STUDIES OF HAIL DATA
IN 1970-72

by

Stanley A. Changnon, Jr., and
Nell G. Towery

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Principal Investigator: Stanley A. Changnon, Jr.

Illinois State Water Survey
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Table of Contents

INTRODUCTION

The Illinois State Water Survey began a hail research program in 1967 that was aimed at developing a proper design for a hail suppression experiment in Illinois. Such an experiment in Illinois was considered to have viable prospects within a national framework since the Illinois hail climate is representative of that throughout the Midwest and the crop-hail losses in the Midwest rank second nationally only to those of the Great Plains.

The Illinois design program was not envisioned to be a hurried effort, but one composed of a series of studies and incorporating a 'building block,' stop-go approach. In the logical sequence of such a program, the initial studies were those considered critical to answering prime unknowns about midwestern hail, and thus essential to proper planning of the later studies of the design program. They included:

1) ascertaining the potential benefits of hail suppression (1969-71);
2) the gathering of basic surface hail data to understand adequately its time-space variability, size and shape of experimental area, density of sampling points, and damage-producing characteristics (1967-72);
3) developing instruments that would provide meaningful measures of surface hail (1967-72);
4) investigating the utility of available 3-cm wavelength weather radars to detect hailstorms in field operations and for evaluation of suppression efforts (1967-69);
5) analyzing historical hail data so as to ascertain the optimum statistical design and evaluation techniques and the probable length of a well-designed program (1967-69); and
6) modeling of hailstone development (1971-72).

All of these initial studies have been performed under state and National Science Foundation sponsorship (NSF GA-482, GA-1520, and GA-4618) and the present grant GA-16917. The research effort of this project has primarily concerned continuation of the 1967-69 field network operations and ensuing analyses, plus studies relating to the 1) potential benefits and economics of hail suppression, 2) varied types of surface hail and rain data, 3) evaluation of hail suppression efforts, and 4) continued refinement of a hail recording gage. An unfulfilled goal was to gather hail data to be used in evaluating the hail detection capabilities of a unique dual wavelength radar system. Unfortunately, this radar first became operational in the fall of 1972 and no hail occurred on the network being operated as part of this project.

This grant was received in May 1970, a date too late to initiate meaningful field operations in 1970. Hence, the major field operations were conducted in the March-October periods of 1971 and 1972.

Background

A hail prevention experiment in Illinois was set as a goal of the Water Survey Atmospheric Sciences Section in 1966 (Changnon, 1969a), and considerable research effort since that time has been directed toward establishing the design for such a program. The operations and research in this project were a continuation of this effort to design properly a hail suppression experiment in Illinois. Certainly, as a result of this and earlier research, the Survey staff has developed considerable expertise on the requirements for hail research in terms of 1) measurements (both from the instrumental and the sampling points of view), 2) statistical evaluation, and 3) economic aspects of hail.

The past Illinois hail studies have produced a wide variety of useful information summarized in several papers and reports. The major study areas have included: radar-hail relationships (Towery and Changnon, 1970; Towery et al., 1970; Rinehart and Staggs, 1968; Rinehart et al., 1968; Staggs, 1968; Changnon, 1969a; and Changnon, 1972b); hail equipment development (Changnon and Staggs, 1969; Mueller and Changnon, 1968); surface rain-hail patterns (Changnon et al., 1967; Changnon, 1968a; Changnon, 1968b; Changnon, 1969b; Changnon, 1971a); crop-damage hail parameters (Changnon, 1969c; Changnon, 1971b; Changnon and Barron, 1971); and the design and evaluation of hail suppression projects (Schickedanz et al., 1969; Changnon and Schickedanz, 1969; Changnon, 1968c; Schickedanz and Changnon, 1970a and 1970b; Changnon, 1970; and Henderson and Changnon, 1972). A very significant result of the operation of the dense Illinois hail network since 1967 has been the discovery that hailswaths are often composed of many sub-structures which have been defined as hailstreaks (Changnon, 1970; Changnon, 1968d). The importance of the discovery of the hailstreak to the evaluation of hail prevention experiments has been emphasized by Weickmann and Schumann (1970).

This latest phase of the Illinois hail research program (NSF GA-16917) covers the last 2 years of research on the continuing hail research effort of the Survey. Basically, the 1970-72 project has been a series of studies, many centering on data from two surface networks. Data and results from the major, (800 mi^2) network effort are presented in the initial portion of the report. A network of this type provides various background data needed in designing a suppression experiment as well as in understanding hail production. The modification, operation, and data for 15 recording hailgages, developed in an earlier grant, are the subjects of the second portion of this report. Then, data and results from a micro-network of hailstools are presented to look at small scale variations in hail and at characteristics of windblown hailstones. The fourth section of the report deals with studies of hail models, crop loss and hail, economic aspects of hail, and evaluation of hail suppression. The final section is a summary with and recommendations including a list of publications derived from this project.

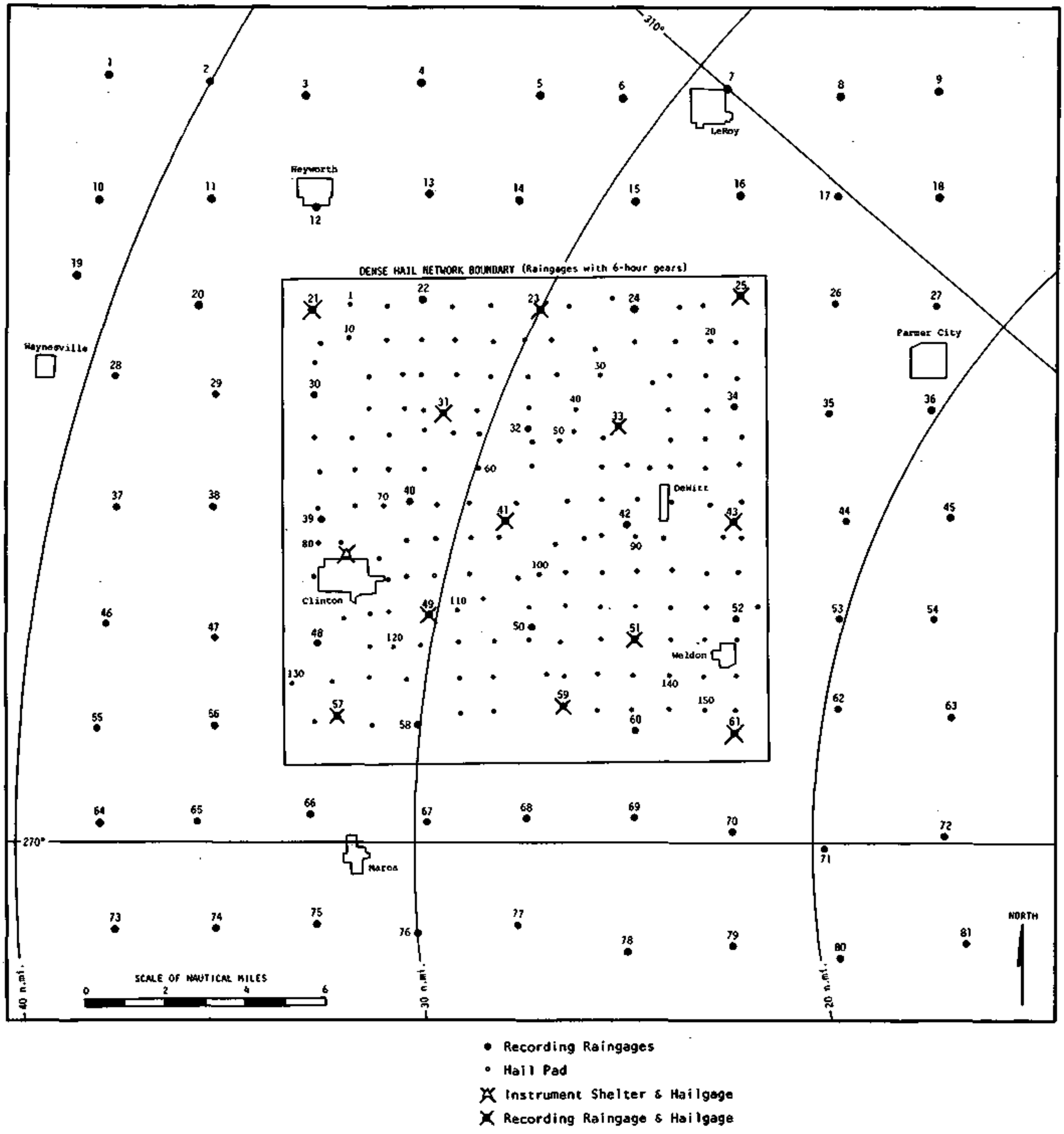


Figure 1. The Eastern Illinois Network for 1972

EASTERN ILLINOIS HAIL-RAIN NETWORK

Instrumentation and Operations

A primary objective of this hail project was to operate a large, relatively hail-rain network in the warm season (March-October) for 2 years (1971-72), and to analyze the data for application in several study areas. Included in these areas were: 1) studies of surface rain-hail patterns; 2) investigations of the mesoscale climatology of hail; 3) operations and evaluation of recording types of hail instruments; and 4) definition of relationships between surface hail and that detected by a dual-wavelength radar system.

The Eastern Illinois Network (EIN) was operated in 1971-72 largely as depicted in Fig. 1. This network included 81 recording raingages modified to record hail (without funnels), and 232 passive hailpads. A hailpad was located at each raingage site (81 total), an additional 151 hailpad-only locations were installed and operated in a 150 mi^2 area within EIN and labeled as the Dense Hail Network (DHN). In the DHN there were 176 hailpad locations (151 + 25 at raingages). In 1972 recording hailgages were added at 13 raingage-hailpad locations in the DHN. In early 1971, 510 people located within the 5-county area enveloping EIN were contacted and 345 agreed to serve as cooperative hail observers for 1971-72. In addition, crop hail losses to crops in the network area were provided by insurance companies. Only the DHN portion of EIN was opened for operation in 1972. This decision was made because of several factors including costs and the fact that the dual wavelength radar was never made operational prior to leaving in April 1972 for operations on the NHRE project. Thus, comparative analyses over the broadest possible area could not be accomplished.

Point and Network Hail Frequencies

There were 18 hail days (as measured at hailpads) in EIN during 1971. The 1971 number in the DHN was 13 with 16 hail days in the Dense Hail Network in 1972. Table 1 gives the monthly frequency of hail days in the DHN.

The point hail frequencies in the 2-year period were near normal with a network point average of 5 days (2.5/year). This was fairly evenly distributed over the 2-year period (frequency of 2 in 1971 and 3 in 1972). Eventhough the average frequency was near normal, the pattern in Fig. 2 exhibits some extreme 2-year variability. Several places on the pattern exhibit differences of 7 or more occurrences at one point and 3 or less at locations one mile away. The point extremes were 2 and 10, a 5 to 1 ratio.

Although the above-average areas (≥ 7 occurrences that are crosshatched in Fig. 2) are widely dispersed in location over the network, they occurred generally in the northern half of the network. The areas of below-normal (5 3) are largely in the southern portions. The above-normal areas totaled 22.5 mi^2 and the below-normal areas was 25 mi^2.

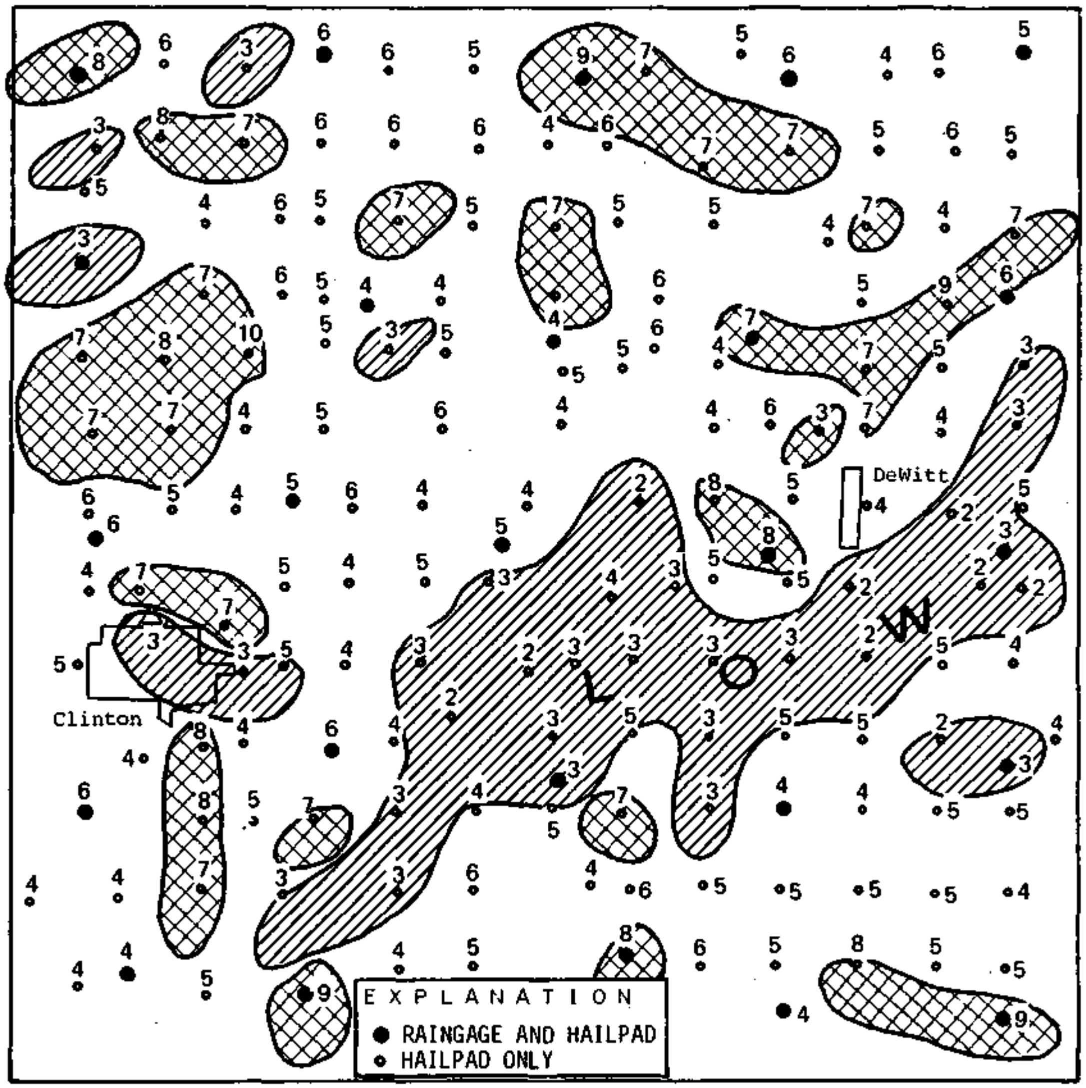


Figure 2. Pattern based on Point Hail occurrences in 1971 and 1972

Table 1. Number of Hail Days in Dense Hail Network ($150\ mi^2$) and Ob server Network.

	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
DHN 1971	0	2	4	5	3	2	2	0	18
DHN 1972	1	3	1	2	3	3	2	1	16
Hail Observer Data (5-County Area)									
Number of Hail Days:									
1971	0	2	5	7	4	2	2	0	22
1972	1	3	1	2	3	3	0	0	13
Number of Reports:									
1971	0	37	57	59	15	1	2	0	171
1972	25	23	3	13	7	12	0	0	83

The cooperative hail observers reported hail on 35 days over the 2-year period (22 for 1971 and 13 for 1972). There were 254 reports of hail submitted for the 5-county area (Table 1). The average size stone reported by the observers was 0.35 inch and the average for the largest size observed was 0.5 inch. The average number of hailstones per square foot was 65, with a minimum of 1, a maximum of 500, and a median of 12. The average hailfall duration based on observer reports was 6.1 minutes, with maximum of 30 minutes, minimum of 1 minute, and a median of 5.

Hailstone Sizes

Table 2 is based on 87,916 hailstones measured from 913 occurrences, labeled as hailfalls, on hailpads over the 2-year period. There were 421 hailfalls in 1971 and 492 in 1972. There is very little difference in the stone size data from 1967-68 and that from 1971-72 as shown in Table 3, the average number of stones on the 1 ft^2 hailpads (a hailfall) was 98 which is 31 less than in 1967-68. However, the median number of stones per hailfall in 1971-72 was 27 which is only 3 greater than for 1967-68. Nine percent of hailfalls in 1971-72 had 5 or fewer hailstones.

Although the percent of total stones is quite similar (Table 3), the occurrence of 1 or more stones of a given size in a hailfall was somewhat higher in 1971-72 than in 1967-68. For instance, for the 1/2, 3/4, and 1-inch sizes, the 1971-72 data indicate these sizes occurred in 88, 50, and 38% of the hailfalls, respectively; whereas in 1967-68, the comparable percentages were 54, 24, and 13. The maximum hailstone sizes recorded in each of the 913 hailfalls were expressed as percent of the total (913), and are listed in Table 3. These show relatively fewer large stones (> 1 inch) in 1971-72.

Table 2. Hailstone Size Frequencies for 1971 and 1972.

	Hailstone Diameter, Inch						
	≤ 1/8	1/4	1/2	3/4	1	>1	Total
Number of Stones:							
1971	32,295	6,589	3,983	640	117	38	43,662
1972	38,572	3,445	2,072	151	12	0	44,252
Percent of Total:							
1971	73.9	15.0	9.1	1.5	.003	.001	
1972	87.1	7.8	4.7	.003	.0003	0	

Table 3. Frequency of Hailstone Sizes in 1971-72 with Comparative Data for 1967-68 Network Data.

	Stone Diameters, Inches						
	< 1/8	1/4	1/2	3/4	1	>1	Totals
Percent of Total Stones	81	11	7	0.9	0.1	0.04	--
(Percent in 1967-68)	77	11	9	2	0.8	0.2	--
Average Number of Stones Per Hailfall (on 1 ft^2)	79	11	7	0.9	0.1	0.04	98
(Average for 1967-68)	100	14	12	2	1	0	129
Median Number of Stones Per Hailfall (on 1 ft^2)	24	3	0	0	0	0	27
(Median in 1967-68)	21	2	1	0	0	0	24
Percent of Hailfalls When ≥ 1 Stone of Given Size Occurred	100	100	88	59	38	6	--
(Percent in 1967-68)	94	72	54	24	13	8	--
Maximum Number of Stones Per Hailfall (on 1 ft^2)	1146	186	215	56	17	7	1627
(Maximum Values for 1967-68)	1240	202	258	108	25	11	1844
Percent of Hailfalls When Given Size was Maximum Size (on 1 ft^2)	21	25	38	11	4	1	--
(Percent for 1967-68)	22	24	30	11	6	7	--

Hailstreaks

Hailstreaks are areas of hail continuous in space with temporal coherence; that is, they represent a single hail volume produced in a storm and its resulting surface pattern (Changnon, 1970). These were developed from the 1971-72 EIN data, and their values were compared with those obtained in 1968-69.

Table 4 presents results for the 1971-72 hailstreaks. There were 205 hailstreaks in 1971-72, but 60% of those were defined by only 1 pad location and are thus poorly defined in areal extent. Only 24% extended across 3 or more points. Areal extents and mean energies of these 51 better-defined hailstreaks appear in Table 3.

Their average (6.9 mi^2) and median (4.8 mi^2) sizes are considerably less than for 1967-68 when the average and median were 15.8 mi^2 and 7.9 mi^2, respectively. There are two possible explanations for this difference. The first and probably most plausible is the network size and density (hailpad) differences. Most of the hailstreaks defined in 1971-72 were based on data from the DHN which was a more dense network than existed in 1967-68. Hence, better spatial definition could be attained in 1971–72. The second possible explanation is that the 1971-72 sample is too small (53 hailstreaks) to be adequate in calculating meaningful average and median sizes of hailstreaks. The 1971-72 data definitely indicate that the hailstreaks are somewhat smaller than had been calculated for 1967-68, and if the 1971-72 results are correct, it indicates that very dense (1 or more hailpads per 1 mi^2) networks are needed for suppression experiments verifying on hailstreaks.

In 1971-72, 74% of the hailstreaks had energy values > .0101 ft lb/ft^2. Only 42% of the 1967-68 hailstreaks had energies of that magnitude. The average, median, and maximum energy values from the 51 hailstreaks in 1971-72 are comparable with those in 1967–68. The average energy of 0.1780 ft lbs/ft^2 compares with 0.2247 in 1967-68, and the maximum hailstreak energy (1.0722) for 1971-72 was 1.7619 versus 1.1508 for 1967-68.

It is interesting to note (Table 4) that the energy values for 1971 are markedly different than those for 1972. This is explained largely by the differences in stone sizes for the two years (Table 2). For 1971, almost 74% of the stones had diameters less than 1/4 inch, and in 1972 87% of the stones fell into that class. There is also a remarkable difference in the 1/4 inch and the 1/2 inch size classes as 1971 had 24% in these two classes, and 1972 had only 12.5% in these sizes. This is an excellent example of the usefulness of long-term values in hail research and the potential unrepresentativeness in 1 or 2 year samples of field data.

Table 5 presents information on duration, direction of motion, speed, length, and width of hailstreaks, as based on those 81 hailstreaks in 1971-72 defined by 2 or more points. Also shown are values for the hailstreaks measured in 1967-68. In general, the values for duration, direction, and speed are comparable, but the 1971-72 hailstreak width and length values are smaller, as might be expected from Table 4. Median values for the 1971-72 hailstreaks and those for 1967-68 (listed in parenthesis) are 12 minutes (10) for duration, 270° (264°) for direction, 33 mph (20) for speed, 1.4 mi (1.1) width, and 3.7 mi (5.9) for length. The primary reason for the difference in hailstreak area is that the median length of the 1971-72 hailstreaks is shorter by about two miles.

Table 4. Hailstreaks in 1971-72.

	1971	1972	1971 and 1972	Percent of Total
Number of Hailstreaks:				
Defined by 1 Point	83	41	124	60
Defined by 2 Points	16	14	30	16
Defined by ≥ 3 Points	21	30	51	240
Total	120	85	205	100.0
Number of Hailstreaks (Defined by ≥ 3 Points) for Various Areal Extent Categories				
0.1 - 3.9 mi^2	9	13	22	43.2
4.0 - 7.9 mi^2	7	10	17	33.3
8.0 - 11.9 mi^2	3	2	5	9.8
12.0 - 15.9 mi^2	0	2	2	3.9
≥ 16.0 mi^2	2	3	5	9.8
Total	21	30	51	100.0
Average Size	6.8	6.9	6.9	
Median Size	5.4	4.4	4.8	
Maximum Size	28.3	28.6	28.5	
Minimum Size	1.0	1.5	1.3	
Number of Hailstreaks (Defined by ≥ 3 Points) in Various Mean Energy				
.0001 - .0005 ft lbs/ft^2	0	7	7	14
.0006 - .0100 ft lbs/ft^2	2	4	6	12
.0101 - .1000 ft lbs/ft^2	6	14	20	39
> 0.1 ft lbs/ft^2	11	7	18	35
Total	19	32	51	100.0
Average Energy	.3389	.0855	.1780	
Median Energy	.1318	.0212	.0439	
Maximum Energy	1.7619	.6751	--	
Minimum Energy	.0022	0	--	

Table 5. Hailstreak Characteristics for 1971-72[1] and those for 1967-68.

Percentages for Various Classes are Based on Total Hailstreaks

	Duration of Hailstreak, Minutes								
	0-1	2-3	4-5	6-7	8-9	10-11	12-13	14-15	>15
1971-72	0	3.7	3.7	14.8	14.8	7.4	14.8	3.7	37
1967-68	1.6	4.3	8.9	14.7	13.2	12.1	12.1	6.3	26.8

	Direction of Hailstreak Motion, Degrees							
	200-219	220-239	240-259	260-279	280-299	300-319	320-339	340-359
1971-72	0	16.2	25.0	43.7	15.0	0	1.0	0
1967-68	1.5	8.1	28.6	39.2	15.0	3.3	3.9	0.4

	Speed of Hailstreaks, mph								
	1-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90
1971-72	0	14.8	25.9	37.0	22.2	0	0	0	0
1967-68	1.6	15.6	32.9	22.0	18.8	4.8	1.1	1.6	1.6

	Maximum Hailstreak Width, Miles							
	0.1-0.5	0.6-1.0	1.1-1.5	1.6-2.0	2.1-2.5	2.6-3.0	3.1-3.5	>3.5
1971-72	2.4	30.1	21.7	22.9	16.9	1.2	2.4	2.4
1967-68	0.4	37.1	37.9	9.7	2.6	4.0	2.6	5.7

	Maximum Hailstreak Length, Miles							
	1.0-2.9	3.0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	≥15.0
1971-72	38.3	25.9	24.7	3.7	1.2	4.9	1.2	0
1967-68	12.6	16.6	26.5	18.8	9.0	8.5	4.0	40

[1]Hailstreaks defined on 2 or more points with hail.

Table 6 gives various values associated with point hail-rain relationships in all 205 of the 1971-72 hailstreaks. The least and greatest time intervals between the start of rain and hail at points within each hailstreak were summarized. This shows for greatest difference that 77% of the time the hail began within 10 minutes after the rain began. The medians for least and greatest are 3 and 5 minutes, respectively. The 1967-68 hailstreaks study indicated that 50% of the points had hail and rain initiation simultaneously; whereas only 17% of those in 1971-72 had rain and hail initiating simultaneously. However, in the "least difference" category 74% were in the 0 to 10 minutes in 1971-72, and 78% were in this class in 1967-68 period.

Table 6. Point Hail-Rain Relations in all 1971-1972 Hailstreaks.

Percentages for Various Classes Based on Total Hailstreaks

	Time Interval between Beginning of Rain and Occurrence of Hail, Minutes							
	0	1-10	11-20	21-30	31-40	41-50	51-60	>60
Least Difference at any Point in Hailstreak	16.7	57.3	12.5	9.4	0	3.1	0	1.0
Greatest Difference at any Point in Hailstreak	25.0	52.0	11.5	7.3	0	3.1	0	1.0

	Maximum Point Rainfall, Inches					
	.01-.10	.11-.20	.21-.40	.41-.60	.61-.80	≥.81
In Hailstreak	14.4	14.4	30.5	19.2	7.2	14.4
In Associated Raincell(1)	2.7	10.0	39.1	17.3	10.0	20.9

Mean Rainfall in Hailstreaks, Inches						
.01-.10	.11-.20	.21-.30	.31-.40	.41-.50	.51-.60	>.60
17.4	13.8	19.2	13.8	12.6	4.8	18.6

(1)Based on 1971 data only (110 hailstreaks) when the network was larger and associated raincells could be more adequately defined.

Maximum point rainfall values in the hailstreaks and anywhere within the associated raincell entity were used to develop percentage frequencies in Table 6. Accumulation of the percentages for rain in the hailstreaks reveals that 70% of the hailstreaks had less than 0.4 inch as their maximum point rainfall. Median in hailstreak rain values for 1971-72 were 0.33 inch compared with 0.25 inch in 1967-68. The median of the mean hailstreak rainfalls was 0.30 inch compared with 0.19 inch for 1967-68.

Table 7 gives various characteristics of hailstreaks stratified by four major synoptic weather classifications, and is based on all 205 hailstreaks. Cold fronts were the most frequent producer of hail systems with 14 cold-front hail systems as compared to 15 for the other classifications combined. However, the average number of hailstreaks per system with cold fronts is less than that for air mass, although the air mass sample is small.

Cold fronts and warm-stationary fronts were quite similar in their area mean energy, direction of motion, maximum stone size, number of stones produced, and duration of hail. The frontal hailstreaks are larger, produce larger and more hailstones, yield greater energy, and last longer than hailstreaks produced by lows and air masses. Hailstreaks produced in air mass storms did produce more rainfall than did other streaks and this agrees with earlier studies. The point time difference between rain and hail initiation is similar for the air mass, cold front, warm-stationary fronts, but is somewhat greater than for the streaks produced by lows.

Table 7. Hailstreak Characteristics for Basic Synoptic Weather Conditions.

	Air Mass	Cold Front	Low, Waves, & Troughs	Stationary-Warm Fronts
Number of Hail Systems	2	14	3	10
Number of Streaks	20	115	17	73
Average Streaks Per System	10.0	8.2	5.7	7.3
Average Per Condition:				
Duration (Min)	M(1)	11.5	M	17.7
Area (Mi^2)	1.9	2.8	1.7	3.2
Mean Energy ($Ft\text{-}Lb/Ft^2$)	.0267	.2758	.0190	.2310
Speed (MPH)	M	35	M	29.5
Direction	244°	258°	266°	260°
Maximum Stone Diameter, Inch				
Largest	0.33	0.43	0.18	0.46
Smallest	0.19	0.34	0.18	0.30
Maximum Number Stones/Ft^2	43	111	94	115
Point Hailfall Duration, (Min)	2.6	3.3	2.0	3.0
Time Difference (Point) between Rain and Hail Initiations; (Min)				
Greatest	7.1	8.1	13.4	8.9
Least	7.1	6.8	12.6	7.4
Hailstreak Mean Rainfall, Inches	0.57	0.45	0.14	0.27

(1) M - means inadequate data to develop an average.

Effect of Sensing Area Size

One phase of the earlier surface hail studies in Illinois concerned a preliminary analysis of the effect of sensing area size on the measurement of hail energy (Changnon, 1969a). This effort consisted of using data from 90 hailpads, each subdivided and then inter-compared.

Sensing size is a potentially significant problem when hailpad energy-values are used 1) to evaluate hail suppression activities and 2) to design various recording hailgages where cost and feasibility, both relating to the sensing area, are major limiting factors.

To examine the question of optimum size of a sensing area, two activities were pursued in the 1971-72 project. First, four 1-ft^2 hailpads were installed in two locations to essentially form a square of 2 x 2 feet, or an effective hailpad of 4 ft^2. Unfortunately, hail fell on one such array only once and none fell at the other array site. Hence, data adequate for analysis of the 'large' sensing area were not available. •

The other phase of study of sensing area size was based on the analysis of data from the 1-ft^2 hailpads in the EIN. For each of the 913 pads with hail during 1971-72, an energy value was determined for a) each of the four quarters (6 x 6 inch dimension) of the pad. These were classed by position (NE, NW, SE, and SW), and subsequently the energy value for each was multiplied by 4 to obtain a value representative of a 144–in^2 area and thus ready for comparison with the entire 12 x 12-inch pad.

A listing of the frequency of the energy values from the entire pads and those derived from each quarter section (as adjusted by multiplying by 4) appears in Table 8, as sorted into 7 energy classes. All of the quarter pad energy values in the 0 to .0049 class, which included about 50% of their values, were zero (no energy), whereas none of the values from the entire pad were zero. This indicates that each of the 36 in^2 areas did not detect half of the hailfalls that occurred over the 144-in^2 areas. Admittedly, these are hailfalls of little consequence in relation to crop or property damage capability. This tendency for the smaller area to sample a lower energy spectrum also is evident for energies in the range of .0050 to 0.1 ft lb/ft^2. Energy values in this range have been shown to be related to minor, less than 10%, wheat and soybean losses (Changnon, 1971), and thus underestimates are of some concern. In the energy class ranging from 0.1 to 0.7, there are no essential differences between the small area and large area percentages. For the highest energy class, ≥0.7 ft lb/ft^2, the smaller areas all more frequently sampled high values with 5.1 to 6.5% of their values in this high class, whereas only 4.3% of the entire pad values fell in this class. Thus, the small areas sampled large energies 20 (5.1 to 4.3) to 50% (6.5 to 4.3) more often than did the large area.

This tendency for small areas to underestimate low energy values and to overestimate large energy values obviously relates to stone sizes and their spatial distributions. That is, when low energy values occurred only a few small stones fell, often resulting in no stones (and no energy) on some quarter/s of the large (144-in^2) pad. Conversely, when large energy values occurred, more stones fell but only a few large stones (that produced most of the energy) occurred. In this situation, 1 or 2 of the quarter areas normally experienced large stones and their resulting adjusted (multiplied by 4) energy estimates for the 144-in^2 area were relatively larger than that for the entire pad.

If one assumes that the 144-in^2 sensing area provides the better estimate of hailfall energy, the results indicate that the smaller 36-in^2

area misses 50% of very small hailfalls occurring in a square foot, underestimates the number of low energy values, correctly samples the number of moderate to high energy values, but overestimates (by 20 to 50%) the number of extremely large energy values. All of this results because of spatial distribution of hailstones found in the Illinois hailstorms. The relative similarity between the energy distributions for the small and large sensing areas for the energies above 0.1 ft lb/ft^2 (range from 24 to 25%) do suggest that the size difference is not critical for those energy values of greatest significance.

Table 8. Comparison of Distributions of Energy Value for 1-ft^2 Hailpad and 0.25-ft^2 Hailpads.

	Percent of all the Energy Values for a Given Pad, or Section of Pad in a Given Energy Class, ft lbs/ft^2						
	0 to .0049	.0050 to .0199	.0200 to .0499	.0500 to .0999	.1 to .1999	.2 to .6999	≥.7
Entire Pad	35.6	16.5	12.2	10.9	9.2	11.3	4.3
NE ¼ of Pad	50.0	6.6	10.3	8.1	10.0	9.9	5.1
NW ¼ of Pad	52.6	5.3	9.1	9.0	9.1	9.7	5.2
SE ¼ of Pad	50.0	8.3	9.0	8.0	8.3	11.4	5.1
SW ¼ of Pad	50.8	7.6	9.5	7.6	8.6	9.5	6.4

HAILGAGES

Modifications

The 15 recording hailgages installed and operated during the March-October 1972 field program had the same basic design as described in a prior report (Changnon and Staggs, 1969). The Illinois hailgage is a momentum sensing device that is designed to record the time and momentum of individual hailstones, and to operate untended for three 10-minute periods of hail. Operations in 1968-69 revealed certain problems, and several modifications were performed in 1970-71 to obtain more satisfactory field operations and data. The major modifications are listed below:

1) The wire-mesh sensing platform was made more rigid but lighter, and with 18% more open area. The weight of the platform was reduced by 110 grams, and this was done using thin wall aluminum for the rim and the diagonal supports of the sensing platform. The mesh was made less fine to reduce build-up of a water film on it.

2) The sensing platform was lowered slightly below the outer shielding rim to make it less sensitive to the wind.

3) Some internal alignment problems were corrected.

4) The restoring arm and restoring weight were changed slightly to give less friction on the bearings.

5) The electronic package was rebuilt.

Operations

The modification work began in 1971 and was completed for the 15 gages in time for field installation by 15 March 1972. The hailgages were each placed alongside a recording raingage and hailpad, (see Fig. 1), and they were operated until 15 November 1972. Two hailgages were located in Champaign-Urbana for close monitoring. During the 1972 field program the 13 gages in EIN were generally serviced twice weekly (61 visits made to each gage) to closely monitor the gage operations and problems.

Data and Results

The initiation of a 10-minute operational cycle of a gage could be initiated by 1/4-inch diameter or larger hail or by "false starts" due to wind, tampering, or an inadvertent electronic signal. During the 7-month period of operation of the 15 hailgages there were 431 false starts and 19 starts by hail. In comparison, there were a total of 29 occurrences of hail on the hailpads adjacent to the hailgage locations, 10 more than recorded on the hailgages. On 3 of these occasions the hailgage was not functional, and on 7 occasions the hail (on the pads) was too small (≤ 1/4-inch diameter) to start the gages.

An example of the hail record at one gage appears in Fig. 3. The hail began at 2352 CDT and hailstone #2 occurred 10 seconds later followed by #3 in 2 seconds. Each line is made by the revolution of the moving drum (to get a constantly changing base line for clearer analysis) and the revolution speed is 1 rpm. The deflection magnitude is a measure of stone size, and stone #2 was 1/2 inch diameter and stone #3 was 1/4 inch.

Close inspection of the 19 hailgage charts revealed that only 11 charts had usable data. Table 9 is a tabulation of the number of stones by sizes, as recorded by the hailgage and as measured by the adjacent hailpad at each location where usable hailgage information was available. Inspection of this table indicates that the hailgage was reasonably good (if one assumes the hailpad is correct) for stones greater than 1/4 inch diameter, but was poor for stones ≤ 1/4 inch. The hailgages recorded only 14% of the 1/4-inch diameter stones on the hailpads, whereas they recorded 107% of the 3/8 inch stones and 44% of 1/2 inch stones.

One of the primary objectives of the hailgage was to provide more precise information on the duration of hail and on the temporal distribution of hailstones. The average point duration of hail recorded by the hailgages was 3.032 minutes (3 minutes, 2 seconds), and the median duration was 2.781 minutes (2 minutes, 47 seconds). These figures agree closely with the mean values provided by the raingages using hailspikes in the 1967-68 study and

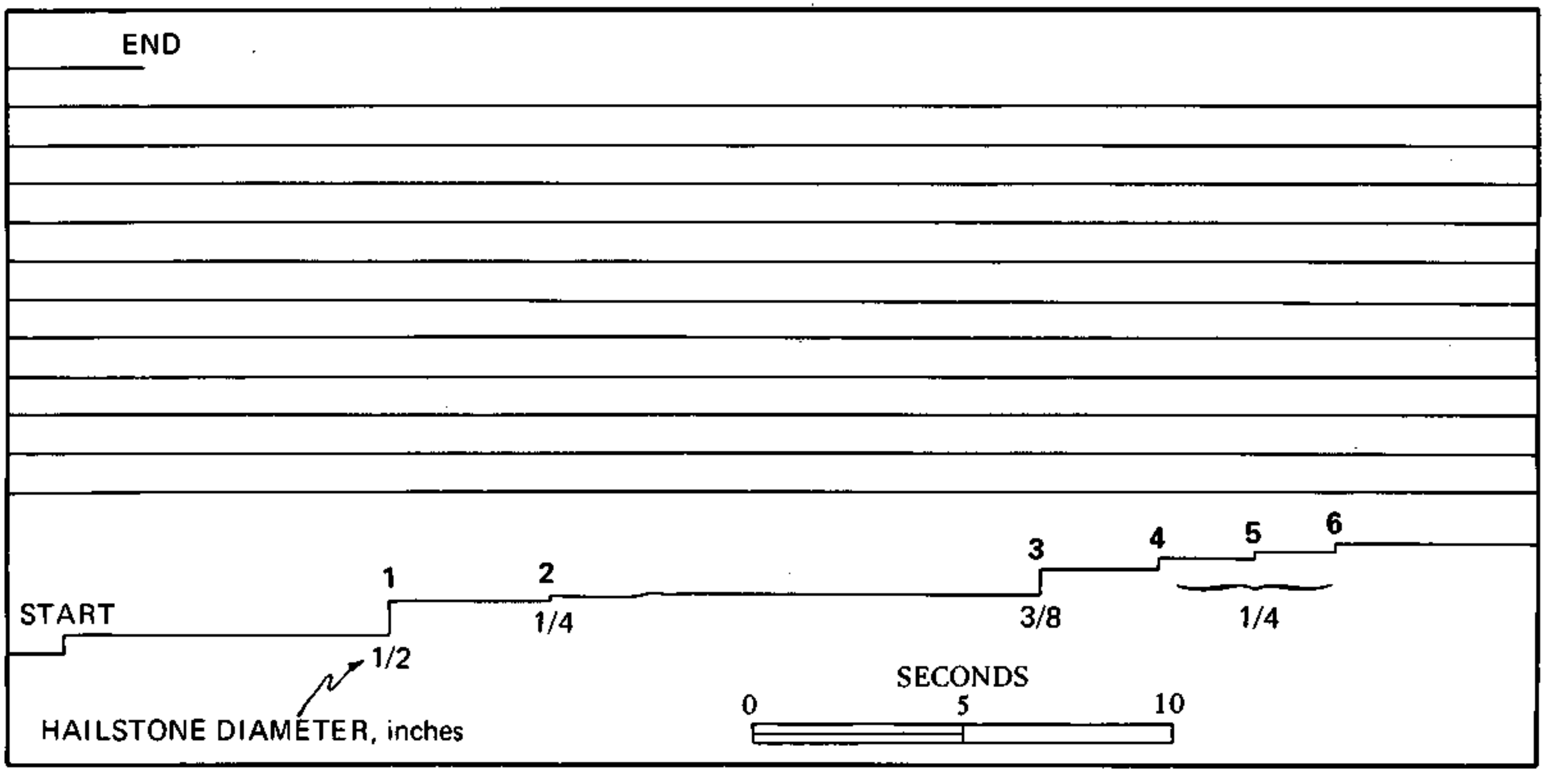


Figure 3. Hail trace at gage 6 (site 23)

for 1971-72 (3.1 minutes). The average time between occurring hailstones was 0.18 minute (about 10 seconds), and the median time was .060 minute (3.6 seconds). The maximum time was 3.02 minutes, and the. minimum time was 0.002 minute.

Table 9. Hailstone Size Frequencies as Measured by Recording Hailgages and Adjacent Hailpads in 1972.

Hail Date	Site		Number in each Size Class, Diameter, Inch ≤1/4	3/8	1/2	>1/2	Total
19 April	51	Hailgage	0	2	0	0	2
		Hailpad	6	0	0	0	6
14 May	49	Hailgage	0	2	0	0	2
		Hailpad	131	2	1	0	134
28 June	23	Hailgage	15	54	0	0	69
		Hailpad	175	65	6	0	246
1 July	Clinton	Hailgage	26	7	0	0	33
		Hailpad	36	12	2	0	50
15 July	31	Hailgage	3	29	6	0	38
		Hailpad	43	10	8	0	61
15 July	33	Hailgage	10	3	2	0	15
		Hailpad	7	2	3	7	19
15 July	43	Hailgage	0	8	1	0	9
		Hailpad	2	0	0	0	2
18 July	61	Hailgage	4	10	0	0	14
		Hailpad	47	16	3	1	67
6 August	21	Hailgage	0	2	0	0	2
		Hailpad	1	0	0	0	1
6 August	23	Hailgage	4	5	1	1	11
		Hailpad	27	11	2	2	42
28 September	59	Hailgage	3	5	1	0	9
		Hailpad	3	0	0	0	3
	Totals:						
		Hailgage	65	127	11	0	203
		Hailpad	478	118	25	10	631

Problems

The major problem with the operation of the Illinois recording hailgage is that it is very wind sensitive. Wind causes many false starts and in some cases gives deflections on the chart similar in magnitude to those of hailstones.

In its present configuration with the sensing platform 8 inches below the outer shielding rim stones that fall with a vertical angle greater than 19° are missed. The wind-related false starts suggest the rim should be even higher above the platform which in turn would cause less sampling of windblown hailstones.

The 0.010-inch pen arm deflection for 1/4 inch stones is essentially very difficult to detect on the chart. The chart drum drive motors need to be thoroughly tested and made more serviceable. Possibly a plug-in type as opposed to the bolted-in type in use.

MICRO-NETWORK HAIL STUDIES

Introduction

Under hail research grant (NSF GA-482), a very dense micro-network for studies of hail variability over short distances was installed at the University of Illinois Airport in central Illinois during the spring of 1967. This network of sensors has been operated thru October 1972. The network, as shown in Fig. 4, has consisted of 7 hailstools installed at 6 sites in a rectangular area having an east-west dimension of 200 ft and a north-south dimension of 1200 ft (an area of 0.01 mi^2). Two of the hailstools, those numbered 5a and 5b, were installed 6 ft apart and were used to investigate differences over a very short distance.

The primary goals of the micro-network operation were twofold. First, information was desired on the small scale, much less than a mile, variations in hail. Secondly, it was desired to obtain data on various aspects of windblown hailstones. To these ends, this portion of the final report presents 1) the basic data for the 13 hail events (hailstreaks) sampled in this network, and 2) various comparisons, by day and for the total sample, to examine the variability in the vertical and azimuth angles of windblown hail. Figures 5 and 6 present base maps of the actual data.

The sensing instrument used in this network, which is considered an improvement over the standard 'hailpad' with its horizontal sensing surface, is called a hailstool. Its design allows for collection of data on windblown hailstones. The hailstool consist of 1) a 2-inch thick layer of polystyrene foam cut in a 12-inch diameter circle and glued to a circular piece of 1/4-inch thick hard fiberboard, and 2) a polystyrene cylinder 12-inch long and 6-inch in diameter that is centered and glued to the base of the upper sensing circular platform, to form a T-shaped device. This hailstool is supported on a 1-inch diameter rod driven into the ground or attached to a fence post. Commercial heavy-duty aluminum foil is wrapped around 1) the upper sensing platform, and 2) around the lower cylinder.

This particular construction and design allow several useful measurements of hailfall. The upper horizontal platform senses hailfall so

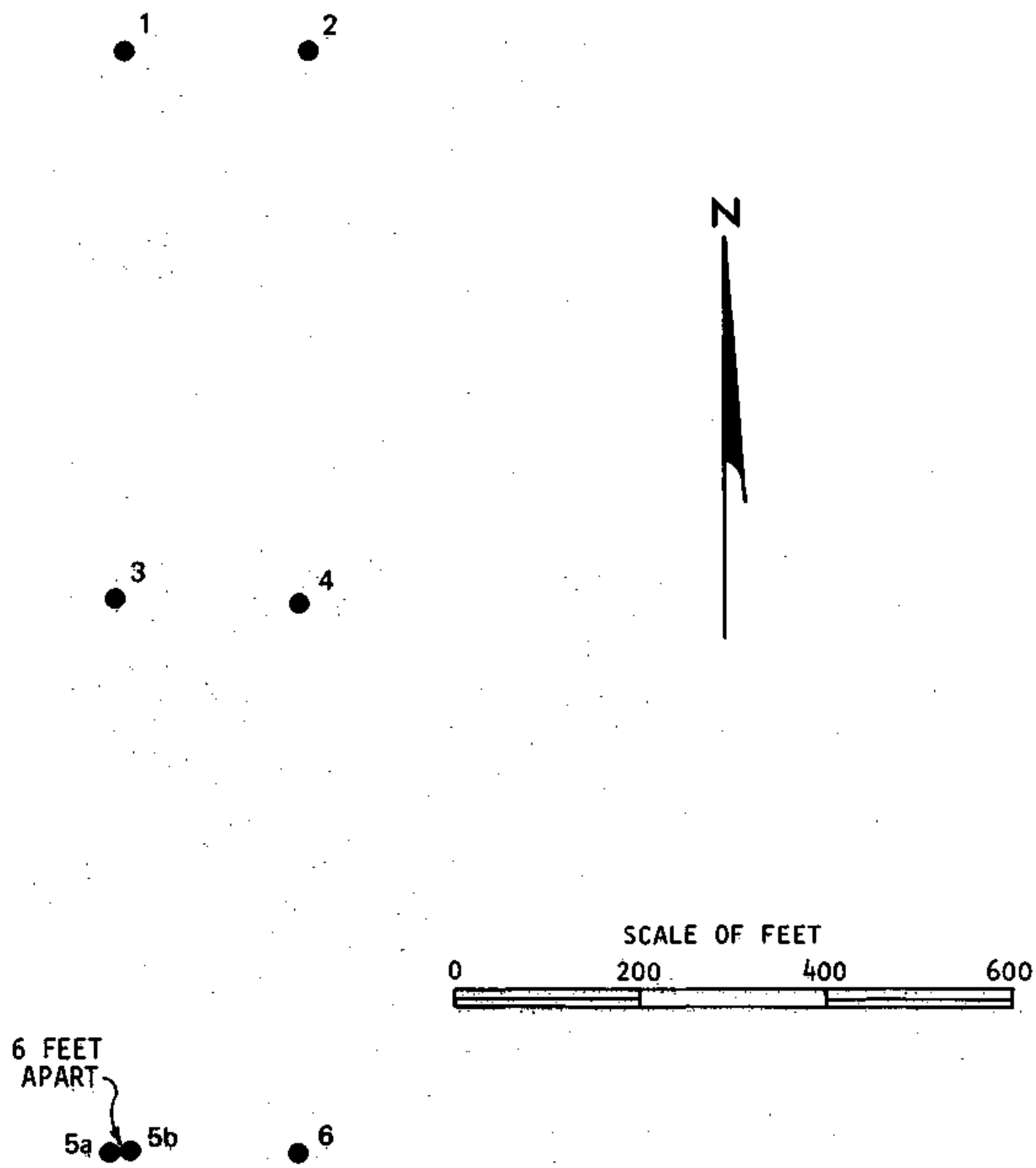


Figure 4. Micro-Network composed of seven hailstools in grass-covered area on the edge of University of Illinois Airport

that stone number, stone sizes, and energy can be calculated in the manner of hailpads used in various other areas. However, the large circular top and the smaller but longer circular sensing area below the top allows measurement of vertical and azimuth angles of windblown hailstones. If stones fall vertically or within 13 degrees of the vertical, none hit the lower cylinder due to the overhang, but if they are windblown sufficiently to fall at angle ≥ 14° from the vertical, they impinge upon the foil wrapped around the lower cylinder and a limiting vertical angle can be assigned. Unfortunately, recorded wind data on the network were not available for most of the hailstreaks.

During the 1967-72 period of operation, 13 individual hailstreaks on 13 different days occurred hitting one or more of the 6 sites in this micro-network. Six of these occurred in 1967, 2 in 1968, 2 in 1969, 2 in 1970, 1 in 1971, and none in 1972. The average point frequency in this area of Illinois is 2.5 hailfalls per year (a 6-year average of 15 days) so the sampled number was below average for a point and more below average for an area. Site 1 had 10 hailfalls, site 2 had 9, site 3 had 9, site 4 had 10, and sites 5 and 6 each had 10 hailfalls.

In analyzing each hailstool, the number of hailstones on the upper (horizontal) sensing surface was counted including the number with diameters greater than 0.2 inch. The energy imparted also was calculated based on the stones on the upper sensing platform. If hailstones impinged on the lower, smaller cylinder, the azimuth angle information that was obtained included the extremes of the hailstone hits (for instance, from 200° to 280° may have been the spread on a side), and the centroid of all the hailstone azimuth values. The vertical angle information, as measured down from straight up, obtained included the maximum vertical angle measured, and the centroid of the vertical angles of all the stones on the side of the cylinder. Thus, there were 5 angular measurements made of the windblown hailstones. The number of windblown hailstones that hit the side 'of the cylinder was also recorded.

In general, the data from the 13 hailstreaks were analyzed either on the basis of all the values from all.streaks, or on the basis of in-streak values. The essence of these analyses were to describe the natural variability for various combinations of conditions. For example, the analysis of hailstone frequencies included the range in number of stones on the horizontal surface (top), the range of values in the number of windblown stones (hitting the sides), and then the relationship between these distributions.

Hailstreaks

There were 13 hailstreaks sampled in that 1 or more of the 6 hailstool sites (sites 5a and 5b were not counted as separate locales in this definition) had hail on its top surface. Interestingly, only 6 of the 13 events produced hail at the 6 sites in the 0.01 square mile sampling area.

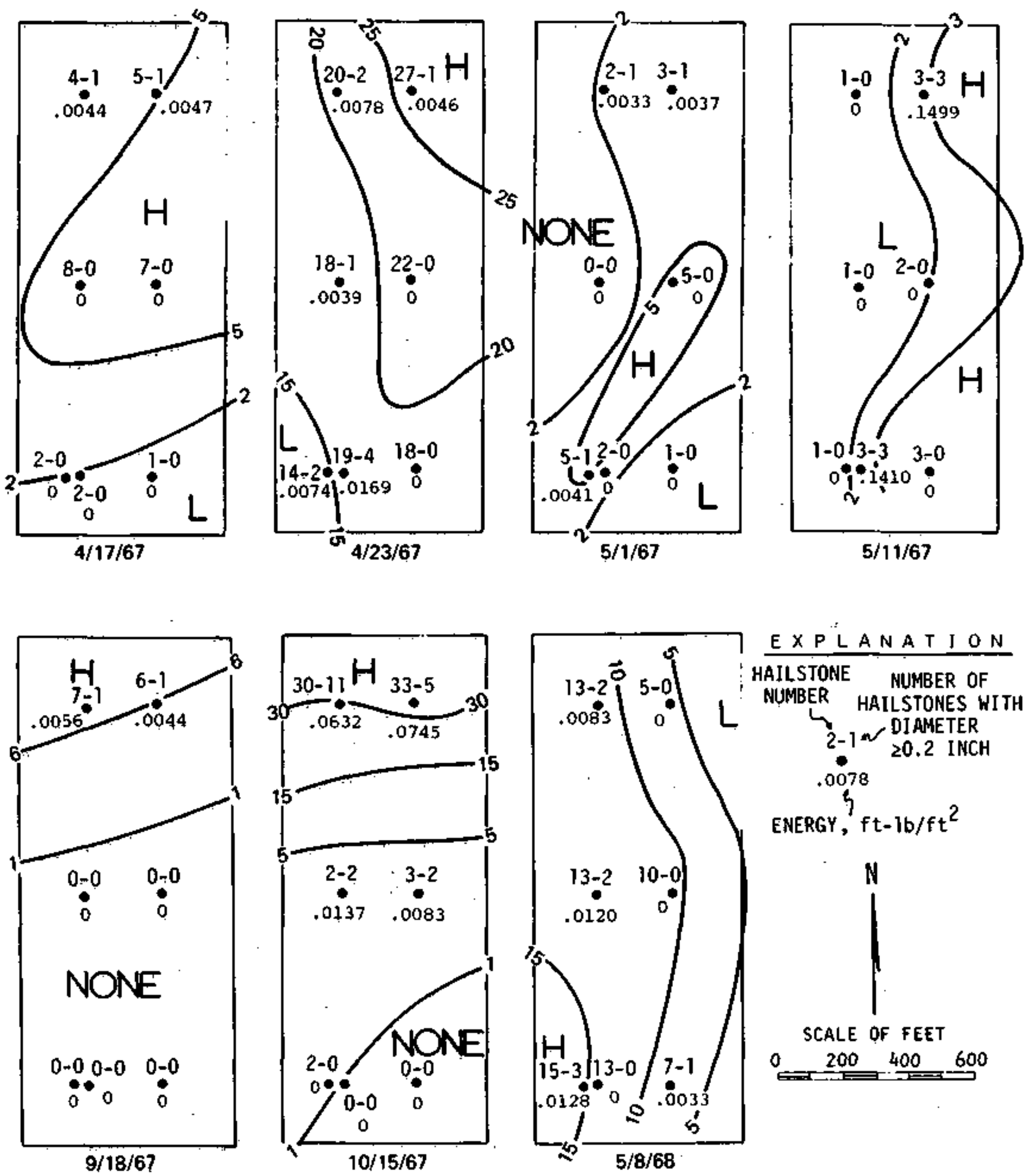


Figure 5. Maps of 13 hailstreaks showing hailpad data for the horizontal (top) sensor and hail frequency patterns. Data shown at each stool includes the total number of hailstones, the number with maximum diameters >0.2 inch, and the energy.

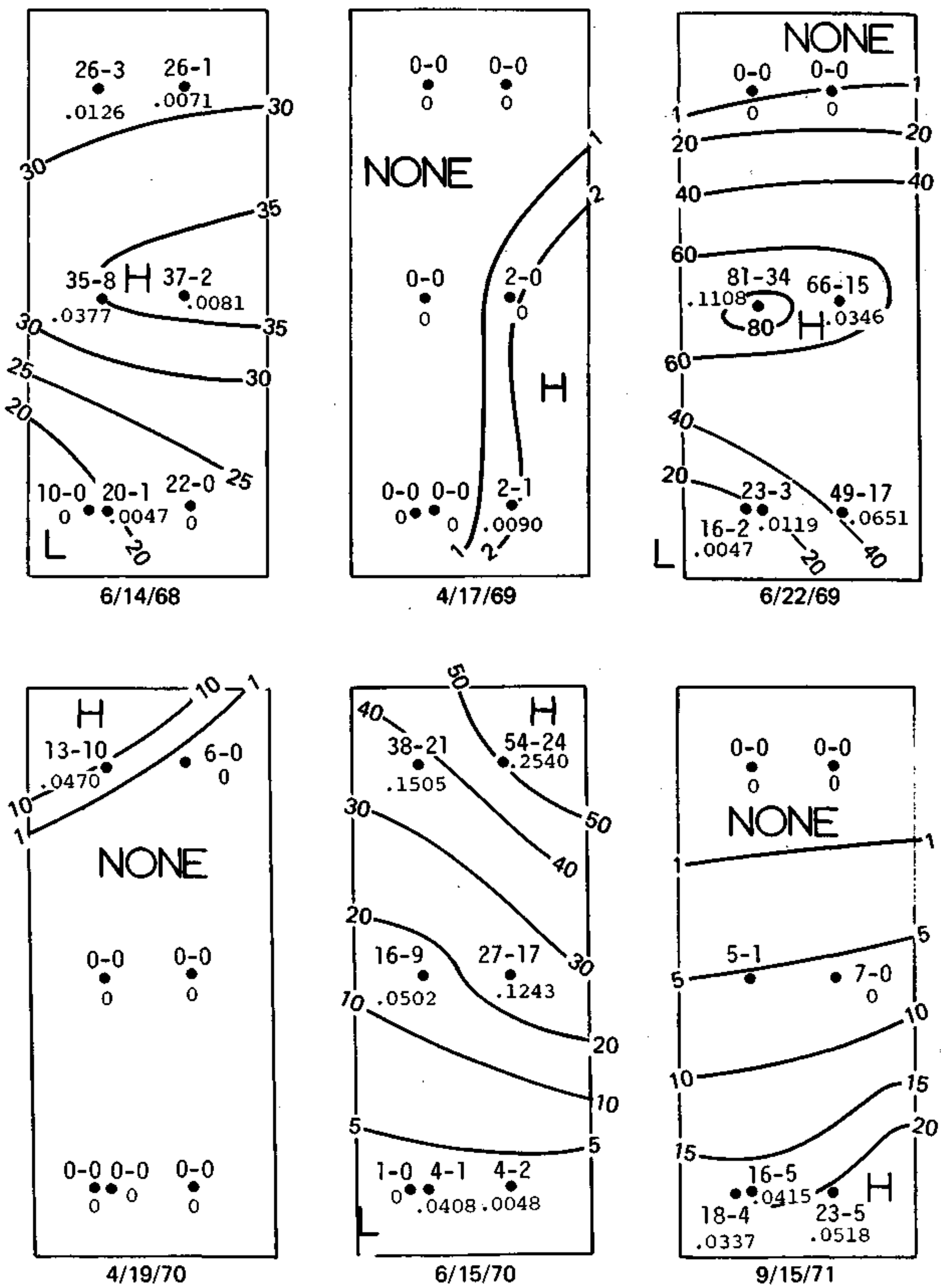


Figure 5 — (Continued)

Table 10. The Number of Sampling Sites in Network with Hail on the 13 Hailstreaks Sampled.

Number of Sites with Hail	Number of Hailstreaks
1	1
2	2
3	0
4	2
5	2
6	6

As shown in Table 10 and Fig. 5, the hailstreaks crossed less than half of the sampling area on 3 of the 13 occurrences. Examination of the 13 hailstreak patterns in Fig. 5 reveals the highly variable nature of the hailfalls in the small network. West-to-east dominated distributions existed in 4 patterns and north-to-south type patterns existed in the other 9 hailstreaks.

Ten of the 13 hailstreaks produced windblown hailstones at 1 or more hailstools. In 3 hailstreaks, windblown hail occurred at all 6 sites. Interestingly, none of the hailstreaks that affected the network were sufficiently narrow (less than 1200 feet) to have both edges defined.

Frequency of Hailstones at a Point

With 13 hailstreaks and 7 hailstools, the possible number of hailstools with hailfalls was 91 (13 x 7), but the number with hailfalls on their horizontal surfaces was only 68. Their frequencies of hailstones, sorted into class intervals, are shown in Table 11. The average number of hailstones per hailstool (with hail) was 14, but the median was 9 stones per hailfall. The maximum number at a point was 81. The average number of hailstones with maximum diameters of 0.2 inch or greater was 3 per hailstool, and the maximum number of these at any one point was 24 (see Fig. 5, the streaks on 22 June 1969 and on 15 June 1970).

The number of hailstools with 1 or more windblown hailstones was 41 (60% of all hailstools with hail on their top). The point (side) frequencies of windblown the hailstones is shown in Table 11, sorted into class intervals. The average number on a side (given that 1 or more stones hit the side) was 8 (6 less than the top average), and the median value was 6 windblown hailstones. The greatest number to hit a side was 26 hailstones.

Table 11. Relationship of Stone Frequencies on Hailstool Top Surface and Side Surface, 1967-72.

Frequency for Given Numbers of Stones on Top Surface	Frequency for Given Numbers of Stones on Side of Hailstool							
	0	1-5	6-10	11-15	16-20	21-25	26-30	Total
1- 5	19	5	4					28
6-10	3	3	1	1				8
11-15	1	1	3	1				6
16-20	1	2	2	3		1		9
21-25		2	1		1			4
26-30	1	1	2	1				5
31-35	1	1						2
36-40	1		1					2
41-50			1					1
51-60							1	1
61-70			1					1
71-80								0
81-90					1			1
	27	15	16	6	2	1	1	68

Comparison of Windblown and Non-Windblown Hailstone Frequencies

The relationship between top (vertical and windblown) and side (windblown only) stone frequencies is revealed in Table 11. Four of the 41 hailstools with windblown hailstones had more stones on the sides than on the top surface. The average ratio of the hailstone top frequency to the side frequency, as based on the 41 stools with top and side stones, was 3.7. However, the sensing area of the top surface is 1.57 times greater than that of the side surface (assuming all stones come from 1 azimuth), making it necessary to adjust the side frequency in order to obtain a meaningful comparison. Therefore, for each hailstool with windblown stones, their number was multiplied by 1.57 to get an estimate of a windblown total comparable to the top total. The average ratio of the top's stone frequency to the side 'adjusted' frequency was 2.3. After the side area adjustments were made to the 41 values, only 10 had side frequencies equal to or greater than their top frequencies. The adjusted T/S ratios based on the adjusted ratios varied from 0.1 (10 times more on the side than top) to 10.0.

Since the windblown stones also impact on the top surface (and are counted with any non-windblown stones), the number of non-windblown stones is = T - S_{adj}. The number of windblown ($\geq$ 14 degree vertical angle) stones were expressed as a percent of the total hailstones at each hailstool (S_{adj} / T), and the frequency distribution appears in Table 12. The median is 66 percent.

Table 12. Percent of Total Hailstones at a Point (Hailstool) that were Windblown, Sorted into Class Intervals.

Number of Hailfalls for each Percent Class Interval										
1-10%	11-20%	21-30%	31-40%	41-50%	51-60%	61-70%	71-80%	81-90%	91-99%	100%
1	5	2	5	1	3	6	4	1	1	12

Azimuths of Windblown Hailstones

The azimuths of all windblown (side hits) stones were determined at each of the 41 hailstools with 1 or more such stones. A centroid angle of all the stones was determined and the maximum angular of values was also measured. These values are shown in Fig. 6. Examination of the centroid arrows reveals a) great in-streak variability, and b) great differences between hailstreaks.

The centroid angles were sorted into 20-degree class intervals and their frequencies appear in Table 13. The median of the 41 centroid values was 320 degrees, with individual centroid angles varying from 204° (see pattern for 11 May 1967, Fig. 6) to 20° (see 14 June 1968, Fig. 6).

Table 13. Distribution of Azimuth Angle Centroids of each Hailstool with Windblown Stones, 1967-72.

Number Per Angular Class Interval									
201°-220°	221°-240°	241°-260°	261°-280°	281°-300°	301°-320°	321°-340°	341°-360°	0°-20°	Total
3	4	5	5	3	7	4	9	1	41

The in-storm variability for the 10 hailstreaks with windblown stones is revealed in Table 14. The median of these values is 30°. When all sites had windblown stones, the smallest difference was 15° and the greatest was 34°. The average angular spread in the stones was 85°, and it varied from a low of 5 degrees on 1 hailstool (site 3 on 15 June 1970) to a high of 177 degrees on site 2 on 23 April 1967 (Fig. 6).

Examination of the centroid azimuth arrows on Fig. 6 for each of the 10 hailstreaks reveals directional consistency across the network in a few hailstreaks (23 April 1967, 15 October 1967, 8 May 1968, 22 June 1969, and 15 June 1970). However, quite variable wind-related patterns are shown on Fig. 6 for 1 May 1967, 11 May 1967, 18 September 1967, 14 June 1968, and 15 September 1971.

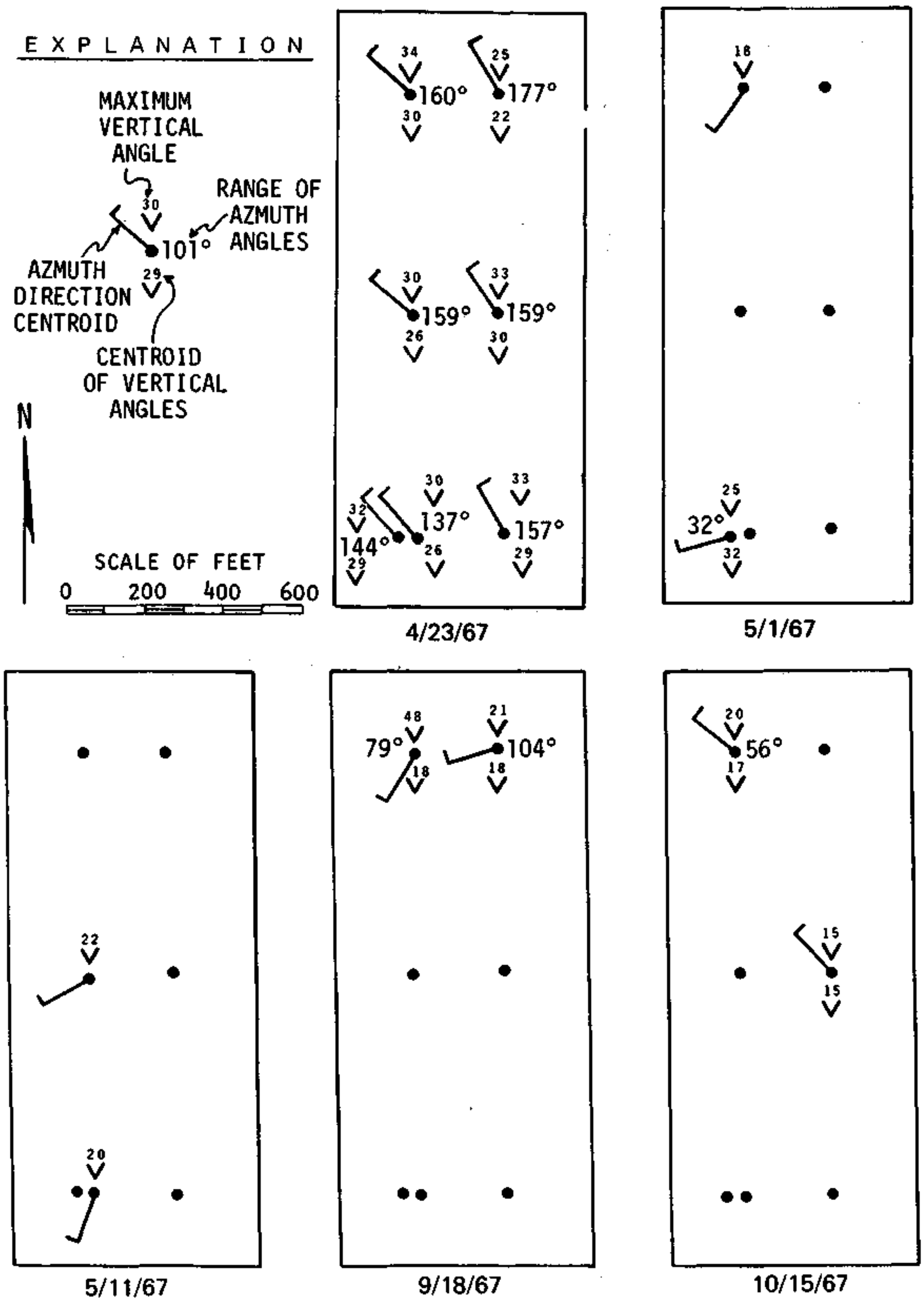


Figure 6. Maps of 10 hailstreaks with wind-blown stones showing hailpad data for the vertical (side) sensor

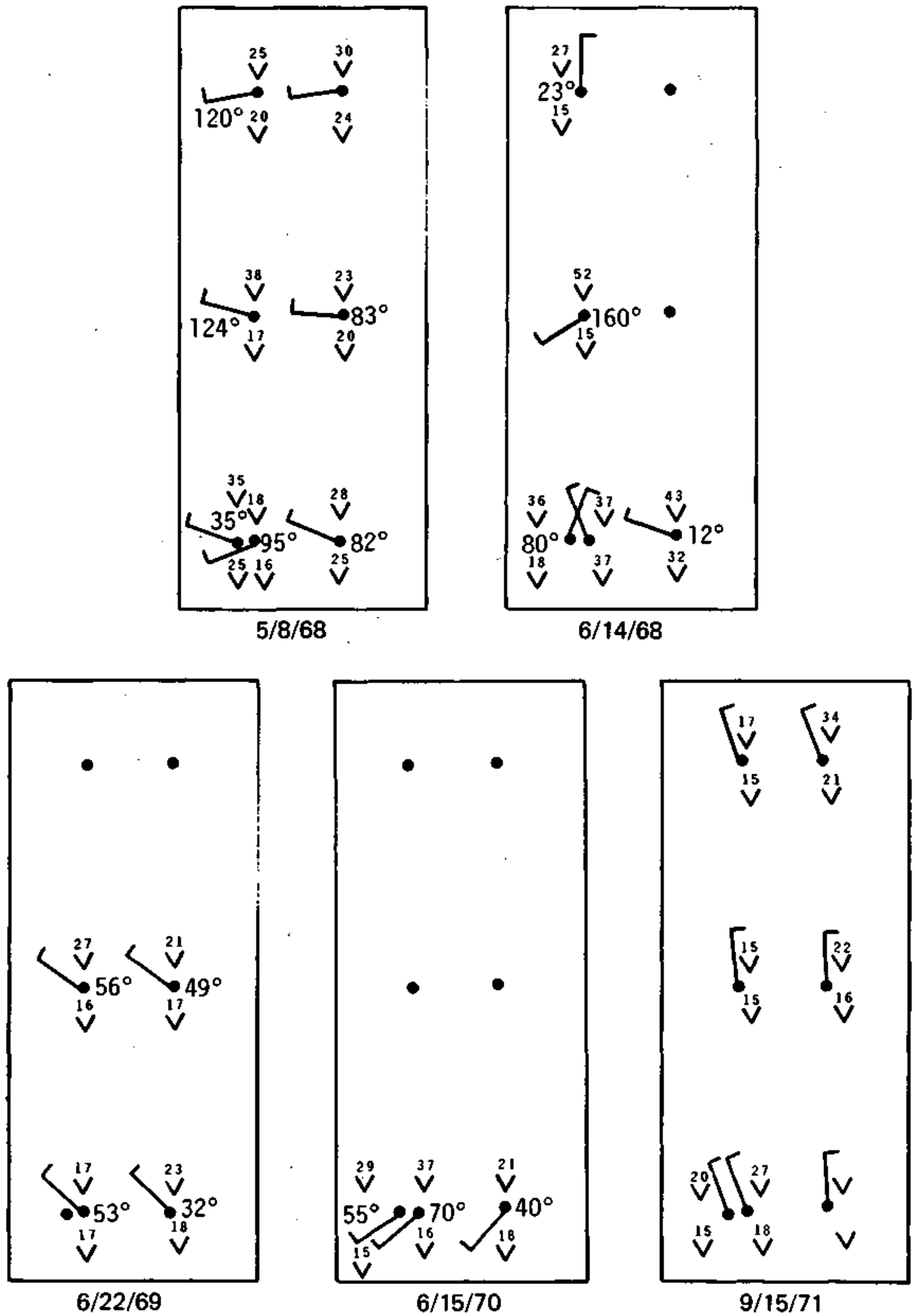


Figure 6 — (Continued)

Table 14. Ranges (in Degrees) in the Centroids of Azimuth Angles on an Individual Hailstreak Basis[1].

Date	Number of Hailstools with Windblown Stones	Measured Extremes of Centroids for Hailstreak	Maximum Difference, Degrees	Median Angle
4/23/67	7	300°-334°	34	325
5/ 1/67	2	235°-263°	28	249
5/11/67	2	204°-247°	43	226
9/18/67	2	205°-250°	45	228
10/15/67	2	308°-315°	7	312
5/ 8/68	7	250°-281°	31	270
6/14/68	5	241°-020°	140	350
6/22/69	4	300°-311°	11	305
6/15/70	7	345°-360°	15	355
9/ 5/71	3	220°-241°	21	235

(1)Based on 2 or more hailstools with windblown stones

Vertical Angles of Windblown Hailstones

The vertical angles of all windblown hailstones were determine at each of the 41 hailstools with 1 or more such stones. A centroid angle of all the stones was determined, and the maximum vertical angle was also listed for study. Vertical angles were assigned based on an assumption that the hailstone fell just beyond the edge of the upper platform, and the angles so calculated must be considered a potential underestimate of the true vertical angle since the hailstone could have come at greater angle.

Table 15. Frequency Distribution of Vertical Angles of Windblown Hailstones, 1967-72.

	Number of Hailstool Values Per Class Interval of Vertical Angle						
	14°-20°	21°-28°	29°-35°	36°-42°	43°-49°	50°-56°	Total
Centroid[1]	26	9	5	1	0	0	41
Maximum[2]	9	14	11	4	2	1	41

(1)Center of concentration of all stones

(2)Greatest vertical angle (up = 0°) on each hailstool

The centroid vertical angles, sorted into 10-degree classes beginning with 14 degrees (the minimum possible angle formed by the hailstool dimensions), appear on Table 15. The median average of these 41 centroids was 20 degrees (Table 16) with extremes of 15 to 32 degrees. The maximum vertical angles measured are also sorted into classes (Table 15), and their average was 28 degrees (Table 16) with extremes of 15 to' 52 degrees.

Table 16. Averages and Extremes for Vertical Angles of Windblown Hailstones.

	Centroid Angle, Degrees	Maximum Angle, Degrees
Average	20	28
Maximum	32	52
Minimum	15	15

Variations in both vertical angles determined between points on an individual hailstreak basis are shown on Fig. 6 and in Table 17. These exhibit some variability, but the average of the range of greatest differences in centroid values (Table 17) is 6 degrees or 8% of the possible range (13° to 90°). The average in the maximum range of azimuth centroids (per hailstreak), as determined from the values in Table 14, is 38 degrees or 11% of the maximum possible range (360°).

Table 17. Variations in the Centroid of Vertical Angles and in Maximum Vertical Angles on an Individual Hailstreak Basis.

		Greatest Measured Differences,°		Range of Greatest Difference,°		Median Angle,°	
Date	Number of Hailstools	Centroid Angle	Maximum Angle	Centroid Angle	Maximum Angle	Centroid Angle	Maximum Angle
4/23/67	7	22-30	25-34	8	9	29	32
5/ 1/67	2	18-25	18-25	7	7	22	22
5/11/67	2	20-22	20-22	2	2	21	21
9/18/67	2	18-18	21-48	0	27	18	35
10/15/67	2	15-17	15-20	2	5	16	18
5/ 8/68	7	16-25	18-38	9	20	20	28
6/14/68	5	15-37	27-52	22	25	18	37
6/22/69	4	16-18	17-27	2	10	17	22
6/15/70	7	15-21	15-34	6	19	16	22
9/ 5/71	3	15-18	21-37	3	16	16	29

Comparison of Hailfall Measurements at Close Range

The data for hailstools 5a and 5b (Fig. 4), although based on only 13 possible incidents, allow for approximations of differences in hailfalls across a 6-foot distance. The differences noted can be attributed to natural small-scale variability and possibly to inadequacy in the sampling devices (size and/or shape). The number of samples were too small for a correlation analysis, but graphical representation of the results offers some interesting observations.

As shown in Fig. 7, there was 1 hailfall occurrence when one stool (5a) had hail (2 stones) with none at the other (5b), and 3 network hailstreaks when there were no stones at either. Comparison of windblown stones (Fig. 7) shows a moderately good relationship, but there were 3 hailstreaks that produced windblown hailstones at only 1 of the 2 hailstools. Differences per streak in the centroids of their azimuth and vertical angles also were examined for the 5 streaks when both hailstools had windblown stones. The 5 differences in azimuth angles were 0°, 3°, 5°, 28°, and 30° (an average difference of 13°), and those for the vertical angles were 1°, 2°, 3°, 9°, and 19° (an average of 7°). The azimuth average difference of 13° is less than that based on all hailstools (per hailstreak) of 38 degrees, but the average difference in the centroid elevation angle of 7 degrees is the same as that for all the hailstools (per hailstool).

In general, the results indicate that there is some difference between the two sites, but it exists largely when there were very few stones produced.

Energy Values

The energy imparted by the hailstones falling on the top surfaces of the 68 hailstools was calculated, and the values appear on the hailstreak maps of Fig. 5. The point energy values covered a wide range, 0 to 0.254 ft lbs/ft^2, (more than 3 orders of magnitude), but as shown in Table 18, most were quite low. The median value was only 0.0047 ft lbs/ft^2.

Table 18. Hailstool Energy Values Sorted into Class Intervals of Various Size.

Number in Energy (ft lb/ft^2) Class						
0	.0001-.0050	.0051-.0100	.0101-.0500	.0501-.1000	.1001-.1500	.1501-.3000
25	12	8	12	5	4	2

Areal variations in energy values in a given hailstreak also were sizeable, particularly since at least 1 hailstool had a 0 energy value in each of the 13 hailstreaks. The area average energy values were calculated

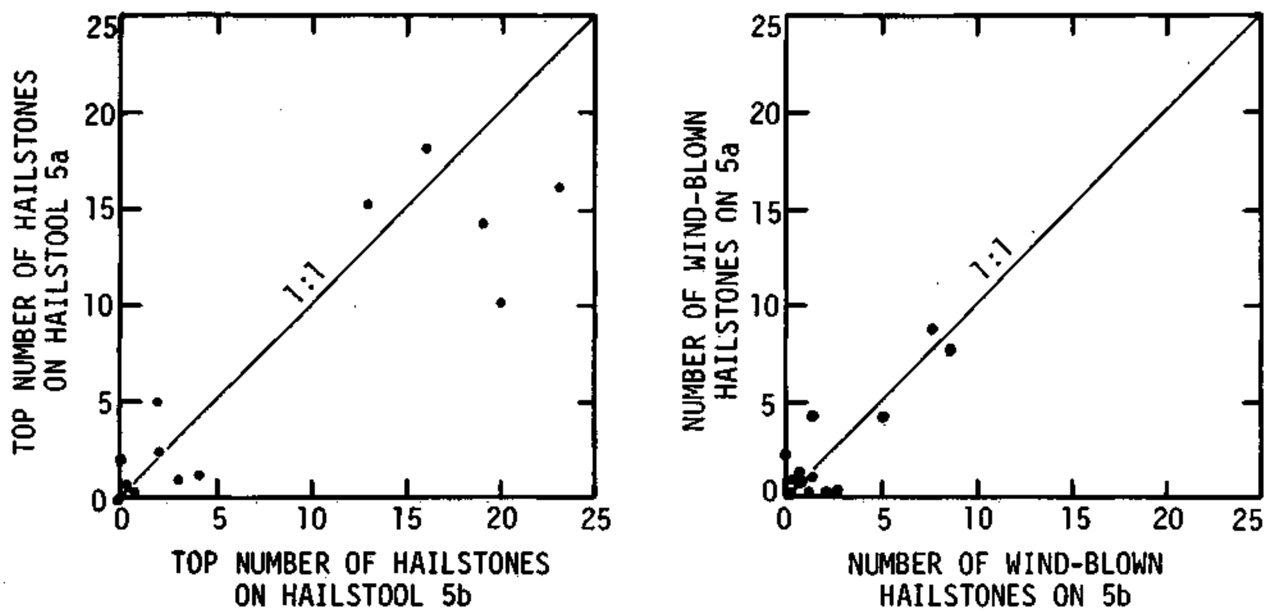


Figure 7. Comparison of hailstone frequencies on the top and sides of hailstools six feet apart

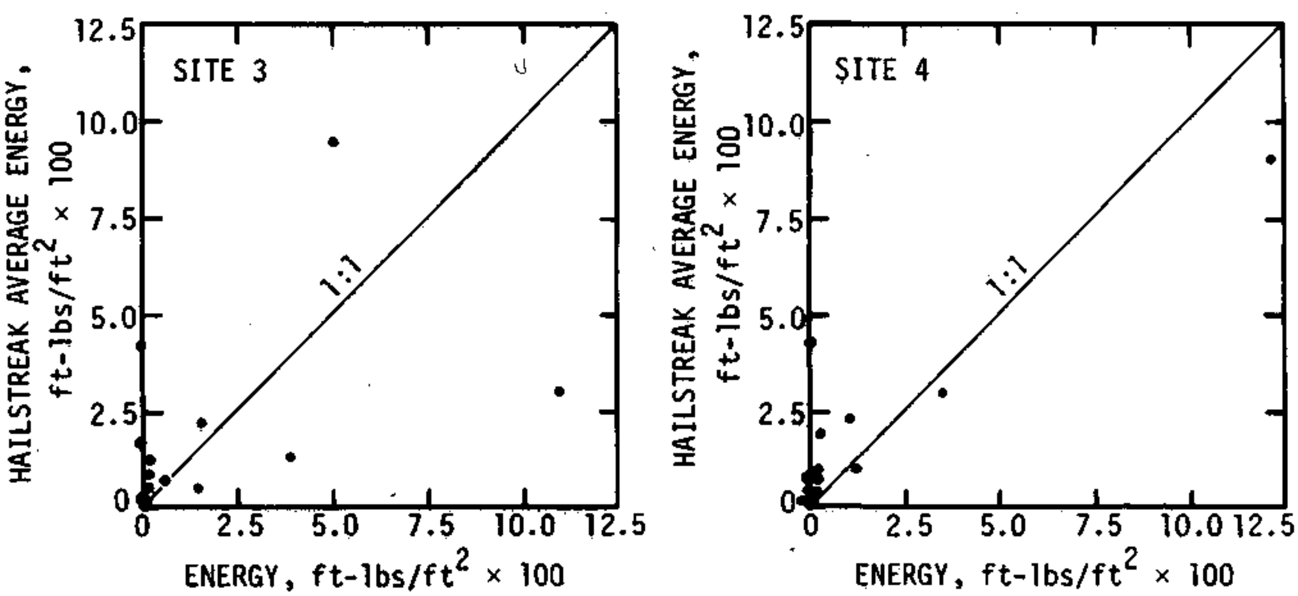


Figure 8. Relationship between point energy values and area mean values

for each hailstreak. These ranged from a low of 0.0013 ft lb/ft^2 to a high of 0.0892 for 15 June 1970. The mean of these averages was 0.0183 and the median was 0.0100.

To illustrate the in-streak variability of energy, the hailstreak energy values at site 3 and at site 4 were compared with the corresponding network average hailstreak energy values. The graphs of these two relationship (Fig. 8) reveal the poor relationships between the point values and the average energy for an area of 0.01 square mile.

OTHER HAIL STUDIES

Storm Modeling

Research into the possible in-cloud processes leading to the development of large hailstones was completed as a part of this project. A description of the research and the results obtained are presented in a paper by Morgan (1972).

Relations Between Crop Losses and Hail Parameters

Research into the degree (percentage) of loss to wheat, corn, and soybean crops adjacent to Illinois hailpads was pursued to ascertain the hail parameters (hailstone number, hailstone size, and/or energy) best related to crop loss. A paper summarizing these results was completed as a part of this project (Changnon, 1971b).

Economic Aspects of Hail

Research with the Crop-Hail Insurance Actuarial Association in the 1960-69 period provided a wealth of data on the economic aspects of hail loss. These data were analyzed on various scales including portions of states, states, and the nation. Available economic data on losses to property in Illinois were also analyzed. Furthermore, two investigations comparing hail losses with those due to other severe weather extremes were performed. The results of these various investigations were used to prepare a paper presented at the 7th National Conference on Severe Local Storms at Kansas City in October 1971, and a paper subsequently published (Changnon, 1972a).

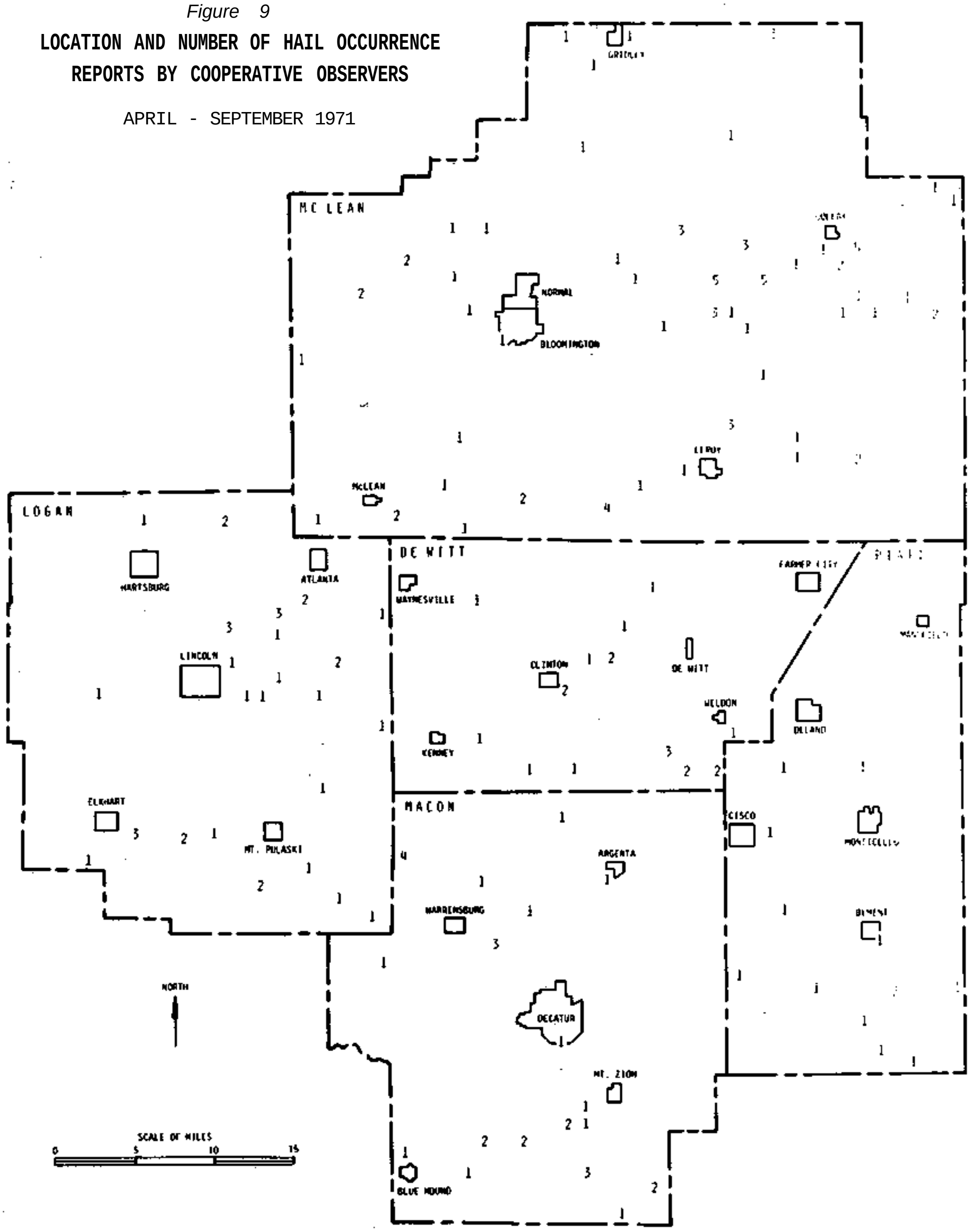
Evaluation of Hail Suppression

Prior Illinois research into statistical methodology of evaluating hail suppression activities had concerned data and studies for Illinois

Figure 9

LOCATION AND NUMBER OF HAIL OCCURRENCE REPORTS BY COOPERATIVE OBSERVERS

APRIL - SEPTEMBER 1971



(Changnon and Schickedanz, 1969; Schickedanz and Changnon, 1970a) and for Colorado (Schickedanz and Changnon, 1970b). The existence of a 2-year commercial hail suppression project in Texas offered an opportunity to apply the methodology. Therefore, as a part of this hail project, the Weather Bureau data and the crop-hail insurance data (courtesy of the Crop-Hail Insurance Actuarial Association) were obtained and analyzed. The results were used to prepare a paper (Henderson and Changnon, 1972).

Communications with Hail Observers

One facet of the Illinois hail project has involved securing hail observers, monitoring their data (quantity and quality), and communication routinely with them to sustain their interest. Detailed letters, explaining the project were prepared twice annually and sent to them. An example of one of the figures sent to them in the letter at the end of the 1971 data season is included as Fig. 10. This shows the distribution of hail reports in the 5-county area which encompasses the EIN. The cooperative hail observers do furnish useful hail data to a field program (see Table 1), and provide a valuable basis for establishing contacts with the local populace when a hail suppression experiment is launched in Illinois. Although the observer activity, if well done, is time consuming, it is considered to be an extremely important "study" for a research project which has as its goals the betterment of the agricultural community in Illinois.

SUMMARY AND RECOMMENDATIONS

The 2-year hail project was able to successfully pursue the goals set forth.

The operation of the Eastern Illinois Network provided the additional surface hail data desired to continue and broaden prior research. The 1971-72 data further verified the existence of great areal-spatial variability of hail. Importantly, this network of hailpads, which was denser than the prior Illinois networks, provided results on hailstreaks which indicated their average size was smaller (1.1 mile wide by 3.7 miles long) than found in the prior Illinois studies. The detailed and extensive network-derived surface hail data now available in Illinois appears adequate for its use in the future design of an Illinois hail suppression experiment. Essentially, the network for such an experiment must be densely instrumented (at least one hail sensor per square mile). The major failure in the 2-year network studies was the inability to perform an evaluation of the capability of the dual wavelength (CHILL) radar to detect hail. This was caused by the lack of radar-operations which were limited to two thunderstorm days in the fall of 1972 when hail did not occur in the network.

Studies of size of sensing areas of hail sensors (using hailpads) showed that the 12 x 12-inch size was superior to 6 x 6-inch size. The smaller size gives unrepresentative results for hailfalls producing very high and very low energies.

Further operation and evaluation of the Illinois recording hailgage proved that useful hail data could be obtained. However, the data are difficult to analyze and the gage has many operational problems mainly relating to the recording of false (non-hail) signals. Construction of added gages for use in a field project would not be worthwhile, although they should be used in any future hail suppression experiment.

A 6-year study of small-scale variations in hailfalls and of windblown hailstones on a micro-network was limited by a small sample of only 13 hailstreaks. The single word describing all the results is 'variability'. There were 13 hailstreaks, but only 6 produced hail at all sites in the 0.01 mi^2 area. Ten of the 13 produced windblown hailstones at 1 or more sites. No hailstreak was totally defined within the network indicating that most hailstreaks are >1200 feet wide. Energy values were extremely variable and point values in a storm were not representative of the network area average storm value. Hailstones were windblown from many directions, ranging from SSW through W, NW, N, and onto NNE. Their vertical angles also varied considerably, but most angles were less 40 degrees. Patterns of windblown stones (directions and vertical angles) were either relatively homogeneous across the network, or were highly variable reflecting very localized variable circulation. Windblown stones occurred 60% of the time when hail fell at a point; and when windblown hail fell, 66% of the hailstones were windblown (fell at vertical angles $\geq$ 14 degrees).

The data from the two networks operated as a part of this research project allow one to estimate the types of errors of estimate obtainable in hail energy measurements, including those due to sensing area size (a matter of inches), across a 6-foot distance, within a 0.01 mi^2 area, and those inherent in a network with a density of 1 point per 1 mi^2.

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