Ice Multiplication in Clouds[1]

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ABSTRACT

Simultaneous measurements of the concentration of ice particles and ice nuclei in natural clouds have shown that the concentration of ice particles can be several orders of magnitude greater than the concentration of ice nuclei effective at the cloud top temperature. However, the ratio of ice particles to ice nuclei appears to decrease sharply with decreasing cloud top temperature, and approaches a value of unity for cloud top temperatures in the neighborhood of −25C. These results suggest that the freezing of supercooled droplets is responsible for the multiplication of the number of ice particles in clouds.

1. Introduction

A number of observations in natural clouds have shown that the concentrations of ice particles are sometimes much greater than the measured concentrations of ice nuclei. For example, Koenig (1963) and Braham (1964) have reported that summer cumulus clouds in Missouri, with cloud top temperatures >-10C, often contain ice particles in concentrations which are several orders of magnitude greater than would be expected from ice nucleus measurements. Similar results have been reported by Mossop *et al.* (1967). These workers found in one cloud, which had a top temperature of −4C, that the measured concentration of ice particles was 3 or 4 orders of magnitude greater than the estimated concentration of ice nuclei. More recently, Koenig (1968) has reported three measurements made in clouds with top temperatures >-9C in which the concentrations of ice particles were much greater than than would have been predicted from ice nucleus measurements.

In this paper I describe the results of a series of measurements of the concentrations of ice particles and ice nuclei in natural clouds. These measurements show that the ratio of the concentration of particles to the concentration of ice nuclei can be very high, but that the ratio decreases with decreasing cloud top temperature.

2. Measurements

The measurements were made during February and March 1968 at the University of Washington's research station in the Olympic Mountains, Washington. The station is situated at an altitude of 2025 m and is 2.5 km NNE of Mt. Olympus. The Pacific coastline is about 65 km to the west of the station. Since the region between the coast and the station is occupied by the Olympic National Park which is virtually free of human habitation, the air that reaches the station in the prevailing southwesterly and westerly flows is probably unmodified maritime air (in westerly flows the Aitken count at the station commonly falls below 100 cm^{-3}). Moreover, since the station is located on an isolated ridge with deep glaciers immediately to the west, any measurements on precipitation and cloud particles that are made at the station in westerly airstreams may be considered to be reasonably representative of the free atmosphere. (For winds from the south-southwest there is a possibility that blowing snow from Mt. Olympus could contribute to the number of ice particles in the air measured at the station; however, in the measurements described in this paper there was no indication that this was happening.)

The concentrations of ice particles in the air were measured on different occasions in the following way. A solid black cylinder, 30 cm in length and 4 cm in diameter, was dipped into a mixture of 1 part of 1 per cent Formvar in ethylene dichloride and 10 parts of ordinary rubber solution. This produced a clear coating on the cylinder which remained very sticky over a long period of time and could replicate any ice particles that landed on it. The coated cylinder was held at arm's length and rotated several times in a horizontal plane through the air. The number of ice particles collected on the forward-facing half of the cylinder was counted visually, the minimum detectable particle size being about 50 μ. The concentration of ice particles in the air was then estimated from this measurement and the known volume of air through which the cylinder had swept. The collision efficiencies of the ice particles with the cylinder were assumed to be unity so that concentrations of ice particles estimated in this way may have been on the low side. Measurements were never taken in winds which were strong enough to produce blowing

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TABLE 1. Summary results of ice particle and ice nuclei measurements.

Date and time of observation	Estimated temperature of cloud top (°C)	Estimated number of ice nuclei effective at cloud top (cm^{-3})	Number of ice particles (cm^{-3})	Ratio of concentration of ice particles to ice nuclei	Types of ice particles
7 March 1968 1630 PST	−6	2.3×10^{-6}	1.7×10^{-2}	7.4×10^{3}	Long columns Hexagonal plates
9 March 1968 2100 PST	−12	4.3×10^{-6}	3.0×10^{-4}	6.9×10	Irregular particles Hexagonal plates Frozen drops Dendrites (rare)
10 March 1968 1015 PST	−12	1.8×10^{-5}	3.0×10^{-3}	1.7×10^{2}	Long rimed columns Irregular particles Frozen drops
13 March 1968 1300 PST	−6	2.4×10^{-6}	3.0×10^{-3}	1.3×10^{3}	Irregular particles Frozen drops
15 March 1968 1745 PST	−11	1.0×10^{-5}	6.0×10^{-3}	6.0×10^{2}	Long, thin, rimed columns Irregular particles
17 March 1968 1110 PST	−16	2.0×10^{-5}	9.0×10^{-4}	4.5×10	Dendrites; columns Irregular particles
22 March 1968 1750 PST	−12	5.5×10^{-6}	6.0×10^{-4}	1.1×10^{2}	Needles; columns Irregular particles
22 March 1968 1805 PST	−12	5.5×10^{-6}	5.0×10^{-4}	9.0×10	Needles; columns Irregular particles
22 March 1968 1940 PST	−12	5.5×10^{-6}	2.0×10^{-3}	3.7×10^{2}	Rimed and capped columns (some long and fragile)
23 March 1968 0900 PST	−5	2.2×10^{-6}	7.0×10^{-3}	3.2×10^{3}	—
25 March 1968 1425 PST	−4	2.0×10^{-6}	8.0×10^{-3}	4.0×10^{3}	—

snow. Ordinary glass slide replicas were also taken, and the general synoptic conditions were noted.

The concentrations of ice nuclei at −21C were measured continuously at the station using the NCAR acoustical ice nucleus counter. In addition, the concentrations of ice nuclei at −15 and −10C were measured at noon each day. The NCAR counter generally gives readings which are 16–52% lower than those obtained with a mixing chamber (Steele *et al.*, 1967), but this small correction was ignored. Cloud top temperatures were estimated from radiosonde measurements taken by the Weather Bureau at Quillayute Airport (~32 km to the west of the research station), from synoptic observations, and from the habits of the ice crystals collected at ground level. The concentration of ice nuclei which should have been effective at the cloud top was estimated from the measured concentration of ice nuclei at the station, or by extrapolating the temperature variation of the concentration of ice nuclei measured at the station to the estimated temperature of the could top.

3. Results

The results of the measurements are summarized in Table 1 and Fig. 1. The principal points which emerge from these results are as follows.

1) Significant concentrations of ice particles (1–10 $liter^{-1}$) were measured in clouds which had top temperatures as high as −4C.

2) Over the range of cloud top temperatures that were encountered (−4 to −16C), the concentration of ice particles was always several orders of magnitude greater than the estimated concentration of ice nuclei effective at the temperature of the cloud top.

3) The ratio of the concentration of ice particles to the concentration of ice nuclei appears to decrease with decreasing cloud top temperature. For example, for cloud top temperatures of −6C, the ratio measured on two different occasions were 1300 and 7400; for top temperatures of −12C the ratio varied from 69 to 370; and for the one measurement at −16C the ratio was 45.

4. Discussion

The first two points listed in the above section confirm the observations of Koenig (1963, 1968), Braham (1964), and Mossop *et al.* (1967). It now seems fairly well established, therefore, that in some clouds the concentration of ice particles can be several orders of magnitude greater than the measured concentration of ice nuclei.

The new and important observation which is suggested by the results described in this paper is that the

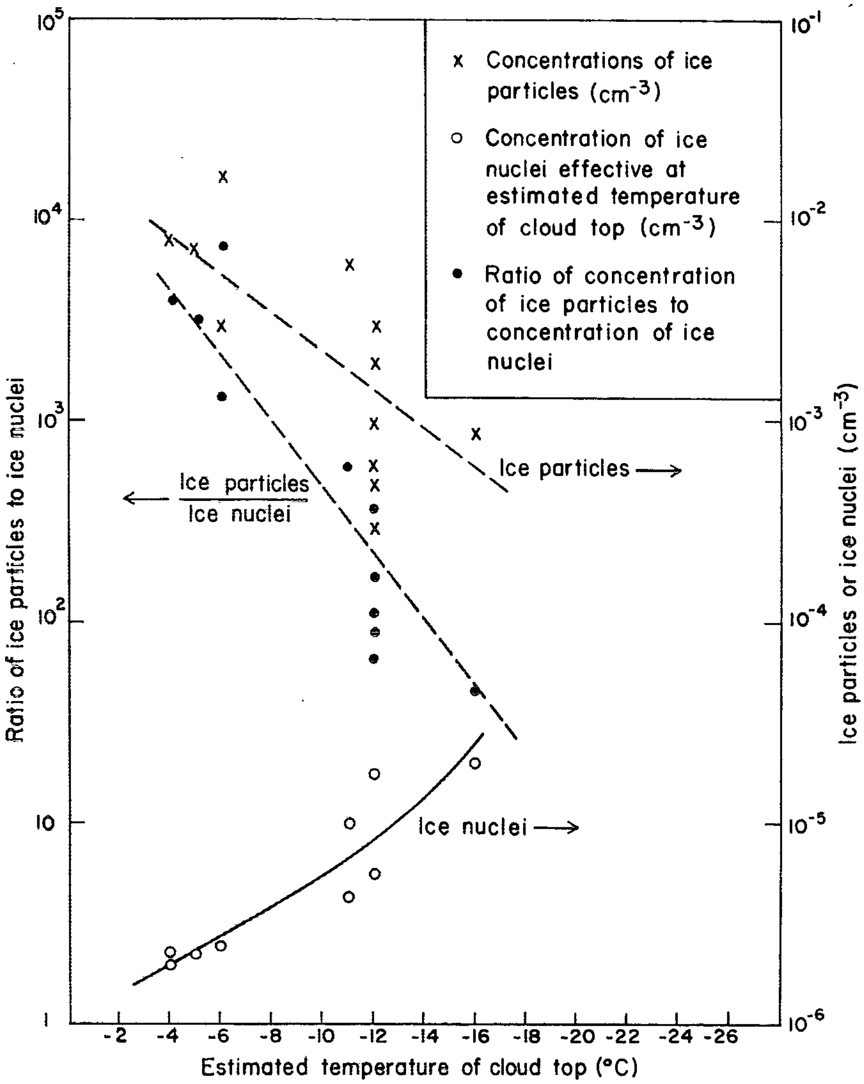

FIG. 1. Concentrations of ice particles, ice nuclei, and ratio of ice particles to ice nuclei as a function of cloud top temperature.

ratio of ice particles to ice nuclei in a cloud decreases with decreasing cloud top temperature. Measurements obtained by Prof. L. O. Grant (1968, and private communication) in clouds over the Colorado Rockies lend support to this conclusion. These results are shown in Fig. 2 where they are compared with the results presented in this paper (dotted line). The three measurements at cloud top temperatures of −14 and −15C lie close to our line. Moreover, for cloud top temperatures of −20 and −26C, Grant observed that the ratio of ice particles to ice nuclei was generally in the range 1 10. This observation is in excellent agreement with our extrapolated results (Fig. 2) which give a ratio of unity at a cloud top temperature of −26C.

We believe that the results presented in this paper are best explained by assuming that the freezing of supercooled droplets in a cloud is responsible for the high ratio of ice particles to ice nuclei. With decreasing cloud temperatures the growth of ice crystals from the vapor phase probably becomes increasingly important compared to the nucleation of supercooled droplets. Moreover, the lower the temperature the less important will be the nucleation of droplets by riming. Therefore, on the basis of our assumption, the ratio of ice particles to ice nuclei should approach a value of unity as the temperature of the cloud decreases.

There are several mechanisms by which the freezing of droplets might cause a multiplication of the number of ice particles in a cloud. The fragmentation and ejection of ice splinters from freezing water droplets has often been suggested as a possible mechanism. This idea originated from laboratory observations which showed that water droplets often fragmented during freezing (e.g. Mason and Maybank, 1960). However,

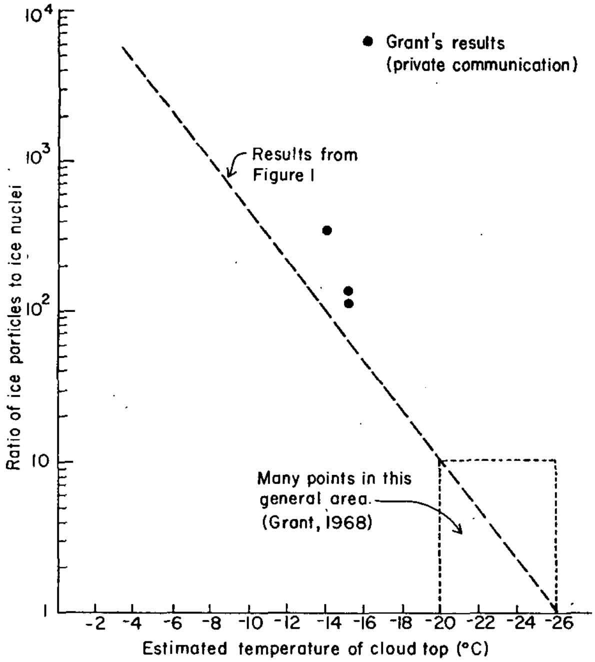

FIG. 2. Comparison of ratio of ice particles to ice nuclei from results shown in Fig. 1 with Grant's results.

the work of Dye and Hobbs (1966, 1968) showed quite clearly that most of these early laboratory experiments were erroneous insofar as application to the atmosphere was concerned, and that water droplets fragment during freezing only under rather special conditions. In particular, the droplet must freeze symmetrically inward. More recently, Hobbs and Alkezweeny (1968) have shown that a certain fraction of water droplets in the size range 50–100 μ diameter do fragment and shed ice splinters during freezing in free fall under conditions which are similar to those in natural clouds. (The freezing behavior of droplets $\gg 100\ \mu$ diameter, under conditions similar to those in the atmosphere, has not been investigated.) It is possible, therefore, that the fragmentation of individual cloud droplets during freezing might play a role in multiplying the number of ice particles in natural clouds.

Another possible mechanism for ice multiplication is the fragmentation of freezing droplets following their collision with ice particles in the cloud. Brownscombe and Hallet (1967) have pointed out that fragmentation of droplets under these conditions is not very likely since the droplet will generally freeze rapidly outward from the surface of the ice particle. However, if a supercooled droplet lands on a fine spike of ice it may freeze fairly symmetrically and therefore fragment. Another mechanism which might be important in mixed clouds is the mechanical breakup of delicate ice crystals due to the thermal shock they receive when they collide with and nucleate supercooled droplets. Dye and Hobbs (1968) found in laboratory experiments that fragile ice crystals often broke up into 5–10 pieces after they had come into contact with a supercooled drop.

Finally, it should be emphasized that a comparatively high cloud top temperature is probably not a sufficient condition for a high ratio of ice particles to ice nuclei. For example, if the ice multiplication mechansims suggested above are important, the production of secondary ice particles will probably be also dependent on the drop size distribution and the types of ice particles in the cloud.

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