Aust. Met. Mag. 30 (1982) 81-88 551.576.11(945)

Location and extent of supercooled water regions in deep stratiform cloud in western Victoria

W. D. King, CSIRO Division of Cloud Physics, Sydney

(Manuscript received December 1981)

On the basis of measurements accompanying a cloud-seeding experiment in western Victoria in 1979 and 1980, the conclusion is drawn that regions of supercooled water in stratiform clouds are far less prevalent than has previously been believed, and indeed are rare. The concentration of ice crystals in these clouds appears to be determined by the cloud-top temperature; this concentration is so high in clouds with temperatures colder than −18°C that there would be few opportunities for cloud seeding, even if abundant supercooled liquid water were present.

Introduction

In most cloud-seeding experiments conducted in Australia and overseas, emphasis has been placed on seeding only those clouds whose tops are substantially colder than zero. This has been so for a variety of reasons, some of which are historical, but three major reasons for the continued emphasis on cold clouds would include the following:

(a) Much of the rain in the cereal-growing mid-latitudes of the world originates as ice particles.

(b) The mass of seeding material required for any volume of cold clouds is at least three orders of magnitude less than that required for warm clouds.

(c) The physical basis for seeding cold clouds is attractively simple — the cloud seeder adds artificial ice nuclei to those regions of cloud containing supercooled water but no ice crystals, and the ice particles so produced act as precursors to precipitation-size particles. In this simple static concept of seeding the dynamics of the cloud processes are not considered important, and the time is less critical than when seeding warm cumulus clouds with hygroscopic nuclei.

With the knowledge that supercooled clouds occurred sufficiently often to constitute an aviation hazard, early cloud seeders assumed that regions of supercooled water were sufficiently prevalent and extensive in these clouds for the effects of cloud seeding to be both detectable and economic. It is unfortunate that actual measurements of liquid water content (l.w.c.) in seeding experiments were not made until reliable measuring instruments became available for use in aircraft in the early 1970s. In particular, there were no routine measurements of cloud liquid water content in any of the Australian cloud-seeding experiments until the most recent one in western Victoria (King et al. 1979a,b).

This paper presents results of some measurements of l.w.c. and ice particle concentrations taken from the experiment in western Victoria and discusses the implications of these results for the future of cloud seeding.

Liquid water content and cloud suitability

In the seeding experiment carried out in 1979 and 1980 in western Victoria (King et al. 1979a) the primary emphasis was placed on seeding the deep stratiform clouds associated with the extratropical depressions affecting the regions about five times per spring season; any deep stratiform cloud from any other major weather system was also to be considered and treated in a similar fashion. Although the number of opportunities expected was small, the total rainfall from these systems would contribute about 30 per cent of the season's total. Further, numerical simulations of the seeding experiment showed that the rainfall was sufficiently uniform spatially that the prospects of detecting a 15 per cent seasonal increase were good (King et al. 1979b).

Although in many respects the experiment was similar to previous ones conducted by CSIRO, it differed in three major areas:

(a) An F-27 research aircraft equipped with instrumentation for the measurement of cloud microphysical properties flew in all significant cloud for the duration of the seeding experiment.

(b) An automatic raingauge network of 105 gauges with a time resolution of a few seconds and a rainfall resolution of 0.2 mm was installed in the area so that seeding episodes of less than 24-hours' duration could be examined.

(c) The definition of what constituted a suitable cloud for seeding included a condition on the required minimum supercooled liquid water content. The ability to impose conditions on the l.w.c. was due to the development of two cloud physics instruments during the 1970s: the reverse-flow thermometer by Rodi and Spyers-Duran (1972) and the hot-wire liquid water probe by King et al. (1979a,b). Both these instruments could be fitted to the two seeding aircraft from which the assessment of suitability was made.

The required conditions on temperature and l.w.c. for stratiform clouds were that the cloud top had to be −8°C or colder and that the l.w.c. at the seeding level had to be greater than 0.1 g m^{-3} when averaged over a 5-minute period. The temperature condition was imposed because of the rapidly decreasing activity of AgI as an ice nucleus at temperatures warmer than −8°C, and the value of 0.1 g m^{-3} as the l.w.c. limit was chosen after the following considerations:

(a) It was important that the limit was not so high that even a marginal opportunity was missed by invoking the liquid water condition. Analysts of cloud-seeding experiments have stressed that the loss of a single genuine opportunity is more damaging to the analysis than the inclusion of several doubtful ones.

(b) On the seeding aircraft the mode of operation of the hot-wire probe was such that the inherent accuracy of the instrument (0.02 g m^{-3}) was not achievable, the usable accuracy being about 0.04 g m^{-3}. Thus a limit of less than 0.1 g m^{-3} was not really feasible from the measurement point of view.

(c) Under the static seeding concept the maximum amount of rain ΔR that can be extracted from a cloud of l.w.c. w spread over a height h is given by

$$\Delta R = \int \frac{w}{\rho} \, dh ,$$

where ρ is the density of water. For a typical value of h = 2 km we have ΔR = 0.2 mm for w = 0.1 g m^{-3}. Thus a value of 0.1 g m^{-3} corresponds to the smallest amount of cloud water that could realistically be expected to be detected as extra rain.

It is important to note that the limit of 0.1 g m^{-3} is very low (it is the amount of l.w.c. generated by an adiabatic rise of only 150 m at −10°C) and that no conditions were imposed on ice crystal concentrations (to do so would have involved a prohibitively expensive and complex task as well as contravening the sense of (a) above).

Suitability indices

Definitions

The measures of cloud suitability used here are similar to those first used by Gabor Vali (private communication) in analysing data from the WMO cloud-seeding experiment in Spain. In brief, the indices are designed to give some quantitative measure of how well the cloud rates as a seeding target, and generally represent various amounts of flight time (usually normalised in some way to exclude non-relevant data such as out-of-cloud times, multiple passes, etc.) during which combinations of microphysical cloud parameters were met. In this paper we are concerned with indices determined by the values of l.w.c. w and ice crystal concentrations I_c, these being the two fundamental microphysical determinants of whether a cloud is considered seedable or not under the static seeding concept. Three indices SA_1, SA_2 and SA_3 have been computed according to the following sets of conditions:

SA_1	$w > 0.1\ g\ m^{-3}$	$I_c < 10\ l^{-1}$
SA_2	$w > 0.05\ g\ m^{-3}$	$I_c < 10\ l^{-1}$
SA_3	$w > 0.1\ g\ m^{-3}$	$I_c < 100\ l^{-1}$

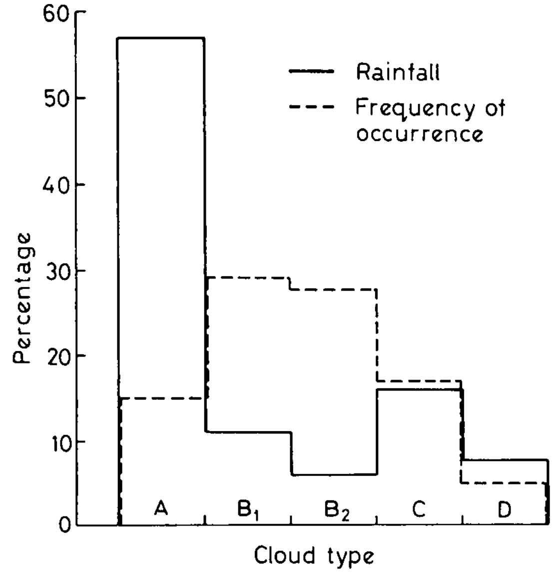
The data used were 5 s averages of particle information from three opto-electronic probes — the FSSP, which measures cloud droplet sizes from 3 to 45 μm, the OAP-2D-C, which provides large particle images from 25 to 800 μm, and the OAP-200-Y, which measures the effective diameter of large particles from 0.3 to 4.5 mm.* The indices have been normalised by dividing the time during which the specified conditions on w and I_c were satisfied by the total in-cloud flight time at each value of the independent variable (temperature or altitude). In-cloud times were defined by the cloud droplet concentration $>1\ cm^{-3}$ or $I_c > 0.01\ l^{-1}$. Any bias that could occur because of excessive flight times at particular levels is consequently removed, and the indices therefore represent that fraction of time spent in cloud at each temperature or altitude level during which a cloud seeder could expect to find the cloud suitable for seeding.

The indices are currently being computed for five different cloud classifications adopted for the analysis of the western Victorian experiment. These classifications are: A (deep stratus, including As if the depth exceeds 1.5 km); B1 (shallow mid-level cloud such as Ac, As); B2 (shallow low-level cloud such as Sc); C (medium-depth convective cloud such as Cu congestus) and D (deep convective cloud such as Cb). Figure 1 shows the frequency of the cloud types as sampled by the F-27 in 1980, together with the rainfall from them. In this paper we will be concerned only with type A cloud from 1980, which contributed 57 per cent of the season's rainfall.

---

*All three probes are manufactured by Particle Measuring Systems, Boulder, Colorado.

Fig. 1 Relative-frequency of occurrence and percentage rainfall from the various cloud types during the 1980 season.



These clouds occurred on 12 days in 1980, and the data presented here are taken from 41 hours of flying time and 14 flights. Average height characteristics for the type A clouds were as follows:

Cloud-base height	2.6 km
Cloud-base temperature	+3°C
Cloud-top height	5.8 km
Cloud-top temperature	−18°C.

Index SA_1 is regarded as providing the most realistic assessment of cloud suitability, the other two being used primarily to demonstrate the sensitivity of the indices to changing the limits. $I_c = 10\ l^{-1}$ was chosen as the realistic ice crystal concentration as follows. At −15°C the rate of release of liquid water in an adiabatic ascent of 10 cm s^{-1} is 8×10^{-5} g m^{-3} s^{-1}. Now at −15°C, the removal of this water in deep cold clouds occurs primarily by evaporation and subsequent sublimation on to ice crystals, as well as direct collection by falling ice crystals. The rate of growth of ice crystals by vapour deposition is about 3×10^{-9} g s^{-1} after a few minutes (Ryan et al. 1976), and the rate of removal of water by riming is approximately $\pi a^2 v_T w$, where a is an effective crystal radius, v_T the terminal velocity of the crystal, and w the l.w.c. For a typical value of $a = 100\ \mu m$ (see later) we have $v_T \approx 0.4$ m s^{-1} and $w = 0.1$ g m^{-3}, and the removal rate due to riming is 1.2×10^{-9} g s^{-1}, giving a total removal rate of about 4×10^{-9} g s^{-1} per ice crystal. Therefore at −15°C and 10 cm s^{-1} the rate of release could just supply the uptake for an ice crystal concentration of the order of 10 to 20 l^{-1}.

Results

Index SA_1 is shown in Figs 2 and 3 as a function of sample temperature and altitude respectively. The first feature that is apparent from these figures is the extremely low values of the index — the maximum is only 0.069 for temperatures in the range −10 to −12°C, and these typically occur at 5 to 5.5 km in these clouds. Indeed, only 0.56 per cent of the total in-cloud time above the −8°C level had cloud conditions satisfying the index. (We shall call this single measure of suitability above −8°C the fraction FA_i.) Inspection of the index values on a day-by-day basis shows that one particular day (19 October 1980) contributed almost all of the suitable time elements to the average, and a value of 0.5 for SA_1 for the −10 to −12°C level was found on that day. (It is noteworthy that despite this comparatively high value, the cloud was still considered unsuitable for seeding because the cloud base of 4.0 km was considered too high and the sub-cloud region too dry for any precipitation to reach the ground.)

Fig. 2 Fraction of in-cloud time at the sampling level during which $w > 0.1$ g m^{-3} and $I < 10\ l^{-1}$.

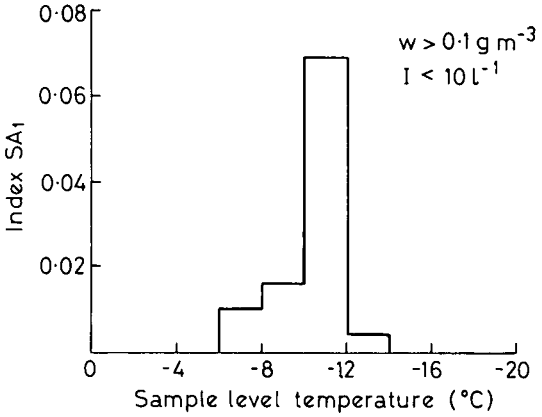
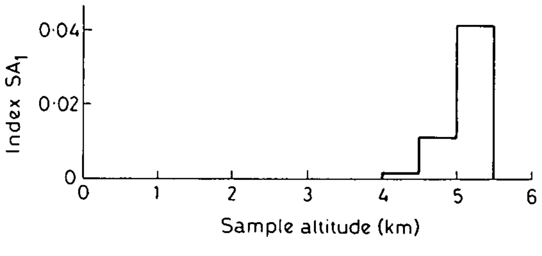


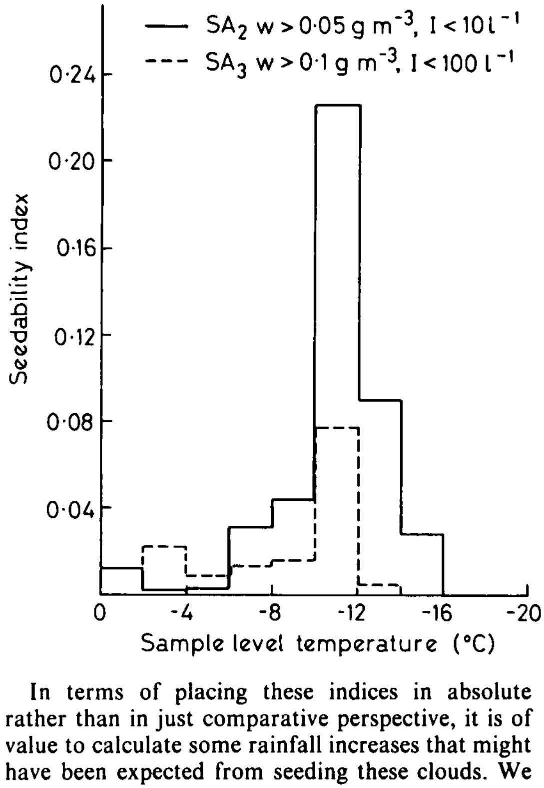
Fig. 3 Fraction of in-cloud time at the sample altitude during which $w > 0.1$ g m^{-3} and $I < 10\ l^{-1}$.



For comparative purposes, indices SA_2 and SA_3 are shown in Fig. 4 as a function of sample temperature, and it is immediately apparent that changing the limit on the l.w.c. by only a small amount has a much larger effect on the index values than changing the limit on ice crystal concentrations by an order of magnitude. This of course justifies to some extent the original decision not to include a condition on ice crystal concentrations in the suitability criterion as implemented by the cloud seeders. Even with the somewhat weakened indices

SA_2 and SA_3 the maxima still occur in the −10 to −12°C temperature range and are 0.226 and 0.078 respectively. (Overall in-cloud values FA_2 and FA_3 for temperatures colder than −8°C are 0.023 and 0.006.)

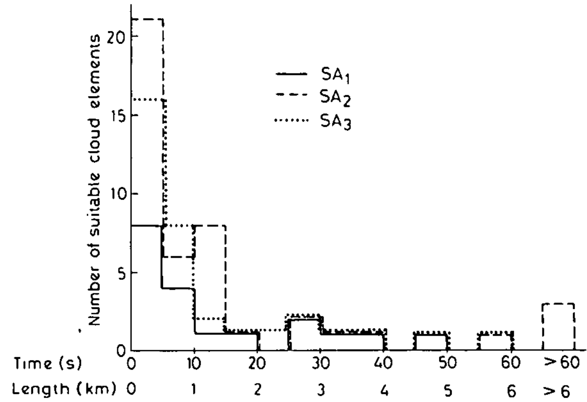
Fig. 4 Seedability indices SA_2 and SA_3 as a function of sample temperature.



In terms of placing these indices in absolute rather than in just comparative perspective, it is of value to calculate some rainfall increases that might have been expected from seeding these clouds. We shall do this in two ways, based on the seeding indices. In the first we assume that at best the rainfall from the suitable regions could only be augmented up to that which is falling from the surrounding glaciated cloud. On this assumption, since only a fraction FA_i of the cloud volume at seedable levels was suitable, then the rainfall increase would be approximately 100 FA_i per cent. This therefore suggests a 2 per cent increase based on FA_1. In the second approach, we can calculate $\int \frac{SA_i(h)\ w(h)\ dh}{\rho}$, where the integration takes place over the cloud depth and the $SA_i(h)$ takes account of the fraction of cloud volume which is suitable. (Note that this approach ignores the contribution to rainfall that coalescence with cloud droplets below the freezing level would make: but for the type A clouds for which the cloud base is close to the freezing level this effect is negligible.) For this calculation with SA_1 the computed rainfall increase is only about 0.1 mm.

The second technique has the advantage that the computed rainfall increase is not very susceptible to whichever index is chosen, because both w and SA_i move in opposite directions as the value of w_L is changed. In any case it is quite apparent that on average the possible rainfall increases that could have been extracted from those clouds were trivially small and that one would need FA_i values of the order of 0.1 to get detectable increases on a seasonal basis. As mentioned previously, one day of the 12 had an SA_1 value of 0.5 at −10 to −12°C, with an overall FA_1 value of 0.17 for temperatures colder than −8°C. No rain fell from these clouds and if cloud base had been lower than the 4 km that it was, then useful rain could have been extracted from those clouds. It is still extremely unlikely, however, that the effects would have been detected in the overall experiment. In terms of detecting a seeding effect, experience has shown that it is the magnitude of the overall seasonal increase which determines the success with which it is detected, and it is only of secondary importance whether the increase falls as a few large increases, or is spread more uniformly over a large number of occasions. Therefore the indices computed for the whole season, rather than on a daily basis, give a better indication of the detectability of any increases.

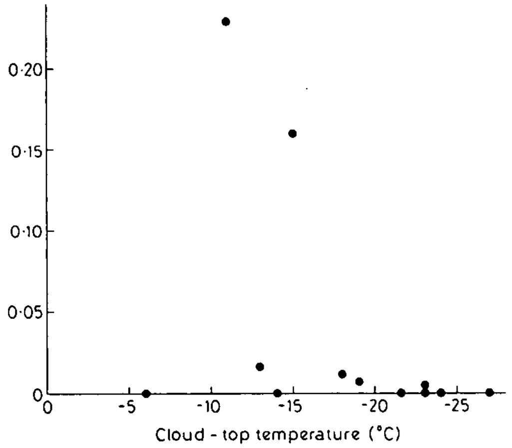
Fig. 5 Distribution of the lengths of suitable cloud elements as defined by conditions SA_1 to SA_3.



Further information pointing to the non-usefulness of these clouds for seeding is provided in Fig. 5, in which the distribution of the time length of the suitable regions is shown. It is apparent that the mean length of the suitable regions for all three indices is less than 10 s (~1 km), with only SA_2 having any supercooled regions in length greater than 1 minute (6 km). In fact, since the peak in these distributions occurs at 5 s, the smallest time interval resolvable with this data set, it is highly likely that the mean time length of the suitable cloud elements is considerably less than this. Thus, not only are there not enough regions of supercooled water suitable for seeding, but what few regions do exist are so small, and presumably so short-lived, that the cloud seeder would have no prospects of identifying and treating them in real time.

An examination of the location of the suitable regions also shows that over 80 per cent occurred within 0.6 km of cloud top, and more than 50 per cent within 300 m of cloud top. Given that the average cloud characteristics as detailed earlier had a cloud-top temperature of −18°C, this suggests that cloud-top temperatures on those days with the most supercooled elements were warmer than average, and this is in fact reflected by the data presented in Fig. 6. Here FA_2 has been plotted as a function of cloud-top temperature, and it is quite apparent that the average figure is dominated by three or four days whose average cloud-top temperature is about −13°C.

Fig. 6 The fraction of cloud defined by FA_2 which was suitable plotted against cloud-top temperature.

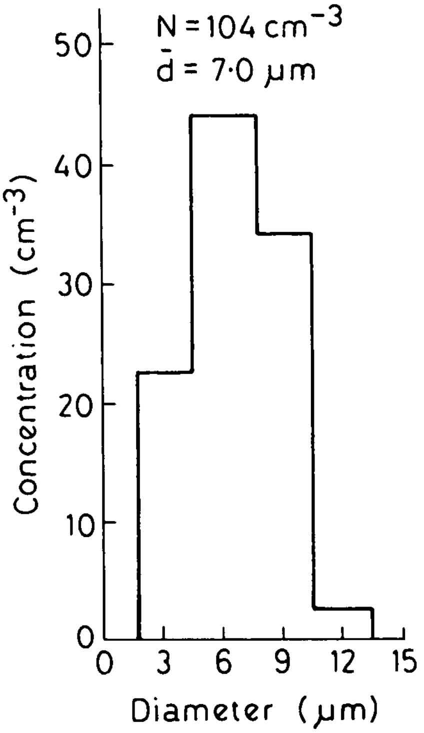


Particle sizes

A typical cloud droplet spectrum for those parts of the cloud having cloud water is shown in Fig. 7. This spectrum has a mean diameter of about 10 μm and total droplet concentration of about 100 cm^{-3}, which is consistent with an uplift rate of about 10 cm s^{-1} and maximum supersaturation of 0.1 per cent experienced by the intake air. (The CCN spectrum of this intake air was measured as $N(S) = 400\ S^{0.8}$, where N(S) is the number of particles per cubic centimetre active at supersaturation S.) The small average diameter not only indicates growth at low supersaturations but also that the drops were not experiencing that supersaturation for long periods. With an average supersaturation of only 0.1 per cent, a drop could grow to 10 μm in about 300 s, which corresponds to a layer of only 30 m thick at 10 cm s^{-1}.

The size distribution of the larger particles as measured by the two array probes is shown in Fig. 8 and the corresponding particle images in Fig. 9. These data are fairly typical of the crystals found in these deep clouds with tops above −20°C. The crystal images are fairly nondescript in appearance, with little resemblance to the classical snowflake shapes characteristic of diffusional growth. This shape information, together with the knowledge that the concentrations were of the order of 100−200 l^{-1}, leads to a picture which shows most of these crystals growing on natural ice nuclei near cloud top, and undergoing small but sufficient amounts of riming to give the generally circular cross-section. (Cloud-top temperature for the data shown was −25°C, and at −25°C the natural ice nucleus background is of the order of 30 l^{-1}.)

Fig. 7 Typical cloud droplet spectrum in the Type A clouds.



The dominant feature of Fig. 8 is the steep fall-off in particle numbers with increasing particle size above 500 μm. Thus there are only 0.1 l^{-1} of particles greater than 1 mm diameter, and they only contribute a small fraction of the total ice mass. In Fig. 8 we have also plotted the ice water content of the various size categories, for an assumed particle bulk density of $\rho_{ice} = 0.5$ g m^{-3}. The total ice water content is about 0.8 g m^{-3}, of which 0.1 g m^{-3} or 12 per cent is in the size range greater than 1.2 mm (this corresponds to a melted diameter of 1 mm, the traditional size definition of precipitation particles). These clouds are therefore fairly inefficient in turning non-vapour-phase water into precipitation — a result which is almost entirely due to the proliferation of ice crystals formed as a result of the cold cloud-top temperature.

We can contrast this with comparable data from the same day on which cloud-top temperature a little further east of the same system was only −18°C. The particle images and size distributions are show

Fig. 8 Ice particle size distribution, and ice water content for cloud-top temperature of −25°C.

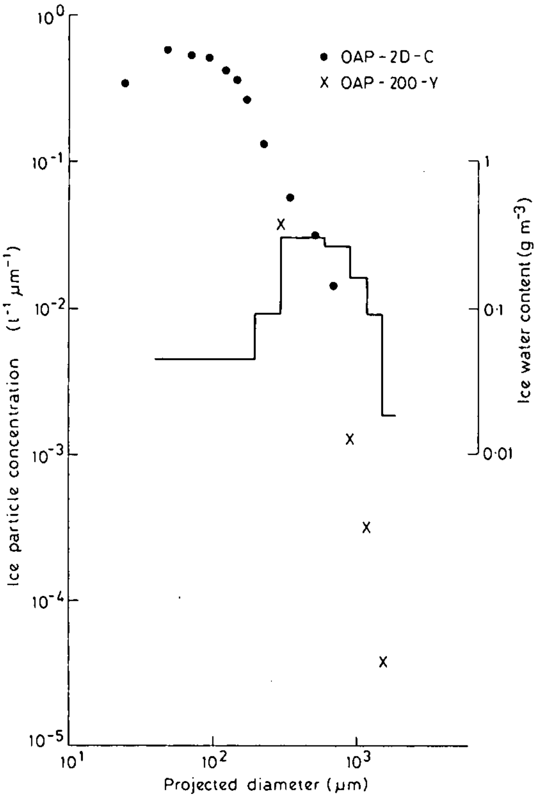


Fig. 9 Ice particle images appropriate to Fig. 8.

Fig. 10 Ice particle size distribution, and ice water content for cloud-top temperature of −18°C.

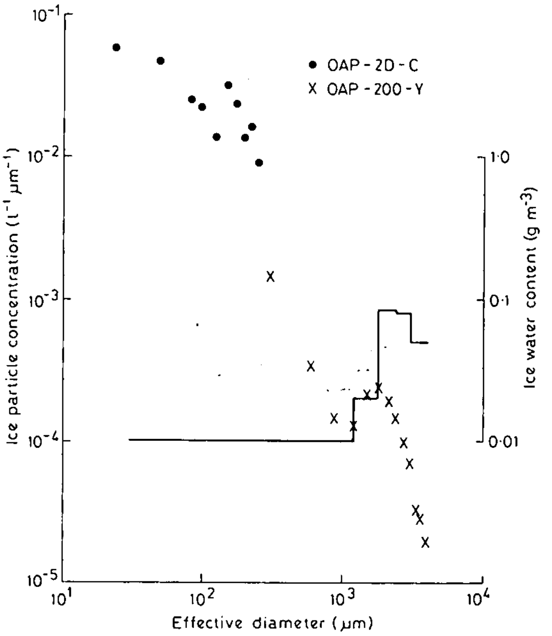
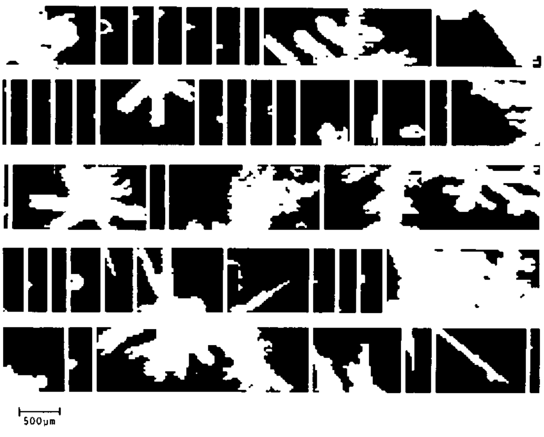


Fig. 11 Ice particle images appropriate to Fig. 10.



in Figs 10 and 11. Here the crystal shapes are more recognisable, and the concentration (2 to 10 l^{-1}) and shapes are again consistent with growing near water saturation at −18°C. Indeed, not only does the shape suggest growth near water saturation, and hence the presence of cloud droplets, but the intricate detail on the edge of the crystals is a good indicator of the presence of riming. For this particular cloud data the ice water content was 0.3 g m^{-3} (for an assumed bulk density of 0.2 g cm^{-3}), of which 0.2 g m^{-3} or 70 per cent was in the size range with a melt diameter greater than 1 mm. The warmer cloud was therefore four or five times more efficient in terms of producing precipitation-size particles.

If the typical ice crystal concentration found for each day is plotted against cloud-top temperature for that day, as in Fig. 12, then apart from one day at −6°C, there is a steady and consistent increase of ice crystal concentration with decreasing temperature, and the ice crystal concentrations (l^{-1}) can be described fairly well by $N = 1.69 \times 10^{-2} \exp(-0.37\ T_c)$. Although these concentrations are up to one order of magnitude greater than average ice nucleus concentrations (Fletcher 1962), which are also shown in Fig. 12, there does not seem to be a need to invoke larger-number ice multiplication mechanisms to explain the ice crystal concentrations, apart from the 'odd' day which has yet to be thoroughly investigated but which displays many of the symptoms of the Hallett and Mossop (1974) multiplication mechanism.

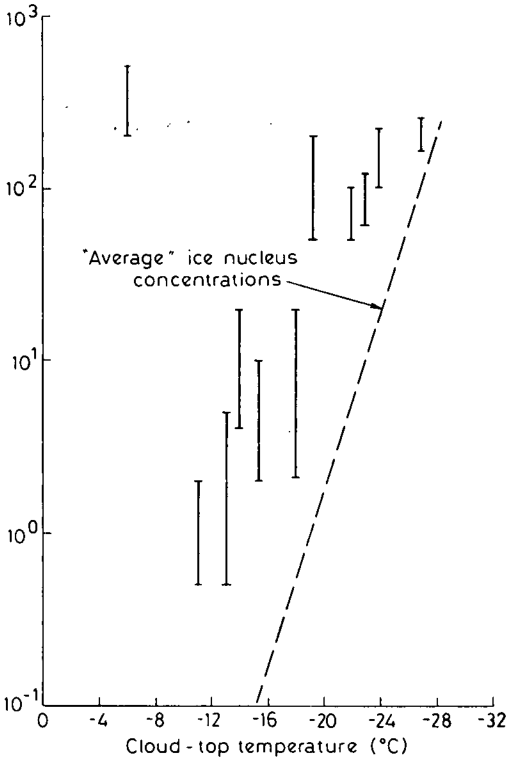


Fig. 12 Ice particle concentrations as a function of cloud-top temperature. The dashed line is the 'average' concentration of ice nuclei as suggested by Fletcher (1962).

The multiplication mechanism of rime break-up as proposed by Vali (1980) could possibly account for the difference between ice crystal and ice nucleus counts, particularly since the difference appears largest at the warmer temperatures where the riming seems most important.

Thus one is left with the following picture of ice particle production in these type A clouds:

(a) The regions of supercooled water, if any, are near cloud top.

(b) The total ice particle production is also governed by the cloud-top temperature, as are the shape and crystal type.

(c) Clouds with the warmer temperatures are not only likely to have more liquid water, but are also more efficient in converting the available non-vapour water into precipitation-size particles.

(d) Those clouds whose tops are colder than −12°C seem to be able to cope with the generation of liquid water to such a degree that regions of supercooled water in these clouds are both scarce and very small. Clouds whose tops are colder than −18°C will invariably have more than 10 l^{-1} ice crystals, and therefore would be unsuitable for seeding even if they had abundant supercool water.

Implications for cloud seeding

On the basis of the information presented here it is not surprising that no cloud seeding was carried out on type A clouds during the western Victorian experiment in 1980. In fact, there was no seeding of any cloud types during the 1980 season. An analysis of the reasons why all of the clouds were considered unsuitable is given in Table 1. On many of the sampled days the clouds were declared unsuitable for a multiplicity of reasons, but on eight days insufficient supercooled water was the sole reason why the clouds were considered unsuitable. Had the condition on liquid water content not been included (and we have already noted that this was a very weak requirement) then eight days of very dubious worth would have been included in the experiment. It was possible to exclude those days only because of the hot-wire probe. The hot-wire probe, which was designed to play an important role in helping cloud seeders to find the regions of supercooled water, has in fact been used primarily to eliminate spurious data and hence has shown that the number of seeding opportunities is much fewer than was previously assumed. In many ways this result is typical of the way in which the progress in cloud physics understanding during the last decade has led to reversals in the prospects for cloud seeding.

Table 1. Reasons for cloud being declared unsuitable.

Not enough cloud	8
Cloud too thin	15
Cloud base too high	10
Adverse winds	7
Cloud too warm	28
Insufficient l.w.c.	23
Insufficient l.w.c. sole reason	8

Acknowledgments

The author wishes to acknowledge the assistance of Mr John Meadows in compiling background material for this paper, and of Mr Ken Seton and Ms Laurel Arthur in computing areas.

References

Fletcher, N. H. 1962. *The Physics of Rain Clouds.* University Press, Cambridge, 386 pp.

Hallett, J. and Mossop, S. C. 1974. The production of secondary ice particles during the riming process. *Nature, 249,* 26-8.

King, W. D., Parkin, D. A. and Handsworth, R. J. 1978. A hot-wire liquid water device having fully calculable response characteristics. *Jnl. appl. Met., 17,* 1809-13.

King, W. D., Manton, M. J., Shaw, D. E., Smith, E. J. and Warner, J. 1979a. Prospectus for a cloud-seeding experiment in western Victoria. *CSIRO Division of Cloud Physics Internal Report CP 222.* Sydney, 48 pp.

King, W. D., Manton, M. J., Shaw, D. E., Smith, E. J. and Warner, J. 1979b. A cloud-seeding experiment in western Victoria: Statistical aspects. In *Preprints of Seventh Conference on Inadvertent and Planned Weather Modification,* held Banff, Canada, October 1979. American Met. Soc., Boston, Mass.

Rodi, A. R. and Spyers-Duran, P. A. 1972. Analysis of time response of airborne temperature sensors. *Jnl appl. Met., 11,* 554-6.

Ryan, B. F., Wishart, E. R. and Shaw, D. E. 1976. The densities and growth rates of ice crystals between −5C and −9C. *J. Atmos. Sci., 31,* 2136-41.

Vali, G. 1980. Ice multiplication by rime breakup. In *Preprints of the Eighth International Cloud Physics Conference,* held Clermont-Ferrand, France, July 1980. International Commission on Cloud Physics, CNRS, 63170, Aubure, France.