Preliminary Tests of a Cumulus Cloud Seeding Technique

G. A. ISAAC, R. S. SCHEMENAUER, C. L. CROZIER AND A. J. CHISHOLM

Atmospheric Environment Service, Downsview, Ontario, Canada M3H 5T4

J. I. MACPHERSON AND N. R. BOBBITT

National Research Council of Canada, Ottawa, Ontario, Canada K1A 0R6

L. B. MACHATTIE

Canadian Forestry Service, Ottawa, Ontario, Canada K2P 1X4

(Manuscript received 19 October 1976, in revised form 2 July 1977)

ABSTRACT

A cloud seeding technique is proposed which has the objective of stimulating rainfall from cumulus clouds drifting over forest fires. Preliminary tests of the ice crystal production capability of the cloud seeding technique were conducted on five cumulus clouds near Yellowknife, N.W.T., Canada, during July 1975. These clouds were over forest but not near forest fires. A T-33 turbulence research aircraft performed the seeding by burning wing-mounted TB1 AgI flares while flying through the clouds at the −5 to −10°C level. The T-33 turbulence measurements enabled estimates to be made of the rate of dispersion of the AgI. Microphysical measurements were made before and after seeding by an instrumented DHC-6 Twin Otter aircraft flying at the seeding level, and these were compared with measurements in six untreated cumulus clouds. High concentrations of ice crystals appeared after seeding in four of the five seeded cumulus clouds, and on two occasions precipitation-sized particles appeared at the seeding level. The evidence indicates that the AgI aerosol produced large quantities of ice crystals.

1. Introduction

Fires burn over approximately 8×10^3 km^2 of Canadian forest land per year. About 70% of this area is burned by large fires (greater than 40 km^2 in size), although these comprise only 0.5% of the total number of fires. Besides the damage they do to forests, these large fires may destroy industrial and recreational facilities and force the evacuation of towns. Some $70 million per year is spent in fighting forest fires in Canada. However, no effective method of combating large forest fires has yet been developed.

Early Canadian cloud seeding experiments using dry ice (Orr *et al.*, 1949) attempted to determine if weather modification techniques could be used in controlling fires. They concluded that isolated cumulus clouds could be modified to produce rain, but that the main usefulness of cloud seeding would be to prevent rather than to extinguish fires. In the USSR (Sumin, 1971; Sorokovik, 1972) scientists seeding clouds with AgI or PbI_2 claim to have induced rain to fall from cumulus clouds onto forest fires. For example, Artsybashev *et al.* (1974) stated that fires covering a total area of 2×10^3 km^2 were suppressed by cloud seeding during the period 1970–72.

Canadian and Russian foresters have found that a depth of 1–2 mm of water is required to suppress a forest fire. A Canso water bomber carrying 3.6 m^3 of water can cover an area of 10^{-3} km^2 per load with a minimum depth of 1 mm (MacPherson, 1967). By comparison, estimates of the rainfall production by seeded cumulus clouds vary from 2×10^4 to 2×10^5 m^3 of rain (Bethwaite *et al.*, 1966; McNaughton, 1975). If a precipitating cumulus were 2 km wide and traveled at 10 m s^{-1} with rain falling for 20 min, it could cover an area 10 km^2 or more with 1 mm of rain. Clearly, if cumuli passing over fires could be made to produce rain with sufficient frequency and at reasonable cost, then an effective method of suppressing *large* fires would be available. A discussion of the prospects in Canada for economic suppression of large fires by induced showers is given by MacHattie *et al.* (1976).

In order to develop and test a cloud seeding technique to suppress forest fires, a cooperative project of the Atmospheric Environment Service, the Canadian Forestry Service and the National Aeronautical Establishment (NAE) was begun in 1974. Before beginning any statistical evaluation of the ability of cloud seeding to produce rain, it was felt necessary that the seeding mechanism itself should be better understood and

FIG. 1a. T-33 aircraft with gust probe on nose and flare racks underneath wings.

FIG. 1b. DHC-6 Twin Otter aircraft instrumented for cloud microphysical measurements.

documented. As a first step, it had to be determined if cloud seeding could induce a substantial increase in the concentration of ice particles. This is not a trivial problem. For example, Sax (1974) found no significant microphysical differences between populations of seeded and unseeded Florida cumuli. Dye *et al.* (1976) describe their own and other work where microphysical changes in clouds were induced by seeding. However, these results are not directly transferrable to potentially different Canadian cumulus clouds or to the specific seeding technique that was proposed. Consequently, field trials out of Yellowknife were begun in 1975 in order to determine if the background concentration of ice particles in cumuli could be increased by cloud seeding.

2. Aircraft and instrumentation

a. General description

Two NAE aircraft were used: a T-33 jet trainer aircraft (Fig. 1a) and a DHC-6 Twin Otter STOL type aircraft (Fig. 1b).

The T-33 turbulence instrumentation system and its application to the measurement of turbulent parameters in cumuliform cloud over Canadian forests is described in detail by MacPherson and Isaac (1977).

The DHC-6 Twin Otter was instrumented during 1975 to perform cloud microphysical measurements. Three Particle Measuring System (PMS) probes (Knollenberg, 1970, 1972) were installed beneath the wings: an FSSP forward scattering probe counted particles in 15 size intervals 2 μm wide in the 2–30 μm size range, an OAP 200X probe in 15 size intervals 20 μm wide in the 20–300 μm size range, and an OAP 200Y probe in 15 size intervals 300 μm wide covering the 300–4500 μm size range. An ice particle counter (Sheets and Odencrantz, 1974) and a cloud particle replicator, both manufactured by Mee Industries, were installed under the wing and on the top aft part of the fuselage, respectively. A filter system for measuring ice nucleus concentrations and a precipitation sampler were also installed on the aircraft. Liquid water content was measured by a Johnson-Williams meter. Parameters such as temperature, dew point, altitude and air speed were measured with standard instrumentation.

Both aircraft were equipped with a VLF Global Navigation System. The T-33 take-off time was 30–60 min after that of the Twin Otter and this navigation system allowed the aircraft to easily rendezvous near the cloud selected for observation. It also facilitated operations in the Northwest Territories where standard navigation aids (VOR and DME) are widely scattered.

b. Reliability of the Twin Otter instrumentation

Many instruments were being flown for the first time during 1975 and one aim of the program was to assess the reliability of the instruments and the compatability of the measurements. A brief comment on the operation of the cloud physics instruments will suffice.

Data from the PMS FSSP probe were not used since the instrument calibration was subsequently proven unreliable. The Mee replicator functioned irregularly due to mechanical problems and did not provide a satisfactory data set. Since the aircraft never encountered moderate or heavy precipitation, the precipitation sampling system did not collect useable samples of rainwater. The filter system for measuring ice nucleus concentrations did not provide reliable data due to icing problems. The Johnson-Williams liquid water content meter performed within the manufacturer's specifications.

The Mee ice particle counter in laboratory tests prior to the field experiment counted ice particles greater than 100–150 μm at threshold voltages of 50–90 mV. The instrument does respond to water drops but only drops >1 mm in size will be counted with the same efficiency as 100–150 μm ice crystals. An examination of the sensor pod electronics after the field experiment indicated that an intermittent problem in the electronics

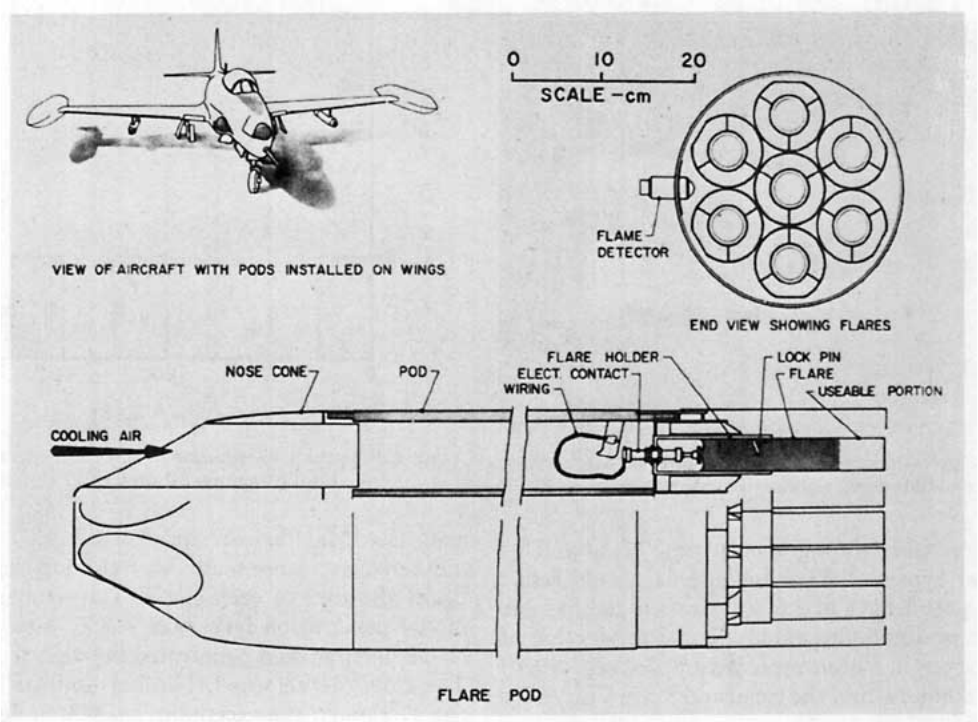

FIG. 2. Modified rocket pod which holds seven flares.

could have produced counts on occasion that were ~70% higher than normal. The recorded ice particle concentrations are felt to represent the concentrations of ice particles greater than 100–150 μm to within a factor of about ±2.

The PMS OAP-200X and OAP-200Y probes were flown with a minimum of advance preparation and were subsequently found to suffer from a series of problems. Mist forming on the probe optics and ice buildup on exterior probe surfaces eliminated some data. Part of this problem was due to the installation of incorrect probe heaters. The optical alignment of the probes was affected by the epoxy mounting of the mirrors in the probes and mechanical factors involved in removing and reinserting the probes in the pods. Although problems in the electronics were minimal, one intermittent problem with the OAP-200X would have resulted in some data being shifted to higher channels and some data being lost. Channels 1–3 of the OAP-200X (Knollenberg, 1975) and probably channel 1 of the OAP-200Y probe undercount the number of particles which fall within the channel boundaries. In addition, ice crystals of all sizes are undersized by an amount depending on the crystal habit. This is discussed later when the data are presented. Overall, the OAP-200X and OAP-200Y particle concentrations presented are expected to be accurate to within a factor of about ±2.

3. Seeding technique

The enhancement of rainfall from cumuliform clouds within this experiment was based on an increase of the ice-crystal content in the upper portion of the cloud and subsequent precipitation growth by the Bergeron-Findeisen process. Silver iodide pyrotechnic flares were chosen to produce the ice nucleant as a result of the efficiency with which they can produce high concentrations of ice nuclei at relatively warm temperatures. Delivery of the AgI aerosol at cloud base was considered ineffective due to the weak and inconsistent updrafts found in small Canadian cumuli (MacPherson and Isaac, 1977). Droppable flares cannot be targeted as accurately and present a safety hazard to forests and water bomber aircraft flying below cloud base. Consequently, a seeding system was developed for the T-33 aircraft which could use end-burning AgI flares, permitting direct and accurate injection of the ice nucleant into the cloud by flying through it at the -5 to -10°C level.

The T-33 was equipped with flare racks consisting of two modified military rocket pods each carrying seven end-burning flares. One rack was suspended under each wing. Fig. 2 shows the modified pod fitted with a special nose section which minimizes drag while allowing adequate ventilation of the flares. An electrical firing mechanism was developed which allowed flares to be ignited individually or in an automatic sequence which quickly fired all flares in a pod. The firing button also activated the event marker of the data recording system. A ground test of the flare rack was made in a 100 m s^{-1} airstream (Fig. 3) before an airborne safety test of the system was made (Fig. 1a).

The flares, manufactured by Nuclei Engineering Incorporated of Louiseville, Colo., produced 50 g of AgI

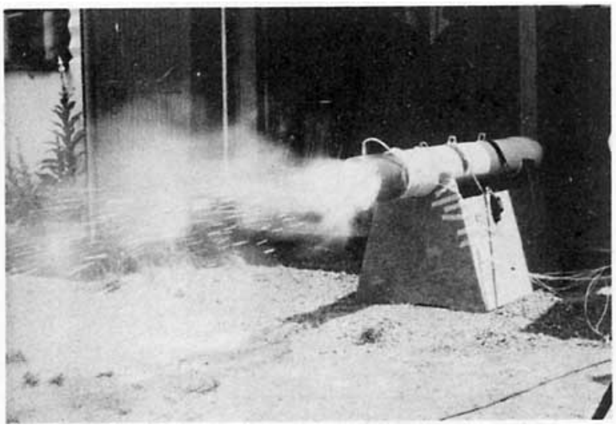

FIG. 3. Photograph taken during ground tests of flare rack. Note pieces of flare mixture being blown away from rack.

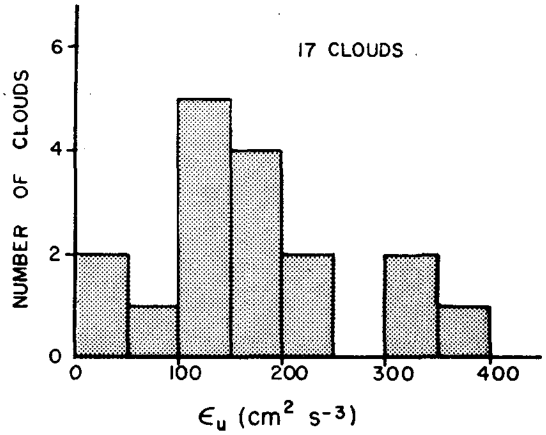

FIG. 4. Frequency distribution of turbulent energy dissipation rates computed for each of 17 clouds.

from a TB1 mixture during a burn time of 20 s. This burn time, at typical T-33 flying speeds, would result in a seeding path length of 2.6 km which is comparable to the width of a cumulus cloud. Nuclei production of the flare mixture has been reported by Garvey (1976) using measurements from the Colorado State University (CSU) facility (see Table 1).

The shedding of partially burned AgI particles (see Figs. 1a and 3) and the typical T-33 speeds (130 m s^{-1}) are not simulated by the CSU wind tunnel and the ice nucleus sampling technique which it employs. Additionally, the CSU cloud chamber does not simulate either the cloud droplet distributions or the supersaturations under which ice crystals are produced in Canadian cumuliform clouds. Consequently, the number of ice crystals produced from the AgI flare aerosol in a natural cloud may be different than the number created within the CSU chamber. The most effective way of evaluating the nucleus output of the flares is to determine the number of ice crystals that can be generated within a cumulus cloud.

4. Turbulence measurements and implications

Fig. 4 shows a summary of cumulus cloud turbulent energy dissipation rates calculated from the spectra of the longitudinal component of turbulence in aircraft axes (see MacPherson and Isaac, 1977). These T-33 measurements were made near the top (usually 300 m below the top) of each cloud. The temperature at the modal penetration level was −4°C with 15 of the 17 clouds having been penetrated between 0° and −10°C. The cloud depth was between 1 and 4.5 km for 16 of the 17 clouds; the exception was 600 m deep.

TABLE 1. The effectiveness of the Nuclei Engineering Inc. 50 g TB1 flares (Garvey, private communication).

Temperature (°C)	Nuclei production (g^{-1})
−4	3.0×10^{7}
−6	4.5×10^{10}
−8	1.5×10^{12}
−12	5.0×10^{12}
−16	6.0×10^{12}
−20	1.0×10^{13}

For estimating the rate of dispersion of nucleating material in a cloud, Todd (1965), Summers *et al.* (1972) and Kyle (1974) used the equation $d^2=\epsilon t^3$, where $t<1000$ s and d represents the diameter of a plume of

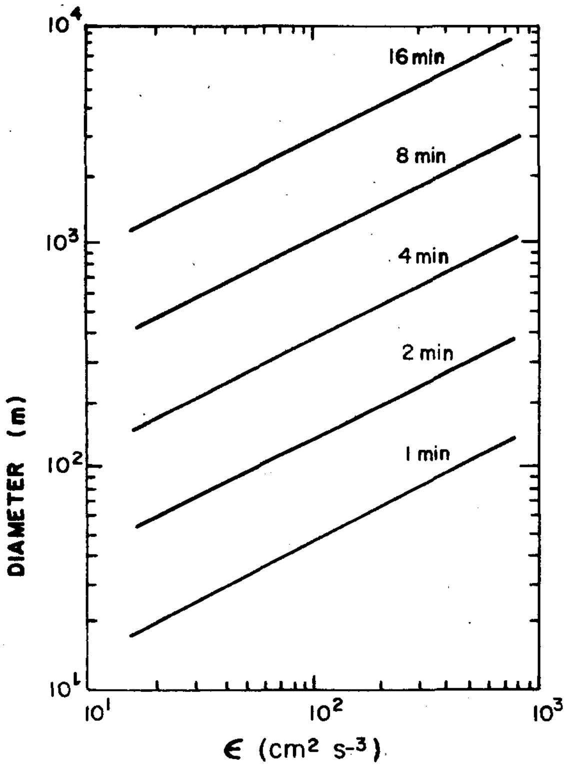

FIG. 5. The diameter of a plume of nuclei as a function of dissipation rate and time from release.

nuclei as a function of time (t) and dissipation rate (ϵ). The diameter refers to a column expanding from an axis which is formed by the passage of a burning flare. The equation should hold if the column is formed vertically by a freely falling flare or horizontally by a flare fixed to an aircraft. That is, the dissipation rate is assumed to be approximately the same for the u, v and w components of turbulence. In the calculations below, the length of the column is assumed to be the width of the cloud and the initial aircraft-induced diameter of the plume is assumed negligible.

Fig. 5 shows the computed diameter of the column plotted against dissipation rate for several selected times. At 100 cm^2 s^{-3} the diameter increases from 45 m at 1 min to 3 km at 16 min. This represents an effective velocity of 1.6 m s^{-1}. At 500 cm^2 s^{-3} this effective velocity increases to 3.6 m s^{-1}.

A single flare used in this experiment would release 50 g of AgI in 20 s over a path length (L) of 2.6 km. From the nucleus output of the flares (N) at a specific temperature (T), the concentration (C) of nuclei in the plume inside a cloud of specified width (W) can be determined from

$$C(T)=\frac{N(T)(W/L)}{W(\pi d^2/4)}$$
$$=KN(T)\epsilon^{-1}t^{-3},$$

where $K=4.9\times10^{-4}$ m^{-1}, $L=2600$ m. Fig. 6 shows the expected plume concentration at -8°C after burning one flare. The concentration of nuclei is inversely proportional to the dissipation rate and does not depend on cloud width for clouds <2.6 km wide. Considering the range of dissipation rates found in cumulus clouds (Fig. 4), it is important to measure ϵ if an accurate temporal estimate of the concentration of nuclei in a cloud is to be determined.

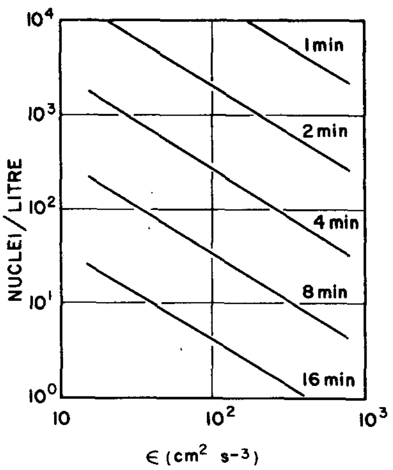

FIG. 6. The concentration of nuclei active at -8°C in a cloud as a function of dissipation rate and time from burning one NEI TB1 flare within the cloud. A 50 g NEI TB1 flare produces 7.5×10^{13} nuclei effective at -8°C.

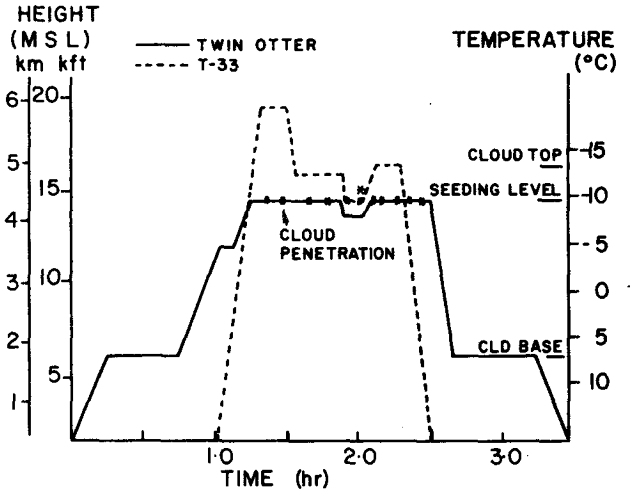

FIG. 7. The flight plan of the Twin Otter and T-33 for cloud seeding experiments. Cloud penetrations are indicated by two closely spaced vertical lines and the T-33 would seed during the penetration marked by an asterisk.

5. Flight profiles

The basic plan for the T-33 and Twin Otter flights in 1975 is depicted in Fig. 7. After the Twin Otter and T-33 made a rendezvous at the preselected site, a well-defined and relatively isolated cumulus cloud was chosen that had the following characteristics:

1) A depth greater than 1 km
2) A top with a solid and growing appearance
3) A cloud-top temperature between -5° and -20°C.

Then, at an altitude 300 m below cloud top or at the -10°C level, whichever was lower, the Twin Otter flew through the selected cloud. Penetrations were made in pairs (cross-wind and along-wind) wherever possible. Meanwhile, photographs were taken from the T-33 while it circled at cloud-top level. As soon as microphysical measurements by the Twin Otter were completed, the T-33 descended and penetrated the cloud twice (along-wind and cross-wind) at the same height as the Twin Otter passes. Turbulence measurements were made during both cloud penetrations by the T-33. The cloud was seeded on the cross-wind leg slightly toward the upwind side of the cloud where updrafts were expected to be stronger. Following seeding, the T-33 climbed and circled at cloud top and any visual changes in the cloud were noted. Then, with the Twin Otter making cloud penetrations for as long as possible, microphysical measurements were made at the seeding level. If time permitted before the T-33 or Twin Otter left the cloud area, the cloud base would be examined for the presence of rain.

6. Results from seeding tests

Table 2 summarizes measurements on five seeded cumulus clouds which were obtained while the aircraft

TABLE 2. A summary of the measurements describing five seeded cumulus clouds.

	HEIGHT CLD TOP CLD BASE m/m	SEEDING LEVEL HEIGHT TEMPERATURE m/°c	AgI EXPENDED gm	LIQUID WATER BEFORE AFTER gm/m³	PARTICLES > 70 μm RUNS 1,2,··· BEFORE RUNS 1,2,··· AFTER l^{-1}	PARTICLES > 300 μm RUNS 1,2,··· BEFORE RUNS 1,2,··· AFTER $0{\cdot}1\ m^{-3}$	TURBULENCE ε IN/OUT cm^2/sec^3	RAIN
JULY 17	7160 2740	4880 -10	350	— —	192,86 41,26,26,2	482, 337 294,151,133,5	8 4	YES
JULY 19	4210 3230	3750 -8	200	0·1 0·06	0,0 0,64,97,63,0,0	0,0 0,0,0,0,0,0	18 0·2	NO
JULY 22 A	3660 1220	3350 -5·5	550	1·1 0·8	1,3 33,8,3,0,0,1,0	2,9 110,1,1,0,0,0,1	100 2	YES
JULY 22 B	3810 1680	3350 -6	300	0·8 0·6	0,0,6,4 27,14,6,4,4,4,1,2,2,1,0	2,0,2,5 1,6,1,3,5,13,11,6,10,6,2	230 15	YES
JULY 25	3660 1520E	3350 -5	300	0·4 0·2	0,0 46,52,24,73,0,13	1,1 42,101,67,167,0,0	105 14	NO

followed the flight plans of Fig. 7. The cloud-base and cloud-top height at the time of seeding, the seeding level height, the environmental temperature at this level, the amount of AgI expended, the average liquid water content (Johnson-Williams) on the first two passes immediately before and immediately after seeding, and the average turbulent energy dissipation rate (in cloud and out of cloud) for the T-33 penetrations are noted in their respective columns. The penetration average concentration of particles $>70\ \mu m$ in size and $>300\ \mu m$ in size measured by the PMS probes for each cloud penetration before and after seeding is also shown. Excluding the seeding interval, the time between successive penetrations was 1–7 min and the time between the first and last penetrations on the five days was 38, 24, 42, 41 and 39 min, respectively. If rain was observed below cloud base at any time, it is indicated in Table 2. Because the flight plans of Fig. 7 were followed, rain would not necessarily be observed even if it occurred.

Although the PMS probes provide greater size resolution than is indicated in Table 2, only concentrations of particles with sizes $>70\ \mu m$ and $>300\ \mu m$ are described here. This is due to the uncertainty with which ice crystals are sized and counted by the OAP-200X probe, particularly in the first three channels. Consequently, the sum of particles recorded on channels 4 to 15 (70–310 μm), plus the sum of channels 1 to 15 for the OAP 200Y probe, were used to calculate concentrations of particles $>70\ \mu m$. The total number of particles observed with the OAP 200Y precipitation probe was used to calculate concentrations of particles larger than 300 μm. The 300 μm size is the nominal minimum detectable size for the precipitation probe.

For the 17 July case, the cloud eventually exceeded the height criteria outlined in Section 5 and actually grew as high as 7300 m. Precipitation-sized particles in high concentrations existed in the cloud before and after seeding and the Johnson-Williams LWC meter showed that no appreciable water was in cloud droplet form before or after seeding occurred. The turbulence levels were extremely low when compared with the values shown in Fig. 4. Although rain was observed falling out of cloud base after seeding, it appears probable that the cloud was raining before seeding commenced. Seeding did not increase the concentration of particles $>70\ \mu m$ in size.

On 19 July, a very thin cloud with low liquid water content and low turbulent energy dissipation rate was seeded. The concentration of particles $>70\ \mu m$ in size increased after seeding. No particles $>300\ \mu m$ were observed before or after seeding.

The 22A, 22B and 25 July cases were very similar. In each case higher concentrations of particles $>70\ \mu m$ in size appeared after seeding. For the clouds of 22A and 25 July, particles $>750\ \mu m$ appeared after seeding in average concentrations >20 and $>200\ m^{-3}$, respectively.

Fig. 8 shows the variations of the PMS probe data, sizes $>70\ \mu m$ and $>300\ \mu m$, and Mee ice particle counter measurements as a function of time for two cases (22A July and 25 July). All three instruments show increased concentrations after seeding. For all of the cloud cases of Table 2, the ice particle counter indicated higher concentrations after seeding than before seeding. Assuming a reasonable minimum detectable size (100–200 μm) for the Mee counter, the PMS and Mee counters do not give identical absolute concentrations (Fig. 8) but a second-by-second analysis of the penetrations shows that regions of high and low concentrations are measured simultaneously on both instruments. The PMS probe counts are generally lower than those of the Mee counter and this discrepancy is being examined in laboratory calibrations underway at present. Within the errors assumed for these instruments, the data are in reasonable agreement except when the PMS concentrations are very low.

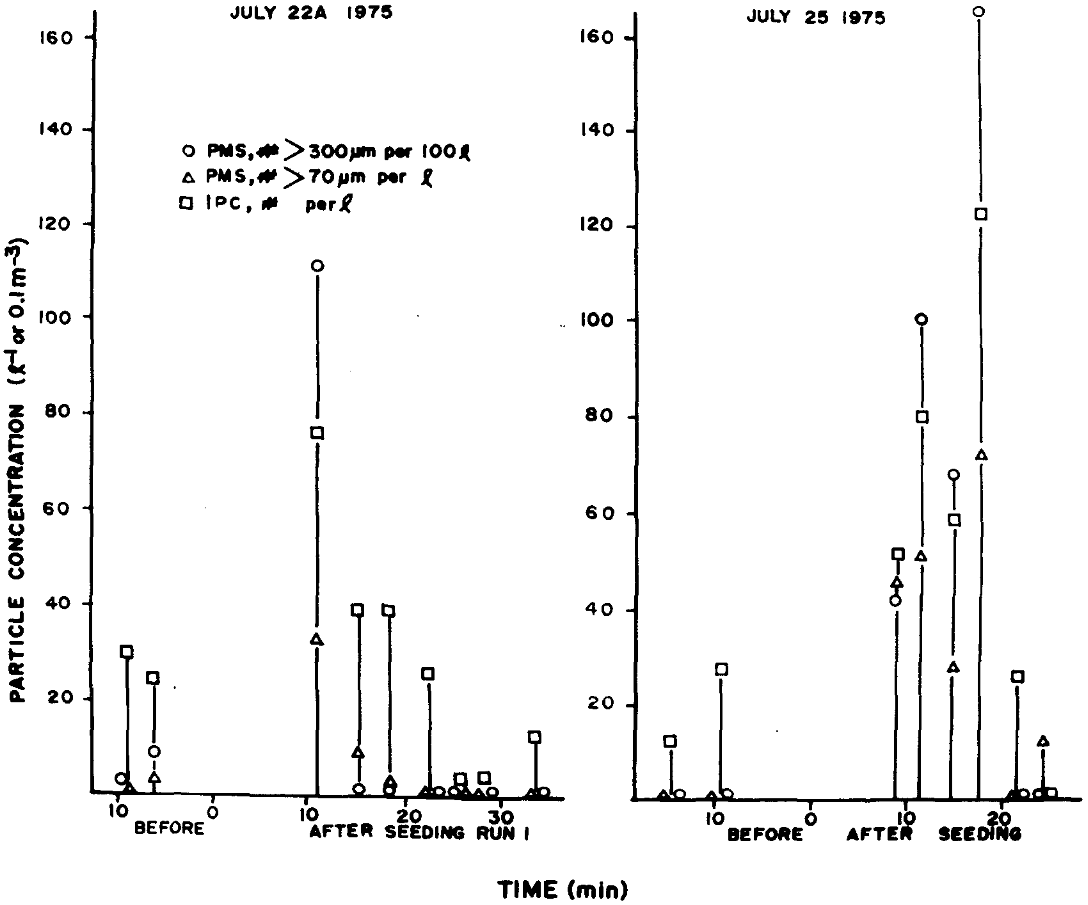

FIG. 8. The average concentration measurements from the PMS and Mee counters during each penetration before and after seeding for the 22A and 25 July cases of Table 2. For the 22A case, a second seeding run was made 10 min after the first run.

On 25 July, 8.5 min after seeding, on a 3.6 km penetration downwind (across the seeding run), the Twin Otter flew through a 1.4 km section of cloud where the concentration of particles $>70\,\mu$m was greater than 4 ℓ^{-1}. On the next pass, 2.4 km in a direction along the seeding run (crosswind) and 15 min after seeding on the next downwind pass 2.6 km long, concentrations >4 ℓ^{-1} were found throughout the entire width of the cloud. Section 7, describing unseeded clouds, indicates the rationale for the choice of 4 ℓ^{-1}; concentrations >4 ℓ^{-1} were sufficiently high to be considered unusual.

These observations support the hypothesis that a plume of ice crystals, generated by AgI nuclei, spread at a rate consistent with the turbulence measurements of the T-33 which showed an average dissipation rate of 107 cm^2 s^{-3}. For example, Fig. 5 indicates that for this value of ϵ, the diameter of the plume of AgI 8.5 min after seeding should be $\sim$1.2 km; this is comparable with the value of 1.4 km determined from the particle measurements mentioned above. At 15 min, Fig. 5 indicates that the AgI nuclei should have spread throughout the penetration and this is consistent with the observations.

The expected average concentration of nuclei effective at -8°C in the cloud, calculated using the computed dissipation rate, was compared with the measured average concentration of particles with sizes $>70\,\mu$m. Fig. 9 shows this ratio for the data of 19, 22B and 25 July. The 17 July case was omitted because the high concentrations of particles $>70\,\mu$m observed before seeding make it unlikely that any particles created by seeding could have been differentiated from those naturally produced. The 22A July case was omitted because, due to operational problems, the cloud was seeded on two runs 10 min apart and it was difficult to know which plume of AgI nuclei was being penetrated. The first run after seeding on 19 July was not plotted as it is believed that the plume could have been missed on that occasion. When the clouds began to dissipate and their cloud tops descended, the data were not plotted. No correction in concentration was made for the width or depth of the plume as a fraction of the total cloud seeded. This would only create a large error

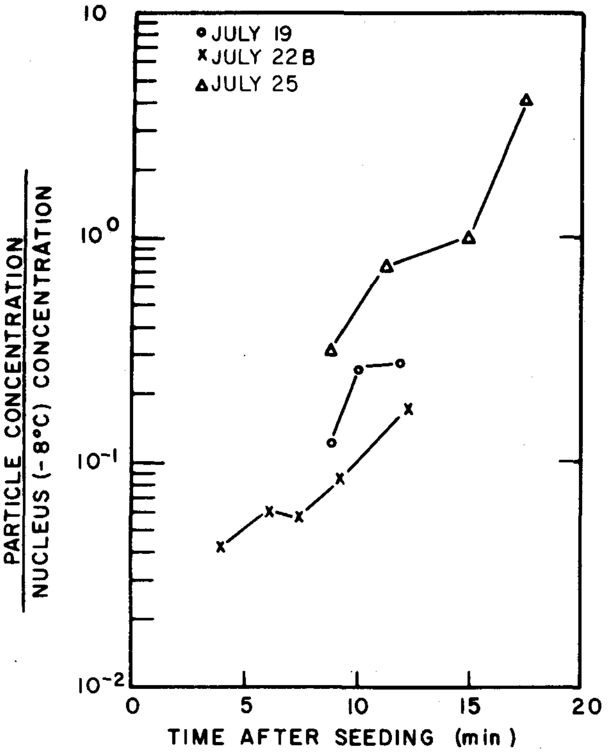

Fig. 9. The time dependence for the ratio of the measured concentration of particles $>70\ \mu m$ to the computed concentration of nuclei effective at $-8°C$.

(factor 2 to 3) for the first run after seeding on 25 July when the plume did not have enough time to completely spread through the cloud. Errors for other penetrations would be smaller.

A reasonable estimate for the environmental temperature at cloud top for the 19, 22B and 25 July cases would be $-11°$, $-8°$ and $-7°C$, respectively. However, it is a problem to know which temperature to choose in order to determine the effective number of AgI nuclei for the comparison of Fig. 9. A value of $-8°C$ was selected and Table 1 indicates that significant errors could result from this simplification.

Bearing in mind the foregoing assumptions and explanations, it appears that the ratio of observed particles $>70\ \mu m$ in size to the calculated nucleus concentration increases with time after seeding. The ratio is close to a value of unity about 10 min after seeding.

Section 3 outlined reasons whereby the values given in Table 1 might be in error. Considering the precision of the theory and measurements described in this paper, one can conclude from Fig. 9 that the values quoted in Table 1 are compatible with the ice crystal measurements. Using measurements within one seeded cumulus and a different analysis technique, Dye *et al.* (1976) also concluded that an AgI aerosol produced similar numbers of ice crystals within cloud chambers and natural cumuli. It must be remembered that the values given in Table 1 represent ice crystal production from NEI TB1 AgI over periods as long as 50 min within the CSU chamber (Garvey, 1975). In short-lived clouds, with AgI acting through a contact nucleation mechanism, time might be an important parameter (Isaac and Douglas, 1972). From Fig. 9, it appears that more nuclei are activated with time but additional measurements are required in order to better define this time dependence.

7. Unseeded clouds

Performing the seeding experiment and subsequent monitoring of changes in microphysical characteristics typically permitted only one seeded cloud per flight to be examined by the T-33. However, due to the greater flight endurance of the Twin Otter aircraft, it was possible to make limited microphysical observations in unseeded clouds on the same flights that seeded clouds were examined. These data are given in Table 3. Unfortunately, data on cloud top and cloud base heights as well as information on rain from the base are not available.

The average environmental temperature at the penetration level and the average liquid water content encountered are listed in Table 3 along with the average concentration of particles $>70\ \mu m$ and $>300\ \mu m$ measured for each penetration. With the exception of the case on 19 July, all unseeded clouds were examined before any seeding material was utilized. The same selection criteria were used for the unseeded cases as the seeded cases, and penetrations were flown a few hundred meters below cloud top.

With the exception of the unseeded case on 25 July (where the cloud-top temperature is estimated at $-16°C$ or colder), the maximum particle count for particles $>70\ \mu m$, was $3\ \ell^{-1}$ and the modal value was $<1\ \ell^{-1}$. Low concentrations were also noted for particles $>300\ \mu m$ in the unseeded cases. This is in general agreement with the particle concentrations obtained in seeded clouds prior to seeding.

The unseeded cloud of 25 July and the cloud seeded on 17 July exhibit characteristics which appear to be due to a natural precipitation growth mechanism. Precipitation sized particles (>1 mm) existed in concentrations $>150\ m^{-3}$ in these two clouds. Both clouds were penetrated at temperatures of $-10°C$ and colder and had cloud-top temperatures which were colder than $-16°C$.

While the maximum time duration between the first and last penetration was 8 min in the above unseeded cases, no clear trend of particle concentration is found as a function of time. The clouds were penetrated at an unknown point in their life cycle. It is reasonable to believe that both the seeded and unseeded clouds with tops warmer than $-12°C$ had been in existence for relatively long periods of time without generating substantial numbers of particles $>70\ \mu m$. This supports

TABLE 3. As in Table 2 except for six unseeded cumulus clouds.

Date	Penetration Temperature °C	Liquid Water Content gm m^{-3}	Particles >70 μm Runs 1,2,3,... ℓ^{-1}	Particles >300 μm Runs 1,2,3,.... 0.1 m^{-3}
July 17	-8.0	-	0,0,0	5,7,0
July 19	-9.0	0.05	0	8
July 22A	-5.5	1.0	1,1,1	18,10,2
July 22B	-7.0	0.7	0,0,0,3	12,7,9,2
July 25	-14.5/-10.0	0.1	132,233/143,118	377,442/261,403
July 25	-4.5	0.3	0,1	0,1

the concept that the increases in particle concentration following cloud seeding were due to the modification of the cloud microphysical structure by AgI aerosol. This can only be confirmed by making penetrations in unseeded clouds over longer periods of time.

8. Discussion and conclusions

As shown by the PMS measurements of Table 2, with the exception of the 17 July case, the concentration of particles $>70\,\mu$m increased after seeding. Although the Mee ice particle counter and PMS measurements showed unexplained differences (Fig. 8), the Mee counter also showed higher concentrations after seeding. These higher concentrations after seeding might have been due to a droplet condensation-coalescence mechanism, an aircraft induced effect, a natural ice multiplication mechanism or a seeding effect. The droplet condensation-coalescence explanation was rejected because of the ice particle counter measurements and the short time available for such a mechanism to act (Fig. 8). The aircraft themselves might have generated efficient ice nuclei or larger ($>20\,\mu$m) condensation nuclei in their exhaust but there is no evidence to suggest that the aircraft fuel could generate sufficient quantities of nuclei. There is not a high probability of a natural ice multiplication mechanism occurring because natural cloud observations indicate that concentrations of particles $>70\,\mu$m are less than 3 ℓ^{-1} when the cloud top is warmer than −11°C. In addition, it is difficult to believe that an aircraft effect or an ice multiplication mechanism was responsible because repeated penetrations by the Twin Otter in the same unseeded cloud showed that particle concentrations did not change over small but significant time periods (<8 min). Summarizing the above arguments, it seems probable that the AgI flares did induce increases in ice crystal concentrations.

Based on the 25 July measurements, Fig. 5 appears to provide a good estimate of the width of the plume of AgI nuclei in a cloud. Fig. 9 indicates that the concentration of AgI nuclei within the cloud can be estimated with the theory illustrated by Fig. 6 and the cloud chamber measurements of Table 1.

Large particles (>1 mm) appeared at the seeding level in two of the seeded cases. These precipitation size particles should grow and fall out of the cloud. Consequently, it appears likely that precipitation can be induced in some cumulus clouds although the frequency of success and probable amount of rain still remain unknown variables.

Although not mentioned specifically in the foregoing discussion, the liquid water contents of the seeded clouds as measured by the Johnson-Williams meter did not dramatically drop after seeding. For the 19, 22A, 22B and 25 July cases, the average liquid water content after seeding was consistently lower by 25–50% (Table 2). Seeding did not completely glaciate the cloud. In addition, cloud-top heights did not increase by more than 600 m. It appears likely that a Bergeron-Findeisen process, rather than a dynamic seeding effect, was being simulated in these clouds.

None of the seeded clouds were drifting over a forest fire. Since fires could conceivably modify the microphysics or dynamics of cumulus clouds, research is being conducted to evaluate the magnitude of any such effects.

With respect to seeding, more emphasis in the future will be on studying precipitation formation. If additional physical evidence is gathered to indicate that precipitation can be induced by this or a modified technique, and data are obtained to define approximate cloud characteristics for "seedability," then a statistical experiment should be run to indicate if the technique is economical for use in suppressing forest fires.

REFERENCES

Artsybashev, E. S., P. A. Gubin, A. I. Sumin and N. S. Shishkin, 1974: Results of experiment and operational work on combating forest fires. *Proc. WMO/IAMAP Sci. Conf. Weather Modification*, Tashkent, USSR, 265–266.

Bethwaite, F. D., E. J. Smith, T. A. Warburton and K. J. Heffernan, 1966: Effects of seeding isolated cumulus clouds with silver iodide. *J. Appl. Meteor.*, **5**, 513–520.

Dye, J. E., G. Langer, V. Toutenhoofd, T. W. Cannon and C. A. Knight, 1976: Use of a sailplane to measure microphysical effects of silver iodide seeding in cumulus clouds. *J. Appl. Meteor.*, **15**, 264–274.

Garvey, D. M., 1975: Testing of cloud seeding materials at the cloud simulation and aerosol laboratory. *J. Appl. Meteor.*, **14**, 883–890.

Isaac, G. A., and R. H. Douglas, 1972: Another "time lag" in the activation of atmospheric ice nuclei. *J. Appl. Meteor.*, **11**, 490–493.

Knollenberg, R. G., 1970: The optical array: An alternative to scattering or extinction for airborne particle size determination. *J. Appl. Meteor.*, **9**, 86–103.

——, 1972: Comparative liquid water content measurements of conventional instruments with an optical array spectrometer. *J. Appl. Meteor.*, **11**, 501–508.

——, 1975: The response of optical array spectrometers to ice and snow: A study of probe size to crystal mass relationships. Rep. AFCRL-TR-75-0494, Air Force Cambridge Research Laboratories, 70 pp.

Kyle, T. G., 1974: The dispersal of seeding material in the updrafts of storms. *Preprints 4th Conf. Weather Modification*, Ft. Lauderdale, Amer. Meteor. Soc., 69–72.

MacHattie, L. B., G. A. Isaac and N. R. Bobbitt, 1976: Prospects for economic suppression of large forest fires by induced showers. Ottawa, Canadian Forestry Service, Information Rep. FF-X-59, 22 pp.

MacPherson, J. I., 1967: Ground distribution contour measurements for five fire-bombers currently used in Canada. Ottawa, National Research Council of Canada, Laboratory Rep. LR-493, 66 pp.

——, and G. A. Isaac, 1977: Turbulent characteristics of some Canadian cumulus clouds. *J. Appl. Meteor.*, **16**, 81–90.

McNaughton, D. L., 1975: Seeding single clouds using pyrotechnic cartridges, 1973–74. *J. Wea. Mod.*, **7**, 4–16.

Orr, J. L., K. G. Pettit and D. Fraser, 1949: Canadian experiments on induced precipitation. *Proc. U. N. Sci. Conf. Conservation and Utilization of Resources*, Lake Success, N. Y., 27–36.

Sax, R. I., 1974: On the microphysical differences between populations of seeded vs non-seeded Florida cumuli. *Preprints 4th Conf. Weather Modification*, Ft. Lauderdale, Amer. Meteor. Soc., 65–68.

Sheets, R. C., and F. K. Odencrantz, 1974: Response characteristics of two automatic ice particle counters. *J. Appl. Meteor.*, **13**, 148–155.

Sorokovik, M. V., 1972: Suppressing forest fires by Cu cloud seeding. *Tr. Gl. Geofiz. Observ.*, No. 279, 101–105 (Meteor. Translation No. 24 of Environment Canada).

Sumin, Yu. P., 1971: Cloud seeding experiments for suppressing forest fires. *Tr. Gl. Geofiz. Observ.*, No. 262, 54–60 (Meteor. Translation No. 24 of Environment Canada).

Summers, P. W., G. K. Mather and D. S. Treddenick, 1972: The development and testing of an airborne droppable pyrotechnic flare system for seeding Alberta hailstorms. *J. Appl. Meteor.*, **11**, 695–703.

Todd, C. J., 1965: Ice crystal development in a seeded cumulus cloud. *J. Atmos. Sci.*, **22**, 70–78.