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COMMENTS ON 'THE ANALYSIS OF A HAILSTONE' BY W. C. MACKLIN, L. MERLVAT AND C. M. STEVENSON

By N. R. GOKHALE and K. M. RAO

A recent paper by W. C. Macklin, L. Merlivat and C. M. Stevenson (1970) reports on the analysis of the isotopic composition of a hailstone from a severe storm. These authors have successfully used the isotopic technique developed by Facy, Merlivat, Nief and Roth (1963) to determine the air temperatures, updraught speeds and liquid water concentrations experienced by a stone during its growth. Moreover, they correctly point out that the interpretation of the data of the isotopic method is simpler and more accurate than that of other techniques such as the analysis of the bubble and crystalline structures.

The authors conclude that their analysis of the isotopic composition and the deduced trajectories confirm a zone of descent of the hailstone outside the main body of the updraught and a recycling process of the nature envisaged in the severe storm model of Browning and Ludlam (1962). This conclusion cannot be valid for the following reasons:

Using the curves of Figs. 7 and 9, they plotted how the height of the hailstone varied with radius (Fig. 10). The conclusion was drawn that there were two main growth zones numbered 1 and 2 in Fig. 10. It is not quite clear why the height for $\delta D \approx -50$% and $R \approx 0.27$ cm has not been plotted in Fig. 10. We have plotted this point and drawn the curves and offer a significantly different interpretation of the growth trajectories as discussed below.

Recently Gokhale and Rao (1969) proposed a model for hailstone growth, where major growth of embryos takes place in the upper part of the updraught. The hailstones, however, do not leave the core of the updraught during their lifetimes as they are locked into the upper part due to the profile of the updraught (namely $du/dz$ is negative in this upper region), and the particles get sufficient time to grow to large sizes. They fall out only when their terminal velocities overcome the maximum updraught velocities.

With this mechanism of hail growth as the basis and the observed fact that the updraughts in a developing cumulus are pulsating and accelerating, it is possible to construct the trajectory of the hailstone as shown in Fig. 1. It is suggested that the growth of the hailstone resulted in five successive stages:

Figure 1. The growth trajectory and development of internal structure of hailstone in the upper part of the pulsating and accelerating updraught. The fall speeds of the hailstone during its growth are taken from Macklin et al. (1970) Fig. 11. The updraught velocities are plotted on X-axis which are equal to the fall speeds.

**Stage I:** Embryo ($d = 0.54$ cm) at $-8^\circ$C grew to $1.2$ cm diameter while falling slowly against an increasing updraught to $-5^\circ$C. (For the upper part of the updraught $du/dz$ is negative.)
Stage II: The stone is then carried upward by the accelerating updraught and it grew to 2.4 cm and reached the height where the temperature was -25°C.

Stage III: The hailstone (d = 2.4 cm) did not leave the core of the updraught but grew to 2.7 cm while it was falling rather rapidly in the updraught and reached the lower level where the temperature was -15°C.

Stage IV: Updraught was accelerated once again and the stone was taken to -30°C. During this period it continued to grow and reached a size of 5.4 cm.

Stage V: This is similar to Stage I except hailstone was balanced for some time at one level and then started to fall slowly and it grew to 6.4 cm in diameter.

The growth in stages II and IV is similar to the growth suggested by Macklin et al. in ascents 1 and 2 in their Fig. 10. However, they do not adequately explain the growth in stages I and V. The growth in stage III was suggested to have occurred while the stone was falling from 7.5 km to 6.0 km outside the main body of the updraught and was picked up at the lower level where the temperature was -15°C.

Their explanation raises certain discrepancies in the nature of the hailstone growth as outlined below.

(i) According to their suggestion, the stone leaves the updraught at a level where temperature is -25°C and is picked up at -15°C level; the distance of fall would be approximately 1.5 km. Assuming its relative fall speed as 15 m s⁻¹ (which would depend on how far away it is from the axis of the cell) the duration of fall would be 100 seconds. Even assuming average value of effective LWC equal to 1 gm⁻³ in the region of its fall outside the main body of the updraught, hailstone of 2.4 cm would grow to less than 2.5 cm in diameter in 100 seconds. However, it did grow to 2.7 cm during this descent which would require much higher liquid water content. This indicates that the hailstone did not leave the core of the updraught.

(ii) The updraught profile with very sharp curvature will be necessary to envisage 2.4 cm hailstone to be thrown out of the main part of the updraught at 7.5 km level and then to be picked up at 6.0 km level. It is difficult to justify such a sharp curvature as the relative wind speed values are 11.0 and 9.0 m s⁻¹ respectively at those levels as seen from their Fig. 3.

(iii) Besides, to explain the hailstone growth in stages I and V with recycling process outside the main updraught, would pose similar problems.

We therefore conclude that the hailstone did not undergo Browning and Ludlam recycling process as suggested by Macklin et al. to grow to such a large size, but the entire growth is more likely to have occurred as shown in Fig. 1 in the core of the updraught.

Fig. 1 also shows how the internal structure of alternate layers of dry and wet growth developed which agrees well with the mechanism proposed in our model (Gokhale and Rao 1969).

References


Department of Atmospheric Science, State University of New York at Albany, Albany, New York 12203.
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Reply

By W. C. Macklin, L. Merlivat and C. M. Stevenson

In reply to Gokhale and Rao's comments, we must first point out that, to obtain sufficiently large samples of ice for mass-spectrometric analysis, it was necessary to cut the hailstone section
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into small pieces 2 to 3 mm across. The isotopic ratios are then the average over a small volume (about 20 mm³) and this limits the radial resolution of the data to 1 to 1.5 mm. In the case of the core (R < 0.35 cm) only three measurements could be made and these were insufficient to give the variation of the isotopic ratio with radius. For this reason we omitted these values from Fig. 10 of our paper. For the same reason it cannot be assumed that the values are representative of a given height, as Gokhale and Rao have done.

Because of this limitation of the experimental technique, isotopic ratios could be obtained only within about 1 mm of the boundaries of the growth layers. Otherwise, mixtures of the ratios of adjacent growth layers would have resulted. Consequently, the fact that there is no isotopic data for 0.3 < R < 0.6 cm and 1.1 < R < 1.3 cm does not mean that the hailstones grew outside the updraught between these radial limits. The actual abruptness of the discontinuity between the two ascents in Fig. 10 of our paper cannot be determined from the isotopic data alone and has to be inferred from other evidence. During the analysis calculations were made of the rate of rise of the hailstone as a function of height. For the first ascent the hailstone was accelerating upwards. The rate of rise was approximately linear with height and ranged from 10 m s⁻¹ when R = 0.6 to 20 m s⁻¹ when R = 1.1 cm. There was no indication that the hailstone began to decelerate as would be expected in a pulsating updraught. On the contrary, it appears that, for a time at least, the hailstone continued rising rapidly. Secondly, the sharpness of the boundary between the layers of crystals of different sizes also suggests an abrupt discontinuity, corresponding to a radius increase of not more than a few hundred microns. For these reasons we do not agree with Stage III of the growth proposed by Gokhale and Rao.

We did not suggest that the final clear layer was produced by recycling of the stone. We in fact stated that the flattening of the second ascent at a height of 8.5 km was due to the fallspeed of the hailstone becoming comparable with the updraught speed. The stone would then begin to fall downwards and it is in this downward fall that the outer layer was formed. However, there is insufficient isotopic data to infer any details of this growth stage.

It should be noted also that the interpretation of the isotopic data is based on the assumption that the masses of the various isotopic species are conserved in the updraught, i.e., that the ascent is adiabatic. It is difficult to see how to interpret the data in the case of updraughts with fluctuations which are small compared with the growth time of the stones and where mixing is taking place. Certainly the trajectories in our Fig. 10 cannot be used to substantiate the kind of model proposed by Gokhale and Rao. We therefore consider that our interpretation gives a self-consistent picture of the growth of large hail in a quasi-steady updraught with recycling as a reasonable mechanism for the formation of the main growth layers.

Department of Physics,
University of Western Australia,
Nedlands,
Western Australia 6009.
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A WARM THUNDERSTORM

By D. R. LANE-SMITH

The residence K22 at Fourah Bay College, Freetown, Sierra Leone, is at a height of 350 m above sea level and has a panoramic view of the Sierra Leone river and the country beyond.

At 17.15 on 17 September 1965, the sky was blue with some scattered cumulus and a single isolated, convective shower cloud over the port of Pepel at a distance of 21 km to the east-north-east. The location of the shower could be verified because the rain from it obliterated the view of the lights at Pepel. Immediately in front of Pepel is Tasso Island and this was used as a 'yard stick' to measure the height of the visible top of the cloud, since the height of the cloud subtended, at the observer, an angle a little less than that subtended by the island, nearly the same distance away. This observation placed the top of the cloud at a height of 3,000 ± 600 m.

At this time of year in the early evening the ambient sea-level temperature is 27 ± 3°C. The cloud base was observed to be about 300 m (normal for this part of the world) and, assuming the