Note on Hailstone Size Distributions

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7 April 1970 and 5 October 1970

This note presents some new data on the interpretation and use of hailstone size frequency distributions. Hail research studies of the past 20 years have concerned the sizes of hailstones in particular study areas. In general, field studies have led to frequency distributions of hailstone sizes, usually the "most common" hailstones or the maximum sizes indicated by point measurements of individual hailfalls (Eliot, 1899; Beckwith, 1957; Donaldson *et al.*, 1960; Carte and Kidder, 1966; Summers and Paul, 1967; Changnon, 1967). Others have studied the distributions to derive various conclusions regarding hailstone formation (Battan and Wilson, 1969; Gokhale, 1970), radar reflectivity of hail (Douglas, 1962; Sulakvedlize, 1966), and climatic variations in hail (Hull, 1957; Douglas, 1963; Carte and Kidder, 1966).

Past data have been derived largely from hail-observer networks, occasionally supplemented by post-storm field surveys. For each hailfall the observers reported sizes of the maximum and most common (or average) hailstones, and occasionally the smallest stone. The bias involved in human observations of hailstones, expecially small ones, has been an obvious problem, as noted 70 years ago by Eliot (1899). Awareness of the effects of potential errors is important if the distributions are to be interpreted correctly.

The operation of dense hail observation networks during the 1967–69 period in rural central Illinois provided two sets of hailstone size data used to evaluate the hail-observer data and to compare it with the objective hailpad data using size-frequency distributions. The 1967 network comprised 86 volunteer hail observers and 49 hailpad sites interspersed throughout a 400-mi² area. The network in 1968 and 1969 included 261 observers and 196 hailpads distributed evenly throughout a 1600-mi² area. The observers reported the maximum stone size and the size of the most frequent stones by card. The observers were asked to measure stone diameter carefully and then to record the sizes as being 0.64 cm ($\frac{1}{4}$ inch) or smaller, 1.27 cm ($\frac{1}{2}$ inch), 1.91 cm ($\frac{3}{4}$ inch), 2.54 cm (1 inch), or larger than 2.54 cm. This procedure meant that the 0.64-cm category included all stones with diameters $\leqslant$0.95 cm (midway between 0.64 and 1.27 cm); the 1.27-cm category was from 0.96 to 1.57 cm; the 1.91-cm category from 1.58 to 2.21 cm; the 2.54-cm category from 2.22 to 2.83 cm; and the greater than 2.54-cm category included all those with diameters $\geqslant$2.84 cm.

The hailpads employed were 1 inch thick, 1 ft² styrofoam blocks wrapped in 0.015 inch aluminum foil. The diameter of each hailstone was calculated from the "dent size" (average of longest and shortest dimension) in the foil using a calibration procedure described by Changnon (1969). The stone sizes derived from the hailpad data were measured to the nearest 0.025 cm, but for comparison with Illinois observer values, they were grouped into the same five categories available in the observer data.

The hail observers submitted 1189 individual hailstone size reports for hailfalls from a total of 78 different hail dates in the 1967–69 period. The hailpad data used were from 1018 hailpads that experienced hailfalls during the same storms. Although the data from each source have the same underlying population, the method of sampling may have produced two samples which were dissimilar in appearance.

The number of hailfalls with stones in each of the five size categories, as obtained for each data source, was expressed as a percent of the total for each data source class group (Table 1) to compare the data sources. For instance, 5% of the 1189 observer-hailfall reports of maximum size was in the >2.54-cm category, whereas 6% of the 1018 hailfalls on pads were in this category. Further comparison of the maximum stone size values

TABLE 1. Number of hailfall reports in each stone-size category expressed as a percent of total hailfall reports in each data source-size class.

Data source and class	Diameter of stone size category (cm) 0.64	1.27	1.91	2.54	>2.54
Hailpads, maximum size	48	32	11	4	5
Observers, maximum size	29	47	11	7	6
Hailpads, most frequent size	78	16	5	1	0
Observers, most frequent size	68	24	6	2	0
Hailpads, all stones measured	88	9	2	0.8	0.2

reveals good agreement between sources for the frequencies in the three larger size categories, but considerable difference in the frequencies for the 0.64- and 1.27-cm categories. This same small-stone difference exists in the distributions of the "most frequent" stone sizes from the two data sources (Table 1). Thus, in both stone categories the hailpad data indicated a greater frequency of hailfalls with stones in the 0.64-cm size category than did the observers. This could result because 1) people do not detect many hailstones when they are 0.64 cm and smaller, or 2) people tend to derive incorrect measurements of sizes of small ($\leqslant$1.27 cm) stones. However, this latter reason for the error in observer data seems to be somewhat negated by the fact that the observers apparently measured the larger ($\geqslant$1.91 cm) hailstones well, as reflected in the comparable frequencies for the larger stones in both data sources. Regardless, the observer-derived frequencies for the preponderance of the hailstones (those $\leqslant$1.27 cm) do not relate well to those from the hailpad data which are considered to be much more accurate size data.

The frequency distribution based on all 130,022 stones measured on the 1018 hailpads is also listed in Table 1, and it reveals that only 3% of all hailstones had sizes >1.27 cm, and that most of the Illinois hailstones had diameters $\leqslant$0.64 cm. In fact, 76% of all stones had diameters $\leqslant$0.31 cm ($\leqslant$0.38 cm), and 12% had diameters classed as 0.64 cm (0.39–0.94 cm).

To assess the effect of the difference in the two Illinois distributions for maximum stone sizes, these distributions were compared graphically (Fig. 1) with those readily available from other hail-study areas. Graphical presentation was employed for such data since it can allow for a general comparison of results that are not exactly comparable because of the slightly different stone-size categories used in the different regional studies. The histograms from seven locations were arranged according to the magnitude (high to low) of their values in the smallest class interval established for each from 0.1 to ~1.0 cm.

The distributions for Arizona, New England, South Africa, Illinois (hailpads) and France indicate their mode is in the smallest size class. Gerson (1946) reported a slightly higher modal value for hail in central Europe, but data for this area were not adequate to present a

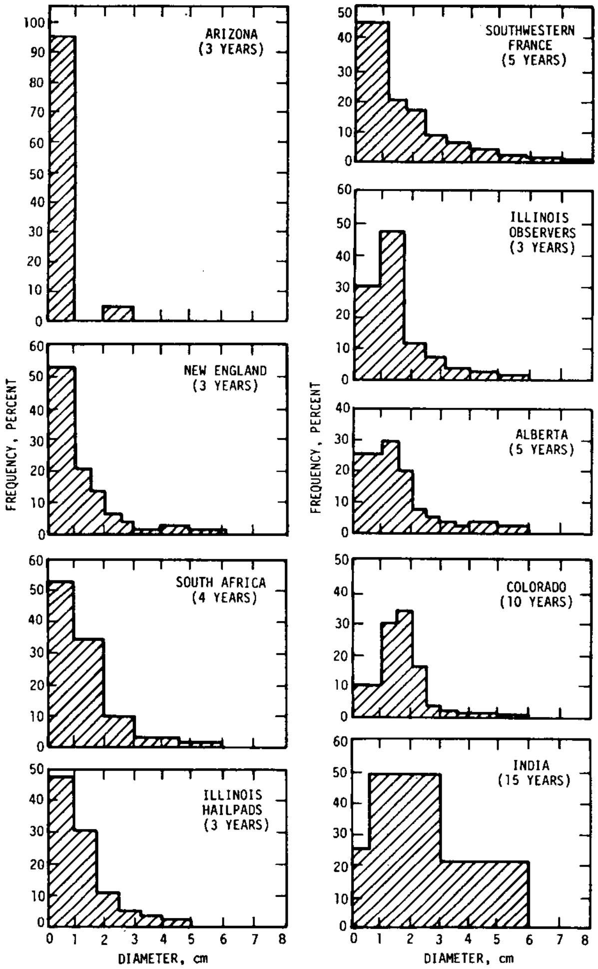

FIG. 1. Frequency distributions of maximum hailstone sizes for various locations.

distribution on Fig. 1. The Illinois (observer), Alberta and Colorado distributions exhibited modes in the 1–2 cm class intervals. The Indian distribution was limited to only three size classes, and was not ranked last by its low frequency in the 0.1–0.6 cm interval, but rather because of its high frequency of hailstones >3 cm in diameter. Stones of this size occurred in 21% of the Indian hailfalls, 12% of the Alberta hailfalls, and in 6% or fewer of the hailfalls in all other six areas.

The large hailstones in northern India are produced by the very tall thunderstorms that develop in the pre-monsoon squall lines (Nor'westers), and the two other areas with quite frequent large hailstones (Denver and Alberta) experience lee-of-the-mountain hailstorms which have been noted to produce quite intense hailfalls (Changnon and Stout, 1967). A good relationship between strong upper level winds and major hailstorms has been noted in India (Ramaswamy, 1956), in Colorado (Beckwith, 1956), and in Alberta (Longley and Thompson, 1965). Regardless of the hailstorm model envisioned, sizes of hailstones appear to be largely dependent on the vertical extent (depth) of the storm, the amount of shear and/or the distance between cloud base, and the surface (amount of evaporation and melting).

The Illinois frequency distribution based on hailpad data indicates that the Illinois observer-derived modal value is too large. Comparison of the rank of the two Illinois histograms (Fig. 1) reveals how use of the observer data alone would produce incorrect conclusions regarding hail in Illinois. This difference also suggests that the distributions in the observer-derived stone size frequencies for the seven other hail study areas (Fig. 1) may be unrepresentative of the actual distributions.

Acknowledgments. This work was performed as part of the research sponsored by the National Science Foundation under Grant GA-4618. The assistance of Edna Anderson, Eberhard Brieschke and Dan Watson in the measuring and tabulating of hailstone sizes is appreciated.

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