CASE STUDIES OF MICROPHYSICAL RESPONSES TO VALLEY-RELEASED OPERATIONAL AgI SEEDING OF THE WASATCH PLATEAU, UTAH

Arlin B. Super

Bureau of Reclamation
Denver, CO 80225

ABSTRACT

An experimental field program was conducted on the Wasatch Plateau of central Utah in early 1991. Objectives included monitoring of the transport and dispersion of valley-released silver iodide and associated microphysical effects within the seeded clouds. Silver iodide ice nuclei were monitored by acoustical ice nucleus counters in a truck, an aircraft and at a Plateau-top observatory. An aircraft-mounted ice particle imaging probe was used to search for ice particle concentration differences between the seeded cloud and crosswind, nonseeded cloud. Other instruments monitored wind, cloud liquid water content, temperature and other parameters of interest.

Six experiments are described in detail, representing all aircraft sampling periods during which valley-released AgI (silver iodide) was transported to both Plateau-top and aircraft altitudes. Embedded convection was present during five of the experiments which probably enhanced vertical AgI transport. Clouds bases were generally a few hundred meters below the Plateau top with one exception which had bases above the Plateau. The valley-released AgI consistently had a pronounced vertical gradient above the Plateau. Concentrations of AgI ice nuclei, effective at -20°C, were typically at least an order of magnitude less at lowest aircraft altitudes than found on top of the Plateau. Silver iodide was seldom detected as high as 1 km above the Plateau top.

No evidence was found for enhanced ice particle concentrations at aircraft altitudes during the three experiments with sampling zone temperatures of -9°C and above. However, suggestions of increased ice particle concentrations were found when sampling zone temperatures were colder. Silver iodide ice nuclei estimates, effective at prevailing supercooled liquid cloud temperatures, were lower than believed desirable for effective seeding during the three experiments with warmer cloud at aircraft sampling altitudes.

The results presented are believed to indicate that current operational cloud seeding in Utah produces insignificant increases in ice particle concentrations and snowfall rates during warmer storm episodes. The main problem appears to be that concentrations of effective ice nuclei are too low for the typical mildly supercooled liquid water clouds reached by the AgI. Seeding appeared to markedly increase the ice particle concentration in colder supercooled clouds, and precipitation observations suggested associated limited snowfall increases during some cases. A number of recommendations are made for increasing ice particles concentrations in the warmer supercooled liquid clouds.

1. INTRODUCTION

The Utah/NOAA (National Oceanic and Atmospheric Administration) Atmospheric Modification Program conducted a series of experiments over the Plateau (Wasatch Plateau) of central Utah between mid-January and mid-March 1991. The main experimental goals were to monitor the transport and dispersion of ground-released AgI (silver iodide) IN (ice nuclei), and possible associated changes in cloud microphysics. The most obvious cloud microphysical change was expected to be increased IPC (ice particle concentration) when AgI IN created additional ice crystals in SLW (supercooled liquid water) cloud.

The main purpose of this paper is to attempt to document seeding effects, in particular IPC changes, at aircraft sampling altitudes during storm periods seeded by *valley* generators (ground-based AgI generators located in mountain valleys). It is important to document any microphysical changes associated with valley seeding because the Utah operational seeding program relies almost completely on valley AgI releases. In order for the valley seeding to be effective in snowfall enhancement, the seeding must increase IPC within SLW cloud, at least part of the time with orographic (mountain-induced) clouds present.

Experimental periods were selected which had significant valley AgI IN transport into SLW cloud over the Plateau. The AgI was monitored along a 6.7 km north-south portion of the Plateau top's windward edge and at aircraft levels.

Some past physical studies have questioned the effectiveness of valley seeding in Utah. For example, Super and Huggins (1992a) showed a low frequency of above-background silver-in-snow from valley AgI seeding. Limited silver-in-snow was found even above a canyon that had consistent AgI transport from its lower portions to a sampling site well up the canyon. Super and Huggins (1992a) presented calculations that suggested the Utah valley AgI generator network was unlikely to produce snowfall enhancements approaching 10 percent unless either: (a) AgI IN effectiveness in winter orographic clouds was substantially greater than indicated in cloud simulation laboratory generator calibrations or (b) ice multiplication was often effective in Utah winter clouds.

Super and Huggins (1992a) made a number of optimistic assumptions in their calculations including that, on average, 5 X 10^{13} ice nuclei per gram of AgI effective at SLW cloud temperatures would be produced by the NAWC (North American Weather Consultants) manual AgI generators operationally used in Utah. That assumption was based on the most recent Colorado State University Cloud Simulation Laboratory calibration of the NAWC generator then available, done in 1981 (reported April 1982). Their assumption has been reconsidered because a more recent calibration, reported by DeMott et al. (1995), showed greatly enhanced ice formation activity at temperatures warmer than -10°C, apparently due to improvements in the combustion design of the NAWC generator. The latest calibration indicates that 5 X 10^{13} ice nuclei per gram of AgI might be achieved at cloud temperatures colder than -7.5°C. Consequently, the generator effectiveness value used in the calculations by Super and Huggins (1992a) now appears more realistic than optimistic. Nevertheless, review of the several other optimistic assumptions they made suggests there remains a need to be concerned about possible low seeding rates in the Utah operational program.

Super and Huggins (1992b) presented the results of five aircraft missions under near-storm prefrontal conditions during early 1990. Four of the missions showed real or simulated (tracer gas) valley-released AgI was transported parallel to the mountain barrier rather than over it, or the material was trapped by low-level stability. The single mission with plume transport over the barrier suggested low AgI IN concentrations. However, the five missions did not have embedded convection present, as did all but one of the early 1991 missions to be presented.

Sassen and Zhao (1993) discussed the

cloud seeding implications of remote-sensing data obtained in the Tushar Mountains of southern Utah. They concluded that, "there appears to be only a limited 'window' for success involving mainly the upper portions of the relatively warm (greater than -7°C cloud-base temperature) SLW clouds containing significant (>0.15 mm) LW depths. In other words, cloud layers with inferred cloud-top temperatures of colder than about -12°C in this region appear to be efficient users of orographically generated SLW." Therefore, according to Sassen and Zhao (1993), clouds with the top of their SLW layer warmer than -12°C and their base warmer than -7°C appear to be the primary "target" for southern Utah cloud seeding. (Visual cloud tops may be much higher and colder than the inferred SLW cloud tops if the former consist of ice particles.) As will be discussed, it may be difficult to achieve significant IPCs in such warm clouds with AgI seeding as currently practiced in Utah.

Super (1994) summarized AgI IN observations on the Plateau top during 12 days of the early 1991 field program that had valley seeding and observations during at least part of the day. The 6 experiments described herein are from 4 of those 12 days. Figure 4 of Super (1994) suggests that less than half of the 144 h with AgI IN observations and detectable SLW would have exceeded 2 IN L^{-1} on the Plateau top, effective at -10°C. The AgI would have to be transported well above the Plateau top to reach the -10°C level during most winter storms, and, as will be shown, AgI IN concentrations decrease rapidly with altitude above the Plateau top. However, Super (1994) based his estimates on a 1981 calibration of the NAWC AgI generator which indicated AgI IN effectiveness at -10°C was 1 percent of that measured at -20°C (the cloud chamber temperature for the acoustical IN counter used to monitor AgI concentrations). A recent calibration of that generator reported by DeMott (1995) indicates that the -10°C effectiveness is about 33 percent of the -20°C value. Hence, the abscissa values of Fig. 4 of Super (1994) should be multiplied by 33 to correspond with the latest calibration, resulting in a more optimistic assessment of valley seeding potential. However, a major uncertainty in that assessment remains; namely, how representative are Plateau top observations of AgI IN concentrations at higher, colder altitudes where AgI nucleation is more likely. The present study addresses that uncertainty.

2. EXPERIMENTAL APPROACH

Some past investigations have documented physical seeding effects from high altitude, ground-based AgI generators (e.g., Super and Heimbach 1988; Super and Boe 1988; Super and Holroyd 1994) or aircraft seeding (e.g., Deshler et al. 1990; Deshler and Reynolds 1990). A recent paper documents physical responses to a high-altitude ground release of AgI over the Plateau (Holroyd et al. 1995). The most obvious microphysical effect in these studies was a distinct increase in the IPC associated with seeding plumes. Accordingly, the early 1991 Utah experiments were designed to monitor the IPC within seeded orographic clouds and neighboring (crosswind) unseeded clouds. An aircraft-mounted Particle Measuring Systems 2D-C laser imaging probe was used for IPC measurements in the 1991 Utah field program. The software of Holroyd (1987), used in most of the studies referenced in this paragraph, was also used with the Utah data in this investigation. As in the past studies, particles smaller than 100 µm (4 pixels length) were ignored by the processing software.

No surface IPC measurements were made on top the Plateau during the experiments to be discussed. An attempt to monitor IPCs with a truck-mounted 2D-C probe was thwarted by a road accident earlier in the field program. A network of five shielded precipitation gauges, sited in locations protected from the wind, provided snowfall rates with a resolution of 0.25 mm h^{-1}. Some visual observations were made of snowfall rates and ice crystal types and sizes. These surface observations will be referred to where appropriate.

Silver iodide was released from a network of AgI generators of the type discussed by Griffith et al. (1991). Each generator released 8 g AgI IN h^{-1} according to Griffith et al. (1992). The north-south extent of the network, shown on Fig. 1, was 40 km. The number of generators was increased for the 1991 experiments to reduce the probability of nonseeded gaps between plumes over the Plateau. Eight generators were used during the 1991 field program in the portion of the Sanpete Valley shown on Fig. 1 rather than the five generators used before and after that field program. Generator elevations ranged from 1735 to 1835 m with the exception of the northernmost generator which was at 2050 m (all elevations and altitudes are given above mean sea level).

Silver iodide IN was monitored by three NCAR (National Center for Atmospheric Research) acoustical IN counters (hereafter NCAR counter), described by Langer (1973). One NCAR counter was located in the NOAA KingAir C-90 instrumented aircraft, one was located in a 4-wheel drive vehicle (hereafter Suburban), and one was located at the DOT (Department of Transportation snowplow shed) weather observatory located at 2700 m near the head of Fairview Canyon which is

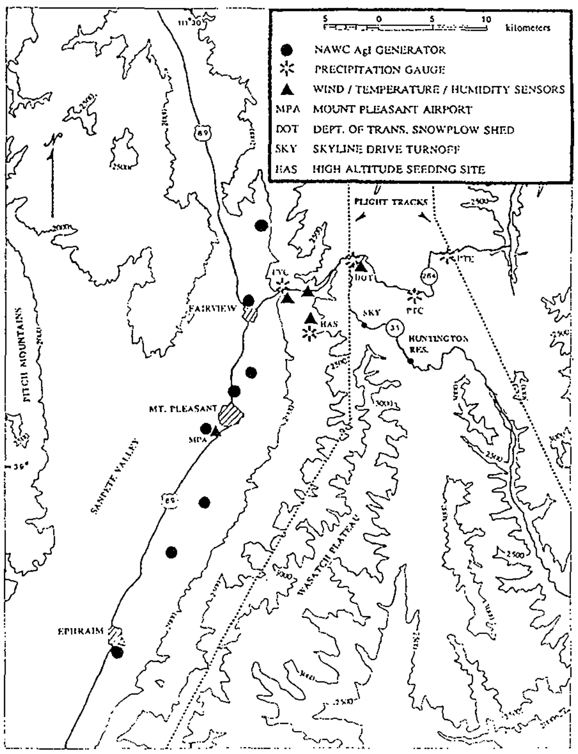

Fig. 1. Map of the Wasatch Plateau Experimental Area. Contours are in meters above mean sea level.

east-northeast of the town of Fairview (Fig. 1). This pronounced canyon was expected to provide a preferred path for transport of valley-released AgI IN to the Plateau top.

Rawinsondes were released and tracked from the MPA (Mt. Pleasant Airport) at 1780 m during experimental periods. Surface winds, temperatures, and relative humidities were monitored by automated weather stations at the airport, at two sites within Fairview Canyon (2025 and 2205 m) and at the 2500 m HAS (High Altitude seeding Site), all shown on Fig. 1. Wind, temperature and dewpoint temperature observations were made at the DOT. A microwave radiometer (Hogg et al. 1983) measured vertically-integrated SLW above the DOT which was rarely warmer than 0°C during storms.

Six aircraft missions (also called experiments) were selected for detailed analysis from 4 days: 28 February, 1 March, 2 March, and 6 March, 1991. These missions provided the most comprehensive 1991 aircraft observations during valley-seeded storm periods which had AgI transported over the Plateau. A few other aircraft missions were conducted during storm periods with valley seeding, but possible problems exist with aircraft data (e.g., suspected ice blockage of sample air intake), or little evidence of valley-released AgI was found at aircraft altitudes (e.g., the experiment of 17 February discussed by Super and Holroyd 1994). Transport to aircraft levels on the dates noted is believed to have been aided by embedded convection with the possible exception of 6 March which, however, experienced an upper level trough passage.

Instrumentation characteristics and analysis procedures are described in detail for 28 February, the first experiment discussed, except for the surface precipitation network. Since no snowfall was measured during the 28 February experiment the surface precipitation network is instead described with the first experiment of 1 March. The same types of measurements and procedures were used with the other experiments.

3. SINGLE EXPERIMENT OF 28 FEBRUARY

3.1 Overview

All eight valley AgI generators were ignited between 0800 and 0900 (all times MST [mountain standard time]) and continued to operate throughout the day. Aircraft sampling over the Plateau was done between 1330 and 1620 in marginal VFR (visual flight rules) and IFR (instrument flight rules) conditions.

Although a mid-morning frontal passage had occurred, conditions during the experiment were more typical of a prefrontal environment because southwesterly flow continued with significant SLW over the Plateau (Huggins et al. 1992).

The MPA rawinsonde launched at 1500 showed a neutral atmosphere below cloud base and convective instability within the cloud layer. The liquid cloud base was above the Plateau near 3500 m. Visible cloud bases were variable in altitude above the Plateau. Weak embedded convection was visible and occasional snow showers reached the ground. Clouds tops, as measured by K_a-band radar and visual observations, were between 4200 and 5500 m during the aircraft mission. Corresponding radar top temperatures, estimated from rawinsonde observations, were between -12 and -21°C.

Surface winds measured about 3 km east of the entrance to Fairview Canyon, at 2205 m elevation, were westerly (up-canyon) during the experiment at between 3 and 4 m s^{-1}. (All references to canyon flow are from this site's measurements.) Winds on top of the Plateau at the DOT were southwesterly between 5 and 9 m s^{-1}. The DOT site is a relatively protected location and its winds were consistently less than occasionally measured at canyon heads along the upwind highway. Aircraft-measured winds were southwesterly between 10 and 18 m s^{-1} in the 3000 to 4000 m layer.

The lower panel of Fig. 2 shows the time history of vertically-integrated SLW observed by microwave radiometer above the DOT site. Figure 2 indicates that SLW was present throughout the experiment with amounts sometimes exceeding 1 mm, a relatively high value for Utah winter storms (Super 1994). The rapid SLW fluctuations over time are characteristic of embedded convection.

The DOT air temperature and dewpoint temperature were nearly constant during this experiment, at 0 and -5°C, respectively.

3.2 NCAR Counter Observations

Each ice crystal nucleated in the NCAR counter's cloud chamber that grows larger than about 20 µm produces an audible "click" when exiting the chamber through a specially-shaped glass sensor.
This sound is electronically monitored, producing a "count." About 10 L of air are drawn through the cloud chamber each minute. The raw counts were multiplied by a factor of ten to correct for known crystal losses to glycol-covered cloud chamber walls and bottom cone (Langer 1973). All NCAR counter IN concentrations will be reported as effective at -20°C, the cloud chamber

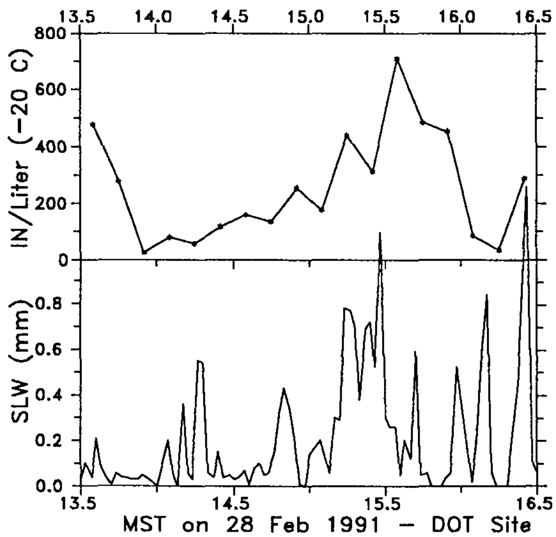

Fig. 2. Temporal distributions of vertically-integrated SLW (microwave radiometer) and AgI IN (NCAR counter) at the Wasatch Plateau DOT site during the aircraft mission of 28 February 1991. Averaging times are 2 min for SLW and 10 min for AgI IN.

temperature, unless otherwise noted, and all IN concentrations will include the times ten correction for crystal losses. A recent series of comparisons between NCAR counters (using the times ten correction) and the Colorado State University isothermal cloud chamber showed reasonable agreement with AgI aerosol (DeMott et al. 1995).

The 1991 field observations showed that IN concentrations as measured by the NCAR counter did not exceed 1 IN L^{-1} in the absence of AgI release, and were usually well below that value. This is in agreement with past and more recent NCAR counter observations in the intermountain West. It is unknown how well such observations represent actual concentrations of natural and anthropogenic IN in the absence of AgI. However, with the low background under 1 IN L^{-1}, the NCAR counter is very sensitive to AgI IN concentrations exceeding even a few per liter.

The upper panel of Fig. 2 shows the presence of AgI IN from the valley generators as measured by the DOT NCAR counter. Ice nuclei concentrations were mostly between 100 and 500 IN L^{-1}. Similar IN concentrations were measured with the Suburban-mounted NCAR counter during this experiment along the portion of Highway 31 which follows the Plateau top's west edge, hereafter called the "upwind highway." Referring to Fig. 1, the upwind highway extends from the junction of Highways 31 and 264, just north of the DOT, to SKY (Skyline Drive turnoff), a north-south distance of 6.7 km. Elevations along the upwind highway increase from 2695 m on its north end to 2985 m on its south end.

3.3 Aircraft Observations

Figure 3 summarizes averaged aircraft observations for the seven terrain-following passes made over the west track (Fig. 1), above the Plateau top's windward edge. All measurements are referenced to horizontal distance north or south of SKY.

The lower panel shows the aircraft altitude and the terrain altitude beneath the aircraft as monitored by the aircraft's radar altimeter. The dashed line is the aircraft-measured air temperature. The eight "G" symbols along the bottom of the figure represent the north-south positions of the AgI generators in the valley west of the Plateau, also shown on Fig. 1.

North and south edges of the valley-released AgI plume, or more likely intermingled plumes (hereafter referred to simply as a plume), were estimated from NCAR counter data for individual passes. These edge positions are noted by "N" and "S" for north and south entry edges, respectively. Only the entry location can be estimated on each pass because of the slow decay of the NCAR counter's response to IN. A 60-s lag was used between the initial response of the NCAR counter, defined as the first second of

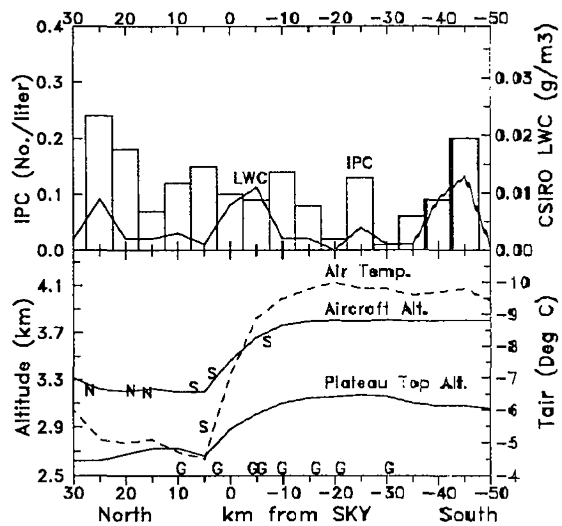

Fig. 3. A north-south oriented vertical cross section referenced to SKY on the Wasatch Plateau top. Data are averaged for 7 terrain-following passes on 28 February 1991. The upper panel shows the distributions of IPC (bar graph) and cloud LWC (solid line). The lower panel shows aircraft altitude (upper solid line), Plateau top altitude (lower solid line), and air temperature (dashed line). North and south AgI plume edges are noted by "N" and "S" for individual passes. The north-south position of each valley AgI generator is noted by a "G" along the bottom of the plot (all 8 generators were west of the cross section).

the first 10-s block with 2 or more counts. Comparisons between co-released tracer gas plumes and AgI plumes on 17 February and 14 March, 1991, showed lag times ranged from 40 to 75 s for the limited AgI IN per pass found at aircraft altitudes. At aircraft sampling speeds, NCAR counter plume edge positions should be accurate to within 1.5 km or better.

Figure 3 shows that the lowest-level aircraft sampling was done in a terrain-following mode rather than at constant altitude. Aircraft sampling was done under a special waiver from the Federal Aviation Administration that permitted in-cloud flight to within 300 m of the *highest* terrain within 8 km of the flight path (standard rules require a 600-m vertical separation). Aircraft navigation used LORAN (long range navigation) with GPS (global positioning system) as a backup. The GPS was not then certified for in-cloud navigation. Flight operations under the special waiver resulted in typical vertical separations of 600 m between the *average* Plateau top and the lowest aircraft sampling tracks. The observations will show that AgI plumes would rarely have been sampled by the aircraft on any mission if flight operations had been done under standard terrain clearance rules, with lowest sampling 300 m higher than actually occurred. Constant altitude sampling would also have resulted in fewer detections of the AgI plume. The results to be presented illustrate the need for careful selection of terrain and aircraft sampling procedures in order to sample ground-released plumes during IFR conditions.

As seen on Fig. 3, AgI plume edges were detected from 7 km south to 27 km north of SKY, although most edges were found between 3 and 20 km north of SKY. Most plume encounters during this mission were below liquid cloud base which was near 3500 m (virga showers sometimes lowered visible bases). The plume location was in the vicinity of the head of Fairview Canyon, suggesting that the canyon provided a preferred transport path over the Plateau. Silver iodide may have been transported over the Plateau farther south, but at lower altitudes than could be safely sampled by aircraft.

3.4 NCAR Counter Estimates of Effective IN

Super and Holroyd (1994) discussed use of NCAR counter measurements in estimating effective IN concentrations. They showed first approximation agreement between such estimates and measured IPCs for the single experiment considered, using a Montana State University AgI generator rather than the NAWC type used for Utah valley seeding. Super and Holroyd's (1994) IN concentrations based on NCAR counter observations were usually lower than the IPCs observed with the 2D-C probe, on average by about a factor of two, but with considerable scatter. Two major factors contribute to the uncertainty of the estimates: (a) uncertainties in how well NCAR counter AgI IN concentrations represent AgI IN effective in orographic cloud, and (b) how well cloud simulation laboratory calibrations of AgI generator effectiveness represent the temperature dependence of AgI nucleation effectiveness in orographic cloud. While Super and Holroyd (1994) used a dated 1972 AgI generator calibration, recent results reported by DeMott (1995) were very consistent with the earlier Montana State University generator tests.

Any secondary production of ice particles would also exacerbate differences between AgI IN estimates and observed IPCs, as would unobserved very recently nucleated ice particles (less than 100 μm size) and errors in aircraft IPC sampling. Gayet et al. (1993) showed IPC measurement differences up to 1.5 depending upon individual 2D-C probes. Different external mounting points on various aircraft resulted in smaller variations.

Although the Super and Holroyd (1994) study suggested NCAR counter observations could be used to estimate effective AgI IN concentrations with some accuracy, it is not known how well similar estimates would simulate reality with the NAWC AgI generators and different cloud conditions. However, such estimates will be made, assuming they are within an order of magnitude or so of seeded IPCs. Even such approximate values can be useful because AgI's ability to nucleate ice crystals varies over several orders of magnitude with changes in SLW cloud temperature. Another reason for estimating AgI IN concentrations from NCAR counter data is that aircraft observations can be compared with surface observations made at the DOT and with the Suburban NCAR counter.

The average AgI IN concentration will now be estimated for several aircraft passes. It is recognized that *instantaneous* AgI IN concentrations vary markedly from average values depending upon how much AgI is being transported up to aircraft altitudes, plume width and meandering and other factors. However, it can be argued that for seeding to be effective in augmenting seasonal snowfall, average conditions are important over long time intervals (hours). A high AgI IN concentration over a brief period may significantly increase the snowfall rate during that period. However, sustained snowfall enhancement will be required over many hours to produce economically important amounts. Consequently, it is believed appropriate to examine average AgI IN concentrations from several aircraft passes.

Total NCAR counts per pass for the seven aircraft passes of Fig. 3 were between 9 and 93 with an average of 30. This average value will be used to estimate the average concentration of effective IN at -20°C. Similarly, because the average distance between north and south plume edges on Fig. 3 is about 20 km, that value will be used in the calculations. The NCAR counter sampled about 10 L min^{-1} outside air while the aircraft speed was near 85 m s^{-1}. Consequently, the average volume of air sampled by the NCAR counter while passing through the AgI was:

$$(20{,}000 \text{ m}/85 \text{ m s}^{-1}) \times (10 \text{ L}/60 \text{ s}) = 39 \text{ L}$$

Using the usual times 10 correction factor for known ice crystal losses, the average IN concentration, effective at -20°C, is:

$$(30 \text{ counts} \times 10 \text{ IN/count})/39 \text{ L} = 8 \text{ IN L}^{-1}$$

Several early 1991 field comparisons between the DOT NCAR counter and the Suburban-mounted NCAR counter parked nearby resulted in similar concentrations measured by the two counters. These counters rarely differed by a factor of two, and usually were in much closer agreement. A single comparison was made between the Suburban unit parked near the aircraft while both were in the plume of a NAWC AgI generator. The aircraft unit consistently counted a factor of three less than the Suburban unit. Therefore, for the purpose of comparing aircraft AgI IN observations with surface observations from the other two NCAR counters, all aircraft NCAR counter data reported in this paper have been adjusted upward by a factor of three.

In this example, a mean concentration of 24 IN L^{-1} (3 X 8) resulted from the aircraft measurements. This result is about an order of magnitude less than the 100 to 500 L^{-1} observed at the DOT and along the upwind highway during this experiment, and suggests the aircraft was near the AgI plume top. Observations on several other missions indicated the aircraft was near plume top, because AgI IN concentrations were much lower than found on the Plateau top, and/or because no AgI was detected on some (sometimes none) of the lowest-level, terrain-following aircraft passes. Part of the difference between Plateau-top and aircraft-level AgI IN measurements might be attributed to greater AgI removal by nucleation of ice particles at the colder aircraft levels. Conversely, scavenging of AgI by falling ice particles might remove more AgI at Plateau top levels where snowfall rates are greater. The net effect of losses of AgI by nucleation and scavènging is not known, but is assumed to be a secondary factor in the observed order of magnitude decreases from Plateau-top to aircraft-level AgI IN concentrations. That is, the typical large decrease in AgI IN with altitude observed above the Plateau is believe to be primarily caused by transport and dispersion processes.

Thus far, AgI IN concentrations have been reported effective at -20°C, the NCAR counter cloud chamber temperature.

However, the concentration of interest is that effective at the cloud temperature outside the aircraft. This concentration will be estimated using the recent cloud simulation laboratory calibration of the NAWC AgI generator by DeMott et al. (1995). That calibration showed that under natural tunnel draft conditions typical of light valley winds during most storms, 0.2, 8 and 75 percent of the IN effective at -20°C (1.8 X 10^{15} IN g^{-1} of AgI) were effective at temperatures of -6, -8 and -12°C, respectively. The effectiveness at -16°C was essentially the same as at -20°C. These measured values were plotted and values were estimated for intermediate temperatures where necessary to correspond to aircraft sampling temperatures. Using these values assumes the cloud simulation laboratory calibration provides a good approximation of AgI's temperature dependence as an effective IN in natural orographic clouds over the Plateau. That assumption is admittedly open to question, but some indication of its validity will be provided by later examination of aircraft-measured IPC's within seeded cloud.

Because most aircraft sampling within the AgI plume was near the -5°C level during the experiment under discussion (Fig. 3), the concentration of effective AgI IN would be expected to be less than 0.2 percent of the -20°C value; that is, 0.002 X 24 IN L^{-1}, or about 0.05 IN L^{-1}. As discussed by Super (1994), ice crystal concentrations less than 10 IN L^{-1} do not appear likely to produce economically beneficial snowfall rates under most cloud conditions. Moreover, most aircraft sampling within the AgI plume was below cloud base during this experiment.

Some AgI may have ascended to higher, colder altitudes above cloud base, resulting in nucleation and settling of ice particles down to terrain-following aircraft sampling altitudes. It appears unlikely that significant IPCs were formed in this manner in view of the low IN concentrations sampled by the aircraft's NCAR counter. Moreover, no valley-released AgI was detected by a pair of passes (not shown) flown at a constant altitude of 3950 m (-10.5°C over the west flight track.

3.5 Ice Particle Concentrations

The best evidence for any seeding effects is believed to be the IPC calculated from 2D-C observations. Of course, even if the IPC is enhanced by seeding at aircraft levels, that does not prove that seeding affected the surface snowfall because the crystals may be small and may not settle to the surface before being transported beyond the Plateau. However, if no IPC increase can be demonstrated within the AgI plume at relatively cold aircraft levels, it might be expected that seeding was ineffective in modifying surface snowfall on the Plateau.

Cloud conditions did not appear particularly suitable for seeding at aircraft altitudes during the mission of 28 February in spite of the relative high SLW amounts observed by the microwave radiometer (Sec. 3.1). Cloud at aircraft levels had very limited LWC (liquid water content) as measured by the aircraft CSIRO probe (King et al. 1985). The solid line on the upper panel of Fig. 3 shows the LWC averaged for 5-km intervals and multiple passes. The low average LWC would be expected on the northern portion of the flight track because the aircraft was frequently below cloud base. However, the LWC was also quite low even on the southern portion of the flight track where the aircraft was usually in cloud. Liquid water contents were somewhat higher, between 0.02 and 0.15 g m^{-3}, on the pair of passes flown at 3950 m, about 500 m above cloud base.

The bar graph on the upper panel of Fig. 3 shows the IPC averaged for 5-km intervals. The argument previously given for examining average AgI IN concentrations for several aircraft passes is believed equally valid for examination of average IPCs between seeded and nonseeded zones.

Average IPCs were calculated for individual 5-km intervals without regard for whether the aircraft was in or out of visual cloud. The large majority of time the aircraft was in cloud during the experiments to be discussed. However, visual breaks sometimes occurred in the cloud decks and some sampling was done below visual cloud base on 28 February. Of course, ice crystals can exist between visual cloud elements, or below visual cloud base, in concentrations too low to appear as cloud.

Ice particle concentration averages for multiple aircraft passes were weighted in the following way. The total count of particles over all passes within each 5-km interval was divided by the sum of the sample volumes actually observed by the 2D-C probe, which normally recorded two buffers of data per second. When the IPC was high (not observed on this day), the 2D-C probe sampled a limited volume of air each second. A simple average of IPC values from multiple passes could therefore be biased by one or more high concentration values from potentially unrepresentative samples. In other words, the calculated simple average might be higher than the real average because of equal weight being given to a one or more very high values that represented only very small cloud volumes. Conversely, the weighted averages to be presented may err in the opposite direction, letting low concentrations from large volumes dominate the average.

The weighted average IPCs tended to be a factor of two or three to sometimes a factor of several lower than the simple averages. However, the weighted IPC average is believed to provide the more conservative and correct means of assessing possible changes resulting from cloud seeding.

Figure 3 shows low average IPCs over the 75-km north-south distance portrayed, with maximum values near 0.2 ice particles L^{-1}. No convincing evidence exists to show that valley seeding increased the IPC. The IPC in the region of AgI plume is similar to that found farther crosswind. Of course, aircraft sampling was often about 300 m below visual cloud base in the zone where the AgI IN were found, and no AgI was detected on the pair of passes 500 m above cloud base. Consequently, one might not expect any seeding effects during this experiment. Cloud bases were below the Plateau top on the other experiments to be examined.

3.6 Precipitation Observations

No precipitation was detected by any of the five Plateau gauges during this experiment at the minimum gauge resolution of 0.25 mm h^{-1}. A trace was suggested by the gauge chart on the center of the Plateau top (all charts were carefully reduced with the aid of magnification). With the southwesterly flow, the AgI plume detected by aircraft may have been transported north of the two easternmost gauges. However, AgI probably existed below practical aircraft sampling altitudes farther south than shown on Fig. 3. Silver iodide in that region could have the potential to affect gauge snowfall east of the aircraft track if enough ice crystals were nucleated. Therefore, the absence of measurable precipitation on top the Plateau can be considered further evidence that seeding was ineffective during the experiment of 28 February.

More detailed discussion of the implications of precipitation gauge network measurements is given for the following experiment which had measurable snowfall at all gauges.

3.7 Summary of 28 February Experiment

Although the microwave radiometer detected relatively high SLW amounts above the Plateau, the liquid water presumably was concentrated above the highest aircraft sampling altitude of 3950 m because cloud LWC was low at aircraft levels. Consequently, seeding potential might have been anticipated to be limited or nonexistent. The lack of observed snowfall certainly indicates that valley seeding was unsuccessful in converting cloud SLW into precipitation during this experiment.

4. FIRST EXPERIMENT OF 1 MARCH

4.1 Overview

The eight valley AgI generators were operated continuously from the morning of 28 February until the afternoon of 2 March. Two experiments were conducted on 1 March. Aircraft sampling over the Plateau took place between 1125 and 1410 during the first experiment. The aircraft was in cloud during all 12 sampling passes.

Prefrontal southwesterly flow persisted during the first mission. The 1200 rawinsonde showed relative humidities near 100 percent from the Plateau top to 5700 m. K_a-band radar tops were near 6300 m (-27°C) from 1200 till the end of the experiment, and higher earlier. The rawinsonde data showed a stable layer between 3500 and 4000 m (equivalent potential temperature increased with altitude) with neutral stability in the rest of the cloud layer. A stable layer existed in the first few hundred meters above the valley floor.

The wind in Fairview Canyon was up-canyon (westerly) during the experiment, but averaged only about 1 m s^{-1}. Winds were unusually light at the DOT, averaging 190° in direction and decreasing from 3 to 1 m s^{-1} in speed during the experiment. Aircraft-measured winds at 3200 and 3800 m were both near 215° and 11 m s^{-1}.

4.2 Plateau Top Observations

Observations along the upwind highway indicated the Plateau top was generally in cloud with light snowfall rates. Visibility was quite limited near the heads of canyons because of local liquid cloud production.

The DOT air temperature was -2°C during the period of aircraft sampling and the dewpoint depression was about 1°C.

The vertically-integrated SLW above the DOT (Fig. 4) was limited prior to 1200 and thereafter increased with time until about 1345. Ice nuclei concentrations at the DOT were quite low until almost 1300. After 1300, both IN and SLW increased, and both peaked just after 1330. The aircraft crew noted increased turbulence about 1300, suggesting enhancement of embedded convection as the first deep cloud band left the Plateau. The 1500 sounding, between aircraft missions, showed a moist, unstable atmosphere from the valley floor to 4300 m (equivalent potential temperature decreased with altitude).

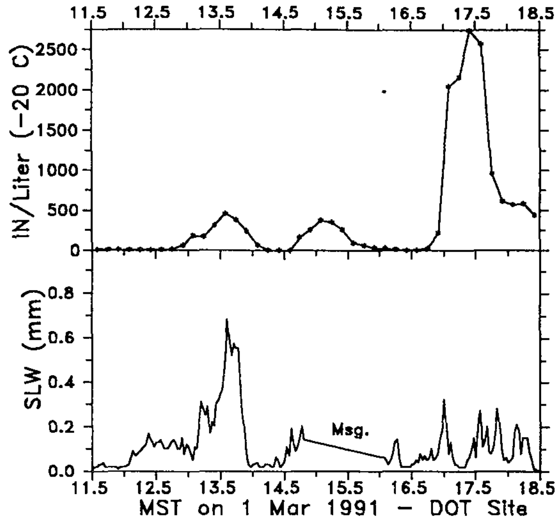

Fig. 4. Similar to Fig. 2 except for the 2 aircraft missions of 1 March 1991.

DOT IN measurements shown on Fig. 4 were 5 to 25 IN L^{-1} until 1245, and thereafter 200 to 500 IN L^{-1}. Similar low values were found along the upwind highway prior to 1245, with values between 200 and 800 IN L^{-1} during the remainder of the aircraft mission.

The highest portion of the upwind highway (SKY) is about 300 m higher and 2°C colder than the DOT, so the SKY temperature was about -4°C during this experiment. Consequently, AgI IN concentrations effective at temperatures along the upwind highway would be expected to be very low.

4.3 Aircraft Observations

All 12 aircraft passes were made in the terrain-following mode over the west flight track. Entry positions into the AgI plume were estimated for 10 of the passes; amounts were too low on the others. Figure 5 shows the estimated positions of the north and south edges of the AgI plume, and average values of other parameters, for 10 passes. It is seen that the AgI was concentrated on the lower portion of the flight track, generally above the head of Fairview Canyon. Cloud temperatures were near -6.5°C in that region. Two AgI encounters occurred about 25 km south of SKY where the temperature was below -9°C. Silver iodide may have been transported over the Plateau south of SKY during the other passes, but below the aircraft.

Liquid water measured by the CSIRO probe was not continuous and amounts varied rapidly when liquid was detected. Peak LWC values were 0.2 to 0.3 g m^{-3}, but mean values shown on Fig. 5 were an order of magnitude less.

Average IPCs were in the 0.2 to 0.4 L^{-1} range all along the flight track. No suggestion of higher IPCs occurred in the region from 5 to 25 km north of SKY, where AgI was most commonly found. It is not known how long the AgI was in cloud before being sampled by the aircraft, but only a few minutes after nucleation would usually be required for growth to the 100 µm minimum size used with the processing software.

The lack of obvious seeding-enhanced IPCs at aircraft altitudes is probably because of two factors. The cloud temperature was relatively warm and the concentrations of seeding material were low at aircraft levels. The average NCAR counter counts per pass ranged between 8 and 46 with an average value of 21. Figure 5 indicates most of the AgI was found along a 20-km portion of the flight track. Using the approach previously shown, the mean estimated IN concentration over the 20-km width is 15 IN L^{-1} at -20°C, similar to Plateau top values prior to 1245, but much lower than later Plateau top concentrations. The corresponding concentration of effective IN for the cloud temperatures sampled by the aircraft is estimated as about 0.3 IN L^{-1}.

Figure 4 showed that Plateau-top AgI IN concentrations increased markedly after 1245. Total NCAR counter counts per aircraft pass averaged 11 for the 6 passes prior to 1245 and 32 for the 6 passes after 1245. Although the increase at aircraft altitudes was much less dramatic than on the Plateau top, a decision was made to calculate IPCs for the 6 passes after 1245 which may have had a larger seeding signal. A plot similar to Fig. 5 was prepared (not shown).

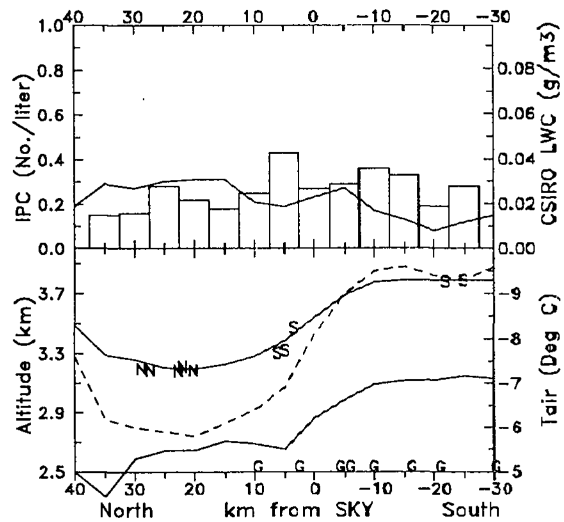

Fig. 5. Similar to Fig. 3 except for 10 terrain-following passes on the first mission of 1 March 1991.

The 6 plume entry edges were between 3 and 30 km north of SKY. The average IPC in that region ranged between 0.2 and 0.6 L^{-1}, with an average of 0.4 L^{-1}. The IPC in the 35 km south of the seeded region ranged from 0.1 to 0.4 L^{-1}, with an average of 0.2 L^{-1}, half that of the seeded region. Samples were not available north of the seeded region. The observed differences might suggest some increase in IPC associated with seeding. However, the seeded zone IPC was still quite low.

4.4 <u>Precipitation Observations</u>

The surface precipitation will now be considered. Typical ice crystals with a fall speed of 75 cm s^{-1} would require between 10 and 23 min to settle from terrain-following aircraft pass locations over the west track to the two eastern precipitation gauges. These gauges, shown on Fig. 1 as PTC (Plateau top center) and PTE (Plateau top east), were located at 2720 and 2850 m, respectively. (The gauge on the Plateau top's west edge, near the DOT, was directly under the west track.) This calculation ignores any net vertical motion in the atmosphere over the Plateau because no vertical wind observations were available. With a southwest flow and wind speed of 10 m s^{-1}, 17 min would be required for horizontal transport from SKY to the PTE gauge. Less time would be required to reach the PTC gauge. Based on these calculations, it is reasonable to assume that some of the ice particles measured along the west track's lowest passes could impact the two downwind gauges about 15 min after aircraft detection. The PTC and PTE gauges will hereafter be referred to as the "target gauges" with the realization that this refers to their potential targeting by ice particles observed by the aircraft over the west track.

The DOT gauge on the Plateau top's west edge could also be affected by valley seeding nucleating ice particles upwind of, and at lower altitude than, the west aircraft sampling track. Under some conditions (sufficiently cold and moist), valley-released AgI might nucleate ice crystals near the windward slope which could settle to the surface along the upper portion of the windward slope and western portion of the Plateau top including the DOT gauge. In support of this hypothesis, yet to be reported observations during the 1994-95 winter have sometimes shown modest snowfall increases at a site on the upwind highway associated with AgI seeding from a site 1 km south of HAS on Fig. 1. The horizontal distance between the generator used during the 1994-95 winter and the upwind highway ice particle and snowfall observing site is 4.4 km. Typical wind speeds near the windward slope between these two sites translate into about 15 min growth time provided that ice crystals nucleate near the AgI generator. This is sufficient time for crystals to grow to a few hundred micrometers or larger under some conditions.

Valley seeding would not be expected to affect the westernmost gauge, FVC on Fig. 1, located at the mouth of Fairview Canyon at 2010 m. Moreover, it is unlikely that valley seeding would significantly modify snowfall at the HAS gauge. To affect snowfall, valley-released AgI must be transported vertically to relatively cold SLW cloud where nucleation can take place. Contact nucleation, known to be a slow process, would be expected with the type of AgI used (DeMott et al. 1995). After nucleation, ice particles must grow large enough to achieve significant fall velocities and then must settle to the surface. All these processes must take place in air forced to ascend over the Plateau's windward slope for seeding to affect the HAS gauge. For all but rare conditions, it can be assumed that the Fairview Canyon mouth and HAS gauges will not be affected by seeding. Those gauge observations can be used to make a crude estimate of natural snowfall rates on top of the Plateau.

Total precipitation was examined for the entire early 1991 field season to provide some basis for comparing individual gauge observations during experiments. Of course, natural short-term variations among gauges can be significantly greater than seasonal variations, so the field season comparisons provide only a very general idea of what the natural (nonseeded) snowfall pattern might be during an individual experiment.

All gauge measurements will be referenced to the HAS gauge in this and following discussions of precipitation patterns over the Plateau. Hours with missing data from one or more gauges were excluded from the seasonal comparisons. The HAS gauge collected a total of 119 mm snowfall during 115 hours with detectable snowfall (all references to precipitation or snowfall will use melted snow water equivalent, not snow depth). The median snowfall rate was 0.64 mm h^{-1}. Using the HAS seasonal total as 100 percent, the west-to-east profile from the 5 gauges over the Plateau was 62, 100, 122, 116 and 87 percent for gauges FVC, HAS, DOT, PTC and PTE, respectively. The greatest snowfall (122 percent of HAS or 145 mm) fell at the DOT gauge near the Plateau top's west edge which detected snowfall on 169 h with a median rate of 0.51 mm h^{-1}.

For the prevailing south-southwesterly flow from the Plateau top to aircraft levels during the first experiment of 1 March, most of the AgI shown on Fig. 5 would have been transported north of the target gauges. However, two of the five southerly plume edges shown on Fig. 5 were more than 20 km south of SKY. Silver iodide may have been transported that far south on other aircraft passes, while below the aircraft. If so, any seeded ice crystals should have been transported toward the target gauges.

Aircraft sampling was conducted between 1125 and 1410, so the corresponding target gauge period of interest is about 1140 to 1425, using the 15 min fall and transport time lag previously discussed. The total snowfall at the HAS gauge during this period was 0.51 mm corresponding to 0.18 mm h^{-1}, a low rate. The west-to-east profile, using 0.51 mm as 100 percent, was 100, 100, 200, 250 and 375 percent. The 3 Plateau top gauges received more snowfall than would be expected from the comparison of seasonal amounts. However, snowfall rates were limited during the 2.75 h experiment and the observed snowfall profile over the Plateau may simply represent natural variability. Even the PTE gauge which received the most snowfall had an average hourly rate of only 0.69 mm h^{-1}. Hourly rates during all experiments are summarized in Table 2 of Sec. 9.

4.5 Summary of First Experiment of 1 March

Precipitation gauge observations suggest that seeding may have provided limited enhancement of the Plateau top snowfall during this experiment. However, the microphysical and AgI IN observations do not support the hypothesis of significant snowfall enhancement caused by seeding. The most defendable conclusion is that seeding did not significantly increase the Plateau top snowfall during this experiment.

5. SECOND EXPERIMENT OF 1 MARCH

5.1 Overview

The second aircraft mission of the day encountered well-developed convection in a line of showers associated with a cold front passage. The cold front passed the area at about 1700 (Huggins et al. 1992). A total of ten aircraft passes were made over the west track between 1645 and 1830. Five passes followed the terrain contour and five were flown at a constant altitude near 3750 m.

Radar tops descended rapidly from 9000 m (<-40°C) at 1610 to 4000 m (-11°C) at 1710. After 1730, the aircraft was in and out of cloud at 3750 m. By the final pass, the cloud deck was breaking up and visual ground contact was frequent. The 1800 sounding showed an unstable atmosphere throughout the cloud layer and considerable drying above 3800 m.

Fairview Canyon winds were light and variable during the experiment. Winds at the DOT averaged 250° and increased in speed from 2 to 7 m s^{-1}. Average aircraft wind speeds were 12 m s^{-1} at both 3200 and 3750 m. Aircraft-level wind directions had become more westerly since this day's first experiment, veering from 225 to 240° in the 3200 to 3750-m layer.

5.2 Plateau Top Observations

The DOT air temperature was -2.5°C during this experiment and the dewpoint depression averaged less than 1°C.

Figure 4 shows vertically-integrated SLW amounts measured by the DOT microwave radiometer varied rapidly during the second mission, characteristic of embedded convection. The average value exceeded 0.1 mm and peak amounts were near 0.3 mm. For reference, the median value was 0.06 mm for all 333 h that the DOT microwave radiometer detected SLW during the 1991 field program and only 10 percent of all hours had an average value exceeding 0.3 mm (Super 1994).

The upper panel of Fig. 4 shows that little AgI reached the DOT until after 1645. Then, an unusually high maximum of 2750 IN L^{-1} occurred between 1700 and 1745, followed by a rapid decrease in IN. This rapid change in IN coincided with an abrupt veering of wind direction and increase in wind speed on top the Plateau, believed to be caused by the frontal passage. High AgI IN values also were detected along the upwind highway with the Suburban NCAR counter. Four Suburban passes were made from 1654 to 1814 during the aircraft mission. The IN concentrations were averaged by 0.5-km intervals north of SKY, and resulting values ranged between 600 and 1500 IN L^{-1}. In contrast, average concentrations for Suburban passes just before and after this period were in the 100 to 300 IN L^{-1} range. The data support the concept of the frontal passage "flushing out" pooled AgI from the upwind valley and transporting the AgI over the Plateau.

Interestingly, Fairview Canyon winds did not reflect the frontal passage and rapid increase in AgI on top the Plateau. The Canyon wind fluctuated between up- and down-canyon with speeds between 0 and 2 m s^{-1}. Valley floor winds were also light and variable. These wind observations suggest that convection was partially responsible for the transport of the presumably pooled AgI from near the valley floor to Plateau top altitudes.

In spite of the high Plateau-top AgI IN concentrations during part of this experiment, concentrations effective at the warm temperatures along the upwind highway (-2.5 to -4.5°C) would be expected to be very low, less than 1 IN L^{-1} according to the laboratory calibration of DeMott et al. (1995).

5.3 Aircraft Observations

Figure 6 shows averaged data for the five terrain-following aircraft passes. The entry edge positions of the AgI plume varied from pass to pass, but once again the plume was most frequent above the head of Fairview Canyon. Temperatures were still relatively warm at aircraft altitudes, in the -6 to -9°C range where AgI was detected. The cloud LWC was higher than for previous missions, with peak values consistently near 0.4 g m^{-3} Average values shown on Fig. 6 were mostly in the 0.04 to 0.08 g m^{-3} range.

The 5-km averaged IPCs shown on Fig. 6 are variable. A problem with the 2D-C probe's recording system produced many "zero area images" during this particular mission. Consequently, sampling statistics were less reliable than usual and the IPC was uncertain in the interval centered 5 km north of SKY. Enough valid ice particles were sampled to produce reasonably

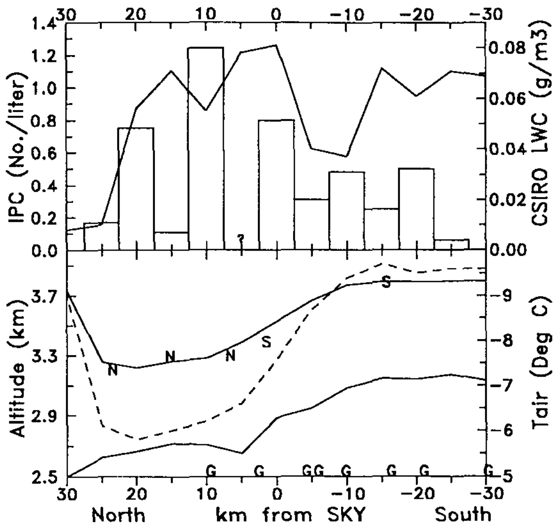

Fig. 6. Similar to Fig. 3 except for 5 terrain-following passes on the second mission of 1 March 1991.

accurate averages in the remaining intervals. Figure 6 provides no convincing evidence that seeding modified the IPC more than about 0.5 L^{-1}, if that. With the exception of one 5-km bin, the averaged IPC was below 1 L^{-1} all along the flight track.

NCAR counts measured on the aircraft were relatively high compared with other missions, ranging between 39 and 173, and averaging 92 counts per pass for the 5 terrain-following passes. Assuming the AgI plume width averaged 25 km, and using the approach described for 28 February, the resulting concentration is 56 IN L^{-1}. Although higher than for previously discussed experiments, this aircraft IN concentration is much lower than upwind highway values which were in the 100 to 1500 IN L^{-1} range. This result again indicates a pronounced vertical gradient and suggests the aircraft was near the top of the AgI plume (and any plume of enhanced IPC).

The cloud simulation chamber AgI generator calibration and aircraft NCAR counter data were again used to estimate the average IN concentration effective at cloud temperatures sampled by the aircraft. The resulting value was about 3 IN L^{-1}, somewhat higher than the observed IPCs.

Five constant altitude passes were flown over the west track near 3750 m (not shown). Entry edges into the AgI plume could be estimated on only two of the passes because of the low NCAR counter response. The 5-km IPC averages did not exceed 0.5 L^{-1}, and no indication existed to show that seeding increased the IPC above background levels.

5.4 Precipitation Observations

With the southwesterly flow, the AgI plume shown on Fig. 6 should have been transported over the two target gauges. Recalling that aircraft sampling took place between 1645 and 1830, the corresponding precipitation gauge period of interest is 1700 to 1845. Using the 1.52 mm received by the HAS gauge as 100 percent, the west-to-east profile was 33, 100, 183, 83 and 83 percent. This profile does not suggest that seeding increased the Plateau-top snowfall with the possible exception of the DOT gauge.

5.5 Summary of Second Mission of 1 March

The observations that were presented do not lend strong support to the hypothesis that valley seeding had a significant impact on cloud microphysics or precipitation during this experiment.

6. FIRST EXPERIMENT OF 2 MARCH

6.1 Overview

All eight valley AgI generators had been on continuously since the morning of 28 February. They were operated until near 1600 on this day, which was characterized by moist, post-frontal flow. Mt. Pleasant Airport soundings showed a shift to northwesterly flow with drying in the upper levels after 1000 (Huggins et al. 1992). The morning had thick orographic clouds with embedded convection. The cloud deck became broken during the afternoon.

Both aircraft missions on 2 March were terminated early because of icing-related problems. The first mission sampled over the Plateau only from 1015 to 1110. The mission was ended when the outside air sampling manifold froze over. The second mission was terminated because heavy airframe and antenna icing affected aircraft performance and receipt of radio navigation signals, respectively.

Rawinsondes were released from MPA at 1000 and 1200. The 1000 sounding indicated a stable atmosphere below the Plateau top, instability in the lowest kilometer above the Plateau top and a neutral-to-stable atmosphere above that layer. The 1200 sounding indicated an unstable atmosphere from the valley floor to about 1 km above the Plateau top and stability at higher altitudes. Rawinsonde winds in the lowest kilometer above the Plateau top were west-northwesterly near 14 m s^{-1}. Steady up-canyon winds prevailed during the first aircraft mission, between 3 to 4 m s^{-1}. Winds at the DOT were 255° between 5 to 7 m s^{-1}. Aircraft winds in the 3300- to 3800-m sampled layer were west-northwesterly near 20 m s^{-1}.

The K_a-band radar monitored cloud tops near 4700 m (-19°C) throughout the first mission. The aircraft was in cloud the entire mission except for a brief breakout above cloud top at 1101, which occurred 25 km north of SKY at 3800 m.

6.2 Plateau Top Observations

The DOT air temperature and dewpoint temperature were both -4°C during this experiment.

Figure 7 shows the temporal distribution of vertically-integrated SLW above the DOT radiometer. Peak amounts over 0.3 mm were common during both missions. The rapid fluctuations are further evidence of convective activity. Graupel was sometimes observed at the surface along the upwind highway during this experiment, indicating relatively high cloud LWC. All indications are that substantial moisture existed over the Plateau on this day.

The upper panel of Fig. 7 shows that valley-released AgI was transported to the

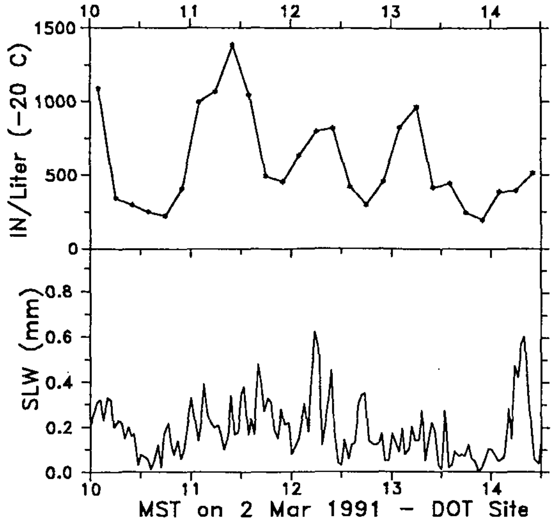

Fig. 7. Similar to Fig. 2 except for 2 aircraft missions of 2 March 1991.

Plateau top during and between the two 2 March missions (the second mission was between 1300-1430). Concentrations of AgI IN observed at the DOT during the first mission ranged between 250 and 1250 IN L^{-1}. Similar values were found along the upwind highway with the Suburban's NCAR counter between 0954 and 1049. Suburban sampling was thereafter interrupted because the vehicle became stuck in a snowdrift until after the aircraft mission.

Since upwind highway temperatures were between -4 and -6°C, AgI IN concentrations effective along the upwind highway are estimated as usually less than 1 IN L^{-1}.

6.3 Aircraft Observations

Four passes were made prior to freeze-up of the air sampling manifold, all over the west track. The first three were terrain-following passes, and the fourth pass was level at 3750 m. Cloud LWC was high, with considerable spatial variation indicating convection. Pass average values according to the CSIRO probe were near 0.1 g m^{-3} at 3300 m and near 0.2 g m^{-3} at 3750 m, with peak contents about 3 times the mean values.

Total NCAR counter counts per pass ranged from 59 to 105 on the first 3 aircraft passes, and these encounters occurred in the 3300- to 3500-m layer. Only background level IN concentrations were found on the higher fourth pass.

Figure 8 portrays the three estimated AgI plume edges from the first mission. Both north edges were 17 km north of SKY and the single south edge was 19 km south of SKY. The average IPC for that zone was 20 ice particles L^{-1}, twice that found in the 10 km immediately south of the seeded zone. However, the concentration was 16 L^{-1} in the 10 km just north of the seeded zone, and only two of the seven 5-km seeded zone intervals had markedly higher concentrations. Therefore, while seeding may have enhanced the IPC, the evidence is not conclusive. The difference in the seeded zone's IPC and the average IPC for the two 10-km zones just north and south of the seeded zone was 7 L^{-1} which supports the hypothesis that seeding did increase the IPC. Seeded zone cloud temperatures on individual passes ranged from -9 to -12.5°C, certainly cold enough for AgI nucleation. Some IPC enhancement could have been expected within the seeded zone.

Further support for the hypothesis of seeding-caused IPC enhancement is provided by the NCAR counter observations. The

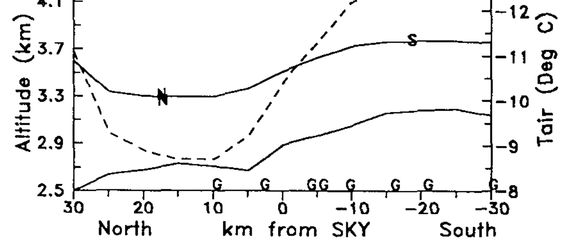

Fig. 8. Similar to Fig. 3 except for 3 terrain-following passes on the first mission of 2 March 1991.

average NCAR counter values for the 3 passes shown on Fig. 8 was 84 counts per pass. Assuming that average affected a 36-km north-south distance as suggested by Fig. 8's estimated plume edges, and applying the approach discussed earlier, yields a mean IN concentration of 35 IN L^{-1}. When adjusted from the cloud chamber temperature to the sampled cloud temperatures, resulting concentrations of effective IN would be near 15 IN L^{-1}.

It is possible that seeding produced IPCs sufficient to affect snowfall rates for some distance below lowest aircraft sampling levels. The temperature increased by about 6°C from the terrain-following aircraft passes (near -11 °C) to the upwind highway (near -5 °C). Silver iodide IN effectiveness varies by about three orders of magnitude over that temperature range, but in a non-linear manner. The vertical distribution of total AgI IN (at -20°C) is not known between the upwind highway, where observed concentrations were high, and the lowest aircraft sampling altitudes where concentrations were usually more than an order of magnitude lower. Therefore, the net effect of more total AgI IN at warmer cloud levels below the aircraft is not known. But if AgI IN concentrations were relatively high up to altitudes not far below the aircraft, IPCs of a few to several per liter could have resulted.

6.4 Precipitation Observations

With the prevailing winds, the AgI plume shown on Fig. 8 should have been transported over the two target gauges, PTC and PTE. Allowing 15 min for ice crystal settling and transport, the precipitation period corresponding to aircraft sampling was 1030 to 1125. The HAS gauge received 0.51 mm during this period and the corresponding west-to-east profile over the Plateau was 50, 100, 325, 200 and 125 percent. The Plateau-top percentages are markedly higher than the seasonal values, but are based on a limited snowfall total at the HAS and may reflect nothing but natural variability. With that caveat in mind, it is nevertheless a real possibility that seeding increased snowfall on the Plateau top during this experiment. It will be recalled that cloud liquid water content was abundant and AgI reached relatively cold cloud levels.

6.5 Summary of First Mission of 2 March

In summary, the various observations obtained during this experiment suggest that seeding increased the IPC above the Plateau top and snowfall on the Plateau top.

7. SECOND EXPERIMENT OF 2 MARCH

7.1 Overview

Aircraft sampling over the Plateau resumed at 1300 and continued until 1430, by which time airframe and antenna icing forced termination of the second mission. The aircraft scientist noted that several turrets rose above the general cloud deck, indicating embedded convection was present. Radar tops ranged between 3400 m (-9°C) and 4700 m (-18°C) during aircraft sampling.

The MPA rawinsonde launched at 1500 showed a slightly stable atmosphere below 3500 m, then a 1 km unstable layer overlain by stability aloft. Rawinsonde winds in the first 1.5 km above the Plateau top were near 275° at 12 m s^{-1}.

Up-canyon flow continued during the second experiment with speeds between 1 and 4 m s^{-1}. The DOT winds were steady near 255° and 5 m s^{-1}, and aircraft-measured winds near 3750 m averaged 285° at 14 m s^{-1}.

7.2 Plateau Top Observations

As during the earlier mission on this day, the DOT air temperature and dewpoint temperature were both -4°C during aircraft sampling.

Figure 7 shows a peak vertically-integrated SLW amount of 0.6 mm observed by the DOT radiometer near the end of the second aircraft mission, and earlier peaks between 0.1 and 0.2 mm. Continued transport of valley-released AgI to the DOT in concentrations between 200 to 1000 IN L^{-1} is also shown on Fig. 7.

Suburban sampling along the upwind highway showed 0.5 km means of 200 to 700 IN L^{-1} during this aircraft mission, in good agreement with the DOT observations. Again because of the slightly supercooled temperatures along the upwind highway, AgI IN concentrations effective at those temperatures are estimated at less than 1 IN L^{-1}.

7.3 Aircraft Observations

Five aircraft passes were made over the west track, all at a constant altitude. Because of the high average LWC (Fig. 9) and associated heavy airframe icing, no lower-level, terrain-following passes were attempted.

All five passes encountered AgI in spite of the relatively high altitude, near 3750 m. The estimated entry edge positions are shown on Fig. 9, between 6 km north to 3 km south of SKY. The narrowness of the AgI plume suggests it may have come from only one or two generators and/or been funneled up the two major canyons upwind of the DOT and SKY. Silver iodide from other generators may have been below the aircraft both north and south of the detected AgI plume. Cloud temperatures at aircraft altitudes were near -12.5°C, certainly cold enough for substantial nucleation by AgI.

The upper panel of Fig. 9 indicates a pronounced IPC enhancement associated with the AgI plume position. The maximum IPC was 24 L^{-1} in the 5-km interval centered on SKY, which appears to be the plume core according to the entry edges. The background IPC was about 2 to 4 L^{-1}, except in the 10 km south of the IPC maximum where concentrations were 10 L^{-1}. It is speculated that this 10-km region may have been affected by seeding, if the AgI was transported above the aircraft and the wind direction veered with height. But even if the 10 L^{-1} region was a natural phenomena associated with the high LWC region, the data strongly suggest that seeding caused an IPC enhancement of at least 14 L^{-1} directly over SKY.

Total NCAR counter counts per pass

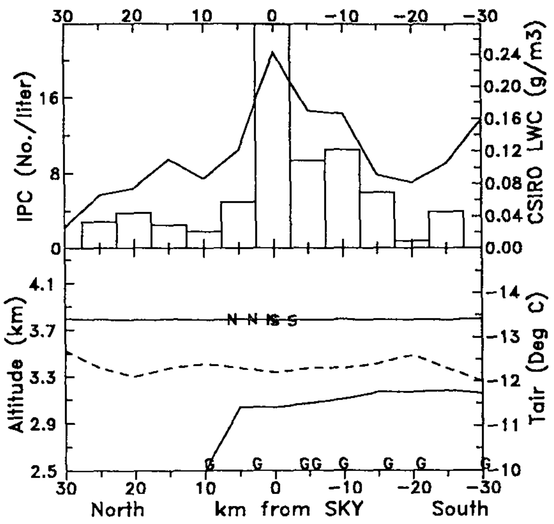

Fig. 9. Similar to Fig. 3 except for 5 constant altitude passes on the second mission of 2 March 1991.

ranged between 10 and 64 with an average of 30. Assuming the plume width averaged only 5 km at the relatively high sampling altitude, as suggested by Fig. 9, and applying the previous approach yields an estimated IN concentration of 90 L^{-1}. This concentration is about half of the lowest values sampled on the Plateau top. This relatively high aircraft average value at 3750 m indicates good vertical transport, presumably aided by embedded convection.

The cloud simulation chamber calibration reported by DeMott et al. (1995) indicates AgI IN effectiveness at -12°C, near the sampled cloud temperature, to be 75 percent of that at the NCAR cloud chamber temperature. Using that adjustment results in an estimated effective IN concentration of about 70 L^{-1}, well above the enhanced IPC of 14 to 20 L^{-1} suggested by Fig. 9. Of course, not all available AgI IN necessarily nucleated ice crystals, especially if relatively slow contact nucleation occurred as expected with the AgI solution used.

This aircraft mission was the first of the series of missions reported in this paper that demonstrated an obvious IPC enhancement associated with valley AgI seeding. The IPC appears to have been increased by 14 to 20

L^{-1} by the seeding, a high enough enhancement to potentially have affected the snowfall rate.

The AgI plume was centered just north of SKY at an altitude of 3750 m. Passes were not made at lower levels where the plume was likely much wider than shown on Fig. 9. With the observed westerly flow, the seeding plume was probably transported over target gauges PTC and PTE.

7.4 Precipitation Observations

Precipitation rates had decreased from the morning mission though vertically-integrated SLW values above the DOT were similar during both missions. The second mission's period of interest for precipitation gauge observations is 1315 to 1445. The only gauges to detect snowfall during this period were the DOT gauge and the PTE gauge, each of which recorded the minimum detectable amount of 0.25 mm h^{-1}.

7.5 Summary of Second Experiment of 2 March

Even though seeding apparently increased the IPC at the aircraft sampling level, available precipitation gauge observations do not indicate any significant increase during this experiment as snowfall rates were very low. Seeding potential might have been expected to be high during this experiment since cloud liquid water amounts were relatively abundant and snowfall rates were minor. However, the valley seeding did not result in significant snowfall on the Plateau.

8. SINGLE EXPERIMENT OF 6 MARCH

8.1 Overview

The 6 March case was the coldest storm sampled during the 1991 field program. The eight valley AgI generators were ignited between 1215 and 1335 and thereafter operated until after the experiment. Aircraft sampling over the Plateau took place between 1620 and 1915.

Northwesterly flow was affecting Utah at 700 and 500 mb because the State was west of the mean long wave trough axis (Huggins et al. 1992). A small region of moisture and cold air advection reached Utah on this day, associated with movement of a short wave. A distinct band of cold-topped clouds accompanied an upper level trough passage during the experiment. The cloud band passed over the Plateau from 1300 to 2000.

The only K_a-band radar echo to reach the Plateau top did so between 1700 and 2000, during and after the aircraft mission. The upper level cloud produced very weak echo to a maximum altitude of 5100 m (-27°C). However, the vertically-pointed radar was unable to detect cloud higher than 4000 m (-20°C) most of the time during the mission.

The 1500 MPA rawinsonde showed a slightly stable atmosphere from the Sanpete Valley floor to near 3500 m, and increased stability at higher altitudes. The only layer with relative humidity above 90 percent was between 3300 to 3500 m. Rawinsonde winds were westerly near 6 m s^{-1} at Plateau top levels. The 1800 sounding showed neutral stability from the valley floor to about 3300 m and increased stability above that altitude. The single thin layer of high relative humidity persisted, with values exceeding 90 percent between 2800 to 3500 m. Rawinsonde winds at Plateau-top levels remained westerly near 7 m s^{-1}. Higher level winds were west-northwest and the speed increased to 13 m s^{-1} near 3750 m.

Light up-canyon flow persisted during the experiment, near 1 m s^{-1}. The DOT winds were westerly, usually between 3-4 m s^{-1}. Aircraft winds were not available for this mission.

This experiment was simulated with a numerical model by Heimbach and Hall (1994). Their results showed pooling of valley-released AgI but some transport over the Plateau in a shallow layer. The vertical transport was apparently enhanced by gravity waves in the stable atmosphere.

8.2 Plateau Top Observations

The DOT air temperature and dewpoint temperature both averaged -11°C during this experiment.

A mesoscale feature moved over the Plateau from about 1630 to 1700, characterized by aggregation of ice crystals and reduced visibility on top the Plateau. Aircraft and ground scientists speculated at the time that a convective band was passing by. That view is not supported by the available rawinsonde data which indicate a stable atmosphere, or the model simulation by Heimbach and Hall (1994) based on sounding data. But the small mesoscale feature moved through the area between the 1500 and 1800 rawinsondes and likely escaped detection. At any rate, both the SLW and AgI IN monitored at the DOT peaked between 1700 and 1730, a period of increasing visibility with limited ice particles settling along the upwind highway. A mobile radiometer detected the greatest SLW amount of the experiment, with a maximum value of 0.25 mm, while being driven midway up Fairview Canyon between 1710 and 1725 (Huggins et al. 1992). (Further discussion of 1991 mobile radiometer sampling is given by Huggins 1995.) Clearly, some mesoscale phenomena affected the Plateau from about 1630 to 1730, resulting in increased SLW and AgI transport over the Plateau.

Figure 10 shows that valley-released AgI was transported to the Plateau top during aircraft sampling in concentrations between 200 and 1500 IN L^{-1}. Six Suburban passes were made during the aircraft mission. The Suburban data, when averaged for 0.5 km-intervals north of SKY, ranged between 400 and 1000 IN L^{-1}. As temperatures along the upwind highway were -11 to -13°C, effective AgI IN concentrations in that region are estimated as about 75 percent of the values just cited. Presuming that liquid condensate was being produced along the Plateau's west slope, high concentrations of seeded ice crystals would be anticipated along the upwind highway.

Several visual observations of ice crystals were made while driving along the upwind

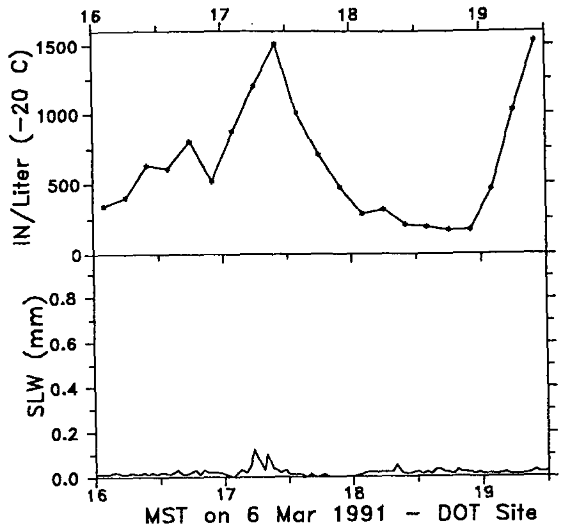

Fig. 10. Similar to Fig. 2 except for the aircraft mission of 6 March 1991.

highway during this experiment. Crystals were typically very small, but aggregates were sometimes observed. However, no evidence of riming existed, which indicates SLW was limited. The impression along the upwind highway was of being within an essentially all-ice cloud. The largely ice particle cloud may have been primarily a natural phenomena because of the cold prevailing temperatures. But if any excess SLW did exist, it seems probable that the AgI seeding converted much of it to ice crystals.

The bottom panel of Fig. 10 shows this day had little vertically-integrated SLW observed by the DOT radiometer. The highest peak was 0.1 mm, but most of the period was in the range 0.0 to 0.03 mm. These observations suggest that natural and/or seeded ice crystals were rapidly converting any liquid condensate, produced by uplift over the Plateau, into ice crystals. The result was an orographic cloud composed predominantly of ice over the Plateau top, with minor amounts of SLW occasionally observed.

8.3 Aircraft Observations

Figure 11 shows averages for the seven terrain-following passes made over the west flight track. The NCAR counter entry edges

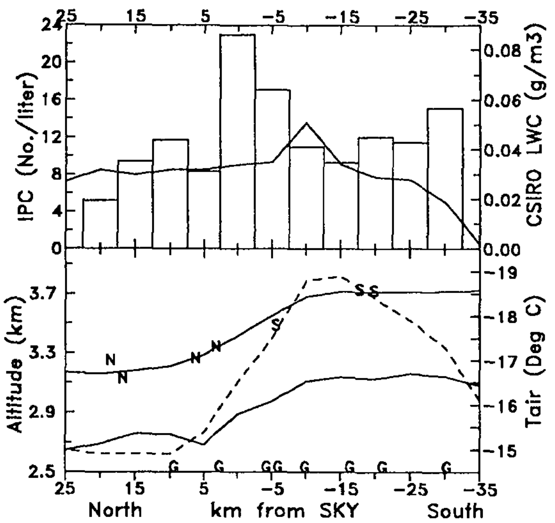

Fig. 11. Similar to Fig. 3 except for 7 terrain-following passes on 6 March 1991.

into the AgI plume shown on Fig. 11 vary considerably with extremes between 18 km north to 20 km south of SKY. On average,the plume was between 11.2 km north to 14.4 km south of SKY, a width of 26 km.

Average CSIRO LWC values were low, generally in the 0.02 to 0.04 g m^{-3} range, both for terrain-following passes (Fig. 11) and for constant altitude passes flown near 3750 m (Fig. 12).

A strong indication exists in Fig. 11 that seeding increased the IPC in the 5-km intervals from 2.5 km north to 7.5 km south of SKY. The average IPC for this 10-km zone is 20 L^{-1}, compared with 10 L^{-1} for the remaining intervals, and 11 L^{-1} for the four 5-km zones that rarely had AgI present (1 northernmost and 3 southernmost). The 10-km zone of apparently enhanced IPC corresponds to the AgI core according to the entry edge positions; that is, AgI appeared to be present in that zone on every pass. Silver iodide was detected north and south of that zone on some of the passes.

Temperatures were cold in the seeded zone along the lowest aircraft sampling profile, between -15 and -19°C on individual passes.

Figure 12 is similar to Fig. 11 except for the five passes made at a constant altitude of 3750 m where the temperature was near -19°C. The two 5-km intervals from 2.5 to 12.5 km south of SKY had the highest IPC with an average of 37 L^{-1}. For comparison, the average for the remaining intervals is 10 L^{-1}. The 10-km zone with increased IPC is again in good spatial agreement with the north and south AgI plume entry edges which, on average, were located between 3 and 13 km south of SKY. The southward shift of the IPC maximum from Fig. 11 to Fig. 12 is consistent with rawinsonde observations that showed the wind direction veering with altitude.

The total NCAR counter counts per pass for the 7 passes of Fig. 11 ranged between 30 and 355 with an average of 115. Assuming this average affected a 26-km width, the resulting AgI concentration was about 70 IN L^{-1}. No adjustment is needed for the cold prevailing cloud temperatures because AgI IN effectiveness is essentially constant at temperatures below -15°C for the NAWC generator (DeMott et al. 1995). Once again the NCAR counter-based estimate of AgI IN was above the 10 IN L^{-1} IPC enhancement indicated by the 2D-C probe observations. The AgI was consistently found at the higher, colder 3750-m level, so seeded crystals from

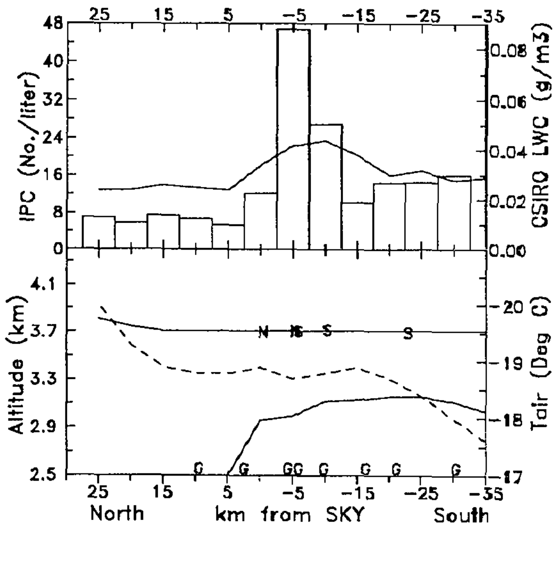

Fig. 12. Similar to Fig. 3 except for 5 constant altitude passes on 6 March 1991.

above may have settled to the altitude of the terrain-following passes. Any such enhancement of the observed IPC would result in less agreement with the AgI IN estimation, as would any adjustment for expected slow nucleation by the AgI in the cold, dry cloud. It is speculated that only a fraction of the available AgI IN nucleated ice crystals because cloud liquid water was very limited. Conversely, better agreement was found for the 5 passes of Fig. 12 for which total NCAR counter counts per pass ranged between 17 and 78 with an average of 40. Assuming a 10-km plume width results in an estimated AgI concentration of 60 IN L^{-1} for the cold air temperature. This AgI IN estimate is in reasonable agreement with the IPC enhancement of 27 L^{-1} suggested by Fig. 12.

8.4 Precipitation Observations

The AgI plume position shown on Fig. 11 should have been transported over the target gauges with observed winds between westerly and west-northwesterly. The aircraft sampling period, increased by 15 min for ice crystal settling to gauge altitudes, was 1635 to 1930. The total precipitation recorded during this period was none in the two west slope gauges, 0.76 mm at the DOT, 0.38 mm on the Plateau-top center, and 0.25 mm at the easternmost gauge. The fact that no snowfall was observed on the west slope while some fell on the Plateau top suggests that seeding may have enhanced Plateau-top snowfall. Of course, there is no way to be certain that the observed snowfall distribution represents anything but natural processes. However, it can be stated that if seeding was effective, the *maximum* possible rate averaged 0.25 mm h^{-1} at the DOT gauge and less further downwind.

8.5 Summary of Experiment of 6 March

Valley seeding appears to have markedly increased the IPC during this experiment. The increased IPC zone was spatially consistent with the AgI plume position. The NCAR counter-based estimates of effective AgI IN concentrations also support the view of IPC enhancement within the seeded zone. Apparently, the limited amount of LWC was sufficient for nucleation of additional ice particles at the unusually cold cloud temperatures reached by the AgI. The seeding may have increased snowfall on the Plateau top, but at limited rates, presumably because of the limited SLW available in the cold cloud system.

9. SUMMARY AND CONCLUSIONS

Six early 1991 seeding experiments were examined in which AgI, released from a network of eight valley generators, was observed over the Wasatch Plateau of central Utah. These experiments, corresponding to aircraft sampling periods over the Plateau, were selected as all available cases with valley-released AgI detected at aircraft altitudes over the Plateau. Therefore, these cases are not representative of valley seeding in general. Valley-released AgI was not transported to Plateau top and aircraft altitudes during some other early 1991 sampling periods (e.g., Super and Holroyd 1994, Super 1994).

All the storm periods reported herein had SLW cloud over the Plateau as measured by microwave radiometer and aircraft, although amounts were very limited in the coldest experiment and the SLW was well above the Plateau top during another experiment. Five of the experimental periods had embedded convection present. The sixth period, the coldest storm sampled during 1991, experienced passage of a mesoscale feature which may have aided transport over the Plateau.

Silver iodide IN were measured by NCAR acoustical IN counters in an aircraft, in a 4-wheel drive vehicle and at a fixed site near the head of a major canyon. Concentrations of AgI IN, effective at -20°C in each NCAR counter's cloud chamber, were often hundreds per liter at the fixed site and along the upwind highway following the Plateau top's windward edge for a 6.7 km north-south distance. Concentrations at lowest aircraft sampling altitudes were typically over an order of magnitude less than along the Plateau top. These measurements indicate a consistent, rapid decrease in valley-released AgI IN concentrations with height above the

Plateau. Little AgI IN were found as high as 1 km above the Plateau top, and the aircraft sometimes overflew the plume while within 600 m of the Plateau top.

The evidence available suggests it is reasonable to assume that ground-released AgI is seldom transported as high as 1 km above the Plateau. This is in agreement with earlier observations over other mountain barriers. Because cloud temperatures are usually only slightly supercooled in this shallow seeded layer, the challenge is to produce enough AgI IN, *effective* at slightly supercooled temperatures. An abundance of observations exists in the intermountain West to demonstrate that the lowest kilometer over mountain barriers is often too warm for significant nucleation with conventional types of AgI and generators, and typical release rates. The problem is even more serious in the Sierra Nevada, which led the State of California to investigate propane seeding (Reynolds 1991).

Aircraft 2D-C probe measurements of IPC were examined for possible microphysical changes associated with the AgI seeding. NCAR counter observations were used to estimate the average positions of the AgI plume (or, more likely, intermingled plumes), and in-plume IPCs were compared with natural IPCs crosswind from the AgI.

The main findings of the six previously described experiments are summarized in Tables 1 and 2. NCAR counter measurements and a recent cloud simulation laboratory generator calibration were used to estimate AgI IN concentrations effective at in-plume aircraft sampling temperatures in Table 1. The most important and reliable values in Table 1 are the IPC increases based on *observed* differences in 2D-C particle imaging probe measurements within and crosswind from seeded zones.

Table 1 shows increases for both the estimated AgI IN concentrations and the observed IPC enhancements as the seeded zone temperature decreases. No discernable increase occurred in seeded zone IPC in the first three experiments where temperatures were no colder than -9°C. Valley seeding during the first experiment of 2 March may have increased the IPC. The second experiment of 2 March and the single experiment of 6 March both strongly suggest IPC enhancements within the seeded zone. The 6 March case showed IPC increases from both terrain-following and constant altitude passes. The two experiments with apparent IPC increases had the coldest clouds, below -12°C at aircraft sampling altitudes.

The AgI IN estimates in Table 1 and the estimates of seeding-caused IPC are in reasonable agreement when it is recognized that not all available AgI IN will nucleate ice crystals, especially when cloud LWC is limited. The type of AgI used is expected to result in contact nucleation, a slow process. The degree of agreement between AgI IN and IPC in Table 1 may be fortuitous. Instrumentation limitations and the uncertainties in the representativeness of

Table 1. - Summary of results for six valley seeding experiments. All values are averages for the seeded zone. The IPC calculations ignored particles smaller than 100 μm size.

MMDD/Exp.	Temp. range (°C)	Ave. Plume width (km)	Est. AgI IN conc. (L^{-1})	2D-C IPC increase (L^{-1})
0228/1*	-5 to -9	20.6	0.05	0
0301/1	-6 to -9	30.8	0.3	<0.2
0301/2	-6 to -9	25.2	3	<0.5
0302/1	-9 to -12.5	36.2	15	<7
0302/2	-12.5	4.7	70	>14
0306/1	-15 to -18.5	25.6	70	10
0306/1	-19	10.2	60	27

* Most aircraft AgI IN observations were made below cloud base.

Table 2. - Summary of precipitation network measurements during six early 1991 experiments from west to east over the Plateau. Values are average *hourly* precipitation rates in mm h^{-1} for the indicated time periods. The times correspond to the aircraft sampling periods lagged by 15 min.

MMDD/Exp.	MST	FVC	HAS	DOT	PTC	PTE
0228/1	1345-1635	0.0	0.0	0.0	0.0	0.0
0301/1	1140-1425	0.18	0.18	0.37	0.46	0.69
0301/2	1700-1845	0.29	0.87	1.60	0.73	0.73
0302/2	1030-1125	0.28	0.55	1.79	1.10	0.69
0306/1	1315-1445	0.0	0.0	0.17	0.0	0.17
0306/1	1635-1930	0.0	0.0	0.26	0.13	0.09

cloud chamber generator calibrations result in lack of precision for the AgI IN estimates. Estimates of seeding-caused IPC are also approximations, but should be significantly more accurate than the AgI IN estimates.

None of the estimated average AgI plume widths of Table 1 are as wide as the 40-km north-south extent of the AgI generator network. The median plume width from Table 1 is 25 km, suggesting that either some of the individual generator plumes were not transported over the Plateau or that the aircraft was simply overflying some plumes. The latter case is suspected to be most common because the generators were all located in similar valley floor locations. Moreover, observations along the upwind highway indicated that when AgI was transported over the Plateau, it usually was found all along the 6.7 km north-south extent of the highway. These highway observations suggest that AgI from multiple generators was usually transported over the Plateau when any Plateau-top transport was occurring.

Observations from the network of 5 precipitation gauges could not be expected to be conclusive regarding the effectiveness of seeding since only a limited number of non-randomized experiments was conducted. However, the gauge observations may be suggestive and they do set upper limits on possible snowfall enhancement. No seeding effects would be expected at gauges FVC and HAS on the Plateau's western slope.

The gauge observations given in Table 2 do not provide evidence of significant seeding-related snowfall increases on top of the Plateau during two of the six experiments because hardly any snow fell. Little AgI IN reached the high-based SLW cloud of 28 February so no significant response to seeding would be anticipated. Limited snowfall rates may have been caused by seeding during some of the other experiments, each of which had cloud base located below the Plateau top. Seeding may have increased snowfall particularly during the first experiment of 2 March and the single experiment of 6 March. But any enhancement of snowfall rates was limited, especially on 6 March, as shown by the average hourly rates in Table 2.

The minor snowfall amounts of the second experiment of 2 March raise special cause for concern. Supercooled liquid water amounts were relatively abundant as measured by microwave radiometer and an aircraft probe. Further, the mission was terminated early because of aircraft icing. Relatively high AgI IN concentrations were transported up to aircraft altitudes where cloud was certainly cold enough for nucleation of much of the AgI. A noticeable increase in IPC resulted in the seeded zone. However, in spite of the apparently quite seedable conditions and transport of AgI to aircraft altitudes, the valley seeding did not result in significant snowfall on the Plateau top.

10. RECOMMENDATIONS

The overall results summarized in Sec. 9 provide cause for concern about valley AgI seeding as practiced in the Utah operational program. While not the topic of this paper, targeting of valley-released AgI to cloud levels is known to be a problem under some storm conditions (e.g. pooling during valley-based inversions). Although SLW cloud frequently is present during winter storms, the temperature of the region reached by ground-released AgI is often only mildly supercooled. The measurements presented strongly suggest that concentrations of AgI, effective at SLW temperatures in the lowest several hundred meters above mountain barriers, should be higher than are being obtained with the current operational combination of AgI generator locations, generator type, seeding rates, type of AgI solution, and generator spacing.

It is recommended that effective AgI IN concentrations at supercooled cloud levels be increased in the Utah operational program. This increase could be achieved by some combination of a denser AgI generator network, higher AgI release rates, use of AgI solutions that promote nucleation at warmer temperatures, and improved generator siting. It also may be possible to increase generator yield although a recent cloud simulation laboratory calibration indicates the present operational generators are already quite effective at slightly supercooled cloud temperatures.

Where practical, siting of generators on windward slopes can markedly improve targeting frequency as compared with valley generators. Observations downwind of the HAS site in early 1991 and two similar high altitude sites in early 1994 showed that released AgI and tracer gas routinely reached Plateau-top altitudes and often aircraft altitudes. Similar experience was gained over the Bridger Range of Montana (e.g., Super and Heimbach 1988) and Grand Mesa of Colorado (e.g., Holroyd et al. 1988). High altitude, windward slope siting usually requires use of remote-control generators, admittedly a more expensive option than using manual generators along valley floors. However, high altitude generators avoid the problem of pooling of AgI within a shallow layer on the valley floor. Such pooling can result in failure to treat potentially seedable clouds during some storm conditions. A further advantage of high altitude generators may be rapid nucleation at relatively warm temperatures because of forced condensation-freezing (e.g., Finnegan and Pitter 1988, Chai et al. 1993).

While delivery of relatively high concentrations of AgI to cloud levels can and should be improved, a significant fraction of winter storm periods probably will be too warm for effective ice nucleation with ground-released AgI. It is recommended that means be investigated of effectively seeding storm periods with only slightly supercooled temperatures (0 to -4°C) in the lowest several hundred meters above mountain barriers, where ground-released seeding material is transported. Such storm episodes often have very abundant SLW flux. Liquid propane seeding may provide a possible augmentation to AgI seeding in such conditions. The technology exists to automatically release liquid propane when SLW is present (Super et al. 1995). However, further physical evidence of the effectiveness of liquid propane seeding is needed. Development of a technology to effectively seed warmer storms should substantially increase the frequency of storms that can be seeded.

The recommendations given above could significantly improve the effectiveness of the Utah operational seeding program. Moreover, many of the recommendations should be pertinent for other operational programs designed for winter orographic cloud seeding.

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