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CHARACTERISTICS OF HAIL-PRODUCING RADAR ECHOES IN ILLINOIS

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ABSTRACT

Data from 103 hail echoes on 24 days in 1967 and 50 no-hail echoes from the same days were analyzed to describe hailstorm characteristics and to provide information useful in operational detection and forecasting of hail-producing echoes. Echo characteristics investigated included locations of echo formation and dissipation, echo reflectivities, echo-top heights, echo duration, direction of motion, speed, time of occurrence, and associated synoptic weather conditions. A single hail-echo model could not be derived because of the extreme variability found in all characteristics. However, distinctive echo models could be developed for the three predominant hail-producing synoptic weather conditions, cold fronts, stationary fronts, and low-pressure centers. The frontal hailstorms were faster moving, longer lived, and had taller echoes than those with low-pressure systems. Hail production after echo inception varied from an average of 32 min for low conditions to 59 min for cold frontal echoes. The average hail-echo top exhibited a 5,000-ft growth in the 15-min period prior to the average time of hail, suggesting that a major updraft surge was the prime producer of hail. The no-hail echoes occurring on hail days had characteristics of speed, direction of motion, reflectivity, and location that were very similar to the hail-producing echoes. The only distinct consistent difference between the hail and no-hail echoes in all synoptic situations was that the hail-echo tops averaged between 2,000 and 4,000 ft higher throughout their entire durations.

1. INTRODUCTION

Information concerning the behavior of hail-producing echoes was sought as part of a comprehensive hail research program in Illinois (Changnon 1969). Knowledge of the characteristics of both hail-producing and no-hail echoes has value in two areas. One concerns the identification and point-area prediction of hailstorms on an operational basis for aircraft storm avoidance, public warnings, and selection of approaching storms for seeding in hail suppression projects. Most prior research on hail-echo identification has concerned their heights (Douglas 1963) or reflectivity profiles (Donaldson 1958, Wilk 1961), but recent studies (Rinehart et al. 1968, Dennis and Musil 1968) have shown that high-reflectivity characteristics aloft are not well correlated with surface hail. Information about characteristics of hail-producing echoes is also quite meaningful for increasing knowledge of the causes of hail generation.

Results on various hail-echo characteristics including location, duration, direction of motion, speed, time of occurrence, reflectivity values, echo-top heights, and associated synoptic weather conditions were obtained for 103 hail-producing echoes. These results are compared with those obtained for 50 no-hail echoes. From these analyses, models of typical Illinois hailstorm echoes are developed, and results that have meaning for either hailstorm identification or hailstorm physics are identified and summarized.

2. DATA AND ANALYTICAL TECHNIQUES

The radar data consisted of PPI photographs taken in CPS–9 radar operations on 24 days during April–September 1967. The radar was operated with a maximum range of 80 n.mi. and with automatic sequential antenna-tilt and receiver gain reductions (gain step). A photograph was taken at each tilt angle and gain step. The surface reports of hail and no-hail came from a network of 1,380 cooperative hail observers and two smaller networks of 65 raingage-hailpad sites in an 18,000-sq mi area of central Illinois (fig. 1). These sources provided a total of 352 observer reports of hail time, 271 observer reports of no-hail, and 130 hail-time occurrences from the raingage-hailpad sites for the 24 days studied.

Initially, the analytical procedure consisted of making a "track" of each hail-producing echo by plotting the location of the hail, finding the echo on the film that corresponded, and plotting its location as far back in time (prior to hail) and as far forward in time (after hail) as possible. The plots were of the centroid of the echo on every 0° tilt photograph (available approximately once every 10 min) as depicted on a medium level of receiver gain. The line connecting the centroid positions became the echo track for its entire duration. The tracks of 50 randomly chosen no-hail echoes were determined in much the same way, except that the track was started from the echo formation time and continued for approximately 1 hr.

The medium gain-step level chosen for echo definition was normally the one midway between maximum sensitivity level and that level where all echoes were eliminated. This generally was in the 20–28 dB (decibel) range of reduction from maximum sensitivity.

Table 1 gives the number of hail-echo tracks that occurred with each synoptic situation, classified according to their formation and dissipation locations. The location of the first identifiable appearance (beginning) and the last identifiable appearance (ending) was determined for all echoes. However, the actual formation and/or dissipation locations of about half of the echoes could not be

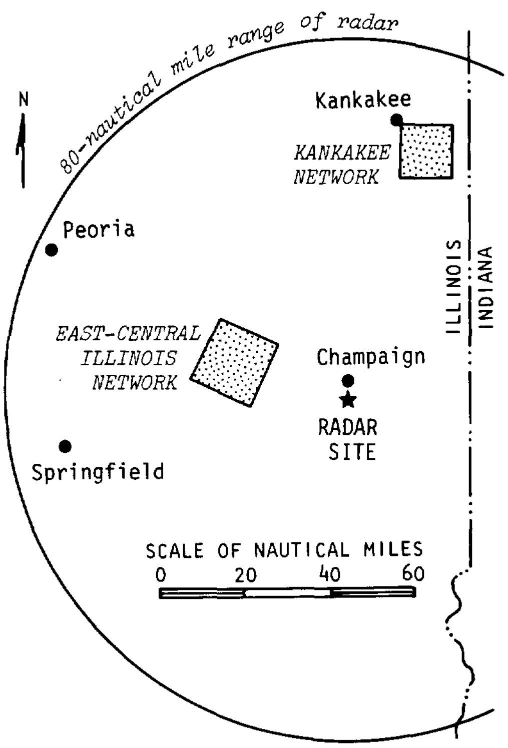

FIGURE 1.—Areas from which 1967 hail data were collected.

TABLE 1.—*Frequency of hail-echo tracks by synoptic weather classifications*

Echo characteristic	Number of tracks				
	Cold front	Stationary front	Low	Air mass	Total
Formed and dissipated in range	5	7	21	2	35
Formed in range, but did not dissipate in range	5	9	1	0	15
Dissipated in range, but did not form in range	5	9	2	1	17
Neither formed nor dissipated in range	4	21	8	3	36
Total	19	46	32	6	103

established because they formed or dissipated beyond the maximum radar range or within a large echo mass. The totals in table 1 reveal that 50 echoes formed in range, 52 echoes dissipated in range, and 35 of these had known formation and dissipation points.

In addition to the 103 hail-echo tracks, 50 randomly chosen no-hail echoes were tracked, each of which formed in range. Sixty percent of the no-hail echoes passed over 10 or more volunteer observers reporting no hail, and all passed over four or more observers reporting no hail. These no-hail echoes were chosen from the 14 days on which the 50 hail echoes (formed in range) occurred, and the number from each day was made proportional to the number of hail echoes on that day.

In the analyses, the data for most hailstorm characteristics were ranked and divided into thirds, with each third considered to be a class of that characteristic.

TABLE 2.—*Total duration and duration from formation to first hail for hail-producing echoes*

Duration, formation to hail, min (50 echoes)	% of total	Cumulative %	Total echo duration, min (35 echoes)	% of total	Cumulative %
0–19	18	18	20– 39	14	14
20–39	38	56	40– 59	17	31
40–59	22	78	60– 79	14	45
60–79	8	86	80– 99	23	68
80–99	8	94	100–119	23	91
≥100	6	100	≥120	9	100
Median = 37 min			Median = 80 min		
Average = 44 min			Average = 84 min		
Shortest = 6 min			Shortest = 30 min		
Longest = 152 min			Longest = 197 min		

The seven synoptic situations sampled in this study were grouped into four categories. The first category was the cold front, and the second was the stationary frontal category which included the few warm frontal cases. The few cases with closed Lows or troughs at the surface and aloft were included in the low category. The fourth category was air mass, but certain analyses of this category were limited by the small sample (table 1).

3. LOCATION

Possible preferred areas of formation and dissipation of hailstorms were studied from map plots of echo tracks. Since the sample was relatively small for the area involved, the echo formations and dissipations were grouped and studied according to their occurrence in six 60° sectors. The analyses revealed that the northwest sector (270°–330° azimuth) was a slightly preferred area for individual echo formation, and the northern sector (330°–030° azimuth) was a preferred area for dissipation or endings.

An analysis of formation and dissipation areas for the hail echoes when sampled by synoptic causes, time of day, direction of motion, and duration did not reveal any preferred areas.

4. DURATION

The aspects of echo duration are summarized in table 2. More than half of the 50 echoes that formed in range produced hail in less than 40 min after formation (first detected on 0° tilt), and the average time was 44 min. More than two-thirds of the 35 echoes that both formed and dissipated in range had a total duration of less than 99 min, and the average duration was 84 min.

A comparison of direction of movement and echo duration before hail for the 50 echoes that formed in range revealed that northeast-moving echoes had moderate (30–49 min) to long (≥50 min) durations prior to hail with one-half having long durations prior to hail. The echoes moving southeast and east-southeast had a tendency for short (≤29 min) durations prior to the hail with 56 percent producing hail within 29 min after formation.

TABLE 3.—*Comparison of echo duration from formation to first hail with average echo speed and time of day*

Characteristics	Percent of total for each duration class		
	Short ≤29 min	Moderate 30–49 min	Long ≥50 min
Speed:			
Slow, ≤19 kt	11	24	42
Moderate, 20–29 kt	68	76	42
Fast, ≥30 kt	21	0	16
Time of day:			
Morning (0000–1159)	35	31	15
Afternoon (1200–1759)	65	63	64
Evening (1800–2359)	0	6	21

TABLE 4.—*Average speed (kt) for the three speed categories during each phase of echo duration*

Speed class	Before hail	During hail	After hail
Fast, ≥30 kt	39.6	39.0	35.8
Moderate, 20–29 kt	23.6	22.9	23.6
Slow, ≤19 kt	15.1	15.2	15.3

A comparison of echo durations prior to hail with average echo speeds is shown in table 3. Moderate speeds dominated the moderate and short durations, and there was an equal occurrence of moderate and slow speeds in the long-duration class.

The comparisons of durations prior to hail and time of day (table 3) reveal that the morning storms had a tendency to produce hail quickly. The evening storms showed no short durations, and a greater frequency of long durations than of moderate durations. For echoes that both formed and dissipated in range, there was no relationship between time of day and duration.

5. DIRECTION OF MOTION

A comparison of hail-echo speed against direction of motion revealed that 89 percent of the southeast- and east-southeast-moving echoes moved faster than 19 kt with 70 percent in the 20- to 29-kt class. The north- and northeast-moving echoes moved most frequently at slower speeds with 50 percent between 5 and 19 kt. Echoes moving east-northeast and east had slow-to-moderate speeds averaging 24 kt. The predominant echo direction in the morning was east-southeast, that in the afternoon was toward the northeast, and that in the evening was to the southeast.

6. SPEED

The average speed over the entire track of all the echoes was 24 kt, and this agrees with the movement of lines of thunderstorms given by Changnon (1960*a*). Average speeds for the periods before, during, and after hail were 23.6, 24.6, and 24.1 kt, respectively. The average speeds for echoes in the morning, afternoon, and evening were 26.6, 21.9, and 30.8 kt, respectively. The higher speeds in the evening were related to the fact that 75 percent of the evening echoes were cold frontal, and this category produced the fastest moving echoes. The average speeds of the three (fast, moderate, slow) categories of speed in the periods before, during, and after hail are shown in table 4.

7. TIME OF DAY

The morning, afternoon, and evening storms comprise 24, 64, and 12 percent, respectively, of the 103 echoes. The decided preference for afternoon occurrence agrees with results for surface hail studies (Changnon 1969). Comparison of the time of echo occurrence and the frequency of echo turn prior to hail according to left turn, right turn, or no turn was made. This was achieved by drawing a line from the beginning location of the hail echo through the echo location just prior to hail, and then another line from this prior location through the first known location after hail. The angle formed by these two lines was the echo turn. This analysis revealed that 50 percent of the evening storms had right turns, 17 percent had no turn, and 33 percent had left turns. With morning storms, 44 percent turned left, 32 percent had no turn, and 24 percent turned right. Afternoon storms showed no distinct preference for turning.

8. REFLECTIVITY

The average equivalent radar reflectivity factor (hereafter called reflectivity) at formation of the 50 hail echoes that formed in range was 6.1×10^2 mm^6 m^{-3}, and the average reflectivity at dissipation for the 52 hail echoes which dissipated in range was 1.62×10^3 mm^6 m^{-3}. The average reflectivity at formation for the 50 no-hail echoes was 5.5×10^2 mm^6 m^{-3}, which is very close to the hail-echo reflectivity at formation. The average reflectivity at or within 5 min of hail time for the 103 hail echoes was 2×10^5 mm^6 m^{-3}. The average reflectivity of the no-hail echoes at 44 min after their formation (the average time of hail after formation for the hail echoes) was about an order of magnitude lower, 1.6×10^4 mm^6 m^{-3}.

The average range from the radar to the formation point for echoes (which formed in range) was 51 n.mi., that to the dissipation point was 46 n.mi., and that to the hail location for all 103 hail echoes was 43 n.mi. Thus, range differences were not great and could not markedly affect the differences between the average reflectivities.

9. ECHO-TOP HEIGHTS

The analysis of echo heights was performed for the 50 hail and 50 no-hail echoes that formed in range. The radar was operated with variable sequential tilting of the antenna up to 8°, and this made it possible to calculate most echo-top heights during the echo duration. A plot of all hail echo-top heights against time after formation was used to prepare 90 percent envelope curves and an average height curve (fig. 2). The range of echo heights measured at any time is quite large, but tends to become smaller with time. The relatively rapid growth in the average echo height in the 10–15 min prior to the average hail time (at 44 min) and the decline in the ensuing 10 min suggest a strong convective surge during hail growth, and then a loss of strong updrafts immediately after hail.

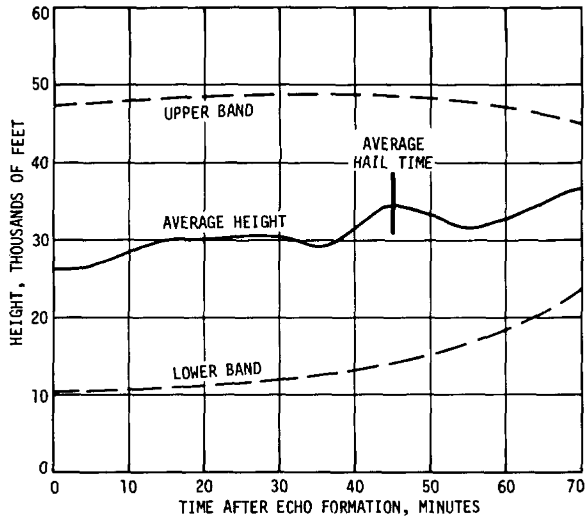

FIGURE 2.—Average height curve and 90 percent envelope curves (made by upper and lower bands) for hail echoes for time after echo formation. Ten-minute intervals after formation were used to prepare the curves.

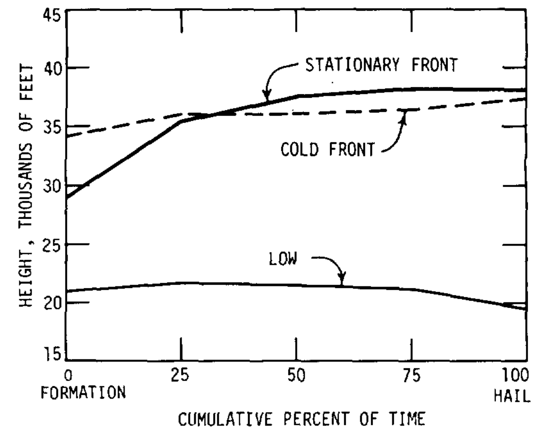

FIGURE 3.—Height curves of hail echoes for three synoptic weather categories as determined for the indicated percent of time from formation to the time of hail.

Figure 3 is a time-height graph based on average echo height for three weather categories. To allow comparison of echo-top behavior between echoes of varying duration, the heights were determined for the 0 (formation), 25, 50, 75, and 100 percent (hail time) points in time from formation to the time of hail. Hail-producing echoes occurring with the three synoptic conditions exhibit most of their growth in the first 25 percent of their life prior to hail. Growth is still apparent in the last 25 percent time interval before hail for the cold and stationary frontal cases. The differences in the amount of growth between figures 2 and 3 result from the different means of expressing time (real time versus percentage time).

Several comparisons between the 50 hail-echo tops and the 50 no-hail-echo tops, all of which formed in range, were made. Figure 4 is a real time average height graph depicting curves for hail and no-hail echoes as stratified by synoptic weather conditions. The average hail-echo tops were higher than those of the no-hail echoes in all but the earliest 20 min of stationary frontal echoes. The no-hail echoes exhibited very little growth after the 11–20-min time interval, whereas the hail echoes almost always exhibited some increase after this interval.

Table 5 shows probabilities for different frequencies of taller echoes that will produce hail on any given hail day. Values indicate the possible confidence in predicting that tall echoes will be hailstorms. These probabilities are based on a comparison of the heights of the 50 hail echoes with those of the 50 no-hail echos at formation, at average hailtime, and at dissipation. The taller half of the echoes on each day were used in this analysis. The probabilities at formation time show that on 38 percent of the days 81 percent or more of the taller echoes will become hailstorms and that on 54 percent of the days more than 60 percent will become hailstorms. On 84 percent of the hail days, more than 60 percent of the taller half of the echoes at hail time and at dissipation will be hailstorms. Since prediction at formation time is the most useful operational knowledge, it is important to realize that on 77 percent of the days more than half of the taller echoes at formation became hailstorms, and on 54 percent of the hail days more than 65 percent of the taller echoes became hailstorms.

Figure 5 is a plot of the echo heights against percentage of total echo life for all the hail and no-hail echoes that formed and dissipated in range. The hail echoes were higher than the no-hail echoes, but the shapes of the curves are quite similar with a constant difference in height of about 2,500 ft. This suggests similar processes in cloud echo evolution, but more vigorous convection throughout the life of a hailstorm. In a study of heights of 33 echoes at hail time, as depicted on an RHI of a 3-cm TPS–10 radar, Changnon (1969) calculated an average height of 29,600 ft. The average height at hail time for the 35 hail echoes that formed and dissipated in range was 27,000 ft.

10. COMPARISONS OF HAIL AND NO-HAIL ECHOES

The comparisons of characteristics of hail echoes and no-hail echoes are summarized in table 6. In general, the 50 hail echoes that formed in range were used for the comparison. As can be seen, there is very little difference in the values for echo time, direction, speed, and reflectivity at echo formation. There was some difference in the average reflectivities at the average hail time (44 min) after echo formation. For the echoes that formed and dissipated in range, the average heights of the hail echoes were higher than those of the no-hail echoes at all times.

11. SYNOPTIC WEATHER CONDITIONS

The durations of echoes between formation and first hail were determined for three primary synoptic categories. Cold frontal storms tend to have longer prehail durations than do echoes with the other categories with 50 percent having long (≥ 50 min) durations. Echoes formed under stationary frontal conditions showed about equal preference for short (32 percent), moderate (32 percent), and long (36 percent) durations. Echoes with

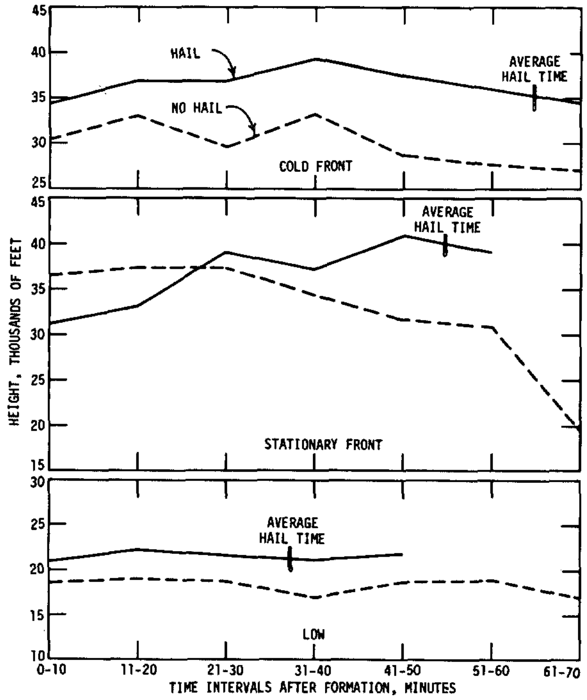

FIGURE 4.—Height curves of hail and no-hail echoes for three major synoptic weather categories for time intervals after formation.

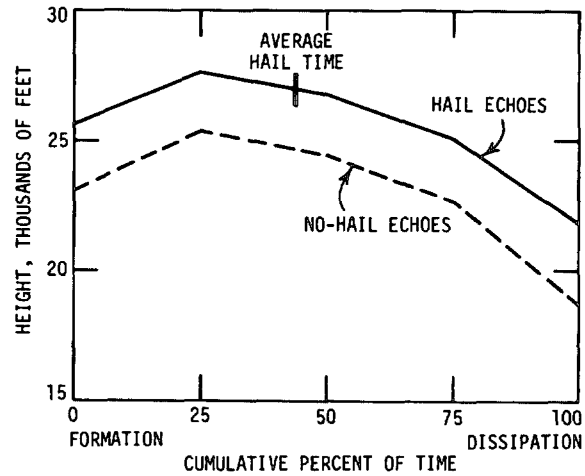

FIGURE 5.—Height curves for all hail and no-hail echoes as determined for the indicated percent of time from formation to dissipation in range.

TABLE 5.—*Daily probabilities that the tallest half of the echoes at different stages will produce hail*

Percent of tallest half of the echoes	Probability, percent, at different stages		
	Formation	Hail time*	Dissipation
81-100	38	46	54
61-80	16	38	30
41-60	23	8	16
21-40	23	8	0
0-20	0	0	0

*The heights used for analyzing no-hail echoes were those at the time corresponding to the average time of hail (44 min after formation), as based on all 50 hail echoes.

TABLE 6.—*Comparison of characteristics of hail echoes with those of no-hail echoes**

Echo characteristics	Hail	No-hail
Preferred time of occurrence, CST	1200–1800	1200–1800
Average direction of movement, degrees	81.9	85.9
Average speed, kt	23.8	24.2
Average reflectivity at formation, $mm^6 m^{-3}$	6.1×10^2	5.5×10^2
Average reflectivity at hail time,† $mm^6 m^{-3}$	7.3×10^4	1.6×10^4
Average height at formation, ft	25,600	23,000
Average height at hail time,† ft	27,000	24,700
Average height at dissipation, ft	21,800	18,500

*All values are based on the 50 no-hail echoes and on the 50 hail echoes that formed in range, except the height values which are based on the 35 hail echoes that formed and dissipated in range.
†Average hail time was 44 min after formation.

Lows produced hail more quickly after echo formation with 50 percent producing hail in less than 29 min.

The analysis of speed with each synoptic category showed in general that the cold frontal echoes moved with moderate (20–29 kt) to fast (≥30 kt) speeds with 90 percent moving faster than 19 kt. More than 40 percent moved with fast (≥30 kt) speeds. Stationary frontal echoes moved with slow (≤19 kt) to moderate (20–29 kt) speeds. Forty-seven percent moved with slow speeds, and 43 percent moved with moderate speeds. Low echoes moved with moderate speeds. More than 70 percent moved with moderate speeds. An analysis of echo speeds before, during, and after hail for each synoptic category showed no significant differences against time.

The directions of echo motion (toward which the 103 echoes were moving) were grouped by synoptic categories (fig. 6). Stationary frontal echoes (fig. 6a) had a marked tendency to move in a northeast direction, and those with Lows frequently moved to the east-southeast and southeast. The cold frontal echoes showed a preference for northeast or southeast motions. When the directions of all 103 echoes were grouped, preferences for northeast and east-southeast were indicated (fig. 6d).

An analysis by synoptic category was also done for the echo turning in the period prior to first hail, according to left turn, right turn, or no turn. This analysis revealed no marked preference among the three turn options for the echoes with cold and stationary fronts (figs. 7a and 7b). The echoes with Lows had more of a tendency to turn to the left, or to not turn, than to turn to the right (fig. 7c). This indicates considerable variability in steering level winds with each category.

Also shown in figures 7a, 7b, and 7c are the average degrees of turn to the right or left for each synoptic situation. The cold frontal echoes which turn tend to have a 50 percent greater turn to the right than to the left, whereas the echoes with other synoptic categories average about the same degrees of turn to the right as to the left.

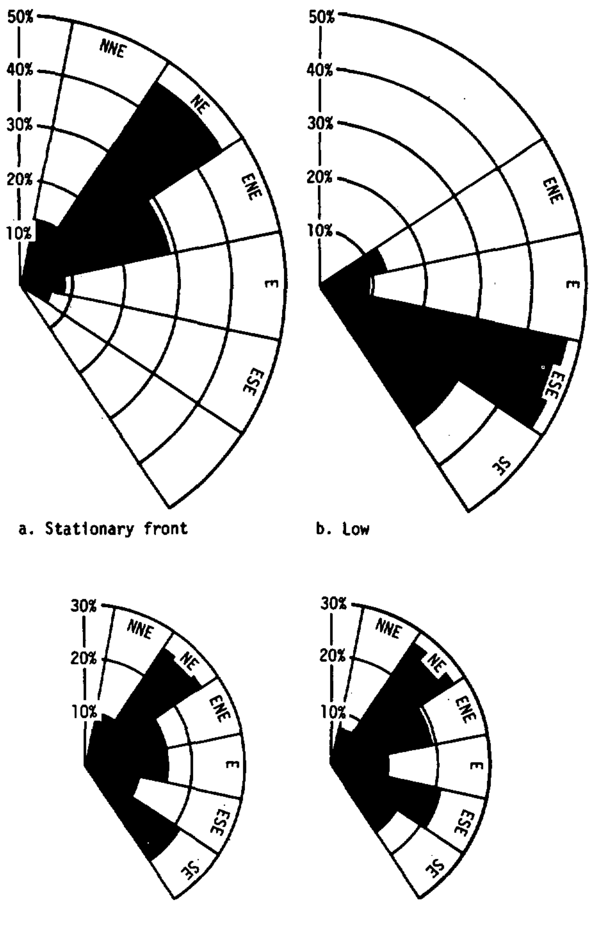

FIGURE 6.—Percent of occurrence of hail-echo motion (toward which the echoes were moving) for each synoptic weather category and for all cases.

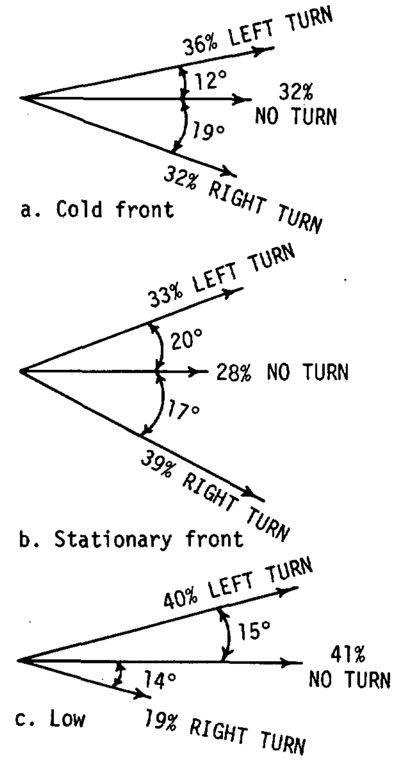

FIGURE 7.—Percent of occurrence of hail echoes turning and not turning and average degrees of turns for each synotic weather category.

When the times of day for the beginning times of the 103 echo tracks were grouped by synoptic situations, the cold frontal cases were found to occur largely in the afternoon and evening. Afternoon tendency for beginnings was very predominant for the stationary frontal echoes. The echoes with low conditions had a decided preference for beginning in the morning and afternoon. Diurnal heating was obviously an important factor in hailstorm occurrence in all three classes.

12. ECHO MODELS

Analyses of the echo characteristics, when sorted and then grouped for the three synoptic weather categories, revealed distinctly different and reasonable models for each (table 7). These synoptic models, or typical hail echoes, provide some information that can be used as guidance in making operational decisions concerning potential hail-producing echoes.

The hail-echo model for cold fronts is faster moving, as would be expected from the normal upper level steering winds with cold fronts, than are the other echo models. The cold frontal model also is the longest lived and highest storm (entire duration), and has relatively high reflectivities. The considerable instability associated with cold fronts indicates these findings are reasonable. The high reflectivity values also may relate to the fact that hail from cold frontal storms is relatively long lasting and that cold frontal hailstorms usually are associated with relatively heavy rainfall (Changnon 1969).

The stationary frontal model of hail echoes indicates a right turn prior to the development of hail. Newton (1963) has indicated that severe storms embedded in warm moist air masses (which is the case for this condition) tend to obtain their indraft air at low levels along their southeast flank. Thus, new growth develops along the right flank which results in an apparent right turn in such an environment. The preference for afternoon echo development in the stationary frontal conditions further reflects the importance of low-level local heating on the development of hail echoes under this condition. The tendency for a left turn by hail echoes with cold fronts suggests that the heavier precipitation in these storms effectively blocks the primary upward inflow for the storm (Phillips 1969). The primary flow circles inward on the left flank, which results in displacement of the updraft to the left and growth on the left flank in many cold frontal storms.

The stationary frontal hail-echo model (table 7) is shown by its reflectivity and height values to be a strong vigorous storm. This is not unexpected. Changnon (1960*b*)

TABLE 7.—*Summary of echo characteristics for each synoptic classification*

Echo characteristics	Cold front	Stationary front	Low
Average speed (kt)	30	21	25
Average duration prior to hail (min)	59	49	32
Average total duration (min)	90	83	75
Preferred direction of motion	NE	NE	ESE
Preferred direction of turn	Left	Right	No turn
Average number of degrees turn (when turning) in preferred direction	12	17	0
Preferred time of day, CST	1200–2400	1200–1800	0000–1800
Average reflectivity at formation ($mm^6 m^{-3}$)	5.6×10^2	5.1×10^2	4.6×10^2
Average reflectivity at hail time ($mm^6 m^{-3}$)	2.6×10^5	4.6×10^5	5.2×10^4
Average reflectivity at dissipation ($mm^6 m^{-3}$)	3.5×10^3	9.1×10^2	2.6×10^3
Average top height for echo duration (10^3 ft)	38	36	19
Average top height at hail time (10^3 ft)	37	38	20

indicated that a large number of damaging Illinois hailstorms were produced under stationary frontal conditions, and a recent study of hailstreaks (Changnon 1969) shows that the volume of hail per unit area was quite large from hailstorms occurring during stationary frontal conditions.

The typical hailstorm produced by low conditions is the weakest and shortest lived of the three synoptic weather models. These storms exhibit a capability of producing hail fairly quickly after echo formation, but in turn the echo life is considerably shorter than those of the other models.

In general, the values in table 7, which are considered to be models of Illinois hail echoes, appear to be reasonable because they are in agreement with prior findings on surface hail, instability with severe weather, and the mechanics of hailstorm development.

13. SUMMARY AND CONCLUSIONS

This study has considered various parameters associated with hail-producing echoes in Illinois. Those parameters included echo location, duration, direction of motion, speed, time of day, associated synoptic weather conditions, and their relationships with each other. In addition, analyses were done on echo reflectivities and heights.

The echo location analysis indicated that the echoes have a slight tendency to form in the area northwest of the radar site. Dissipation location of the hail echoes shows a preference for the north sector, a condition related to the preferred area of formation. The sample was too small to ascertain any small (1,000 sq mi) areas of echo development, but the findings concerning greater hail-echo frequency in the northwest and north sectors agree with climatological findings on warm-season-average hail-day frequencies (Changnon 1963) which show a maximum in these areas of central Illinois.

The average height of the hail-echo tops revealed a 5,000-ft increase during the 10–15 min prior to first hail (fig. 2) which was the most rapid growth on the average echo height profile. This indicates that a sustained updraft surge was related to the hail production, and this could fit the hailstorm model proposed by Gaviola and Fuertes (1947) and subsequently elaborated on by Ludlam (1958), as well as the Bates model (1965).

The most striking finding from this hail-echo study was the great variability. Hail-producing echoes had maximum tops ranging anywhere between 9,000 and 54,000 ft at the time of hail, lifetimes from 30–197 min, average speeds from 5–50 kt, reflectivities at hail time from 10^2 to 10^8 $mm^6 m^{-3}$, and were produced by all types of synoptic weather classifications that produce summer precipitation in Illinois. Consequently, the establishment of a single model of a hail-producing echo would be difficult, and any such model would be relatively meaningless. However, three synoptic models were developed as discussed in the previous section.

Comparison of the characteristics of the hail-producing echoes with those of no-hail echoes on the same days to discern forecasting guides revealed great similiarity in all aspects except echo height. Throughout the echo duration for each synoptic category, the hail-echo top had an average height that was between 2,000 and 4,000 ft higher than that of the no-hail echo. The similarity in the shapes of the time-height curves of the average hail echo and the no-hail echo indicates a similar evolution of growth and dissipation of convection. However, the continuously greater height of the average hail echo indicates 1) stronger early convection prior to echo development, and 2) sustenance of greater convection throughout its duration. Thus, as has been shown by Douglas (1963) for Alberta hailstorms, the probability of hail in an Illinois storm is tied to the degree of vertical development of a storm.

Two-thirds of the echoes turned to the right or left prior to hail production. However, there was no marked preference for right or left turns.

Echo speed at time of hail was not markedly different from that prior to and after hail. Thus, changes in echo speed could not be used to indicate hail-producing echoes.

The average echo-top heights at hail time shown in table 7 for the two frontal models agree remarkably well with the average maximum heights for frontal thunderstorms in Ohio (Byers and Braham 1949). The average total durations of the hail echoes, 75–90 min (table 7), were 15–30 min longer than those found for thunderstorm echoes in Ohio (Byers and Braham 1949).

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