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HAILSTORM CHARACTERIZATION AND THE CRYSTAL STRUCTURE OF HAIL

RICHARD A. SCHLEUSENER

Colorado State University, Fort Collins, Colo.

1. Hailstorm characterization

The difficulty of quantifying hail intensity is evidenced by the fact that most researchers on hail have felt it necessary to establish special networks and reporting procedures in order to obtain more precise information on hail occurrences (Beckwith, 1960; Decker and Calvin, 1961; Donaldson, *et al.*, 1960; Douglas, 1960; Schleusener and Grant, 1961; Stout, Blackmer and Wilk, 1960).

With the exception of such special studies, quantitative data on hailstorms are meager. One quantitative measure which can be obtained from existing climatological data is the "number of days" with hail, which is being used as the variable for evaluation in one experiment in hail suppression (Sanger, 1957; Thom, 1957). This method of characterization, however, makes no distinction as to intensity of hail. Current reports of hail in published climatological data (U. S. Weather Bureau, Storm Data) in the United States, in addition to location and date, give an estimate of dollar damage from hailstorms. Since these reports are frequently compiled from press clippings, their accuracy is open to question, and in addition, the reports are subject to a bias, since severe storms in heavily populated areas will receive wider press coverage than in those uninhabited regions. Summaries of these data, such as given by Flora (1956), suffer the same limitations.

Post-storm reconnaissance has provided in recent years a number of case-history studies of hail events, including details of time and space distribution of hailfall, and details of the structure of individual stones (Browning and Ludlam, 1960; Ludlam and Macklin, 1959; Mossop *et al.*, 1961; Schaefer, 1960).

None of these techniques alone, however, provides a reliable quantitative measure of hail occurrence and intensity.

The use of passive recorders made of aluminum foil and styrofoam was being developed at about the same time in Oregon by Decker, in Illinois by Stout, and in Colorado by Schleusener and Jennings. Characterization of hailfalls in terms of estimated impact energy from passive hail recorders in the Colorado hail studies provides a method for such quantitative estimates of hail size and intensity, and therewith a method for comparison of intensity of hail among hail events (Schleusener and Jennings, 1960). Examination of the data obtained in 1960–1961 from passive recorders from the Colorado State University network (Schleusener and Grant, 1961) provides an insight into the differences that can exist between successive hail seasons, and the relations between quantity of hail, impact energy, and crop damage over a wide region. Table 1 shows a comparison of the volume of ice ($cm^3\ cm^{-2}$) and impact energy (ft-lb ft^{-2}) for 1960–1961, obtained from the hail indicators exposed in the Colorado State University hail network.

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TABLE 1. Volume of ice ($cm^3\ cm^{-2}$) and estimated impact energy (ft-lb ft^{-2}) by hail size class for 1960–1961. Data from hail indicators were obtained from the Colorado State University hail network.

Size class median diameter		1960				1961			
		Volume		Energy		Volume		Energy	
Inches	Cm	cm^3/cm^2	Per cent	ft-lb/ft^2	Per cent	cm^3/cm^2	Per cent	ft-lb/ft^2	Per cent
1/8	0.32	0.012	23	0.0*	0	0.007	6	0.0*	0
1/4	0.64	0.014	30	1.6	22	0.031	23	3.4	13
1/2	1.27	0.011	22	2.4	32	0.055	40	12.0	47
3/4	1.91	0.004	9	1.0	14	0.037	27	8.6	34
≥1-1/8	2.86	0.008	16	2.4	32	0.005	4	1.5	6
Total		0.049	100	7.4	100	0.135	100	25.5	100

* Stones of this size do not dent the hail indicators.

most of the hail impact energy, came from stones of 1.27 cm diameter or smaller. Further, while 1960 had a higher fraction of volume and impact energy in the largest stone size class, the *total* volume and *total* impact energy were substantially higher in 1961.

It is of interest to compare these data with records of sugar beet damage from the same geographic region. Table 2 shows such a comparison.

TABLE 2. Comparison of total volume of hail and total impact energy from hail with area of sugar beets damaged from hail, 1960–1961.

Year	Volume of hail $\frac{cm^3}{cm^2}$ (Table 1)	Impact energy $\frac{ft\text{-}lb}{ft^2}$ (Table 1)	Total acres of beets damaged by hail*
1960	.049	7.4	41,428
1961	.135	25.5	124,634
Ratio $\frac{1961}{1960}$	2.8:1	3.4:1	3.0:1

* Mr. Lymon H. Andrews, Southern District Manager of Great Western Sugar Company of Denver, Colorado, writes as follows:

"In response to your inquiry . . . , I have asked our statistician to compile the following figures, which give in total the number of acres of beets that were hailed in the past three years, which includes all of Northern and Eastern Colorado, some acreage in Nebraska east of Julesburg, and in the Holdrege, Nebraska area:

1961	124,634 Acres
1960	41,428 Acres
1959	37,958 Acres

You will note that this checks very closely with your observations that three times as much total ice fell in Northeastern Colorado in 1961 as fell in 1960. 124,634 acres hailed, which includes acreage that was hailed more than once, is the largest damage suffered from hail in this district in many years."

From the preceding data, one may conclude that there is room for improvement in our ability to characterize hailstorms in a quantitative manner. Further, one should be cautious in characterizing the severity of a hail season by the number of cases of large hail. While hailstorms with large stones are spectacular, it appears from the foregoing limited sample that crop damage is more closely related to the total volume of ice, or total impact energy, than to the occurrence of large stones.

2. The crystal structure of hail

The structure of hailstones has been the subject of study for many years. Construction of laboratory facilities by the Swiss (List, 1960) for growth of artificial stones has given new interest to such studies. Early hopes for unique interpretation of hailstone growth rings do not seem justified. List (1961) concludes that current results are somewhat discouraging that "the type of ice in each different layer of hailstone may be interpreted on a theoretical basis," since the various types of ice in hailstones might be formed in several ways. However, there seems to be general agreement on the fact that formation of small crystals is indicative of hailstone growth in an environment composed predominately of ice crystals and larger crystals indicate growth in a wet environment, predominantly of liquid water drops[1] (List, 1961; Weickmann, 1960).

Hailstones collected in the Colorado State University hail network were analyzed to determine the relative amounts of ice in the stones composed of large and small crystals, which presumably are indicative of the relative volumes of hail grown in "wet" and "dry" environments, respectively.

Photographs were made of sections of hailstones viewed under ordinary light to obtain air bubble structure, and then photographed under polarized light to get crystal structure (Eaton, 1961). With this technique, individual crystals can be identified easily.

The various layers within the stone were then categorized as having predominantly "Large," "Medium," or "Small" crystals, using 3 mm and 1 mm as the dimensions of crystals separating the three categories.

If one considers the "medium" class of crystal as being uncertain as to environment during growth, then the relative amounts of "large" and "small" crystals can give some indication of the volumes of ice grown in a predominantly "wet" and "dry" environment, respectively.

The fractional part of the total volume of the stones composed of large and small crystals, based on analysis of 154 stones collected in 1960–61 (Fig. 1), shows an increase in the volume of small crystals for intermediate stone sizes.

A similar analysis of crystalline structure of 26 hailstones collected from the storm of 29 June 1960 shows the same general characteristics as shown in Fig. 1, except that there is a greater average volume of *small* than large crystals for stone diameters of 2.0 to 4.4 cm.

It should be emphasized that these data are for the *average* structure for the stones within each size class. Specific stones, of course, may depart significantly from the average values. As an example, some stones of diameter 1.0 to 2.0 cm were composed entirely of small crystals.

The foregoing data suggest a process by which the average hailstone formed in the lower ("wet") portion of the cloud, grew to intermediate size in the upper ("dry") portion of the cloud, and grew to large size as they fell through the lower ("wet") portion of the cloud.

It may be noted that this average structure for Colorado hailstones is in general agreement with the

[1] *Editor's note:* For other interpretations of the crystalline structure of hail see Douglas' paper and Hallett's critique of Douglas' paper, as well as Ludlam's discussion.

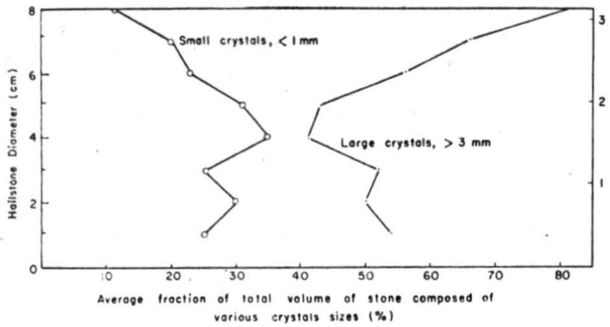

FIG. 1. Average crystal structure of hailstone, based on analysis of hailstones collected during 1960–1961.

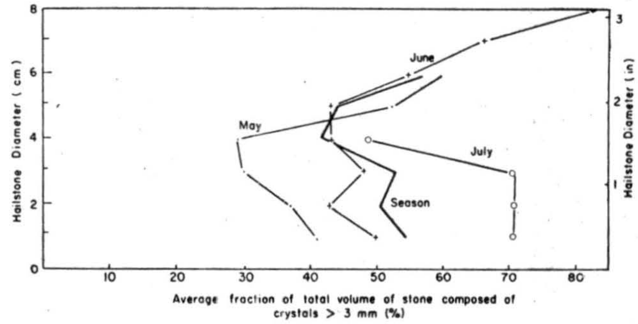

FIG. 2. Average crystal structure of hailstones by month, 1960–1961.

structure that would result from the trajectories computed by Hitschfeld and Douglas (1961).

The average fraction of the total volume of hailstones composed of large crystals for each of the months of May, June, and July, as shown in Fig. 2, increases as the season progresses. One possible explanation for this trend could be a seasonal increase in liquid water content which would give a greater chance for "wet" growth later in the season.

3. Wind shear and hail formation

An analysis of wind shear was made for 18 cases during 1961. Six cases each were for days of severe hail occurrence, moderate hail occurrence and no hail. The average wind from the surface to the tropopause was determined for Denver (DEN), Lander (LND), Scottsbluff (BFF), North Platte (LBF), and Goodland (GLD), and the wind component along the mean direction was determined for each station. Average profiles for all stations were then prepared for each category of hail occurrence: severe, moderate, or none. The results are shown in Fig. 3.

The foregoing data indicate higher wind speeds aloft for days with severe hail. The data from Fig. 3 tend to support the findings of Dessens (1960, 1961) who found a relation between severe hail and strong winds aloft, in contrast to those of Ratner (1961), who concluded that Dessens' theories do not apply to the United States.

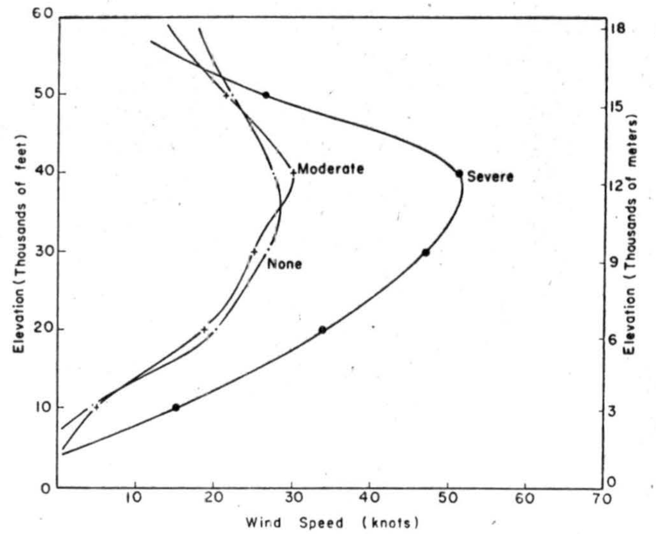

FIG. 3. Average wind profiles along mean wind direction for "severe hail," "moderate hail," and "no hail" categories, 1961. Each category consists of six days. Wind profiles are averages of DEN, LND, BFF, LBF, and GLD.

4. Summary and conclusions

a) There is need for improvement in the techniques for observing and reporting climatological data on hail, since little quantitative data can be obtained from present reports.

b) While structural damage to aircraft and property damage are probably closely related to maximum hailstone size, crop damage appears to be more closely related to the total volume of ice that falls per unit area, or to the impact energy per unit area from a hailstorm.

c) The average structure of about 150 stones collected in 1960–61 in Colorado suggests an average process of formation involving formation in a "wet" environment, growth at intermediate hailstone diameter of 4–6 cm in a "dry" environment, and growth diameter in excess of 6 cm in a "wet" environment.

d) Strong winds aloft have been found to be closely correlated with the occurrence of severe hail.

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