Measurements of Ice Crystal Concentration in Clouds

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ABSTRACT

Measurements of ice crystal concentration in five clouds in northern New South Wales are reported. These confirm earlier studies in which it was found that glaciated altostratus clouds contain approximately the same concentration of ice crystals and ice nuclei. On the other hand, cumulus and stratocumulus, generally sampled at temperatures > -10C, were found to contain about 10^2 times as many ice crystals as expected on the basis of ice nucleus measurements.

1. Introduction

For many years, starting with the classical research of Findeisen and Schultz (1944), attempts have been made to elucidate the glaciation processes of natural clouds by studying supercooled clouds in laboratory cloud chambers. The suspicion that the latter might not always give a true picture of natural processes first arose from the work of Palmer (1949), who showed that the number of ice crystals required to produce rain by the Bergeron process ranged from 1–10 liter^{-1} (depending on the starting assumptions) and that such concentrations of ice crystals appeared in the laboratory cloud chamber only at temperatures from -22 to -27C. On the other hand, it was well known from the work of German observers (e.g., Mann, 1940) that a large proportion of precipitating clouds containing snowflakes were entirely warmer than -20C.

It was then suggested that the small concentration of ice crystals measured in artificial clouds might be augmented by a multiplication process (Brewer and Palmer, 1949). Various possible processes were proposed by these and later authors but conclusive evidence as to which mechanism or mechanisms are operative has not yet been produced.

In the meantime there have been numbers of reports of ice particles occurring in clouds at temperatures only slightly below 0C. Coons *et al.* (1949), for instance, make the interesting observation that over the Gulf Coast the majority of cumuli reaching a temperature < -6C contain ice crystals; this contrasts markedly with their findings in Ohio clouds, where much lower temperatures are necessary before ice crystals are detectable. In England, Murgatroyd and Garrod (1960) report several cases of ice crystal formation in clouds of coldest temperature about -10C, even though their measurements of ice nucleus concentration would not lead one to expect ice above -20C. Braham (1964), in summarizing the work of the University of Chicago "Project Whitetop" in Missouri, mentions that ice particles were present in about one-third of the summer cumuli by the time they reached the -10C level. Koenig (1963) was able to measure the concentration of ice particles using a metal-foil impactor and found cases where the concentration was 1000 times higher than would be predicted from measurements of ice nucleus concentration made at the ground.

The development of techniques of replicating ice crystals (Schaefer, 1956; MacCready and Todd, 1964) has made it possible to measure the concentration of the more robust ice crystals, and this has been done in clouds in southeast Australia by Mossop *et al.* (1967, 1968) and Mossop (1968). Altogether seven clouds were studied and in six of these the concentration of ice crystals was about 1000 times higher than the concentration of ice nuclei. In the remaining cloud, a glaciated altostratus, there was good agreement between the measured concentrations of ice crystals and ice nuclei.

In the present paper further measurements of concentration of ice crystals are reported. These were made in northern New South Wales during winter at distances of 200 km or more from the sea. They were supplemented by ground measurements of the concentration of ice nuclei.

2. Techniques of measurement

a. Ice crystal concentrations

Three instruments were used for measuring the concentration of ice crystals in cloud:

1) An impactor of a type designed by Garrod (1957) was used to obtain permanent impressions from drops or ice crystals on aluminium foil 0.0025 cm in thickness. The foil travelled at a speed of 1.6 cm sec^{-1} past a forward-facing aperture 2.8 cm square. The smallest imprints detected correspond to drops of diameters about 0.3 mm or slightly smaller crystals.

2) A continuous replicator similar to that described by MacCready and Todd (1964) was mounted above

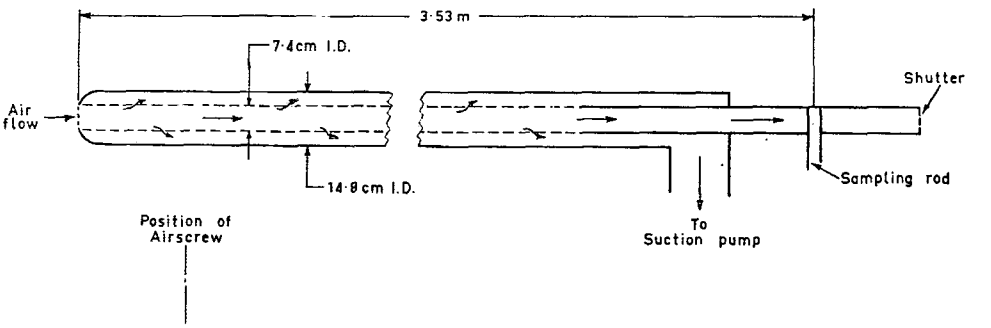

FIG. 1. Ice crystal sampling device designated decelerator C (see text).

the fuselage of the aircraft. In this a 16-mm film was continuously coated with a 2% solution of formvar in chloroform. It then travelled at a speed of about 20 cm sec ^{1} past an orifice slot 3 mm in width (in the direction of film travel), through which cloud particles could enter and impact on the coated film. The coating was then dried so that replicas of the cloud particles were permanently preserved on the film.

3) In its present form the usefulness of the continuous replicator is limited by the break-up of the larger and frailer ice crystals. To try to overcome this difficulty we have used various devices for reducing the relative speed between particles and collecting surface (Mossop *et al.*, 1967). In the present investigation we tested a new device which we shall call decelerator C. This consisted of two co-axial tubes of internal diameters 14.8 and 7.4 cm, mounted on the aircraft fuselage (Fig. 1). The annular space between them was closed at the front end by a shaped nose-piece. By the use of a fan within the aircraft connected to the outer tube, air could be drawn out of the central tube through holes in its wall. In this way any desired fraction of the air entering the front end of the central tube could be removed and the axial velocity thus reduced. Adjustment of a shutter at the back end of the central tube enabled the intake velocity to be matched to the free-stream velocity. The intake was sited well ahead of the airscrews. Glass slides 2.5 cm wide coated with a 1% solution of formvar in ethylene dichloride could be inserted near the rear end of the central pipe to sample cloud particles. A microswitch contact was used to measure slide exposure time. At an aircraft velocity of 46 m sec ^{1} the system reduced the air velocity at the sampling point to 15 m sec^{-1}.

Though reliable measurements of ice crystal concentration were made with this device on three occasions, the proportion of crystals broken was higher than with decelerator B (Mossop *et al.*, 1967). The latter was therefore used after 25 July 1967. The relative failure of decelerator C is ascribed to its narrowness in relation to its length. There was a strong chance that ice crystals entering at even a small angle to the axis would strike the walls. The removal of the boundary layer of air from the central tube apparently did not prevent the crystal fragments from reaching the sampling slide.

b. Ice nucleus concentration

Measurements of ice nucleus concentration were made, simultaneously with the cloud sampling, at a ground site at Moree in the middle of our operational

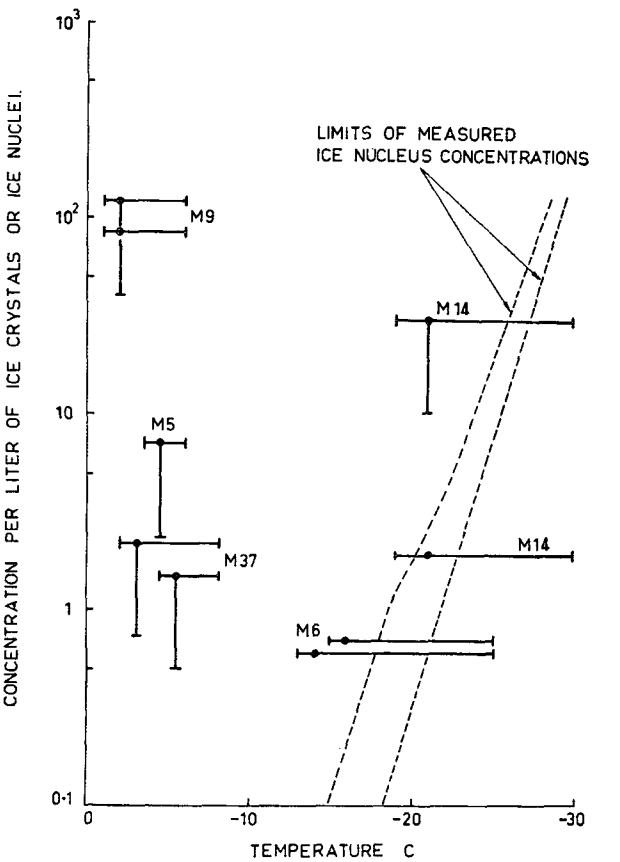

FIG. 2. Measured concentration of ice crystals in natural clouds vs temperature at sampling level. The temperature limits between which the crystals might have formed and the limits of accuracy of the concentration values are shown. The ice nucleus concentrations measured at various temperatures in a cloud chamber at Moree all lie within the broken lines.

TABLE 1. Measured concentrations of ice crystals in clouds.

Cloud no.	Date	Place	Cloud type	Cloud top (i) Sampling level (ii)	Altitude (ft)	Altitude (km)	Temperature (°C)	Sampling instrument	Ice crystals (liter^{-1})	Sampling distance (km)	Volume of air examined (liters)	Crystal shapes	Fig. no.
M5	12 July 1967	150 km SE of Moree	Strato-cumulus	(i)	10200	3.1	−5 ±1					Columns and bullets	
				(ii)	9900		−4.5±1	Decelerator C	7	0.2	20		
M6	19 July 1967	200 km SW of Moree	Alto-stratus	(i)	21000	6.4	−23 ±2					Columns, bullets, side planes, and plates	
				(ii)	15600	4.8	−14 ±1	Foil impactor	0.6	12	500		
				(ii)	17500	5.35	−16 ±1	Foil impactor	0.7	10	400		
M9	22 July 1967	150 km SE of Moree	Strato-cumulus	(i)	11000	3.35	−5 ±1					Columns and sheaths	3a
				(ii)	9500	2.9	−2 ±1	Continuous replicator	80	1.1	14		3b
				(ii)	9500	2.9	−2 ±1	Decelerator C	120	1.1	55		
M14	25 July 1967	50 km NW of Moree	Alto-stratus	(i)	21000	6.4	−28 ±2					Columns, bullets, side planes and plates	
				(ii)	17500	5.35	−21 ±2	Foil impactor	1.9	15	600		
				(ii)	17500	5.35	−21 ±2	Decelerator C	30	0.8	27		
M37	1 Aug. 1967	100 km SE of Moree	Strato-cumulus	(i)	8000	2.45	−6 ±2					Sheaths	4
				(ii)	7700	2.35	−5 ±1	Decelerator B	1.5	0.3	30		
				(ii)	6200	1.9	−3 ±1	Decelerator B	2.2	0.3	25		

area. A 10-liter mixing-type cloud chamber was used, with a tray of supercooled sucrose in the bottom for ice crystal detection.

As a cross check that the ground observations gave a reasonable indication of ice nucleus concentrations in the cloud air, measurements were made with a cloud chamber in the aircraft on 19 and 22 July, and these agreed closely with the ground level values. We therefore have no reason to suspect that the air entering the clouds we studied contained higher concentrations of ice nuclei than were measured on the ground at Moree.

3. Results of measurements

Our results are summarized in Table 1 and the Appendix. The measurements of ice crystal concentration represent the occasions when our records contained clear impressions (in the case of the foil sampler) or replicas of intact crystals (in the case of the other two instruments) over reasonably long cloud paths.

The measured concentrations of ice crystals are plotted against sampling temperature in Fig. 2. The temperature limits shown indicate the range of temperatures within which the crystals must have formed, taking into account the temperature of the cloud top and the estimated accuracy of the temperature values.

In the case of the concentrations measured in the decelerators, allowance must be made for uncertainty in the volume of air effectively sampled by these devices. Cloud penetrations were carried out at an airplane velocity as close to 46 m sec^{-1} as possible, and the air velocity at the position of the sampling slide was approximately one-third of this value. It appears likely that even though the air is slowed down through spreading out to a greater effective cross section, the incoming crystals will not deviate correspondingly from their original paths. In using a velocity of 15 m sec^{-1} to calculate the effective sampled volume of air, we may therefore be overestimating the ice crystal concentration by a factor of 3, and this is indicated in the limits shown in Fig. 2.

The ice nucleus concentrations measured on the ground at Moree did not vary much from day to day. The upper and lower limits of measured values are plotted in Fig. 2 and reflect this small range of variation. Actual concentrations measured at various temperatures are given in the Appendix.

The tabulated temperatures at sampling level are clear-air values as measured by a vortex thermometer. Frequent checks against calibrated spirit thermometers indicate that these values are accurate to ±1C. In some cases the cloud top height had to be visually estimated and the temperature limits have been widened to allow for this uncertainty.

4. Description of sampled clouds

Cloud M5 of 12 July 1967. The base was at 5700 ft (1.74 km) and a field of small cumulus clouds extended

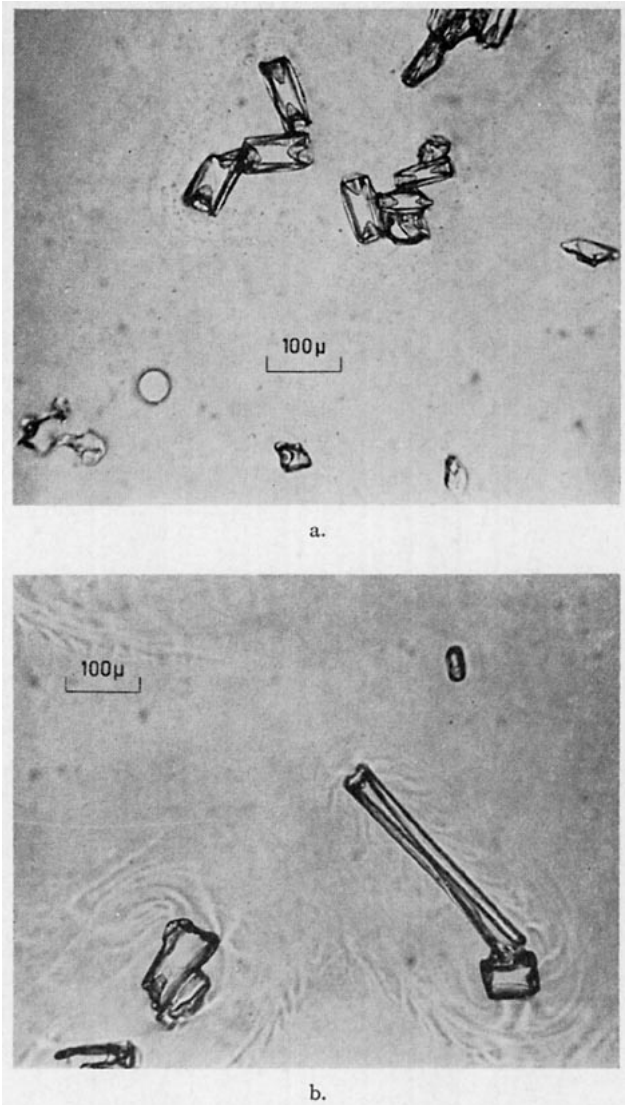

FIG. 3. Replicas from cloud M9, 22 July 1967, sampled with decelerator C at a temperature of −2C showing short columns and a drop, a., and a 300 μ sheath, b.

south from Moree. At a distance of 150 km southeast of Moree the clouds were deeper, and three cumuli rising to 10,000 ft (3.05 km) were sampled and found to contain only water drops. Interspersed among them were stratiform clouds up to an altitude of 10,300 ft (3.15 km), temperature −5C, where cumuli had apparently spread out on reaching an isothermal layer. Two of these stratocumuli were penetrated and found to contain small patches of ice crystals. In one of these, good replicas of columnar and bullet-shaped crystals were obtained using decelerator C. No higher cloud was present.

Cloud M6 of 19 July 1967. An extensive bank of altostratus covered much of inland southeast Australia. It was sampled at temperatures in the vicinity of −15C, the base being at 14,000 ft (4.3 km), the top estimated

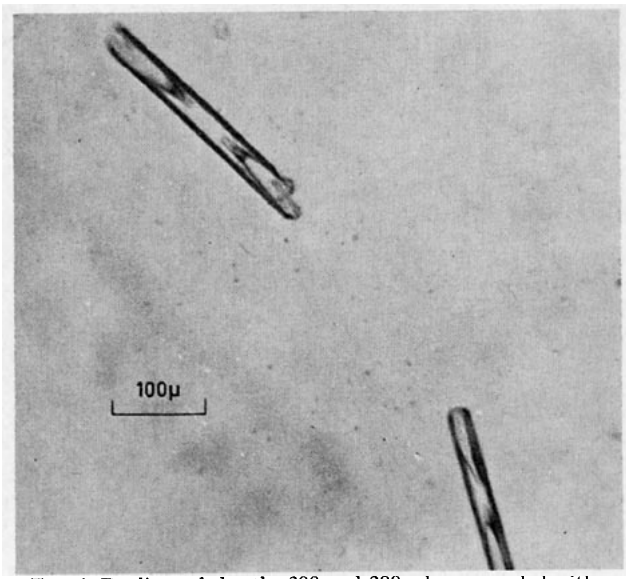

FIG. 4. Replicas of sheaths 300 and 200 μ long sampled with decelerator B in cloud M37, 1 August 1967, at −3C.

at 21,000 ft (6.4 km), and the temperature −23C. Because of crystal shatter, no reliable concentrations could be deduced from the replicas, though some good specimens of columns, bullets, plates and side planes were found. The concentration of ice particles was measured over two long stretches of cloud at different levels using the foil impactor and similar values of average concentration were found. The cloud was almost completely glaciated.

Cloud M9 of 22 July 1967. Small cumuli, bases at 5000 ft (1.53 km), tops 9000–11,000 ft (2.75–3.35 km), occurred over an area of about 10,000 km² to the southeast of Moree. No higher cloud was present. Two of these cumuli were sampled on ascent and found to contain only liquid water. Among these numerous cumuli, apparently consisting only of water drops, one cloud was seen which had spread laterally and was precipitating. Several sampling runs were made through this cloud and numerous columnar and sheath-type crystals were replicated. Examples of both types are shown in Fig. 3. This cloud contained large drops below the freezing level.

In Table 1 we have assumed that this cloud formerly reached the level of its highest neighbors, though when sampled the top altitude was 10,000 ft (3.05 km), temperature −3C.

Cloud M14 of 25 July 1967. As on 19 July, a long-lived extensive bank of altostratus was sampled. This had been present in the vicinity of Moree since the previous day. It consisted only of ice crystals; namely, columns, bullets, side planes and plates. The estimated top height was 21,000 ft (6.4 km), temperature −28C.

Simultaneously records were obtained with the foil sampler and with decelerator C. The former yielded about one-tenth the concentration of the latter, indicating that most of the crystals were too small to give an impression on the foil.

Cloud M37 of 1 August 1967. On ascent, a number of small cumuli extending to 7500 ft (2.3 km), top temperature −5C, were sampled and found to contain only water drops. Later, clouds grew to 9000 ft (2.75 km) with a few tops to 11,000 ft (3.4 km), temperature −12C, where a strong inversion limited further growth. No higher cloud was present. Among this vast field of cumuli two precipitating clouds were observed. These appeared to have subsided and spread out as compared with neighboring clouds. One of them was sampled [top, 8000 ft (2.45 km)] and long columnar crystals were replicated (see Fig. 4). These crystals strongly resemble the "elementary sheaths" of Magono and Lee (1966) occurring in the temperature range −6 to −8C.

5. Photographs of ice crystals

We have restricted our photographs to types of crystal which we have not illustrated in previous publications. We add examples of bullet and side plane crystals in Fig. 5. These were replicated on 26 July at 15,000 ft (4.6 km) in a stratus cloud which extended to about 20,000 ft (6.1 km), top temperature −26C. Our observations of side planes on this day and on 19 and 25 July agree with Magono and Lee's range of −20 to −30C for the occurrence of this type of crystal.

6. Discussion

The five case studies that we have briefly presented here reinforce the conclusions we reached from measurements in clouds in other parts of southeast Australia (Mossop, 1968). We have therefore combined all our measurements of concentrations of ice crystals and ice nuclei in one diagram (Fig. 6). The limits of measured ice nucleus concentrations have been widened to include

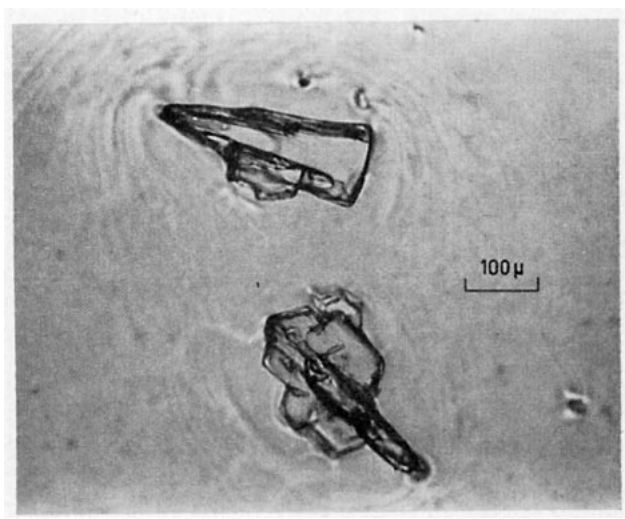

FIG. 5. Replicas of bullet and side plane crystals sampled with decelerator C in stratus cloud M23, 26 July 1967, at −16C.

TABLE 2. Proportion of clouds which glaciate.

Date	Sampled cloud (glaciated)	Number of glaciated clouds observed	Number of unglaciated clouds of similar height observed	Number of unglaciated clouds of similar height sampled	Lowest cloud temperature (°C)	Reference
1966						
10 August	B2	1	>10	2	−4±2	Mossop (1968)
21 August	G2	~10	100–1000	1	−7±1	Mossop (1968)
1967						
22 July	M9	1	~100	2	−5±1	This paper
1 August	M37	2	10–100	—	−12±1	This paper

the earlier results. These limits straddle the average ice nucleus spectrum for Sydney given by Bigg (1965).

These observations show reasonable agreement between ice crystal concentration and ice nucleus concentration in the three cases where we have sampled long-lived altostratus clouds that were completely or almost completely glaciated.

In the remaining nine cases, mainly warmer cumulus or stratocumulus clouds, the measured concentration of ice crystals was greater than the concentration of ice nuclei by three or four orders of magnitude.

Fig. 6 does not give a representative picture of the glaciation behavior of clouds over southeast Australia. The only clouds included are those in which we were able to make reliable measurements of concentration. It therefore takes no account of clouds which contained only water drops or clouds in which the ice crystal concentration could not be measured because of crystal fracture. In choosing the clouds to sample we were biased towards the unusual ones which showed obvious signs of glaciation.

A better idea of the probability of glaciation in cumulus clouds of various summit temperatures may be obtained by considering four cases where the sampled cloud was one of a few clouds which glaciated, while around it were clouds of similar dimensions which showed none of the outward signs of change of phase present in the sampled cloud (either a fuzzy, streaky appearance, and/or the presence of precipitation). These cases are summarized in Table 2.

While the amount of available data is still inadequate, these cases indicate that glaciation of cumulus clouds, defined as the formation of sufficient ice crystals to affect the external appearance of the cloud, is rare in continental southeast Australia at summit temperatures > -8C. It is possible that some of the clouds that gave no visual signs of glaciation did actually contain small concentrations of ice crystals; the number of clouds sampled, however, was inadequate to test this possibility. If we extrapolate the cloud chamber measurements of ice nucleus concentration we find that less than 1 crystal m^{-3} would be expected to form at −8C. Such concentrations would escape detection either by sampling or by visual inspection of the cloud. In our experience, once glaciation becomes apparent from the external appearance of the cloud, then an ice crystal concentration of at least 1 $liter^{-1}$ is present. Such a concentration could be expected to form on ice nuclei only at a temperature of about −20C. Visually apparent glaciation at warmer cloud temperatures, therefore, implies a crystal enhancement process.

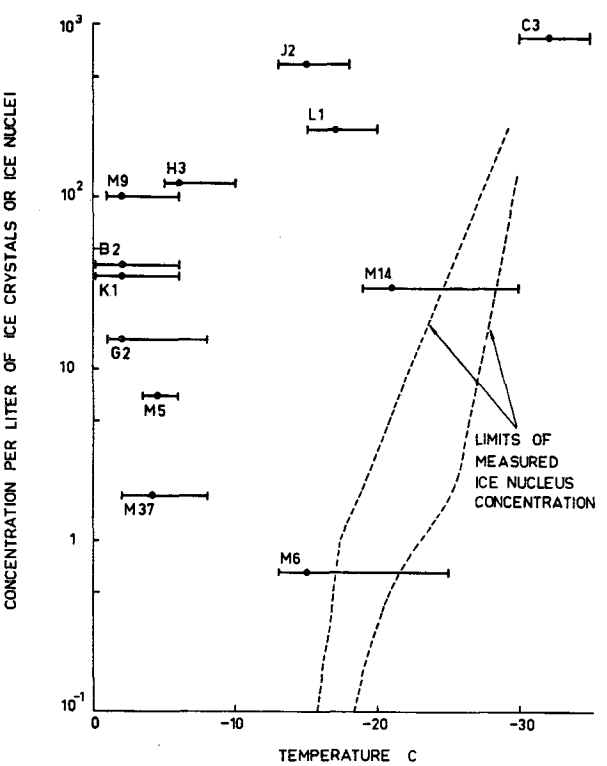

FIG. 6. Summary of all measurements to date of ice crystal and ice nucleus concentration vs temperature. This embraces results reported in the present paper and by Mossop (1968).

The most satisfactory hypothesis to fit our observations is that a process of ice crystal multiplication exists which can cause the "primary" ice crystals formed upon the ice nuclei that one detects in a laboratory cloud chamber to increase in number by some orders of magnitude. Various authors [e.g. Koenig (1963, 1965, 1966) and Mossop *et al.* (1968)] have discussed the nature of this mechanism without reaching any firm conclusions. The microphysical conditions conducive to multiplication apparently do not occur in stratiform ice clouds, such as the three altostratus clouds that we have investigated. Multiplication does occur in continental cumuliform clouds over southeast Australia but only in a small proportion of clouds warmer than about −8C. The evidence of Coons *et al.* (1949) and of the University of Chicago group (Braham, 1964) cited above, implies that conditions for ice crystal multiplication are much more common in maritime clouds. It is interesting to recall, too, that Findeisen (1942) found that the summit temperatures of maritime cumulus clouds containing ice crystals were, on the average, 6–8C higher than those for clouds over land.

Our observations have been concentrated upon clouds where the glaciation process has been well advanced and the microphysical conditions which gave rise to it may already have disappeared. Our measurements are therefore inadequate to explore further the conditions under which multiplication can take place. It would be of more relevance to have successive penetrations of the same cloud starting at the time of first appearance of ice in a cloud. Nevertheless, we are inclined to agree with Koenig (1963) that the necessary condition for crystal multiplication is the coexistence with the primary ice crystals of a population of water drops larger than a certain minimum size so that a process of accretion and "splinter" production can be sustained. This would be consistent with the alleged ease with which maritime clouds glaciate as compared with continental clouds, since conditions in the former favor the development of a wide spectrum of drop sizes.

These arguments, if correct, imply that artificial seeding by the introduction of ice crystals is less likely to be profitable in the case of maritime clouds than in continental clouds of the same summit temperature, and that artificially introduced crystals may be multiplied in number by several orders of magnitude by the same mechanism that operates on natural crystals. Evidence of the latter phenomenon has been given by MacCready and Baughman (1968) from a cloud-seeding experiment in western Montana.

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APPENDIX

Concentration of Ice Nuclei on Cloud Sampling Days

Date 1967	Ground measurements at Moree: Temperature (°C)	Ground measurements at Moree: Ice nuclei (liter^{-1})	Measurements in aircraft: Temperature (°C)	Measurements in aircraft: Ice nuclei (liter^{-1})
12 July	−16.6	0.1		
	−18.0	0.2		
	−21.6	2.7		
	−26.0	14		
19 July	−17.3	0.2	−18.4	0.3
	−19.0	0.4	−18.4	0.2
	−21.0	1.2	−22.8	0.9
	−23.1	6		
22 July	−16.0	0.1	−19.8	0.7
	−18.4	0.2		
	−21.2	1.0		
	−25.6	12		
25 July	−15.6	0.1		
	−17.8	0.7		
	−20.2	2		
	−23.3	8		
1 August	−14.8	0.1		
	−17.2	0.2		
	−19.9	0.6		
	−25.0	9		

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