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 in the area were 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
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.

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 6° 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 1.—Frequency of hail-echo tracks by synoptic weather classifications

<table>
<thead>
<tr>
<th>Echo characteristic</th>
<th>Number of tracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formed and dissipated in range</td>
<td>35</td>
</tr>
<tr>
<td>Formed in range, but did not dissipate in range</td>
<td>15</td>
</tr>
<tr>
<td>Dissipated in range, but did not form in range</td>
<td>17</td>
</tr>
<tr>
<td>Neither formed nor dissipated in range</td>
<td>36</td>
</tr>
<tr>
<td>Total</td>
<td>103</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Duration, formation to hail, min (50 echoes)</th>
<th>% of total</th>
<th>Total echo duration, min (35 echoes)</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-19</td>
<td>18</td>
<td>20-29</td>
<td>14</td>
</tr>
<tr>
<td>20-29</td>
<td>38</td>
<td>40-59</td>
<td>17</td>
</tr>
<tr>
<td>40-59</td>
<td>22</td>
<td>60-79</td>
<td>14</td>
</tr>
<tr>
<td>50-79</td>
<td>8</td>
<td>80-99</td>
<td>23</td>
</tr>
<tr>
<td>80-99</td>
<td>9</td>
<td>100-119</td>
<td>23</td>
</tr>
<tr>
<td>≥100</td>
<td>6</td>
<td>≥120</td>
<td>9</td>
</tr>
</tbody>
</table>

Median = 32 min
Average = 44 min
Shortest = 6 min
Longest = 197 min

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

EAST-CENTRAL ILLINOIS NETWORK

SCALE OF NAUTICAL MILES

0 20 40 60

Peoria
Kankakee
Champaign
Springfield

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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).
Values indicate the possible confidence in predicting that based on a comparison of the heights of the hailtime, and at dissipation. The taller half of the echoes hailstorms and that on with those of the
81 percent or more of the taller echoes will become hailstorms. These probabilities are on each day were used in this analysis. The probabilities are tall echoes will be hailstorms. These probabilities are at formation time show that on
The no-hail echoes exhibited very little growth after the but the earliest 20 min of stationary frontal echoes. 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 echoes 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 35 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 pre hail durations than do echoes with the other categories with 50 percent having long (250 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...
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 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.
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 in-draft 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 (1960b)
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 hailday 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 $10^4$ mm$^2$ 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 similarity 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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