The Liquid Water Content of Hailstones

SONIA N. GITLIN AND GUY G. GOYER

National Center for Atmospheric Research, Boulder, Colo.

AND THOMAS J. HENDERSON

Atmospherics Inc., Fresno, Calif.

(Manuscript received 6 February 1967, in revised form 3 August 1967)

ABSTRACT

Calorimetric measurements of hailstones in Kenya, Africa, showed that 57% of the samples contained no water; these hailstones were described as hard. The average water content for the remaining samples was 4.2%; almost all of these had a clear outer shell of soft ice. In Colorado and South Dakota, liquid water content of hailstones from five storms tended to decrease from an average of 14.6% for soft, small, opaque hailstones collected in June, to 0.4% for large, mostly clear hailstones collected in August.

1. Introduction

In the calorimetric method used for the measurement of water content in hailstones, a weighed amount of water is heated a few degrees above ambient temperature in a Dewar flask. Introduction of hailstones causes the water temperature to decrease by an amount proportional to the number of calories given up by the water and its container to melt the ice and heat the resulting water until equilibrium is reached. Procedures used, including method of calibration and accuracies obtained, are described in a previous article (Gitlin *et al.*, 1966).

For field work the equipment was transported in a Dodge Power Wagon. The United States portion of the field experiment was carried out in cooperation with the Colorado State University hail research program based in New Raymer, and Project Hailswath, based at the South Dakota School of Mines and Technology. In both South Dakota and Colorado, the ground crew was directed to areas of most probable hail through efficient radio communications from radar station personnel. Hail forecasts based on radar echo characteristics, and their own visual observations, enabled the experienced ground crew in most cases to intercept hailfall or at least to catch up with it. Hailstones were analyzed in the field laboratory usually within minutes after their fall.

In the African portion of the experiment, because of absence of radar support, of road conditions and of transportation difficulties, hailstones were often sampled long after their fall and analyzed in the laboratory some hours later.

2. Data

Hailstones from nine hailstorms, at four localities, were measured as follows during 1966:

Kericho, Kenya, Africa, 17, 26, 28 and 29 March.
Boulder, Colo., 7 June.
Rapid City, S. Dak., 5 July (two storms).
New Raymer, Colo., 21 July and 9 August.

The results of the measurements and a brief description of the hailstones is summarized in Table 1. The overall results are summarized below. Note that about 90% of the stones sampled had less than 4% liquid water.

Cases (%)	Liquid water content (%)
52.0	0
36.6	0–4
11.4	>4

Two conditions are necessary for accurate measurements. First, the absorption of melt water after the stones reach the ground should be negligible. To eliminate the possibility of absorption of water from melting, or from rain water on the ground, opaque or porous hailstones should ideally be measured as soon as they reach the ground. However, this is not always possible, but absorption can greatly be reduced if the hailstones are collected from grassy patches as soon as they reach the ground and are placed in a refrigerator kept at a temperature slightly above 0C. Laboratory experiments show that if the refrigerator is kept at 0 or 1C, melting is no larger than 0.2 gm hr^{-1} and that absorbed water from melting cannot be detected. This observation is

TABLE 1. Results of hailstone measurements.

Date	Place	Water content (%)	Accuracy (±%)	Description
17 March	Kericho, Kitumbe Estate	0.0 (10 samples)	1.2 (average)	Spherical, 2–16 mm diameter, opaque or opaque embryos with clear outer shell; *very hard*. Others oblate 12×3 mm *hard* and clear with 1 mm opaque embryos.
26 March	Kericho, Kimari Estate	0.0 (4 samples)	1.1 (average)	10–29 mm diameter with 2–5 mm opaque white embryos encircled by ring of bubbles; rest clear ice, *very hard*.
28 March	Kericho, Chomogonday Estate	0.0 (4 samples)	1.0 (average)	3–7 mm diameter with 1–3 mm opaque white embryos; *hard* with few bubbles in clear outer shell.
	Kericho, Kymulot Estate and forest area	3.2	1.8	Oblate spheroids (10–18 by 7–12 mm) and spherical (10–24 mm diameter); a few very hard, clear. Majority had hard opaque cores surrounded by outer portions of *soft*, clear ice with some bubbles.
		3.2	1.3	
		3.2	0.9	
		2.2	0.9	
		1.4	0.0	
		1.4	0.8	
		1.4	0.7	
		3.0	1.3	
		1.9	0.8	
		1.9	0.7	
		2.4	1.0	
		3.1	1.1	
		2.0	1.1	
		2.0	0.9	
		2.5 (2 samples)	1.0	
		2.8 (2 samples)	1.6	
		1.7	0.7	
		4.2	1.4	
		3.3	1.8	
		2.6	1.1	
		0.0 (8 samples)	1.1 (average)	4–15 mm diameter, *very hard*, opaque or opaque embryos with clear outer shells.
29 March	Kericho, Sambret Estate	0.0 (4 samples)	1.0 (average)	Spherical (4–10 mm diameter) some *hard*, completely opaque; others *hard* and clear; teardrop-shaped (4×12 mm) opaque apex, rest clear, *hard*; irregular (15×20 mm) mostly clear with few bubbles, *hard*.
7 June	Boulder, Colo. (NCAR)	11.0	3.7	Small conical, *soft* and mostly opaque.
		15.0	2.3	
		15.2	2.5	
		16.0	2.3	
		16.0	4.0	
5 July	Rapid City, S. Dak. 1) South Dakota School of Mines & Technology	0.0	1.7	15–20 mm diameter almost entirely opaque, *hard*.
		2.4	1.2	
		2.5	1.0	
		2.9	1.2	
		4.0	2.0	
5 July	Rapid City, S. Dak. 2) Scenic, Highway 40	5.7	2.8	12 mm diameter, flat and clear.
		8.3	2.7	
		55.0*	9.1	
21 July	New Raymer, Colo. 1) 7 mi. N of Purcell	0.0 (3 samples)	2.3 (average)	6–10 mm diameter, "milky."
		4.0	1.6	
		3.5	1.8	
9 August	New Raymer, Colo. 2) New Raymer Fairgrounds	0.0 (7 samples)	0.8 (average)	25–44 mm diameter some opaque, most with clear, large knobby outer shells, *very hard*.
		2.1	0.4	
		1.8	0.4	

* Small hailstone (1.1 gm) that had melted considerably.

supported by the fact that in Kenya some opaque, white stones were kept in a cooler at 0C for several hours before tests could be made, and no water was measured. It is not possible to determine whether some absorption takes place during the fall of the hailstone from the cloud to the ground or how much melting occurs during the descent.

The second condition is that the hailstone temperature should be very close to 0C. This condition was assumed fulfilled on the basis of theoretical calculations discussed in the previous paper and of field measurements by Vittori and Gilleland (1966). Although these measurements suffer from the limitations discussed in Vittori's report, no temperatures colder than −1 or −2C were observed, even at the center of hailstones as large as 3 cm in diameter. A small mass of ice at this temperature at the center of the hailstones would not alter the results by any detectable amount. Nevertheless, in most cases hailstones were kept on a screen in a 0C cooler long enough to insure temperature equilibrium before being tested in the calorimeter.

Because of different initial calorimeter temperatures, proper corrections (Gitlin *et al.*, 1966) to standard conditions had to be made when computing percentages.

In the field it was difficult to keep temperatures of the water in the Dewar flask, the water in the insulating jacket, and the ambient air within 1C of each other. Therefore, conditions in the field were simulated in the laboratory, and heat losses of the system were plotted for a time equal to the maximum duration of the lengthiest measurements. When compared to heat losses plotted for the system under conditions used for calibration, the differences were negligible for the accuracies claimed (±0.1 gm of water).

The larger the hailstone the more accurate the measurement. In many cases several hailstones were measured together, in order to reduce the error, and for these samples the percentages recorded correspond to an average. A summary of the measurement errors is given below:

Weight of samples (gm)	No. of measurements	Error (%)
>10	26	<1
8–10	15	1.0–1.2
5–8	25	1.2–2.0
<5	13	>2

3. Discussion

If a correlation could be made between water content and seasonal variations in size, shape and physical appearance of hailstones, it might be possible to shed additional light on the growth processes of hail.

From the data we have collected three main observations can be made:

1) There is, for the Kenya storms, a close correlation between water content and hardness, hard stones having low water contents or no water, while soft, easily crushed stones had higher water contents. Liquid water was found mostly in hailstones with soft, large, clear-ice, outer shells.

For Colorado and South Dakota hailstones, no consistent correlation was found between the opacity and the liquid water content. There are opaque stones with a high percentage of water and other opaque stones without water. The same is true of clear hailstones.

2) For the Colorado and South Dakota samples the water content is highest for 7 June measurements, intermediate for the 5 July storms, and lowest for 21 July and 9 August. This area may tend to produce soft hail with high water content in the spring and hard hail with less water in the late summer; more measurements would be required to verify this observation. Summers[1] found that in Central Alberta the frequency of occurrence of soft hail decreases from about 50% in June to approximately 30% in July.

3) Browning (1966) observed that more often than not large hailstones have knobs. He believes that these protuberances increase considerably both drag and heat transfer and that, if this is so, hailstones can grow large without becoming appreciably spongy.

All of the giant hailstones from the 9 August storm had very prominent knobs and showed well-defined lobes when sliced. The lack of water in these hailstones or the very small percentages found (1.8 and 2.1) agree well with the "dry" growth mechanism proposed by Browning.

Acknowledgments. The authors wish to acknowledge the contributions of the following: Jeffery Bauer and Gregory Bullen, the U. S. field crew; John Marwitz of Colorado State University and his crew for radar support in Colorado; personnel of the Institute of Atmospheric Sciences at the South Dakota School of Mines and Technology for radar and logistic support in South Dakota; Dr. Samson of the East African Meteorological Service, Dr. Ernest Hainsworth of the Tea Research Institute, and Mr. Peter McGrigor of the African Highlands Produce Company, for making possible hailstone studies in Kenya.

REFERENCES

Browning, K. A., 1966: The lobe structure of giant hailstones. *Quart. J. Roy. Meteor. Soc.*, **92**, 1–14.

Gitlin, S., H. S. Fogler and G. G. Goyer, 1966: A calorimetric method for measuring water content of hailstones. *J. Appl. Meteor.*, **5**, 715–721.

Vittori, O., and J. B. Gilleland, 1966: Temperature of hailstones. Project Hailswath, Group 11, Final Rept., Contract NSF-C461, E. Bollay associates, Boulder, Colo., 22 pp.

[1] Summers, P. W., 1966: Note on the frequency of soft hail in central Alberta. Paper presented at the National Meteorological Congress, Sherbrooke, Quebec, 8–10 June.