Production of secondary ice particles during the growth of graupel by riming

By S. C. MOSSOP

Division of Cloud Physics, CSIRO, Sydney, Australia

(Received 28 April 1975; revised 9 September 1975)

SUMMARY

Experiments indicate that secondary ice crystals are produced when rime grows in a supercooled cloud containing drops $\geq 24\mu m$ in diameter. This occurs between temperatures of $-3$ and $-8^\circ C$, the production rate being greatest at $-5^\circ C$. These temperatures are constant to about $\pm 0.5^\circ C$ for velocities of the riming body ranging from 1-4 to 3-0 m $s^{-1}$. On average, one ice splinter is thrown off for every 250 drops of diameter $\geq 24\mu m$ accreted, at cloud temperature $-5^\circ C$, and this value does not change much with target velocity. Various possible splintering mechanisms are discussed.

1. INTRODUCTION

Hallett and Mossop (1974) (hereafter referred to as (I)) reported recently on laboratory experiments which demonstrated the production of copious ice ‘splinters’ when a moving target gathers rime in a supercooled cloud at about $-5^\circ C$. Subsequent experiments (Mossop and Hallett 1974; (II) hereafter) showed that the phenomenon is dependent upon the size of the cloud drops, the rate of production of secondary ice particles being closely correlated with the rate of accretion of drops $\geq 24\mu m$ diameter. Rough calculations indicated that the laboratory results, if applied to the riming growth of graupel in natural clouds, could well account for the high concentration of ice crystals found in some cumulus clouds as compared with the concentration of ice nuclei measured in cloud chambers in the vicinity (Koenig 1963; Braham 1964; Mossop 1970). Furthermore, the dependence of splinter production upon the presence of drops of a certain minimum size could explain the lack of evidence of ice crystal ‘multiplication’ in continental cumuli (Gagin 1971), where such drops are rare.

In the present paper I report new experiments in which various aspects of splintering are explored, in particular the effect of temperature and target velocity upon the rate of production of secondary ice particles.

2. EXPERIMENTAL APPARATUS

(a) Cloud chamber

The cloud chamber was similar to that used in (I) and (II), with minor improvements. The chamber dimensions were $2 \times 1.2 \times 1.8$ m high, and the walls were made of polyethylene sheet. It was kept in a room colder than $0^\circ C$. To make a cloud, steam from a boiler was introduced through an inlet in the floor of the chamber (Fig. 1(a)). The riming target was a vertical stainless steel rod, 30 cm long and 0.18 cm diameter, which could be moved in a circular path 30 cm in diameter about a vertical axis at velocities up to 3 m $s^{-1}$ (Fig. 1(b)). In a supercooled cloud the moving cylinder gathered drops which froze as rime upon the front face. The rod had an internal electric heater which could be used to keep its temperature above $0^\circ C$ and prevent the formation of rime when so desired.

Thermocouples hung in the cloud a few centimetres above and below the ends of the
rod. From them the cloud temperature at the mid-point of the rod could be found. The greatest temperature difference between the levels of top and bottom of the rod was 1 deg C.

The object of these experiments was to study the production of secondary ice crystals associated with the growth of rime upon the moving rod. Ice crystals could be detected by eye in a light beam which traversed the chamber just below the rotating rod. A visor (Fig. 1) was used to define the viewing volume so that crystals could be observed in forward scattered light at a small angle to the beam and could be clearly distinguished by their twinkling. The number of crystals passing through the beam per unit time (1 min) could then be determined at regular intervals throughout an experiment. This was related to the total rate of production of crystals by a number of calibration experiments in which trays of a supercooled solution of sugar and polyvinyl alcohol were drawn across the floor of the chamber at a constant velocity along guide rails. From the number of crystals observed to fall into the syrup in a known transit time, the total rate of fallout in the chamber could be deduced. From simultaneous visual observations a calibration curve was drawn relating the rate of appearance of crystals in the beam to the total fallout rate. Since experiments were always
continued for long enough for the rate of appearance of crystals in the beam to become approximately constant, we can assume that the rate of fallout then equalled the rate of production.

(b) Liquid water content meter

The liquid water content (l.w.c.) of the cloud was continuously monitored with the aid of an instrument designed by Dr. Edmund W. Holroyd III. Cloud air was drawn into a metal tube where it was heated sufficiently to evaporate all drops. The airstream then divided, each half passing over a fine wire thermocouple, one dry and the other wetted by a fine cotton wick. From the wet and dry thermocouple temperatures the dew point of the air could be deduced and hence the amount of liquid water present at the temperature of the supercooled cloud.

(c) Drop size spectrum

Two instruments were used for measuring the drop size distribution, the Knollenberg Axial Scattering Probe* (A.S.P.) and an impactor in which cloud drops were caught on MgO-coated glass slides.

In the A.S.P. the cloud drops pass through a laser beam and light scattered at a small angle in the forward direction falls upon a detector. The light pulses are counted and sorted in amplitude ranges corresponding to drop diameters from 3 to 45μm in 3μm steps. The sizing accuracy of the A.S.P. was checked by using it to measure drops of uniform size generated with an oscillating wire (Abbott and Cannon 1972). Simultaneously, drops were caught on MgO-coated slides and sized using the calibration of May (1950). There was good agreement between the two methods over a wide size range. In the cloud measurements the A.S.P. was set to count the number of drops in each size category over 1min intervals. In this time about 30cm³ of cloud air passed through the sampling volume. Because of some uncertainty about the area of the sampling cross-section, the A.S.P. was used only to derive the relative size distribution of the cloud drops, the drop concentrations then being deduced from the l.w.c. measurements.

With this continuous measurement system available the impactor used in (II) was retained only to give a check measurement midway through each experiment. This instrument was identical with the first stage of the Cascade Impactor (May 1945) except that the glass slide on which the drops were impacted was transported past the intake nozzle at 5cm s⁻¹ in order to separate the impacted drops. The drops corresponding to a sampled volume of about 0-5cm³ were counted and sized by measuring the impressions made in the MgO coating on the impactor slide (May 1950). The relative size distribution obtained in this way agreed well with that given by the A.S.P.

The positions of the three cloud-sampling instruments are shown in Fig. 1(a). Their intakes were all level with the midpoint of the riming rod.

Prior to the start of an experiment the boiler was operated at constant power setting and at constant cloud temperature for at least an hour. Under these conditions the cloud drop spectrum remained satisfactorily constant for the duration of an experiment, about 30min. From experiment to experiment and from day to day there were changes in the cloud drop spectrum. The concentration and size of drops were presumably governed by the rate of entry of cloud nuclei into the chamber and their rate of removal in drops reaching walls and floor. The variability of cloud drop spectra will be illustrated later.

3. THE COLLECTION EFFICIENCY OF THE RIMING ROD

In analysing some of the experimental results we need to know the collection efficiency of the target rod for cloud drops of various sizes.

The collection efficiency of cylinders has been computed by Davies and Peetz (1956) for two cases: (i) for ideal flow, which corresponds to high flow speed and drops small compared with the obstacle; (ii) for Reynolds number of the cylinder equal to 10. These results are generalized by plotting \( E \), the collection efficiency of a drop, against \( P \), the Stokes number, where \( P = \frac{\rho d^2 U}{9 \eta D} \), \( \rho \) being density of drop, \( d \) its diameter; \( \eta \) dynamic viscosity of fluid, \( U \) velocity relative to cylinder; \( D \) cylinder diameter. The two curves are shown in Fig. 2. Also shown are the experimental curves of Ranz and Wong (1952) and Wong et al. (1955) for cylindrical collectors.

![Figure 2. The collection efficiency \( E \) of a cylinder for spheres, in flow perpendicular to the axis of the cylinder, expressed as a function of the Stokes parameter \( P \). The curves shown are (1) Wong et al. (1955), (2) Ranz and Wong (1952), (3) Davies and Peetz (1956) for ideal flow, (4) Davies and Peetz (1956) for \( Re = 10 \), (5) the present empirical curve. For further details see text.](image)

Because the shape of the collector deviates from the cylindrical as rime is accreted, it was necessary to determine which of these curves, if any, is appropriate to the present experimental situation.

In a series of experiments I measured the weight of rime gathered by the rod in a known time at target velocities \( U \) of 1·4, 1·8, 2·4 and 3·0m s\(^{-1}\). The overall collection efficiency, \( E' \), was found by dividing this weight of rime by the weight of water drops of all sizes in the volume swept out by the moving cylinder.

From a given curve of \( E \) against \( P \) one can deduce a series of curves relating \( E \) to drop size for a particular value of \( U \), assuming a cylinder diameter of 2mm. This was taken as a reasonable average value considering that the rime grows from the original cylinder diameter of 1·8mm to a diameter slightly greater than 2mm by the end of an experiment. Knowing the size distribution of the drops (from the A.S.P. measurement) and the l.w.c., we can then calculate the expected overall collection efficiency, \( E' \), for a particular experiment.

Comparison with the actual measured values of \( E' \) gave closest agreement in the case
of curve 4 of Fig. 2. In these experiments, where the Reynolds number of the cylinder was in the range 200–460, the results agree best with the theoretical curve for \( Re = 10 \) We thus see that the collection efficiency of the target rod is less than that of a simple cylinder of the same diameter, presumably because of changes in the air flow pattern caused by the rime on the front face.

![Graph](image)

**Figure 3.** The collection efficiency of a 2mm cylinder plotted as a function of drop diameter for various values of the relative velocity between cylinder and drops. These curves are derived from the empirical curve (5) in Fig. 2.

Still better agreement between computed and experimental values of \( E' \) is obtained by using the empirical curve 5 of Fig. 2, which was obtained by trial and error. The values of \( E \) for various drop sizes and target velocities deduced from it are shown in Fig. 3. When these are used to compute values of \( E' \), the agreement with experiment is shown in Table 1. Tabulated values represent the averages for at least four experiments at each velocity.

**TABLE 1. Measured and computed values of overall collection efficiency, \( E' \)**

<table>
<thead>
<tr>
<th>Target velocity (m s(^{-1}))</th>
<th>( E' ) measured</th>
<th>( E' ) computed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>0.30</td>
<td>0.32</td>
</tr>
<tr>
<td>1.8</td>
<td>0.39</td>
<td>0.35</td>
</tr>
<tr>
<td>2.4</td>
<td>0.42</td>
<td>0.43</td>
</tr>
<tr>
<td>3.0</td>
<td>0.47</td>
<td>0.49</td>
</tr>
</tbody>
</table>

4. **Experimental Procedure**

In subsequent sections I describe the effect of changing various parameters on the rate of splinter production. The experimental procedure can best be illustrated by reference to an actual experimental run (experiment 3 of 26 March 1974).

The cloud temperature was \(-4.6°C\), l.w.c., \( 0.8 \text{g m}^{-3} \). Fig. 4 illustrates the number of crystals observed in the field of view per minute as the experiment proceeded. From A to B the electrically heated target rod was stationary and the crystals observed were presumably those formed on ice nuclei in the chamber, or were fragments detached from the chamber walls. The rotator motor was switched on at B, and the hot rod, moving at \( 2.7 \text{m s}^{-1} \), swept up drops which did not freeze. The crystal counts climbed after 3min to a value which stayed approximately constant from C to D. When the heater was switched off at D so
that rime could grow upon the rod, the counts again rose, reaching the plateau EF after 3 min. Switching on the heater at F caused the counts to fall back to values GH similar to those from C to D. When rotation ceased at H the counts fell to 'stationary background values', JK.

This experiment leaves little room for doubt that the increase in counts over the period EF is associated with the growth of rime upon the rod. The higher counts during periods CD, GH as compared with the stationary background values can probably be ascribed to rime growth upon the unheated cross-arms which support the target rod. From the calibration procedure described in section 2(a) above, the total rate of production of crystals during the period EF can be deduced, and from this we subtract the average rate of production during periods CD and GH to give the number of crystals produced by the riming of the rod alone.

Although several experiments were carried out along the above lines with similar results, the normal routine was slightly different. At point F in the experiment rotation was stopped without switching on the heater again. Step FH was omitted. In this way the rime on the rod was preserved for subsequent weighing and examination.

5. THE RELATIONSHIP BETWEEN CLOUD TEMPERATURE AND SECONDARY ICE CRYSTAL PRODUCTION

It was shown in (1) that for a target velocity of 2-7 m s\(^{-1}\) splinter production during riming took place between temperatures of about \(-2\) and \(-10^\circ\)C with a maximum rate at about \(-5-5^\circ\)C.

This work has now been repeated at target velocities of 3-0, 2-4, 1-8 and 1-4 m s\(^{-1}\), and the results are shown in Fig. 5. The boiler voltage was set to give a l.w.c. of \(1-1 \pm 0-1\) g m\(^{-3}\). The scatter of points in these diagrams is probably largely due to changes in the drop spectrum from experiment to experiment. The curves must therefore be regarded as applying to the average cloud drop spectrum used in these experiments. Drop spectra are discussed in section 6.

Fig. 5 shows that the maximum rate of production of secondary ice crystals occurs at
about \(-5^\circ\text{C}\). They are produced over the temperature range \(-3\) to \(-8^\circ\text{C}\) and these limits are constant to about \(\pm 0.5\) deg C, regardless of target velocity, over the range 1.4 to 3.0 m s\(^{-1}\). These new results define the temperature range for splintering even more narrowly than in (I).

No splintering could be found at temperatures from \(-8\) to \(-17^\circ\text{C}\).

6. **The relationship between the production of secondary ice crystals and the accretion of large drops at various velocities**

As mentioned in section 1, the rate of splinter production is strongly influenced by the concentration of large drops present in cloud, the correlation with splinter production rate being closest for the concentration of drops \(\geq 24\mu\text{m}\) diameter. This was postulated in (II)
on the basis of experiments at cloud temperature \(-4.7 \pm 0.5^\circ\text{C}\) and target velocity \(2.6 \pm 0.1\text{ m s}^{-1}\).

I have now investigated whether the velocity of the riming target influences the effectiveness of these large drops in producing secondary ice particles, extracting from the data of Fig. 5 those experiments carried out at \(-5 \pm 0.5^\circ\text{C}\) (l.w.c. 1.1g m\(^{-3}\)). There were 20 such experiments, five at each of the target velocities 3, 0.2, 4, 1.8 and 1.4m s\(^{-1}\). The rate of production of secondary ice crystals was determined in the usual way and was then divided into the rate of accretion of drops \(\geq 24\mu\text{m}\) diameter. (The latter was calculated from the volume of air swept out per second, the measured drop size spectrum and the collection efficiency appropriate to each drop size as given in Fig. 3.) The average number of drops per crystal for each set of five experiments at a particular velocity was then plotted against target velocity in Fig. 6. The individual values are also indicated.

From Fig. 6 we see that the number of large drops accreted, for each splinter produced, shows a wide scatter in the experimental points, so that one cannot deduce any clear dependence on target velocity. It is therefore appropriate at this stage to average all the experimental points regardless of velocity. We then find that, on average, one secondary ice crystal is produced for every 250 drops \(\geq 24\mu\text{m}\) diameter accreted at a temperature of \(-5 \pm 0.5^\circ\text{C}\).

![Graph](image)

Figure 6. The number of drops of diameter \(\geq 24\mu\text{m}\) accreted per secondary ice crystal produced, plotted as a function of target velocity. The line joins average values. Cloud temperature \(-5 \pm 0.5^\circ\text{C}\).

This is regarded as more accurate than the figure of 160 drops per splinter given in (II), being based on more accurate estimates of the numbers of drops accreted.

The average drop size distribution in these 20 experiments, as measured by the A.S.P., is shown in Fig. 7. The two extreme spectra are also shown to give some idea of the greatest scatter. The average spectrum gives a droplet concentration of 523cm\(^{-3}\) and l.w.c. of 1.1g m\(^{-3}\). The median drop diameter is 14\(\mu\text{m}\) and the mean volume diameter 16\(\mu\text{m}\).

7. ANALOGY BETWEEN PRESENT EXPERIMENTS AND RIMING IN NATURAL CLOUDS

We have pointed out in (I) and (II) that if our laboratory results can be applied to natural clouds, then the splintering mechanism is likely to provide the observed concentration of ice crystals in maritime cumulus clouds within a reasonable cloud lifetime. It is therefore appropriate at this stage to consider how close the analogy is between the present experiments and the natural riming situation.
In modified maritime cumuli in Australia, Mossop et al. (1972) found high concentrations of ice crystals (indicating that a multiplication process was active), and also found rimed particles up to 4mm diameter. Consideration of the concentration, diameter and fall-speed of these graupel particles indicates that riming in these clouds is generally dominated by particles of 1mm diameter and over – i.e. they sweep up drops at a faster total rate than do graupel smaller than 1mm. The fall velocities of spherical graupel of diameter 1, 2 and 4mm are 1.5, 2.0 and 2.5m s\(^{-1}\) respectively (Zikmunda and Vali 1972). The target velocities used in our experiments cover this important range.

The diameter of the target rod (1.8mm) was chosen to be similar to those of the important natural riming particles.

(b) Circular path of riming rod

In our experiments the vertical rod moves in a circular path and gathers rime on its leading edge. This grows forward into the airstream, steadily increasing in diameter, thus imitating the growth of a conical graupel in a natural cloud. However, because the target moves in a circle it has a centripetal acceleration equivalent to 1.3 and 6\(g\) (where \(g\) is gravitational acceleration) at velocities of 1.4 and 3.0m s\(^{-1}\) respectively. This could conceivably affect the structure of the rime, since newly accreted drops would have a tendency to flow away from the centre of rotation.
The effect of rotation is not considered to be serious, for two reasons. Inspection of the rime gives no indication of growth away from the centre of rotation. Secondly, as shown in section 6 above, the velocity of rotation has little obvious effect on the number of secondary ice particles produced per large drop accreted. Splintering persists to velocities as low as 0.9 m s\(^{-1}\), as shown in (I).

(c) Surface temperature of the rime

The surface temperature of the rime is of great importance. It strongly influences the rime structure and density (Macklin 1962). In addition, the magnitude of the temperature-elevation of the surface above that of the cloud air governs whether the surface is evaporating or growing by diffusion and is therefore likely to play a vital role in several possible splintering mechanisms, as discussed later. It is therefore important to ensure that our experiments cover the range of surface temperature and temperature elevation expected in nature.

![Figure 8. Surface temperature elevation plotted as a function of LWC for spherical graupel particles of diameter 2, 1 and 0.5mm growing in a supercooled cloud at \(-5^\circ\)C, pressure 700mb. The broken line indicates the surface temperature elevation when the ice surface is in vapour equilibrium with the cloud.](image)

The surface temperature elevation may be computed for a spherical graupel gathering rime uniformly over its surface in a cloud at \(-5^\circ\)C (see e.g. Mason 1971, p. 351). Fig. 8 shows the surface temperature elevation plotted as a function of LWC for spherical graupel of diameters 0.5, 1 and 2mm. The masses and fall-speeds used are those appropriate to lump graupel at a pressure of 700mb (Zikmunds and Vali 1972). The overall collection efficiency for the mean droplet spectrum of Fig. 7 was computed following Fonda and Herne (1960).

At a cloud temperature of \(-5^\circ\)C the surface temperature of ice has to be higher by about 0.6\(^\circ\)C to be in vapour equilibrium. We see from Fig. 8 that a graupel particle growing in a cloud of LWC 1g m\(^{-3}\) will enter the evaporative condition as soon as the diameter exceeds about 0.7mm.

Our observations of high crystal concentrations (see e.g. Mossop et al. 1972) have been made in clouds of LWC about 1g m\(^{-3}\) where graupel sizes have ranged as high as 4mm, so that there have been simultaneously present some graupel particles evaporating and other smaller ones growing by deposition. As mentioned in (a) above, the riming process is usually dominated by particles \(\geq\) 1mm in diameter, which will be in a state of surface evaporation.

The computation of surface temperature of the rime in these experiments has not been
SECONDARY ICE PARTICLES

attempted because of the difficulty of allowing for the presence of the metal rod, and also for the fact that accretion takes place only on the front surface of the moving cylinder.

Rough estimates of the surface temperature elevation of the rime in these experiments may be made for two extreme cases:

(i) The density of rime, \( \rho' (\text{g cm}^{-3}) \), is related to the surface temperature \( T_s \), the target velocity \( U (\text{m s}^{-1}) \) and the median volume radius \( r (\mu\text{m}) \) of the cloud drops by the equation, suggested by Macklin (1962), \( \rho' = 0.11((-rU/T_s)^{0.76} \).

Substitution in this equation of values obtained from a number of experiments at a cloud temperature of \( -5 \pm 0.5^\circ\text{C} \), velocity 3.0m s\(^{-1}\) s, l.w.c. 1.1g m\(^{-3}\) gives an average surface temperature elevation of 1.1 deg C. We see from Fig. 8 that this value would correspond in a natural cloud to a graupel particle somewhat larger than 2mm diameter.

(ii) Examination under a microscope of the surface structure of the rime (fragments embedded in silicone fluid) does not show any evidence of growth by diffusion except at the lowest velocity (1.4m s\(^{-1}\)) for l.w.c. 1.1g m\(^{-3}\). The development of flat crystal faces and plate-like growths is observed at temperatures of \(-5^\circ\text{C}\) and lower. This growth by deposition indicates that the surface temperature elevation must be \(< 0.6^\circ\text{deg}\) C. This condition corresponds to that prevailing on the surface of a natural graupel particle of diameter 0.5mm or less, at cloud temperature \(-5^\circ\text{C}\).

These arguments indicate that the present experiments adequately cover the range of surface temperature conditions expected for natural graupel of diameters 0.5 to 2mm.

Though the graupel surface has here been treated as uniform it seems likely that this is an over-simplification. We must reckon with the possibility that temperature and vapour pressure differences on the droplet scale, which certainly exist on the rime surface, are important in the splintering process. This will be discussed further in the next section.

8. DISCUSSION

Arguments were put forward in the previous section to show that the present experiments cover the range of conditions that prevail in natural clouds where ice crystal ‘multiplication’ has been observed. Nevertheless this cannot be claimed with certainty until the splintering mechanism is fully understood. The construction of elaborate theoretical models of the ice phase in cumulus clouds on the basis of present results is therefore premature.

There are at least four possible mechanisms by which splinters might be produced during the growth of rime:

(i) The formation of an ice shell round the periphery of an accreted drop. Build-up of pressure when the drop finally freezes causes the shell to burst and splinters are thrown off.

This mechanism has received considerable attention in the past, and a number of experimenters have produced evidence that it operates when drops freeze in free fall, but only if the drop is larger than 50\(\mu\text{m}\) diameter. Drops freezing on an ice surface are even less likely to form a symmetrical shell, particularly at the sizes of interest in the present work. This mechanism must therefore be rejected.

(ii) Freezing of drops that make glancing contact with rime. One could postulate that when a supercooled drop makes glancing contact with the rime surface, an ice ‘dendrite’ starts to grow into the drop. Given the right conditions of drop size, temperature and relative velocity, this ice growth might be frail enough to be detached from the rime surface as the drop passes on.

The time of contact of a 24\(\mu\text{m}\) diameter drop with an ice surface moving at a relative velocity of say 2m s\(^{-1}\) will be only about 10\(\mu\text{s}\). In this time an ice dendrite will grow about 0.2\(\mu\text{m}\) into the drop, since the velocity of growth of ice parallel to the basal plane is about
1.7 cm s⁻¹ at −5°C (Hallett 1964). It seems highly unlikely that an ice protrusion of this size would be broken off and carried away by the drop.

This conclusion is in agreement with the finding of Aufdermaur and Johnson (1972) that drops which make glancing contact with rime do not freeze when the relative velocity is much higher than the ice growth velocity.

(iii) Growth and subsequent detachment of frail ice needles. This could be postulated to happen on a rime surface that was generally growing by deposition or where local vapour pressure gradients (due to still-freezing drops) favoured rapid growth. The theory is attractive in that it explains the sharp splintering maximum at −5°C, since this is the temperature at which ice crystals growing by diffusion characteristically take up needle-like shapes (Magono and Lee 1966).

Examination under a microscope of the surface structure of the rime produced in the present experiments has so far failed to reveal any evidence of frail needle-like growths. Considering that there are at least 4000 drops accreted for each splintering event, it is clear that any evidence from the rime structure on the nature of the splintering mechanism, will only be obtained by a much more detailed and comprehensive study than has hitherto been undertaken.

(iv) Detachment of ice by evaporation. Although one can visualize situations where local growth by deposition might be taking place as suggested in (iii), the average surface condition of the larger natural spherical graupel is one of evaporation, as explained in section 7(c). This suggests the possibility of 'necking-off' of ice structures that are attached only by narrow ice bridges to the main rime.

An argument against this mechanism is the apparent constancy of the temperature limits and the peak temperature for splintering. One would expect that raising the velocity from 1.4 to 3.0 m s⁻¹ would greatly increase evaporation and cause the splintering limits and production peak to shift to lower temperatures.

While the above discussion leaves only mechanisms (iii) and (iv) as possibilities, it is obvious that much more evidence is needed. Two lines of attack appear promising.

The production of splinters either from needle-like growths or by evaporation must be strongly influenced by the elevation of surface temperature of the rime relative to cloud temperature. We therefore need to be able not only to measure the surface temperature but also to alter it independently of cloud conditions. This is not possible in the present experimental system. We now need an apparatus in which the riming cylinder is stationary and the cloud moves past it.

Secondly we need to be able to study more closely the effect of drop size on splintering. This could be investigated by injecting large monodisperse drops into the present cloud.

ACKNOWLEDGMENTS

I wish to thank Mr. R. E. Cottis for help in the experimental work, and Mrs. B. Georgeson for help in data reduction.

REFERENCES


Aufdermaur, A. N. and Johnson, D. A. 1972 Charge separation due to riming in an electric field, Quart. J. R. Met. Soc., 98, pp. 369-382.


