Some Radar Measurements of Hailstorms[1]

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ABSTRACT

The radar reflectivity of thunderstorms at 10 cm is shown to be a good indicator of hail and a rough measure of its size. The physical characteristics of the hailstorm, as deduced from 3- and 10-cm echoes of a large number of New England hailstorms of 1961, are described. It is shown that the hailstorm possesses no great singularity beyond that of its significantly high reflectivity. It is concluded that the larger hailstones contribute little to the total liquid water content of the thunderstorm as the highest reflectivities measured are easily accounted for by low concentrations of large hail, wet or dry.

1. Introduction

The use of radar to the cloud physicist interested in hailstorms requires little discussion. It is surely the safest feasible means of learning more about the amount, distribution and movement of liquid water within the thunderstorm. The problem has been to separate the hail-bearers from the non-hail-bearers. Over the last few years we have found that hail at the ground is usually associated with storms whose radar reflectivities exceed a certain fairly critical value but, until recently, ground reports of hail occurrences have been too sparse to allow the drawing of definite conclusions. During the summer of 1961, requests for hail reports were made on television weathercasts, and the great response has made the radar measurements much more meaningful. These measurements of 1961 and the physical characteristics of the hailstorm deduced therefrom make up the subject of this paper.

2. Techniques of measurement

Most of our measurements of precipitation intensity are made with the iso-echo contouring device which has been described by Kodaira.[2] In this instrument the radar signal is integrated to average out the audio frequency fluctuations and corrected for the spreading of the beam with range. The output, lines of equal reflectivity, may be interpreted as lines of equal precipitation rate. This device may be operated with either of two radars, the AN/CPS-9 ($\lambda = 3.2$ cm) being used for snow and light rain, and the SCR-615-B ($\lambda = 10.7$ cm) for moderate rain or heavier precipitation. In the hail measurements to be described, only the SCR-615-B has been used because of the unfortunate effects of attenuation at 3 cm (Austin, 1961).

Hail reflectivities at 3 cm were measured with a pulse integrator, an instrument which measures signal intensity at a selected point in space. Most of these were made at close ranges when there was, hopefully, not too much heavy rain intervening.

The usual method of observation has been to take photographs of the 10-cm contours at successive levels of reflectivity, separated by 3–5 db, with the antenna normally at 1° elevation but sometimes at other angles to show the vertical structure. Storms whose reflectivities exceed the critical value for hail are photographed extensively at different gains on the RHI of the AN/CPS-9. These RHI photographs provide a reliable measure of cloud tops and a rough qualitative picture of the vertical structure.

Considerable effort has been spent to calibrate the two radars accurately; and the uncertainty in the measurements, except for atmospheric effects, is small, certainly less than 3 db. The resolutions of the two radars as determined by the beam width and half the pulse length are 1° and 75 meters for the AN/CPS-9 and 3° and 225 meters for the SCR-615-B. Both radars have conical beams.

The reflectivity factor which is used throughout the text requires some discussion. When the scatterers are small compared to the wavelength and the dielectric is known, the radar reflectivity is proportional to a factor $Z = \Sigma nd^6$, where n is the number of scatterers per unit volume and d their diameter. When Z is obtained from measured reflectivity values rather than from observed drop diameters, it is called equivalent Z and denoted Z_e. In the following text Z_e is in mm^6 per m^3 and the scatterers are considered to be water.

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[1] The research reported in this paper has been sponsored in part by the U. S. Army Electronics Research and Development Laboratory, Fort Monmouth, N. J., and the Geophysics Research Directorate of Air Force Cambridge Research Laboratories.

[2] Kodaira, N., 1959: Quantitative mapping of radar weather echoes. M.I.T. Weather Radar Research Report No. 30, 39 pp.

3. Hail data

Most of the hail reports used in this study were provided by the general public in answer to requests issued on television weathercasts by WBZ-TV meteorologists Don Kent, Bob Copeland and Norman Macdonald. Additional reports were obtained from the volunteer network of the Geophysics Research Directorate of Air Force Cambridge Research Laboratories and from public response to an article in the *Boston Globe* by Sumner Barton. The TV requests, which proved very successful and produced many good reports, were issued on days when the radar indicated widespread hail.

In all, the radar indicated hail on 12 days and hail was reported for all 12. In addition, a few reports were received for several other days when the radar was not operating. The total number of reports for the summer was approximately 1000. This number was reduced somewhat by pruning out those reports of hail which occurred beyond radar range, in shadows or when the radar was not operating. On six days of widespread hail, both the radar and report data were complete enough to allow detailed analysis, and it is from these data that this paper is largely drawn.

4. Analysis of 10-cm data

The 10-cm data consist entirely of movies of the iso-echo contours, and these were analyzed by first tracing from the movie film onto maps the loci of echoes exceeding the empirical hail criterion of $Z_e = 10^{5.5}$. On separate maps, ground reports were plotted and, by overlaying one upon the other, times and locations were compared. This method worked well for storms producing tracks. Tracks are defined, arbitrarily, as the paths of storms whose echoes exceed the hail criterion for at least 15 minutes in time and 10 miles in distance, while paths which are shorter in either time or space are called spots. During the summer of 1961, 34 such tracks were observed. Of these, 4 occurred over the ocean and one over the swamps of Ipswich. The remaining 29 were confirmed by hail reports. Confirmation of storms which produced spots rather than tracks was understandably less, on the order of 33 per cent. Here we will be concerned primarily with the track-producing storms, not only because there is little doubt that they were indeed hailstorms, but also because they were the storms upon which observations were naturally focussed. Some typical comparisons of radar tracks and hail reports for 6 and 30 June 1961 are shown in Figs. 1 and 2, respectively. For both days many of the report points represent several hail reports which were either too close together to plot separately or not easily located and therefore plotted at the center of town. Approximately 200 reports were received for each day. The long track of 30 June is the longest yet recorded by us, but is not quite as long as it appears in Fig. 2. A second storm formed near the southern end of the track, retraced part of the path, and then continued for almost an hour. The gaps near the center of this same track are radar shadows from nearby buildings.

Contour measurements at different elevation angles show that the maximum reflectivity usually occurs in the lowest 15,000 to 20,000 ft and is essentially constant at these lower levels. Fig. 3 is a plot of measured

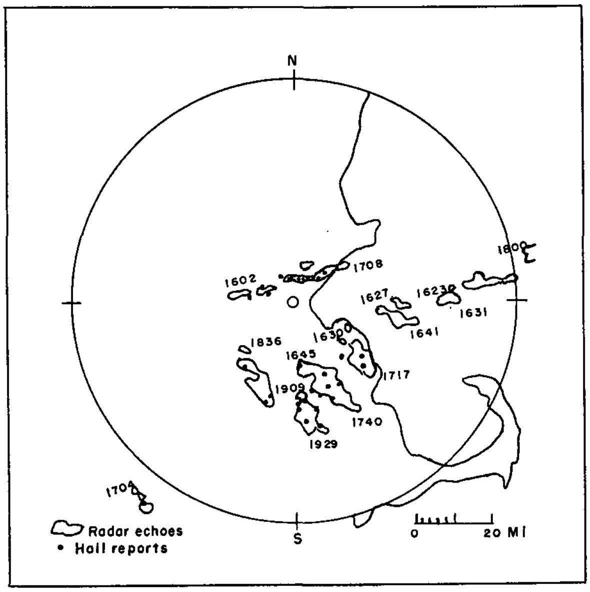

Fig. 1. Hail tracks as detected by radar and reported by ground observers. Radar hail tracks are loci of echoes whose reflectivity, Z_e, exceeded $10^{5.5}$, 6 June 1961. All times are EST.

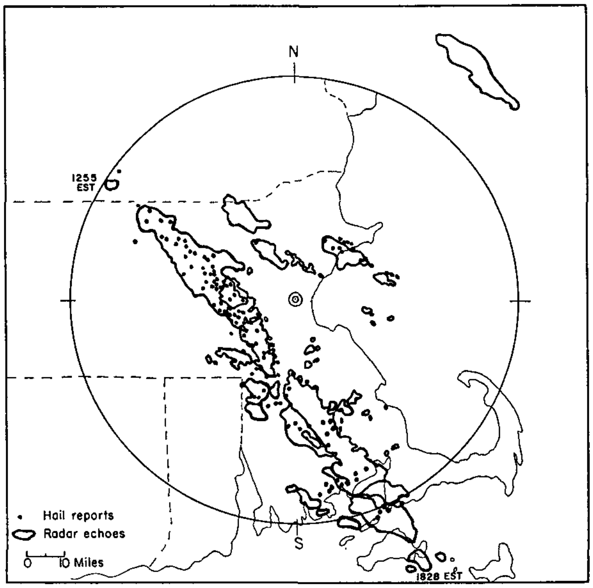

Fig. 2. Hail tracks as detected by radar and reported by ground observers. Radar hail tracks are loci of echoes whose reflectivity, Z_e, exceeded $10^{5.5}$, 30 June 1961. All times are EST.

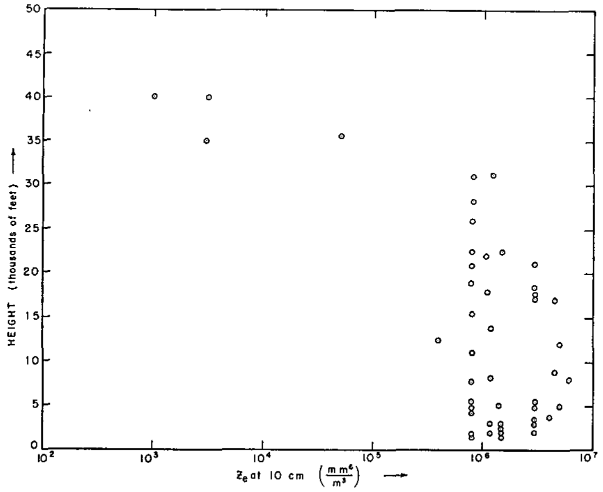

FIG. 3. Z_e values at 10 cm as a function of height within the damaging storm of 30 June 1961.

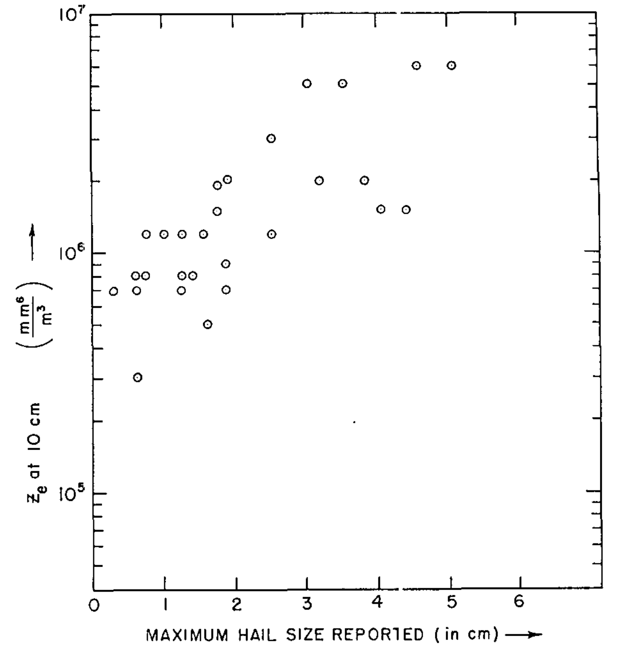

FIG. 4. Maximum measured Z_e at 10 cm vs. maximum reported hail diameter for the track-producing storms of 1961.

10-cm Z_e values against height for the storm which produced the long track in Fig. 2. The graph covers a period of about 3 hours, the time when the storm was close enough to allow height resolution of well under a mile on the part of the radar. No attempt was made to construct a synoptic profile, as the time required for a complete cycle in elevation and signal strength was of the order of cell lifetimes. The Z_e values of approximately 10^6 at 25,000 to 30,000 ft were recorded during a short period when Z_e values of around $10^{6.8}$ were measured from near the surface. Very large hail and much damage was reported both before and after this time. This was, incidentally, the only storm of 1961 in which Z_e values of 10^6 were found higher than 20,000 ft.

The location of the hail echo with respect to total thunderstorm area in the horizontal dimension was plotted for several of the hailstorms and found to be usually more or less in the center. Although at times it tended toward one side or another, there was no clear preference for any side.

Finally, a relation between 10-cm signal intensity and maximum hail size reported has been found. This is illustrated in Fig. 4 which is a plot of maximum reported hail diameter against maximum measured 10-cm Z_e values for all the track-producing hailstorms of 1961. Further, in most cases only a small portion of the radar hail track reached the maximum reflectivity, and the largest hailstones were usually observed in the corresponding area.

5. Analysis of 3-cm data

The 3-cm data consist primarily of RHI photographs from which storm heights were obtained. Echo tops of the hailstorms of 1961 ranged from 18,000 to 42,000 ft with no clear dependence of either storm duration or hail size on the height. Some hail as large as one inch in diameter fell from storms which were only 21,000 ft high, and track lengths of 10 miles or more were produced by storms which did not exceed 18,000 ft in height. There was, however, a broadening of the distribution of reported hail size with height. That is, the lowest storms generally produced only small hail, while the maximum size reported from the taller storms ranged from small to the largest reported. This is illustrated in Fig. 5, a plot of maximum reported hail diameter against height, for all the storms which produced tracks and about which height information was available.

Echo tops are, of course, obtained from full-gain RHI photographs. At reduced gains the echo decreases in size in both the vertical and horizontal dimensions; and the core, at the lowest gains, is generally 2 to 5 miles wide and 3 or 4 miles high, usually beginning near the surface of the earth. Typical vertical sections of a hailstorm are shown in Figs. 6a and 6b, RHI photographs, at low and full gain, respectively, of a storm on 6 June. This storm, which was dropping $\frac{1}{2}$ inch hail during and after the time of the photographs, passed within 6 miles of the laboratory, thus allowing full use of the resolution of the AN/CPS-9. The presence of the echoes on the film in Fig. 6a at the range indicated by the arrow (position of hail reports) implies Z_e values of the order of 10^5. This is a typical low-gain RHI of hailstorms, and indeed thunderstorms in general, with the cells appearing as chaotic clumps of still smaller cells. These little subcells can also be seen at very low gain on the R-scope, as in Fig. 7, where there is no smearing or blooming as on the RHI, and there they appear no wider than the range ring which is less than a microsecond in width. Since 0.5 μsec of this width is the result of the transmitted pulse, the actual size of those cells must be of the order of 100 m. The peaks are somewhat exaggerated by the AN/CPS-9 receiver which differentiates a bit at these very low gain settings. They are actually only 3 or 4 db stronger than the immediately surrounding echo.

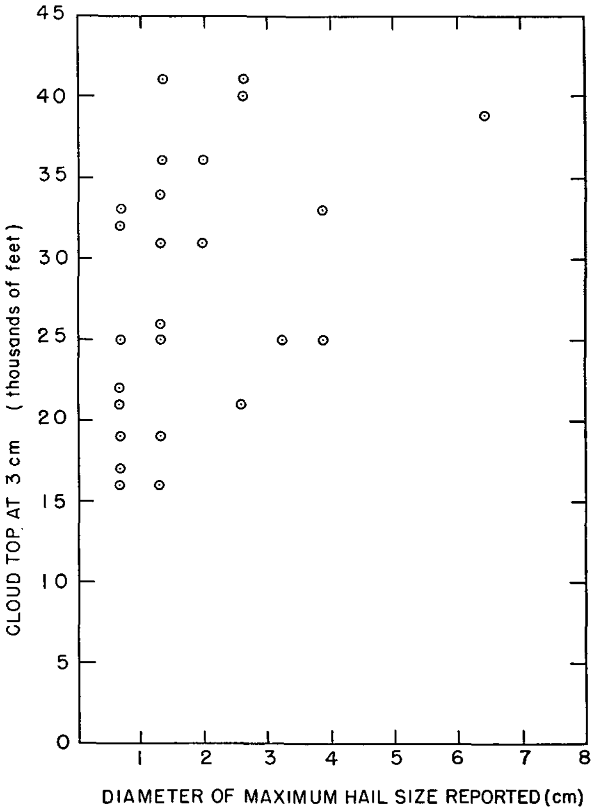

FIG. 5. Maximum reported hail diameters from track-producing storms of 1961 as a function of storm height (measured at 3 cm).

Values of Z_e at 3 cm were obtained, as previously mentioned, with the pulse integrator. Measurements at close ranges, with the integrator gated at the peaks of cells similar to those in Fig. 7, have yielded Z_e values ranging from $10^{4.5}$ to $10^{5.8}$. The latter was registered on a cell which was measuring a couple of db higher at 10 cm, and from which reports of 3/4 inch hail were received.

6. Discussion

The radar data of 1961 accompanied by approximately 1000 ground reports show that a properly instrumented 10-cm radar can identify the hailstorm. If the reflectivity, Z_e, of a storm equals or exceeds $10^{5.5}$ *and maintains these values for several minutes*, then, in New England at least, it can be identified as a hailstorm. The fact that this threshold holds in New England does not, of course, preclude the possibility that

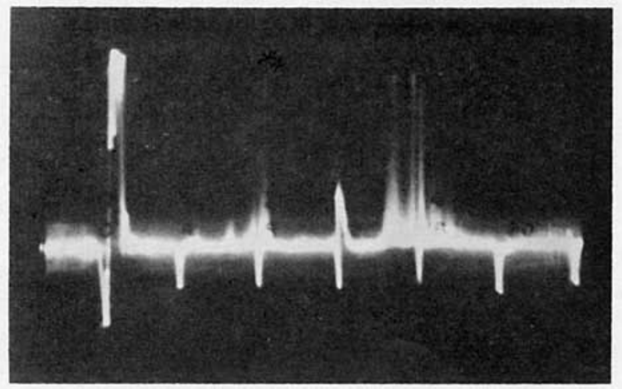

FIG. 7. Subcells observed on R-scope of AN/CPS-9 radar. Marker spacing is one mile with range ring at 3 mi.

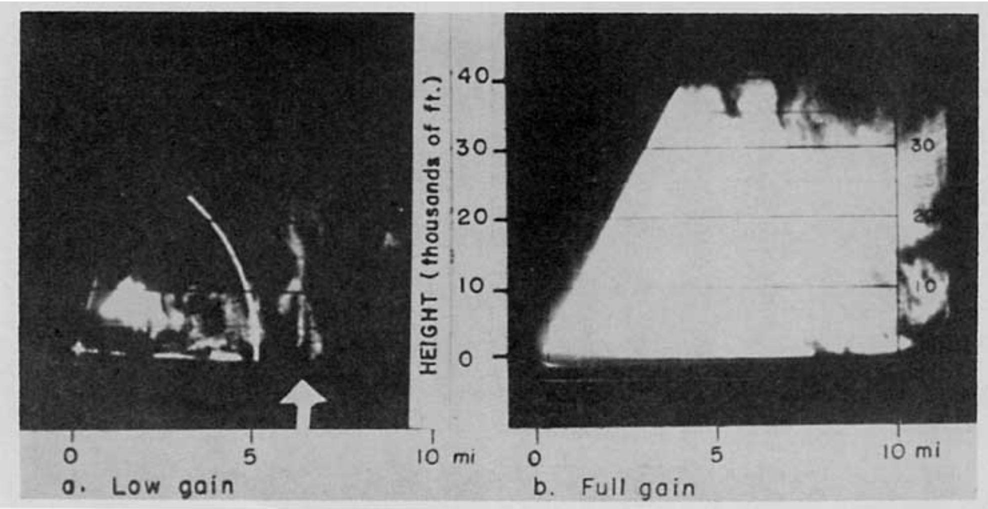

FIG. 6 (a and b). RHI photographs of a hailstorm on 6 June 1961. Arrow points to sector containing hail.

it may be different, or even non-existent, in other areas. Storms which reach this reflectivity only momentarily cannot be handled with as much confidence. Hail observations are just not complete enough for us to say with certainty that *all* such storms are hailstorms or that they may reach this intensity and yet contain no hail. Suffice it to say that about a third of them have been confirmed as hailstorms. Some hail reports, on the other hand, were received for storms which did not reach hail reflectivity, and a few even from areas of no echo at the time of the report. Most of these were from the longer ranges on two days when the storms were low, reaching only 20,000–25,000 ft. Beam filling becomes an important problem in these situations, and probably accounts for most of the discrepancies. Also, out of 1000 reports there are bound to be at least a few mistakes.

The size of the hailstone coupled with the d^6 prejudice of the radar is enough to explain the existence of a threshold at wavelengths of 10 cm or longer. This can be seen in Fig. 8, derived from Ryde (1946), which is a plot of Z_e at 3.2 and 10.7 cm against water sphere diameter at a constant liquid water content of 0.5 g m^{-3}. The water curve was chosen for the computations since recent work (List, 1961) suggests that most hailstones contain a good deal of water, and it is physically unrealistic to expect them to scatter as either dry ice or some uniform mixture of water and ice. In any case, if the particles are considered to be pure ice the 10.7-cm curve would not change much, but the liquid water content would be about 5 times as great for the same Z_e values. The fact that the 10-cm curve in Fig. 8 approximates and even exceeds the Rayleigh scattering curve for all but the largest hail is sufficient reason to explain the ability of a 10-cm radar to detect hail, and to discriminate between small and large hail up to diameters of around 3 or 3.5 cm. Measured Z_e values, however, continue to rise with maximum reported hail size even for stones of 4 to 5 cm in diameter (see Fig. 4) where the curve in Fig. 8 is dropping off. The probable explanation is that there is a distribution of sizes in the hailstorm, and the presence of very large hail is indicative of increasing concentrations of hail of all sizes. Numerous reports in 1961 support this contention as do measurements of actual hail samples in Alberta by Douglas (1960) and Douglas and Hitschfeld (1961).

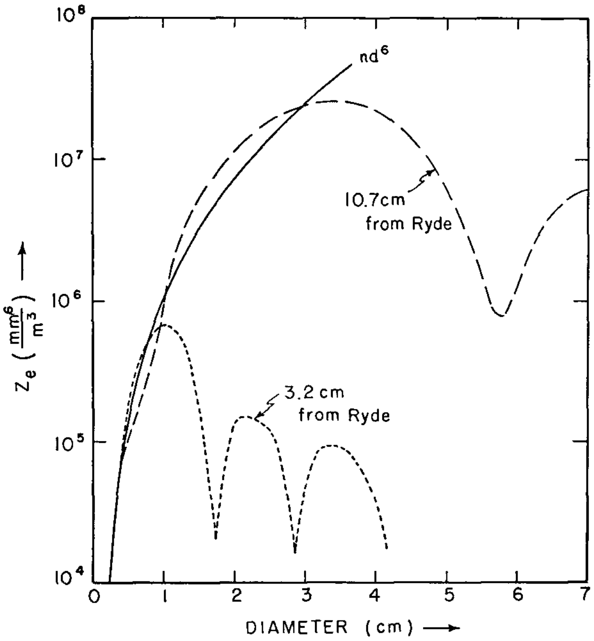

FIG. 8. Computed Z_e at 3.2 and 10.7 cm for water spheres at a constant liquid water content of 0.5 g/m^3. Rayleigh approximation (nd^6) is included for reference.

Further it can be seen from Fig. 8 that but little of the total liquid water content of the thunderstorm can be in the form of large hail. If the hailstones scatter as water particles, only a fraction of a gram per m^3 of water in the large hailstones could easily account for the highest reflectivities observed. If they scatter as ice, on the order of a gram per m^3 would suffice. The concentrations within small cells such as those in Figs. 6 and 7 could, of course, be somewhat greater but not enough to substantially change the argument.

Measurements of the reflectivity of hailstorms at 3 cm, using the pulse integrator, have yielded peak values of Z_e ranging from $10^{4.5}$ to $10^{5.8}$. Whether these values are indicative of the end of Rayleigh scattering at 3 cm as in Fig. 8, or the fortuitous effects of attenuation is a moot point.

The lack of any clear dependence of either hail size or hail echo duration upon the height is interesting. Apparently the hailstorm does not require as much room to produce hail as one might suppose—on one day 1.5-inch hail fell from 25,000 ft storms. There is, however, a broadening of the distribution of hail sizes reported with height, as was seen in Fig. 5. The largest hail was produced by tall storms but all tall storms did not necessarily produce large hail, or even more small hail. The 4-hr storm of 30 June, undoubtedly the most damaging hailstorm of 1961, with many reports of large hail (some in excess of 2 inches in diameter), broken windows and screens, ruined crops, torn convertible tops, etc., did not exceed 36,000 ft during most of its lifetime. A few times it approached 40,000 ft in height with no noticeable correlation with severity or hail size.

Further, both 3-cm RHI's at low gain and 10-cm contours at different elevation angles show the most intense part of the hail echo to be usually contained within the lowest 15,000 or 20,000 ft. The distinguishing peak aloft found by Donaldson (1959), Atlas and Ludlam[3] and others has eluded us. We have observed an occasional momentary one but it is certainly not the rule.

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[3] Atlas, D., and F. Ludlam, 1960: Multi-wavelength radar reflectivity of hailstorms. Imperial College of Science and Technology Technical Note No. 4, 96 pp.

The distinguishing feature of the hailstorm, as compared with the storm without hail at the ground, is the significantly greater reflectivity at all heights.

It is tempting to speculate on the role of the little subcells observed when the radar resolution is good enough. It is certainly difficult to fit them into any existing models most of which portray only the grossest features of the thunderstorm.

Finally, judging from the 1961 reports, the oft mentioned ratio of hail days to thunderstorm days (Appleman, 1959) would appear to be largely a function of detection, and the severity of a hailstorm depends strongly on the position of the observer.

7. Conclusions

We conclude that a well calibrated 10-cm radar equipped with the proper instrumentation can detect hail and provide an estimate of its size. If the reflectivity of thunderstorms in New England exceeds $Z_e = 10^{5.5}$, the occurrence of hail at the ground is very likely. If this reflectivity criterion is exceeded continuously for several minutes hail at the ground is virtually certain. Further, the greater the reflectivity the larger the hail. We find 3-cm radiation inadequate to the task because of the severe and unpredictable effects of attenuation.

There is no clear dependence of either hail size or hail echo duration upon the height of the storm. The very largest hail is usually produced by tall storms, but tall storms do not necessarily produce large hail, or even more small hail.

The hail echo, or zone of maximum reflectivity, at both 3 and 10 cm is usually contained within the lowest 20,000 ft of the thunderstorm. In the horizontal dimension it is generally well within the total storm outline and, more often than not, near the center. When viewed at close ranges with a high-resolution radar this hail echo is found to be composed of very intense subcells of the order of 100 meters in size.

The contribution of large hail to the total water content of the thunderstorm, as deduced from the radar signal, is found to be small. Wet hail of diameter 1.5 cm or larger at a concentration of a fraction of a gram per m^3, or dry hail of the same size at a gram per m^3, is enough to account for the highest reflectivities measured. The presence of smaller hail and rain, which appears to be the usual case, would make these values smaller yet.

Acknowledgments. We are indebted to WBZ-TV and their associated meteorologists, Don Kent, Bob Copeland and Norman Macdonald and to the people of New England whose response to their requests provided such excellent data on hail occurrences. Without the help of all these people this study could not have been made.

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