanks are also due to the insurance companies who willingly furnished the adjustor worksheets.

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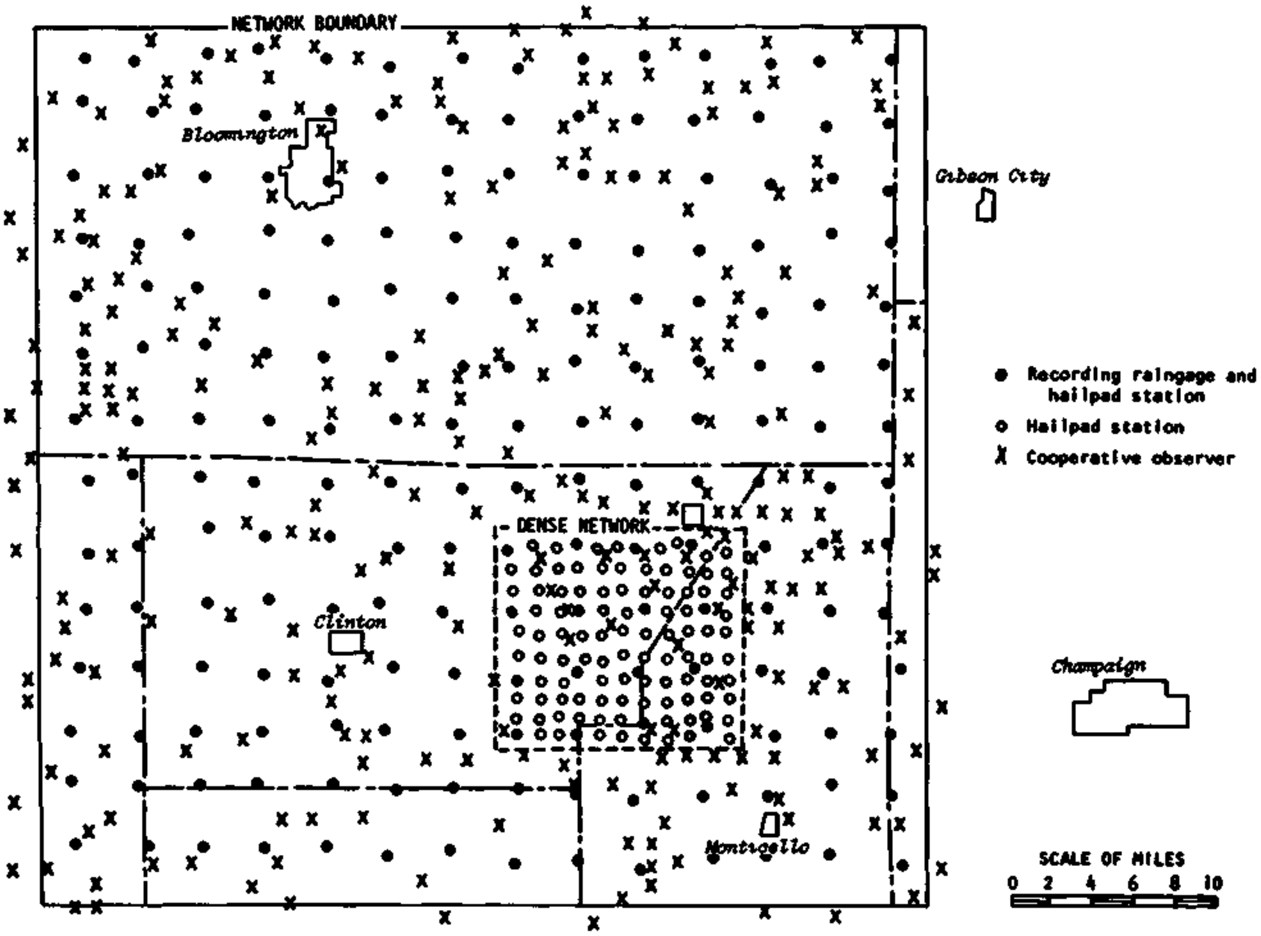


FIG. 1 ILLINOIS RAIN - HAIL NEIWORK IN 1968
(75% OF CROPS INSURED)

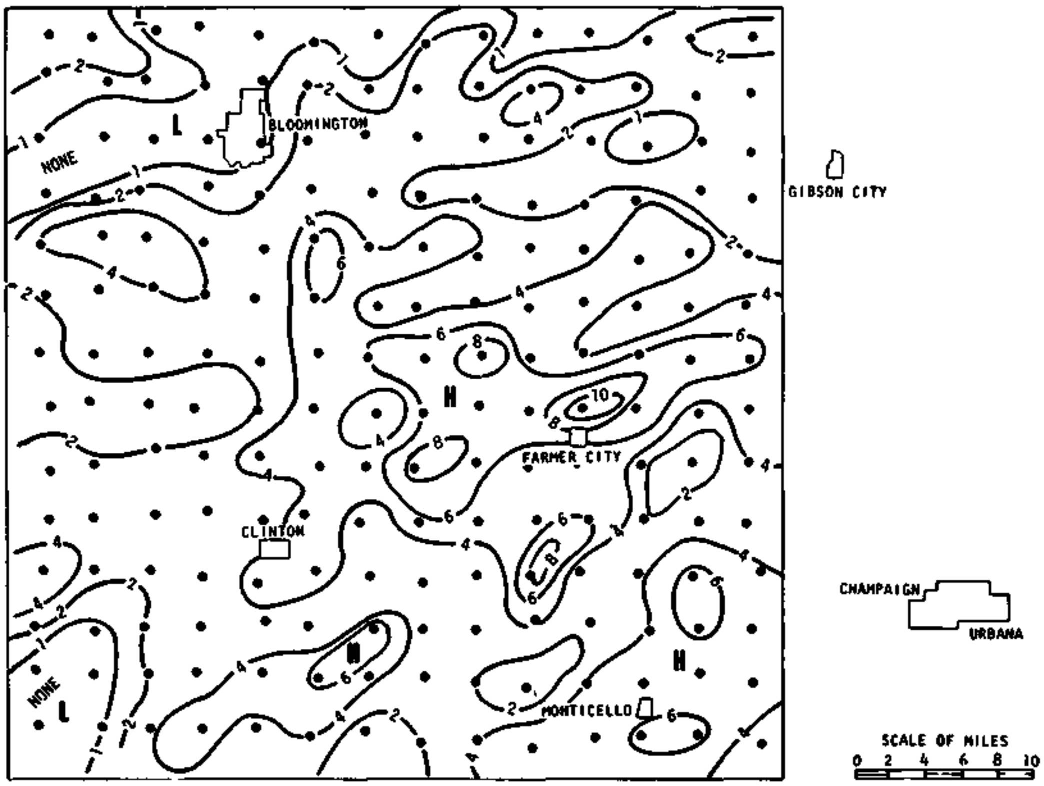


FIG. 2 TOTAL HAILFALL OCCURRENCES IN MAY - SEPTEMBER 1968

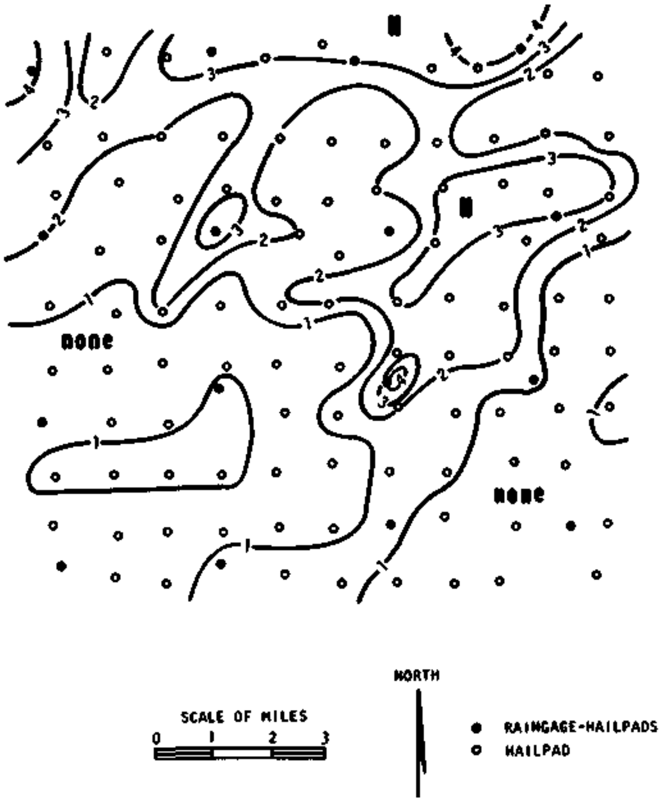


FIG. 3 NUMBER OF HAIL DAYS, JUNE - SEPTEMBER, 1968, IN CENTRAL ILLINOIS DENSE HAILPAD NETWORK

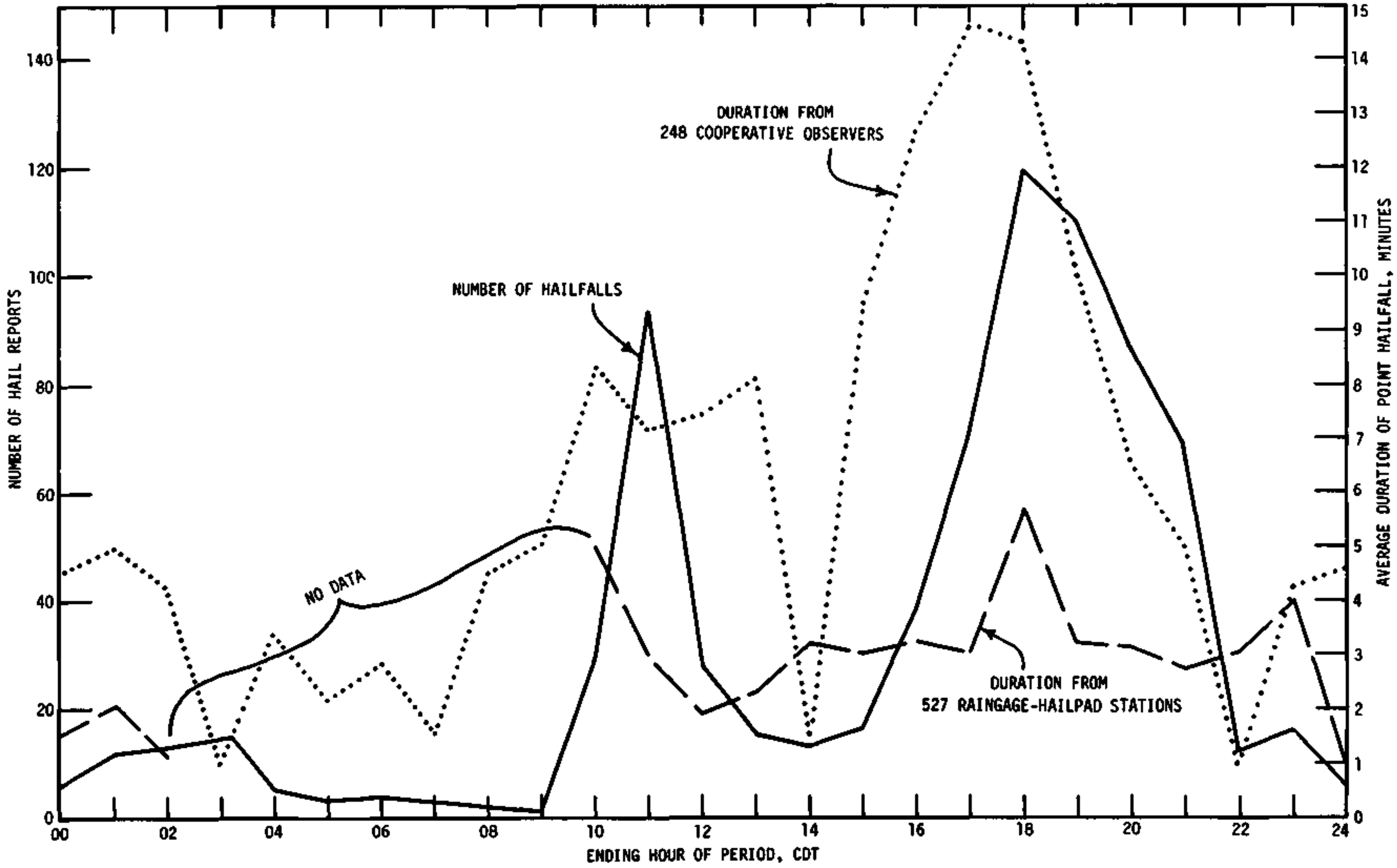


FIG. 4 DIURNAL DISTRIBUTION OF 1968 HAIL REPORTS AND AVERAGE POINT DURATIONS PER HOUR DETERMINED FROM OBSERVER REPORTS AND FROM RAINGAGES MODIFIED TO RECORD HAIL

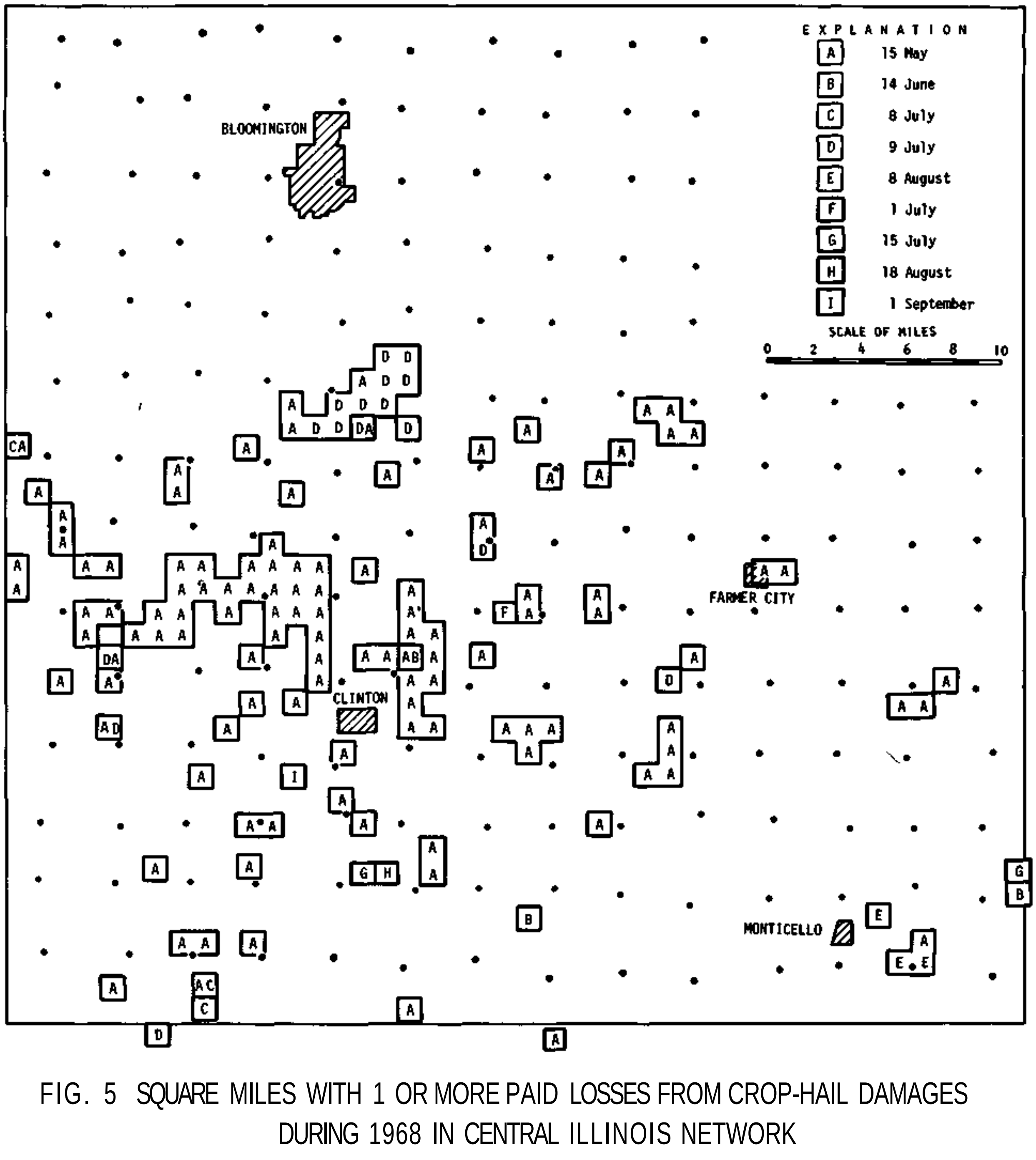
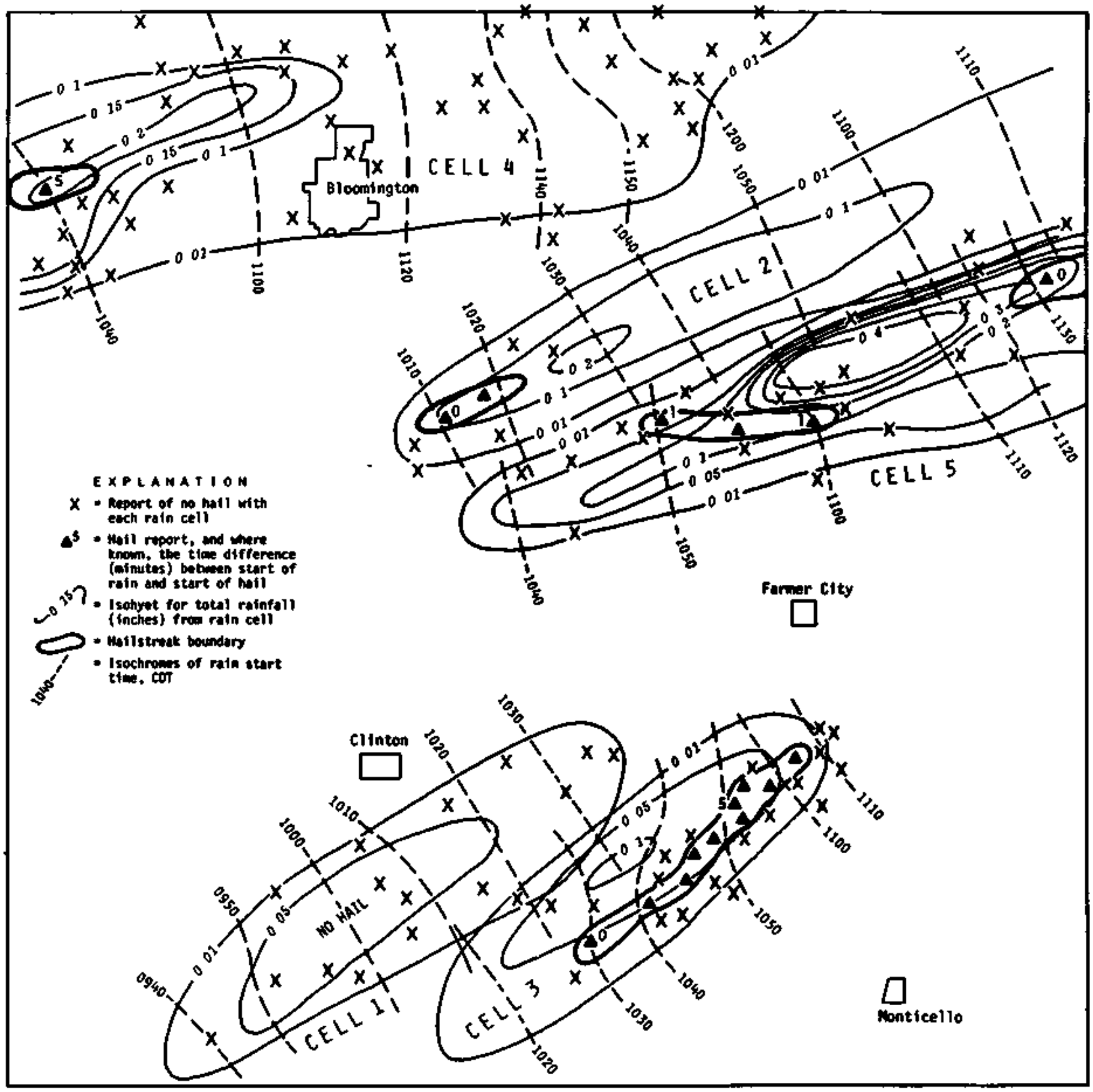
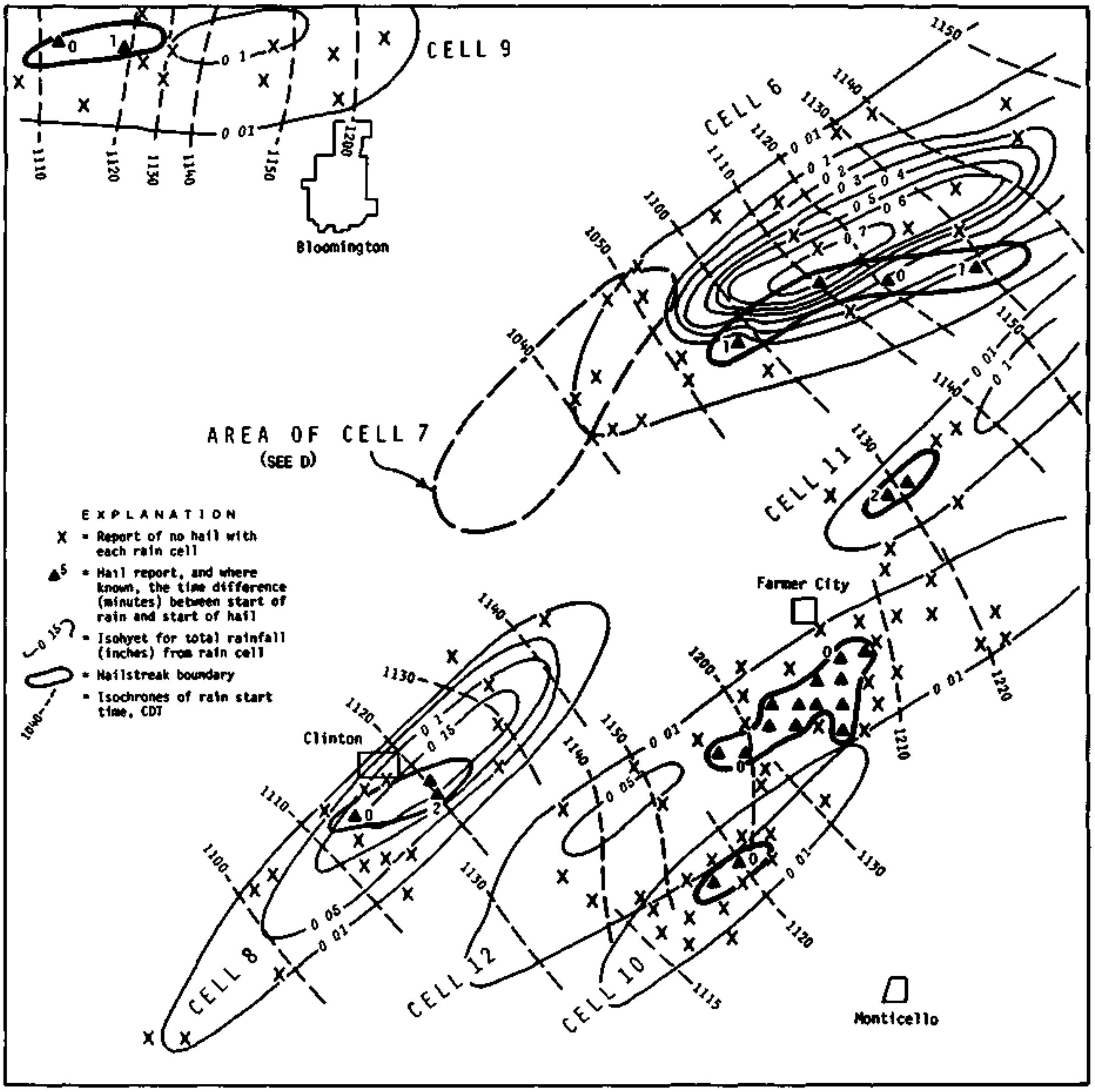


FIG. 5 SQUARE MILES WITH 1 OR MORE PAID LOSSES FROM CROP-HAIL DAMAGES DURING 1968 IN CENTRAL ILLINOIS NETWORK



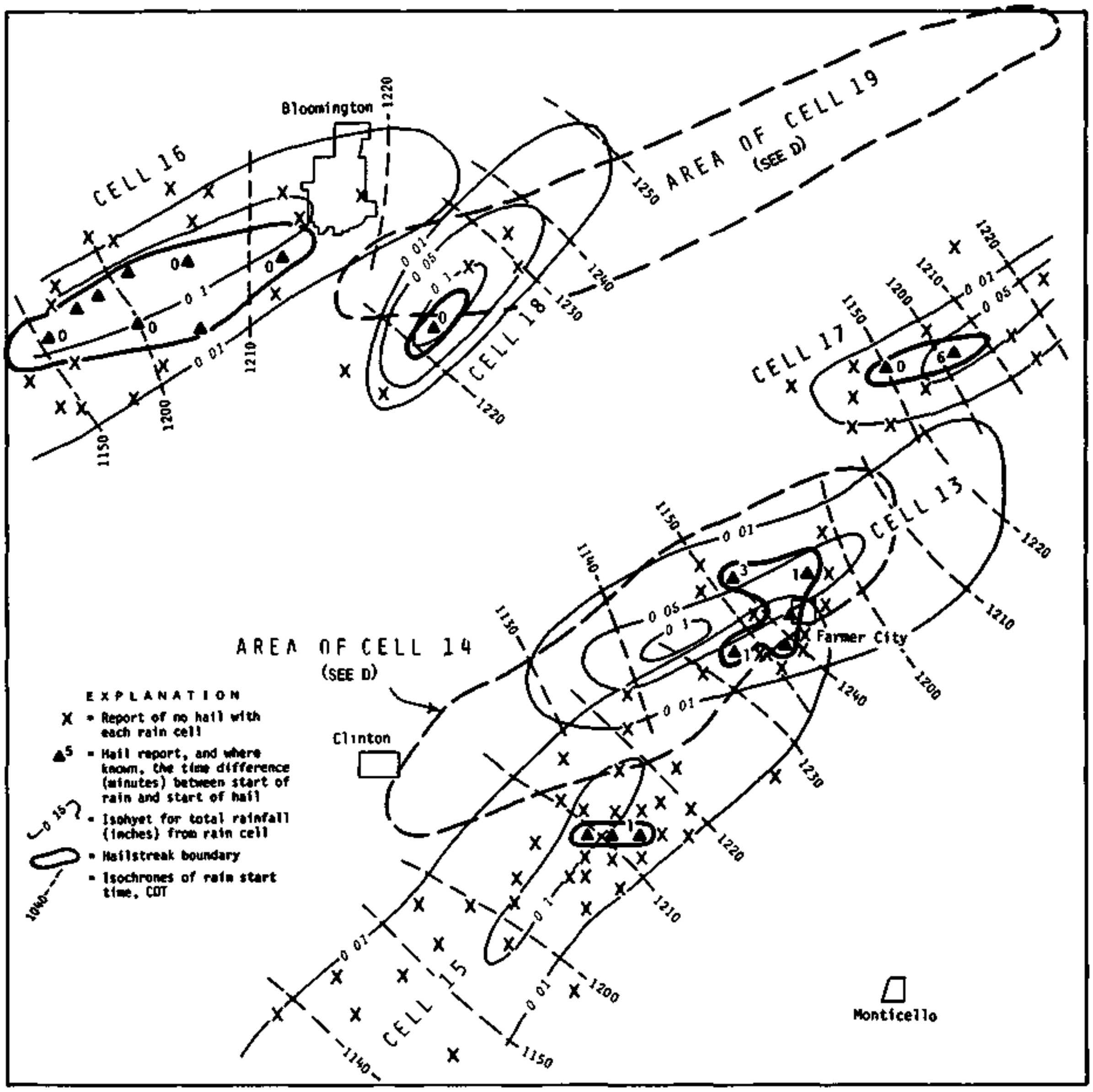
A. 0940 - 1040 CDT

FIG. 6 RAIN CELL - HAILSTREAK PATTERNS IN THE CENTRAL ILLINOIS NETWORK ON 23 SEPTEMBER 1968



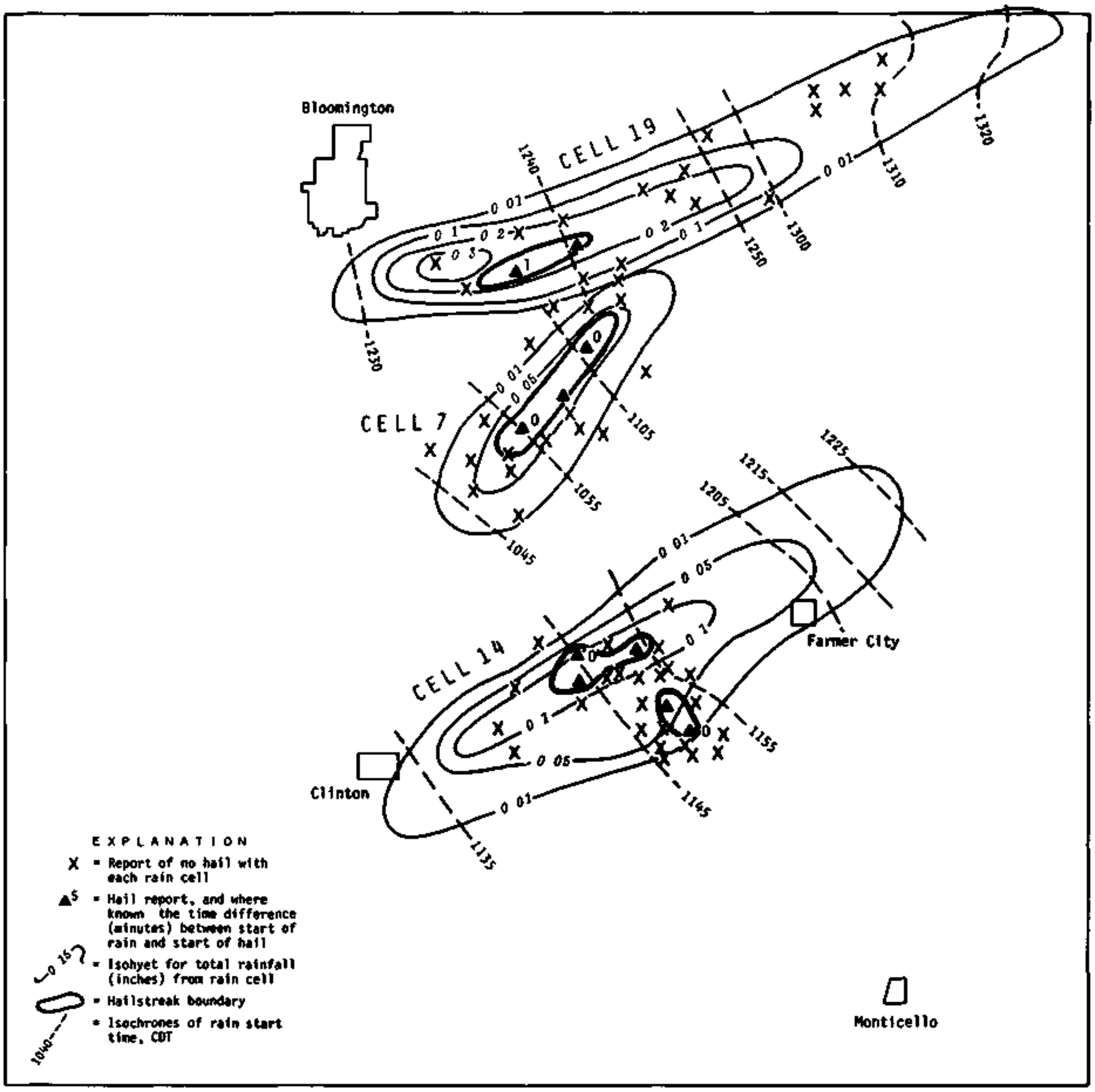
B. 1040 - 1130

FIG. 6 RAIN CELL - HAILSTREAK PATTERNS IN THE CENTRAL ILLINOIS NETWORK ON 23 SEPTEMBER 1968



c. 1130 - 1220

FIG. 6 RAIN CELL - HAILSTREAK PATTERNS IN THE CENTRAL ILLINOIS METWORK ON 23 SEPTEMBER 1968



D. OVERLAPPING CELLS

FIG. 6 RAIN CELL - HAILSTPEAK PATTERNS IN THE CENTRAL ILLINOIS NETWORK ON 23 SEPTEMBER 1968

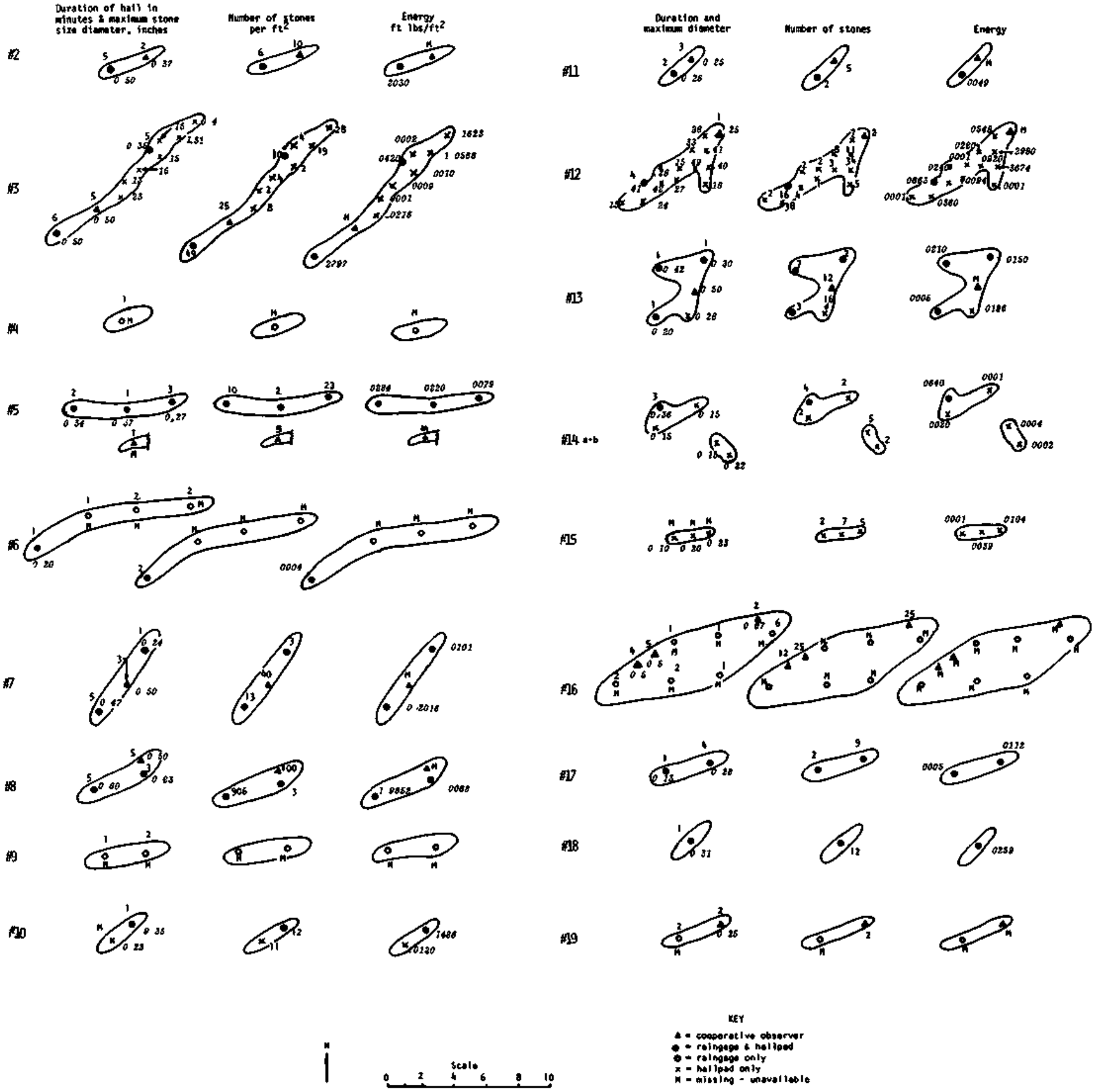
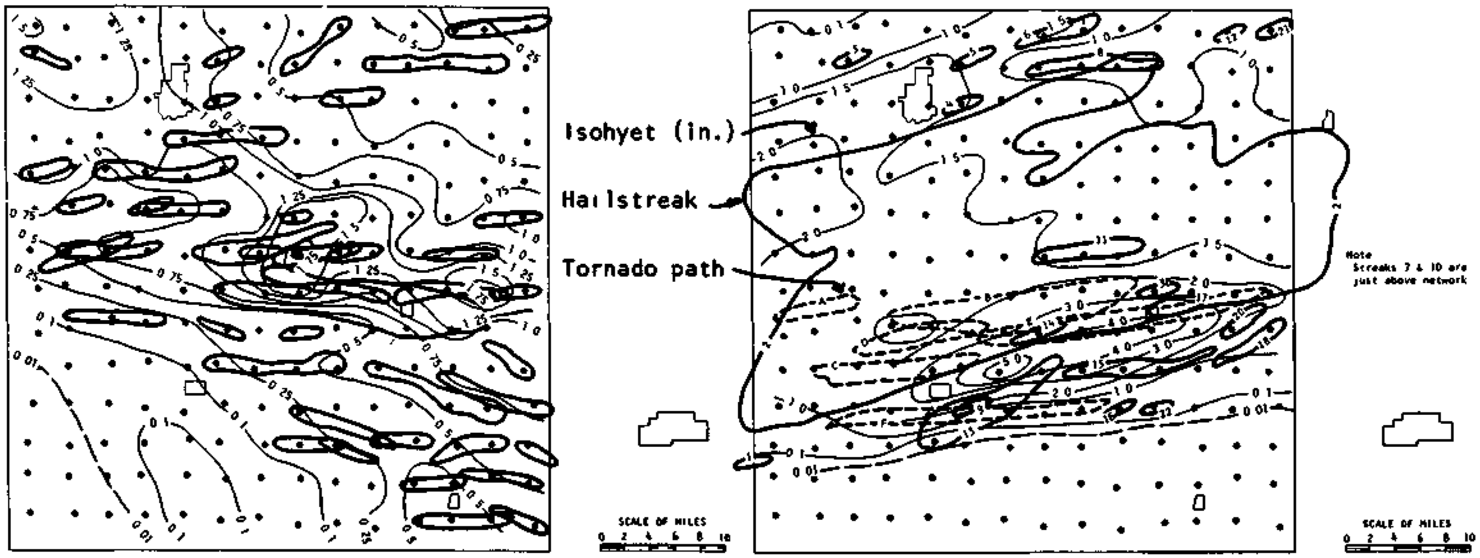
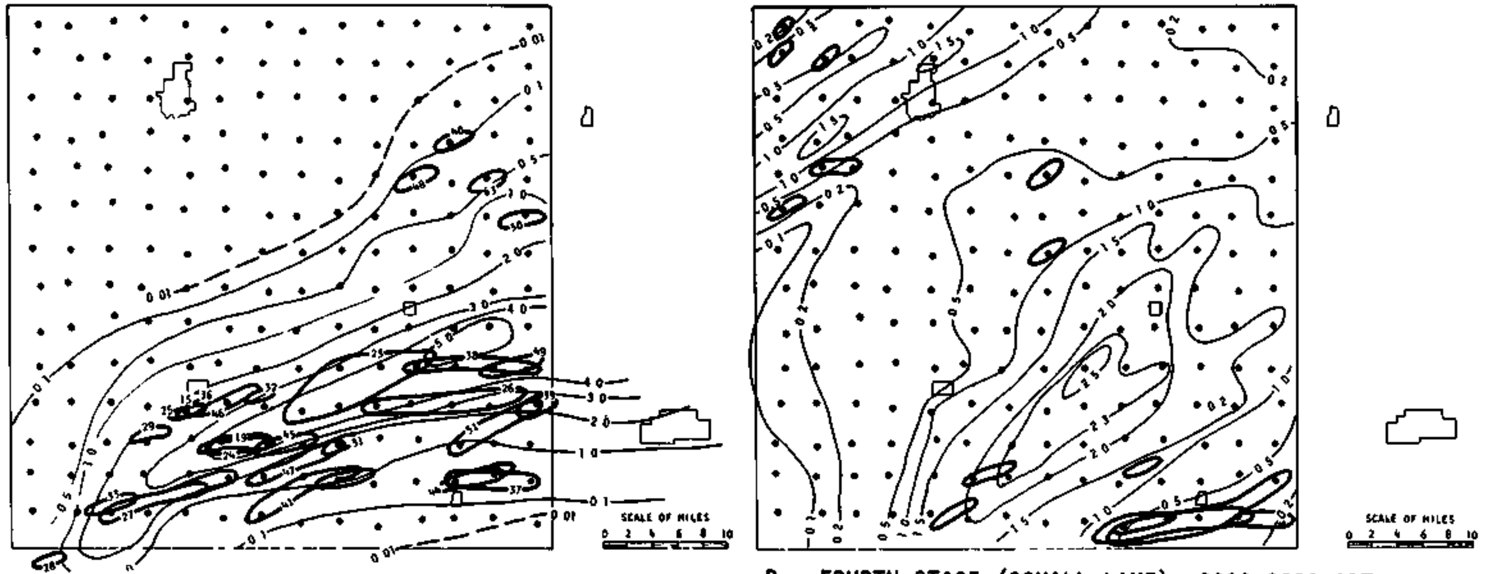


FIG. 7 PATTERNS OF HAIL CHARACTERISTICS FOR HAILSTREAKS ON 23 SEPTEMBER 1968



A FIRST STAGE, 0900-1145 CDT

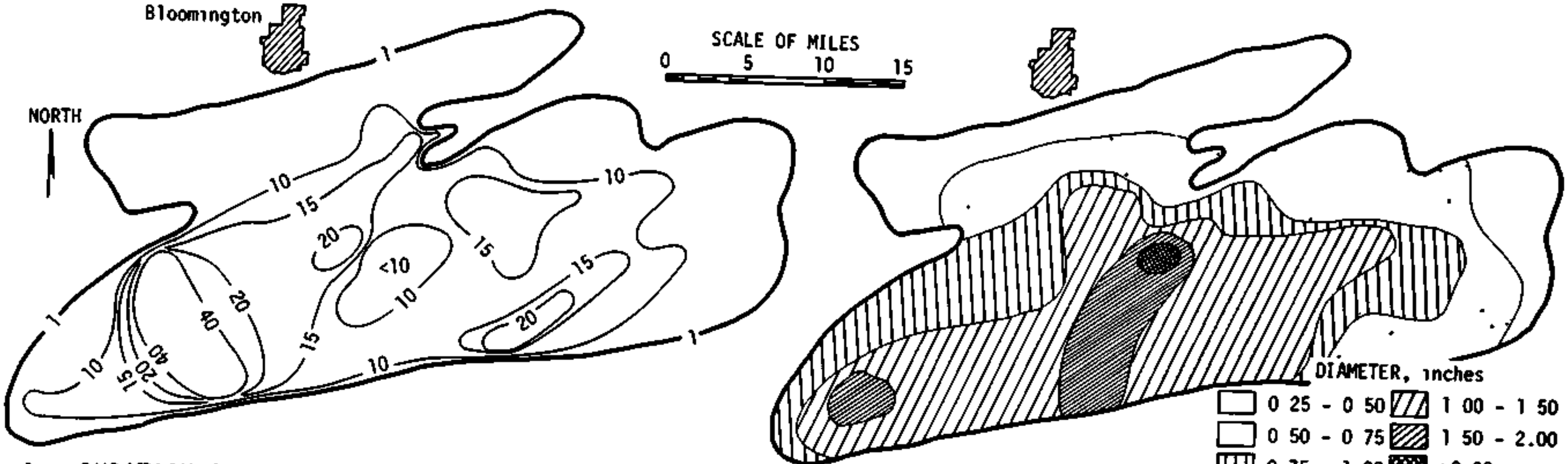
B SECOND STAGE (STEADY-STATE STORM), 1600-1845 CDT



C. THIRD STAGE (FEEDER SYSTEM), 1800-2045 CDT

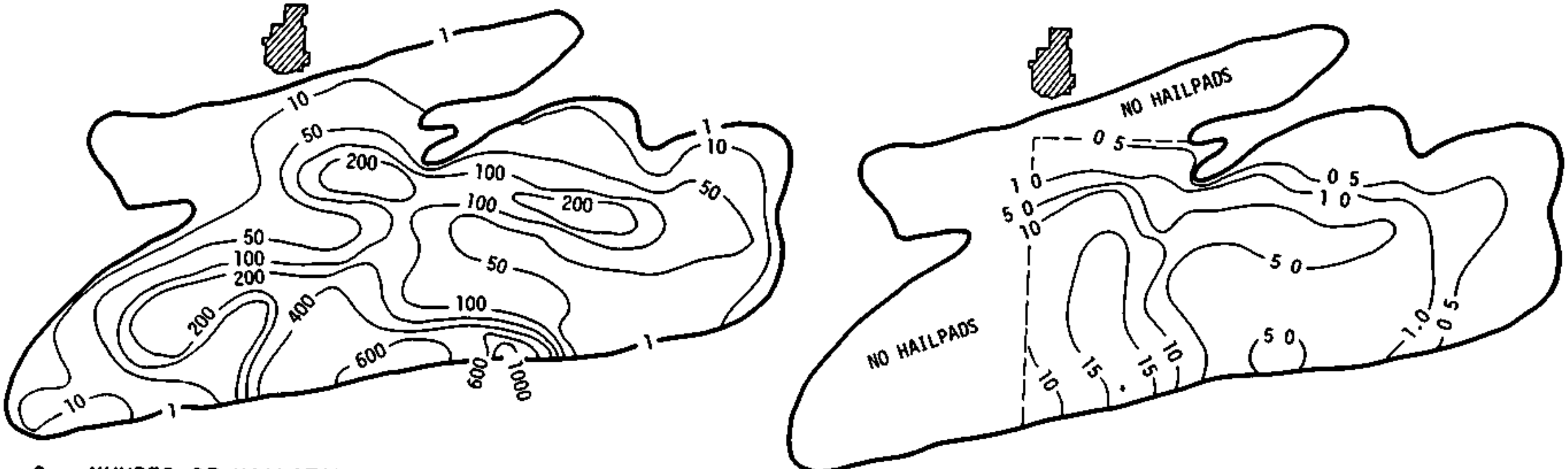
D. FOURTH STAGE (SQUALL LINE), 2000-2200 CDT

FIG. 8 RAIN AND HAILSTREAK PATTERNS OF FOUR STORM STAGES IN NETWORK ON 15 MAY 1968



A. DURATION OF HAILFALL, MINUTES

B. DIAMETER OF LARGEST STONES, INCHES



C. NUMBER OF HAILSTONES PER SQUARE FOOT

D. ENERGY IN POUNDS PER SQUARE FOOT

FIG. 9 VARIOUS FEATURES OF SUPER HAILSTREAK BETWEEN 1627 AND 1756 CDT ON 15 MAY 1968

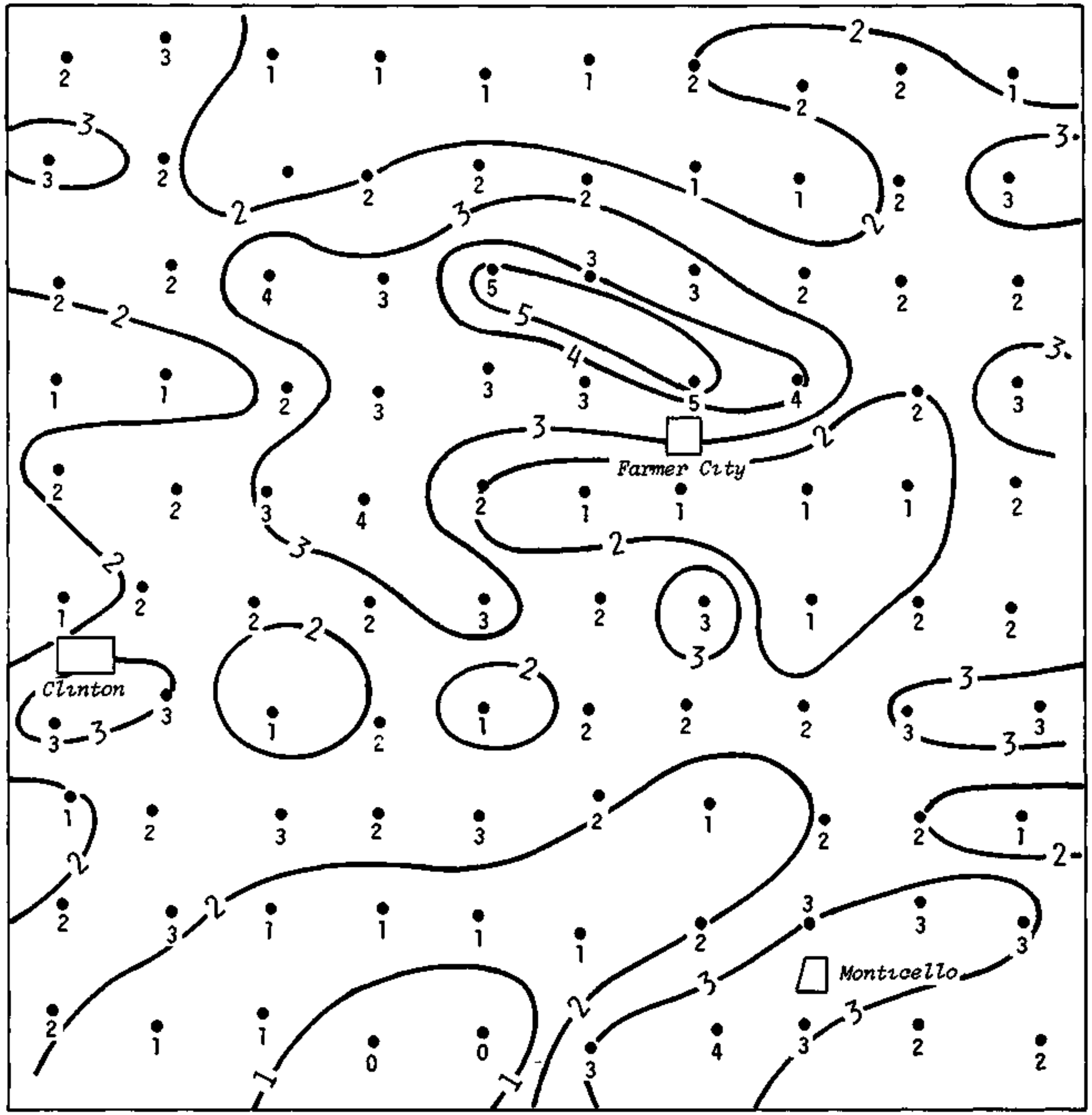


FIG. 10 TOTAL NUMBER OF DISTINCT HAILFALLS ON 15 MAY 1968

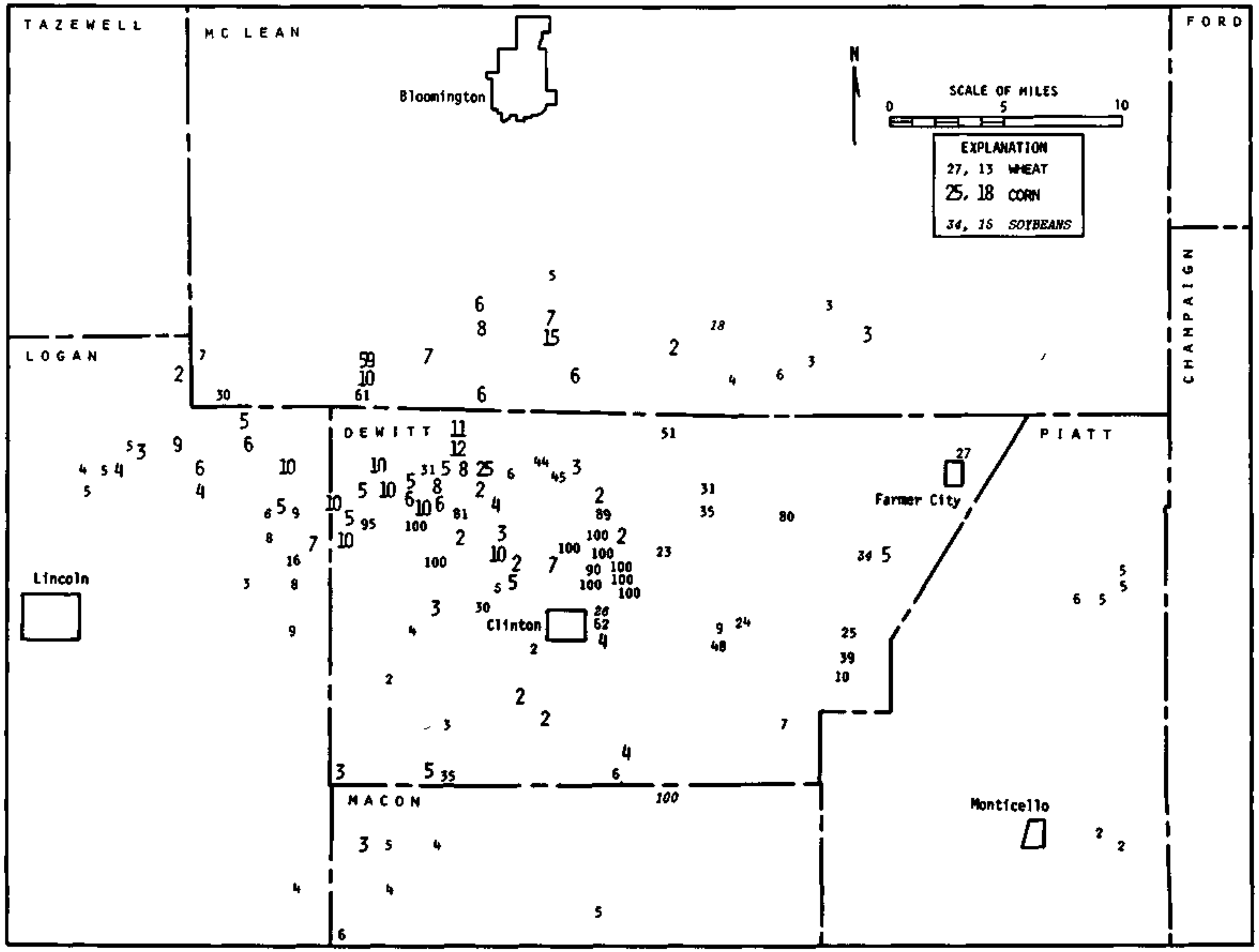


FIG. 11 PERCENT CROP LOSSES ON 15 MAY 1968

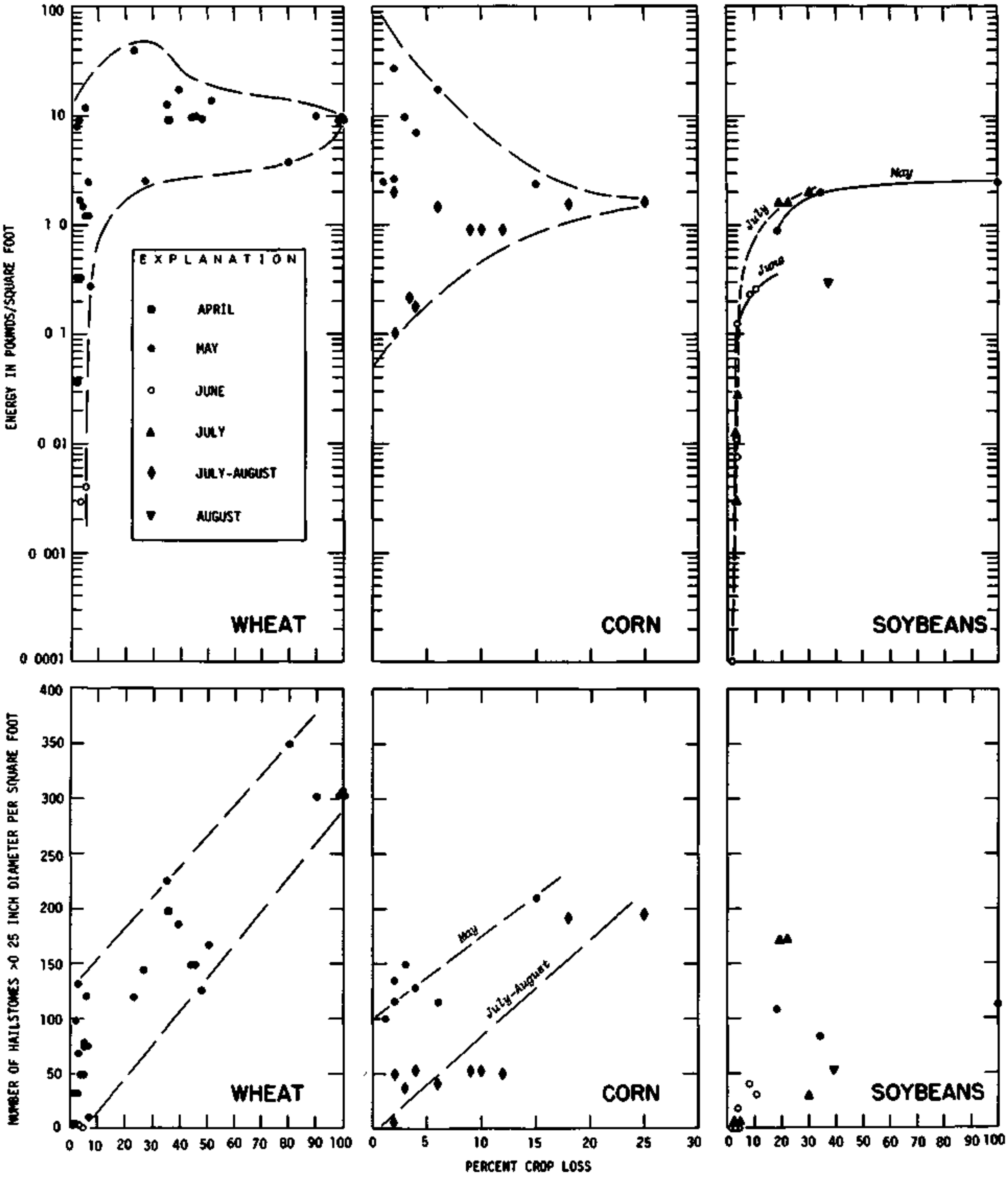


FIG. 12 COMPARISON OF CROP LOSSES CD WITH HAILPAD INDICATED ENERGY AND NUMBER OF HAILSTONES

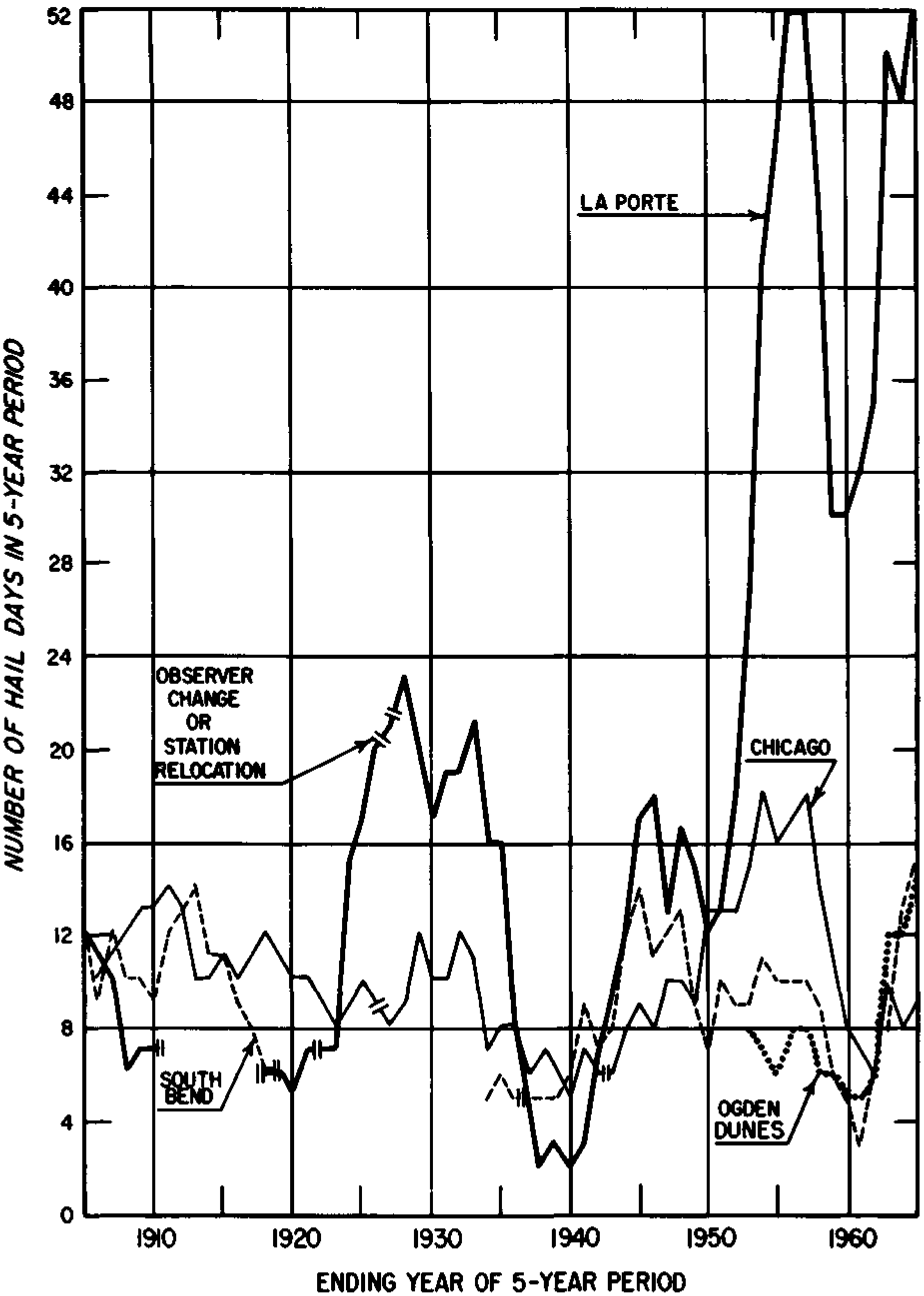


FIG. 13 TEMPORAL CHANGES IN U. S. WEATHER BUREAU HAIL DAYS

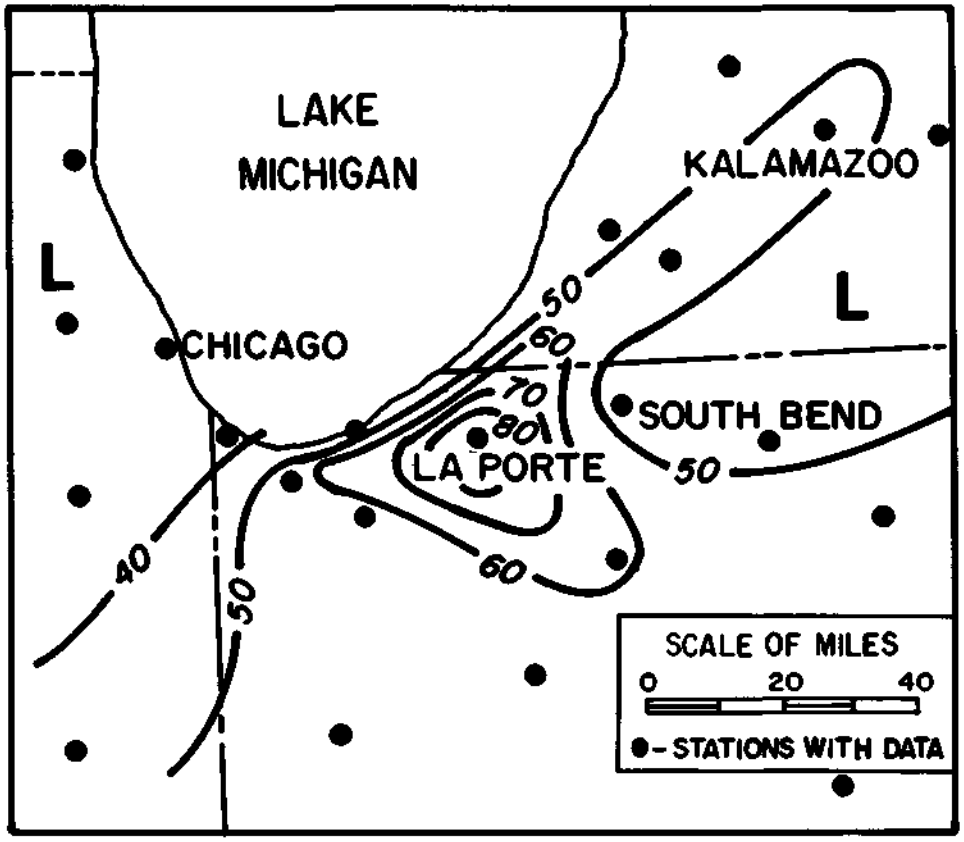


FIG. 14 NUMBER OF HAIL DAYS IN AVERAGE 20-YEAR PERIOD

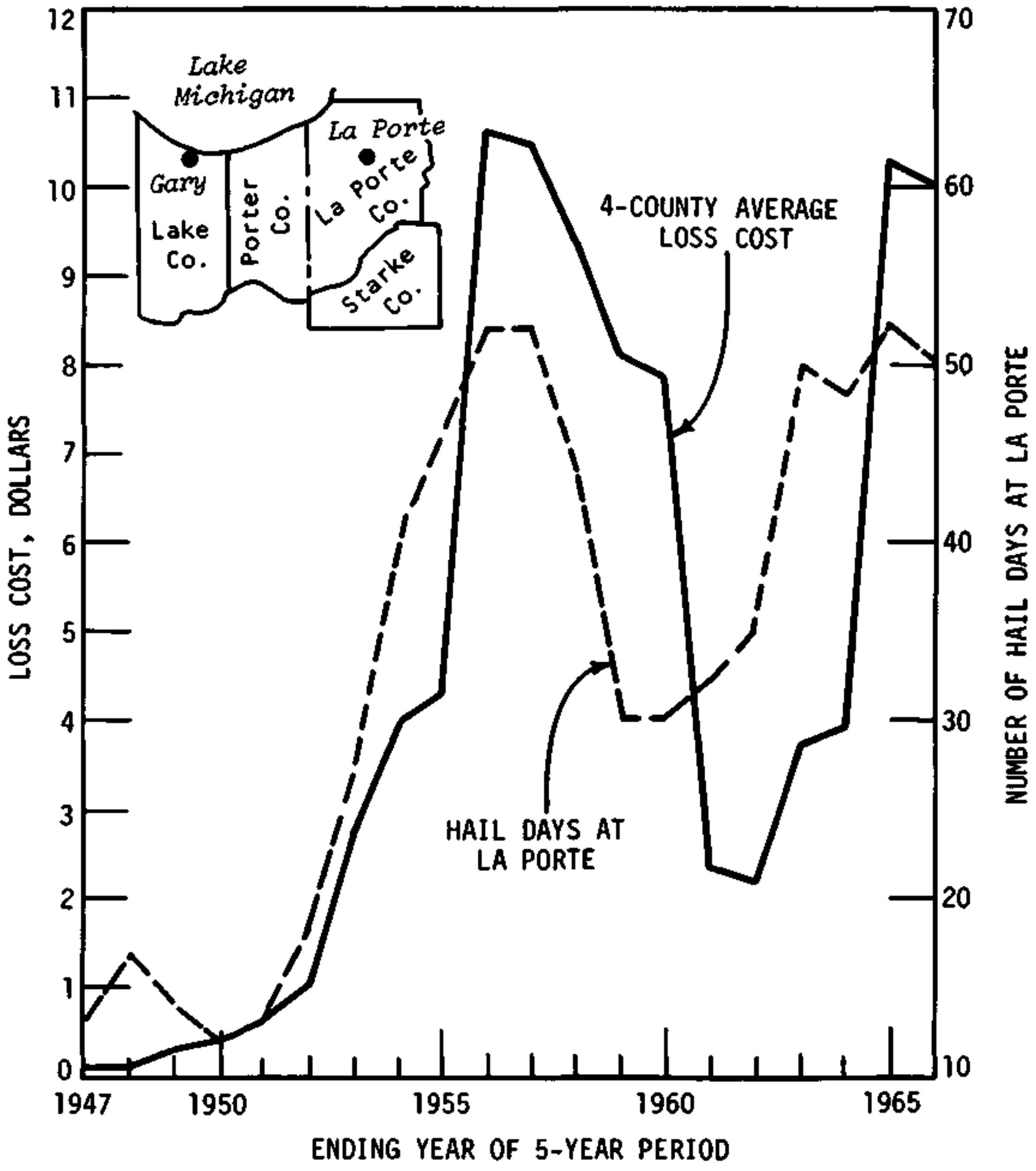


FIG. 15 FOUR-COUNTY LOSS COST VALUES FROM CROP-HAIL INSURANCE DATA AND HAIL DAYS AT LA PORTE, PLOTTED AS 5-YEAR MOVING TOTALS

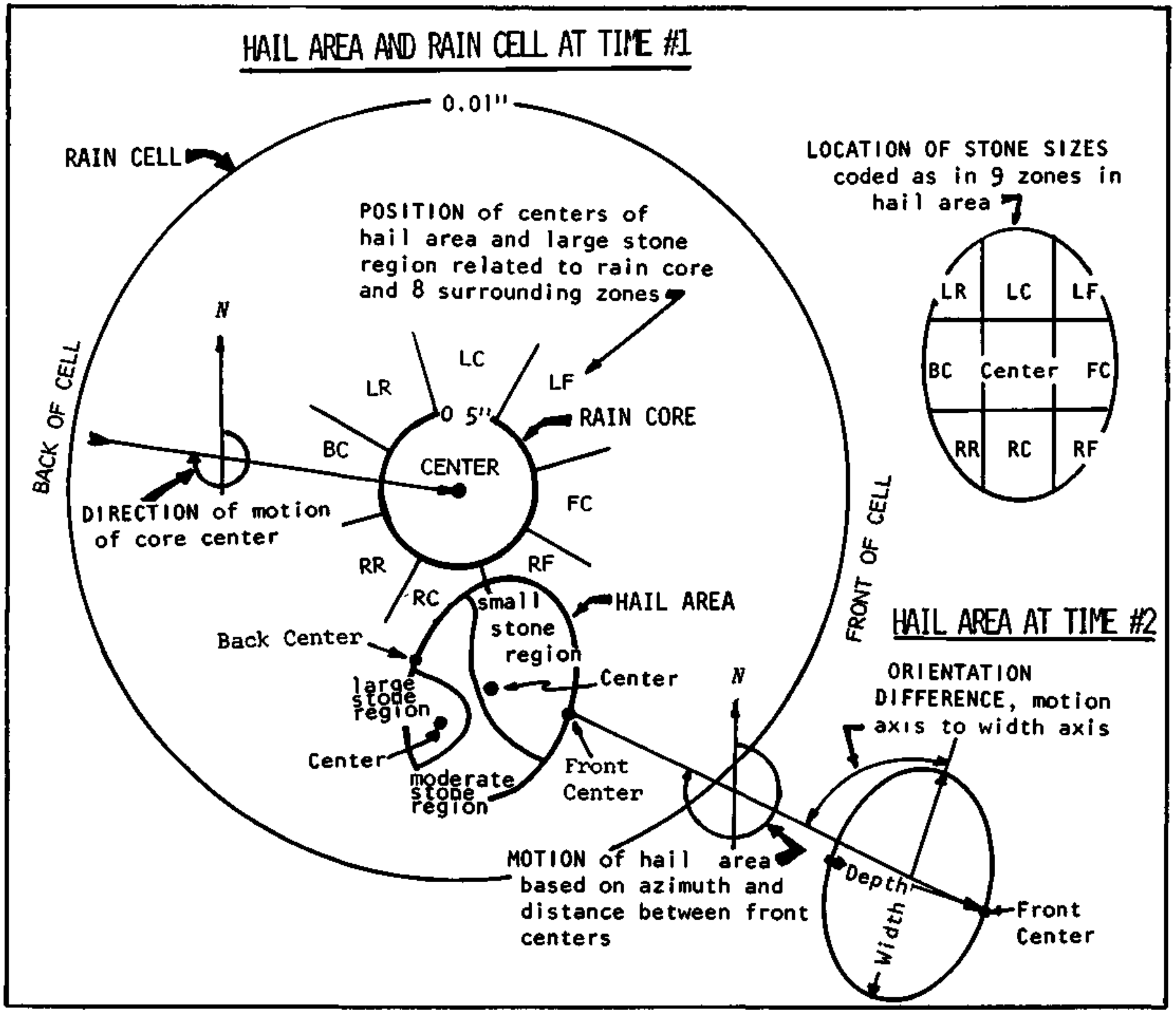


FIG. 16 SCHEMATIC OF INSTANTANEOUS PORTRAYAL OF HAIL AREA AND PAIN CELL

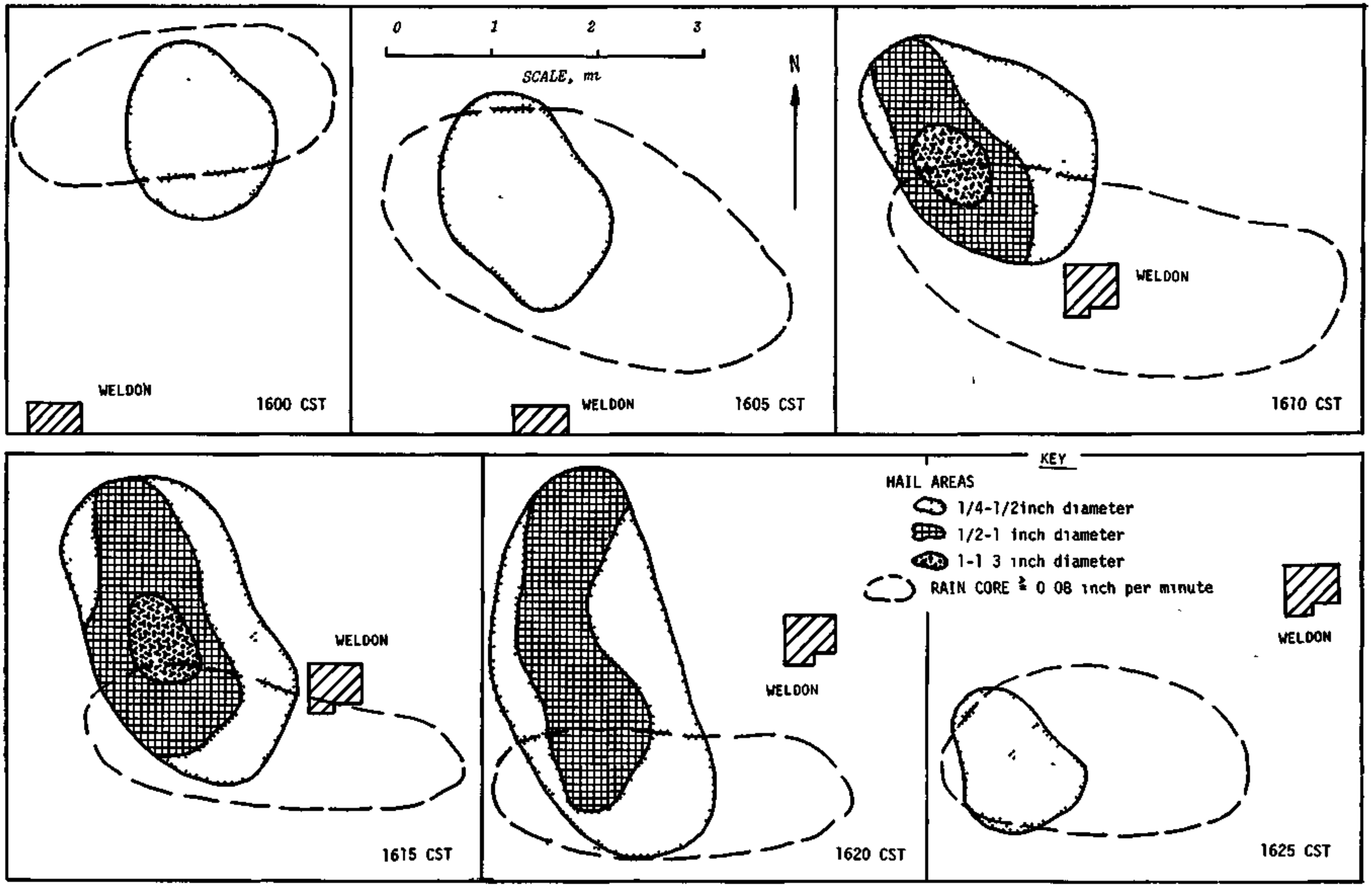


FIG. 17 SELECTED HAIL AREAS AND RAIN CORES ON 8 AUGUST 1963

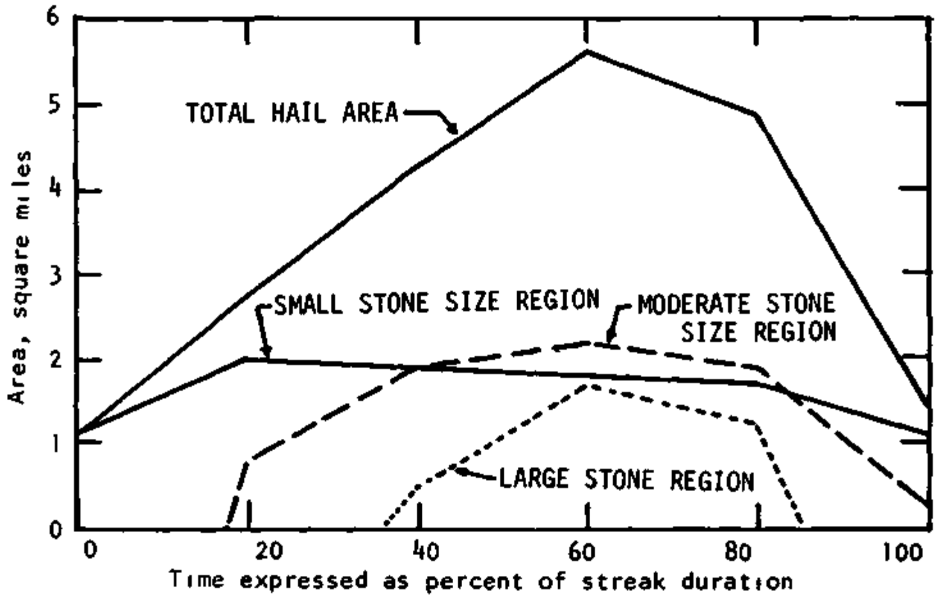


FIG. 18 MEDIAN AREAL EXTENT OF HAIL DURING HAILSTREAK

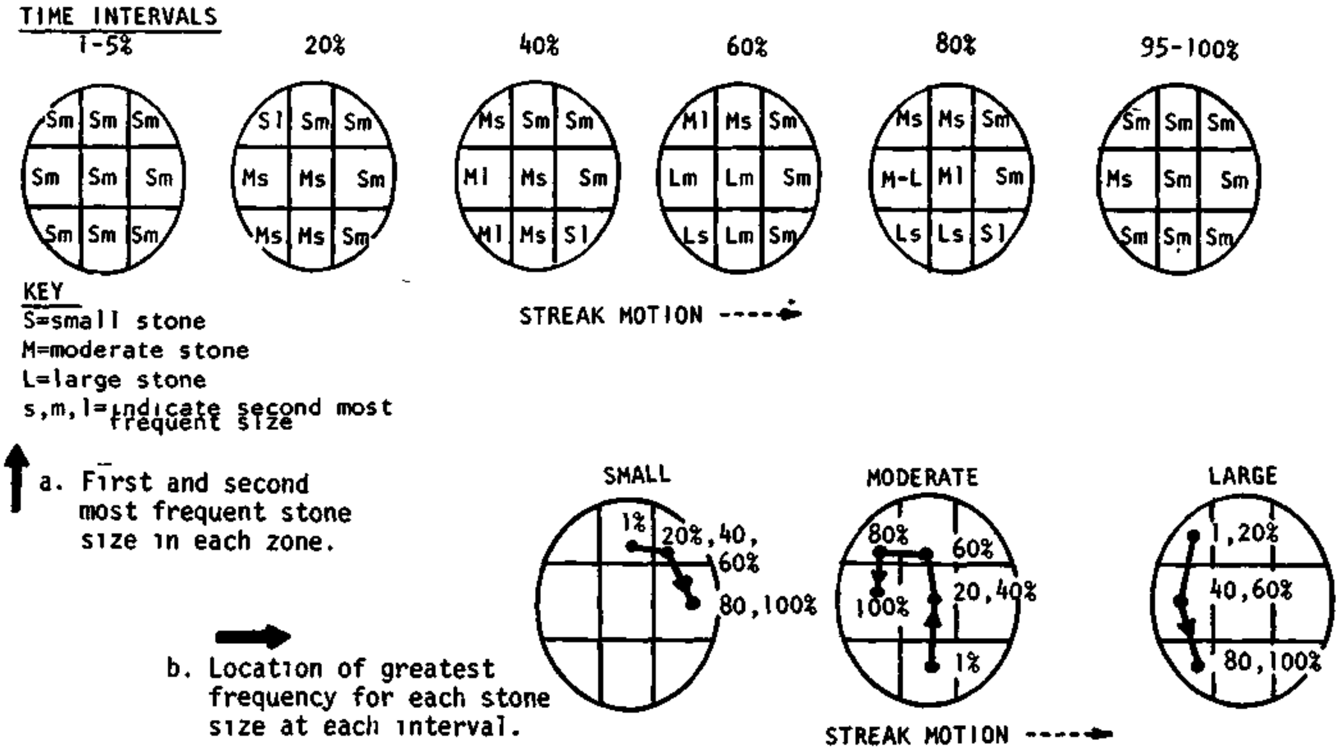


FIG. 19 POSITIONING OF STONE SIZES IN HAIL AREA

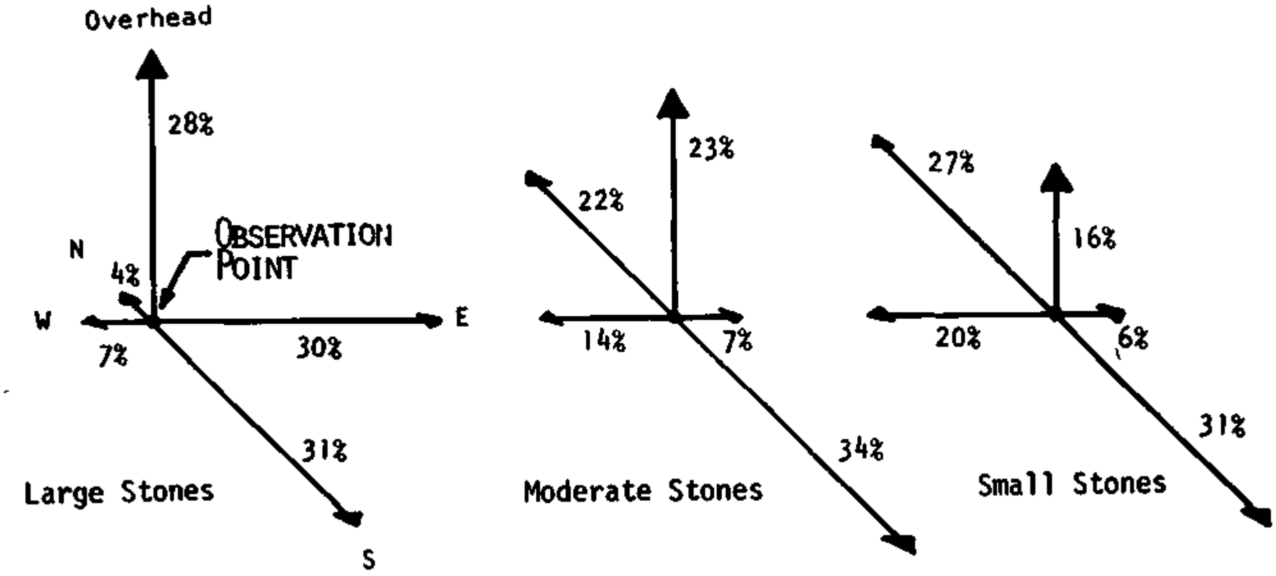


FIG. 20 FREQUENCY OF DIRECTION TO NEARBY LIGHTNING FROM HAIL OBSERVERS

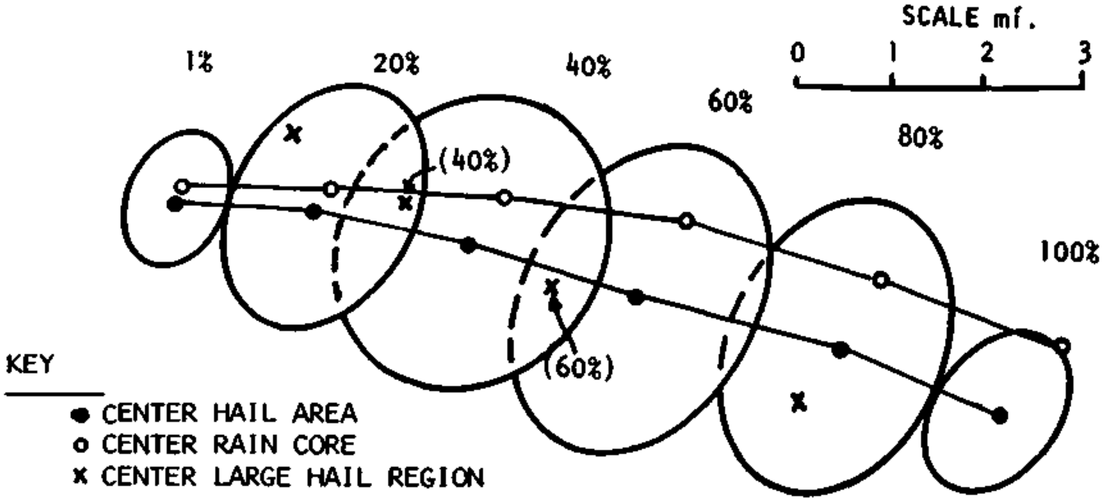


FIG. 21 DIMENSIONAL MODELS OF HAIL AREAS DURING HAILSTREAK LIFE

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A Mesoscale Study of Corn-Weather Response on Cash-Grain Farms

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ABSTRACT

Weather records for 49 locations and detailed agronomic data from 60 farms in a 400-mi^2 area in central Illinois were used to study corn-weather relations exhibited by actual farming operations in a typical agricultural area of the American Corn Belt Weekly, monthly and seasonal rainfall and temperature values plus agronomic data were correlated with corn yields during 1955-1963 The results are of added importance because the data sample was from a period when new agronomic practices, which could alter corn-weather relationships established in previous studies, were being widely employed

July and August mean temperatures and cumulative degrees above 90F during July and August had the strongest correlations with corn yield, —0 50, —0 69 and —0 51, respectively July rainfall had a stronger association with yields than rainfall in any other month, but it was considerably less than the association for July temperature

Weekly rainfalls and temperatures in early June and early August correlated moderately well with yields, a finding that does not agree with those from certain other corn-weather studies Several weather variables were more highly correlated with corn yield than were any of the newer agronomic practices generally considered to be important factors relating to corn yields A trend of increasing yields with time during the 9-yr period was related to steady improvement in technological practices and also to a trend for better (cooler) corn weather in July and August

In general, the results indicate that corn-weather relations defined by data from cash-grain farms during a recent 9-yr period of technological change are somewhat different from those defined in earlier studies using either experimental farm data or regional average yield data

1. Introduction

Many studies of weather influences on corn yields have been performed over the past 50 years Wallace in 1920 and subsequently Davis and Palleson (1940), Ezekiel (1941), Houseman (1942), and Hendrichs and Scholl (1943) were among the first scientists to employ advanced statistical analyses in studies of corn-weather relationships In more recent years, studies by Runge and Odell (1958) and Dale and Shaw (1965) have been made to determine the weather-yield relationships using phenological (stage of growth) data These referenced corn-weather studies were based either on point data from university-operated experimental farms or on area-mean data from large (county or state) regions

A major problem facing all corn-weather studies has been to ascertain accurately the roles of weather factors, treated individually or collectively, and those of man-made (technology) factors which interact to produce a corn yield The adoption of hybrid corn in the 1935-1945 period altered the previously established interactions between technology factors and weather factors Widespread employment of commercial fertilizers, particularly nitrogen, since 1950 and the adoption of higher planting rates since 1955 have further altered this interaction This latest phase of technological change has been associated with a period of continuous and rapid increases in corn yields, and this has made delineation of corn-weather relations more difficult However, assessment of the current role of weather in corn production is now essential because of the rapid increase in national and world food needs and the need to establish proper governmental controls on crop production Recent studies relating to these needs have produced conflicting results concerning the role of weather and that of technology (Thompson, 1966, Shaw and Durost, 1965)

The availability of nine years of recent (1955-1963) data on weather conditions, corn yields, and associated agricultural practices on cash-grain farms in a small area of central Illinois offered a unique opportunity to make a mesoscale study of corn-weather relations during this latest technology phase It also allowed an assessment of corn-weather relations derived from actual farming operations as opposed to those established using experimental farm data or that for large areas The data for this study were obtained from 60 farms, 49 recording rain gages, and 7 temperature stations located in a 400-mi^2 area Nine years of data at the 60 locations provided a sample size of 540 yield values for correlation with weather and agronomic observations The study area is in a high-value, cash-grain farming region representative of large segments of the American Corn Belt The value of the crops produced in this area in 1963 was

$16,500,000 Physiographically, the area is quite homogeneous It is a flat, featureless plain (maximum relief of only 260 ft) having deep, moderately permeable prairie soils that are highly productive Because the surface and soils are generally uniform, corn-weather responses are not strongly affected by variations of soil quality and drainage

Analysis of the corn-weather data from this mesoscale area was limited in that detailed phenological records of the crops were not available, although the general times of corn planting periods were known This lack of phenological data meant that the weather-yield analyses had to be based on weather data for fixed time periods rather than on non-calendar periods associated with times of emergence, silking, tasseling, or other growth stages However, corn-weather relations determined for each of the three possible planting periods (early, middle and late) were quite similar, indicating that variations in stages of growth were not affecting the results based on arbitrary calendar periods

Knowledge of the degree of correlation between weather conditions and yields from an actual group of farms has applications for 1) improving farm management practices (Runge, 1966), 2) ascertaining irrigation potential (Swanson and Jones, 1966), 3) determining the weather conditions that need to be modified to get increases in yields, and 4) estimating possible gains that could be derived from weather modification (Kirkbride and Trelogan, 1966) Corn has become the most important crop in the United States (Thompson, 1966), and the possible increase in production through weather modification is a matter of national concern

2 Data

Precipitation and temperature Most of the research was based on argicultural and weather data collected within a 400-mi^2 area in central Illinois (Fig 1) The 49 recording rain gages in this area are about 3 mi apart in a grid pattern, forming a square network of 20 mi per side Numerous measurements are needed to furnish an accurate picture of the rainfall variability in the area (Huff and Neill, 1957) which is typical of the rainfall regime of the Middle West Rainfall values for each farm were those measured at the nearest rain gage, usually less than 1 mi from the farm

Temperature data for the 60 farm sites were obtained by regional interpolation of values recorded by seven U S Weather Bureau stations located in and around the network area (Fig 1) Because weekly and monthly temperatures in this region have a uniform gradient across 10- and 20-mi distances, these temperature estimates were considered valid The basic weather information used consisted of June through August data for weekly and monthly precipitation, weekly mean maximum temperatures, weekly and seasonal frequencies of days with 90F or higher temperatures, May-August data for monthly mean temperatures, pre-season precipitation (September through May), and cumulative degrees above 90F for the July-August period

One limitation of this research and its results is the

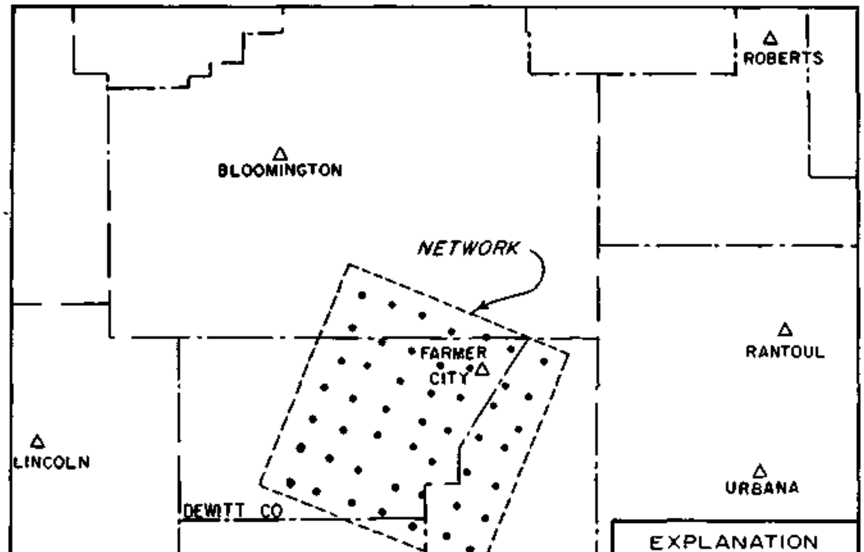

FIG 1 Location of rain gage network in central Illinois

9-yr sample of weather data which, unfortunately, measured only one moderate drought season, 1959 In the summer of 1955, the network area had between 39 and 43 days of 90F or higher temperatures, but near-normal rainfall somewhat alleviated the high temperature effect In 1959 there were 36-40 days of 90F or higher temperatures, and the rainfall totals were only 50% of normal The 1955-1963 period in Illinois has been classified as a uniquely good corn-weather period (Thompson, 1966) However, the ranges of the point (farm) weather values in the 9-yr sample are representative of the extremes recorded over a 60-yr period for 1) pre-season precipitation, 2) May temperature, 3) June precipitation, and 4) July precipitation On the other hand, mean temperatures in June, July and August have been higher than the maximum sample values 10% of the time and August rainfall has been higher than the sample maximum (6 7 inches) 5% of the time, as measured over the 60-yr period Normally, the area has 34 days per summer with 90F or higher temperatures, but in the 9-yr period only 1955 and 1959 had more than normal, and the 7 other years had values between 9 days (1958) and 28 days (1963)

Soil moisture calculations representative of the study area were made by Swanson and Jones (1966) for a period they considered critical for corn, 18 July-3 August, for 58 yr including 1955-1963 Their results showed that soil moisture available in the top 5 ft of soil was more than 70% of capacity in 8 of the 9 study years, and more than 80% in 5 yr (1957, 1958, 1960, 1962 and 1963) It was limiting only in 1959, when the amount in this 17-day period was 36% of capacity For this 17-day period, the 58-yr average available soil moisture was 6 5 inches, but the average determined for 1955-1963 was 8 4 inches, further attesting to the generally good corn-weather conditions during most of the sample period Since the soil moisture in this period was seldom limiting, it was expected that temperatures would show a stronger relation with yields than would rainfall

Agricultural Sixty farms (shown as shaded areas on Fig 2) were chosen to furnish argicultural information on the basis of availability and completeness of data for the 9-yr period Illinois Farm Bureau Farm Management Service records were available for most of the farms Annual data for each farm included information on planting period, plant population, corn yield, soil productivity rating, and nitrogen application Planting periods were recorded as occurring in one of three periods 1) early planting (prior to 1 May), 2) middle planting (1-15 May), and 3) late planting (after 15 May) Plant population was based on an estimate of the number of kernels planted per acre

The 9-yr mean annual corn yield of the 60 farms was 96 bushels acre^{-1}, attesting to the high levels of productivity of these farms Individual annual yields ranged from a low of 44 to a high of 145 bushels acre^{-1} Farm size ranged from 60 to 760 acres with an average of 210 acres

3 General correlations

First impressions of associations of corn yield with four agricultural variables and ten weather variables were obtained from simple linear correlations Agricultural variables were planting period, plant population, soil productivity rating, and nitrogen applied in the year Weather variables were pre-season precipitation, monthly mean temperature for May, June, July and August, number of days with 90F or higher for the June-August period, number of cumulative degrees above 90F in July and August, and monthly rainfall totals for June, July and August The year of observation was also included as a variable to check for correlations which would suggest the presence of linear time trends among the variables

TABLE 1 Linear correlation coefficients

Variables	Corn yield Individual observations	Yearly-mean values	Year (trend)
Year	0 70	0 89	
August mean temperature	—0 69	—0 89	—0 69
Sum of degrees above 90F in July-August	-0 51	-0 66	-0 61
July mean temperature	—0 50	—064	—0 58
Nitrogen	0 41	0 91	0 87
Number of days above 90F, June-August	-037	-047	-0 31
Plant population	0 35	0 87	0 97
August rainfall	0 29	0 37	0 30
June mean temperature	0 29	0 37	0 33
July rainfall	0 24	0 34	015
June rainfall	-022	-029	-0 35
Pre-season precipitation	0 13	0 22	0 14
May mean temperature	—0 07	—0 09	—0 13
Soil productivity	0 05		
Planting period	-0 01	-0 25	-0 42

The sample from 60 farms over 9 yr provided a total of 540 individual observations for each variable, except soil productivity, for which one observation was available for each farm for the period In addition, a mean value for each variable was determined for each year Correlation coefficients were computed for the 540 individual observations and for the 9 yearly-mean values for each variable These coefficients are shown in Table 1 Correlations based on the 540 individual observations denote the strength of associations for those interested in individual yield variation Correlations based on yearly-means are appropriate when average production is considered The latter correlations are also more appropriate for comparisons with the correlations in the year (trend) column which are also based on yearly-mean values For a sample size of the order of 540 individual yields, correlations with yield on the order of ± 0 09 and ± 0 11 are sufficient for significance

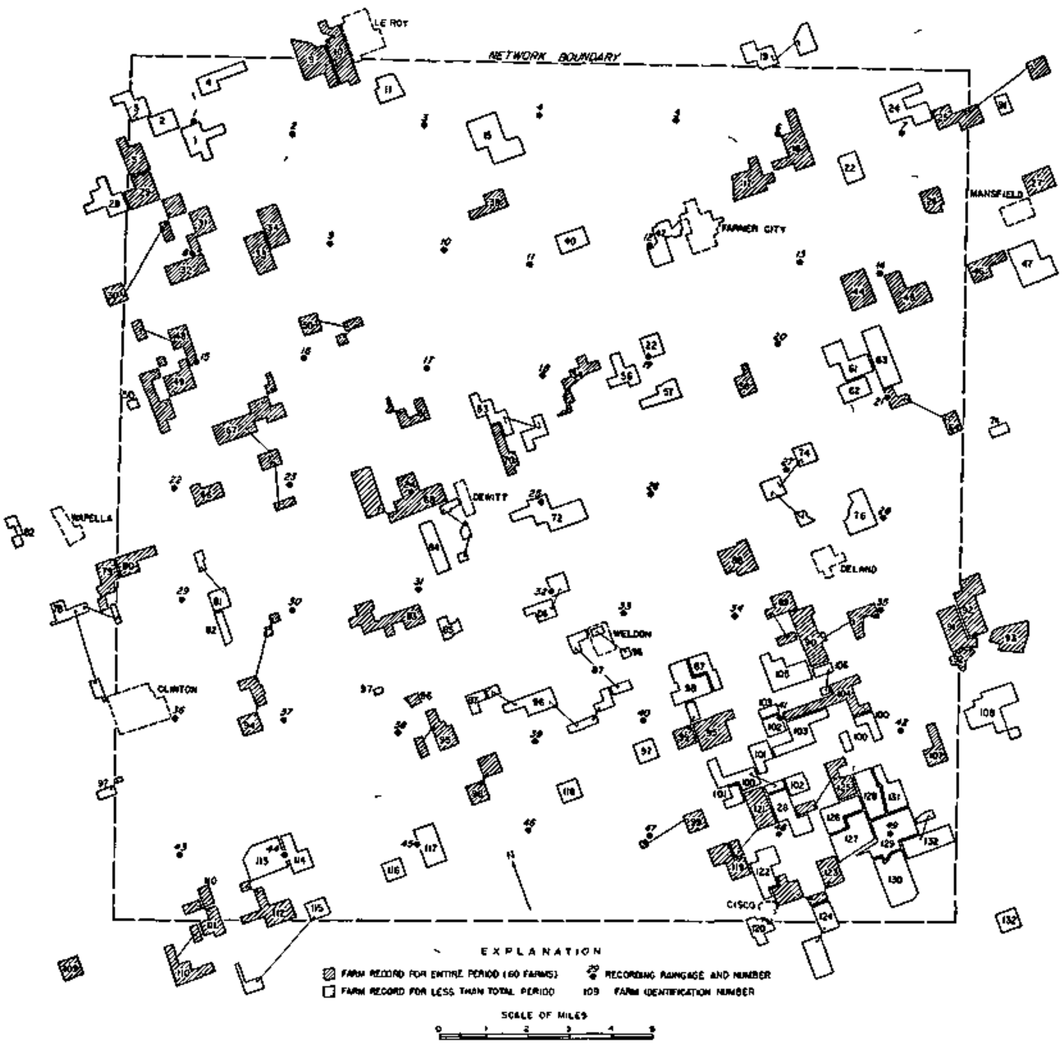

FIG 2 Location of farms in ram gage network

at the commonly used 0 95 and 0 99 probability levels, respectively (Snedecor, 1946) Considering 9 yearly-means of each variable as a sample of size 9 correlations, of the order of 0 63 and 0 76 are required for significance at the 0 95 and 0 99 probability levels, respectively

Agricultural variables The correlations of individual and yearly-mean farm yields with nitrogen are substantial at 0 41 and 0 91, respectively Doll *et al* (1958) established that nitrogen was the single most important fertilizer relating to corn yields The square of the correlation of individual yields with plant population suggests that this variable explamed about 12% of the individual yield variation The two remaining agricultural variables have correlations with yield which are less than those required for statistical significance The association between farm yields and nitrogen applications, plant populations, and the soil productivity rating are shown also m Fig 3 The smoothed dashed lines were drawn to incorporate 95% of the 540 data points, and their great separation on each graph illustrates the wide scatter of the data These graphs emphasize the tremendous variation m farm yields about the best-fit curves (Figs 3a and 3b) for two agricultural variables involving management (technological variables) considered by many to be very important in determining corn yields (Runge, 1966, Shaw and'Durost, 1965)

A correlation of 0 70 was obtained between the individual farm yields and the year, which suggests a definite upward trend in yield over the 1955-1963 period of observation (Fig 3d) In part, this is an expression of steady improvement m technology for increasing corn yield Increase in average plant populations and nitrogen applications, the two most important technological factors analyzed in this study, have occurred during the sample period according to trend correlations of 0 97 and 0 87, respectively (Table 1) The yearly-mean values of these two variables are comparably well correlated with yield Thus, there is evidence

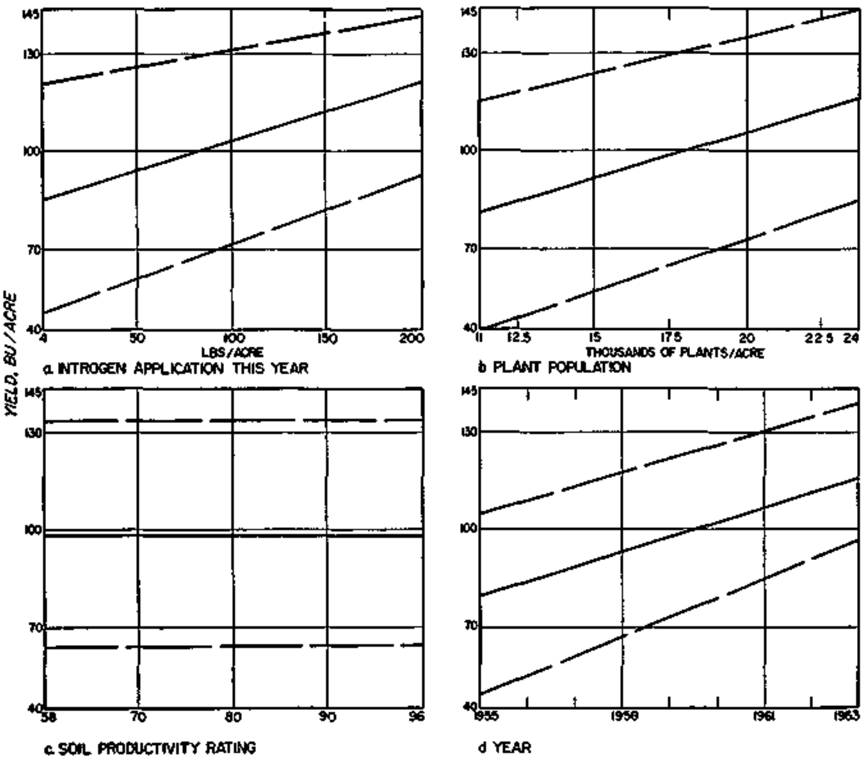

FIG 3 Relation of corn yields with technological practices, soil and time

that these two technological factors contributed to the increase in yield during the observation period

Monthly and seasonal weather variables The best correlations of yield with weather variables in Table 1 are with temperature factors Correlations based on the 540 individual values of yield with July and August mean temperatures, with cumulative degrees above 90F during the July through August period, and with number of days of maximum temperature of 90F or above were -0 50, -0 69, -0 51, and —0 37, respectively Thompson (1963) showed the importance of July and August mean temperatures, however, Thompson found that on a statewide basis July temperature is more hightly correlated with Illinois yields than is August temperature The cumulative degrees above 90F in July-August, and the number of days with maximum temperature of 90F or higher for the period June through August were included to test for relations between corn yield and excessively high temperatures Thompson (1966) has indicated that the best single measure of the effect of weather on corn yield was the cumulative degrees above 90F during July and August These accumulations determined for the various farms were less than 55 in eight of the nine years Only in 1955 were the accumulations relatively high, ranging from 124 to 150 for the 60-farm sample Correlations for these two measures of high temperature might have been considerably higher if the sample period had included more years with greater numbers of high temperature days For example, Dale and Shaw (1965) have shown that the relation of corn yields to frequency of moisture stress days in midsummer was poor until the number exceeded 30, above which a close relationship existed

Since the relation of monthly rainfall to yield may be curvilinear rather than linear, correlation indices were also computed from quadratic regressions of individual yields and rainfall These computations produced an index of 0 37 for July rainfall, a considerable improvement over the 0 24 linear correlation in Table 1 The quadratic relationship explained 14% of the yield variation, as compared to 6% for the linear, and produced an F-ratio test value which exceeded the 0 999 probability level However, the curvilinear fit of yields with June, August, and pre-season rainfall totals resulted in correlation indices not appreciably greater than the linear coefficients

The best-fit curves determined for the six most relevant monthly weather variables are displayed in Fig 4 The smoothed dashed lines incorporate 95% of the data points and outline the general configuration of the data scatter

June mean temperatures fitted a quadratic regression curve significantly better than a linear regression line However, the spread of the 95% bands (Figs 4a and 4b) and the low correlation for June temperature and rainfall in Table 1 indicate that the corn yields in this area were poorly related to the range of monthly weather conditions for June

July rainfall (Fig 4c) exhibited a curvilinear fit with corn yields, indicating that the optimum July rainfall

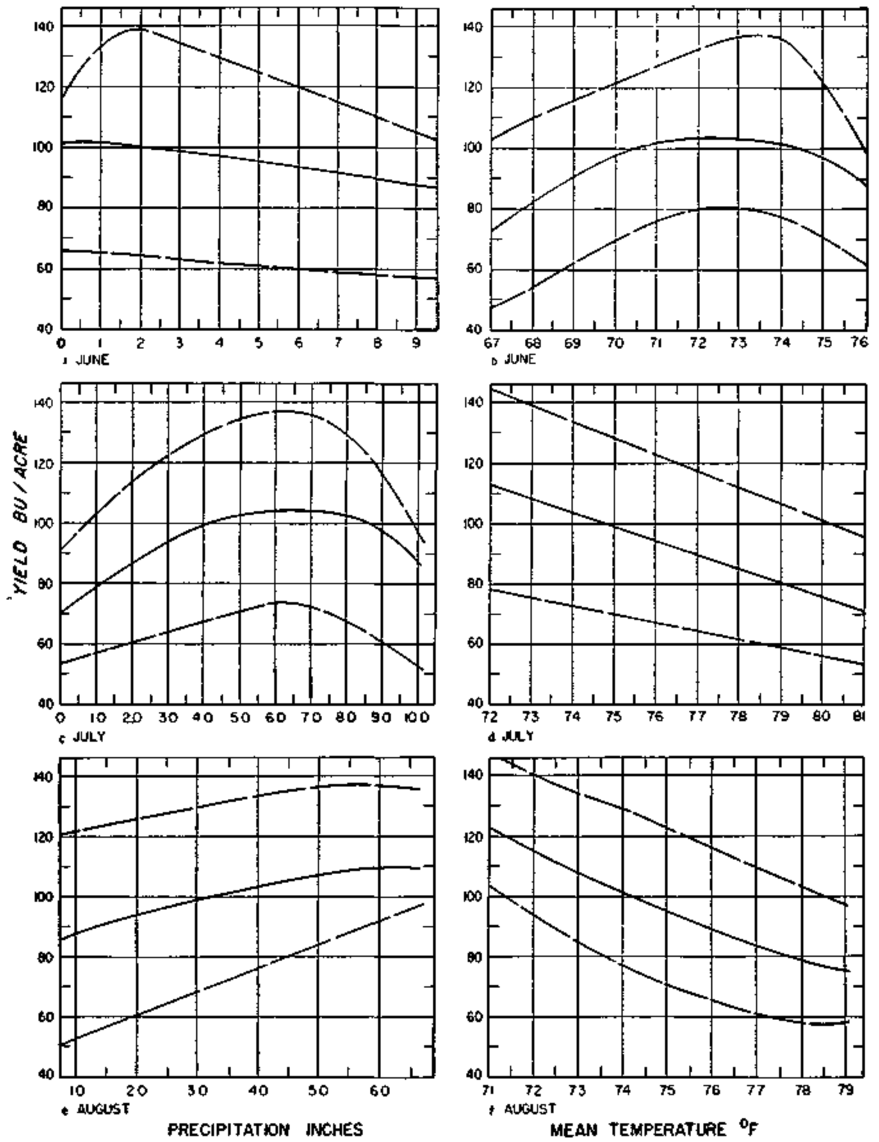

FIG 4 Relation of corn yields with monthly weather conditions

for maximum corn yields is between 6 and 7 inches However, July rainfall explained only 14% of the corn yield variability In a corn-weather study of all Illinois counties using 33-yr records of county yields and rainfall, Changnon and Neill (1967) showed relatively low correlations for July rainfall with corn yields in the counties encompassing their study area In the present study, the relationship of corn yield with July mean temperature was linear (Fig 4d), and the correlation coefficient of -0 50 (Table 1) indicates that 25% of the yield variations might be attributed to July temperature

Fig 4e indicates that corn yields were at a maximum when August rainfall totals were 6 inches or more and the quadratic regression line suggests that additional rain would not increase yields Unfortunately, the 9-yr sampling period on the network did not include an extremely wet August at any farm August temperatures (Fig 4f) fit a quadratic distribution slightly better than a linear, but the correlation index of 0 70 was not significantly better than the linear coefficient of —0 69 in Table 1 The —0 69 was the highest correlation obtained for the monthly weather variables It was also higher than those obtained for either of the excessive temperature factors and those for any of the weekly rainfall and temperature variables

A weather-trend correlation (Table 1) for the sample period suggests that weather may have been partially responsible for the upward yield trend during 1955-1963 July and August temperature-trend correlations, significant at the 0 90 and 0 95 probability levels, respectively, are indicative of a cooling trend for these months As noted previously, corn yield has a sub-

TABLE 2 Data and linear correlation coefficients for different planting periods

	Planting periods		
	Early, prior to 1 May	Middle, 1-15 May	Late, after 15 May
Number of samples	17	443	80
Average yield, bushels acre^{-1}	98 4	95 3	96 3
Variables			
Year	0 80	0 71	0 63
Plant population	0 65	0 34	0 22
Soil productivity	0 36	0 05	-0 02
Nitrogen	0 65	0 48	0 03
Pre-season precipitation	-0 15	013	0 25
May temperature	-0 11	-007	-0 04
June rainfall	-050	-022	-0 15
June temperature	0 58	0 29	019
July rainfall	0 02	0 25	0 24
July temperature	-0 61	-0 49	-0 54
August rainfall	0 45	0 26	0 38
August temperature	-074	-070	-068

stantial inverse correlation with these weather factors Consequently, these downward temperature trends during the observation period should have favored an increase in corn yield It is therefore likely that weather and technological trends interacted to favor corn production in this 9-yr sample, but the value of either influence on corn yield cannot be completely assessed in the available sample Research on corn yields in Iowa (Bean, 1967) has shown that for the 1955-1963 period, weather effects caused an increase of 18 bushels acre^{-1}, whereas technological variables added 15 bushels, or less than the weather effects

As shown in Table 2, 443 of the 540 corn-year values had planting periods during 1-15, May indicating that 82% of the crops sampled reached their various stages of growth at about the same time The lack of phenological variability in the sample is further revealed by data for the crop-reporting district incorporating the study area These data for the sampled 9 yr indicate that the dates when 50% tasseling occurred were between 18 July (1962) and 29 July (1960) The correlations presented in Table 2 allow inspection of the corn-weather relations for the different times of planting, and differences between them could be assessed as indicative of phenological variations The general lack of major differences between the monthly weather correlations for the middle and late planting periods, which represent 97% of the data, indicates that the effect of phenological variations on the corn-weather relations established for the entire sample was negligible Therefore, the use of weather conditions for fixed calendar periods should provide meaningful results The results for the early planting cases have higher correlations with the early weather conditions, which suggests phenological associations, but the 17 samples are too few to derive reliable results The major differences in the correlations of the 3 planting periods are those pertaining to the agricultural variables which show that technology-yield relations become poorer as planting time becomes later

4 Weekly rainfall

Some crop-weather response studies have been done with monthly and seasonal weather data, primarily because these data are more rapidly available than short-term data However, several investigators, including Runge and Odell (1958), have shown that corn yields are correlated with weather conditions during critical 7-, 10- and 14-day periods Daily rainfall amounts for the rain gages nearest each farm were summed to obtain weekly rainfall amounts for correlation with the 540 farm yields Running totals for 2-week, 3-week, and 4-week periods were then calculated and also correlated with the yields

Correlations for both linear and curvilinear (quadratic) associations for rainfall and yields were determined In every instance the curvilinear values, presented in Table 3, were higher than the linear values

An examination of the correlations for 1-week rainfall totals with yield (Table 3) reveals several rather prominent features 1) poor correlations in the first four weeks of June, 2) a change to a substantial indication of association during the weeks of 29 June-5 July and 6-12 July, 3) a return to poor associations for the weeks from 13 July through 2 August, 4) a relatively high correlation during the week of 3-9 August, and 5) poor correlations for the last three weeks of August Fig 5 depicts the best-fit curves for four selected weeks, and the 95% bands reflect the considerable data scatter found in these and all 1-week periods By comparison with tabulated multiple correlations for 3 variables and a sample size of 540, correlations indices in Table 3 could be judged significant at the 0 95 and 0 99 probability levels if they exceed 011 and 0 14, respectively (Snedecor, 1946) However, a correlation of less than

TABLE 3 Corn yield versus rainfall for 1-, 2-, 3- and 4-week periods

Beginning date of period	Quadratic indices of correlation for rainfall totals for given periods			
	1-week	2-week	3-week	4-week
6/1	0 08	0 46	030	0 26
6/8	0 27	0 24	0 24	0 28
6/15	0 04	0 13	0 43	0 46
6/22	0 20	0 26	0 35	0 31
6/29	047	039	034	032
7/6	0 48	0 36	0 25	0 22
7/13	0 05	0 15	0 19	0 09
7/20	0 16	0 31	0 12	0 04
7/27	0 13	0 29	0 26	0 21
8/3	0 54	035	037	031
8/10	0 17	011	0 07	—
8/17	0 27	0 17	—	—
8/24	0 26	—	—	—

± 0 30 represents an association which explains a small percentage of the yield variation and is of questionable value in a practical sense

The small correlations during the first four weeks of June agree with prior results (Runge, 1966) and reflect the common belief of farmers that below-normal rain in June favors corn production The shift to relatively good correlation during 29 June-12 July (Figs 5a and 5c) sug-

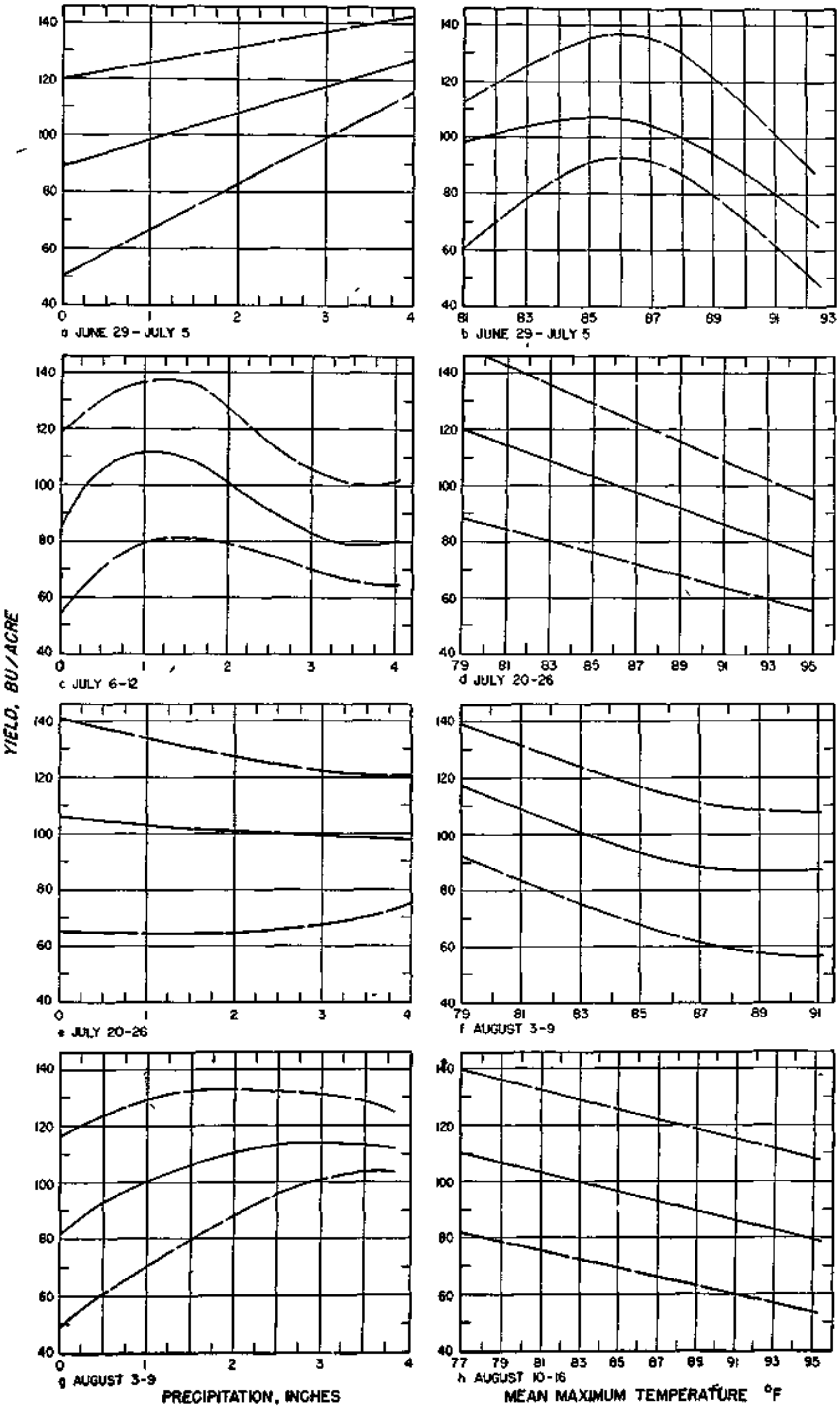

FIG 5 Relation of corn yields with weekly weather conditions

gests the corn plant had reached a stage of growth when it would show a greater response to rainfall However, this rain-yield response is a week or more earlier than that found by Runge and Odell (1958) from analyses of 1903-1956 crop-weather data from an experimental farm near the study area At this experimental farm, the greatest response of corn to rainfall was during 7 July-24 July As illustrated by Fig 5e, the 60-farm data did not show any appreciable response to rainfall during this middle to late July period, but this may have resulted because the soil moisture values for this period were generally not limiting The correlation indices for 2-, 3- and 4-week rainfall values (Table 3) support the weekly findings, particularly showing the importance of rainfall in the late June-early July period Also, the relatively strong rain-yield response of 3-9 August (Fig 5g) for the 60-farm sample does not appear in the experimental farm data

These dissimilar results may be due to the short duration of the network sample, or they may reflect differences in the operations of the experimental farm and those generally practiced by the cash-grain farmer Improvements in technology for corn production such as earlier planting, increased use of a commercial fertilizers, and other factors may have helped the crop reach a rain-responsive stage of growth earlier in the season during this 9-yr period It is reasonable to expect that a longer, more representative period of record for the 60 farms could account for some of the difference

These findings for weekly rainfall also may partially result from using a period as short as one week For example, Fig 5e illustrates that many of the higher yields tend to occur with very low weekly rainfall and lower yields tend to occur with much higher rainfall during the week of 20-26 July This is evidence that a single week of dry weather at this time was not critical and may have been beneficial when preceded by a wet week Many of the good yields associated with very low rain were cases in which rain occurred either before or after a dry week Thus, the interaction of rainfall for adjacent periods as short as one week may have helped to effect an optimum rain of near zero Fig 5a may be showing a linear trend because 1) corn plants may have generally reached a stage of growth by 29 June to 5 July when they could respond strongly and positively to rainfall, 2) the maximum amount of rain received was not enough to determine the optimum, or 3) portions of the rain in this period provided much of the soil moisture required and used to sustain the crop through July The values in Table 3 for 2-, 3- and 4-week periods indicate that the two most important 2-week rainfall periods were 1-14 June and 29 June-12 July The 15 June-5 July period was the most critical 3 weeks for corn, and 15 June-12 July was the most critical 4-week period

TABLE 4 Corn yield vs weekly mean maximum temperature

Week	Correlation Linear	Quadratic
6/1-6/7	015	020
6/8-6/14	-007	0 08
6/15-6/21	014	0 21
6/22-6/28	0 05	0 06
6/29-7/5	-0 40	0 51
7/6-7/12	-0 1 8	0 53
7/13-7/19	-0 01	0 23
7/20-7/26	-0 56	0 56
7/27-8/2	-0 1 2	0 21
8/3-8/9	-056	0 61
8/10-8/16	-0 44	0 44
8/18-8/23	-0 43	0 47
8/24-8/30	-0 06	0 23

5. Weekly temperature

The importance of temperature as a weather index of corn yield in the sample under study was established by the correlations shown in Table 1 Short-period comparisons were made to examine further the effect of temperature during the corn growth period

Linear and quadratic curve fitting were carried out and scatter diagrams prepared for each of the 13 weeks beginning 1 June Correlations (Table 4) and graphs (Fig 5) document the seasonal variation of yield association with maximum weekly temperature for the 9-yr sample of 540 yields The relationship between the frequency of days per week with high temperatures, above 85 and 90F, was also investigated, but these produced lower correlations than were obtained for the weekly mean maximum temperature

Associations between weekly mean maximum temperature and yield were weak for the first four weeks of June High temperature had a pronounced negative effect for the week of 29 June-5 July (Fig 5b), which corresponds with a pronounced yield response to rainfall (Table 3 and Fig 5a) Negative correlation between corn yield and the weekly mean maximum temperature was substantial for most of the weeks during late July and August (Figs 5d, 5f, 5h) Significant negative correlations in the two weeks of mid-July may be lacking because the highest maximum temperatures sampled were 3-5F lower than those sampled in preceding and succeeding weeks Comparison of the weekly temperature correlations (Table 4) with those for weekly rainfall (Table 3) reveals that the temperature correlations are higher for most of the weeks

6 Conclusions

The primary purpose of this study was to investigate the degree of response of corn yields to various weather variables using non-experimental farm data collected during a period of new and expanding agricultural practices The results have several practical applications, since the research was based on extensive rainfall and current agronomic data from a cash-grain farming area of high management and productivity and of homogeneous climate, and similar topography and soils

The correlation between August mean temperatures and yields was —0 69, which was higher than that for any other weather condition The next best weather correlation, —0 51, was for the cumulative number of degrees above 90F during July and August July mean temperature ranked as the second best monthly variable, and July rainfall ranked third Most previous studies have shown that July rainfall is the most important monthly variable, July temperature second, and the August temperature third This disagreement partially results from the weather conditions sampled in the 9-yr period Many previous studies also have shown that the most critical weather period for corn is in late July, but this study showed that temperature and rainfall in late June and early July were the most critical short-term weather conditions for corn Such disagreement reflects differences between farming practices at experimental farm sites and those currently employed by cash-grain farmers, and it partially results from the inadequacies of the 9-yr sample

During the 9-yr period a temporal increase in yield was evident Upward temporal trends were found in the employment of major technologic practices, and a trend for better corn-weather conditions (cooler July and August temperatures) also occurred during the 1955-1963 period Analysis of the corn-weather relations determined for each of the three planting-period groups indicated that phenological variations in corn did not materially affect the final corn-weather results that were based on the entire data sample and on weather data for fixed calendar periods

The results also indicate that added water from irrigation or man-made rainfall would be beneficial only in late June and July, but that added water would not produce significant increases in yields because of the relatively poor correlation between rainfall and corn yields in this area The results suggest that lowering of high temperatures in July and August would be of considerably greater value in increasing corn yields

Although certain weather conditions and technological practices could be identified as having some association with yields, no single variable explained more than 50% of the variability in the 540 yields Of importance was the finding that in this apparently homogeneous sample, the yields varied considerably for any specific weather factor or level of technological practice Such great variability of yields about a given rainfall amount, temperature level, or amount of nitrogen indicates the lack of major dependence of corn yields on any one weather condition or single agronomic activity in the sample area and sample period Knowledge of this is especially important in making individual farm management decisions concerning the use and amount of fertilizer, the planting rate (population) or date of planting The generally poor correlations between individual yields and these three technological practices indicate that weather conditions and other unmeasured technological practices are of considerable importance on an individual basis

The correlations based on the individual observations indicated that several weekly, monthly, and seasonal weather variables had closer relations with yield than did nitrogen application, which had the strongest association with yield of the agronomic practices investigated However, the correlations based on yearly-mean values indicated that nitrogen application was more closely associated with the area-mean yields than were any of the weather variables This reversal in correlations indicates how different treatments of data for corn-weather studies can produce quite different conclusions These reversals may also indicate why there has been disagreement between the results of some corn-weather studies using experimental farm data and those based on large-scale regional mean data

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Effect of Sampling Density on Areal Extent of Damaging Hail[1,2]

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27 January 1968

One of the important design problems to be resolved in hail modification experiments concerns the number of surface sampling points necessary to measure adequately the areal extent of damaging hail Schleusener *el al* (1965) indicated that hailfall energies measured at Colorado observation points (passive hail pads) located 2 mi apart were poorly correlated (<0 5) After careful field studies of 6 damaging hailstorms, Changnon (1964) concluded that at least 1 observation point per 2 mi^2 was required to define accurately the areas of the damaging hail

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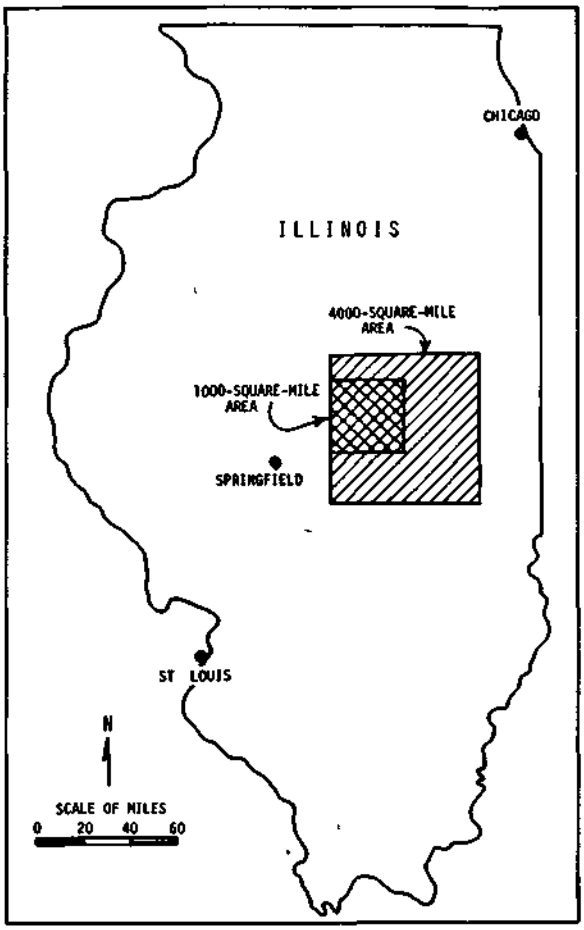
[1] This research was supported by the Atmospheric Sciences Section, National Science Foundation, NSF Grant GA-482

[2] Insurance data were supplied largely by the Crop-Hail Insurance Actuarial Association



TIG 1 Location of two study areas in Illinois

Two square-shaped areas in central Illinois, one comprising 4000 and the other 1000 mi^2 located inside the larger one (Fig 1), were chosen to make a statistical study of the surface sampling requirements for the areal measurement of damaging hail (Changnon *et al* 1967) The insurance liability within these areas e\ceeded 85% of the total areal extent of each over an 11-yr period, 1952-1963

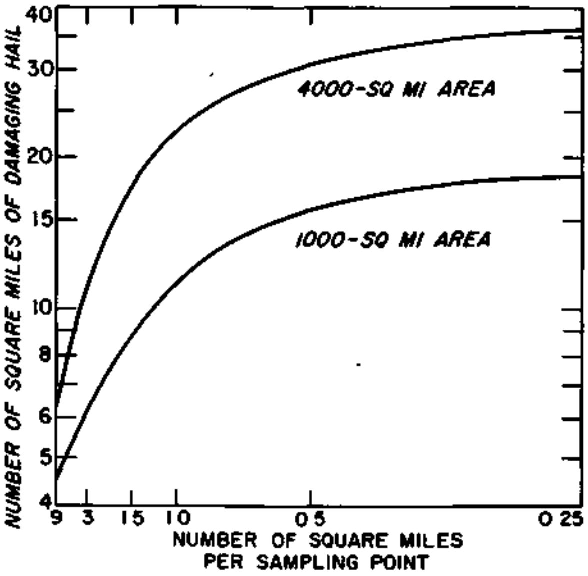


FIG 2 Average areal extent of crop-damaging hail on a hailstorm day in Illinois based on different densities of sampling points in 1000- and 4000-mi^2 areas

Maps for each storm day were prepared showing the actual areas of paid losses using all the available insurance data which represented an average sampling density of 4 location points (farms) mi^{-2} Transparent overlays at the same map scale with evenly distributed points representing observation sites with densities of 0 5, 1 0, 3 0 and 9 0 mi^2 were superimposed on each daily damage map to determine the area of damage defined by each density The area of hail damage designated as measured by each point in a damage area was **0 25 mi^2**

The average number of storm days per area, as defined for each sampling density, is shown in Table 1 In the 1000-mi^2 area, a density of 1 point per 0 25 mi^2, on the average, detected twice as many days' with

TABLE 1 Frequency of crop-damaging hailstorm days and variations in areal extents of damaging hail in 1000- and 4000-mi^2 regions as defined by different sampling densities and April-October data in 1952-1963 period

	Number of mi^2 damaged for each sampling point									
Number of storm	1000-mi^2 region					4000-mi^2, region				
days per season	9	3	1	05	0 25	9	3	1	05	0 25
Average	6	10	11	12	13	11	16	17	18	19
Maximum	14	19	20	21	21	22	25	28	29	29
Minimum	1	3	3	4	4	5	6	7	9	9
	Number of mi^2 damaged per storm day									
Average	4 5	6 1	110	15 9	18 3	6 3	1 - 1 0 7	22 6	310	36 1
Maximum	21	51	156	200	218	76	242	713	856	913
Minimum	0	0	0	0	1	0	0	0	0	1
	Number of mi^2 damaged per season									
Average	27	59	123	192	237	69	174	385	560	680
Maximum	75	144	316	518	575	208	501	911	1002	1098
Minimum	3	6	13	20	27	17	52	98	169	186

TABLE 2 Per cent of total area of damaging hail in two regions measured by different densities of observation pomts during a crop season

Number of storms days per season	Per cent of damaged area for given number of mi^2 per sampling point $1000\text{-}mi^2$ region 9	3	1	05	$4000\text{-}mi^2$ region 9	3	1	05
Average	11	25	67	85	10	26	70	86
Highest	13	30	75	91	13	28	77	96
Lowest	8	20	62	80	9	23	64	81

TABLE 3 Density of surface hail measurements in various hail study areas

Study area	Years of operation	Number of measurement pomts (observers and/or hail pads)	Size of study area (mi^2)	Area represented by each point (mi^2)
South Dakota-Iowa-Minnesota (Frisby, 1963)	1961	22	7,500	3410
Southwestern South Dakota (Stout and Changnon, 1966)	1966	91	3,000*	33 0
Central Illinois (Wilk, 1961)	1958-61	1000	22,250	22 3
Northeastern Colorado (Schleusener, 1962)	1959	200	3,400	' 17 0
Northwestern North Dakota (Koscielski, 1967)	1967	63	980*	15 6
Southwestern North Dakota (Butchbaker *et al*, 1966)	1965	90	1,340*	14 9
Western Nebraska (Smith *et al*, 1967)	1966	160	1,300*	81
Central Alberta (Summers and Paul, 1967)	1962-66	5000*	22,000	4 4
Eastern Illinois (Changnon *et al*, 1967)	1967	135	400	2 9
South Africa (Carte, 1963)	1962-63	800	1,000	13
Oregon (Decker and Calvin, 1961)	1959	230	145	0 6

* Approximate value (true value unknown)

damaging hail as did 1 point in 9 mi^2 In one year (1953), the $1000\text{-}mi^2$ area had 21 damaging hail days, as denned by 1 observation point per 0 25 mi^2, whereas a density of 1 point per 9 mi^2 detected damaging hail on only 7 days

The average values for the areal extent of damaging hail on storm days also shows a considerable variation with sampling density (Fig 2) In the $4000\text{-}mi^2$ area, 16,000 sampling points (0 25 mi^2 per point) indicated that the average daily areal extent of damaging hail was 36 mi^2, whereas 445 points (9, mi^2 per point) measured only 6 3 mi^2 of damaging hail per day Thus, on the average, a study area with 1 point per 9 mi^2 will measure only 18% of the actual daily areal extent of damaging hail and an area with 1 point per 3 mi^2 will measure only 30% of the daily damage area

The crop-season averages m Table 1 were expressed as percentages of the total damaged hail area, as defined by 4 points mi^{-2}, and these values appear in Table 2 On the average, a hail network with a density of 1 point per 9 mi^2 in a $1000\text{-}mi^2$ area measures 11% of the actual area of damaging hail in a season In one year, this density measured a high of 13% and the 1-year low was 8% A sampling network of 1 point mi^{-2} would measure only about 70% of the damaging hail in a crop season

The number of surface samplmg points in several recent hail studies is shown in Table 3 Values for the area sampled by each point reveal densities ranging from 1 point per 0 6 mi^2 to a. high of 1 per 341 mi^2 Only the African and Oregon studies had a density of points that apparently would provide a reasonably accurate measure of the daily and seasonal areal 'extent of damagmg hail

In summary, the average and extreme values in Tables 1 and 2 indicate the magnitude of the potential measurement errors associated with varying densities of point hail data in Illinois The results also indicate that a network comprised of 1 or more observation sites mi^{-2} is necessary to measure adequately the areal extent of damaging hail

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