Temperature dependence of secondary ice crystal production during soft hail growth by riming

BY ANDREW J. HEYMSFIELD

National Center for Atmospheric Research, Boulder, Colorado, U.S.A.

and

S.C. MOSSOP

Cloud Physics Laboratory, Division of Atmospheric Research, CSIRO, Sydney, Australia

(Received 16 August 1983; revised 7 February 1984)

SUMMARY

Simple experiments confirm that the production of secondary ice particles during the growth of rime depends upon the surface temperature of the riming particle rather than upon the cloud temperature. The required surface temperature of about -2.5 to -7.5 °C may be produced over a wide range of cloud temperatures depending on the liquid water content of the cloud and the nature of the riming particle. A particle of high fall velocity in a cloud of high liquid water content may produce secondary ice particles at cloud temperatures considerably below -8 °C.

1. INTRODUCTION

When an ice particle grows by sweeping up supercooled water drops in a cloud having a wide range of drop sizes, secondary ice particles may be ejected under certain conditions. Hallett and Mossop (1974) and Mossop and Hallett (1974) showed that this ‘splinter’ production takes place in the laboratory at cloud temperatures between -3 and -8 °C provided drops >=25 μm in diameter are present in the cloud. Hallett and Mossop suggested that the phenomenon is probably related to the surface temperature of the growing particle rather than to the cloud temperature. (The surface temperature is higher than the cloud temperature because of the release of latent heat as the accreted drops freeze.) This view is supported by experiments of Foster and Hallett (1982). They showed that the cloud temperature for maximum production of secondary ice particles can be moved downwards either by increasing the liquid water content (l.w.c.) of the cloud or by increasing the velocity of the drops relative to the ice surface on which they are being accreted. Both these measures would increase the surface temperature of the rime; it is then necessary to move to a lower cloud temperature to attain the particular surface temperature that gives maximum splinter production.

The interpretation of Foster and Hallett’s experiments at different velocities is complicated by the fact that the cloud temperature for maximum splinter production may be influenced not only by the change in the rate of rime accretion but also by changes in the size distribution of the drops that are captured. In the present paper we give a simpler and more direct demonstration that splinter production is governed by surface temperature rather than by cloud temperature.

2. EXPERIMENTAL TECHNIQUE

The apparatus used was similar to that described by Mossop (1976) except that in the present instance the supercooled cloud was generated within a chamber 1.6 × 1.6 × 4 m high, enclosed in a cold room. The riming body was a vertical stainless steel rod, 30 cm long and 0.18 cm in diameter which could be moved in a circular path 40 cm in diameter about a vertical axis at a velocity of 1.8 m s⁻¹. (This velocity corresponds to the terminal velocity of graupel particles 1 to 2 mm in diameter which are commonly found in natural clouds in which high ice particle concentrations occur (Mossop 1976).) The moving cylinder then gathered supercooled drops which froze as rime on the front face. Secondary ice crystals produced during rime growth were detected by eye in a light beam which traversed the chamber below the moving rod. The number of crystals counted per minute could be related to the total crystal production by calibration experiments in which the crystals fell for a known time upon sheets of carbon paper laid upon the floor of the chamber. The crystals were subsequently allowed to grow and were photographed. This technique is due to Dr N. Fukuta (private communication).

The supercooled cloud was produced by injecting steam from two insulated boilers situated within the chamber 3 m above the floor. By running the boilers at constant power we could make
a cloud that remained fairly stable in drop size distribution over the space of several hours and from day to day. The average drop size distribution and the scatter of measurements is indicated in Fig. 1. The cloud temperature was taken as the average reading of two thermocouples situated above and below the moving rod. The cloud increased in temperature upwards, the temperature difference between top and bottom of the rod being $<1^\circ$C. The vertical temperature gradient is small enough for even the largest cloud drops to be well within 0-1°C of the air temperature (Hobbs and Alkezweeny 1968).

Two sets of experiments were performed. In the first, the rate of secondary ice crystal production was determined when rime was accreted on the moving rod at constant cloud temperatures between $-2$ and $-9^\circ$C. During 8 min of growth the rime reached a thickness of approximately 1 mm. Ice crystal counts over the last 4 min were substantially constant and were averaged to obtain the rate of crystal production.

The second series of experiments differed only in that the rod was heated by an internal electric heater of 0.7 W output during rime growth. In this way the surface temperature of the rime was raised sufficiently to produce a substantial change in the rate of splinter production.

3. Results

The results of these experiments are illustrated in Fig. 2(a), where the production of secondary ice particles per milligram of ice accreted is plotted as a function of cloud temperature. Since this plot does not allow for changes in drop spectrum from one experiment to another, we plot in Fig. 2(b) the ice crystal production per drop $\geq 25 \mu$m in diameter accreted, since earlier experiments have shown that ice crystal production is related to the number of these larger drops accreted (Mossop and Hallett 1974). The number of drops of a given size accreted per second is calculated from the weight of rime gathered per second, the size distribution of the drops, and the collection efficiency of a cylinder for drops of that size (Langmuir and Blodgett 1946).

Both these figures indicate that the constant heat input to the riming rod had the effect of displacing the entire splintering curve to cloud temperature approximately 1°C lower. From this we conclude that the heating of the rod raised the surface temperature of the rime approximately 1°C and that it is this surface temperature rather than the temperature of the cloud which governs secondary ice production.
Figure 2. (a) The number of secondary ice crystals produced per milligram of rime accreted upon a metal rod moving at 1.8 m s⁻¹. One curve applies to the case where the rod is electrically heated, the other to the unheated case. 'Error bars' indicate the range of values which have been averaged in deriving the plotted points. (b) As for (a) except that the ordinate represents the number of secondary ice crystals produced per large drop (≥25 µm diameter) accreted. For the sake of clarity 'error bars' have been omitted. For a point at a given temperature they would be proportionately similar to those in (a).

It is of interest to determine the range of surface temperatures over which secondary ice particles were produced in these experiments. The surface temperature elevation (relative to cloud temperature) increases with rate of accretion of supercooled drops and therefore with cloud l.w.c. and fall velocity of the rimer. It may be readily calculated in the case of spherical graupel or long cylinders riming uniformly over their entire surfaces. We can make only a rough estimate of the temperature elevation of the rime surface in our experiments because of the complex nature of the heat transfer when rime accretes only on the leading face of the moving rod. This elevation is estimated to be about 0.5°C, giving a range of surface temperatures for splinter production of about −2.5 to −7.5 °C.
4. APPLICATION TO NATURAL CLOUDS

It has hitherto been assumed that secondary ice production by the 'Hallett–Mossop process' would be confined to cloud regions between the −3 and −8 °C level. We now see that splintering may take place over a wider range of cloud temperatures provided that the surface temperature requirements are satisfied. The surface temperature range may vary somewhat with drop size distribution, velocity and cloud l.w.c. But experiments using different values of these variables (Mossop 1976; Goldsmith et al. 1976; Foster and Hallett 1982) have found splintering to occur over cloud temperatures that imply surface temperatures not very different from our −2.5 to −7.5 °C range. If anything the range may extend to lower temperatures.

We now investigate what surface temperature elevations may be expected during graupel growth in natural clouds and use these values to deduce what the cloud temperature must be to produce surface temperatures in the range −2.5 to −7.5 °C. The surface temperature elevation was calculated for various l.w.c. and graupel diameters using the particle growth model described by Heymsfield (1982). The graupel were assumed to be spheres of density either 0.9 (to simulate newly frozen drops) or 0.3 g cm⁻³ (to simulate fairly small graupel growing from ice crystals (Heymsfield 1982)). The droplet size spectra used at various values of l.w.c. up to 5 g m⁻³ were based upon spectra measured in clouds in Oklahoma, U.S.A., by one of the authors (A.J.H.). Calculations for two graupel densities and three diameters (0.05, 0.1 and 0.5 cm) show how the cloud temperature range for splinter production varies as a function of the l.w.c. (Fig. 3).

![Figure 3](image-url)

Figure 3. Calculations of the cloud temperatures at which splinters are produced as a function of the l.w.c. and graupel diameter. Left panels denote graupel of density 0.9 g cm⁻³, right panels of density 0.3 g cm⁻³. Horizontal dashed lines bound the −2.5 to −7.5 °C layer. Hatched regions indicate the layer where splinters are produced. (a) Graupel diameter $D = 0.05$ cm; (b) $D = 0.1$ cm; (c) $D = 0.5$ cm.
At low l.w.c., splinters are produced almost entirely within the $-2.5$ to $-7.5\,^\circ C$ cloud temperature range, regardless of graupel diameter. As the l.w.c. and graupel diameter increase, splinter production shifts to progressively lower cloud temperatures. In the extreme case of high l.w.c., high density and large diameter (0.5 cm) shown in Fig. 3(c), the surface temperature elevation is about $6\,^\circ C$, implying that the cloud temperature for splinter production would range from about $-8$ to $-14\,^\circ C$. The secondary crystals which form at temperatures below $-8\,^\circ C$ in Fig. 3 are likely to take on a planar crystal shape, differing from previous assumptions that secondary crystals produced by a Hallett and Mossop (1974) type mechanism are needle crystals.

Our present results show that by raising the surface temperature of the rime $1\,^\circ C$ we transpose the splinter production curve virtually unchanged to air temperatures $1\,^\circ C$ lower. Similarly the experiments of Foster and Hallett (1982) at a rod velocity of 1.5 m s$^{-1}$ and a range of l.w.c. from 1.2 to 3.5 g m$^{-3}$ show that the air temperature for peak production can be shifted from $-6$ to $-8.2\,^\circ C$, implying a surface temperature elevation of about $2\,^\circ C$, without any major change in secondary ice crystal production. However, we need to consider whether we are justified in extrapolating these laboratory results to surface temperature elevations as large as $6\,^\circ C$, as implied in Fig. 3(c).

In doing so let us examine the physical processes involved in the production of secondary ice crystals as postulated by Choularton et al. (1980) and by Griggs and Choularton (1983), whose explanation of the phenomenon is the most satisfactory so far devised. For the purpose of brevity we confine ourselves to discussing the ‘cut-off’ of splinter production at the high and low temperature ends rather than the physical processes at peak production. The high temperature cut-off is thought to be due to the spreading of accreted drops over the rime surface. This depends chiefly upon the ice surface temperature rather than the air temperature (Macklin and Payne 1967). The low temperature cut-off is thought to be influenced to some degree by the fact that as air temperature falls an increased fraction of the drop freezes on initial impact. The air temperature as well as the surface temperature is therefore likely to influence the low temperature cut-off. This implies that in natural clouds, where high surface temperature elevations may occur on large dense graupel in high l.w.c. conditions, there may be a lower limit to air temperature below which splintering may not occur, even though the surface temperature is above $-7.5\,^\circ C$.

On the basis of these arguments we suggest that Fig. 3(c) should be regarded with caution until such time as experiments can be carried out with surface temperature elevations greater than $2\,^\circ C$.

ACKNOWLEDGMENT

We would like to thank Mrs B. Georges for her help in the experimental work.

REFERENCES


Hobbs, P. V. and Alkezweeny, A. J. 1968 The fragmentation of freezing water drops in free fall. ibid., 25, 881-888


Mossop, S. C. 1976  Production of secondary ice particles during the growth of graupel by rimeing. *ibid.*, 102, 45–57