Discussions

16 October 1974: Papers read by Dr. J. L. Brownscombe:

1. 'The production of sub-micron ice fragments by water droplets freezing in free fall or on accretion upon an ice surface' by M. Bader, J. Gloster, J. L. Brownscombe and P. Goldsmith (*Q.J.*, **100**, pp. 420–426)
2. 'The production of secondary ice particles during riming' by S. C. Mossop, J. L. Brownscombe and G. J. Collins (*Q.J.*, **100**, pp. 427–436)

Dr. B. J. Mason: The differences between the experimental results described by Dr. Brownscombe and those recently obtained by Hallett and Mossop, who report production rates of a few hundred splinters per milligramme of rime at temperatures between $-4°$ and $-6°$C falling sharply to zero at $-3°$C and $-8°$C, illustrate how sensitive the process is to temperature, the size and impact velocity of the droplets, and the structure of the rime deposit. They also point to the difficulty of simulating the growth of natural rimed elements in the laboratory and the uncertainties involved in using these laboratory data. I also wonder whether very small splinters may have escaped detection in the settling chamber experiment described by Dr. Brownscombe.

Dr. J. L. Brownscombe (*in reply*): I think it is very unlikely that a significant fraction of the small ice splinters produced in the settling chamber experiment would have escaped detection.

Water cloud was produced by condensation in the chamber and extended throughout the chamber. Under these conditions ice crystals larger than $\sim 0{\cdot}02\mu$m radius would grow quite rapidly to several μm in size.

It is not likely that more than a small fraction of these ice crystals could be swept to the walls of the chamber before falling into the detecting solution at the base of the chamber.

In this context, we may recall that most of the splinters detected in the diffusion chamber experiment appeared to be larger than $\sim 0{\cdot}1\mu$m radius.

16 October 1974: Papers read by Professor J. Latham:

1. 'A stochastic model of ice particle multiplication by drop splintering' by R. F. Chisnell and J. Latham (*Q.J.*, **100**, pp. 296–308)
2. 'Electrical corona from ice hydrometeors' by R. F. Griffiths and J. Latham (*Q.J.*, **100**, pp. 163–180)
3. 'Corona from colliding drops as a possible mechanism for the triggering of lightning' by J. A. Crabb and J. Latham (*Q.J.*, **100**, pp. 191–202)

Dr. B. J. Mason: As the authors make clear, their calculated rates of splinter production are very sensitive to the values assumed for r, the average number of splinters produced per drop, and τ, the mean lifetime of a splinter between production and capture by a drop. It is therefore relevant to point out that there is very little convincing evidence to support the adoption of values of r as high as 6 and values of τ as low as 30min. Reducing r from 6 to 3, or doubling τ, reduces the calculated multiplication factors by two orders of magnitude. I would also question the underlying assumptions of their basic Eq. (11), viz. that the ice splinters remain negligibly small with negligible fall speeds relative to those of the collecting drops, and that the removal of droplets by the ice particles is negligible. During an average life time $\tau \simeq$ 30min, splinters would grow into a riming element of order 1mm in diameter, i.e. much larger than the droplets which are supposed to capture them. Even in a period of only 10min the splinters would grow into rimed particles of radius $\sim 100\mu$m. After a given time $t > T$, with $\tau = 30$min, the fraction of splinters more than $T = 10$min old is at least one quarter if $r = 5$, and at least one half if $r = 3$. If τ were doubled the corresponding fractions would be nearly $\frac{1}{2}$ and $\frac{3}{4}$. The reduced collision kernels for these particles colliding with drops of average radius 75μm implies appreciably larger values of τ than those calculated by Chisnell and Latham and a corresponding reduction in the calculated number of splinters available for capture by these drops.

This reinforces my view that the release of splinters during the growth of rimed particles is likely to be much more important than the capture of newly formed splinters by individual small drizzle drops.

Certainly if one adopts the high rates of splinter production reported by Hallett and Mossop, it is possible to demonstrate that the growth of rimed pellets may account for multiplication factors of order 10^4 in clouds whose tops reach only to the $-8°$C level if about one-half of the splinters produced in the first thermal are ingested and continue to grow and splinter in each of two successive thermals, the whole process taking about 1h.

But the main point I wish to make is the following. It is dangerous to draw quantitative conclusions about levels of particle production in clouds from calculations based on stochastic models that are neither self-limiting nor limited by realistic time and space scales set by the cloud dynamics. Explosive, exponential growth mechanisms cannot continue for very long in convective clouds before becoming self-destructive. It is very difficult to judge the credibility of any suggested chain-reaction mechanism unless the dissipative processes are also adequately treated.

Dr. J. LATHAM (*in reply*): We shall consider Dr. Mason's comments in the order presented.

The task of determining the mean splinter lifetime τ from the sparse and sometimes suspect experimental evidence was admittedly rather uncertain. The value quoted, around 25 minutes, corresponds to a water content C in the diameter range 50 to 200μm of about $0{\cdot}1\,g\,m^{-3}$. Such values of C were estimated, for example, from Fig. 7 of the paper by Mossop *et al.* (1968) which revealed two extensive regions within the cloud of high concentrations of drops whose replicas are of diameter $d > 100\mu m$. Our assumed value of C could be achieved with $100\,l^{-1}$ of drops of $d = 125\mu m$ or $50\,l^{-1}$ of $d = 160\mu m$; these requirements seem consistent with this evidence. Again, although Mossop *et al.* (1972) did not make regular measurements of drop sizes in our range of interest they present in their addendum to appendix 1 some limited information, obtained with the Squires gun, covering the diameter range 50 to 106μm. The value of C in this range for slides F5, F15 and F17 are about 0·12, 0·05 and $0{\cdot}10\,g\,m^{-3}$. Since our range is larger, extending to $d = 200\mu m$, a value of $C = 0{\cdot}1\,g\,m^{-3}$ again seems reasonable. Finally, we refer to the Californian multiplication studies of Koenig (1968). He makes the following comment concerning clouds which exhibit large concentrations of ice particles: 'Typically, drops greater than 100μm in diameter occurred in concentrations of about $0{\cdot}04\,cm^{-3}$'. For these drops $C = 0{\cdot}1\,g\,m^{-3}$ can be achieved with an average drop diameter of about 170μm. We believe, on the basis of this and similar evidence, that $C = 0{\cdot}1\,g\,m^{-3}$ is a reasonable estimate of the water content in our diameter range.

We agree with Mason's comment that the evidence for values of r, the average number of splinters ejected per freezing drop, as high as 6 is not convincing. Existing reports are too scanty and contradictory for definitive conclusions to be drawn on this point. The experimental evidence available is fully reviewed in our original paper (Chisnell and Latham 1974). Of this evidence we single out the detailed experiments of Hobbs and Alkezweeny (1968) as lending support to the use of splinter numbers r as high as 6. In addition, recent experiments by Gay (private communication), in which the freezing behaviour of drops in the diameter range 60 to 150μm was studied, provide estimates of r close to the values assumed in our paper.

We turn now to Mason's point that during our average lifetime of $\tau \simeq 30$min, splinters become much larger than the drops which are supposed to capture them. The estimated number of particles existing at time t arising from one splinter has been given as $m(t) \simeq r^2\exp\{(r-1)t/\tau\}/(r-1)$. The fraction of these splinters having an age greater than T is $m(t-T)/m(t) = \exp\{-(r-1)T/\tau\}$ and as pointed out by Mason is at least one-quarter for $r = 5$ and $T = 10$min. To assess the importance of this effect we refer to our more recent calculations of multiplication by drop splintering, in which account is taken of the limited time T during which a splinter may be captured by a drop. If the splinter is not captured during this time it remains dormant in the cloud for a further time T'. For times greater than about $2T$ the estimated number of ice particles resulting from one splinter born at $t = 0$ is $m(t) = Ae^{pt}$, where p is the real positive root of

$$r - 1 - p\tau - r\exp\{-(1 + p\tau)T/\tau\} = 0,$$

and τ is the mean splinter lifetime used in our paper. For large T the root is $p = (r-1)/\tau$ as before. The choice of T' has a small effect on A but does not affect the growth parameter p. For the case $r = 6$, $T' = 14{\cdot}9$min, $T/\tau = 0{\cdot}29$ corresponding to $T = 8{\cdot}6$min for $\tau = 30$min, $p/\tau = 3{\cdot}19$, $A = 0{\cdot}26$ and the time taken for m to reach 10^4 is 73min. For $r = 8$ the required time is reduced to 41min. Thus the splintering of small raindrops remains a possible explanation of the observed multiplication factor of 10^4 within about an hour.

We shall shortly be submitting for publication calculations which include the processes of splinter production by both drop freezing and riming. Multiplication is assumed to occur within a cloud of similar dimensions, temperature range and water content to those recorded by Mossop *et al.* (1972). Account is taken of the finite lifetimes of the ice particles within the cloud. In the absence of drops and with the large values of splinter production by riming found by Hallett and Mossop (1974), a multiplication factor of 10^4 is achieved in about 45min. We therefore agree with Mason that splinter production by riming only is a possible explanation of the multiplication phenomenon. However, we find that if both splinter production processes co-exist, the multiplication factor of 10^4 can be achieved in one hour without resorting to the Hallett–Mossop values.

REFERENCES

Chisnell, R. F. and Latham, J. 1974 'A stochastic model of ice particle multiplication by drop splintering,' *Quart. J. R. Met. Soc.*, **100**, pp. 296–308.

Hallett, J. and Mossop, S. C. 1974 'Production of secondary ice particles during the riming process,' *Nature*, **249**, pp. 26–28.

Hobbs, P. V. and Alkezweeny, A. J. 1968 'The fragmentation of freezing water drops in free fall,' *J. Atmos. Sci.*, **25**, pp. 881–888.

Koenig, L. R. 1968 'Some observations suggesting ice multiplication in the atmosphere,' *Ibid.*, **25**, pp. 460–463.

Mossop, S. C., Cottis, R. E. and Bartlett, B. M. 1972 'Ice crystal concentiations in cumulus and stratocumulus clouds,' *Quart. J. R. Met. Soc.*, **98**, pp. 105–123.

Mossop, S. C., Ruskin, R. E. and Heffernan, K. J. 1968 'Glaciation of a cumulus at approximately −4°C,' *J. Atmos. Sci.*, **25**, pp. 889–899.

16 October 1974: Papers read by Dr. P. R. Jonas:

1. 'The evolution of droplet spectra and large droplets by condensation in cumulus clouds' by B. J. Mason and P. R. Jonas (*Q.J.*, **100**, pp. 23–38)
2. 'The evolution of droplet spectra by condensation and coalescence in cumulus clouds' by P. R. Jonas and B. J. Mason (*Q.J.*, **100**, pp. 286–295)

Professor F. H. LUDLAM (*communicated*): The authors' papers lend weight to the view that the droplet spectra found in cumulus can be explained only if droplets are brought together in air arriving in one place from a variety of sources. However, the essence of the manner in which this happens is the interesting puzzle, and the authors' one-dimensional treatment of the air motion (for all the mention of 'thermals') tends to obscure more than it clarifies.

Particular issues which deserve more discussion are whether nuclei can be activated in air drawn into the cloud from the sides or above rather than through the base, whether one thermal can leave saturated residues for another to enter, and whether to produce the kind of droplet spectrum observed a second thermal must arrive in the brief interval before a few surviving droplets of the first have evaporated.

Among related and perhaps surprising details of the calculations are

(a) the great enhancement of cloud growth produced by sheltering a thermal from unsaturated air in only the first 300m above the cloud base (Fig. 1),

(b) an increase with height of the supersaturation while the updraught speed is decreasing,

(c) the sudden appearance in significant concentrations of droplets of nearly 10 microns radius just above cloud base in the second thermal (Fig. 3(c)), and an increase in the total concentration of droplets towards the top of the cloud it produces.

Dr. J. T. BARTLETT: I would like to ask two questions. My first is, to what extent do you consider that the bimodal distribution of drop sizes derived in your paper is due to the fact that you have only considered two thermals? Would this structure not be lost if you considered a more complete model in which there was a succession of thermals? My second question is how valid is your prediction that there will be small droplets in the interior of the cloud? It seems to me that the model only produces small drops by instantaneously transferring nuclei from the surrounding environment into the interior of the cloud, whereas if the transfer were to take a finite time the nuclei would grow at the supersaturation existing in the cloud before they reached the central region.

Dr. B. J. MASON (*in reply*): In reply to Professor Ludlam, we see no reason why nuclei drawn into the cloud from the sides and top should not become activated if they are entrained into the updraught and subjected to increasing supersaturation. The question is whether the droplets already present will allow the supersaturation to rise sufficiently to allow the new nuclei to grow and our model calculations show that this is usually the case when the updraught is increasing. Dr. Bartlett raises a related question as to whether the model produces small droplets only by instantaneously transferring nuclei from the surroundings into the cloud interior. In a sense this is true but, for example, in our second maritime thermal of radius 350m rising at 2m s^{-1}, $\varepsilon = 160$ $cm^2 s^{-1}$ and $\sigma_\omega = 2m\ s^{-1}$, so that the average time taken for a particle to travel from the edge to the centre would be 3min compared with a total rise time of 18min. The effect of allowing earlier growth would be to transfer some of the droplets from the smallest size groups further up the spectrum and probably to sharpen the first peak. By treating the motion of the droplets inside the turbulent thermal as a random-walk problem it would be possible to derive a spread of life times which would be reflected as a further slight broadening of the droplet spectrum.