SOME PHYSICAL EVIDENCE OF AGI AND LIQUID PROPANE SEEDING EFFECTS ON UTAH'S WASATCH PLATEAU

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ABSTRACT

A series of cloud seeding experiments were conducted on Utah's Wasatch Plateau during the winter of 1994-95. Their purpose was to permit physical assessment of the effects of both silver iodide and liquid propane seeding, particularly at only slightly supercooled temperatures. Seeding materials were released in 1-hour pulses from a location well up the plateau's windward slope. The terrain often channeled the seeding plumes to an observing site, or target, located at a canyon head on the plateau top's upwind edge. Snow particles were detected at the target with a vane-mounted 2D-C optical array probe whose strobing speed was governed by an anemometer. AgI nuclei were detected there by an NCAR ice nucleus counter to confirm the presence and successful targeting of seeding materials.

Seeding with AgI under cold conditions produced obvious large increases in ice particle concentrations and measurable increases in precipitation at the ground during one experiment. Seeding with AgI under only slightly supercooled conditions, in which the contact-freezing mechanism is not expected to be effective, typically produced a negligible ice particle supplement. A forced condensation-freezing mechanism may have been operable during two experiments, producing detectable enhancements in the ice particle concentrations, but further verification is needed. Liquid propane seeding produced measurable increases in ice particle concentrations in some experiments, showing it to be an alternative to AgI at only slightly supercooled temperatures.

1. INTRODUCTION

Cloud seeding experiments with both silver iodide (AgI) and liquid propane were conducted during the 1994-95 winter on the Wasatch Plateau (Plateau) of central Utah. Their purpose was to investigate the ability of these seeding agents to create significant ice particle concentrations within orographic (mountain-induced) cloud. Of particular concern was determination of the warmest air temperatures at which the two seeding methods could do anything significant. A number of articles have cautioned that ground-based AgI seeding might often be ineffective in Utah's relatively warm winter orographic clouds (e.g., Super 1995). Seeding was done in a variety of conditions, including some with intense snowfall rates, and some with only slightly supercooled temperatures at which AgI effectiveness was expected to be minimal according to laboratory studies.

AgI ice nucleation has been investigated in laboratories, but orographic cloud characteristics raise questions about laboratory results. Laboratory clouds usually have much higher droplet concentrations and liquid water contents, are more homogeneous, and have less turbulence.

Laboratory estimates by Hicks and Vali (1973) indicated the effectiveness or yield (ice crystals produced per gram) of liquid propane is about 3 X 10^{11} ice crystals g^{-1} at temperatures colder than -2°C with yield decreasing to 10^{10} crystals g^{-1} near 0°C. However, laboratory work by Kumai (1982) indicated near 10^{11} crystals g^{-1} at temperatures colder than -5°C and an exponential decrease at warmer temperatures to only 10^{8} crystals g^{-1} near 0°C. Estimates based on field measurements by Hicks and Vali (1973) were more variable. However, they concluded that, "Thus, it can be stated that the liquefied propane will produce 10^{12} crystals per gram of propane under average conditions and at temperatures colder than -2°C. Particular circumstances may lead to approximately tenfold increases or decreases in efficiency."

The California propane seeding program described by Reynolds (1989) was based on the 10^{12} crystals per gram yield claimed by Hicks and Vali (1973). However, there is enough variability in the published yields to justify further field testing, especially at temperatures warmer than -5°C where AgI is expected to be ineffective. Observations at several mountain locations in California (e.g. Reynolds 1989) and the intermountain West (e.g. Sassen and Zhao 1993; Huggins 1995) have shown that supercooled liquid water (SLW) warmer than -5°C is common in winter orographic storms. Therefore, it is important to document propane's ability to create ice crystals and snowfall in slightly supercooled liquid water cloud.

All AgI and liquid propane seeding experiments for the 1994-95 season used 1-h releases ("pulses") from the High Altitude Site (HAS) at 2540 m elevation on the west-facing Plateau slope (Fig. 1). The HAS is a minor peak very exposed to winds with any westerly component. Microphysical effects of seeding were observed at the Target (TAR) on the Plateau top's west edge at 2855 m, 4.2 km northeast of the HAS. Instruments verified that seeded cloudy air passed by the TAR. Ice particle characteristics were monitored before, during, and after each passage of seeded air (each pulse). Instruments at both sites provided measurements of wind, air temperature, and presence of SLW.

Similar experiments were conducted during the 1995-96 season to continue gathering data on the effectiveness of the two seeding techniques at slightly supercooled temperatures. Data from these experiments, still being analyzed, should provide a basis for further refinements of the experimental results discussed here.

2. EXPERIMENTAL EQUIPMENT AND DATA REDUCTION

A manual North American Weather Consultants (NAWC) AgI generator released 8 g h^{-1} of AgI (Griffith et al. 1992) from the HAS. Two-percent AgI was complexed with NH_4I in acetone solution. This generator and solution has a high yield at warm temperatures according to DeMott et al. (1995). For example, under natural draft conditions in the Colorado State University Isothermal Cloud Chamber (ICC), effectiveness values were over 4 X 10^{12} ice particles g^{-1} of AgI at -6°C and about 10^{14} at -8°C.

The propane dispenser was based on the design of Reynolds (1991) as described by Super et al. (1995). Liquid propane was released at about 6000 g h^{-1} (3 lb h^{-1}) through a nozzle which chilled a volume of cloudy air to colder than -40°C. High concentrations of ice crystals were formed in this chilled volume by condensation of tiny liquid droplets which immediately froze by the homogeneous freezing mechanism.

The HAS had an unheated wind sensor and a Rosemount tower-type icing detector about 7 m above ground level (a.g.l.); air temperature and relative humidity were observed about 3 m a.g.l. Measurements were averaged or summed at 6-min intervals by a data logger. The site was manned during experiments for operation of the NAWC generator. Moreover, the site technician recorded cloud base location, visibility, snowfall, and other weather phenomena.

All AgI and ice particle detection occurred at the TAR, located at the head of a major canyon. Sampling with an instrumented van during the 1994 field program (Holroyd et al. 1995) revealed that AgI and tracer gas released from the HAS frequently crossed the Plateau top's west edge near the TAR during southwesterly flow. Channeling by local terrain is believed to be a major factor in the routine targeting of the TAR site with HAS releases.

A Particle Measuring Systems 2D-C particle imaging probe with 800-μm image width and 25-μm resolution was attached to a vane on a tower which kept the probe pointed into the wind about 8 m a.g.l. A nearby heated anemometer provided measurements used to control the probe's strobe rate to ensure production of non-distorted, two-dimensional ice crystal images. This method worked well with wind speeds greater than about 2 m s^{-1} which were frequent at the canyon head location. The approach of using a vane-mounted 2D-C probe on a tower, first used during the early 1994 Utah field program, is believed superior to past ground-based observations which used a large

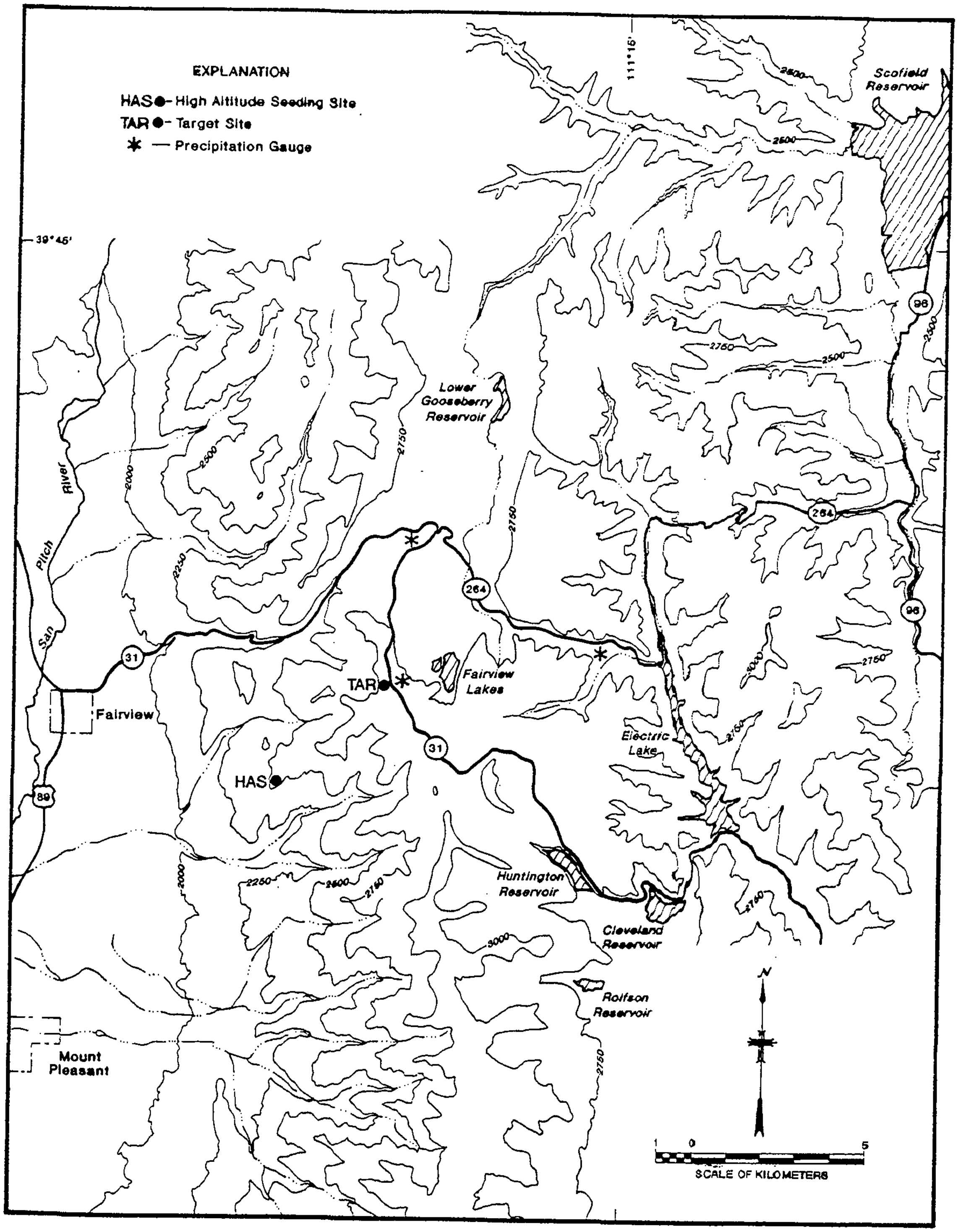

Fig. 1. Wasatch Plateau Experimental Area for the 1994-95 field program. Seeding material was released at the HAS on the windward slope and effects were examined at the TAR located on the Plateau top's west edge. Precipitation gages were operated near the TAR and crosswind and downwind of it as shown.

aspirator to draw air past a vertically-pointed probe. Shattering of fragile crystal types against the aspirator walls has been visually observed on several occasions.

Ice particle concentrations (IPC) and precipitation rate were calculated by the methods discussed in detail by Holroyd (1987). Particles smaller than 100 μm (0.1 mm), only 4 times the probe's resolution, were ignored as were particles with an estimated center of mass outside the probe's 800-μm sampling width. The software was recently enhanced to allow the exclusion of particles greater than a particular size. This has allowed exclusion from analysis of natural particles too large to have been produced by seeding. Such exclusions were done with general studies summarized later in Table 2, but not in the detailed case studies which include all ice particles greater than 0.1 mm.

Expected ice particle sizes, D, were calculated from empirical equations, based on air temperature and estimated growth time, in Redder and Fukuta (1989). It was found from careful size spectrum analyses of cases with crystals obviously produced by seeding that about 95 percent of seeded crystals were at sizes less than twice the expected size, 2*D. The presence of crystals larger than expected is partly a result of some of the air being retarded by surface friction as it ascends the plateau slopes, giving the crystals a longer growth time. It may also be a result of inaccuracies in the calculations. The 2*D size was therefore used as a convenient upper limit for analysis when abundant natural snow was present.

AgI at the TAR was detected by an NCAR acoustical ice nucleus counter (NCAR IN counter) operated at a cloud chamber temperature near -20°C. Langer (1973) and Super et al. (1988) describe NCAR IN counter detail. The IN data were moved 60 s back in time to compensate for the delays caused by air flow through the apparatus and the growth and settling times of the resulting ice particles. A comparison by DeMott et al. (1995) of the ICC and NCAR IN counter showed reasonable agreement between the two measurement approaches.

The TAR technician closely monitored the NCAR IN counter operation.

Other equipment at the TAR included a heated wind vane, a Rosemount tower-type icing detector, and temperature and relative humidity sensors, all mounted 8 m a.g.l. The on-site technician made weather observations at least once and usually twice per hour. Temperature sensors at both the HAS and the TAR were carefully calibrated with Assmann psychrometers to about 0.1°C.

Icing detector "trips" refer to the deicing cycle which occurred after a mass of SLW collected by accretion, freezing on the Rosemount detector sensor. Each deicing cycle produced a heater relay "trip," which was recorded. An approximate value of cloud liquid water content (LWC) can be calculated from the detector trip rate. Assuming a collection efficiency of 1.0 for the sensor, LWC can be related to mass load of ice required to trip the detector and wind speed. Wind tunnel calibrations done in 1985 and 1986 revealed differences in the mass load trip point among 3 different Rosemount tower type icing detectors, with an average value of 0.075 g and range about that value of ±0.015 g. Because no wind tunnel calibrations were done for the similar HAS and TAR icing detectors, it will be assumed that they also tripped (deiced) every time 0.075 g of ice was accreted. The LWC can then be calculated from:

$$LWC = NM/AS \qquad (1)$$

where N is number of trips per hour, M = 0.075 g, A is sensor cross sectional area, 1.77 cm^2, and S = wind speed in m s^{-1}. The expression can be simplified to:

$$LWC\ (g\ m^{-3}) = 0.12\ N/S \qquad (2)$$

Equation 2 will be used in all LWC estimates given in this paper. When trip rate was slow, it was sometimes necessary to estimate what fraction of a trip occurred during a period of interest (e.g., if a trip occurred soon after the end of a seeded hour).

Liquid water contents calculated from the HAS and TAR icing detectors are only point samples near the ground and may not be representative of the entire orographic cloud

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region affected by seeding. More representative SLW observations have been made in earlier field programs with microwave radiometers (e.g. Huggins 1995).

Three Belfort Universal weighing precipitation gages with large orifices were operated at locations shown on Fig. 1. The melted water equivalent resolution of these gages is less than 0.005 in. (0.13 mm) and the time resolution is about 3 minutes. Gages were equipped with Alter wind shields and were located in small protected clearings in conifer forest to minimize wind-induced gage catch losses. One gage, 250 m east of the TAR, was expected to receive essentially the same snowfall as the TAR. A second gage, 6 km east-northeast of the TAR, was expected to often be targeted by the seeding plume at a more downwind location on the Plateau top. The third gage, 4.3 km north of the TAR near the head of Fairview Canyon, was a control gage to monitor natural temporal snowfall variations. The 1994 van observations suggest that the latter location would be crosswind of the seeding plume when the plume passed over the TAR.

3. EXPERIMENTAL DESIGN

Technicians were deployed between early morning and late at night when orographic clouds were present. If they observed cloud base below the TAR and HAS winds in the southwest quadrant, a seeding experiment could commence. Liquid propane would not be released unless the HAS was in cloud because embryonic seeded ice crystals quickly sublimate in undersaturated air. Moreover, AgI experiments were favored with colder temperatures. Either AgI or propane was released for 1 h during a seeding experiment.

Because equipment was not available to detect propane at the TAR, a "tracer" or "tag" was co-released which could be detected. That tracer material was AgI, released for the first and last few minutes of each propane release, and hereafter called "beginning tags" and "end tags," respectively. If both AgI tags were detected at the TAR during a propane experiment, it was assumed that propane was transported to the TAR during the entire 1 h experiment. Although AgI has the potential to nucleate ice particles, later discussion will show that it did not produce significant IPC at the slightly supercooled temperatures existing during the propane seeding experiments.

No consideration was given to natural snowfall or SLW at the sites in deciding when to release seeding material. Experiments were conducted when natural snowfall ranged from none to heavy and SLW was absent or present at one or both manned sites. The purpose was to mimic operational-type seeding for which these conditions are rarely known in real time. However, as might be anticipated, the most obvious seeding effects occurred during periods with little or no natural snowfall. The two experimental days with the most obvious response to seeding, December 15, 1994, and March 5, 1995, are both in that category.

Two types of analyses will be presented. All experiments, even obvious failures due to mistargeting, were given a "general" or overview analysis. Some experiments with apparently obvious seeding signatures were analyzed in detail and are presented as case studies.

The 2D-C analysis software uses pairs of times within which ice particle characteristics are summarized. For the case studies presented later, the seeded plume interval was considered to be a simple 1-hour period that best fit the IN indicators of the interval. For the general analyses an attempt was made for each experiment to define times according to a control-buffer-plume-buffer-control sequence. Seeding results were calculated by comparing the plume conditions with one or both of the adjacent controls. The after-seeding control was often unsuitable for AgI experiments when the AgI lingered for a significant time. It was rarely used in Table 2 to be discussed. The buffers were considered to have only partially seeded conditions. Variations of definition were necessary in a few cases from the crowding of the experiments, wind shifts causing premature endings for the experiments, and occasional premature shutdowns of the data systems. The following rules for defining the time boundaries of the five intervals provided a generally consistent data set which can be refined as needed in future analyses. Figure 2 provides a schematic of the time intervals involved.

The first control was up to one hour long, ending at the time that the NCAR IN counter first detected traces of AgI as a seeding agent or as a tag. Sometimes the control was the same as the second control of the previous experiment. For possible control periods of greater than one hour duration

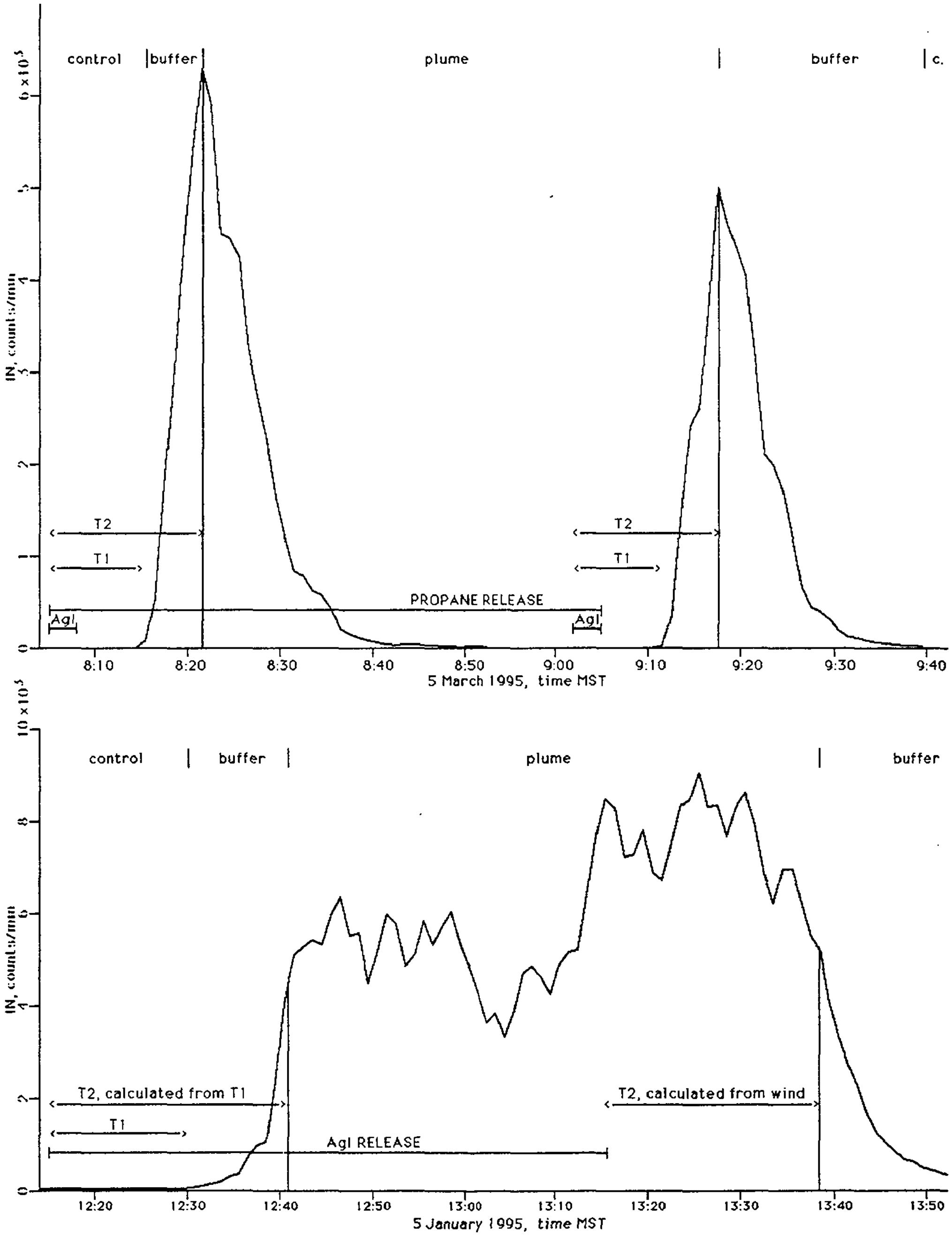

Fig. 2. A schematic diagram showing the time interval definitions used for the AgI and liquid propane experiments and discussed in the text. Some timings are based on average winds and others on IN presence recorded at the TAR.

between experiments, the control period was divided in half between the adjacent experiments.

Let T1 be the time in minutes between the first release of AgI at the HAS and its initial arrival at the TAR (end of first control or start of second tag). Let T2 be the time in minutes between the initial release and the peak AgI IN counts at the TAR for the tags at either end of the propane seeding intervals. It was found for this season that T2 = 1.668 * T1, with a moderate amount of scatter. That relation nearly coincides with a least-squares fit with the square of the correlation coefficient, r^2, of 0.70. For all AgI experiments the T2 had to be calculated in this manner because the counts remained at large values for over an hour due to "blurring" of the 1-h released plume presumably caused by windshear and other factors. The first buffer was defined for both the AgI and propane experiments as the interval between T1 and T2. The plume was defined to start at the time of the observed or calculated T2.

Values for T1 and T2 are not observed for the end of AgI experiments so their estimated durations had to be calculated. Let t1 be the transit time for air to travel from the HAS to the TAR 4.2 km away at the wind speed recorded at the HAS. Similarly, let t2 be the transit time determined from the TAR wind speed. Both wind speeds were averaged from the time of a seeding start or stop or a tag start until its expected detection at the TAR. Based on the propane tags of this season, a T2 was calculated for the end of the AgI experiments as T2 = 1.207 * (t1 + t2)/2 + 0.856, with an r^2 of 0.56. The end of the plume and the start of the second buffer was defined as the observed (propane cases) peak in IN counts for the second tag or else its expected time, calculated from T2 for the AgI experiments. Note that for the propane cases, this T2 is referenced to the start time of the AgI release for the second tag. The propane release actually ended 2 to 5 minutes later. Therefore the propane "plume" is slightly truncated, with the trailing end assigned to the buffer interval. This should not affect the analysis results.

For AgI experiments the end of the second buffer must be when the IN counts return to background values. For propane experiments, it is convenient to use the same definition though a much shorter interval might be justified. The second control begins at the end of the second buffer and extends for up to an hour.

For the start of each experiment, T2 (time to peak of first tag) provides an estimate of the growth time available for the ice particles resulting from seeding. The HAS and TAR temperatures during the plume release or presence, respectively, were examined to determine the *maximum* growth rate (often at -5°C) possible within that temperature range. That growth rate and T2 were used to estimate expected *maximum* crystal sizes. Those sizes were then doubled to serve as an upper limit to exclude large natural snow particles from the analyses. Though some crystals may have followed a trajectory temporarily climbing to colder temperatures, fall speeds of the relatively small seeded crystals are limited and much of the growth will have occurred at warmer temperatures between the HAS and TAR.

4. EXPERIMENTAL RESULTS

4.0 Expectations and general results

It is not possible to estimate AgI nuclei or resulting ice particle concentrations in the plume at the TAR based on the release rate of AgI, the nucleation rates at the observed temperatures, and wind speeds. The lateral and vertical extents of the plume are not known and so a volume cannot be computed. Neither is it known if TAR sampling was in the core of the plume, its fringes, or in between as the wind shifted direction. However, it is possible to convert the concentration of IN observed at the TAR to the expected IPC.

The laboratory measurements of DeMott et al. (1995) indicate that the NCAR IN counter detects about 65 percent of the IN observed by the ICC. The TAR IN counts per minute were therefore transformed to "true" IN concentrations (L^{-1}) by dividing by 0.65. The IN from the NAWC generator had an exponential activation rate for contact nucleation of about 0.085 min^{-1} which varied little with temperature. DeMott et al. (1995) recommend multiplying this rate by the ratio of about 100/2100 for the relative concentrations of cloud droplets in natural clouds versus the ICC. That results in an activation rate constant of 4.05×10^{-3} min^{-1}. For most of the transit times (T2) of the IN, the calculations indicated that between 5 and 15 percent of the potential IN would be activated by the time the plume reached the TAR.

The IN were measured at the TAR in a chamber at -20°C. Based on the DeMott et al. (1995) results, a ratio can be calculated that expresses the fraction of IN that would be active at the temperatures observed at the TAR. In doing so, the logarithm of the effectiveness was linearly interpolated for temperatures between the data points at -6, -8, and -12°C. Effectiveness was crudely estimated by extrapolation for temperatures warmer than -6°C, beyond available observations in a region where rapid change is expected. However, the point of these estimates is that very low IPC values would be expected at temperatures above -6°C.

The activation rates based upon elapsed time were then multiplied by the temperature dependence ratio to give a final fraction, F, indicating the fraction of IN active at -20°C that should have nucleated ice particles at the TAR temperature by the time the air arrived there.

Table 1 is a list of all experiments during the 1994-95 season. For each experiment are listed the time interval of the plume at the TAR, the nucleant type, the HAS and TAR temperatures, the transit times T2 (min) for the start and end of the experiment, the average and maximum IN observed at the TAR (both adjusted by dividing by 0.65), the expected activation fraction F, the expected IPC average and maximum sizes as the product of the adjusted IN and F, and the expected crystal sizes. Note that the IPC expectations are based on the assumption that the AgI will activate by the contact-freezing method that operates in the ICC. If nuclei are activated by a forced condensation-freezing mechanism as they exit the generator (Finnegan and Pitter, 1988; Chai et al. 1993), then the measured IPC values should be much higher.

The average IN for the propane cases is much lower than the maximum IN because only two brief pulses of AgI were released. The maximum IPC is more relevant for such cases as an indicator of the potential ice particle production by the AgI tags under those conditions. In evaluating the experiments, the IN values can indicate how well the plume was directed to the TAR. There are two experiments with obviously poor targeting. The transit times are inverse to the wind speeds.

Experiments 17, 18, and 21 had release temperatures warmer than 0°C and therefore neither forced condensation-freezing of AgI nor liquid propane could create ice particles at the HAS release site. Silver iodide seeding should have enhanced IPC values for experiments 1-4 because of the cold temperatures. Experiment 5 might have produced observable IPC because of the slow wind speed and resulting long transit time. The remaining AgI seeding experiments should have produced negligible IPC values by the contact-freezing mechanism. That leaves forced condensation-freezing for AgI and homogeneous freezing for liquid propane as mechanisms for increased IPC. Both require humidities at least saturated with respect to ice and temperatures colder than 0°C at the HAS release site.

Table 2 lists the same experiments with the IPC values in the *first* control and the plume intervals along with the ratio of plume/control and difference of plume minus control. The seeding agent is again listed. The timings and concentrations discussed in the detailed case studies may differ from the numbers in Tables 1 and 2 because different plume definition criteria were used and upper size limits of ice particles were not used in the case studies. The IPC values in both buffers and the second control were also calculated but are not presented here. The second buffer was necessarily long in the AgI cases. The second control then became separated from the plume by a much longer time than the first control. Further refinements of the interval timings may be attempted in future analyses to exclude the effects of obvious natural showers so that the seeding effectiveness at slightly supercooled temperatures may be more accurately assessed.

Table 1. Some characteristics and expectations for the 1994-95 winter experiments. The seeding agents are abbreviated as A = AgI and P = liquid propane. The temperatures (°C) are the averages at the HAS (left col.) during the agent release and at the TAR (right col.) for the indicated plume time intervals (HHMMSS - MST). Plume transit times, min, are for both the start and end of the experiment. TAR IN counts are given as average and maximum, adjusted to L^{-1}. The expected IPC values are the product of the IN and activation fraction, F. The expected crystal sizes (mm) are based on the temperature range and the transit times.

Exp	Date		Plume Times	Agent	Temperature		Transit		IN Ave.	Max. (L^{-1})	F	IPC Ave		Size, mm
1	941213	A	094051-105030	A	-6.1	-8.1	30.9	40.5	4110	8260	$1.08x10^{-2}$	44.4	89.2	2.30
2	941213	B	123911-132554	A	-6.2	-8.6	29.2	15.9	1860	5786	$9.33x10^{-3}$	17.4	54.0	1.68
3	941213	C	152411-162012	A	-6.1	-8.6	24.2	20.2	2966	8788	$9.19x10^{-3}$	27.3	80.8	1.40
4	941215	A	095051-105300	A	-7.8	-10.4	20.9	23.0	3807	8509	$2.55x10^{-2}$	97.1	217.0	.50
5	950105	A	095233-104536	A	-3.7	-5.6	67.6	60.6	7962	15086	$2.74x10^{-4}$	2.2	4.1	3.90
6	950105	B	124051-133954	A	-3.0	-5.5	25.9	24.9	9282	13880	$9.87x10^{-5}$	.9	1.4	1.52
7	950105	C	154731-170318	A	-4.1	-6.2	17.5	33.3	319	3169	$3.30x10^{-4}$	.1	1.0	1.94
8	950107	A	105430-114830	P	-2.0	-4.0	24.5	23.5	377	2988	$6.94x10^{-6}$	.0	.0	.55
9	950107	B	131330-141230	P	-2.7	-5.0	13.5	13.5	546	3358	$2.25x10^{-5}$	.0	.1	.80
10	950126	A	101733-103630	A	-2.6	-4.3	72.6	31.5	7033	10528	$2.39x10^{-5}$	.2	.3	1.55
11	950126	B	123830-135832	P	-0.8	-4.0	30.5	47.5	399	3842	$1.10x10^{-5}$	.0	.0	1.03
12	950126	C	135832-144224	A	-0.7	-4.4	47.5	31.4	3527	6732	$2.21x10^{-5}$	.1	.1	1.03
13	950126	D	162551-170954	A	-2.0	-4.4	35.9	19.9	7544	15368	$1.60x10^{-5}$	.1	.2	.79
14	950126	E	190911-200806	A	-2.5	-4.6	24.2	23.1	5814	8442	$1.94x10^{-5}$	.1	.2	1.42
15	950126	F	220108-230300	A	-3.6	-5.8	16.1	18.0	2015	7122	$1.13x10^{-4}$	.2	.8	1.06
16	950214	A	112112-123430	P	-3.7	-6.0	6.2	21.5	17	74	$1.30x10^{-4}$	.0	.0	1.26
17	950303	A	202051-211354	A	+0.8	-2.8	20.9	13.9	9944	12617	$6.46x10^{-7}$	.0	.0	.26
18	950303	B	224731-234430	A	+0.4	-3.0	17.5	14.5	12776	16691	$8.15x10^{-7}$	.0	.0	.22
19	950305	A	082130-091730	P	-2.1	-4.1	16.5	15.5	1506	9669	$5.58x10^{-6}$	.0	.1	.38
20	950305	B	094731-104142	A	-1.5	-3.6	17.5	11.7	9001	15900	$2.18x10^{-6}$	.0	.0	.40
21	950305	C	114230-120942	P	+0.3	-2.5	17.5	7.7	7	88	$2.78x10^{-7}$	.0	.0	.22
22	950311	A	191430-201330	P	-1.2	-3.1	14.5	16.5	1752	8358	$9.73x10^{-7}$	.0	.0	.21
23	950311	B	211130-220830	P	-0.9	-3.0	11.5	11.5	823	9203	$5.91x10^{-7}$	.0	.0	.16
24	950311	C	233630-243030	P	-2.0	-4.0	16.5	13.5	1470	11363	$4.42x10^{-6}$	.0	.1	.38

4.1 Results of specific experiments

These are preliminary results. Many experiments are based on timings from wind speed relationships which should be improved with the addition of data from the 1995-96 season, not yet analyzed. Most experiments will receive only a brief discussion. For all experiments plots of 1-minute averages of IPC within the restricted size range (0.1 mm to twice the expected size) were examined to see if any potential increase was reasonably symmetric throughout the plume interval rather than an obvious product of natural variability.

4.1.1 December 13, 1994. The natural background IPC was very high. The cold temperatures allowed an abundant activation of the AgI. A plot of 1-minute averages (not shown) indicated an abrupt IPC increase during the plume passage. IPC values in the second buffer intervals, in air with lingering AgI, were always greater than subsequent control intervals even though there was a variable natural background. Comparing the expected and actual IPC values, it appears that these three experiments produced measurable concentration increases that were smaller in size than the natural background. However, those increases were smaller than the average expected values of Table 1.

Table 2. Calculated IPC (L^{-1}) for the first control and plume intervals for the experiments of Table 1 with the same seeding agent abbreviations. The ratio of plume/ control IPC may be an indicator of seeding effectiveness or of the statistics of natural variability. Some controls had large IPC values because the experiment followed an intense shower, as indicated in the discussion.

Exp.	Date	Agent	IPC (L^{-1}): Control	Plume	Ratio	Increase
1	941213 A	A	47.7	52.1	1.1	4.4
2	941213 B	A	79.9	95.0	1.2	15.1
3	941213 C	A	106.9	117.2	1.1	10.3
4	941215 A	A	11.7	95.0	8.1	83.3
5	950105 A	A	5.1	27.5	5.4	22.4
6	950105 B	A	13.7	91.3	6.7	77.6
7	950105 C	A	49.5	28.8	0.6	-20.7
8	950107 A	P	19.7	18.9	1.0	-0.8
9	950107 B	P	36.7	6.3	0.2	-30.4
10	950126 A	A	45.2	41.4	0.9	-3.8
11	950126 B	P	47.6	12.8	0.3	-34.8
12	950126 C	A	5.7*	12.1	2.1	6.4
13	950126 D	A	5.7	15.6	2.7	9.9
14	950126 E	A	35.4	113.0	3.2	77.6
15	950126 F	A	141.6	44.7	0.3	-96.9
16	950214 A	P	45.8	49.2	1.1	3.4
17	950303 A	A	0.5	0.8	1.6	0.3
18	950303 B	A	1.5	0.7	0.5	-0.8
19	950305 A	P	2.9	29.2	10.1	26.3
20	950305 B	A	49.8*	3.4	0.1	-46.4
21	950305 C	P	49.8	20.0	0.4	-29.8
22	950311 A	P	101.3	105.2	1.0	3.9
23	950311 B	P	8.2	17.6	2.1	9.4
24	950311 C	P	77.7	93.6	1.2	15.9

*second control used as first not available

4.1.2 December 15, 1994: A case study.

A single experiment was conducted, then the storm ended and skies began to clear. AgI was released from 0930 to 1030 (all times MST). The HAS was in cloud from before AgI release until 1130, when the site was at cloud base. By 1153 cloud base was estimated at 75 m above the HAS. Snowfall was nil at 0930 and very light at later 0.5-h observations. Although the icing detector did not trip from 0830 to 1200, the only visibility observation, at 1030, was 100 m. Operating an AgI generator in cloud under nearly water-saturated conditions might cause formation of high concentrations of embryonic ice crystals near the generator (Finnegan and Pitter 1988).

HAS wind was southwesterly near 3 m s^{-1} during AgI release; temperature was -7.8°C. The temperature began to warm after 1030 and the wind shifted to southerly about an hour later as the storm ended. TAR winds were westerly, near 7.5 m s^{-1} during the seeded hour; air temperature was near -10.4°C.

The TAR detector had 3 trips in the hour before AgI arrival and 1 trip during the seeded hour, so SLW was present until at least 1030, the time of the last trip. Using equation 2, cloud LWC was 0.050 g m^{-3} during the preseeded hour and 0.015 g m^{-3} during AgI plume passage.

The middle panel of Fig. 3 shows that NCAR IN concentrations were nil prior to arrival of AgI at 0945. Thereafter, IN concentrations were about 3000 L^{-1} (effective at -20°C) for about an hour, then decreased to background levels by 1100. Fig. 3's top panel shows natural IPC for all sizes above 0.1 mm (no upper limit used) was near 10 L^{-1} before the hour of maximum seeding, 0945 to 1045 (seeded hour), and about 5 L^{-1} after 1100. In contrast, calculated average IPC for the seeded hour was 149 L^{-1}.

As with estimates of IPC, estimates of snowfall are based on the methodology discussed by Holroyd (1987), applied to the 2D-C probe measurements. The term "snowfall" will refer not to snow depth but to the rate of accumulation of *snow water equivalent*, also called precipitation intensity, throughout this paper. The bottom panel of Fig. 3 shows that natural snowfall was near 0.25 mm h^{-1} before seeding and about half that after seeding, with a calculated average rate between 0945 and 1045 of 1.32 mm h^{-1}. Thus, calculations indicated that seeding increased average IPC by 142 L^{-1} and average snowfall by 1.1 mm h^{-1}. Fig. 3 shows a seeding signal with excellent correspondence between the temporal distributions of the AgI IN concentrations, the IPC, and the snowfall.

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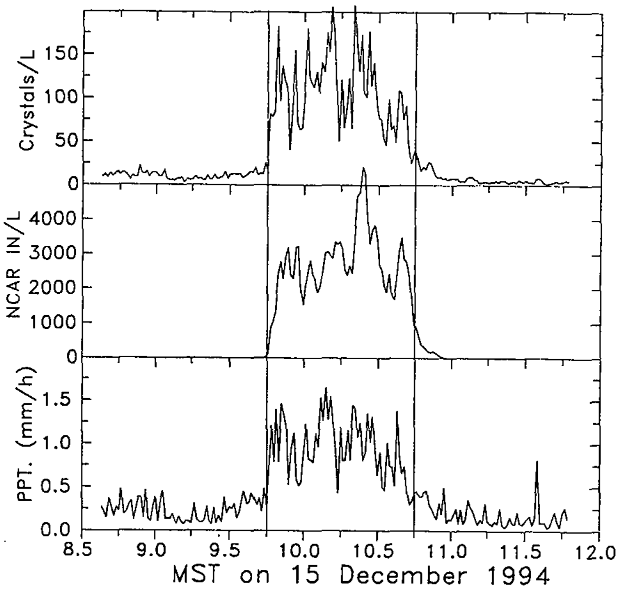

Fig. 3. Temporal distributions of IPC (top) and precipitation intensity (bottom), calculated from TAR 2D-C probe and NCAR IN counter observations of IN L^{-1} effective at -20°C (middle), for the experiment of December 15, 1994. Vertical lines show the estimated hour of maximum seeding plume presence.

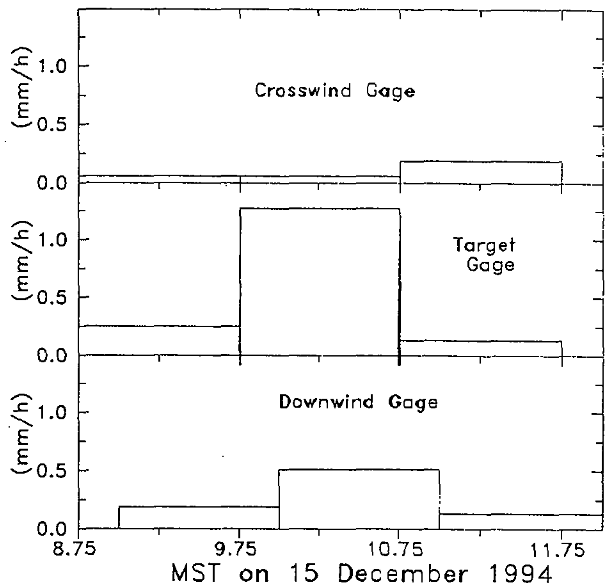

Fig. 4. Hourly precipitation rates measured by crosswind, TAR, and downwind gages for the December 15, 1994, AgI seeding experiment. The Downwind gage chart was read 15 min later than the other gages to allow for AgI plume transport time.

Precipitation gages provided further evidence that the 1-h seeding pulse increased snowfall. Hourly snowfall totals are plotted on Fig. 4 for the seeded hour and the hours before and after. The downwind gage chart was read 15 min later than the other two gages (1000 to 1100) to allow transport time for the AgI pulse presumed to have traveled over that gage with the prevailing westerly flow on the Plateau top. The downwind gage chart's trace changed its slope, indicating a higher snowfall rate near 1000, when arrival of the seeding pulse was anticipated.

Fig. 4 shows limited snowfall crosswind from the TAR during all 3 h with the greatest amount (0.19 mm) in the hour after seeding. The TAR received 0.25 mm the hour before seeding, 1.27 mm in the seeded hour, and 0.19 mm the hour after seeding, indicating that AgI seeding increased TAR snowfall by over 1 mm in the seeded hour, in agreement with the 2D-C probe estimates. Downwind gage values for the same hours were 0.19, 0.51, and 0.13 mm, suggesting that seeding increased snowfall at the gage 6 km east-northeast of the TAR by 0.35 mm during the hour it was presumably seeded.

Figs. 5 and 6 give further evidence of seeding effects. Data are partitioned by crystal sizes and habits for crystals of at least 0.1 mm size. The seeded hour's snowfall (not IPC) was caused by an increase in the proportion of crystal sizes between 0.4 and 1.0 mm. The upper limit was likely less than 1.0 mm because the proportion of crystals larger than 1.0 mm decreased during seeding, and processing software does not provide subcategories within the 0.6- to 1.0-mm range. Fig. 6 shows an increase in "hexagonal" crystals, apparently plates as shown on Fig. 7.

Results are more obvious in 2D-C images. Fig. 7 shows 5 panels, each with "lines" 0.8 mm wide and smallest particles of 0.1 mm. Top and bottom panels are 60 s samples starting at 0940 and 1100, shortly before and after AgI seeding, respectively. The 3 middle panels are 6 s samples during seeding at 1000, 1010, and 1020. Uniformity of crystal sizes and shapes seen on the 3 middle panels was typical of the entire seeded hour and is in contrast with before and after periods. Seeded IPC was increased over an order of magnitude because the top and bottom panels each represent 10 times the duration of each seeded panel. Many seeded crystals had centers transparent to the probe's laser, indicating a thin inner structure. These crystals appear almost round or irregular with sizes near 0.3 mm. They are probably small hexagonal plates that do not appear as such because of the probe's 25-μm resolution.

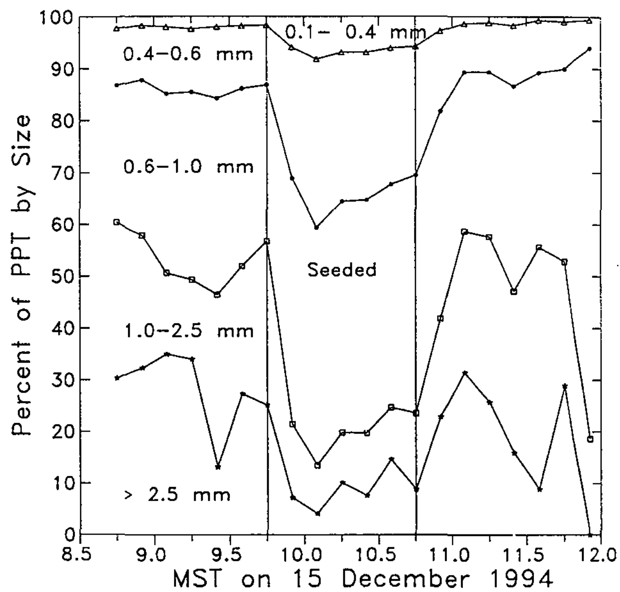

Fig. 5. Cumulative percentage of precipitation intensity, partitioned by size, vs. time for the December 15, 1994, experiment. Vertical lines show estimated hour of maximum seeding plume presence.

Assuming AgI created embryonic crystals near the HAS where the temperature was −7.8°C, then growth times were near 900 s before detection at the TAR where temperature was -10.4°C. A 0.3 mm seeded crystal after 900 s is an average growth rate of 0.33 μm s^{-1}. A somewhat larger size of 0.5 mm was estimated in Table 1 but Fig. 7 suggests few seeded crystals grew that large. Perhaps most seeded crystals nucleated some distance downwind of the HAS.

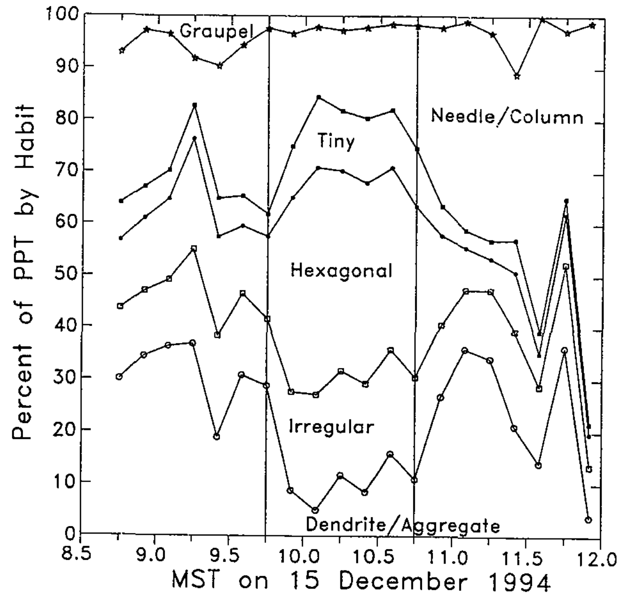

Fig. 6. Cumulative percentage of precipitation intensity, partitioned by crystal habit, vs. time for the December 15, 1994, experiment. Vertical lines show estimated hour of maximum seeding plume presence.

In summary, AgI was released in cloud from the HAS during relatively cold temperatures (-7.8°C) and very limited natural snowfall. Seeding produced an IPC near 140 L^{-1} at the TAR, mostly between 0.2 and 0.5 mm size. These values are in reasonable agreement with the calculated values of Table 1 where the average (maximum) IPC is 97 (217) L^{-1} and the expected size is 0.5 mm. Most of the crystals were hexagonal, often with transparent (thin) centers. Seeding increased precipitation intensity about 1.0 mm h^{-1} at the TAR and possibly about one-third that rate at the gage 6 km farther downwind. The TAR's seeded precipitation intensity is not trivial. For comparison, only about 20 percent of hours with detectable snowfall exceeded 1.0 mm h^{-1} during the early 1991 season (Super 1994).

This experiment presents an obvious case of seeding enhancing the snowfall during a period when nature was ineffective in snowfall production. It is encouraging that AgI seeding produced this snowfall increase during limited cloud LWC. No SLW was detected at the HAS and the highest TAR LWC was about 0.05 g m^{-3} during the hour prior to seeding.

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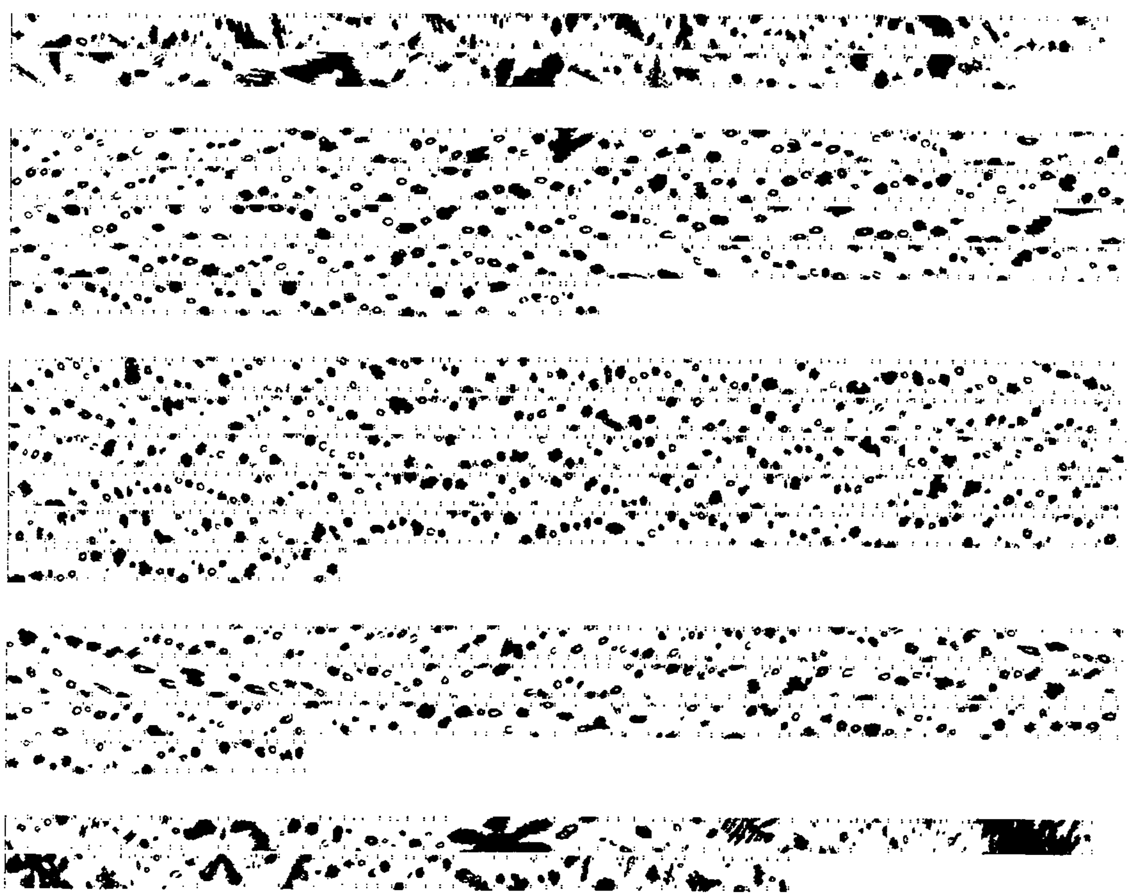

Fig. 7. TAR 2D-C images of ice particles (100- m minimum size) for selected periods during December 15, 1994. The top and bottom panels are 60 s periods (0940 to 0941; 1100 to 1101) before and after passage of the AgI seeding plume. The three middle panels are for 6 s periods during seeding (at 1000, 1010 and 1020).

4.1.3 January 5, 1995. The first experiment of the day produced a major enhancement of IPC within the center of the plume interval; the edges had near-background values. The trailing buffer IPC was greater than that in the following control. The second experiment had a very strong IPC enhancement that entirely filled the plume interval. The trailing buffer interval showed a steadily falling concentration toward initial background values. Then there was a strong increase in natural background IPC. Within the plume interval of the third experiment the natural pulse dominated the first portion while the latter half of the interval had low values near the backgrounds of the other experiments.

Table 2 indicates that the first and second experiments had strong seeding signatures while the third failed to produce any for reasons to be discussed. Seeding appeared to produce an IPC increase of about 22 L^{-1} in the first experiment and 78 L^{-1} in the second, both several times the background level. Snowfall calculated from the 2D-C probe observations for the control and plume periods of Table 2 showed an increase during plume passage in both cases. For the first experiment snowfall increased from 0.28 mm h^{-1} before to 0.40 mm h^{-1} during plume passage, a minor increase. During the second experiment the corresponding values were 0.29 and 1.28 mm h^{-1}, suggesting seeding produced a snowfall increase near 1 mm h^{-1}, a significant rate.

Table 1 indicates that there should have been only minor increases in IPC from the contact-freezing mechanism at the mildly supercooled temperatures between the HAS and TAR. Thus, the evidence suggests that the forced condensation-freezing mechanism may have been effective during the first two experiments. There were no indications from the icing detector of SLW at the HAS during those experiments, but the observer noted that cloud base was below the site. Recorded HAS relative humidity was sufficiently high, within a few percent of water saturation, for the mechanism to work.

The icing detector started cycling just before the beginning of the control for the third experiment and continued throughout it. Therefore the failure of the third experiment to produce an enhanced IPC cannot be attributed to drier conditions at the HAS because it actually became wetter there as a natural shower passed by. The solution is to look at the average IN in Table 1. It is very low compared to the other two experiments indicating poor targeting. The IN increased in the final minutes of plume passage and was higher for much of the trailing buffer than in the plume. The circulation around the natural shower apparently deflected the air flow so that the TAR was only in the fringes of the plume. A lack of IPC enhancement above background was therefore to be expected.

The first two experiments of January 5th have not yet been examined in as much detail as those experiments captioned "case studies," but additional analysis is planned. The suggestion that forced condensation-freezing may have been effective at HAS temperatures as warm as -3.0 and -3.7°C needs further testing. Such warm AgI nucleation, if true, would have important ramifications for seeding with high altitude, in-cloud generators. Chai et al. (1993) speculated that this mechanism was important in both the Lake Almanor and Bridger Range Experiments, but made no claim that forced condensation-freezing was effective at temperatures warmer than about -6°C.

The statistical results of the Bridger Range experiment strongly suggested that seeding-induced snowfall enhancement was limited unless the AgI plumes encountered cloud colder than -9°C (Super and Heimbach 1983). The Bridger Range generators often released AgI in cloud, in an uplift zone that produced liquid condensate, where forced condensation-freezing should have potential. Therefore, lack of evidence for seeding effectiveness at warmer temperatures in the Bridger Range experiment is in conflict with the suggestions from the January 5th experiments. Further physical experiments are needed to test the preliminary January 5th suggestions to insure they are not just the result of natural variability.

4.1.4 <u>January 7, 1995</u>. The first two propane experiments had release temperatures of -2.0 and -2.7°C at the HAS. The icing detectors at both the HAS and TAR showed no SLW sufficient to activate them, but relative humidities appeared to be high enough for the experiments. The targeting appeared adequate because all four tags of AgI were detected with reasonably high IN peaks. The plot of IPC with time showed that both experiments occurred during the trailing portion of natural showers. Both initial control intervals included the shower peaks in IPC. The control values in Table 2 are therefore misleading. It is possible that the first quarter of the "plume" intervals could be excluded because they are dominated by the natural showers. There are intervals after the plumes that could be defined as controls that are not affected by the showers. Such a partitioning would probably result in IPC values of about 10 and 5 L^{-1} within the two shortened plumes and about 1 and 2 L^{-1} in trailing control intervals. Such a recovery from these two experiments should be attempted to see if the results are consistent with observations of other liquid propane experiments.

4.1.5 <u>January 26, 1995</u>. There were six experiments on this day. Table 1 shows that the IN were properly targeted. The HAS icing detector was active during a natural morning snow period lasting three hours. It was highly active, indicating an abundance of SLW, during an intense snow period in the evening. The afternoon showed decreasing relative humidity which may have reduced conditions for survival of any ice particles produced at the HAS by either seeding agent.

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The first experiment released AgI into calm air at -2.6°C. The wind analyses (with light and increasing TAR winds) gave a narrow interval of apparent plume passage which may not express reality. There was, however, a 1-hour interval of enhanced IPC that occurred in the first control and first buffer intervals that looks like a seeding signature. The timings are similar to experiments having an adequate wind speed so perhaps the calm HAS wind observation was not representative of conditions somewhat above the seeding site. The IPC in the calculated plume interval was much less than in this apparent IPC enhancement. This experiment should be examined in more detail to see if different timings are justifiable. It may result in an IPC being three or four times larger in a differently defined plume than in the adjacent controls, even during this period of natural snow.

The second experiment released liquid propane into drying and warming air at an average of -0.8°C. The plot of IPC versus time (not shown) indicated IPC values of about 10 L^{-1} with a spike of higher values in the middle of the plume interval. The previous control interval was fully dominated by natural snow of moderate intensity. Therefore the Table 2 control numbers are misleading. There is no reasonable control interval for this experiment except possibly after the third experiment.

The third experiment released AgI into somewhat dry air at about -0.7°C. It may be unlikely that ice crystals were nucleated at the release site, but the TAR IPC showed a concentration enhancement within the middle of the AgI plume interval that looks like that in the previous propane plume interval and the subsequent AgI experiment. It could be that all three were natural showers of light intensity. After these two experiments the natural background in both buffer and control intervals was about 5 L^{-1}.

The fourth experiment released AgI into air that had returned to greater relative humidities and was at -2.0°C. There was an IPC spike in the core of the plume interval, just like the two previous experiments.

Thereafter the cloud became very wet and slowly cooled. The natural background snow increased to moderate and intense values, masking the results of the final two experiments. The fifth experiment released AgI into air at -2.5°C. The natural background, according to the 1-minute plot of IPC, was steadily increasing throughout the experiment. There appears to be an IPC enhancement superimposed on this trend. The second buffer had a steadily decreasing IPC back to the trend line. This case could be reanalyzed using an increasing background for a control rather than the lower value given in Table 2. Examination of the 2D-C images might also suggest a seeding effect.

However, in the control interval just before the last experiment there was a similar enhancement of IPC that cannot be attributed to any seeding plume. That casts doubt on attributing the fifth experimental results to seeding. It also overwhelms any possible detection of seeding effects in the last experiment in which AgI was released into very wet (much SLW) air at -3.6°C. There was no suitable control data for the sixth experiment. There was no final control interval because the data system was shut down almost immediately after the plume passage at about 2300 on the long experimental day.

It therefore appears that the first five out of the six experiments have data that might yield measurable results from seeding upon reanalysis. The sixth experiment does not appear to be recoverable.

4.1.6 <u>February 14, 1995</u>. Table 1 shows that the AgI tags in this liquid propane experiment were not detected at the TAR. The wind directions were more northerly compared to all of the other experiments and it is believed that the plume went south of the TAR. The IPC values in Table 2 were determined by time intervals based upon wind speeds. It is reassuring that the ratio of plume to control IPC is near unity. The plot of IPC showed natural fluctuations unrelated to the plume interval.

4.1.7 <u>March 3, 1995</u>. The targeting of the IN was very good on this day with two AgI experiments. The real time temperature indication available to the field technician was slightly colder than 0°C, but post-season examination of periodic Assmann psychrometer comparisons revealed the need to adjust the HAS temperature readings for the entire winter. The adjusted release temperatures at the HAS were too warm for experimentation at +0.8 and +0.4°C, respectively, and the TAR temperatures were no colder than -3°C. Table 1 shows that contact-freezing should not have created a detectable IPC. The warm temperatures prohibit any formation and subsequent survival of ice particles from forced condensation-freezing. Table 2 shows that even natural snow was in no more than trace concentrations. All variations in the small IPC came from natural variability. These results are entirely consistent with expectations.

4.1.8 March 5, 1995: Two case studies.

Two experiments, one liquid propane and the other AgI, successfully targeted the TAR this day. A third experiment, using liquid propane, had no effect because cloud base lifted above the HAS by 1137, the air warmed to +0.3°C during the release, and the wind direction shifted to north of west. Table 1 shows the warm temperature and low IN concentrations indicative of the plume missing the TAR.

The first HAS propane release rate was 3 gal h^{-1} from 0805 to 0905 as monitored by a gas flow meter. AgI experiment release was from 0930 to 1030. The HAS was in cloud from before 0800 until 1130; estimated visibility was less than 50 m. The icing detector tripped 8 times between 0800 and 1100; 2 trips occurred during propane release and 4 during AgI release. Estimates of HAS LWC during propane and AgI releases are 0.04 g m^{-3} and 0.08 g m^{-3}, respectively.

Winds at the HAS were southwesterly at about 5 m s^{-1} (wind speed sensor readings were not recorded). HAS temperature was near -2°C during propane release and between -1 and -2°C during AgI release.

The TAR was in SLW cloud in the 0800 to 1100 period, during which the icing detector had 11 trips. Estimated TAR LWC values during the propane-seeded and AgI-seeded periods are 0.04 g m^{-3} and 0.08 g m^{-3}, respectively, the same as the HAS estimates.

Estimated visibility at the TAR remained near 100 m during the experiment. Winds were westerly near 6 to 7 m s^{-1}. Average temperature was -4.1°C during the propane seeding and -3.6°C during AgI plume passage. Laboratory measurements have indicated a cloud temperature of -4°C is too warm for significant AgI nucleation (DeMott et al. 1995). This day's measurements within orographic cloud support those laboratory results.

Fig. 8 shows the AgI beginning and end tags for propane release as they passed the TAR. Periods not seeded by the HAS generator had low concentrations measured by the NCAR IN counter. About 11 min elapsed from first release of each tag to first detection at the TAR. About 6 more minutes passed before maximum AgI IN concentrations were established. Each 3-min release resulted in above-background IN values at the TAR for about 30 min, although most AgI passed the TAR within 10 min.

Fig. 8 also shows IPC and estimated snowfall from 2D-C probe observations. Vertical lines on Fig. 8 show the estimated hour of maximum effect by the propane seeding (0818 to 0918) judged by the NCAR IN data and changes in IPC. Propane seeding had an obvious effect on IPC and snowfall, both of which were at low levels before and after the propane seeding. Moreover, the timing of the 1-h increase in IPC and snowfall was in excellent agreement with the AgI tags. Propane seeding increased the average IPC by about 30 L^{-1}, the average snowfall by about 0.25 mm h^{-1}, and both rates were consistent for the hour of effect.

First snowfall detection was near 1040 for the crosswind and downwind gages, and no snowfall was noted at the HAS until 1042, when occasional small graupel began to fall. In contrast, the TAR technician noted no snowfall at 0755, very light snowfall at 0835 and 0905, and no snowfall at and after 0947. The TAR gage chart trace first indicated snowfall between 0830 and 0845. Apparently, some lag occurred with the light snowfall. The trace stopped moving upward an hour later. The hourly gage total was 0.25 mm, in good agreement with the rate estimated with the 2D-C probe (Fig. 8). Although seeded snowfall was limited, it was typical of many wintertime hours. Super (1994) reported a median rate just under 0.4 mm h^{-1} on the Plateau top for the early 1991 field program.

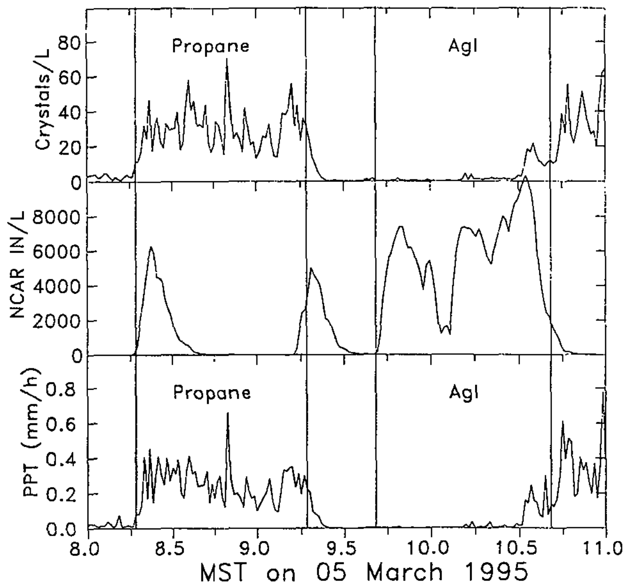

Fig. 8. Temporal distributions of IPC (top) and precipitation intensity (bottom), both calculated from TAR 2D-C probe and NCAR IN counter observations of IN L^{-1} (middle panel), for 1 propane seeding and 1 AgI seeding experiment on March 5, 1995. The estimated hour of maximum seeding plume presence is shown for each experiment by vertical lines.

The lack of natural snowfall and continued presence of dense cloud prompted an AgI experiment soon after propane seeding. The AgI generator was operated from 0930 to 1030. First detection of this release at the TAR was at 0941. Fig. 8 shows high AgI IN concentrations for most of the next hour.

Increased IPC and snowfall after 1030 (1035 according to the TAR gage) is interpreted as the beginning of natural snowfall which was detected by the crosswind and downwind gages 10 min later. The natural snowfall continued for several hours.

Plots similar to Figs. 5 and 6 (not shown) indicated most propane-seeded crystals contributing to snowfall were between 0.4 and 0.8 mm and classified by the computer software as "hexagonal" or "needle/column". Hexagonal plates and needles would be expected from laboratory work at the slightly supercooled temperatures which existed between the HAS and TAR. Propane-seeded ice crystals grew in SLW cloud for about 1000 s before detection at the TAR. Typical crystal sizes on Fig. 9 are near 0.4 mm, equivalent to a growth rate of 0.4 μm s^{-1}, in general agreement with Ryan et al. (1976). The calculated size for this experiment was 0.38 mm in Table 1, essentially the same as observed typical crystals.

Fig. 9 shows images of ice crystals for selected times similar to Fig. 7. The top panel shows all images observed between 0800 and 0805, prior to seeding. The middle three panels show typical 1-min intervals as the propane seeding pulse passed the TAR (0830 to 0831, 0845 to 0846, 0900 to 0901), and the lowest panel shows a 10-min period after seeding (0931 to 0941). Snowfall had almost stopped by the time of the lower panel. IPC was higher during seeding than before or after, and the images were more uniform in size and shape during seeding than before or after. The uniformity shown on Fig. 9 was characteristic of the entire seeded hour. Many seeded images appear to be small plates with a transparent (to the laser) center, suggesting a thin inner structure. Many other seeded images appear to be short columns or thick needles. Capped columns were also frequently observed on edge with the columns quite short.

In summary, the two experiments conducted on this day in slightly supercooled cloud (-1.5 to -4.1°C) between the release and observing sites demonstrated two different results. The propane seeding produced 0.25 mm h^{-1} snowfall at the TAR, and the AgI seeding produced no detectable increase in IPC. This result is obviously an example of cloud conditions for which propane seeding offers a useful adjunct to AgI seeding.

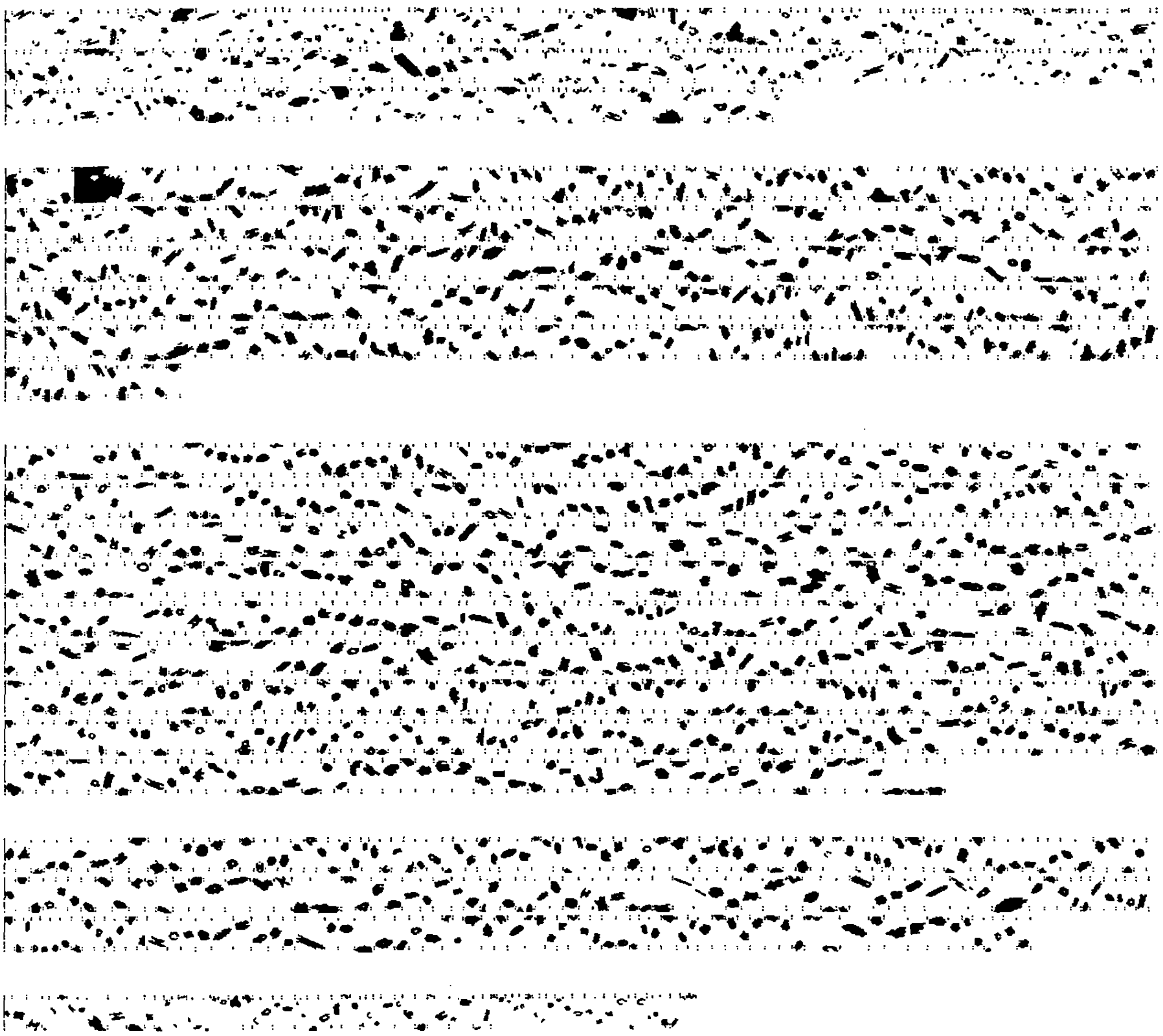

Fig. 9. TAR 2D-C images of ice particles (100- m minimum size) for selected periods during March 5, 1995. The top panel is from 5 min (0800 to 0805) shortly before arrival of the propane seeding plume. The three middle panels are from 1-min periods during seeding (0830 to 0831, 0845 to 0846, and 0900 to 0901). The bottom panel is from 10 min (0931 to 0941) just after seeding.

The low IPC and snowfall from propane seeding suggest that a higher release rate might be appropriate for the slightly supercooled conditions experienced. Of course, an operational seeding program would likely have a significantly greater distance between propane dispensers and the target than the 4.2 km used in these experiments. The associated greater travel time might be expected to result in more ice crystal growth and higher snowfall. Moreover, propane seeding might be more effective at somewhat colder temperatures (Kumai 1982).

4.1.9 <u>March 11, 1995: Three case studies</u>.

Three propane releases, each near 4 gal h^{-1}, were made late on this day and extending into the early morning of March 12, 1995 as shown on Fig. 10. Plots for this day will show 0100 on March 12th as 2500 on March 11th. The IN values in Table 1 indicate that targeting was good for all three experiments.

Figure 10 shows abundant SLW was present at the HAS during and between all 3 propane releases. A total of 44 trips of the icing detector occurred over the 7 h period shown. The greatest icing rate was during the final release when each 6 min sampling period had a trip and one period had two.

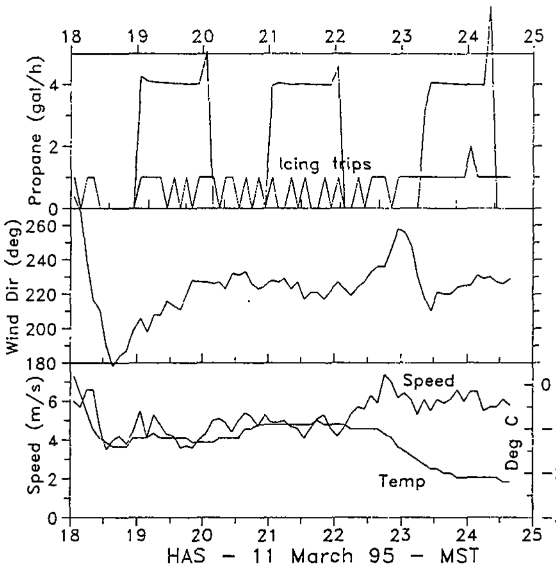

Fig. 10. HAS temporal distributions of wind speed and direction, air temperature, icing detector trips, and propane release rates during three seeding experiments of March 11, 1995.

The HAS wind was southwesterly from 4-7 m s^{-1} and the temperature was only slightly supercooled, usually between -1 and -2°C. Half-hourly observations by the field technician showed the HAS was in cloud throughout the period. Snowfall, typically small graupel, was observed between 1906 (first observation) and 2008 and again between 2242 and 2310. New snow depths were about 0.5 inch per 30 min. It was not snowing at the HAS between 2040 and 2210 and again after 2340.

Figure 11 shows conditions at the TAR. Each hour of propane seeding is shown as estimated from the AgI tags. Westerly winds prevailed near 8 m s^{-1} during the first and third experiments and near 11 m s^{-1} during the second experiment. The TAR temperature was near -3°C during the first and second experiments and cooled to -4°C during the third experiment. Some SLW was detected during all experiments but 26 of the 32 icing detector trips shown occurred before, during and after the second experiment. As will be shown, natural snowfall apparently utilized much of the SLW during the first and third experiments.

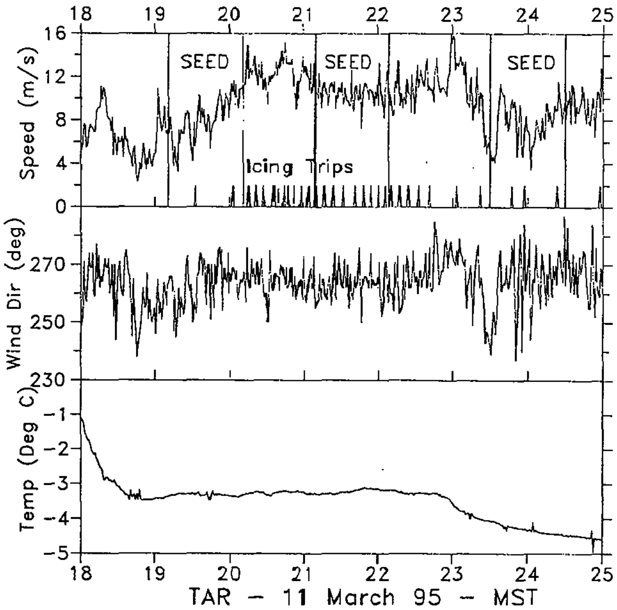

Fig. 11. TAR temporal distributions of wind speed and direction, air temperature, and icing detector trips during three seeding experiments of March 11, 1995. The estimated hour of maximum seeding plume presence is shown for each experiment by vertical lines.

The TAR technician made several references to small graupel and small needles during the course of the experiments. The typical visibility observation was near 30 m in cloud and blowing snow.

The IPC and snowfall based on 2D-C observations are shown on Fig. 12 along with the 3 pairs of beginning and end AgI tags detected by the NCAR IN counter. Estimated hours of maximum propane passage by the TAR are shown by vertical lines, based on the arrival of the beginning tag and the arrival of the end tag plus 3 minutes. The lag time of the NCAR IN counter, about 30 s for high AgI concentrations, was also used in estimating the hour of maximum propane passage.

The highest snowfall occurred prior to any propane release. Each of the 3 gages received more snowfall during the hour prior to the first seeding experiment than during any later hour until termination of all 3 experiments. The TAR gage received the highest snowfall, 7.7 mm h^{-1}, during the hour before first arrival of the propane. That is almost twice the rate estimated with the 2D-C probe data and indicates the software underestimates high snowfalls, probably because of IPC underestimation for large natural snow particles. The first propane experiment is seen to have been during a period of decreasing natural snowfall which had been at an exceptionally high rate for the Plateau. For comparison, the highest snowfall observed on the Plateau during the 1991 field season was 4.5 mm h^{-1} (Super 1994).

Figure 12 shows that snowfall decreased throughout the first propane seeding indicating that any increase caused by seeding was minor compared to the natural snowfall. The highest IPC shown was just after first propane arrival, but the IPC thereafter also decreased with time. Ice particle concentrations during the first experiment ranged from 180 L^{-1} to 45 L^{-1}, all well above the IPC associated with propane seeding on March 5th. It might be anticipated that any seeding affect would not be detectable because of the high natural snowfall which was quite variable with time. For reference, the TAR gage recorded 2.9 mm during the hour of first propane passage.

The third seeding experiment will be discussed next. Figure 12 shows a minimum in both IPC and snowfall just after arrival of the propane, but both decreases had started prior to seeding. Moreover, both minimums were reached about 10 min into the seeded period and both the IPC and the snowfall increased throughout the remainder of the seeded hour. The variations shown are interpreted as primarily caused by natural snowfall with any seeding influence minor by comparison. The TAR gage recorded 1.3 mm during the third seeded hour.

Reference to Fig. 11 shows 2 trips of the icing detector during the first seeded hour and 3 trips during the third seeded hour. In spite of the high rate of natural snowfall, some SLW was present at the TAR, with estimated LWC values of 0.03 and 0.05 g

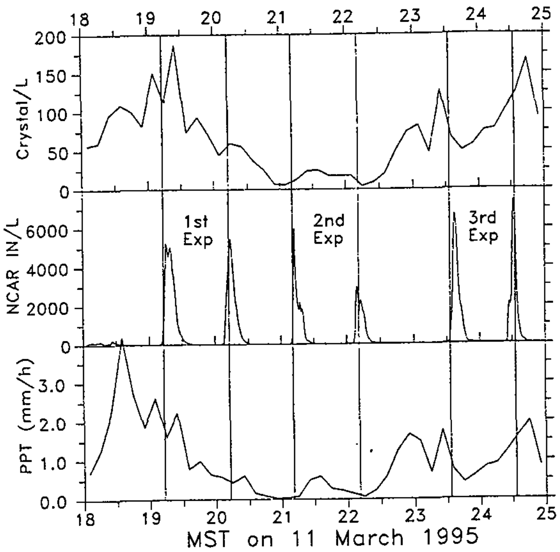

Fig. 12. Temporal distributions of the IPC (top panel) and precipitation intensity (bottom panel), both calculated from the TAR 2D-C probe observations, and the NCAR IN counter observations of IN L^{-1}, effective at -20°C (middle panel), for three propane seeding experiments of March 11, 1995. The estimated hour of maximum seeding plume presence is shown for each experiment by vertical lines.

m^{-3}, respectively, during the first and third seeded hours. As previously shown, SLW was abundant at the HAS throughout the period of interest. Since SLW was present at both sites it is very likely that seeding converted some of the available SLW into ice crystals which grew as they were transported from the HAS to the TAR. It is also likely that a large portion of the presumed seeded crystals were "swept out" by (became aggregates with) larger natural crystals. Thus, while not detectable from the available observations, it seems probable that the first and third seeding experiments increased snowfall albeit at minor rates.

The second propane seeding will now be examined as the sole experiment on this day where a seeding effect might be detectable. It is seen on Fig. 12 that both the IPC and the snowfall were at very low levels just before and after the second seeded hour, but somewhat higher during the seeded hour. The increase during the seeded hour could be due to natural variability as much higher rates were observed earlier and later. Moreover, unlike the propane seeded hour of March 5th, this hour's rate of snowfall was not quasi-constant, suggesting natural variability.

It will be recalled that the TAR SLW was abundant before, during and after the second seeded hour. The estimated HAS LWC during the hour of propane release is 0.20 g m^{-3} while the TAR LWC for the propane-seeded hour is 0.10 g m^{-3}. Relatively abundant LWC often accompanies periods of limited natural snowfall (e.g., Super and Holroyd 1989). Moreover, the crosswind gage observed its lowest hourly value (0.25 mm) for several hours on either side of the second propane experiment indicating natural snowfall was at a minimum. All these factors suggest that seeding may have had a noticeable effect.

The second experiment's seeded crystals were exposed to SLW cloud for at least 700 s while transported from the HAS to the TAR, at temperatures between -1 and -3°C. This is known to be a very slow growth range for ice crystals. According to Ryan et al. (1976) plane plate crystals should form at -3°C (the warmest temperature they examined) which would grow at about 0.2 µm s^{-1}. That rate would produce 0.15 mm crystals in 750 s. Examination of plots (not shown) of percentage contributions of various crystal types, according to the software classification scheme of Holroyd (1987), showed increases in "hexagonal" and "irregular" crystals. These could be plates with some transparent portions which would support the hypothesis that seeding produced tiny plate crystals.

Perhaps the best impression of microphysical changes during this seeding experiment can be gained from examination of the ice particle images themselves. Figure 13 shows 3 panels of 2D-C images at least 0.1 mm in size. The top panel is for 5 min (2104-2109) just prior to arrival of the propane-seeded pulse when the average IPC was 3 L^{-1}. The middle panel is for a typical minute (2116-2117) early in the seeded hour when IPC were near 18 L^{-1} and the bottom panel is for a minute (2130-2131) near the time of highest IPC during the seeded hour.

The uniformity of the middle panel's crystals is striking. This panel is interpreted as primarily seeding-caused crystals. Uniformity in crystal sizes and types would be expected if crystals originated at a point source (the propane dispenser) and thereafter were exposed to a similar growth environment. Similar uniformity was seen in earlier seeding experiments. The crystals appear to be thin (centers transparent to the laser) embryonic plates as expected with prevailing temperatures. Most of the crystals in the middle panel appear to be near 0.15 to 0.30 mm, up to twice as large as estimated in Table 1.

By the time of the bottom panel, many crystals similar to those of the middle panel were interspersed with much larger particles, some of which are small graupel and some of which appear to be columns and/or branches of dendrites. The average IPC during this period was near 28 L^{-1}. The interpretation is that a small natural snow shower occurred during the middle of the seeding experiment. The "additional" crystals of the lower panel are too large to have been caused by seeding with the limited available growth time and they appear characteristic of a colder growth environment.

Images (not shown) were examined just before and after the end of seeding. By 2208 the image population was very similar to the middle panel of Fig. 13 except that some small graupel was evident. By 2222, after the seeded pulse had passed beyond the TAR, larger graupel were common as natural snowfall increased.

Since crystals larger than perhaps 0.4 mm would not be expected to be caused by this particular seeding, most snowfall during the second experiment must have been from natural crystals. Thus, while seeding apparently affected the microphysics, its contribution to the total snowfall was limited during this experiment.

One can establish an upper limit on possible seeding production by optimistically assuming that all snowfall observed at the TAR during the second experiment was due to seeding. Figure 12 shows the average IPC was about 20 L^{-1} and the average estimated

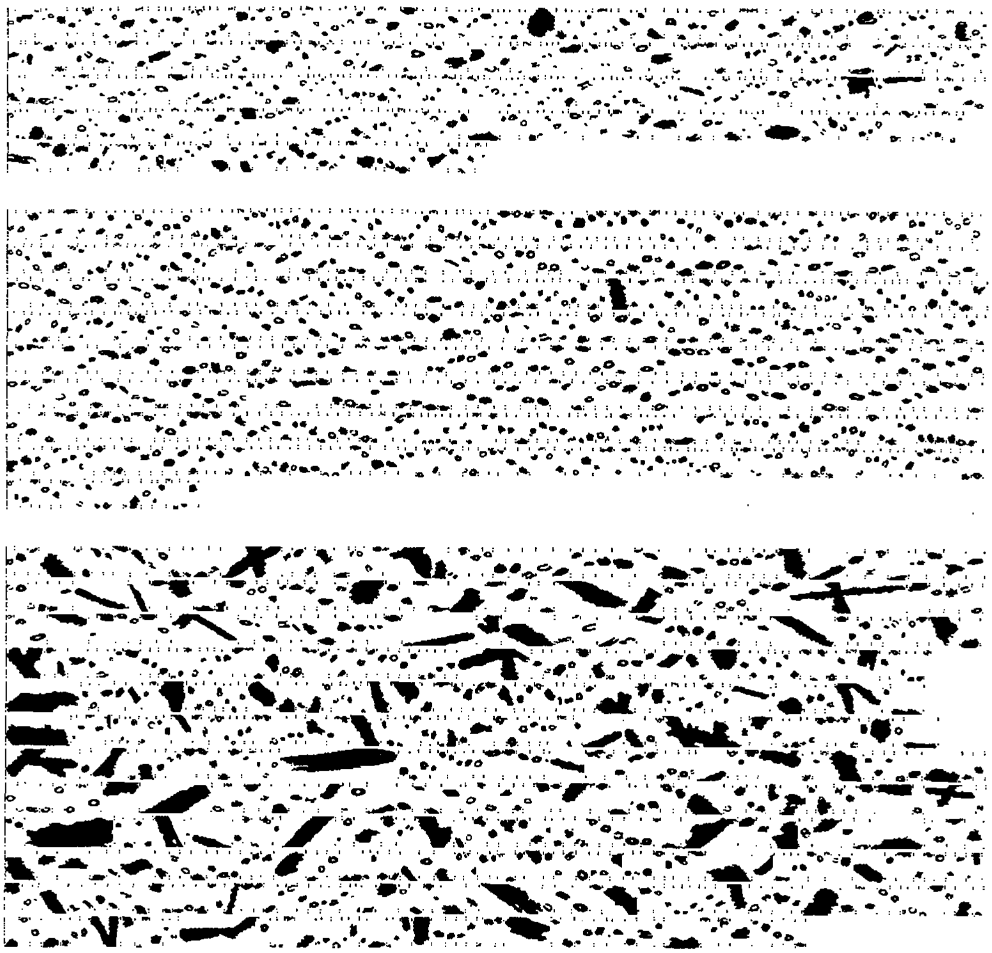

Fig. 13. TAR 2D-C images of ice particles (100 μm minimum size) for selected periods during March 11, 1995. The top panel is from 5 min (2104-2109) shortly before arrival of the propane seeding plume, the middle panel is from 1 min (2116-2117) shortly after seeding plume arrival, and the bottom panel is from 1 min (2130 to 2131) near the time of highest IPC during the seeded hour.

snowfall was near 0.3 mm h^{-1} during this seeded hour. The TAR gage observed 0.38 mm during the same hour. These values represent the highest IPC and snowfall production possible from the type of propane seeding applied to a cloud with abundant LWC but temperature only slightly colder than 0°C. But the evidence of large crystals during part of the seeded hour argues that these values are unrealistically high. The crosswind gage observed 0.25 mm of snowfall during the same hour suggesting the propane-caused component of TAR snowfall may be closer to 0.1 mm h^{-1}.

A more realistic estimate of the propane-caused IPC and snowfall rate is based on the very first portion of the seeded hour before the larger natural crystals shown on the bottom panel of Fig. 13 were evident. The period 2115-2120 had only a few of the larger, natural crystals and the propane-seeded pulse appeared to have been well established by then. By 2123 larger natural crystals were plentiful. The difference between the natural background IPC of 3 L^{-1} for 2100-2110 and the 18 L^{-1} of 2115-2120 is 15 L^{-1}, believed to be the best estimate of propane-caused crystals during this day. The estimated snowfall was 0.12 mm h^{-1} for 2115-2120. If the few natural crystals were eliminated, the propane-caused snowfall is estimated at no more than 0.10 mm h^{-1}. Examination of some brief periods with few large crystals near the end of the seeded hour (images not shown) suggested propane-caused IPCs and snowfall slightly lower than the values stated.

To summarize the microphysical evidence, the second propane experiment resulted in some marked changes in ice particle characteristics, but natural snowfall during much of the seeded hour also affected the ice particle population. Crystal sizes abruptly increased from the pre-seeded period but sizes continued to increase after seeding. Seeding apparently increased "hexagonal" and "irregular" crystal types.

The layer temperature between the HAS and the TAR was only slightly supercooled, between -1 and -3°C during the second experiment. This was about 1°C warmer than during the successful propane seeding experiment of March 5th. It is speculated that the warmer temperature is partially responsible for the lower IPC during this experiment compared with an average of 30 L^{-1} on March 5th. As discussed in Sec. 2, Hicks and Vali (1973) reported decreased yields at temperatures only warmer than -2°C, and relatively constant yields at colder temperatures. However, Kumai (1982) found a marked decrease in propane effectiveness for temperatures warmer than -5°C. Of course, direct comparison of the IPC assumes similar dispersion of the ice crystal plumes created by the two propane releases and there is no direct evidence to support or refute that assumption. TAR wind speeds were higher on March 11th which could reduce the IPC by about 1/3 compared with March 5th, all else being equal. Obviously, additional observations are needed before making definitive statements about the temperature dependence of propane yield.

The very low snowfall likely caused by this propane seeding may be due to the combined factors of decreased propane effectiveness and very slow crystal growth rates, both a result of the warm temperatures. However, it is worth recalling that the horizontal distance between the HAS and TAR is only 4.2 km and the locations were chosen for test purposes because of the ability to routinely target the TAR site. As previously noted, an operational seeding program likely would be designed to affect a more distant target. For example, a fully-automated propane seeding was initiated farther south on the Plateau during the 1993-94 winter as discussed by Super et al. (1995). That program has continued in a region which provides greater distances between propane dispensers and the Plateau crestline. It is important to avoid regions with frequent sustained subsidence between the propane dispensers and the intended target (Reynolds 1996).

5. SUMMARY AND RECOMMENDATIONS

Some of the seeding experiments produced obvious changes in microphysical characteristics and snowfall during periods with very limited natural snowfall. Others produced none, as expected, because of intense natural snowfalls, relatively warm cloud temperatures, drier conditions, or poor targeting of the materials. Natural variability masked some of the results or created misleading control intervals. Though only a few of the experiments were relatively free of such complications, this operational-style design with a variety of cloud environments was intentional. It provided a range of conditions likely to be encountered in operational seeding programs. Furthermore, the stress on physical, rather than statistical (see Heimbach and Super, 1996), verification of the experiments provides a basis for seeing what happened with each experiment, even if the natural variability was a complicating factor.

One of the case study experiments (December 15) used an AgI release while cloud temperatures were relatively cold, near -7.8 at the HAS and -10.4°C at the TAR. The resulting seeded IPC and snowfall was estimated at 140 L^{-1} and 1.0 mm h^{-1}, respectively, 4.2 km east-northeast of the HAS at the TAR. This experiment provides convincing evidence that AgI seeding can produce significant snowfall under certain conditions.

A second case study experiment (March 5) released liquid propane at HAS cloud and TAR temperatures of -2.1°C and -4.1°C, respectively. Propane seeding was estimated to have enhanced IPC by about 30 L^{-1} and snowfall by 0.25 mm h^{-1}. Higher propane release rates may be appropriate for these slightly supercooled temperatures.

A third case study experiment with AgI seeding, conducted just after the March 5 propane seeding, did not enhance IPC during temperatures near -1.5°C at the HAS and -3.6°C at the TAR. It was too warm for the contact-freezing mechanism to operate efficiently, and apparently the forced condensation-freezing mechanism was also ineffective in spite of AgI release within supercooled liquid cloud.

The second experiment of March 11th had a HAS propane release into a cloud temperature of -0.9°C with TAR temperature of -3.0°C. This experiment suggests the seeding resulted in about 15 L^{-1} IPC enhancement at the TAR with perhaps 0.1 mm h^{-1} snowfall.

These March 5th and March 11th results both argue for improved field documentation of propane effectiveness, especially at temperatures warmer than -5°C where AgI is believed ineffective. Higher propane release rates seem appropriate for the slightly supercooled temperatures (-1 to -2°C) experienced at the release site during these two experiments. It may be that the propane rate used, 6000 g h^{-1}, is appropriate for colder cloud temperatures. Unfortunately, no successful propane experiments were conducted when HAS temperatures were in the -2 to -5°C range.

There is no doubt that propane seeding can increase snowfall at temperatures warmer than -5°C when excess SLW is available. The questions yet to be answered are what release rate is required to produce significant snowfall and is such a release rate economical? The potential importance of being able to seed slightly supercooled cloud, found in abundance especially in California but throughout the intermountain West as well, is too great to ignore these questions.

Two experiments conducted on January 5th suggested that the forced condensation-freezing mechanism may have increased both IPC and snowfall when HAS temperatures were between -3.0 to -3.7°C and the TAR was near -5.5°C. If verified, such warm temperature AgI nucleation would have important ramifications. But additional evidence is needed to insure that these preliminary suggestions are not simply the result of natural variability. There is little other evidence from this series of 24 experiments on 9 different days that high altitude AgI seeding was effective in IPC enhancement when Plateau top temperatures were warmer than -6°C.

These experiments have provided valuable information to partially address seeding effectiveness. Data from the subsequent season are now being analyzed. Additional seeding experiments should be conducted on the Plateau between the HAS and the TAR. These experiments are simple and economical, and targeting of the TAR site is routine with southwesterly flow at the HAS. Future experiments of this type should concentrate on periods with no more than very light natural snowfall. Detecting microphysical changes caused by seeding during higher natural snowfall rates is difficult because of the variability of such snowfall.

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