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ESTIMATION OF EFFECTIVE AGI ICE NUCLEI BY TWO METHODS COMPARED WITH MEASURED ICE PARTICLE CONCENTRATIONS IN SEEDED OROGRAPHIC CLOUD

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Abstract. The Utah/NOAA Atmospheric Modification Program conducted a field program during early 1991, with additional support from the Bureau of Reclamation. Several aircraft missions were flown over central Utah's Wasatch Plateau to monitor plumes of AgI (silver iodide) and tracer gas, and microphysical changes caused by the AgI seeding. This paper discusses one mission during which high-altitude, ground-based AgI release resulted in obvious enhancements in ice particle concentration. Fast-response observations of co-released tracer gas, presumably collocated with the AgI plumes, were used to define seeded zones and crosswind control zones.

Two methods were used to estimate concentrations of AgI ice nuclei effective at cloud temperatures sampled by the aircraft. One method used tracer gas concentration measurements while the other was based on acoustical ice nucleus counter observations. Both methods were partially based on a cloud simulation laboratory calibration of the AgI generator done over two decades ago. The methods were compared with the ice particle concentrations apparently caused by the AgI seeding. Both approaches were found to provide a reasonable first approximation for the particular AgI aerosol produced and the sampled cloud conditions. However, caution should be exercised in applying the estimation approaches to other cloud conditions and AgI aerosols.

1. INTRODUCTION

A fundamental problem in winter orographic AgI (silver iodide) cloud seeding is determination of appropriate AgI aerosol release rates for given conditions. Several variables enter into the release rate determination. These include transport and dispersion of the aerosol, ice-forming mechanisms and resulting rates of AgI nucleation at SLW (supercooled liquid water) temperatures reached by the AgI, growth and fallout rates of AgI-nucleated ice particles, and others. As a practical matter, almost all ground-based AgI seeding operations and experiments have used a single release rate with a fixed network of generators. It has been assumed (but seldom demonstrated) that vertical transport and dispersion would often carry the AgI to sufficiently cold SLW cloud levels so that significant ice crystal nucleation, growth and fallout (snowfall) would result.

Few direct measurements of AgI-nucleated IPC (ice particle concentration) in winter orographic cloud have been published in the literature. Most estimates of AgI release rates have been based on AgI effectiveness (number of ice crystals produced per mass of AgI) values from cloud simulation laboratory tests. The best known facility for calibration of AgI generator effectiveness has been the Colorado State University CSL (Cloud Simulation Laboratory).

Publications from scientists associated with the CSL facility have cautioned against applying CSL results to cloud conditions beyond those produced in their cloud chambers. However, in the absence of direct measurements within seeded clouds, cloud seeding experimenters and operators have used results from the CSL and similar facilities to estimate seeding rates. This paper is an attempt to compare estimates of effective AgI IN (ice nuclei) concentrations with direct measurements of seeding-caused IPCs within orographic clouds.

Field experiments were conducted at the Plateau (Wasatch Plateau) of central Utah during mid-January to mid-March 1991, as part of the Utah/NOAA (National Oceanic and Atmospheric Administration) Atmospheric Modification Program. The main goal of these experiments was to document the transport and dispersion of ground-released AgI used in the Utah operational cloud seeding program.

The Utah operational program uses mostly valley floor AgI generators with a few generators located near canyon mouths. However, the experiment reported here used high-altitude co-releases of AgI and SF_6 (sulfur hexafluoride) tracer gas from a site well up the windward slope of the Plateau. The primary purpose of this experiment was to document changes in IPC caused by the AgI seeding at aircraft sampling levels. However, the measurements also allowed for estimation of effective AgI IN concentrations by two methods. This paper compares these estimation methods with the direct IPC measurements apparently caused by AgI seeding.

The AgI and SF_6 plumes were sampled by a specially instrumented NOAA C-90 KingAir aircraft. It was equipped with a 2D-C particle imaging probe to monitor IPCs calculated by the method of Holroyd (1987). Fast-response gas detector (Benner and Lamb 1985) measurements of SF_6 and NCAR (National Center for Atmospheric Research) acoustical IN counter (Langer 1973) observations of AgI IN were used to estimate IPCs which could result from AgI seeding.

It was hoped that one or both of the estimation methods would be useful in the absence of IPC observations. For example, 2D-C measurements are not always available to evaluate the effectiveness of AgI seeding in creating ice crystals. Even when 2D-C measurements are available, cloud temperatures may be too warm for AgI to nucleate significant ice. In such cases, it may be useful to estimate the expected IPC had the atmosphere been colder. Past studies which have used SF_6 or NCAR IN counter measurements to estimate the IPC expected to result from AgI seeding of winter orographic clouds include, among others, Holroyd et al. (1988), Griffith et al. (1992), and Heimbach and Super (1992).

2. OPERATIONS

The aircraft sampling mission of 17 February 1991 was suitable for estimating concentrations of effective AgI IN from AgI and SF_6 gas plumes, co-released from the HAS (High Altitude Site) at 2500 m (all altitudes are above mean sea level) on the Plateau's windward slope. Figure 1 shows the HAS and 8 valley seeding sites, 5 precipitation gauges and various other instrumentation used in the 1991 field program.

Co-releases of SF_6 and AgI were made from the HAS during some other cloud-sampling missions. During those missions either the plumes rarely ascended to aircraft altitudes or the SLW cloud was too warm for the AgI to noticeably enhance the IPC.

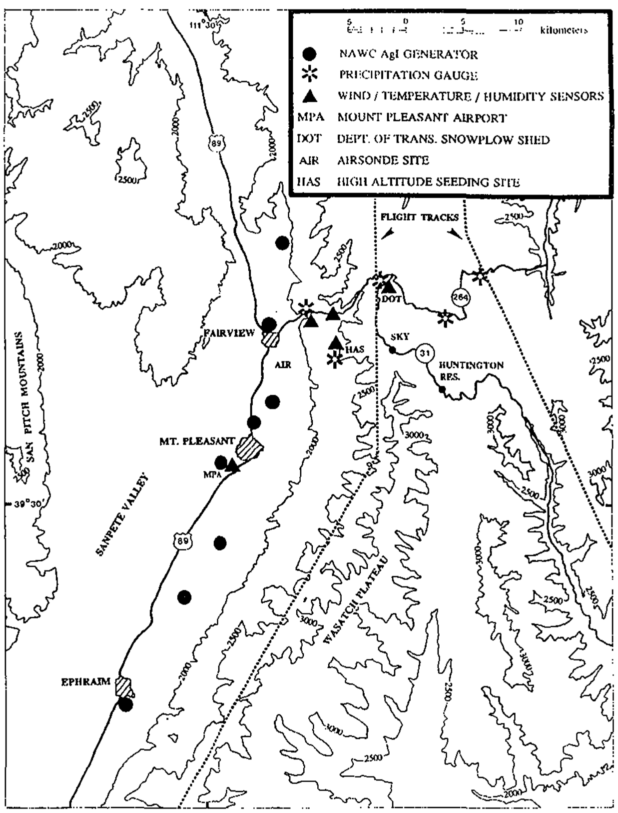

Fig. 1. Map of Wasatch Plateau Experimental Area showing equipment siting for the 1991 field program. Contours are in meters above mean sea level.

The aircraft was flown over two generally north-south (approximately crosswind) tracks above the west (windward) and east (lee) edges of the Plateau's top. These flight tracks are shown on Fig. 1. The Plateau-top elevation increases from north to south. Lowest altitude passes were made by paralleling the terrain elevation, attempting to maintain at least 300 m vertical separation above the highest terrain. These low-level passes were flown under a special waiver from the Federal Aviation Administration since normal minimum vertical separation is 600 m for in-cloud flight. In practice, these low passes were generally about 600 m above the average terrain as measured by a radar altimeter on the aircraft. Higher altitude passes were made at a constant altitude.

All plume penetrations by the aircraft were defined by the maximum extent of the SF_6 plume, ignoring gaps within. Average SF_6 and IN within the plume were used for calculating expected IPC values. On both sides of each plume buffer zones were defined as 12 seconds of flight time (approximately 1 km in length) immediately adjacent to the plume edges. The purpose of the buffer zones was to minimize any contamination by seeded cloud in the event that the AgI and SF_6 plumes were not precisely collocated. Control zones of 24 seconds of flight time were defined immediately beyond the buffer zones. Ice particle concentrations within the SF_6 (and presumably AgI) plume were compared with the natural conditions in the control zones, assuming cloud homogeneity along the flight passes.

Ice particle concentration averages over several plume passages were weighted in a special way. The total count of particles over all plumes was divided by the sum of the sample volumes actually observed. The 2D-C was operated in a limited mode, whereby a maximum of a few buffers of data were recorded each second. Under high concentration conditions this results in a reduction in the volume of air from which particle images were recorded in each second. A simple average of IPC values from each pass can therefore be biased with a high concentration value from a potentially unrepresentative sample. The weighted average errs in the opposite direction, letting a low concentration from a large sample volume dominate the average. Using the weighted IPC average is the more conservative way of assessing possible changes resulting from cloud seeding.

3. AGI GENERATOR OUTPUT

An MSU (Montana State University) generator of the type developed for the Bridger Range Experiment (Super and Heimbach, 1983) was used at the HAS during this experiment. It released 30 g h^{-1} AgI using a 3 percent solution of AgI complexed with NH_4I in acetone. The MSU generator was calibrated at the CSL in 1972 at a liquid water content of 1.5 g m^{-3}. This is admittedly an old calibration and the CSL has been improved over time. A more recent calibration, which might improve the estimation methods to be discussed, is not available at this time.

The MSU AgI generator calibration was done at "natural tunnel draft," equivalent to a wind speed of 2 to 3 m s^{-1} past the burner head (Paul DeMott, personal communication), and under "maximum fan" conditions. Only the former was used in the calculations to be presented because winds at the generator site did not exceed 3 m s^{-1} during the aircraft mission in question. Table 1 lists natural tunnel draft effectiveness value vs cloud temperature from the CSL calibration.

Table 1. - CSL calibration of MSU ground-based AgI generator under natural draft (light wind) conditions.

Temperature (°C)	Ice crystals per gram of AgI
-6	7×10^{10}
-8	2×10^{12}
-10	6×10^{13}
-12	3×10^{14}
-16	6×10^{14}
-20	7×10^{14}

One potentially serious uncertainty in the calculation procedures to be discussed is the representativeness of CSL AgI generator calibrations for winter orographic clouds. Laboratory clouds generally have markedly higher droplet concentrations and liquid water contents, much less turbulence and are much more homogeneous than orographic clouds. Silver iodide nucleation is monitored for an extended period after AgI injection in the CSL. Silver iodide in orographic clouds often has less time to nucleate ice crystals before being transported beyond the SLW zone. Contact nucleation might be expected with the AgI solution used in these experiments, a slow process in laboratory tests (DeMott et al. 1983).

Silver iodide may result in a forced condensation-freezing mechanism immediately after generation within a SLW cloud or ice-saturated atmosphere (Finnegan and Pitter 1988, Chai et al. 1993). During the experiment to be discussed, conditions at the AgI generator sites ranged from in-cloud to about 300 m below cloud base, always at or greater than ice saturation humidities. Therefore forced condensation-freezing was possible, perhaps most of the time. This might have resulted in higher than expected (from the CSL tests) IPCs at the temperature prevailing at the generator altitude. However, that temperature was near -5 °C on 17 February, too warm for significant nucleation by AgI. Moreover, the aircraft sampling temperature was several degrees Celsius colder where AgI nucleation is much more effective. For these reasons, this possible mechanism was unlikely to affect the results to be discussed.

4. NCAR IN COUNTER CHARACTERISTICS

Three similar NCAR IN counters were used in the 1991 Utah field program for detecting the presence of AgI nuclei. One was fixed at the DOT mountain laboratory (see Fig. 1), a second was in a mobile truck, and the third was on the aircraft. All were operated at a cloud chamber temperature near -20 °C. Actual IN counts are multiplied by ten to account for known ice crystal losses (Langer 1973) to the NCAR IN counter's glycol-covered walls and bottom cone of the cloud chamber.

The NCAR IN counter is a semiquantitative instrument based on dated technology. It would be highly desirable to use more quantitative IN counters based on modern technology (e.g., Rogers 1993), but such equipment was not available for the 1991 field program.

Several field comparisons were made between a fixed ground-based NCAR IN counter and a truck-mounted IN counter frequently parked nearby. These comparisons consistently resulted in agreement within a factor of two and usually significantly better. A single field comparison was made between the aircraft unit and the truck-mounted counter parked nearby while both counters were in the plume of an AgI generator operated a few kilometers upwind. The aircraft unit's IN concentrations were consistently a factor of three less than those measured by the truck's IN counter.

Reasons for the discrepancies among the NCAR IN counters are not known but are likely partially caused by differences in outputs of humidifier moisture and atomizer cloud condensation nuclei. NCAR IN counter clouds deliberately have much higher droplet concentrations than orographic clouds to help compensate for the limited time IN are exposed to cloud (1 to 3 min) before being drawn out of the chamber. However, there is no precise control on cloud characteristics which may cause differences between counters. The three units used in the Utah program were overhauled by the system's inventor (G. Langer) just before the field season and were operated by experienced personnel. Nevertheless, the aircraft unit apparently had a lesser response to AgI than the other two IN counters.

In view of the differences between NCAR IN counter clouds and orographic clouds, it is reasonable to question the representativeness of the counter's measurements of IN. Measurements of natural IN at -20 °C were consistently below 1 IN L^{-1} in Utah, which suggests the NCAR IN counter may respond poorly to such nuclei. Good agreement was reported between measurements by an NCAR IN counter and a single observation at the CSL (at -18 °C) for the AgI-NH_4I-acetone seeding agent used in these experiments (Langer and Garvey 1980).

Airborne NCAR IN counter observations of the same type of AgI produced by an MSU generator were used to estimate IN fluxes on several occasions as reported by Super et al. (1975). These estimates were in reasonable agreement with expected generator output from the 1972 CSL calibration for the observed range of surface wind speeds. This observational evidence suggests that a properly maintained and operated NCAR IN counter may provide at least a first approximation estimate of IN from the type of AgI used in Utah operational seeding. However, it must be admitted that the degree of agreement is not well known between CSL observations and NCAR IN counter measurements of the AgI aerosol used in the 1991 Utah seeding experiments. A thorough test program comparing the two systems would be beneficial to this and similar investigations.

An example of the IPC estimation procedure using NCAR IN counter data for the fifth aircraft pass of 17 February is as follows. The IN counter detected 21 ice crystals after passing through the SF_6 plume. Assuming the AgI plume width was the same as that of the co-released SF_6 plume (32 s transit time) and knowing the IN counter samples 10 L min^{-1} outside air, the NCAR IN counter sample volume is just over 5 L. Using the usual factor of ten correction for known ice crystal losses, 40 IN L^{-1} results as the IN concentration effective at -20 °C, the temperature of the instrument's cloud chamber. The CSL AgI generator calibration curve indicates the effective IN concentration at -14 °C is 61 percent of that at -20 °C. Use of that factor results in an estimate of 24 IN L^{-1} (listed in Table 2 for pass 5) effective at the cloud temperature outside the aircraft.

5. CALCULATIONS FROM SF_6

The SF_6 gas detector was calibrated during each mission by injecting a series of calibration gases of known SF_6 concentration into the detector to establish the system's output voltage vs PPTV (parts per trillion by volume). The mean SF_6 concentration was calculated for each aircraft passage (pass) through the tracer gas plume. The calculation was based on second-by-second observations in PPTV from first to last detection of the SF_6 even if "gaps" existed within the plume where the concentration was less than detectable levels (about 10 PPTV).

The mean SF_6 concentration for each pass and the ideal gas law were used to calculate the gas density at ambient temperature and pressure outside the aircraft. The SF_6 density was multiplied by the ratio of the SF_6 and AgI source strengths to estimate the mean AgI density at the location where the aircraft intercepted the gas plume. Finally, calibrations of AgI generator effectiveness and observed cloud temperature at the aircraft altitude were used to convert AgI density into effective AgI IN L^{-1}.

The following is an example of the IPC estimation procedure using SF_6 gas, again for the fifth aircraft pass of 17 February. The aircraft gas detector observed SF_6 gas for 32 s with a mean value of 57 PPTV. For the ambient temperature of -14.0 °C, pressure of 651 mb, and SF_6 molecular weight of 146.05 g mol^{-1}, the ideal gas law yields an SF_6 density of 2.5 X 10^{-10} g L^{-1}. The gas release rate was 23.4 kg h^{-1}, while that of AgI was 30 g h^{-1}. The ratio of the release rates multiplied by the gas density yields an estimated AgI density of 32 X 10^{-14} g L^{-1}. This value was multiplied by the generator effectiveness value for -14.0 °C (4.3 X 10^{14} ice crystals g^{-1} of AgI), estimated by fitting a curve to all natural tunnel draft data points. An estimate of 138 IN L^{-1} resulted from these calculations, listed in Table 2 along with similar calculations for all other aircraft passes.

6. 17 FEBRUARY 1991 EXPERIMENT

The synoptic setting for this storm is discussed by Huggins et al. (1992). Briefly, cold, moist air was advecting into Utah from the northwest on the back side of a trough. A series of minor short waves passed over the experimental area, one of which may have passed near the end of the mission to be described. Weak convective activity occurred in the post-trough environment. Rawinsondes released from the Mount Pleasant Airport (Fig. 1) between 0900 to 1800 (all times LST) showed convectively unstable layers from about 2000 to 4000 m.

A total of 12 passes was made with the instrumented aircraft over the Plateau between 1135-1405. Within plume temperatures ranged between -13.0 and -15.5 °C. The AgI and SF_6 plumes were released from the HAS beginning at 1100 and continuing until the aircraft departed. The seeding site was in cloud at about -5 °C for part of the experiment but cloud base was about 250 m above the HAS most of the time. Precipitation rates during the experiment were very light, ranging from 0.25 mm h^{-1} (limit of gauge resolution) to undetectable at the 3 Plateau-top gauges shown on Fig. 1.

The 8 valley generators shown on Fig. 1 were also operated during this experiment. They had been run continuously since morning of the previous day. A region of AgI IN was detected with the NCAR IN counter on 5 aircraft passes over the west track, approximately east of the town of Ephraim, believed caused by the valley seeding. No other evidence of valley seeding was found at aircraft levels during this mission. The "Ephraim plume" was far enough south of the HAS plumes so that its IN counter response could be identified and removed from the measurements to be presented.

The HAS plumes did not reach the west flight track until the third aircraft pass, about 70 min after start of release. The plume was first intersected 5.7 km horizontally from the HAS, indicating the average transport speed was only 1.4 m s^{-1}. Average HAS winds were less than 1 m s^{-1} during the first portion of the experiment, while aircraft level winds were about 15 m s^{-1} from 290 degrees.

Passes 5-8 were made over the east flight track, followed by 4 more over the west track, after which the aircraft returned to base. All but the first 2 passes detected both AgI and SF_6 downwind of the HAS as shown in Table 2. All passes were at the lowest possible altitude, maintaining 300 m vertical separation from the highest terrain.

The altitude of encounters with the SF_6 plume ranged from 3.31 to 3.66 km, depending upon where the plume was intercepted along the flight tracks. There was no correlation between altitude and SF_6 concentration or NCAR IN counter counts per pass so the exact altitude of the plume top is unknown. Ka-band radar tops above the Plateau ranged from about 3.7 to 4.7 km during the aircraft mission, and occasional visual checks of cloud top with the aircraft were near 3.6 km.

Supercooled liquid water was detected on all aircraft passes. Regions with SLW were interspersed among regions without liquid cloud. Mean amounts per pass were typically near 0.05 g m^{-3} along both the west and east flight tracks as measured by a King liquid water probe. Maximum amounts were about 0.5 g m^{-3} on west track passes and 0.3 g m^{-3} on east track passes.

Mean IPCs were calculated for the time periods that the aircraft was within the SF_6 plume, from first to last detection of the gas, and also for the periods within the buffer and control zones. The mean of the north and south control zones is presented in Table 2 for each pass with SF_6 detected. These mean values, ranging from 7-18 ice particles L^{-1}, represent the natural IPC at aircraft sampling altitudes. The difference between the mean control IPC and the IPC within the SF_6 plumes is assumed to represent the concentration of ice particles caused by AgI seeding.

Plume widths, relative to the release site, ranged from 6 to 24° (0.6 to 2.4 km; median 2.0 km) for the west track passes, and from 10 to 17° (2.6 to 4.6 km; median 3.0 km) for the east track passes. The plume's direction of transport from the HAS to the 6 west track passes ranged between 250 to 281° with a median of 273°. The transport direction for the 4 east track passes ranged from 273 to 279°.

The low average SF_6 concentrations and low total IN counts on two of the higher plume intersections both suggest that the plume tops were near 3.6 km over the east track. This region, near the Plateau's lee side, was likely in descending air. Plume tops may have been somewhat higher over the west track. Aircraft sampling near the AgI plume top would minimize the effect of seeding-caused ice particles settling from above. Some ice particles sampled by the aircraft probably were nucleated by AgI at higher altitudes, where the seeding agent could be more effective because of lower temperatures. This would result in higher IPCs than estimated from the NCAR IN counter measurements adjusted to sampling altitude temperatures.

Data points for pass 9 have been excluded from the figures to follow as obvious outliers. The SF_6 detector and NCAR IN counter measurements were examined in their most basic available form. The second-by-second SF_6 data (PPTV) were summed for each pass as were the NCAR IN counter counts. The former was divided by the latter and, with the exception of pass 9 which had a ratio of 5, all other ratios ranged between 29 and 137 with a median of 60. The SF_6 plume was only 10 s wide, the second narrowest of Table 2, while the total IN counts were well above those of any other pass. In reference to this pass the aircraft scientist's notes state that, "Looks like the SF_6 had two parts, each one about ten seconds long." Only a single 10 s plume existed in the processed SF_6 data supplied by the contractor responsible for the gas detector, and over 4 min of SF_6 data were missing from this pass. While the reasons are not totally understood, the pass 9 observations are clearly outliers.

7. AGI IN ESTIMATES AND COMPARISONS WITH OBSERVED IPCs

The AgI concentrations for 17 February estimated from the SF_6 and NCAR IN counter observations are plotted on Fig. 2 with pass numbers plotted over the data points. A linear least squares regression line is fitted to the 9 points. The Pearson product-moment correlation coefficient for these data is 0.70, significant at the 5 percent level.

It is perhaps fortuitous that the two types of AgI IN estimates agree as well as they do. Both are based on the same plume widths, determined with the SF_6 detector, and the same CSL AgI generator calibration. Beyond that, the two detection methods are quite different with one based on a quantitative gas detector and the other on the semiquantitative NCAR IN counter which responds to ice crystals formed in a refrigerated cloud chamber maintained near -20°C.

Ratios (SF_6/IN) of the Fig. 2 data points vary from 0.11 to 0.60 with a median ratio of 0.24. This median suggests that overall the AgI IN estimates from the particular NCAR IN counter are low by about a factor of four. Previous discussion indicated the other two NCAR counters used on the project likely would have produced higher counts.

Table 2. - Estimates of effective AgI IN based on SF_6 and NCAR IN counter observations and IPCs measured during the aircraft mission of 17 February 1991.

Pass No.	Flt Trak	In SF_6 (s)	Avg. SF_6 (s)	Altitude (km MSL)	IN counts	Est. IN (L^{-1}) SF_6	Est. IN (L^{-1}) NCAR C.	IPC (L^{-1}) Target	IPC (L^{-1}) Control	Diff
3	W	9	112	3.38	13	38	46	56	10	46
4	W	21	91	3.42	14	208	22	102	18	84
5	E	32	57	3.52	21	138	24	28	14	14
6	E	49	4	3.53	7	10	6	26	7	19
7	E	56	20	3.54	19	50	13	20	11	9
8	E	52	8	3.53	7	21	5	32	8	24
9	W	10	26	3.38	48	57	155	124	14	119
10	W	31	35	3.31	32	73	32	61	8	53
11	W	25	51	3.66	27	154	50	112	8	104
12	W	30	42	3.40	33	96	38	47	9	39

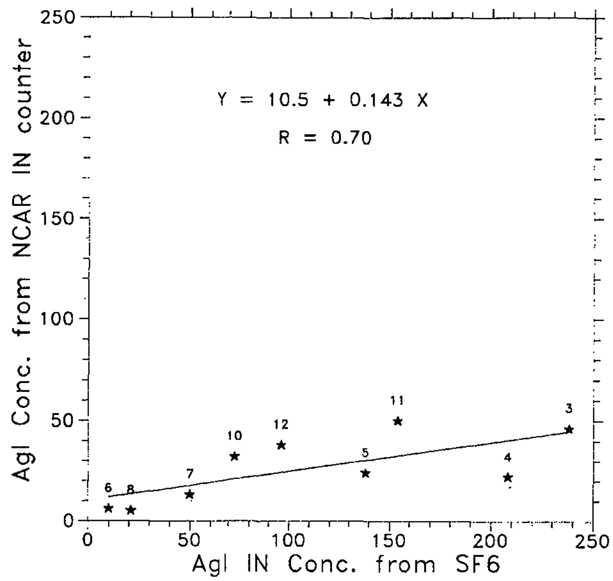

Fig. 2. Concentrations of AgI ice nuclei estimated from SF_6 measurements vs estimates based on NCAR IN measurements for indicated pass numbers on 17 February 1991.

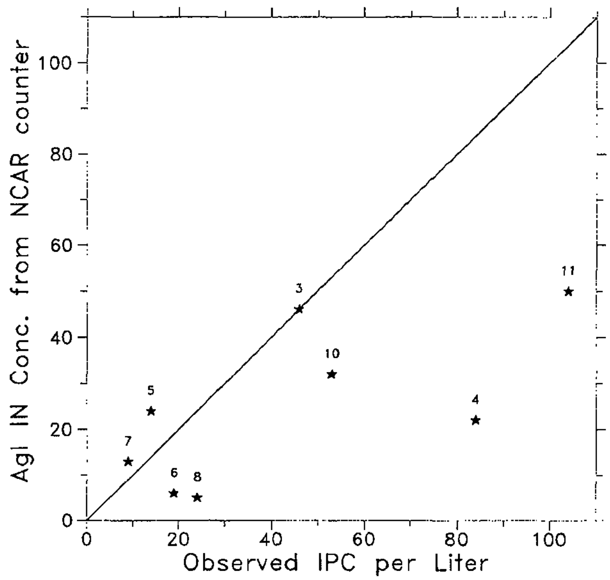

Fig. 4. Concentrations of AgI ice nuclei estimated from NCAR IN counter measurements vs observed ice particle concentrations for indicated pass numbers on 17 February 1991.

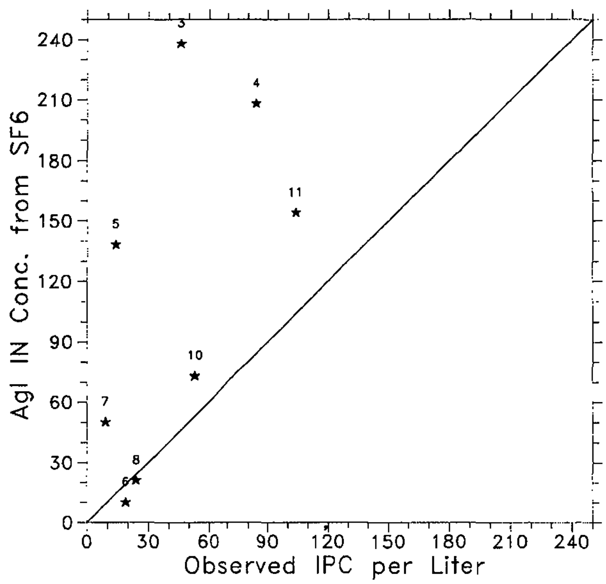

Fig. 3. Concentrations of AgI ice nuclei estimated from SF_6 tracer gas vs observed ice particle concentrations for indicated pass numbers on 17 February 1991.

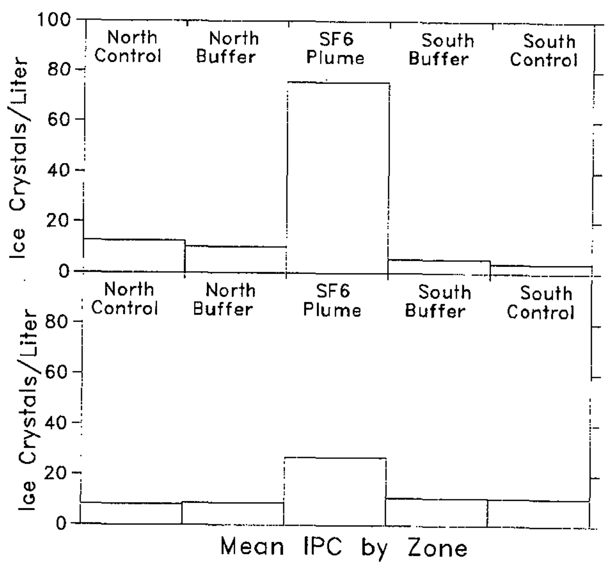

Fig. 5. Ice particle concentration by zone (24 s controls, 12 s buffers, SF_6 plume) for 6 passes over the west flight track (upper panel) and 4 passes over the east track (lower panel) on 17 February 1991.

The estimated AgI IN concentrations from the SF_6 gas detector and NCAR IN counter observations in Table 2 are plotted against the measured IPC (target minus control) in Figs. 3 and 4, respectively.

Figure 3 shows reasonable agreement between the SF_6-based estimates of AgI IN, effective at the sampling temperature, and the observed IPC. The latter tend to be smaller as might be anticipated. While cloud should not constitute a significant sink for SF_6 gas, both scavenging by ice crystals and nucleation can reduce AgI IN concentrations during prolonged passage through cloud. Moreover, not all AgI IN with the potential to nucleate ice at any given temperature necessarily do so (contact nucleation proceeds slowly). These factors should result in fewer ice particles than estimated from the gas measurements as observed in Fig. 3. However, as previously noted, AgI nucleation at colder temperatures above the aircraft can enhance the observed IPC settling past the aircraft's altitude. The data of Fig. 3 suggest this factor was not of major importance during the 17 February experiment.

Figure 4 shows that the estimated IN concentrations from the NCAR IN counter measurements were also in general agreement with observed IPCs. Most observations of IPC were higher than these IN estimates as might be anticipated from Figs. 2 and 3. However, the agreement is better than might be expected when considering the factors mentioned above and various sources of potential error in the estimation method.

The fact that both Figs. 3 and 4 show reasonable agreement suggests that the CSL calibration values may be a good first approximation for AgI nucleation in orographic cloud, at least for the MSU generator at cloud temperatures in the -13 to -20 °C range.

8. MICROPHYSICAL EFFECTS OF AGI SEEDING

Figure 5 shows obvious microphysical effects of the HAS AgI seeding at aircraft levels for 17 February. The bar graph shows weighted average values of IPC within the SF_6 plumes and in the crosswind buffer and control zones. The upper panel shows the averages for the 6 west track passes and the lower panel shows the 4 east track passes.

The IPC enhancement due to AgI seeding is several-fold over the west track's natural IPC, amounting to about 67 L^{-1}. The east track increase is about three-fold, near 17 L^{-1}. It is postulated that the reduction in seeded IPC values over the east track is partially due to the growth and fallout of seeded ice particles below aircraft sampling altitudes.

9. SUMMARY AND CONCLUSIONS

A specially-instrumented aircraft was used to monitor AgI and SF_6 plumes co-released from a high-altitude site on the Wasatch Plateau of central Utah during early 1991. An NCAR IN counter measured AgI while a fast-response detector measured the SF_6 tracer gas. A 2D-C particle imaging probe monitored the IPC within and crosswind of the AgI/SF_6 plumes. Other sensors observed cloud temperature, liquid water content, aircraft position and other variables.

Obvious increases in IPC were associated with the SF_6 plume on the 17 February aircraft mission. Observations from this mission were used to estimate concentrations of AgI IN effective at the sampling temperatures. These estimates were compared with measurements of the IPC enhancement within the SF_6 (and presumably collocated AgI) plume. The IPC enhancement was considered to be the difference between in-plume IPCs and the natural IPCs in crosswind control zones.

Two methods were used to estimate effective AgI IN concentrations. One method was based on SF_6 gas concentration measurements and the other on NCAR IN observations. Both methods relied on cloud simulation laboratory calibrations to establish the source strength and temperature dependence of generated AgI IN. The representativeness of these calibrations for winter orographic clouds is open to question. Nevertheless, in the absence of IPC measurements, cloud simulation AgI generator calibrations have been used in designing several seeding experiments and operational programs.

The ratios of AgI IN estimates by the two methods indicated that the more quantitative SF_6 observations provided on average, about 4-5 times higher values than the NCAR IN counter measurements. The differences in AgI IN estimates may be partially due to AgI losses by nucleation and scavenging and partially to instrumentation limitations. Cloud characteristics and residence times are quite different between winter orographic clouds and NCAR IN counter (and CSL) cloud chambers. The NCAR IN counter uses a dense cloud in an attempt to compensate for the short residence time of IN.

The SF_6 gas measurement method provided first-approximation estimates of measured IPCs with all but one of the estimates within a factor of six. Most estimates were higher than observed IPCs. First-approximation estimates were also provided by the NCAR IN counter method, although values were lower than provided by the SF_6-based method.

The single experiment reported suggests that seeding-caused IPCs can be estimated by tracer gas or NCAR IN counter observations to within about one order of magnitude for the particular AgI generator and aerosol used, and the sampled cloud conditions. While this result is encouraging, further observations would be needed to test whether similar results can be obtained with other AgI generators, AgI solutions and cloud conditions. In view of differences between orographic and simulated clouds, and of known instrumentation limitations, the apparent good agreement from the single experiment may be somewhat fortuitous.

Because of the uncertainties involved in AgI IN estimation, and in ice nucleation processes, it is clearly preferred to directly measure seeding-caused IPCs within winter orographic clouds. More direct IPC measurements must be made if the field of winter orographic cloud seeding is to advance in scientific understanding and credibility. However, such observations are difficult and expensive to obtain, and may be impractical for many programs. Further testing of indirect methods may provide an alternative approach to direct observation of IPCs. It is recommended that any further tests of indirect methods use a current AgI generator calibration from the CSL or similar facility. Use of an improved IN counter, based on current technology, would also be very desirable.

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