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RELATIONS BETWEEN SUMMER HAILSTORMS IN ILLINOIS AND ASSOCIATED SYNOPTIC WEATHER

by

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Introduction

An investigation was made of various relationships between summer hailstorms and synoptic weather. Studies included the frequency distribution of hailstorms with fronts and other types of synoptic weather, the average distance of hailstorms from associated fronts, the speed and orientation of fronts associated with hailstorms, the orientation of hail patterns and rainfall patterns in the same storm, the intensity of storm rainfall associated with hailstorms, the relation between hailstorm frequency and synoptic type in various climatological sections of the state, and several other characteristics of hailstorms and associated weather.

Data for June through August in the 50-year period, 1910-59, were used in the investigation. All hailstorms were analyzed in which four or more U. S. Weather Bureau stations in Illinois reported hail. A total of 113 hailstorms days during the 50-year period met this minimum requirement. By selecting a minimum of four or more Weather Bureau reports, a representative sample of the more extensive storms during the 50-year period was obtained for study. While it would have been desirable to include all hailstorms during the 50-year period, personnel limitations would not permit a study of this magnitude. However, analyses were made of all hailstorm data at selected stations in developing relations between hail and rainfall intensity and in determining relations between hail occurrences and frontal type.

The majority of the storms in which heavy hail damage was reported during the 50-year period were included in the sample used in this investigation. On 33 of

the 50 most damaging hailstorm days during 1915 through 1959, 4 or more U. S. Weather Bureau stations reported hail; of the 25 most severe, 19 were reported by 4 or more Weather Bureau stations.

Data Used

The analyses of fronts and air masses associated with the hailstorms were based upon northern hemisphere synoptic weather maps and U. S. Weather Bureau daily weather maps. Because most of the 50-year period occurred prior to the availability of adequate upper air observations, synoptic analysis was restricted to the surface. Reference to the "1009" daily weather summaries of all U. S. Weather Bureau cooperative stations in the state during the 50-year period aided greatly in many phases of the analysis. These records provided useful data on the time of beginning of hail, the beginning and ending times of rainfall, temperature, wind direction, and cloudiness. Since hail usually occurs near the start of thunderstorms, the rainfall data were particularly useful in determining the time and space distribution of hail with respects to frontal systems, when used in conjunction with the frontal analyses. Figure 1 illustrates the use of the data from Weather Bureau stations in determining the time of occurrence and movement of storms. In this case, the time pattern indicates a, NE-SW squall line in advance of a cold front shown on the surface synoptic map.

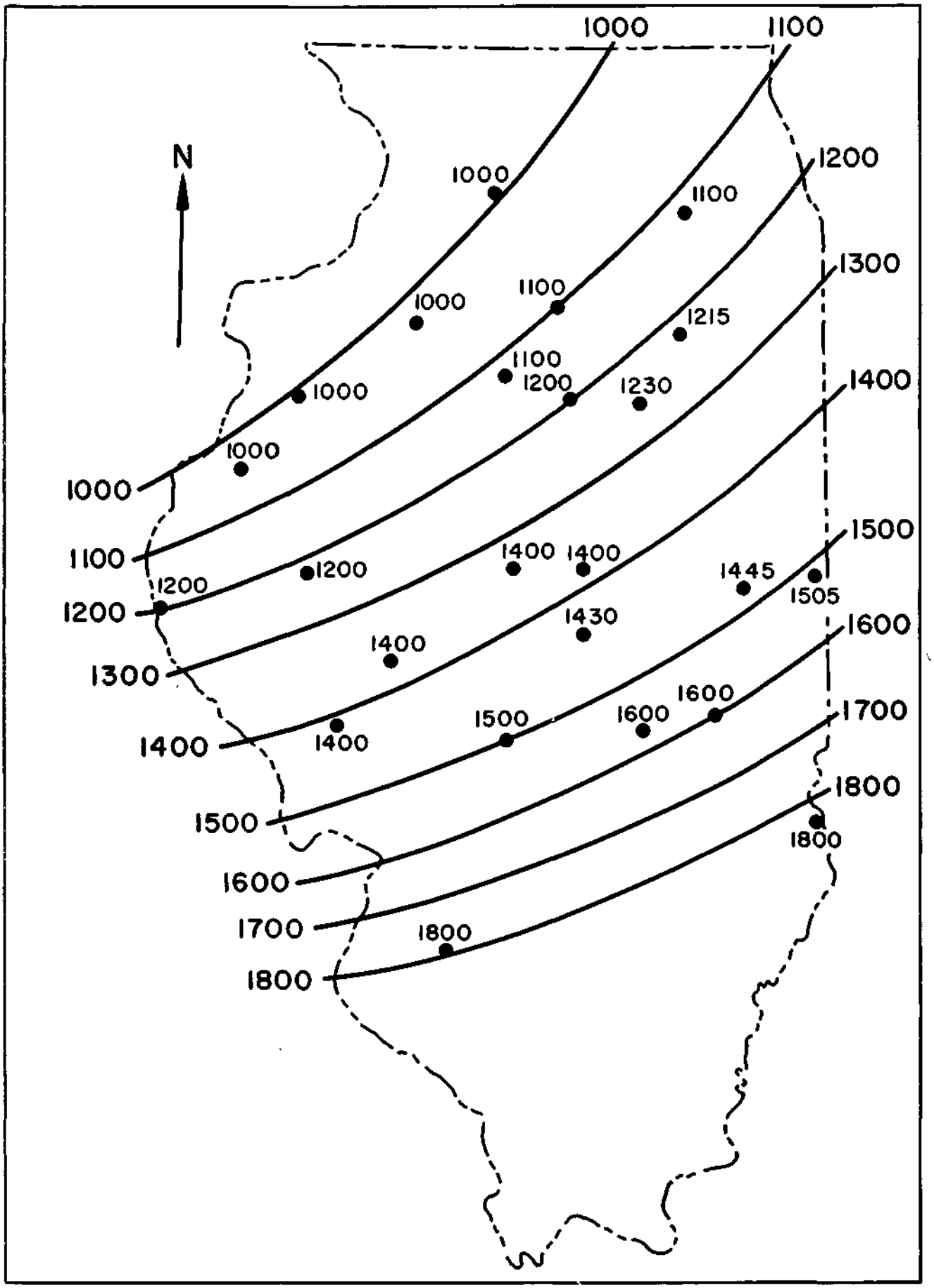

FIG. 1 TIME OF BEGINNING OF RAINFALL, AUGUST 13, 1914

Frequency Distribution of Hailstorms by Synoptic Type

Table 1 shows the frequency distribution of hailstorm days by synoptic type during the 50-year period. The hailstorm days were grouped into five synoptic types for this analysis. Reference to Table 1 shows that 64 per cent of the days on which four or more Weather Bureau stations reported hail occurred in conjunction with cold fronts. This includes both pre-frontal squall lines and frontal passages. Also, 18 percent of the hail days were associated with stationary fronts, 4 percent occurred with warm fronts, 8 percent were air mass storms, and 6 percent occurred in conjunction with the passage of low centers. Hailstorms were classified as air mass storms when no fronts were present within 250 miles of the hailstorm. Low centers included both those associated with fronts and transient lows without fronts. Also shown in Table 1 is the classification of cold front storms as pre-frontal, frontal, and indeterminate. Of the 72 cold fronts, 50 percent occurred well in advance of cold fronts, 44 percent were associated directly with frontal passages, and 6 percent could not be reliably classified from available data. The hailstorms were considered pre-frontal if they occurred more than 50 miles in advance of the cold front. Thus, Table 1 indicates that cold fronts are the predominant synoptic systems associated with summer hailstorms in Illinois and that a slightly greater percentage occur with pre-frontal storms than with frontal passages.

TABLE 1

HAILSTORM DAYS VS. SYNOPTIC TYPE
1910-59 DISTRIBUTION

Synoptic Type	Number of Storms	Percent of Total Cases
Cold Fronts	72	64
Stationary Fronts	20	18
Warm Fronts	5	4
Air Mass Storms	9	8
Low Center Passages	7	6
Total	113	100
Classification of Cold Front Storms		
Pre-Frontal	36	50
Frontal	52	44-
Indeterminate	4	6
Total	72	100

Table 2 shows the frequency distribution of hailstorm days by synoptic type for six selected stations within or near the state. All days with hail during the summer months of June through August were included in this phase of the investigation. The length of record available for analysis was 1914-59 for 4 stations, 1914 to 1947 for 1 station, and 1925-49 for the other station. Table 2 shows that for all stations combined 59 percent of the hail days were associated with cold fronts compared to 14 percent with stationary fronts, 8 percent with warm fronts, 11 percent with air mass storms, and 8 percent with low center passages. This frequency distribution by synoptic type agrees closely with the distribution based upon all hail days within Illinois on which four or more Weather Bureau stations reported hail, particularly considering the sampling error which must be inherent in any study of this type.

TABLE 2

HAILSTORM DAYS VS. SYNOPTIC TYPE
SELECTED STATIONS

Station	Period of Record	Number of Storms	Cold Fronts No.	Cold Fronts %	Warm Fronts No.	Warm Fronts %	Stationary Fronts No.	Stationary Fronts %	Air Mass No.	Air Mass %	Low Centers No.	Low Centers %
Moline	1914-59	27	19	70	1	4	3	11	3	11	1	4
Chicago	1914-59	30	18	60	2	7	4	13	3	10	3	10
Peoria	1925-49	21	11	52	2	10	4	19	1	5	3	14
Springfield	1914-59	26	15	58	2	8	4	15	3	11	2	8
St. Louis	1914-47	20	10	50	2	10	3	15	5	25	0	0
Cairo	1914-59	10	6	60	2	20	1	10	0	0	1	10
All Stations Combined		134	79	59	11	8	19	14	15	11	10	8
Moline-Chicago		57	37	65	3	5	7	12	6	11	4	7
Peoria-Springfield		47	26	56	4	8	8	17	4	8	5	11
St. Louis-Cairo		30	16	54	4	13	4	17	5	13	1	3

Table 2 shows that in the northern part of the state, as indicated by the data for Moline and Chicago, the percentage of all hail occurring with cold fronts was somewhat greater than in the central part of the state, as indicated by Peoria and Springfield, and in the southern part of the state, as indicated by St. Louis and Cairo. Hailstorms with stationary fronts were somewhat more frequent in the central and southern portions of the state than in the northern part. Warm front hailstorms were more prevalent in the southern portion of the state than in the central or north. Low center passages showed a preference for the central part of the state and air mass storms were less frequent in the central portion of the state than in the other two parts.

Relation between Extent of Hailstorms and Synoptic Type

A measure of the areal extent of hailstorms associated with various synoptic types of weather is provided by data in Table 3. This table shows the number of U. S. Weather Bureau stations reporting hail with the various synoptic types during the 50-year period. Reference to the median number of reports shows cold fronts with 6, warm and stationary fronts combined with 5, and air mass and low center storms combined with 4 reports. The preceding combinations were made because of the relatively few reports for warm fronts, air mass, and low center storms. Referring to the columns which give the percentage of total storms with indicated number of reports in Table 3, it is seen that only with cold fronts were more than 10 reports recorded during the 50-year period. However, in the category of 8 to 10 reports, the warm and stationary fronts had considerably more cases than the cold fronts and the air mass and low center storms.

TABLE 3

SYNOPTIC TYPE VS. NUMBER OF HAIL REPORTS PER STORM

Synoptic Types	Number of Storms	Per cent of total storms with indicated number of reports 4-5	6-7	8-10	over 10	Median Number of Reports
Cold Front	72	46	25	17	12	6
Warm Front	5	20	20	60	0	9
Stationary Front	20	65	15	20	0	5
Air Mass	9	67	22	11	0	5
Low Center	7	57	29	14	0	4
Warm and Stationary	25	56	16	28	0	5
Air Mass and Low Center	16	62	25	13	0	4

Distance of Hailstorms from Fronts

An analysis was made of the average distance that hailstorms occur from associated fronts. Combining all fronts, it was found that 50 per cent of the hailstorms occurred within 50 miles of the fronts and 72 per cent within 100 miles of the fronts (Table 4). With cold fronts, it was found that 47 per cent of the hailstorms occurred within 50 miles and 67 per cent within 100 miles of the front. With warm and stationary fronts, 58 per cent of the hailstorms occurred within 50 miles of the fronts and 83 per cent within 100 miles. In all cases, only a small portion of the hailstorms occurred more than 150 miles in advance of the fronts with which they were associated.

TABLE 4

AVERAGE DISTANCE OF HAILSTORMS FROM FRONTS

	Cold Fronts		Warm and Stationary Fronts		All Fronts	
Average Distance, miles	Number of Cases	Per cent of Cases	Number of Cases	Per cent of Cases	Number of Cases	Per cent of Cases
0-50	32	47	14	58	46	50
51-100	14	20	6	25	20	22
101-150	12	18	1	4	13	14
151-200	4	6	2	9	6	6
Over 200	6	9	1	4	7	8
Total	68	100	24	100	92	100

In hailstorms associated with stationary fronts, it was found that hail occurred primarily to the north or cold side of the stationary front. Of the 20 storms associated with stationary fronts, 13 had hail primarily to the north of the front, 6 had hail scattered on both sides of the front, and only one storm had hail primarily to the south or warm side of the front.

Speed and Orientation of Fronts

Tables 5 through 7 provide statistics on the speed and orientation of fronts with which hailstorms were associated. Because of the small number of warm fronts, only the frequency distribution of cold fronts is shown in Table 5. By definition, stationary fronts, as used in this study, are those in which movement was at a rate of 5 mph or less. In Table 5 cold fronts have been divided into three categories, all cold fronts combined, fronts in which hailstorms were associated with pre-frontal weather, and fronts in which hailstorms were associated with the actual frontal passage. Table 5 shows that with all three classifications the median speed of movement was 15 mph, relatively slow for cold fronts. Only a very small percentage of the fronts had speeds of 25 mph or greater. The greatest frequency was in the range from 10 to 20 mph.

Table 6 presents the orientation distribution of cold fronts. This table shows that the cold fronts had a median orientation of 240 degrees and that the greatest frequency was in the range from 230 degrees to 250 degrees, which contained 52 per cent of the total cases. Azimuths in this table are shown only to 180 degrees. Thus, the azimuth 180 to 189 includes fronts which had an orientation from 180 degrees to 0 degrees through 199 degrees to 19 degrees.

TABLE 5

SPEED OF COLD FRONTS

Speed, mph	All Cold Fronts		Fronts Associated with Pre-Frontal Hailstorms		Fronts Associated with Frontal Hailstorms	
	Number of Cases	Per cent of Cases	Number of Cases	Per cent of Cases	Number of Cases	Per cent of Cases
5-9	8	11	3	8	4	13
10-14	22	31	11	31	10	31
15-19	22	31	9	25	11	34
20-24	14	19	9	25	5	16
25-29	5	7	3	8	2	6
Over 29	1	1	1	3	0	0
Total	72	100	36	100	32	100
Median Speed	15		15		15	

TABLE 6

ORIENTATION OF COLD FRONTS

Azimuth, Degrees	Number of Cases	Per cent of Cases	Azimuth, Degrees	Number of Cases	Per cent of Cases
180-199	2	3	250-259	10	14
200-209	4	6	260-269	4	6
210-219	5	7	270-279	2	3
220-229	5	7	280-299	1	1
230-239	18	25	300-359	1	1
240-249	20	27			

Median - 240°

It was noted during the analysis that cold fronts frequently pivoted as they entered Illinois. Analysis of the data indicates that approximately 40 per cent of the cold fronts associated with the extensive hailstorms showed appreciable anti-cyclonic rotation as they approached or passed through the state.

TABLE 7

ORIENTATION OF STATIONARY FRONTS

Azimuth, Degrees	Number of Cases	Per cent of Cases
240-259	2	10
260-279	9	45
280-299	2	10
300-319	6	30
320-339	1	5
Total	20	100

Median - 270°

Table 7 shows the orientation of stationary fronts. The median was found to be 270 degrees with the most frequent orientations 260 to 279 degrees and 300 to 319 degrees, and these two 20-degree sectors included 75 per cent of all the cases. Because of the small number of cases, the orientation distribution of warm fronts has not been shown.

Orientation of Hail and Rainfall Patterns

The orientations of hail patterns for all storms combined and for cold front storms are shown in Table 8. These orientations were obtained from hail occurrences in which the distribution of hail reports from U. S. Weather Bureau stations showed a definite distribution along a line or a zone, indicating the movement of hailstorms in a particular direction. Orientations are those of the major axis of the pattern, In some cases there were several of these zones during a particular hailstorm period, often at different locations along a cold front or a pre-frontal squall line. In many cases, however, no definite pattern or orientation of the hail reports could be reliably determined and these were not included in this portion of the study, From the 113 hailstorm days, a total of 90 cases were obtained in which a definite hail pattern was indicated, and 62 of these were with cold front storms. As mentioned previously, in some cases several of these were within a single storm period. Table 8 shows medians of 280 degrees and 290 degrees, respectively, for all storms and for cold front storms. For all storms combined, the most frequent orientation was in the range from 240 to 259 degrees, or a west-southwest to east-northeast orientation. The most frequent orientations for cold front storms were in the range from 300 to 319 degrees, and from 240 to 259 degrees.

TABLE 8

ORIENTATION OF HAIL PATTERNS

Azimuth, Degrees	All Storms: Number of Cases	All Storms: Per cent of All Cases	Cold Front Storms: Number of Cases	Cold Front Storms: Per cent of All Cases
180-199	1	1	0	0
200-219	7	8	3	5
220-239	9	10	8	13
240-259	23	25	14	22
260-279	5	6	3	5
280-299	10	11	4	7
300-319	17	19	14	22
320-339	12	13	11	18
340-359	6	7	5	8
Total	90	100	62	100
Median	280°		290°	

Table 9 shows the distribution of orientation of rainfall patterns associated with the hailstorms. The orientations were obtained in the same manner described for the hailstorms and have the same limitations. The rainfall patterns were based upon total storm rainfall, which in some cases consisted of several showers in addition to the particular shower producing the hail. However, in the majority of the cases it was found that when more than one rainstorm occurred during the storm period, that the one associated with the hail was the most severe and generally determined the orientation of the rainstorm pattern.

Reference to Table 9 shows that the most frequent orientation of the rainfall patterns was not as well defined as was found with the hail patterns. Combining all storms, there were only small differences in the frequency of orientations from 240 through 340 degrees. With the cold front storms, the most frequent orientations again ranged from 240 through 339 degrees. Median values of 280 and 285 degrees were obtained for all storms combined and for cold front storms, respectively, The median of 280 degrees compares favorably with the median of 260 degrees found for severe rainstorms in Illinois in a study by Huff and Semonin.[2]

TABLE 9

ORIENTATION OF RAINFALL PATTERNS

	All Storms		Cold Front Storms	
Azimuth, Degrees	Number of Cases	Per cent of All Cases	Number of Cases	Per cent of All Cases
180-199	1	1	0	0
200-219	6	5	4	5
220-239	13	10	9	11
240-259	18	15	14	18
260-279	20	17	10	13
280-299	20	17	13	16
300-319	19	16	10	13
320-339	17	14	14	18
340-359	6	5	5	6
Total	120	100	79	100
Median	280°		285°	

Table 10 shows the difference in orientation between hail and rainfall patterns in storms during the 50-year period. The differences were obtained by subtracting the orientation of the rainfall pattern from the orientation of the hail pattern in storms in which both could be determined from the existing data on rainfall and hail. A median difference of 5 degrees was found, both with all storms combined and with cold front storms. In 78 per cent of all storms combined and 80 per cent of the cold front storms, the difference between the orientation of hail and rainfall patterns was 10 degrees or less, and very few cases were found in which the difference exceeded 20 degrees. Thus, the results indicate that hailstorms and rainstorms assume very similar orientations in most storms in which hail is experienced over an extensive area.

TABLE 10

DIFFERENCE IN ORIENTATION BETWEEN HAIL AND RAINFALL PATTERNS

Difference, Degree	All Storms		Cold Front Storms	
	Number of Cases	Per cent of All Cases	Number of Cases	Per cent of All Cases
0-10	66	78	46	80
11-20	12	14	7	12
21-30	2	2	2	3
31-40	3	4	3	5
41-50	2	2	0	0
Total	85	100	58	100
Median	5		5°	

Relation of Frontal Orientation to Hail and Rainfall Patterns

Tables 11 and 12 summarize results of analyses to determine the association between the orientation of fronts and the orientation of hail and rainfall patterns associated with these fronts. Table 11 shows the distribution of the differences between the hail pattern and frontal orientations for all fronts combined and for cold fronts separately. Based upon all fronts combined, Table 11 indicates a median angle of 35 degrees between the orientation of fronts and hail patterns. A median of 45 degrees was obtained for cold fronts. The most frequent difference was found to be between 0 and 10 degrees with a secondary maximum at 71 to 80 degrees. These two modes in the distribution result from two basic patterns created by the movement of hailstorms. The primary maximum at 0 to 10 degrees indicates a hail pattern nearly parallel to the front, and the secondary maximum at 7 1 to 80 degrees represents a hail zone nearly perpendicular to the front. The parallel pattern is usually the result of numerous hailstorms occurring along a front or a squall line in advance of a front, particularly cold fronts, and which occur at nearly the same time of day and have relatively short durations. This creates a hail pattern nearly parallel to the front. The secondary maximum at 7 1 to 80 degrees reflects the effect of longer duration hailstorms. These storms usually break out in advance of a front or within a squall line and continue for several hours, producing a hail band nearly perpendicular to the front. In specific cases, there may be one or several of these bands associated with a front. When only one band is associated with a front, it is usually much longer than any of the bands on days when several are associated with a front.

TABLE 11

DIFFERENCE BETWEEN HAIL PATTERN AND FRONTAL ORIENTATIONS

Difference, Degree	All Fronts: Number of Cases	All Fronts: Per cent of All Cases	Cold Fronts: Number of Cases	Cold Fronts: Per cent of All Cases
0-10	26	31	16	26
11-20	8	10	5	8
21-30	4	5	2	3
31-40	6	7	5	8
41-50	7	8	5	8
51-60	10	12	8	13
61-70	2	2	2	3
71-80	12	15	11	18
81-90	8	10	8	13
Total	83	100	62	100
Median	35°		45°	

Table 12 shows the distribution of the differences between rainfall patterns and frontal orientations, obtained in the same manner as data in Table 11. Median values were the same as those for hail patterns in Table 11, 35 degrees for all fronts combined and 45 degrees for cold fronts separately. A primary maximum is indicated at 0 to 10 degrees, which represents rainfall patterns nearly parallel to the fronts, and a secondary maximum is indicated at 7 1 to 80 degrees. These distribution maxima are the same as found for the hail patterns, and indicate a similar movement relationship between fronts and the two phenomena.

TABLE 12

DIFFERENCE BETWEEN RAINFALL PATTERN AND FRONTAL ORIENTATIONS

Difference, Degree	All Fronts: Number of Cases	All Fronts: Per cent of All Cases	Cold Fronts: Number of Cases	Cold Fronts: Per cent of All Cases
0-10	24	24	14	18
11-20	11	11	8	10
21-30	9	9	6	8
31-40	12	12	11	14
41-50	10	10	9	11
51-60	8	8	7	9
61-70	5	5	4	5
71-80	14	14	13	16
81-90	7	7	7	9
Total	100	100	79	100
Median	35°		45°	

Intensity of Rainfall Associated with Hailstorms

The maximum storm rainfall associated with hailstorms is shown in Table 13. The maximum storm rainfall represents the maximum for the total storm period and does not necessarily represent the maximum rainfall occurring with the hailstorm. That is, the storm rainfall may be made up of several storms in addition to the one which produced the hailstorm. Again, however, it was observed that, if several storms on one day made up the total storm rainfall, in most cases the heaviest rainfall occurred in the area of the hailstorm passage and this storm primarily determined the rainfall pattern. In Table 13, the data

have been presented for all hailstorms and for hailstorms occurring in conjunction with cold fronts. Table 13 indicates that maximum storm rainfall amounts of one to three inches are the most frequent occurrence with widespread hailstorms, such as investigated in this study. Maximum storm rainfall of less than one inch with these hailstorms is uncommon, accounting for only 5 per cent of all hailstorms and 7 per cent of the cases with cold front hailstorms. The median value exceeded two inches with both classifications in Table 13. The percentage of cases in which rainfall exceeded 5 inches, an unusually heavy rainstorm, was greater than the percentage below one inch. Thus, it appears that in the majority of the cases widespread hailstorms occur in conjunction with heavy rainstorms.

TABLE 13

MAXIMUM STORM RAINFALL ASSOCIATED WITH HAILSTORMS REPORTED BY 4 OR MORE STATIONS

Storm Amount, Inches	All Hailstorms		Cold Front Hailstorms	
	Number of Cases	Per cent of All Cases	Number of Cases	Per cent of All Cases
0. 10-1.00	6	5	5	7
1.01-2.00	37	33	23	32
2.01-3.00	35	31	22	31
3.01-4.00	21	19	13	18
4.01-5.00	6	5	4	5
Over 5.00	8	7	5	7
Total	113	100	72	100

A study was made of hail location with respect to rainstorm location, and it was found that approximately 90 per cent of the hail occurred within 25 miles of the rainfall axis or core. In approximately 70 per cent of the cases, hail occurred along the rainfall axis. Hail occurred in advance of the rainfall core in approximately 56 per cent of the cold front storms in which hail was displaced in a particular direction from the rainfall axis. That is, with cold fronts the hail most frequently occurs along and towards the front edge of the rainstorm.

In a further investigation of the association between rainfall and hail, the intensity of rainfall on all days with hail, rather than days with widespread storms, was investigated for selected stations. This study was made for the summer months of June through August. Station data for 1914-59 from Chicago, Moline, Peoria, Springfield, St. Louis, and Cairo were used in the analysis.

For each hail day during the sampling period, at each station, the daily rainfall was tabulated. From the tabulations, the median value of daily rainfall for all hail days was determined for each station. The percentage of all hail days with rainfall equalling or exceeding 0.5 inch, 1 inch, and 2 inches was determined also. Results are summarized in Table 14. This table shows that the median daily rainfall varied from 0.72 to 0.83 inch at the six stations and was 0.74 inch for all stations combined. The percentage of days with rainfall of two inches or more varied from 8 to 15 per cent at the various stations, the percentage with one inch or more from 25 to 41 per cent, and the percentage with 0.5 inch or more from 61 to 75 per cent. The range of amounts varied from 0.01 inch to 8.07 inches. Table 14 indicates a tendency for hail to occur

at a point on days with moderate to heavy rainfall at that point, but also shows that hail may occur with light rainfall.

TABLE 14

RELATION BETWEEN HAIL OCCURRENCES AND DAILY RAINFALL IN SUMMER

Station	Median Daily Rainfall, in.	Range of Daily Rainfall, in.	Per cent of Daily Rainfalls = 2.00"	1.00"	0.50"
Chicago	0.73	0.02-5.15	13	29	61
Moline	0.72	0.01-2.09	8	41	67
Peoria	0.77	0.07-2.88	10	33	67
Springfield	0.74	0.02-5.15	12	27	77
St. Louis	0.72	0.01-8.07	15	40	65
Cairo	0.83	0.05-2.50	8	25	75
All Stations Combined	0.74	0.01-8.07	11	33	70

Next, an analysis was made of the nature of the daily rainfall in the area surrounding stations reporting hail, based on data for the Peoria and Springfield regions. A circle with a radius of 25 miles was drawn about each station, and the rainfall at all stations within this circle was determined for each hail occurrence at the station. The 25-mile radius was selected because it had been determined previously that 90 per cent of the hail on widespread hailstorm days occurred within 25 miles of the associated rainstorm: core. Nine stations with long-period records were available in the circle around each station for analysis of rainfall. In general, the stations within the 25-mile radius showed large variability on hail

days, and the mean areal rainfall did not show any better correlation with the hail occurrences than the single-station rainfall. However, maximum daily rainfall at the surrounding stations further supported the tendency previously observed for hail to be associated with moderate to heavy rainstorms. Thus, it was found that on 28 per cent of the hail days at Springfield and Peoria there were daily amounts of two inches or more recorded within 25 miles. Gn 55 per cent of the hail days at the two stations combined, there were daily rainfall amounts of one inch or more within a 25-mile radius, and on 85 per cent of the hail days the daily rainfall exceeded 0. 50 inch at one or more of the surrounding stations. Table 13 indicates that storm rainfall amounts in excess of two inches occurred with 62 per cent of the widespread hailstorms, and that amounts greater than one inch were recorded in 95 per cent of the cases. The preceding statistics indicate the expected tendency for widespread hailstorms to be accompanied by heavy rainfall more frequently than the storms in the climatological sample which include all cases of hail at a given point.

Finally, a study was made of the relationship between the frequency of hail days per month and monthly rainfall. For this study a comparison was made between the normality of monthly rainfall and the number of hail days per month for all months in which two or more hail days were recorded at selected stations during the 50-year period, 1906-55. Correlation coefficients between number of hail days and monthly rainfall were determined also. Stations used in this study were Moline, Peoria, Springfield, and St. Louis.

Results are summarized in Table 15. This table reveals a tendency for months with two or more hail days to be months of above normal rainfall, but the association is not outstanding. The median per cent of normal rainfall for months with two or more hail days varied from 120 to 156 at the four stations, but 27 to 33 per cent, of the months were below normal. Correlation coefficients between number of hail days and monthly rainfall ranged from 0. 39 to 0. 59 at the four stations, not particularly high since the 0. 59 accounts for only 35 per cent of the variance. Consequently, it appears that monthly rainfall, in general, is not strongly indicative of monthly hailstorm frequency in Illinois and cannot be used to predict hailstorm frequency relations, except possibly in combination with other independent variables.

TABLE 15

RELATION BETWEEN HAIL AND MONTHLY RAINFALL
IN MONTHS WITH TWO OR MORE HAILSTORMS

Station	Per cent of Normal Monthly Rainfall		Per cent of Months Below Normal	Correlation Coefficient
	Median	Range		
Moline	147	30-204	33	0.52
Peoria	128	74-224	30	0.39
Springfield	120	35-271	32	0..59
St. Louis	156	17-288	27	0.59

Dimensions of Hail Zones

An effort was made to determine the length and width of hail zones associated with widespread hailstorms. To accomplish this, a rectangular envelope was drawn about each hail zone and the length and width of this envelope was determined in each case. The results, as shown in Tables 16 and 17, provide a measure of the area affected by the widespread hailstorms which were studied in this investigation. Table 16 indicates that the median length of the hail zones, as indicated by U. S. Weather Bureau reports, was 125 miles with most of the values between 50 and 200 miles. Table 17 shows that the median width of the hail zones was 30 miles and most of these were less than 50 miles. The typical envelope was, therefore, 125 x 30 miles or an area of 3750 square miles in which hailstorms were present.

TABLE 16

LENGTH OF HAIL ZONES

Length, Miles	Number of Cases	Per cent of All Cases
0-50	5	6
51-100	27	30
101-150	26	29
151-200	26	29
Over 200	5	6

Median - 125 miles

TABLE 17

WIDTH OF HAIL ZONES

Width, Miles	Number of Cases	Per cent of All Cases
0-25	43	48
26-50	33	37
51-75	8	9
76-100	3	4
Over 100	2	2

Median - 30 miles

Frequency of Hailstorms in Various Climatological Sections

An analysis was made of the frequency of widespread hailstorms in each of the nine Illinois climatological sections presently used by the U. S. Weather Bureau. These sections are shown in Figure 2. Table 18 shows the frequency of hailstorms in each of the nine sections for various synoptic types. Data have been shown for both the frequency with which each section was part of a hail zone and the frequency with which each section was the center of a hailstorm zone. The section which had the greatest number of hail reports was considered the storm center. Thus, if a storm extended from the northwest through the west to the west-southwest section, all three sections would be considered part of a hailstorm or hail zone, but only one of the sections would be considered the storm center and this would be the one which had the most hail reports. Results have been presented to show both number of cases per section and number of cases per 1000 square miles for each of the nine climatological sections. Combining all storms, Table 18

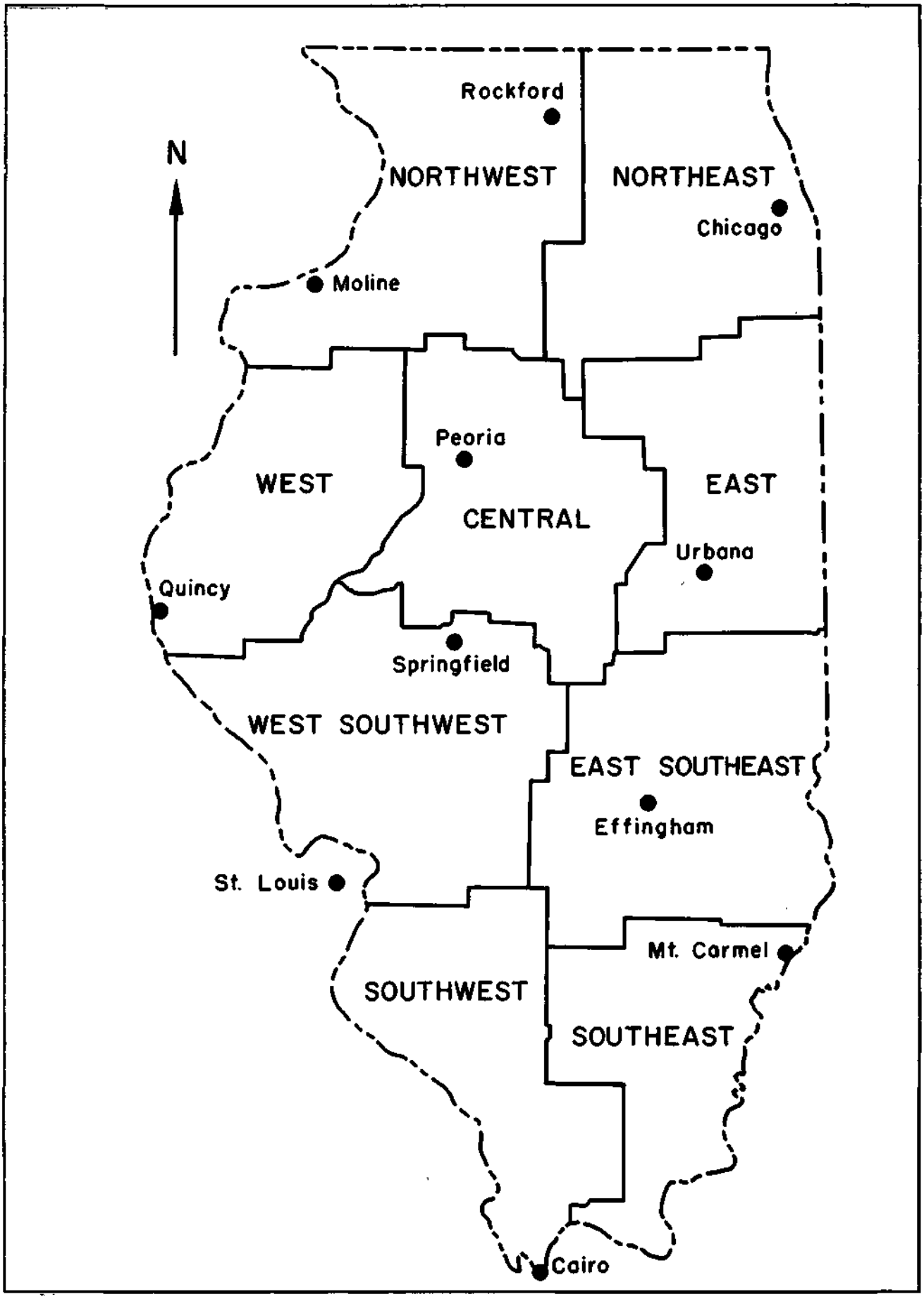

FIG. 2 U.S. WEATHER BUREAU CLIMATOLOGICAL SECTIONS

TABLE 18

FREQUENCY OF HAILSTORMS IN 9 CLIMATOLOGICAL SECTIONS

Frequency with Which Sections Were in Hail Zone

Section	Cold Fronts		Warm and Stationary Fronts		Air Mass		Low Centers		All Storms	
	Number of Cases	Number per 1000 Sq. Mi.	Number of Cases	Number per 1000 Sq. Mi.	Number of Cases	Number per 1000 Sq. Mi.	Number of Cases	Number per 1000 Sq. Mi.	Number of Cases	Number per 1000 Sq. Mi.
Northwest	43	6.0	15	2.1	5	0.7	4	0.6	67	9.4
Northeast	29	4.5	10	1.5	6	0.9	4	0.6	49	7.5
West	38	6.9	12	2.2	3	0.5	3	0.5	56	10.1
Central	32	5.2	9	1.5	4	0.6	1	0.2	46	7.5
East	32	5.6	8	1.4	1	0.2	3	0.5	44	7.7
West-Southwest	39	5.2	13	1.7	2	0.3	2	0.3	56	7.5
East-Southeast	16	2. 1	7	0.9	3	0.4	1	0.1	27	3.5
Southwest	16	3.0	7	1.3	0	0.0	1	0.2	24	4. 5
Southeast	7	1.5	2	0.4	0	0.0	1	0.2	10	2.1

Frequency with Which Sections Were Storm Centers

Northwest	16	2.2	6	0.8	3	0.4	2	0.3	27	3.7
Northeast	12	1.8	2	0.3	1	0.2	2	0.3	17	2.6
West	6	1.1	2	0.4	0	0.0	0	0.0	8	1.5
Central	4	0.7	1	0.2	3	0.5	0	0.0	8	1.4
East	4	0.7	4	0.7	0	0.0	1	0.2	9	1.6
West-Southwest	18	2. 4	4	0.5	1	0.1	1	0.1	24	3.1
East-Southeast	5	0. 7	2	0.3	I	0.1	0	0.0	8	1.1
Southwest	1	0.2	1	0.2	0	0.0	0	0.0	2	0.4
Southeast	1	0.2	1	0.2	0	0.0	0	0.0	2	0.4

shows that the west section.experienced the most hailstorms, based upon number of storms per 1000 square miles. That is, the west section was part of a hail zone a greater number of times during the 50-year period than any of the other eight sections. The northwest section ranked second. However, the northwest section was the center of these hailstorms or hail zones most frequently during the 50-year period, averaging 3.7 storms per 1000 square miles, and the west-southwest section ranked second with a value of 3. 1 storms per 1000 square miles. The west section ranked only fifth with respect to storm centers, although it ranked first with respect to number of times it was part of one of the extensive hailstorms. Analysis indicates that the west section frequently was in hail zones which were centered in the northwest or west-southwest sections, which were the sections with the greatest number of centers. Incidentally, the northwest and west-southwest sections lie in areas which experienced the greatest number of summer hailstorms according to a previous study of Huff and Changnon.[2] As a result of this study, it is indicated that they are also areas where the more widespread hailstorms are centered most frequently.

Hailstorm Frequency Versus Synoptic Type in Climatological Sections

The relation between hailstorm frequency and synoptic types was investigated in the nine climatological sections and the results are summarized in Table 19. In this table, the per cent of all storms from each synoptic type are shown for each of the nine sections. The table shows that cold fronts account for 60 to 73 per cent of all hailstorms in the nine sections, with a maximum of 73 per cent in the east section and a minimum of 60 per cent in the northeast section. Warm

and stationary fronts exert their greatest effect in the southwest section where 29 per cent of all the hailstorms are associated with these two types of fronts. The warm and stationary fronts were least important in the east and central sections where 18 and 19 per cent, respectively, of all the hailstorms were accounted for by these two types of fronts. Air mass storms were most important in the northeast and east-southeast sections with 12 and 11 per cent of the total cases. In the southwest and southeast sections none of the hailstorms were associated with air mass storms. Low centers accounted for 10 per cent of the storms in the southeast section compared to 2 per cent in the central section.

TABLE 19

RELATION BETWEEN HAILSTORM FREQUENCY AND SYNOPTIC TYPE IN 9 CLIMATOLOGICAL SECTIONS

Section	Number of Storms	Per cent of All Storms From Each Synoptic Type			
		Cold Fronts	Warm and Stationary Fronts	Air Mass Storms	Low Centers
Northwest	67	64	22	8	6
Northeast	49	60	20	12	8
West	56	68	22	5	5
Central	46	70	19	9	2
East	44	73	18	2	7
West-Southwest	56	69	23	4	4
East-Southeast.	27	60	26	11	3
Southwest	24	67	29	0	4
Southeast	10	70	20	0	10

Distributions of Hailstorms by Months

The distribution of the widespread hailstorms by months during the summer was investigated. Results are summarized in Table 20. Reference to this table shows that 53 per cent of the widespread storms occurred in June compared to 26 per cent in July and 21 per cent in August. It is interesting to note that warm fronts and stationary fronts are seldom associated with widespread hailstorms except during June. Only cold fronts are of major importance in producing hailstorms in August.

TABLE 20

DISTRIBUTION OF HAILSTORMS BY MONTHS

Synoptic Type	Number of Storms				Per cent of Storms		
	June	July	August	Total	June	July	August
Cold Front	37	17	18	72	51	24	25
Warm Front	4	1	0	5	80	20	0
Stationary Front	14	4	2	20	70	20	10
Air Mass	4	4	1	9	44	44	12
Low Center	1	3	3	7	43	43	14
Total	60	29	24	113	53	26	21

A previous study by Huff and Changnon[2] indicated that warm fronts and low centers are far more important in the production of widespread hail in spring (March-May) than they are in summer (June-August) in Illinois. As spring progresses, cold fronts and stationary fronts become increasingly more important. As pointed out earlier, as summer progresses the stationary front influence decreases, and by August cold fronts become the only synoptic system of major

importance associated with widespread hail in Illinois. The above seasonal sequence of synoptic events suggests that low-level, warm air advection is a prime requisite in spring to produce the necessary atmospheric instability to support widespread hailstorms. In summer, cold air advection aloft, which frequently occurs in advance of cold fronts,[3] may be the primary source of lapse-rate steepening to produce widespread hail activity.

Summary and Conclusions

Summer hailstorms are most frequently associated with cold fronts. Of 113 hailstorm days with widespread activity, 64 per cent occurred with cold fronts compared to 18 per cent with stationary fronts, 4 per cent with warm fronts, 8 per cent with air mass storms, and 6 per cent with low center passages.

A slightly greater percentage of cold front hailstorms occurs in advance of the front than with the frontal passage. Pre-frontal storms, those occurring more than 50 miles in advance of the front, accounted for 50 per cent of the cases, compared to 44 per cent with frontal passages, and 6 per cent which were indeterminate.

The areal extent of hailstorms tends to be slightly greater with cold fronts than with other types of fronts, low pressure centers, and air mass storms.

Combining all fronts, it was found that 50 per cent of the widespread hailstorms in summer occurred within 50 miles of the fronts, and 72 per cent occurred within 100 miles of the fronts. Only a small portion of the hailstorms occurred more than 150 miles in advance of the front with which they were associated. In hailstorms associated with stationary fronts, it was found that hail occurred

primarily to the north or cold side of the front.

It was found that cold fronts associated with widespread hailstorms tend to move slowly. The median speed for 72 cases was 15 mph, and only 8 per cent of the fronts moved 25 mph or faster.

The median orientation of cold fronts for the 72 cases was 240 degrees, and the greatest frequency was in the range from 230 to 250 degrees which contained 52 per cent of the fronts. With stationary fronts, the second most important synoptic type associated with widespread hailstorms, the median orientation was 270 degrees with the greatest frequencies 260 to 279 degrees and 300 to 319 degrees.

The median orientation of the hail patterns in all storms combined was 280 degrees, compared to 290 degrees for cold front storms. The most frequent orientations were 240 to 259 degrees and 300 to 319 degrees. With rainstorms associated with hailstorms, the median orientation was 280 degrees with all storms combined compared to 285 degrees for cold front storms. It was found that hailstorms and rainstorms assume very similar orientations in most cases in which hail is widespread; the median difference in orientation for all storms combined was 5 degrees, and in 78 per cent of the cases the difference did not exceed 10 degrees.

Comparing the orientation of hailstorms with the orientation of the fronts with which they were associated, the most frequent difference was found to be 0 to 10 degrees with a secondary maximum at 71 to 80 degrees. These maxima reflect two basic hail patterns. The primary maximum indicates a hail pattern nearly parallel to the front, usually the result of numerous hailstorms occurring

along a front or squall line, and which occur at nearly the same time and have short durations. The secondary maximum reflects the effect of longer duration hailstorms which break out along a front or squall line and continue for several hours.

It was found that in the majority of the cases that widespread hailstorms were accompanied by heavy rainstorms. The median value of the maximum storm rainfall was found to exceed three inches in the 113 storms investigated. The maximum storm rainfall was less than one inch in only 5 per cent of the cases and exceeded three inches in 35 per cent of the cases. Approximately 90 per cent of the hail in the widespread storms occurred within 25 miles of the associated rainstorm axis or core.

An investigation of rainfall associated with all hail days at selected stations in Illinois indicated a tendency for moderate to heavy rainfall to occur within the vicinity of the station in association with the hail, but the tendency was not as strong nor the rainfall as heavy, in general, as occurred with the widespread hailstorms with which this report is primarily concerned. Relatively poor correlation was found between monthly rainfall and hail frequency at selected stations.

An analysis was made of the frequency of widespread hailstorms in each of the nine Illinois climatological sections presently used by the U. S. Weather Bureau. Results indicated that the western part of the state was most often a part of a widespread hail zone, but that the widespread storms were centered most frequently in the northwest and west-southwest portions of the state.

An analysis of the occurrence of widespread summer hailstorms by months

showed that 53 per cent of these storms occurred in June, compared to 26 per cent and 21 per cent, respectively, in July and August. Except during June, widespread hailstorms in summer are seldom associated with warm and stationary fronts. Only cold fronts are of major importance in producing widespread storms in August.

References

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3. Byers, H. R., General Meteorology, McGraw-Hill Book Co., Inc., New York, First Edition, 1944, pp. 568-570.