The Relationship Between Radar Reflectivity Factor and Hail at the Ground for Northeast Colorado Thunderstorms

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ABSTRACT

Data from the hailpad network of the National Hail Research Experiment were examined in relation to the equivalent radar reflectivity factors recorded in the lowest level sweeps of the radar beam over the pads during hailstorms in 1972 and 1976. The relationship between hail detected at the ground and reflectivity factor was examined for both areal coverage and on a point-by-point basis for each hailpad. The comparisons show that reflectivity factors of 55 dBZ are often measured when no hail is observed at the ground. Rain alone can give rise to reflectivities of this magnitude. The results of the study show that in northeastern Colorado low-level equivalent radar reflectivity factors alone cannot be used to determine the region of hailfall at the ground, nor are they likely to augment quantitative measurements by a ground network of hail sensors. The results found in northeastern Colorado are compared to results from other geographical regions.

1. Introduction

The great spatial variability of hailfall from thunderstorms requires that, for evaluating hail modification experiments, a high density of surface instruments must be used to measure hail at the ground with sufficient accuracy (Changnon, 1977). Radar, with its high spatial resolution and ability to scan large areas rapidly, has been considered as a tool for supplementing or replacing networks of hail detection instruments. It could conveniently extend hailfall information beyond the boundaries of a ground network and fill gaps within it.

Various features of radar information have been examined in other studies in the hope of distinguishing precipitation which contains hail from that which does not. It is important to note the difference between schemes which merely indicate the occurrence of hail *somewhere* in a storm from those which attempt to specify the location of the hailfall. Several echo-top height and maximum reflectivity[2] height studies are of the former type (e.g., Donaldson, 1961; Dennis *et al.*, 1970; Grosh and Morgan, 1975). Radar techniques which seek to map the region of hailfall are more difficult to establish, but such information is more valuable than the simple yes/no indications of hail somewhere in a storm.

Sophisticated techniques which require special radar equipment have been proposed for hail detection and tested with some success. These include the use of depolarization information, as in the work of Barge (1974), and radar return information at two different wavelengths, as proposed by Eccles and Atlas (1973).

Simpler methods which use conventional radar have involved examining reflectivity factors at low elevations in storms to indicate regions of hailfall. The results of these studies vary considerably. In New England, Geotis (1963) found that hail at the ground is virtually certain if reflectivity factors greater than 55 dBZ in low scans persist for several minutes above an area. In seven Alberta storms, Barge (1974) found that hail always occurred beneath low-elevation reflectivity factors exceeding 50 dBZ, while rain only was found when factors were less than 30 dBZ; between 30 and 50 dBZ there were observations of both rain alone and hail with rain. In one intense Alberta storm, Chisholm (1968) found that most hailfall originated within regions of 53 dBZ or greater and that most of the "rain only" reports were from regions of less than 50 dBZ. In Illinois

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[2] For the sake of brevity equivalent radar reflectivity factor (Z_e) is referred to simply as reflectivity or reflectivity factor and given in units of dBZ in this paper.

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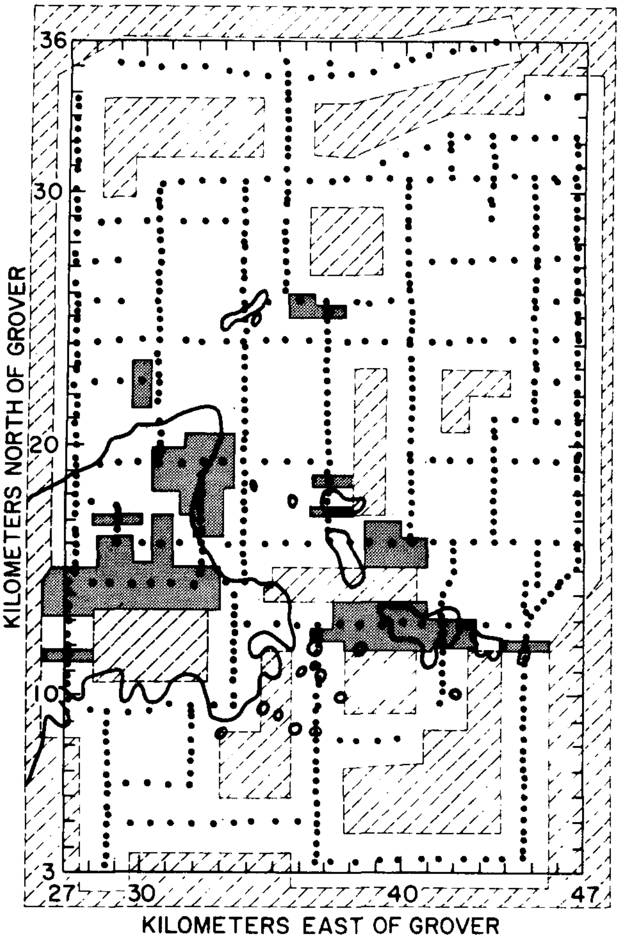

FIG. 1. An example of the areas of hailfall (shaded areas) superimposed on the 55 dBZ reflectivity envelope (heavy solid contours) for 7 July 1976. Hailpad sites are shown by heavy dots. The dashed, hatched areas are those in which hailpad coverage was considered inadequate (see text). These regions were excluded in the determination of the areas of the hailswath or reflectivity.

storms, Rinehart and Staggs (1968) found no threshold of reflectivity which separates hailfall from rainfall regions. Similarly, in Switzerland, Waldvogel and Federer (1976) found that the reflectivity factor alone was insufficient to distinguish regions of hail from rain, but that the value of the time-integrated area covered by echoes of ⩾55 dBZ did provide such a boundary. Calculations of the same parameter (P_{55}) in Crow *et al.* (1976) for storms in northeastern Colorado show that it is weakly correlated with total hail mass found within the NHRE ground network area.

This study will compare and document the relationship between low-level reflectivity and the location of hail at the ground for hailstorms in northeastern Colorado, using radar and hailpad data of the National Hail Research Experiment (NHRE). The thunderstorms occurring in this region commonly have high, cold cloud bases in contrast to lower and generally warmer cloud bases found in regions studied by previous investigators. The relationship between hail detected by the pads and the reflectivity value above them was examined both by comparing the area of hailfall to the area for which low-level reflectivity equaled or exceeded 55 dBZ and by comparing the maximum low-level reflectivity observed over individual hailpads. In addition, the duration of high reflectivity over individual pads was examined as a possible parameter to delineate regions of hailfall. A comparison between radar parameters (including time-integrated reflectivities) and hail mass for the NHRE statistical experiment has been examined by Foote *et al.* (1978).

2. Measurements

NHRE hailpad measurements have been used to define the areas of hailfall on 12 days during 1972 and 5 days during 1976. The 1973 and 1974 data from NHRE were not used because the density of hailpads was much lower in these years than during 1972 and 1976. Also the reliability and quality of the 1973 and 1974 hailpad data were lower, as explained by Dye *et al.* (1976). For the 1972 and 1976 hailpads the lower size limit for hail detection was about 3 mm diameter.

During 1972 there were 381 hailpads distributed over an area of 1758 km^2, giving an average density of 1 pad per 4.6 km^2. During 1976 there were 612 pads distributed over 660 km^2, or about 1.1 km^2 per pad. During both years, particularly 1972, there were large regions inside the network in which there were no hailpads. Since it was not possible to delineate the hail swath in these regions, they are not included in the determination of the area of hailfall or reflectivity. For this purpose, each hailpad was arbitrarily assumed to represent an area extending out 1 km in each direction from the pad. Any area larger than 3 km^2 that was further than 1 km from the nearest hailpad was defined as an area of inadequate coverage.

The radar observations used in this analysis were made with the S-band radar operated at Grover, Colorado, by the National Center for Atmospheric Research. A description of the radar, the calibration techniques and data handling procedures are given by Eccles (1975) and Foote *et al.* (1976). The radar has a 1° pencil beam and in 1976 had the capability of sector scanning entire storms over the precipitation network within 2 min. During 1972 the scanning was manually controlled, with the time between successive low-level scans varying from about 5 to 15 min. The radar was intentionally positioned about 9 km west of north-south oriented bluffs to eliminate ground clutter over the experimental area east of the bluffs.

Radar reflectivity envelopes were constructed from low-level elevation sweeps (0.5–1.5°) to use in comparison with the area of hailfall at the surface. These envelopes outlined the area on the ground above which the reflectivity on a given day equaled or exceeded a certain threshold at some time as the storm moved across the network. The envelopes used for 1972 were largely those presented in Volume IV of the Final Report of the NHRE Randomized Seeding Experiment (Foote *et al.*, 1976).

At the time Volume IV was being prepared there was some uncertainty in the calibration of the radar for 1972 (Foote *et al.*, 1976). This uncertainty has now been resolved (Rinehart, 1978) with the result that the envelopes of 45 and 55 dBZ presented in Volume IV were actually envelopes of 53 and 63 dBZ. These 53 and 63 dBZ envelopes are used in this analysis to compare with hail at the surface for the 1972 season. For the 1976 comparisons 55 and 65 dBZ envelopes are used. For purposes of brevity in the text the reflectivity envelopes will be referred to simply as 55 or 65 dBZ even though the 1972 values really are 53 and 63 dBZ.

3. Area comparisons

The hailfall swath for each day was hand-contoured based on the location of hailpads which were hit by hail. Then the reflectivity envelopes for 55 and 65 dBZ were superimposed over the hail swath (Fig. 1). The area of hailfall, the area of the 55 dBZ envelope, and the area of overlap of the hail and reflectivity were measured using a planimeter. The fraction of the area of hailfall within the 55 dBZ envelope and the fraction of the area of 55 dBZ within the hailfall boundaries were then compared for each day. This procedure was repeated for the 65 dBZ reflectivity level. The results are presented in Tables 1 and 2.

TABLE 1. Comparison of the areas (km²) of hailfall with 55 dBZ reflectivity envelopes.

Date	Area of 55 dBZ	Area of hailfall	Area of overlap	Percent of 55 dBZ area with hail	Percent of hail area with 55 dBZ
1972					
15 June	19	12	0	0	0
17 June	228	100	75	33	75
23 June	475	274	209	44	76
26 June	29	28	2.5	9	9
27 June	90	118	29	32	25
6 July	327	246	113	35	46
7 July	919	493	446	49	90
10 July	60	34	10	17	29
22 July	358	46	43	12	93
24 July	334	148	68	20	46
26 July	321	162	102	32	63
27 July	770	128	117	15	91
Mean				27.1	58.4
Standard deviation				13.2	29.3
1976					
22 June	470	490	470	99	96
2 July	33	62	21	64	34
7 July	72	50	26	36	52
21 July	50	21	11	22	52
27 July	33	19	18	55	95
Mean				55.4	65.8
Standard deviation				29.8	28.0

TABLE 2. As in Table 1 except with 65 dBZ reflectivity envelopes.

Date	Area of 65 dBZ	Area of hailfall	Area of overlap	Percent of 65 dBZ area with hail	Percent of hail area with 65 dBZ
1972					
15 June	0	12	—	—	—
17 June	0	100	—	—	—
23 June	14	274	10	71	4
26 June	0	28	—	—	—
27 June	0	118	—	—	—
6 July	30	246	9	30	4
7 July	181	493	107	59	22
10 July	0	34	—	—	—
22 July	280	46	6	2	13
24 July	11	148	11	100	7
26 July	13	162	10	77	6
27 July	78	128	10	13	8
Mean				50.3	9.1
Standard deviation				36.1	6.4
1976					
22 June	59	490	59	100	12
2 July	0	62	—	—	—
7 July	5	50	4	80	8
21 July	0	21	—	—	—
27 July	0	19	—	—	—
Mean				90	10
Standard deviation				14.1	2.8

Except for the 22 June 1976 case which will be discussed later, it is apparent that the area of hailfall within the 55 dBZ reflectivity envelope is considerably less than the area of the reflectivity envelope. Furthermore, on many days a significant fraction of the hail fell outside of the 55 dBZ reflectivity envelope. These results show that one cannot discriminate between areas of hailfall and no hailfall on the basis of reflectivity alone. The total area of hailfall is plotted versus the total area of the 55 dBZ envelope in Fig. 2. The figure shows that without regard to the location, there is a reasonable correlation (0.75) between the total area of hailfall and the total area of 55 dBZ.

The results presented in Table 2 show that there were even areas of 65 dBZ within which hail did not fall. In contrast, most of the hailfall was in regions of reflectivity less than 65 dBZ.

The mean percent of 55 dBZ area with hail is different for 1972 and 1976. Part of this may be due to the 2 dBZ difference in reflectivity levels used for the two years. Part also may be due to the shorter times between successive radar scans in 1976 and the greater density and more reliable operation of the 1976 hailpad network. The results presented in Tables 1 and 2 are based on

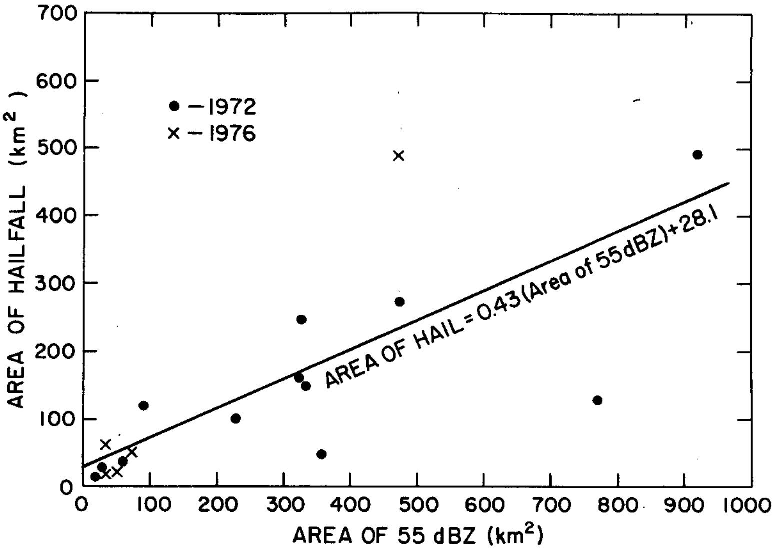

FIG. 2. The area of hailfall plotted as a function of the area of the 55 dBZ reflectivity envelope for each of the storm days.

averages over the entire day. A comparison of instantaneous areas of hailfall and 55 dBZ most probably would result in an even poorer correlation.

4. Point-by-point comparisons

The maximum reflectivity factor measured on the low elevation scans directly above each hailpad during each day was compared to the occurrence of hailfall and the size of hail found on the pad. Spatial interpolation of the reflectivity factors from radar gates adjacent to the pad location yielded values directly over each pad. A reflectivity history over each pad was obtained in this way for each day (Fig. 3).

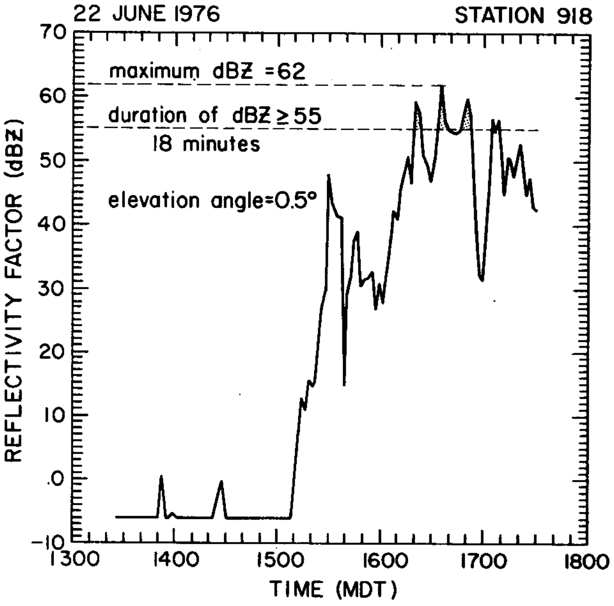

FIG. 3. An example of the reflectivity history from low-level scans above an individual hailpad. This pad was hit by hail as large as 1.7 cm diameter.

The fall distances from the radar beam aloft to the hailpads ranged from 230 m for the lowest elevation scans (0.5°) and the closest pads to 2.2 km for the highest scans (1.5°) and the pads farthest from the radar. A mean subcloud wind of 10 m s^{-1} could move hailstones falling at 15 m s^{-1} (the approximate fallspeed of 1 cm diameter hail) about 0.15–1.5 km horizontally during the fall from the region of radar measurement to the ground.

No attempt was made, however, to correct the data of this study for possible wind drifting of the hailstones due to uncertainties involved in determining appropriate winds. NHRE mesonet stations recorded only surface winds which may not be representative of the velocities even a few hundred meters aloft. In a few cases in 1976 multiple-Doppler radar data could provide subcloud wind information in precipitation, but such information is normally not available on an operational basis. Further, it is known that wind speed and direction often change greatly during the passage of a thunderstorm. Thus, the estimation of a mean fall displacement would be difficult and its usefulness in this study questionable. It is realized that the highly variable wind-drifting effect, left untreated in this study, may cause some degradation of the radar-hailpad data correlations but should not invalidate the conclusions reached herein.

Results of the point-by-point comparisons are illustrated in Fig. 4 for 16 of the 17 study days [the remaining day (22 June 1976) was unusual and is discussed separately in Section 5]. When the data are stratified by year (not shown) the results for 1972 and 1976 are

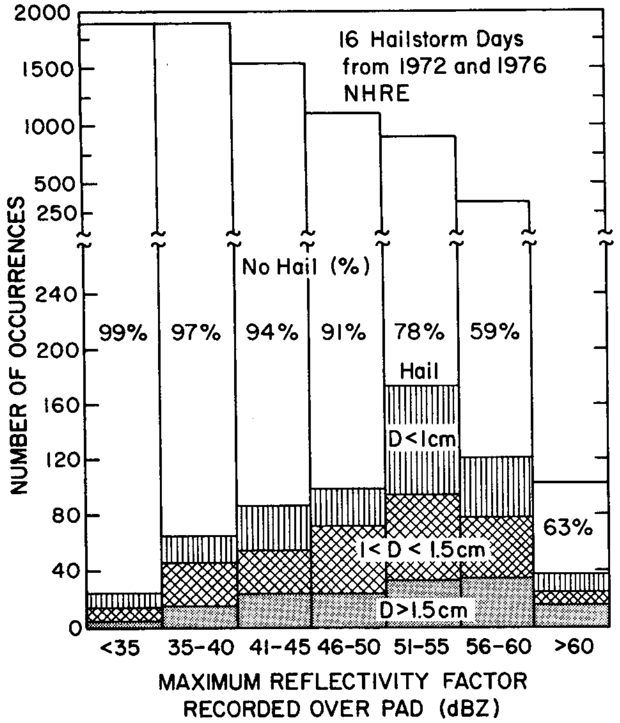

FIG. 4. Histogram of hail sizes as a function of the maximum reflectivity factor recorded from the low radar scans above individual hailpads. Unshaded areas represent the number of pads which were not struck by hail (with indicated percentages of total pads). Shaded regions represent the number of pads which were hit by hailstones of the indicated maximum diameters (*D*).

quite similar. It is apparent from Fig. 4 that when the maximum reflectivity factor recorded during a storm over a pad was 40 dBZ or less there was little likelihood (<4% chance) that hail was found at that point. Such locations could be excluded as possible hailfall sites with considerable confidence. (The occurrence of hail at sites with low reflectivities is perhaps, in part, due to wind drifting and sharp horizontal gradients of reflectivity overhead). The probability of finding hail increases gradually as the overhead reflectivities increase. On pads where hail was detected the incidence of larger sizes also increased with increasing dBZ values. Even for high reflectivity factors, however, there is still less than a 50% chance of finding any hail at a specific point. There is no evidence of an abrupt threshold value above which hail is certain. Hence, the point-by-point comparisons reinforce the conclusion from the areal comparisons, i.e., that the location of hailfall cannot be reliably delineated by the radar reflectivity pattern.

Table 3 shows the effect of the duration or persistence of high reflectivities above a pad. Periods with reflectivity factors ⩾55 dBZ were not continuous for some storms and pad locations (as in the example of Fig. 3). Whether or not the cumulative effect on hailfall of several broken periods is equivalent to a single longer continuous period of high reflectivity above a pad is unknown, and cannot be investigated with this data set, because the hailpad does not record the time of hailfall. The data in Table 3 imply that the probability of finding hail does not exceed 50% unless reflectivity values of 55 dBZ or greater persist for long periods (⩾20 min). In Switzerland, Waldvogel and Federer (1976) found a clear distinction between the duration of 55 dBZ echoes over regions recording hail (>3 min) and the duration over regions with rain alone (<2 min).

TABLE 3. Occurrence of hail on pads beneath reflectivity factors of ⩾55 dBZ.

Time duration of dBZ ⩾ 55 above pads (min)	Sixteen hailstorm days in 1972 and 1976* Pads beneath 55+ dBZ without hail	 Pads beneath 55+ dBZ with hail
1– 9	267 (61%)	172 (39%)
10–19	51 (55%)	41 (45%)
20+	6 (33%)	12 (67%)

* Excluding 22 June 1976.

5. Day-to-day variability

The results of the areal comparisons of reflectivity and hailpad data shown in Tables 1 and 2 reveal large

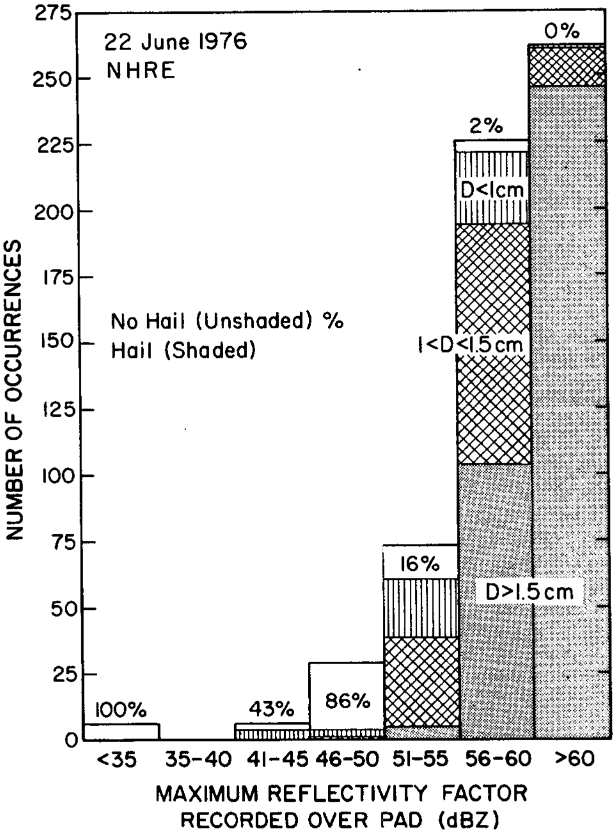

FIG. 5. Histogram of hail sizes as a function of the maximum reflectivity factor for the 22 June 1976 storm (excluded from Fig. 4). A hail/no-hail threshold of about 50–55 dBZ is evident for this storm.

variability from day to day. The point-by-point comparisons also showed large variability on a daily basis. On one day, for instance, only 6% of the pads beneath reflectivity factors greater than 50 dBZ were struck by hail; on another day (22 June 1976), 97% were hit.

The intense storm of 22 June 1976 was an unusual case because it was the only storm examined which did exhibit a distinct hail/no-hail reflectivity threshold. The area comparisons for this day are included in Tables 1 and 2, and the results of the point-by-point comparisons are presented in Fig. 5. Almost every hailpad beneath reflectivities $\geqslant 55$ dBZ was hit by hail but few of the pads beneath reflectivities <50 dBZ (although the total number is small) were hit. It was also found that 94% of the pads underneath reflectivities $\geqslant 55$ dBZ for only 4 min or less were hit by hailstones. This storm seemed to be very effective at producing hail at the ground once the reflectivity factor overhead reached 50–55 dBZ but not before.

An attempt was made to understand why the reflectivity/hail characteristics on 22 June 1976 were so much different than the other storms studied, but a straightforward explanation was not found. The winds observed at the surface by the mesonet were not unusually weak; the cloud base was rather high and cold (4.3 km MSL and 2°C); and although the storm complex was rather stationary, individual cells of high reflectivity moved with speeds of about 15 m s^{-1}, a rather common speed for cell motion in northeast Colorado. The total duration of high reflectivity (resulting from the passage of several cells) over some points was very long, but hail fell at many other sites where the duration of 55 dBZ was 4 min or less. The results for the 22 June 1976 case may be misleading since the storm was so large that the 55 dBZ envelope covered almost the entire dense precipitation network. Nevertheless, in those few regions where a hail/no-hail boundary could be delineated, the agreement between the 55 dBZ envelope and the hail/no-hail boundary was striking.

The results of the hail/reflectivity comparison for 22 June 1976 are what one would hope to find on all days in order to use conventional radar measurements to delineate areas of hailfall. The fact that only one storm out of the 17 studied exhibited such behavior underscores the problems of this approach for northeastern Colorado storms and the highly variable nature of hail production in thunderstorms. In general, the radar/hailpad correlations are too poor and the day-to-day variations too great to allow the method to be operationally useful.

6. Discussion and conclusions

The results from both the areal and point-by-point comparisons show that in northeastern Colorado, reflectivities of 55 and even 65 dBZ occur without hail being detected at the ground. Studies in other regions have shown similar results (e.g., Rinehart and Staggs, 1968; Waldvogel and Federer, 1976). The observations in New England by Geotis (1963) which suggested that radar reflectivity could be used to delineate areas of hailfall if 55 dBZ persisted for several minutes appear not to be borne out in a number of different geographical regions. Evidently, even persistent reflectives of 55 dBZ or greater often arise in rain alone or from small hailstones which melt (Eccles, 1977) before reaching the ground as they fall from the radar beam aloft.

Although the results do not show a threshold for the occurrence of hail they show that the probability of finding hail is very low until reflectivities of about 55 dBZ are reached. They also show that for reflectivities of less than 40 dBZ there is a very high probability of finding rain alone. It is interesting to compare these results with those reported by Barge (1974) for Alberta hailstorms, where hail always occurred with reflectivities $\geqslant 50$ dBZ and the upper limit for rain alone was about 30 dBZ. The reflectivity for which hail always falls in Alberta is 5–10 dB lower than the reflectivity which gives only a 40% chance of hailfall at the surface in northeastern Colorado. This is probably a result of the higher melting levels and warmer surface temperatures found in Colorado which allow more time for melting the smaller hailstones. In Illinois where melting levels and surface temperatures are comparable to Colorado, the results reported by Rinehart and Staggs (1968) are similar to those found for Colorado.

In recent work Waldvogel and Federer (1976) show that in Switzerland the durations of reflectivity greater than 55 dBZ could be used as a criterion for determining the occurrence of hail. Examination of the duration of 55 dBZ reflectivity over hailpads in northeastern Colorado has shown no clear-cut division between the durations of 55 dBZ for which hail occurs and those for which hail does not occur. Even for durations of 55 dBZ up to 20 min, over 50% of the pads detected no hail. Thus, in northeastern Colorado the duration of 55 dBZ above a given point does not help to determine if hail fell at that point.

Comparisons were made to see if meteorological parameters based on representative soundings or storm radar characteristics might be correlated with the days showing the best or poorest agreement between radar and hailpad data. There appeared to be no distinction between the best and poorest days as far as the radar cell characteristics or the representative soundings. One might expect that days with high hail potential (based on high surface mixing ratios, warm cloud bases and high instability) and relatively slow storm and cell motion might be best for defining a hail-reflectivity threshold, but this was not indicated by the sounding and radar data.

While the results obtained in northeastern Colorado are not encouraging as far as using radar reflectivity alone to deduce regions of hailfall in northeastern Colorado, studies in different geographical regions may or may not yield different results. The high cloud bases coupled with very warm surface temperatures typical of thunderstorms in northeastern Colorado apparently allow the smaller hailstones formed in the storms sufficient time to melt before reaching the ground. The results may be quite different in regions where the falling hailstones have less chance of melting. Additionally, the results found here for reflectivity alone in no way negate the possibilities of using more sophisticated techniques for hail detection.

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REFERENCES

Barge, B. L., 1974: Polarization measurements of precipitation backscatter in Alberta. *J. Rech. Atmos.* **8**, 163–173.

Changnon, S. A., Jr., 1977: The scales of hail. *J. Appl. Meteor.*, **16**, 626–648.

Chisholm, A. J., 1968: Observations by 10 cm radar of an Alberta hailstorm in a sheared environment. *Preprints 13th Radar Meteorology Conf.*, Montreal, Amer. Meteor. Soc., 82–87.

Crow, E. L., P. W. Summers, A. B. Long, C. A. Knight, G. B. Foote, and J. E. Dye, 1976: Final Report—National Hail Research Experiment Randomized Seeding Experiment 1972–1974. Volume I: Experimental results and overall summary. NCAR, 255 pp.

Dennis, A. S., C. A. Schock and A. Koscielski, 1970: Characteristics of hailstorms of western South Dakota. *J. Appl. Meteor.*, **9**, 127–135.

Donaldson, R. J., Jr., 1961: Radar reflectivity profiles in thunderstorms. *J. Meteor.*, **18**, 292–305.

Dye, J. E., A. J. Heymsfield, I. Paluch, and D. W. Breed, 1976: Final Report—National Hail Research Experiment Randomized Seeding Experiment 1972–1974. Volume II: Precipitation measurements. NCAR, 621 pp.

Eccles, P. J., 1975: Developments in radar meteorology in the National Hail Research Experiment to 1973. *Atmos. Tech.* Winter 1974–1975, 34–45.

——, 1977: The mitigation of hailstorm severity by free-fall melting of hail and some implications. *Preprints 10th Conf. Severe Local Storms*, Omaha, Amer. Meteor. Soc., 277–282.

——, and D. Atlas, 1973: A dual-wavelength radar hail detector. *J. Appl. Meteor.*, **12**, 847–854.

Foote, G. B., R. C. Srivastava, J. C. Fankhauser, F. I. Harris, T. J. Kelly, R. E. Rinehart, C. G. Wade, P. J. Eccles, E. T. Garvey, M. E. Solak, R. L. Vaughan, B. E. Weiss, and R. J. Wolski, 1976: Final Report—National Hail Research Experiment Randomized Seeding Experiment 1972–1974. Volume IV: Radar summary. NCAR, 326 pp.

——, R. E. Rinehart and E. L. Crow, 1978: Results of a randomized hail suppression experiment in northeast Colorado. Part IV: Analysis of radar data for seeding effect and correlation with hailfall. To be submitted to *J. Appl. Meteor.*

Geotis, S. G., 1963: Some radar measurements of hailstorms. *J. Appl. Meteor.*, **2**, 270–275.

Grosh, R. C., and G. M. Morgan, Jr., 1975: Radar-thermodynamic hail day determination. *Preprints 9th Conf. Severe Local Storms*, Norman, Amer. Meteor. Soc., 454–459.

Rinehart, R. E. 1978: On the use of ground return targets for radar reflectivity factor calibration checks. *J. Appl. Meteor.*, **17**, 1342–1350.

——, and D. W. Staggs, 1968: Use of radar to delineate surface hail areas in weather modification experiments. *Preprints First Nat. Conf. Weather Modification*, Albany, Amer. Meteor. Soc., 464–473.

Waldvogel, A., and B. Federer, 1976: Large raindrops and the boundary between rain and hail. *Preprints 17th Conf. Radar Meteorology*, Seattle, Amer. Meteor. Soc., 167–172.