Hailstone Shape Factor and Its Relation to Radar Interpretation of Hail

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ABSTRACT

The shape factor of hailstones, defined as the ratio of their long and short axes (m'/m), has been measured for hailstones from three geographical areas: northeastern Colorado, central Oklahoma and central Alberta. The results show a general tendency toward decreasing sphericity with increasing size and are different for different areas. The results are relevant to remote hail sensing by radar techniques utilizing polarization.

1. Introduction

Much of the early literature in the field of hail research consists of reports of hailstone shapes and sizes, often from individual hailfalls that were in some way unusual. In a comprehensive discussion of observational data and the formation of precipitation, Weickmann (1953) used reports from the previous 100 yr to classify hailstone shapes and to tabulate the frequencies of shapes and sizes of hail in the moderate climates of Europe and North America. List (1958) reported on the shapes and sizes of stones from collections in the Davos region of Switzerland and gave the results from the first investigation of the internal structure of hailstones through his thin-sectioning technique. Douglas (1963) has characterized the hailstones of Alberta, and Carte and his colleagues (1966, 1970a,b) have given complete descriptions and illustrations of the hailstones of the South African Transvaal.

Before the advent of polarization-dependent radar techniques, the major reasons for interest in the shape of hailstones were related to considerations of hailstone growth rates and calculating terminal velocity, collection efficiency and heat transfer. These factors have been addressed by several investigators. Most current interest in hailstone shapes has been stimulated by inquiries into the characteristics of radar return from precipitation particles, particularly to techniques that rely upon polarization or depolarization of the backscattered radiation. The polarization effects depend upon the nonsphericity of hydrometeors, their preferential fall attitudes and modes of tumbling. Barge (1972) has discussed the importance of these factors in his report of hail detection with a (circular) polarization radar (CDR), as have Bringi et al. (1984) for linear polarization radar (ZDR).

Although other methods have been used to define the shape factor of a hailstone, the ratio of the minimum to the maximum dimension (m'/m) is thought to be the most relevant to calculations of CDR (see discussion by Barge, 1972).

The existence of a large body of data from several geographical areas has made it possible to compile graphs of hailstone shape factor as a function of stone size. The data consist of photographs of hailstone thin-sections, all of which were intended to have the longest and shortest axes of the stone in the plane of the section. For conical stones, sections were cut parallel to the cone axis. Some hailstones, especially very large ones, are so irregularly shaped that mutually perpendicular, longest and shortest axes are not uniquely defined. Such stones have been excluded from this study. Only the final external shape of the hailstones has been measured and reported here. Because the internal structure of hailstones is layered, and the layers are distinguishable one from another by their different crystal and bubble characteristics, it is possible in large stones to use the layered structure to reveal intermediate shapes and thus theoretically to increase the number of measurements contributing to shape factor curves. This has, in fact, been done for five large hailstones by Browning (1966). It has not been done here because of the difficulty encountered in being sure that the major and minor axes of such intermediate shapes were within the plane of the section.

2. Method

The length of the longest (m) and shortest (m') axes were measured from photographs of hailstone thin-sections and the axis ratio, m'/m, tabulated. For all cones, the cone axis was taken automatically as the "long axis" and the maximum dimension perpendicular to the cone axis taken as the short axis. Because many conical hailstones are truncated, this method of

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measurement resulted in an occasional axis ratio in excess of 1.0; however, this convention was chosen because the tendency is for the main cone axis average direction to be vertical in free fall. This method of calculation is therefore more relevant to radar detection techniques that depend upon preferred orientation than the strict m'/m criterion would have been.

3. Results

Figure 1 gives the average axis ratio as a function of size for hailstones from Oklahoma and northeastern Colorado; size is defined as the length of the longest axis. The bars give the 95% confidence level for the population mean, calculated from the t distribution where t is a function of $s/\sqrt{N}$, s the sample standard deviation, and n the number of hailstones in the sample. As the figure shows, the small hail from northeastern Colorado is significantly less spherical than hail of comparable size from Oklahoma. This difference in symmetry is probably a straightforward reflection of the difference in hailstone embryo type between these two areas: Oklahoma hailstone embryos are predominantly frozen drops and are therefore nearly spherical, while those from northeastern Colorado are primarily conical graupel (Knight, 1981). Another factor in the observed difference in symmetry of the small stones could be changes induced by melting, since the freezing level in Oklahoma is higher above the ground than it is in Colorado. However, melting would be more likely to reduce the difference rather than cause it, because the tip regions of conical graupel are typically low density rime and thus more susceptible to melting. Indeed, most conical small hail collected at the ground in summer has blunt tips, suggesting that the tip area has been removed (Knight and Knight, 1973), which would increase m'/m and not reduce it.

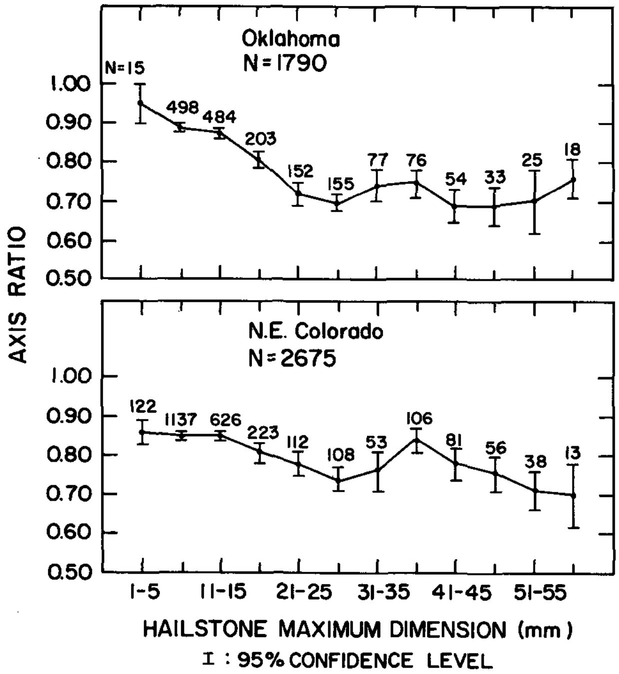

FIG. 1. Average shape factors (m'/m) for Oklahoma and northeast Colorado hailstones as a function of longest hailstone axes (m). Bars indicate 95% confidence level for average shape factor from the t distribution.

The results from both regions show decreasing symmetry with increasing size to approximately 30 mm in longest dimension, and both curves suggest a local maximum in the shape factor at approximately 40 mm. This maximum is not statistically significant in the Oklahoma data but it is significant in the Colorado data. It is interesting to note that the 95% confidence levels of the two samples do not overlap in the size range between 36 and 45 mm.

The explanation for the peculiar bump in the data is not obvious from looking at the thin-section photographs, but it may reflect the onset of tumbling. It is not unusual for Colorado hailstones to retain a conical shape until the cone axis dimension is 20–30 mm or even slightly longer. At this point the hailstones begin to tumble and the whole growth symmetry changes (Mossop and Kidder, 1962; Knight and Knight, 1970). This sequence also occurs in Oklahoma but is much less common since the original conical shape is also less common.

Although no hailstones larger than 60 mm in longest dimension are shown in the figure because of the small amount of data available, there appears to be a trend toward greater sphericity in these very large stones. Because large hail tumbles rapidly as it falls, it is, in any case, impossible to calculate the backscattering cross section as a function of the polarization direction of the radar beam from the hailstone shape alone. Also, the radar return may be dominated by 10–30 mm hail since stones of that size are often present in much higher concentrations, except when size sorting isolates the very large hailstones. Direct detection of large hail by its radar polarization characteristics would seem, therefore, rather uncertain.

Figure 2 gives results in the same form for hailstones from one hail season in Alberta (1979). The average axis ratios of small hail are generally slightly higher than those of Oklahoma and northeastern Colorado but the curves are not significantly different up to a maximum dimension of 26 to 30 mm, at which point the Alberta stones continue a trend to decreasing axis ratio with increasing size. It is interesting that the curve does not exhibit the local maximum shown in the other two curves. No hypothesis for this has been found. Indeed, the suggested explanation for the maximum in the other curves is not very compelling. Conceivably in the maximum there is an artifact—a chance occurrence—unlikely as this seems. The curve in Fig. 2 is truncated at a maximum size of 46 to 50 mm, there having been insufficient data in the larger size ranges.

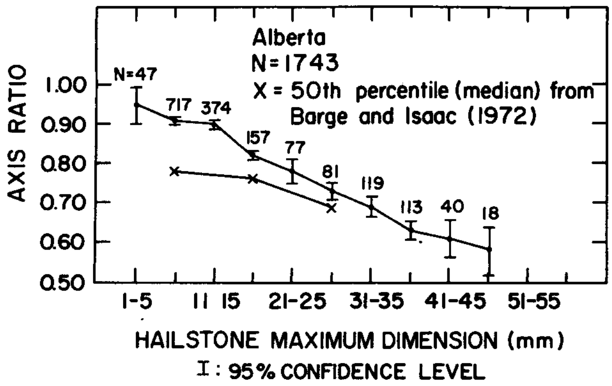

FIG. 2. As in Fig. 1 but for Alberta hailstones. The ×'s indicates 50th percentile (median) from Barge and Isaac (1972).

Barge and Isaac (1973) have given the axis ratios for a slightly larger number of Alberta hailstones as a function of maximum dimension. However, their data are in the form of cumulative percentages, which make direct comparison difficult. The 50th percentile (median) axis ratios from Barge and Isaac's data are given in Fig. 2 for three size ranges and, as can be seen, the trend of the curves is similar although Barge and Isaac's absolute values are lower, especially for hailstones with maximum dimensions 5 to 14.9 mm. This may be a result of differences in measurement procedure, particularly in the measurement of conical hailstones, if *m* was not consistently designated as the cone axis.

4. Discussion

The shape factor curves given here serve to indicate that "hail signatures" from polarization diversity radar, especially from small hail, may be different for different geographical areas. The data from which these curves were drawn also indicate that different storms in the same area sometimes produce consistently different shapes for stones of similar size. Both embryo type and the wetness or dryness of the hailstone growth are clearly important factors in determining shape; both of these factors vary from storm to storm.

The shape factor of hailstones can be measured, but knowledge of the shape factor alone is not sufficient to determine radar response to hail. The tumbling motions of falling hail, which are neither easily measured nor derivable from the shape factor, must also be known. It is the tumbling motion that determines whether the long dimensions of falling stones are, on average, vertically, horizontally or randomly oriented. Both the shape factor and the average orientation determine the effect of hail on the polarization of backscattered radar signals.

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