ASCENT OF SURFACE-RELEASED SILVER IODIDE INTO SUMMER CONVECTION

ALBERTA 1975

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Abstract. During the summer of 1975, an experiment was conducted near Calgary, Alberta, Canada, to test the hypothesis that surface-released silver iodide can reach the inflow regions of cumulonimbus clouds. Effluent from point and quasi-area sources of AgI-impregnated coke-fueled generators were traced using airborne NCAR ice nucleus counters. The evidence shows that it is possible for plumes to ascend to give concentrations up to two orders of magnitude above background at -20°C (>200 nuclei per liter) in cloud-base inflow areas. Targeting was difficult and the horizontal dispersion of the plume less than anticipated. Ice nucleus concentrations were usually above background levels to the top of the mixing layer. Three case studies having relevance to the application of ground-based AgI generators are discussed and a summary of flights during convective periods is given.

1. INTRODUCTION

There has been much speculation regarding the potential for surface released cloud seeding material to be entrained during convective periods. The National Academy of Sciences (NAS-NRC, 1973) has stated that orographic cloud systems may be treated by ground-based units because of the forced vertical motion; however, they recognized that vertical transport processes may be complex. For situations lacking orographic influences, evidence of predictable vertical transport of ground-released material has not been convincing.

Ground-based cloud seeding has been used by many projects. Among the first was the Salt River Arizona, project during 1948 and 1949 (Krick, 1949; MacCready, 1952). Winter orographic clouds have commonly been treated with ground-based units because of the vertical motion forced by the orographic regime, long system life and broad area coverage characteristic of these systems (Hess, 1974; Silverman, 1976). Some skepticism regarding routine targeting effectiveness of ground-based summer cloud treatment was expressed by NAS-NRC (1973). Super and McPartland (1978) and Heimbach *et al.* (1975) report the ascension of concentrations several orders of magnitude above background from the surface to the top of the mixing depth in Montana, 2000-to-3000m AGL. The former study specifically addressed cloud base concentration of silver iodide, whereas the latter was primarily concerned with the rate of diffusion of silver iodide as a tracing material.

Further suggestions regarding the characteristics of surface-originated plumes come from investigations of inadvertent weather modification. Schickedanz (1974) and Changnon *et al.* (1976) reported that, besides thermodynamic and mechanical influences of the St. Louis area, there appeared to be a microphysical change to the clouds which produced increased precipitation downwind of the city. This was presumed to be the result of giant nuclei which would have to ascend from the surface to cloud base.

There is uncertainity regarding the accumulation of suitable concentrations of ground-released seeding material in convective updraft regions. The questions of effectiveness of area treatment, lead time required for treatment, emission rates, and predictability of plume behavior have also brought criticism to ground-based procedures. The photodeactivation of silver iodide has been the topic of much speculation (Changnon, 1975). Marked photodecay of silver iodide was reported in several early experiments (Mason, 1971); however, later work by Super *et al.* (1975) indicates that this deactivation is limited or nonexistent for the AgI-NH_4I-Acetone complex.

In view of these uncertainties, the Alberta Weather Modification Board (formerly Interim Weather Modification Board), Alberta, Canada, (AWMB) conducted a ground-based diffusion experiment during the summer of 1975 (Stone *et al.* 1976). During the years 1956 through 1968 and also 1973 to the present, operational hail suppression and concurrent research have been in process in Alberta. Currently, the operational aspects are the responsibility of the Alberta Hail Project (AHP) based in Red Deer, under the auspices of the Alberta Research Council (ARC). During the earlier period the operations were the responsibility of Irving P. Krick Associates of Canada, Ltd., who used coke ground-based silver iodide generators. The 1975 experiment had the mandate of investigating the earlier ground-based seeding effectiveness, with hopes of clarifying operational aspects for possible future implementation of surface releases.

Further research in ground-based seeding of convective events has been carried out by the Alberta Research Council and Irving P. Krick Associates over roughly the same target area during the summers of 1981, 1982, and 1983. The data from this effort are currently being analyzed.

Presented below are three case studies from the 1975 plume study program which document the rise of ground-based plumes in convective conditions, the broad ascension of ice nuclei in response to a lifting mixing layer and the characteristics of a plume during inversion conditions. These cases were culled from a total of thirty tracing missions, sixteen of which were in unstable conditions ($\gamma \geq \Gamma_d$). A summary of the unstable cases is given in Section 5.

2. EXPERIMENTAL PROCEDURES

Figure 1 shows the placement of the study area among other relevant points. The foothills of the Highwood and Kananaskis Ranges are 32 to 56 km to the west of the study area. Most of the target area is flat to gently rolling hills, sloping from approximately 1120m MSL on the west to 950m at the northeast corner. Seventeen generator sites in and around the area were operated by private citizens; and active sites were monitored by project personnel at least once during each operation day. The sites to be used depended upon wind conditions and the type of tracing mission.

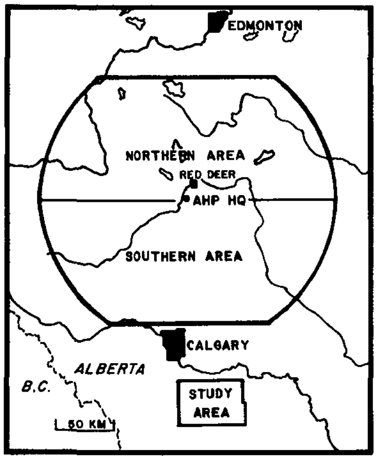

Fig. 1. The Ground-Based Plume Study Area in Relation to the Alberta Hail Project.

The tracing aircraft usually arrived upwind of the operating generators at 3000m MSL or more, then spiraled downward to obtain a temperature sounding, as well as background ice nuclei concentrations, as quickly as possible. The flight profiles were generally 15-to-35 km and were made from 100m (sometimes lower) to 2000m AGL or until background concentrations were reached. Most of the tracing was done without cumulonimbus development, reducing the mission to the exercise of finding the plume and remaining with it until it was lost above the mixing layer. However, several days had significant convective development and particular attention was given to sampling the inflow regions of these systems.

Typically, the wind would have an easterly component during the first portion of an experimental day, shifting to westerly by afternoon. The direction varied not only with time but over short distances; e.g., 180 deg shifts were often observed in the study area. Intermingled plumes of the various sources made inflight assessment of plume behavior very difficult, and the plume often was lost during these conditions. Consequently, several generators were placed at one point source to yield a larger emission rate and reduce the complexity of the plume structure. This made tracking an individual plume far more practical.

It was planned to use VOR/DME coordinates to define the traverse paths, but because of the uncertainties in the electronics and recording systems, later substantiated, a series of clearly visible check points was relied upon. The crossing of a check point was logged on the ice nucleus counter strip chart along with the altitude.

The day's first forecast was completed at the control office by 08 MDT, assigning a "go", "likely", or "no-go" status to the day. If affirmative, the flight crew and field personnel were alerted and briefed. The aircraft instrumentation, in particular the ice nucleus counter, were attended to at least an hour prior to take-off and the generator operators were alerted to start their units at least a half hour, and if possible two to three hours, prior to the arrival of the aircraft, so that conditions could approach steady state. Tracing missions were usually initiated by 1400 MDT.

3. INSTRUMENTATION

3.1 Silver Iodide Generators

Krick Model 15 generators provided silver iodide for most of the experiments. These are basically composed of a fuel hopper, feed mechanism, vaporizing furnace and a blower for maintaining the proper air flow through the furnace.

The fuel burned in the generator consisted of sized quarter-inch foundry coke impregnated with an AgI-NaI complex yielding a burn rate of *approximately 0.5 gm silver iodide per minute.* This type of generator was tested at the Cloud Simulation and Aerosol Laboratory, Colorado State University (1974). The results showed 2 X 10^{14} to 10^{15} ice nuclei per gram of silver iodide effective at -20°C for natural draft and maximum flow, respectively. This testing also showed less than 20% loss of activity for ice nuclei exposed to ultraviolet radiation over the sampling period of five hours. This is considered to be insignificant. Tests of the coke generator in 1981 (Finnegan, 1981) showed similar nuclei production at -20°C, higher efficiencies above -20°C and a *more rapid drop off at -10°C.* There was also more scatter in the derived efficiencies. The 1981 tests showed higher and more consistent efficiencies for the Krick electric arc type generator.

3.2 Aircraft

The primary aircraft was a Piper Cherokee 6. This single-engine aircraft, furnished by INTERA Ltd. of Canada, was based at Calgary International Airport, approximately 45 km north of the study area.

Metrodata M8 and 620 systems were installed on the Cherokee for in-flight monitoring of basic parameters. Some problems in the system were not resolved, and use of the recorded data had to be abandoned. All in-flight data used in the analysis came from flight logs and Rustrak recordings of ice nucleus counts.

A Cessna 411 (also provided by INTERA) assigned to the AHP as a cloud physics aircraft was used on the experiment on an as-available basis. This aircraft had an ice nucleus counter similar to that on the Cherokee 6, and comparison flights were made to test the two systems.

3.3 Ice Nucleus Counter

The operation of the NCAR ice nucleus counter is described by Langer *et al*. (1967); Langer and Weickmann (1971); and Langer (1973). Both counters had their cloud chamber maintained at -20°C, and had been modified slightly by G. Langer. Most of the ice nucleus data for the ground-released plume study came from counter in the Cherokee 6, belonging to the Alberta Research Council. The other NCAR counter was loaned to the AHP by NCAR and was installed in the Cessna 411.

Counts were integrated over 120 sec., 12 sec., or 1.2 sec. intervals, depending upon the choice of scales. Background sampling was usually over 120 sec. integration periods and normal plume tracing was over 12 sec. intervals. Recorded units counts per minute were converted later to counts per liter, using the techniques described by Heimbach *et al*. (1977). The time required to grow acoustically detectable ice crystals around ice nuclei makes response times on the order of a minute, and smoothing of counts, are inherent in the NCAR counter.

Tests of the Cherokee counter with 120 mm Hg flow rate showed the lag to average 35 sec. to the first detection of an input, 65 sec. to mode response, and 97 sec. to median response from input. The time-to-mode would seem the most appropriate response parameter to apply for purposes of time-to-distance conversion for peak counts. The testing also showed that the Cherokee 6 ice nucleus counter contributed an induced standard deviation of approximately 30 sec. to the true input. For all the case studies described in this paper the response lag was removed. The ice nucleus profiles depicted in Fig. 7 have also been adjusted by removing the counter induced smoothing.

Since the 1975 experiment, the ARC counter and its electronics have been rebuilt. This counter, as well as one belonging to the Colorado State University Cloud Simulation Laboratory, were calibrated for efficiencies at that facility. The 10% efficiency factor (actually a chamber fallout correction suggested by Langer, 1973), for the ARC counter, as run in its recent configuration, was too large. For reasons not discussed herein, it is certain that the counter as run in 1975 was more efficient than shown in the recent tests, and the 10% factor is applied in this paper, i.e., one ice nucleus registered by the counter was assumed to represent ten nuclei. This is a conservative approach since the counts reported in this paper represent the maximum counter efficiency possible, i.e., reality must have concentrations that high or higher. Applying the 10% factor and using a sample flow rate of 10 ℓpm gives an approximate one-to-one ratio to convert counts per minute to counts per liter.

4. SURFACE-RELEASED SILVER IODIDE PLUME CHARACTERISTICS

Many factors contributed to the difficulty of sampling cumulus inflow areas. Very often the winds would be light and variable, making plume tracing difficult. Also, inflow regions had to be recognized and sampled in a timely fashion. On several occasions, a line of cumulonimbus appeared to flush the air mass containing the AgI, leaving a background concentration until a new plume would reach the area. Also, the normal technical difficulties with instrumented aircraft had a limiting effect. Although thirty tracing missions were flown in twenty-eight days, only five of these sampled days had cumulus buildups over the area; only one had a plume traced directly into a developing inflow, presented as a case study below. Concurrently, with this major thrust, several other investigations were carried out, examples of which are also described.

4.1 Transport Into Inflow Areas

August 8, 1975, is presented as a case study. A series of squall lines passed the Calgary area producing showers, thunderstorms, and some pea-size hail during the afternoon. A 500 mb long wave trough crossed northern Alberta at 06 MDT (Fig. 2) and cooler air was advected into Alberta during the afternoon. The usual inversion was not present on the morning Calgary sounding; however, the air mass was fairly stable from the surface to slightly above 1800m AGL. The air mass became considerably less stable with time, as shown by the 18 MDT Calgary sounding (Fig. 3).

Originally most of the activity was expected to remain to the north of the study area and the day was given a "test not likely" forecast. However, the Cb potential did increase over the study area, and a single generator was started at 1615 MDT to the northwest of the target area. At 1700 MDT, two more generators were started at the same site (Fig. 4). The Cherokee 6 aircraft took off at 1632 MDT and arrived over the Study Area at 1650 from the west, the upwind direction. The background ice nuclei concentration was the usual 0 to 1 nuclei per liter.

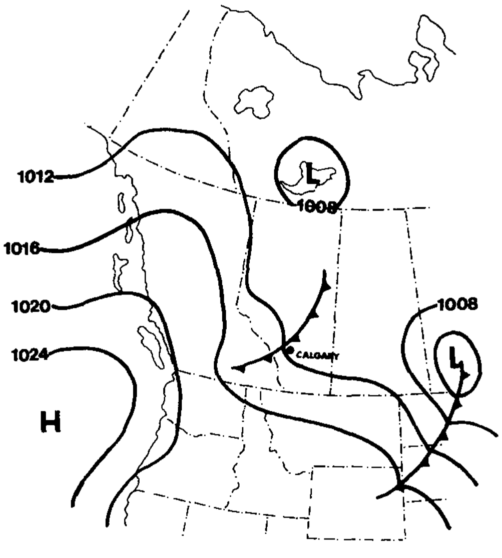

Fig. 2. Surface Synoptic Situation, 0600 MDT, 8 August 1975.

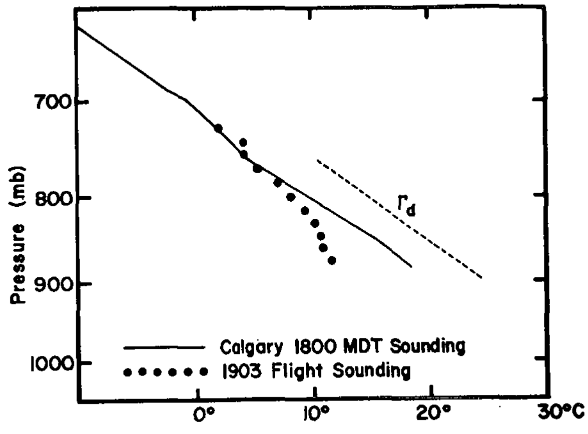

Fig. 3. Afternoon soundings of 8 August 1975.

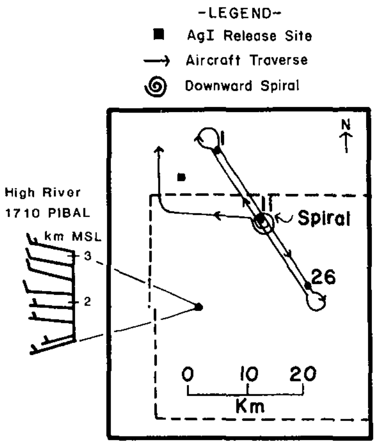

Fig. 4. Flight Path for Mission of 8 August 1975.

The traverses began at 1655 MDT, with only scattered cumuli over the study area, but cumulonimbus activity was observed to the north, moving toward the study area. At 1735 MDT, the flight technician logged a line of cells extending from west-northwest to east-southeast, forming and intensifying over the northern half of the study area. The buildups continued to intensify, and updrafts, as well as showers and small hail, were noted. During sampling the cloud bases lowered to 1800m AGL. Well defined updrafts were detected as low as 1000m AGL.

Shifting winds made locating the plume difficult. Several exploratory passes at approximately 200m AGL indicated that the plume had stabilized to an east-to-northeastward direction. A stacked series of passes was made perpendicular to this observed plume to a level of 3050m MSL. A Cb formed to the east of this path, and moving under this formation was considered but it was decided to complete the series of passes. Shortly thereafter, a line of cumulonimbus cells began to form directly overhead, giving the unique opportunity of sampling developing inflow areas.

Figure 5 is a height-versus-time plot of this series of passes depicting counts lagged by one minute, while Fig. 6 plots the positions of peak concentrations of the same series in which the plume was consistently detected. The first inflow penetration was at flight level 2750m MSL (approx.

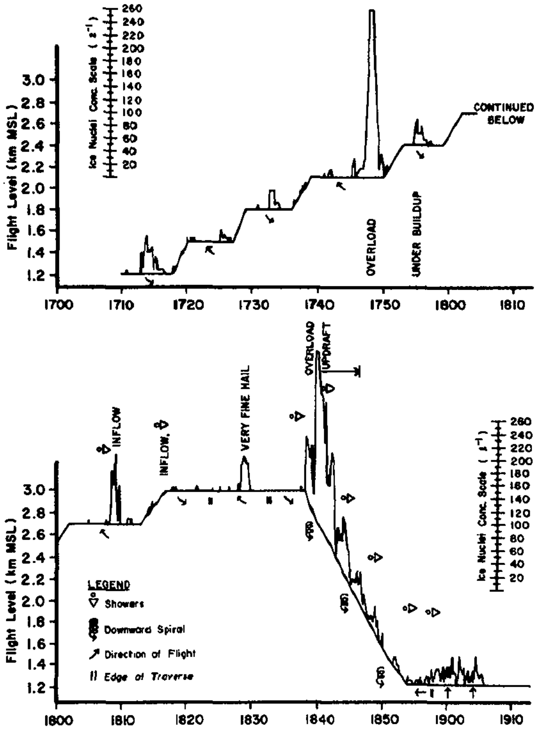

Fig. 5. Aircraft Altitude Versus Time for Stacked Series Taken on 8 August 1975. (Counts, scaled above altitude plots, have been lagged by one minute.)

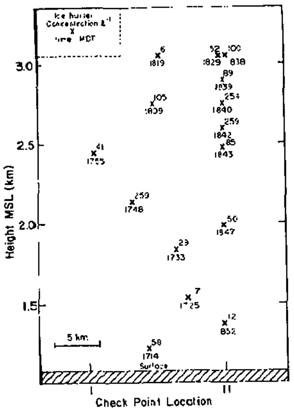

Fig. 6. Peak Concentrations of Ice Nuclei as a Function of Location From Data of Fig. 5. (Peak counts and time located above and below position respectively. See Fig. 4. for check point locations.)

1750m AGL) and up to 105 nuclei per liter measured within this area. The first inflow area sampled at 2050m AGL brought concentrations barely above background; however, on the return pass, a new inflow area showed concentrations significantly above background: 52 and 100 nuclei per liter. The next pass at the same altitude was terminated prematurely due to deteriorating weather conditions, and a spiral descent in an updraft, estimated by the pilot to be as strong as 2-to-3 mps. At this time the (lagged) counts reached 259 nuclei per liter, just after rice-size hail was observed. Significant counts were observed throughout the remainder of the descent, although they tapered off below 700m AGL.

The results of this flight show that, for this particular case at least, the developing Cb provided adequate transport of ground-released seeding material to the cloud base at 2750 to 3050m MSL (approx. 1750 to 2050m AGL). On other days when Cb were present, this transport was enough to rapidly deplete the seeding material in the vicinity. At such times the counts were barely above background in areas that had significant counts prior to the system's passage.

4.2 A Case Study of a Silver Iodide Plume Ascension Rate

On August 3, 1975, a mission was initiated to sample the ascension speed of a ground-released plume. A cold front had passed through the study area, and by late afternoon the air mass was moderately stable below 150m AGL.

When the Cherokee 6 took off from Calgary at 1411 MDT, the sky was clear over the study area, light turbulence was formed up to the maximum measured height of 3050m MSL (approx. 2050m AGL). Four Model 15 generators were started when the aircraft flew past the ground-release site near the center of the study area at 1510 MDT. After the flyby, the aircraft began making a series of traverses at 150-200m AGL in an east-southeast to west-northwest path two miles south-southwest of the generator site at its nearest point.

The first three passes at this level detected nothing above the background of 0-to-1 nuclei per liter. On the fourth pass, a sparse broad plume with a maximum of 17 nuclei per liter was encountered at 1518 MDT (lagged to account for instrument response) at a flight level of approximately 110m AGL. A concise plume peaking at 52 nuclei per liter was found at 1521 MDT. The traverses then increased in altitude, and the aircraft encountered a plume for each traverse through 1150m AGL at 1618 MDT, where a peak count of 41 nuclei per liter was recorded. At 1450m AGL a sparse broad plume was encountered having a peak count of 17 nuclei per liter several minutes later.

No valid ascension rate can be estimated from these data, but it was faster than the ascension rate of the aircraft while sampling. The AgI impregnated coke-burning generators take several minutes to start and need ten minutes of operation to reach normal output. Moreover, the winds were light and variable. Smoke plumes from local industry were seen to rise almost vertically despite a slight drift from the northeast in the lower levels. At approximately 600m AGL, a shear line was found, above which the wind flow was westerly. The silver iodide plume may have drifted southwestwardly, until, upon reaching the shear level, the upper portions doubled back to be transported to the east, explaining the broader plume found at 1450m AGL.

4.3 Plume Characteristics During Inversion Conditions

Several morning missions were conducted to investigate the possibility of seeding air masses prior to dissipation of the morning inversion. In the target area these conditions had light and variable winds, and the silver iodide remained in relatively undispersed pockets which were still broad enough to find easily by aircraft sampling.

August 6, 1975, illustrates such a day. In addition to the usual early morning surface-based inversion, the morning sounding showed a stable layer between 2700 and 3200m MSL (approx. 1700 and 2200m AGL). By late afternoon, the lapse rate had become almost dry adiabatic to 3400m AGL. The first generators were started at 0715 MDT in the northwest portion of the study area. At five sites the Cherokee 6 took off at 0930 MDT and began a north-northwest to south-southeast series (Fig. 7).

In the plume cross-section derived from this series of passes (Fig. 7), the counts have been lagged by one minute and adjusted to remove the smoothing induced by the NCAR counter. Only two plumes were penetrated, but the counts were very high. The winds were not constant in direction with height, and vertical diffusion may have merged the five plumes so as to make only two distinguishable plumes. The top of the mixing layer sloped downward to the south, as verified by

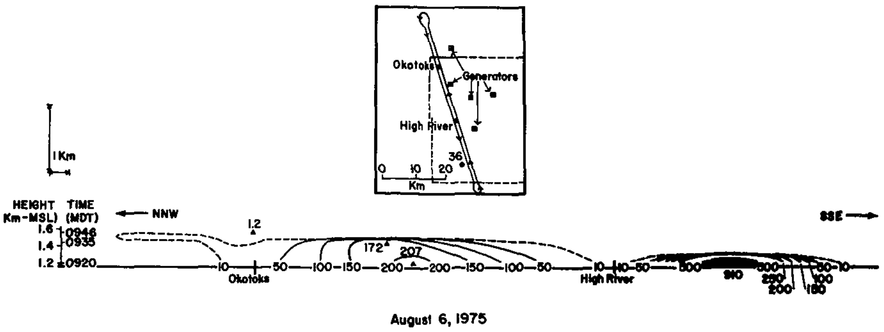

Fig. 7. Plume Cross Section and Flight Pattern for Morning Inversion Mission of 6 August 1975.

observations of haze tops. Ice nucleus concentrations were slight at 1800m MSL. This was to be expected, since the inversion base was below 1675m MSL at 1000 MDT. As the surface temperature increased, the base continued to rise. By about 1100 MDT a series of west-to-east traverses were made in the northern part of the test area. By about 1115 - 1120, a peak count of 259 nuclei per liter was encountered at approximately 675m AGL. Concentrations dropped to slightly above background at approximately 1000m AGL. The remainder of this test found rapid mixing; the peak concentration was approximately 25 nuclei per liter at 1000m AGL.

5. SUMMARY OF OTHER TRACING MISSIONS UNDER UNSTABLE CONDITIONS

Sixteen out of thirty tracing missions were flown over unstable conditions defined as $\gamma \geq \Gamma_d$. Stabilities were defined by the 1800 MDT sounding released at Calgary specifically for the Alberta hail project, and by aircraft temperature profiles. Table 1 summarizes the missions carried out in the vicinity of cumulonimbus clouds and Table 2 lists the remainder of the unstable cases.

The peak counts for each respective mission usually were found at the lowest level flown, on the order of 100 to 200m AGL, as would be expected from diffusion theory. Plumes were routinely traced to the top of the mixing layer except under light and variable wind conditions which hampered the prediction of plume positions.

6. DISCUSSION AND CONCLUSIONS

The case study of 8 August 1975 shows that silver iodide released from ground-based generators can ascend into inflow regions of cumulonimbus clouds. Not only were high ice nucleus concentrations observed beneath a cumulonimbus on this day, but AgI was found to have been lifted without the presence of clouds in the experiments. The ascension was found to be reasonably rapid once the morning inversion was dissipated. However, the 8 August case study was fortuitous, in that the aircraft was properly positioned in time and space to observe a plume being ingested into a developing Cb. Sampling in this as well as in the vicinity of other cumulonimbus activity suggested that the organized mesoscale convective motion rapidly depleted ice nuclei concentrations in the seeded volume. What this means in terms of in-cloud effective ice nucleus concentrations cannot be determined by this study.

The horizontal dispersion rates of the plumes were less than anticipated, possibly a relic of averaging time. In commonly used Gaussian diffusion models, an averaging time must be specified to judge the model results. This gives a quantitative assessment of the meandering of a narrow-dense plume. For example, the well known workbook by Turner (1969) lists diffusion coefficients for 10 minute averages. Aircraft sampling provides a nearly instantaneous viewpoint of plumes, which does not necessarily negate the use of ground-based generators. For example, if a seeding strategy requires a broader plume, the generator(s) could be placed further upwind and/or a generator array spaced further apart.

Ice nuclei were found to rise rapidly in conditions favorable for convection, even without the presence of clouds. The rising plumes were not well dispersed, which is characteristic of "looping" conditions expected during convective periods. Seeding during stable conditions showed a buildup of ice nuclei beneath the inversion as anticipated. The height of the seeded airmass increased as the mixing layer rose, then there was rapid vertical dispersion when the inversion was broken.

The results of this experiment are encouraging in the sense that ground-released AgI was observed to mix vertically within unstable layers. Predicting the trajectory of a ground-based plume remained difficult. Days having cumulonimbus potential often had light and variable winds over the target area. The use of multiple sources in these conditions made tracing confusing and for this reason only a single point source was used on the 8 August case. Moreover, when large cumulonimbus systems passed the vicinity of a plume, counts significantly above background were not found until steady-state conditions began to be re-established, suggesting a flushing of the treated air mass.

Table 1. Summary of Tracing Mission Flown in Vicinity of Cumulonimbus.

Date	No. of AgI Release Points	Peak Ice Nuclei Counts & Approximate Height		Maximum Observed Plume Count & Height		Remarks
		(min^{-1})	(m AGL)	(min^{-1})	(m AGL)	(Hgts. in m AGL)
31 July 1975	4	350	330	10	1100	Cloud bases at 700 unstable to 800.
2 Aug 1975	4	350	790	350	1400	Cloud bases at 1100-1400.
8 Aug 1975	1	200	1100 & 1700	100*	2000	Cloud bases lowered to 1700 during mission.
15 Aug 1975	13	100	489	15	1400	Conditions stabilized

*Recorder off X100 scale but not corrected until peak count rate passed.

Table 2. Summary of Tracing Missions Flown During Unstable Conditions. (Cases of Table 1 excluded).*

Date	No. of AgI Release Points	Peak Ice Nuclei Counts & Approximate Height (min^{-1})	(m AGL)	Maximum Observed Plume Count & Height (min^{-1})	(m AGL)	Remarks (Hgts. in m AGL)
21 June 1975	5	85	150	3.5	1400	Recorder malfunction.
23 June 1975	7	70	150	4.5	1400	Recorder malfunction.
30 June 1975	4	150+	1100	45	1400	
3 July 1975	3	45	150	4	1400	Very unstable below 1100, cloud chamber temperature questionable.
4 July 1975	10	100	150	2.5	1400	Cloud chamber temperature questionable.
5 July 1975	4	150+	790	7	1100	Slightly unstable. Cloud chamber temperature in question.
18 July 1975	10	150	150	20	1400	
26 July 1975	3	100	150	45	2000	AgI flares used as sources.
1 Aug 1975	6	200	150	15	1400	
3 Aug 1975	1	250	330	10	1700	Slightly stable above 1400.
6 Aug 1975	6	200	1400 & 1700	90	2000	
7 Aug 1975	6	80	150 & 1400	35	2000	

*Unstable implies ambient lapse rate greater than or equal to Γ_d.

7. ACKNOWLEDGEMENTS

G. Langer and A.B. Super are gratefully acknowledged for their conscientious and generous advice. This research was supported through a contract from the Alberta Interim Weather Modification Board. The authors would like to thank the members of this board for their interest in this project. INTERA, one of the contractors for the Alberta Hail Project, provided the instrumented aircraft for this study.

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