INVESTIGATIONS OF THE TARGETING OF GROUND-RELEASED SILVER IODIDE IN UTAH PART II: AIRCRAFT OBSERVATIONS

Arlin Super
Bureau of Reclamation
Denver CO 80225

and

Arlen W. Huggins
Desert Research Institute
Reno NV 89506

Abstract: As part of a cooperative research program between the Utah Division of Water Resources, the National Oceanic and Atmospheric Administration, and the Bureau of Reclamation, a series of aircraft missions was flown to track silver iodide plumes in the Utah operational cloud seeding program. Both valley floor and canyon mouth generator sites were tested using releases of sulfur hexafluoride tracer gas and silver iodide. Optically-tracked Airsondes provided supporting wind and stability data. Five missions were flown under atmospheric conditions that either simulated, or were the beginning of, the prefrontal phase of typical Utah winter storms. The silver iodide and tracer gas were confined to the lower atmosphere during four flights and were not transported over the intended mountain barriers. The plumes did cross the Wasatch Plateau during part of the fifth sampling mission. Ice nucleus concentrations were estimated from the tracer gas measurements of the fifth mission for typical supercooled liquid water temperatures. These estimates indicated that limited ice crystal concentrations would be formed with the generators and seeding agent currently used in Utah.

1. INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA) is pursuing a cooperative weather modification research program with Utah's Division of Water Resources. The Bureau of Reclamation is providing scientific expertise and equipment support to this program under a cooperative agreement with NOAA. The goal of all three agencies is to improve weather modification technology by evaluating the effectiveness of current operational seeding practices in Utah and recommending improvement where appropriate.

In a companion paper, Super and Huggins (1992) (hereafter Part I) discuss silver-in-snow and ground ice nucleus observations conducted during the 1989-90 operational cloud seeding program in Utah. Those measurements, and the observations discussed in this paper, were part of a limited field program to assess the effectiveness of the operational winter cloud seeding program that has been conducted in Utah since 1973-74 (Griffith et al. 1991).

The transport and dispersion (T&D) of ground-released seeding material over complex terrain presents a difficult problem. Recognition of the limited understanding of T&D in the complex terrain which characterizes most energy development areas lead to formation of the Department of Energy's Atmospheric Studies in Complex Terrain (ASCOT) program in 1978. Several major field studies have been carried out under ASCOT, mostly in northern California and western Colorado, with the goals of improving fundamental knowledge of T&D processes in complex terrain, and using the improved insight to provide a methodology for air quality assessments. To appreciate the magnitude of the effort devoted to integrating theoretical research, mathematical models and field experiments, one has only to peruse the set of 26 papers that make up the June and July 1989 issues of the Journal of Applied Meteorology.

The ASCOT program is noted here for a number of reasons. First, it illustrates that understanding of T&D in complex terrain is still limited. Second, development of a fundamental understanding is requiring very large resources over an extended period, in terms of scientists, technical support personnel, and sophisticated instrumentation. Third, ASCOT's efforts to date have emphasized rather simple terrain (basins and V-shaped valleys) and nocturnal drainage flows. These conditions have limited applicability to upslope flows over more complex mountain barriers presumed to result in T&D of seeding material to the SLW zone of storm clouds.

The above points provide justification for a limited empirical approach for investigating the T&D problem associated with seeding winter orographic clouds. The T&D problem is too important to be ignored, but cannot be adequately predicted with existing knowledge. Current funding levels do not permit application of a comprehensive "ASCOT-like" approach for investigation of cloud seeding T&D.

The failure of several operational and experimental seeding programs to convincingly demonstrate precipitation increases may have been partially due to ineffective T&D. Because of the difficulties involved, most programs have chosen to assume that T&D is effective at least some of the time, but without demonstrating this to be the case. In fact, the scientific literature has relatively few articles investigating the T&D of ground-released silver iodide (AgI).

Physical evidence concerning seeding agent T&D is particularly limited for valley floor and canyon mouth releases as employed in the Utah operational program. As discussed in Part I, and noted in several reports and publications referenced in Part I, there is cause for increasing concern about the targeting of ground-released AgI.

This paper presents the results of a series of aircraft sampling missions that attempted to track ground-released AgI and sulfur hexafluoride (SF_6) tracer gas under near-storm conditions. Rawinsonde and surface observations supported these missions, providing information on atmospheric winds and stability known to be important factors in T&D.

2. AIRCRAFT SAMPLING OF GROUND-RELEASED AGI AND SF_6

A specially instrumented AeroCommander 690A aircraft, based at Salt Lake City, Utah, was used to track ground-released plumes of AgI and SF_6 during early 1990. North American Weather Consultants (NAWC) personnel operated the aircraft and instrumentation, and decided when to conduct missions. Instrumentation included a fast-response SF_6 detector of the type described by Benner and Lamb (1985), an acoustical ice nucleus counter (Langer, 1973), sensors to monitor air temperature and pressure, and a forward-pointed video camera.

The missions were flown in visual flight rules (VFR) and marginal VFR conditions. The goal was to simulate non-convective storm conditions while allowing for low-level sampling near mountainous terrain and above mountain valleys. Experience has shown the impracticality of using aircraft to sample within mountain valleys during actual storm conditions. While the Federal Aviation Administration (FAA) will issue waivers to allow in-cloud flight within 1000 ft of highest terrain, this altitude usually places an aircraft at least 2000 ft above typical mountaintop terrain. Most ground-released seeding material has been found below that level in non-convective storms (Holroyd et al. 1988; Super and Heimbach, 1988). Consequently, VFR flights provide the only practical means for sampling within the lowest 1000 ft above mountain ranges and adjoining valleys.

All flights were good simulations of the prefrontal stage of non-convective storms. The expected enhanced mixing associated with convection cannot be simulated during VFR missions but requires in-cloud observations during instrument flight rules (IFR) conditions. Several IFR missions were flown in Utah during early 1991 that will be reported when analyses are complete.

It was planned to conduct research flights during near-storm conditions over both the Wasatch Range and the Wasatch Plateau. When suitable conditions were forecast or already existed, technicians went to one of the two areas to release AgI and SF_6, and to track radiosondes to measure atmospheric winds and stability. As is well known, the wind and temperature structure of the lower atmosphere have major influences on the T&D of ground-released effluents. The "Airsonde" radiosondes were optically tracked using a theodolite with shaft encoders for automatic reading of azimuth and elevation angles. Automatic weather stations at Mount Pleasant (Fig. 1) and about 2/3 of the way up Big Cottonwood Canyon (Fig. 2) monitored surface winds and temperatures. Acoustical ice nucleus counters were operated in the aircraft and, as discussed in Part I, at the Big Cottonwood Canyon sampling site.

A total of five research missions were flown. An additional flight was aborted because of low clouds over the experimental area. Only one mission was flown around the Wasatch Range. The aircraft encountered severe turbulence due to the rugged and complex terrain, so no further missions were flown over that area.

Because all flights took place in prefrontal conditions, they may not accurately represent frontal passage or post-frontal conditions. However, considerable quantities of supercooled liquid water (SLW) that offer seeding potential (e.g., Long et al. 1990) have been observed during prefrontal periods in Utah. Therefore, observations of AgI transport during prefrontal conditions are relevant to evaluation of operational seeding effectiveness in Utah.

2.1 Mission of January 26, 1990

The first research flight of the field program took place over the Wasatch Plateau on January 26, 1991. Tracking of the tracer gas was not attempted on this mission, but an AgI generator was operated at 6 g h^{-1} from the north edge of Mount Pleasant (see Fig. 1) from 1045-1330 (all times MST). Aircraft sampling in the Wasatch Plateau area was conducted from about 1215-1315. Erroneous indicated positions from the Loran-C navigation system during portions of this flight (and during the flights of January 30 and February 6) made it necessary to establish approximate positions from terrain features viewed by the aircraft's forward-pointing, time-referenced video camera and voice notes made by the aircraft crew. Integration of heading and true air speed provided relative ground tracks also useful in establishing position provided actual position was occasionally known; however, wind drift distorted these tracks. Estimated aircraft positions are believed accurate to within 2 miles in general, and to within 1 mile when special attention was warranted. For example, stated distances downwind of the release site are believed accurate to within a mile.

The synoptic weather for this day was produced by a 500 mb zonal flow pattern over much of the continental United States, including the Utah research area. Minor shortwave disturbances propagated rapidly through the mean long wave position. At 0500, one shortwave trough axis was positioned over Nevada, producing strong southwesterly flow (15-20 m s^{-1}) and slight warm advection over Utah. Some midlevel moisture extended over northern Utah, but low-level moisture associated with the

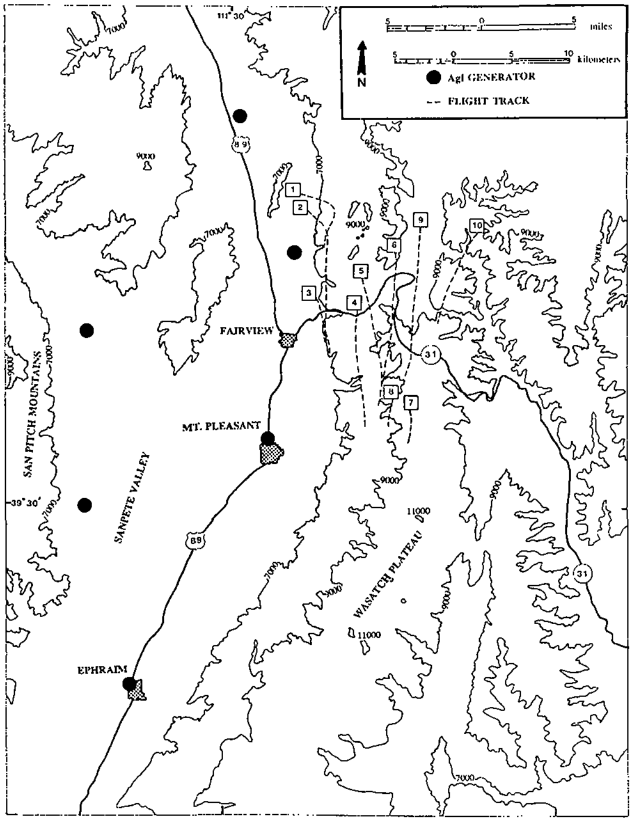

Fig. 1. Map of the Wasatch Plateau experimental area showing silver iodide generator sites for the operational seeding program, selected towns and highways, and elevation contours in 2000 ft intervals.

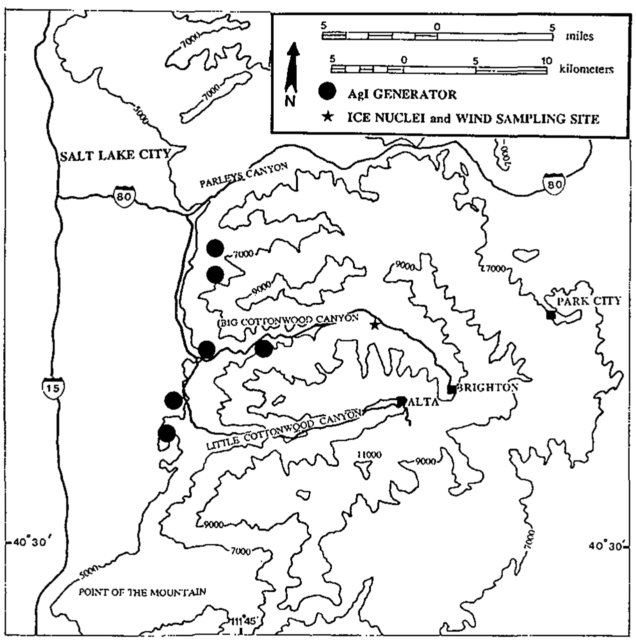

Fig. 2. Map of the Wasatch Range experimental area showing silver iodide generator sites for the operational seeding program, selected towns and highways, and elevation contours in 2000 ft intervals.

shortwave was primarily northwest of central Utah. At the surface a high pressure center was located over the southeast corner of Utah, and a cold front was located across northwestern Nevada. The resulting surface pressure gradient produced 5-10 m s^{-1} southerly winds over most of Utah.

From 0500 until aircraft flight time, the surface cold front moved rapidly across Nevada and into northern Utah. At 1100, the northeast to southwest oriented front was slightly southeast of Salt Lake City, still somewhat north of the Wasatch Plateau. Rain and snow showers were observed along the front, and cloud bases over northwest Utah lowered to 6000-10,000 ft above ground level (AGL). Southerly surface winds continued ahead of the front in the vicinity of the Plateau.

The aircraft flight took place just prior to cold front and shortwave trough passages, in what appeared to be a good simulation of storm conditions. The southerly to southwesterly winds typify prefrontal storm winds from the surface through 700 mb, as described by Long et al. (1990) and Huggins (1990) for several storms occurring in southwest Utah. The 500 mb zonal flow pattern with rapidly moving shortwaves also typify some winter storm situations over the Western United States. Midlevel moisture and altostratus clouds with cloud bases near 13,000 ft were present over the Plateau. The dryness in the lowest levels accompanied by thickening altostratus is also similar to prefrontal cloud conditions described by Long et al. (1990) and Huggins (1990). Frequently in these situations (e.g., Sassen et al., 1990) orographic cloud with SLW and precipitation develops over the mountainous terrain, while a dry layer persists for some time over adjacent valleys.

An Airsonde-type radiosonde was released from Mount Pleasant at 1209 (release site at 5900 ft) and optically tracked to almost 13,000 ft until it disappeared in an altostratus cloud deck over the Plateau. The light radiosonde, carried by a 30 g balloon, continued ascending to about 15,000 ft and was then rapidly carried downward, apparently in a lee wave. As shown on Fig. 3, winds were strong, especially above Plateau-top altitudes (9000-10,000 ft), reaching 28 m s^{-1} at 12,600 ft. Wind directions near 245° (all directions relative to true north) existed at all levels except between about 6500-7500 ft, where a strong up-valley component was evident. The aircraft experienced frequent moderate turbulence throughout the sampling period, especially over the west slopes of the Plateau and the ridges west of the Sanpete Valley.

A temperature inversion existed between 7200-7500 ft as shown on Fig. 4 which also illustrates that potential temperature increased markedly with height below 8000 ft, remained nearly constant from 8000 to 11000 ft, and gradually increased with height at higher elevations. This indicates either stable or neutral conditions at all levels. This stability pattern is similar to conditions found over Utah valleys in actual storm situations. Soundings launched from the Beaver Valley, adjacent to the Tushar

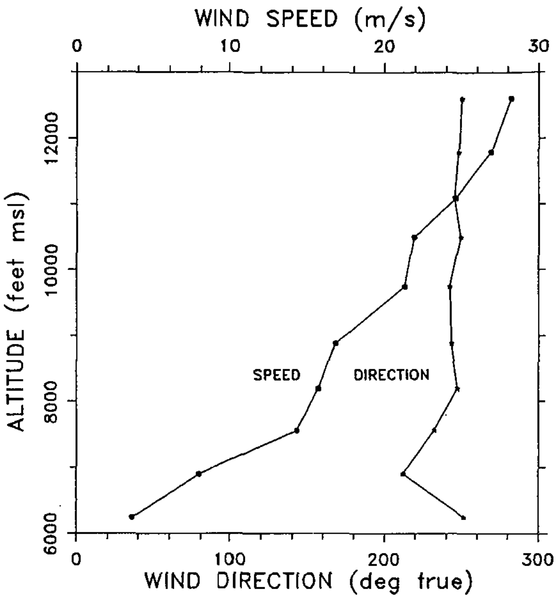

Fig. 3. Vertical distributions of wind speed and direction from Airsonde released at 1209 on January 26, 1990, from Mount Pleasant, Utah.

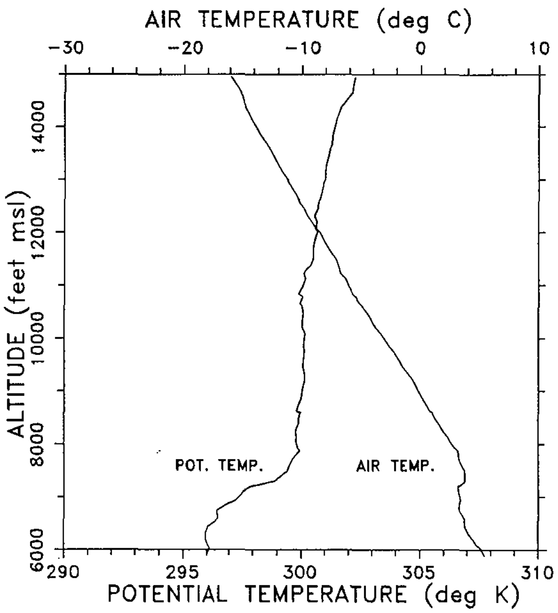

Fig. 4. Vertical distributions of potential temperature and air temperature from Airsonde released at 1209 on January 26, 1990, from Mount Pleasant, Utah.

Mountains of southwest Utah, were examined from two prior Utah/NOAA research programs. Sixty percent of 1989 soundings showed stable conditions in the lowest level, while 45 percent of 1987 soundings had similar stable layers. Temperature inversions, particularly in prefrontal periods, were common during 1989, but rare in 1987. The well-documented storm described by Long et al. (1990) showed low-level stable layers persisted over the Beaver Valley in the prefrontal storm stage well after SLW and precipitation had formed over the mountains to the east. Low-level stability was also found beneath the frontal surface in the postfrontal stage of this storm. These findings suggest that the research flight of January 26 took place in a reasonable simulation of prefrontal conditions.

The anemometer for the Mount Pleasant weather station was disabled on this date. However, the surface wind direction (10 min means) ranged from 223-263 degrees during the aircraft sampling period.

Upon arriving in the area, the pilot commented on a strong up-valley flow at low levels. Consequently, initial passes were made approximately normal to south-southwest flow at fixed downwind distances from the AgI generator. The first series of crosswind passes took place along a northwest-southeast axis, intersecting the plume about 3 miles downwind of the release point. Three terrain-following passes took place about 200-300 ft AGL, reaching minimum altitudes near 6200 ft. Pairs of crosswind passes were made at 6500 and 7000 ft, and one pass was made at 7500 ft, also 3 miles from the AgI generator for up-valley south-southwest flow. AgI was found in similar concentrations on all passes at or below 6500 ft. Only weak concentrations of ice nuclei were found at higher altitudes.

Unfortunately, the aircraft returned to the plume too rapidly to allow the acoustical ice nucleus counter to completely "flush out" AgI from previous passes, so only the position of the initial plume edge could be determined. Assuming a 30 sec lag time for initial counter response (Super, et al. 1988), the east edge of the plume was located on a 30° axis from the generator, in accordance with the 210° wind blowing up the valley near the surface (Fig. 3).

Since the west plume edge could not be defined, no information on plume width or mean concentration can be given. However, maximum count rates reached 14 ice nuclei per second (IN s^{-1}) and mean rates were about 5 IN s^{-1} during the lower level passes. Using the factor of ten correction suggested by Langer (1973), and the 10 liter min^{-1} acoustical counter flow rate, ice nuclei counts per minute equate to ice nuclei per liter. Thus, 10 counts s^{-1} equate to about 600 ice nuclei $liter^{-1}$ at the -20°C cloud chamber temperature. However, the effective IN l^{-1} at -10°C would be about two orders of magnitude less (see Table 2), or 6 IN l^{-1}. Thus, the low-level plume appears to have had limited ability to nucleate ice at typical SLW cloud temperatures only 3 miles from the generator.

The aircraft was flown to a position 10 miles from the generator, over a narrow valley immediately west of the Plateau and almost north of the generator. It circled in the AgI plume for a few minutes at 7000 ft. Mean count rates of about 3 IN s^{-1} were found with maxima three times higher. Even less AgI was found on a crosswind pass at 7500 ft, and, again, the plume was moving along the west side of the Plateau, not over it.

Several passes were made at various levels above the west slopes and west edge of the Plateau, along transects expected to encounter the AgI plume with southwest flow. Ice nuclei concentrations were slightly above background on portions of some passes, but the amounts of AgI transported over the Plateau were very limited. The aircrew returned to base since the plume was largely confined to the valley.

In summary, this mission took place during strong southwest flow channeled toward the north-northeast in the 1500 ft layer above the valley floor. The atmosphere was stable in this layer, but the AgI was mixed at least 1500 ft vertically, presumably by mechanical turbulence. Very little AgI was transported over the Plateau, at least in regions sampled by the aircraft. AgI might have crossed the Plateau well to the north of the intended target area. Low ice nuclei concentrations, as measured by the acoustical counter and extrapolated to -10°C, existed even a few miles downwind of the generator.

2.2 <u>Mission of January 30, 1990</u>

This research flight took place from 1200 to 1400 in the vicinity of the Wasatch Plateau. The synoptic pattern resembled that of 26 January with relatively zonal 500 mb flow (slight anticyclonic curvature) over the continental United States. A relatively deep shortwave trough was centered over the coast of Oregon and northern California. At 1100, the surface analysis showed a low pressure center located at the southeast corner of Idaho with a cold front extending southwestward from the low across the center of Nevada. As on 26 January, a weak surface high was positioned over the southeast corner of Utah. This pattern again produced southerly winds over Utah. By 1400, the surface analysis indicated a weak low had formed along the cold front in northeastern Nevada. Southerly winds of 10 m s^{-1} were reported at several sites in Utah ahead of the front; most of these sites also experienced overcast conditions (primarily midlevel clouds).

Upper air analyses showed 13-18 m s^{-1} southwest winds over Utah at 0500 at 700 mb, on the east side of the trough axis. Warm air advection existed at this level but, similar to 26 January, moisture at and below this level had not yet reached central Utah. The 500 mb winds over Utah were more westerly, and moisture at this level had already moved over central Utah, as evidenced by the midlevel cloudiness.

The midlevel cloud cover and 700 mb southwest winds typical of a prefrontal environment provided good simulated storm conditions (see references for 26 January case). Low-level moisture was lacking, but the surface winds were southerly over much of Utah, also typical of conditions in advance of a cold front. The warm advection pattern at 700 mb likely led to increasing stability over Utah in the lowest levels prior to the research flight.

Soundings were launched from Mount Pleasant at 1049 and 1404. The 1404 sounding had wind data to only 8000 ft (visual theodolite tracking lost the balloon in cloud just above 9000 ft, but data were averaged from 1-minute intervals). Winds at 1049 were light from the southeast below 7000 ft. Winds above 7000 ft increased steadily with height to 20 m s^{-1} at 12,000 ft, and were consistently from the southwest. The 1404 sounding was more representative of the aircraft sampling period over the Wasatch Plateau from 1300-1400. Figure 5 shows winds between 6000-8000 ft had turned to the south-southwest and increased in speed from 7 m s^{-1} near the surface to 20 m s^{-1} at 8000 ft. The Mount Pleasant weather station provided more surface wind detail indicating a wind from the southeast before 1215, but ranging from 200-245 degrees during the remainder of the aircraft sampling period ending at 1400. Wind speeds were estimated each 15 min at the AgI and SF_6 release site. The average speed was 2.2 m s^{-1} from 1200-1320, abruptly increasing to 9-11 m s^{-1} thereafter.

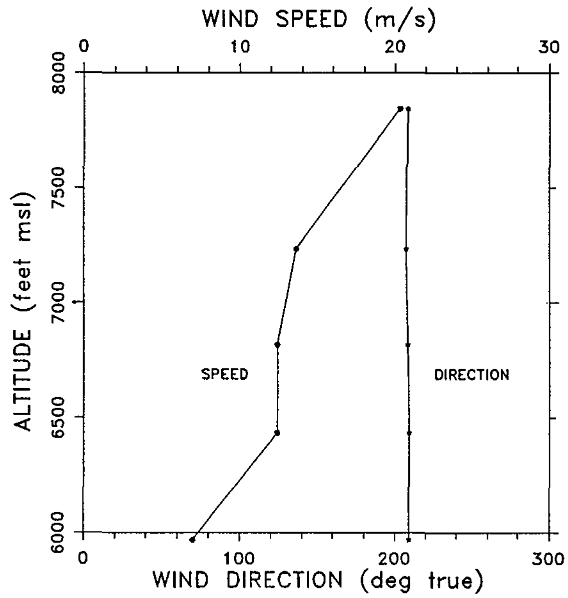

Fig. 5. Vertical distributions of wind speed and direction from Airsonde released at 1404 on January 30, 1990, from Mount Pleasant, Utah.

The potential temperature at 1049 (Fig. 6) increased rapidly below 8900 ft, then gradually through 12000 ft, indicating stability throughout this lower region of the atmosphere. The potential temperature at 1404, also shown on Fig. 6, was essentially constant with height below 10,000 ft, indicating a neutral atmosphere. Figure 7 shows the air temperature distribution from the two soundings. The inversion above 8000 ft at 1049 had broken down by 1404. Atmospheric conditions changed markedly during this sampling mission.

AgI release began at 1100 at 6 g h^{-1}, and SF_6 release commenced at 1154 at 120 lbs h^{-1}, both from the north edge of Mount Pleasant. Both releases continued until the end of the mission, but the SF_6 release rate was reduced to about 50 lbs h^{-1} after 1306 to conserve the diminishing supply.

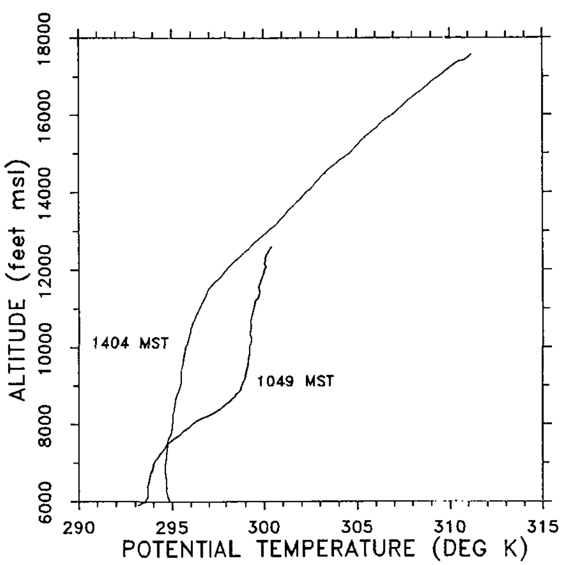

Fig. 6. Vertical distributions of potential temperature from Airsondes released at 1049 and 1404 on January 30, 1990, from Mount Pleasant, Utah.

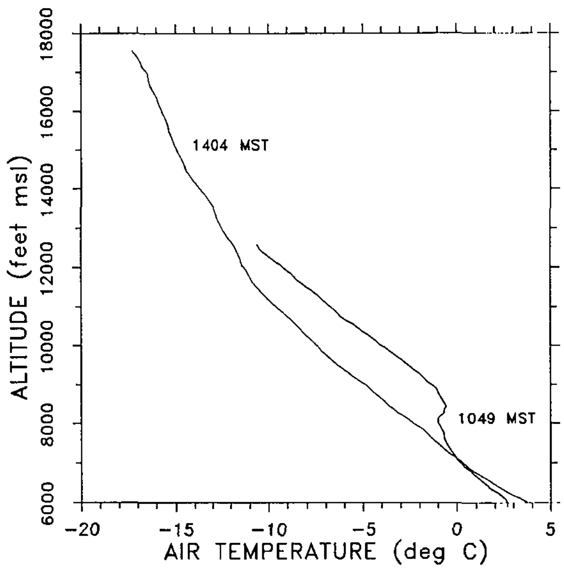

Fig. 7. Vertical distributions of air temperature from Airsondes released at 1049 and 1404 on January 30, 1990, from Mount Pleasant, Utah.

The aircraft arrived in the Mount Pleasant area at 1205 under an overcast sky with cloud base near 11,000 ft. The cloud base gradually descended during the next 2 hours as the aircraft flew the mission.

A series of nine L-shaped passes was flown from 1205-1256. The longer east-west legs were flown over the valley, about 6 miles north of the Mount Pleasant release site, and the shorter north-south legs were flown over the west slope of the Wasatch Plateau south of Highway 31. Plumes were only found on the east-west track just west of Fairview (Fig. 1).

The tracer gas analyzer output voltage drifted significantly with time during this flight, reducing its sensitivity and requiring manual estimation of the time of both plume edges on each pass. The drifting baseline was subtracted from the signal. The SF_6 clearly was evident on the four lowest passes, between 7900 and 8400 ft, with peak concentrations between 50 and 170 ppt (parts per trillion by volume). Plume widths varied from 0.8-1.5 miles. AgI was detected on each of these passes with maximum count rates of 6 IN s^{-1}. There was evidence of AgI (but not SF_6) on some of the higher passes, including one at 9500 ft, but the signal was very weak compared to passes made below 8000 ft. Clearly, the bulk of the ground-released plumes were within about 2000 ft of the surface and were being transported northward, up the valley.

At 1256 it was decided to sample further north of the release site. A pass over the west slope of the Plateau at 8000 ft detected SF_6 about 12 miles from Mount Pleasant, on an axis slightly east of north of the release site. Several additional north-south passes were made over the Plateau during the next hour, and each but the last pass detected the tracer gas. It is not known why the final pass failed to find the tracer gas. AgI also was found on each pass over the Plateau until a compressor stall and associated cloud chamber warming reduced the acoustical counter signal after 1320, and eliminated it by 1335.

As the aircraft ascended, the north-south sampling track was shifted eastward so all but the highest passes took place within a few hundred feet of the terrain. The higher passes took place near the base of snow showers which were lowering with time. Some peaks were obscured in cloud and snow, especially to the south. Aircraft sampling ended when cloud bases descended too low for continued visual flight over the Wasatch Plateau. The latter half of this mission definitely approximated storm conditions as snow was already falling on the higher elevations.

Table 1 summarizes the passes made over the Plateau. The portion of each pass from first to last detection of SF_6 is shown on Fig. 1 along with a pass number corresponding to Table 1. It is seen that SF_6 plume position and width varied with time and altitude. The plume position, first found at an azimuth of 11 degrees true relative to the source, veered to almost due east (84 degrees) as the aircraft climbed from 8000 to 10,700 ft. Vertical wind shear probably caused this directional change. However, the wind backed with time to 51 degrees as sampling continued between 10,700-11,100 ft.

The peak SF_6 concentration on each pass varied from 50 to 400 ppt with the exception of the final pass, while mean concentrations were between 10 and 55 ppt. The general decrease after about 1336 was probably due to the reduced release rate after 1306.

Table 1. Summary of SF_6 measurements over the Wasatch Plateau from 1259-1357. Downwind distances, angular widths and direction to plume center are relative to the Mount Pleasant release site.

Pass No.	Mean time (MST)	Elevation (ft-MSL)	Mean dist. (mi)	Plume width (deg)	Dir. to plume center (deg)	Mean conc. (ppt)	Max. conc. (ppt)
1	1259	8000	12	9	11	15	50
2	1305	8200	9	22	20	15	110
3	1309	8500	7	17	30	40	120
4	1319	9100	6	48	59	55	320
5	1324	9600	7	43	52	30	400
6	1332	10300	8	39	54	15	150
7	1336	10700	7	13	84	50	160
8	1345	11100	6	12	77	15	80
9	1348	10700	10	31	51	10	80
10	1354	10900	13	10	51	10	50
11	1357	10200	-	-	-	0	0

Plume widths ranged from about 10-50 degrees. Essentially the entire Plateau top from northeast to east of Mount Pleasant had SF_6 over it sometime during the period 1319-1354. However, instantaneous plumes were not continuously above the level of detection throughout the plume widths listed in Table 1. Figure 8 has been selected to illustrate typical spatial variations in SF_6 concentrations, showing several "gaps" within the overall plume where the tracer gas was below the limit of detection (about 10-20 ppt).

Using a characteristic distance of 8 miles from the valley floor to the windward slope of the Plateau, the average plume width of 23 degrees from Table 1 equates to a 3.3 mile crosswind distance in the desired seeding zone. That plume width suggests that generators need to be spaced about that distance crosswind to fill most of the desired cloud volume with AgI. Figure 1 shows generator spacing in the Sanpete Valley significantly greater than 3.3 miles.

The concentration of effective ice nuclei present over the Plateau top will be estimated by reference to the tracer gas observations, believed more quantitative than the acoustical counter measurements. The data of Fig. 8, which represent the highest average concentration of SF_6 of any pass (Table 1), were used as follows. The mean value of 55 ppt is equivalent to a tracer gas density of 2.8×10^{-10} g l^{-1} for the temperature and pressure inside the aircraft where the SF_6 detector was operated. This corresponds to 2.5×10^{-10} g l^{-1} when cooled and expanded to outside temperature and pressure (-6°C and 698 mb).

The source strengths of the tracer gas and AgI were 15 g s^{-1} and 1.7×10^{-3} g s^{-1}, respectively. Assuming equal dilution of the plumes, AgI density is given by:

$$\text{AgI density} = [(2.5 \times 10^{-10})(1.7 \times 10^{-3})]/15 = 2.8 \times 10^{-14} \text{ g } l^{-1}.$$

The effectiveness values of the NAWC seeding generator are given in Table 2 as calibrated in the Colorado State University Cloud Simulation Laboratory under natural draft and maximum fan conditions. The former values would apply to the AgI release prior to about 1320, and the latter values would be applicable thereafter when the wind speed was much stronger.

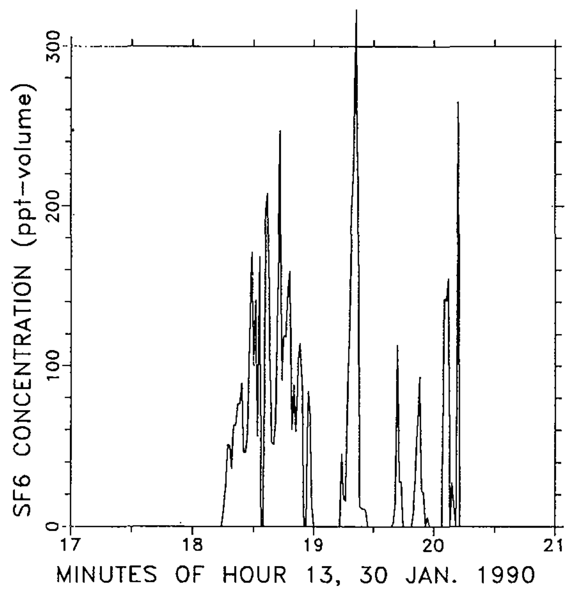

Fig. 8. Plot of SF_6 concentration vs time during an aircraft sampling pass above the Wasatch Plateau at 9100 ft altitude on January 30, 1990.

Ice nuclei concentrations would not reach levels believed significant for seeding at temperatures warmer than about -15°C with light winds, or -11°C with strong

Table 2. Estimated effective ice nuclei per liter, equivalent to 55 ppt SF_6 over the Wasatch Plateau, as a function of temperature and wind. Effectiveness values of the NAWC seeding generator are given for both light and strong wind conditions.

Temperature (°C)	Ice crystals per g AgI Natural draft	Maximum fan	IN l^{-1} light wind	IN l^{-1} strong wind
-6	2×10^{10}	est. 2×10^{11}	.001	0.01
-8	1×10^{12}	9×10^{12}	.03	0.3
-10	9×10^{12}	est. 9×10^{13}	0.3	3.
-12	4×10^{13}	4×10^{14}	1.1	11.
-16	5×10^{14}	3×10^{15}	14.	84.
-20	1×10^{16}	1×10^{16}	28.	280.

winds. But as discussed in Part I, SLW concentrated in the lowest kilometer above Utah mountain barriers is seldom this cold. This suggests that significantly higher seeding rates, and AgI types with higher effectiveness at warm temperatures, would be appropriate for the Utah operational program. Clouds that are only slightly supercooled may require other seeding methods (e.g., Reynolds, 1991).

It is of interest to compare acoustical counter observations with the above estimates based on tracer gas measurements. Total counts per pass from the acoustical counter ranged from 59-86 for the first four passes in Table 1, prior to cloud chamber warming. Assuming the AgI and tracer gas plumes coincided since they were co-released, the SF_6 detector provides time in plume. Mean ice nucleus concentrations can be calculated from the known air sampling rate and the factor of ten correction for known chamber losses (Langer, 1973). For the first four passes of Table 1, IN concentrations, effective at -20°C, were 47, 35, 89 and 34 IN l^{-1}, respectively. These are in good agreement with the light wind estimate for -20°C in Table 2 (28 IN l^{-1}), appropriate since winds by the generator averaged 2.2 m s^{-1} prior to 1320. It is again noted that the estimate based on SF_6 is for the highest pass average. The comparable value for passes 1 and 2 of Table 1 is 8 IN l^{-1}, less than the respective acoustical counter estimates. However, agreement is reasonable when one considers the possible sources of error in each detecting system and the assumptions made in estimating IN concentrations.

The acoustical counter observations agree with the tracer gas estimates in suggesting that seeding rates are low in the Utah operational program. The noted IN concentrations from the acoustical counter should be reduced about two orders of magnitude for a more typical SLW zone temperature of -10°C (see Table 2). That reduction results in IN concentration estimates less than 1 l^{-1}. Substantially smaller IN concentrations would be expected in SLW regions warmer than -10°C, which are frequent in Utah winter orographic clouds.

The above estimates are based on average values across entire plumes. Figure 8 shows considerable instantaneous variability within a plume, including zones below the measurement threshold. Consequently, some portions of a plume would be expected to have IN concentrations several times higher than estimated above. On the other hand, the volume containing higher concentrations would be quite limited, as would areas affected by significant snowfall increases at any moment.

To summarize, this aircraft mission took place during rapidly changing conditions producing snowfall at higher elevations by the end of sampling. Ground-released plumes initially were transported northward up the Sanpete Valley with most of the material in the lowest 2000 ft above the valley floor about 6 miles downwind. The lower atmosphere was likely stable at that time (see Figs. 6 and 7). However, both SF_6 and AgI were transported over the Wasatch Plateau during the latter half of the mission when the atmosphere was probably neutral from the valley floor to above the Plateau. Tracer gas was detected as high as 11,100 ft, over 1000 ft above the Plateau top. Overall plume widths varied from 10-50 degrees, and instantaneous plumes were not continuous through their crosswind extent. The tracer gas measurements from the pass with highest average concentration were used to estimate ice nucleus concentrations over the Plateau as a function of temperature. Ice nucleus measurements from the acoustical counter also were examined. For the type of AgI generator and seeding rate and solution used, it appears that ice nucleus concentrations would be quite low for typical temperatures in the SLW zone near the barrier.

2.3 Mission of February 6, 1990

This research flight took place from 1500 to 1700 in the vicinity of the Wasatch Range near Salt Lake City. The 1700 500 mb analysis positioned a trough axis over the west coast of California. Southwesterly flow ahead of the trough existed over Utah at 500 and 700 mb (20 and 10 m s^{-1}, respectively) with the strongest winds northwest of the research area. Advection of warm, moist air was occurring at 700 mb. There was a well defined moisture boundary across northwest Utah, with central Utah on the dry side. Unlike the two earlier cases, significant moisture (< 3°C dewpoint depression) at 700 mb had already reached the research area at the time of the flight. A

GOES infrared satellite image showed extensive cloud cover over most of Utah as early as 1100. Most of these clouds were altostratus, but cloud base lowered with time as indicated below.

The 1400 surface chart showed a low centered in western Nevada with a stationary front extending eastward across Nevada to the northwest corner of Utah. Light southerly winds were reported in western Utah ahead of the front. These winds varied from the January 26 and 30 cases where stronger surface winds existed ahead of the front because of a stronger pressure gradient over the Great Basin. The cold front extended southwestward from the low across the southern third of California. By 1435, radar and surface observations indicated scattered snow showers in both northern and southern Utah. At 1500 light snow was reported along the stationary front in southwestern Idaho, and cloud bases were 5000 to 8000 ft AGL in northern Utah.

The conditions during the research flight typified prefrontal conditions for Utah storms. The advection of warm, moist air from the southwest can lead to abundant SLW development in orographic clouds over the mountains of southern and central Utah. The observations of thickening cloud cover and scattered snow showers suggest the flight was conducted as the storm began.

No Airsonde release supported this mission. However, the routine National Weather Service rawinsonde was released from nearby Salt Lake City Airport near the end of this mission. Below 7000 ft, winds were south-southeast to south at about 10 m s^{-1}. Above 7000 ft winds veered to the southwest and increased steadily in speed to greater than 30 m s^{-1} above 20,000 ft. The atmosphere was dry below 8500 ft, but nearly saturated at higher levels to above 20,000 ft. The lifted condensation level of 5600 ft matched the cloud base reports over northern Utah. Potential temperatures increased steadily with altitude in the dry layer from the surface to cloud base, indicating stable conditions in that layer during the research flight.

A single AgI generator was operated at the mouth of Little Cottonwood Canyon (Fig. 2) at 6 g h^{-1}, and SF_6 was released from the same site at 80 lbs h^{-1}, from 1457 to 1648. A van equipped with a SF_6 detector sampled along various roads during the aircraft flight. The aircraft took off at 1500. The cloud deck obscured the higher peaks, and snow showers were observed over the higher elevations, so aircraft sampling was not possible over the main ridgelines. (The sky was overcast over the mountains to the west of the Wasatch Range, and the entire valley between, throughout this mission.) Instead, the aircraft made a series of almost north-south passes over the western slopes of the Range. Pairs of passes were made at 500 ft intervals from 6000 ft, up to and including 8500 ft, between 1505 and 1603. The south end of the sampling legs varied from about 2-3 miles south of the AgI and SF_6 release site, while the north end was approximately 9 miles north of the release site, over the entrance to Parleys Canyon which is crossed by Interstate Highway I-80. (Refer to Fig. 2 for the locations of various landmarks).

The shape of the Wasatch Range prevented north-south passes beyond these points. Also, snow showers existed just south of the sampling line in some cases.

The SF_6 detector drifted badly, thus reducing its sensitivity, especially during the latter half of the mission. This problem was more serious than on January 30 and the detector's signal was clearly above the drifting baseline on only three passes, which corresponded to the highest AgI concentrations detected by the acoustical ice nucleus counter. The SF_6 gas could not be positively identified on several passes where lower concentrations of AgI were evident. Consequently, the following discussion will emphasize AgI measurements.

The acoustical ice nucleus counter also experienced problems. The atomizer airflow was low for several minutes during the first hour of sampling, and again during the last 45 minutes of the mission. This low airflow reduced available cloud condensation nuclei in the cloud chamber, resulting in the growth of some droplets to sizes large enough (>25 μm) to be detected (counted) by the acoustical sensor. The second-by-second data record shows this problem as periodic "bursts" of high count rates, bracketed by low or zero count rates. When relatively high concentrations of ice crystals are created by AgI, second-by-second count rates vary more slowly. This problem rendered data from the latter part of the mission unusable. Fortunately, the first hour of the mission is believed to have experienced only minor "contamination" because of the atomizer problem.

Very low, but noticeable, AgI concentrations were found on the two initial north-south passes, made at 6000 ft. This AgI concentration is surprising since the generator had been on since 1353, more than an hour before takeoff. Higher AgI levels were found on the 6500 ft passes, and the highest concentrations were found on the two passes at 7000 ft, between 1522 and 1533 (SF_6 also was detectable on these passes). The highest concentration, encountered near the entrance to Little Cottonwood Canyon, corresponded to a strong updraft region noted by the pilot. However, high concentrations also existed to the north, near the entrance to Parleys Canyon. Strong turbulence occurred frequently at all altitudes during the north-south passes along the west side of the Wasatch Range.

Instantaneous acoustical counter count rates exceeded 50 IN s^{-1} several times along the 7000 ft passes. Mean rates were about half that value, corresponding to around 1500 IN l^{-1} at -20°C. Count rates were roughly half as high during one of the 7500 ft passes, and one of the 8000 ft passes, but significantly lower on other passes at those altitudes. Little AgI was found on the 8500 ft passes, the highest made.

All AgI observations showed that seeding material was not being transported up Little Cottonwood Canyon as intended, but was flowing northward, parallel to the mountain barrier. Of necessity, the aircraft was paralleling, rather than crossing, the AgI plume. The plume was clearly exited to the south of the generator (count rates approached zero), but counts did not always approach background levels on the north end of the passes.

The high counts may be partially due to the fact that a few minutes in clean air is required to "flush" the cloud chamber of the acoustical counter. This time interval was not available on the north end of the sampling track, where higher terrain required the aircraft to turn. Also, the aircraft may not have totally exited the plume when turning 9 miles north of the generator. It is not known where the AgI plume was transported beyond the region sampled.

Periodic wind observations by the technician at the release site showed winds usually from the southeast at 5-9 m s^{-1} during the mission; that is, the winds were mostly downslope into the valley. Personnel in the SF_6 sampling van also noted downcanyon winds just above the entrance to Little Cottonwood Canyon at about 1505 and again at 1710.

The personnel in the van did most of the sampling along the foothills of the Wasatch Range, north of the SF_6 release site. Tracer gas was encountered a number of times, though usually in weak concentrations. Like the aircraft measurements, the van observations indicated the plume was being transported northward parallel to the mountain barrier.

At 1603 the aircraft entered Parleys Canyon and flew over I-80 into the valley east of the Wasatch Range. No AgI was encountered as the aircraft descended from 8500 to 7500 ft while flying above the canyon.

The aircraft made several north-south passes from Park City to a point 7 miles north, at 500 ft intervals between 7,000 and 10,000 ft. Lower cloud bases associated with higher terrain prevented VFR sampling north and south of this track. The acoustical counter was active at 8500 ft and above, but these counts corresponded to an extended period of low atomizer flow and are not believed to be due to AgI. No evidence of SF_6 was found during the sampling east of the Wasatch Range.

An east-to-west pass through Parleys Canyon near 1625 detected no AgI at 8500 ft. Additional sampling was done just west of Parleys Canyon and on north-south passes from there to south of Little Cottonwood Canyon. By this time the atomizer flow problem had so contaminated the acoustical counter measurements that the presence of AgI could not be confirmed. The aircraft returned to base about 1700.

In summary, the mission of February 6 showed that AgI released at the mouth of Little Cottonwood Canyon was transported northward along the west side of the Wasatch Range, rather than up the canyon as intended. The snow showers over the Range may have produced the down-canyon flow observed at the surface. Clearly, canyon mouth seeding could not be effective in the intended target area under the conditions sampled. The AgI may have been transported over the Range well to the north of the intended target, but no evidence exists to support that hypothesis. Given the shape of the barrier, Parleys Canyon would seem to offer the path of least resistance for transport over the Range. However, no AgI or tracer gas was detected between 7500-8500 ft over the canyon.

2.4 Mission of March 2, 1990

An AgI generator was started at 1400 and SF_6 gas was released after 1417, both from the north edge of Mount Pleasant. The AgI output was 6 g h^{-1} and the gas release rate was about 80 lbs h^{-1} throughout the aircraft sampling mission. Aircraft sampling was conducted from 1400-1520.

The 0500 and 1700 upper air analyses showed two branches to the westerlies. The weaker southerly branch influenced Utah. A closed low center was positioned well off the west coast. The height gradient over the Western United States was weak at 0500, reflected in the light winds at 500 mb (west at 10 m s^{-1}) and 700 mb (southwest at 6-7 m s^{-1}). By 1700 the height gradient had tightened slightly west of Utah, but winds over the research area remained light. Between 0500 and 1700 warm air advection over Utah increased temperatures about 3°C at 500 mb and 1°C at 700 mb, a situation that likely led to an increase in stability with time.

Although significant synoptic disturbances were far removed from Utah, the weak flow pattern over the state had significant moisture at both 700 and 500 mb (dewpoint depressions < 4°C), and low to midlevel clouds covered most of western Utah from 0600 to 1600. The moisture and cloudiness were of subtropical origin, arriving over Utah from the flow beneath the closed low west of northern California. Salt Lake City reported cloud bases of 3500 ft AGL (with a rain shower) at 1200 and bases at 6500 ft AGL at 1500. The weak surface pressure gradient over the entire Great Basin resulted in light (< 5 m s^{-1}) and variable winds.

An Airsonde released from Mount Pleasant at 1533 showed potential temperature increased from the surface to about 7500 ft, then was nearly constant to 10,000 ft, and thereafter increased with height (see Fig. 9). No low-level inversions were evident. Figure 10 shows wind speed increasing from 2 m s^{-1} between 6000-6800 ft to 6.5-8 m s^{-1} in the 9000-10,000 ft layer, corresponding to Plateau top elevations. Wind direction, also shown on Fig. 10, veered rapidly with height from northeast at 6000 ft to southwest by 8000 ft, and thereafter veered slowly toward westerly.

The sky was overcast during the mission in all quadrants. Cloud bases were above the Wasatch Plateau although higher elevations were sometimes obscured. Occasional showers were seen and melted snowflakes sometimes impacted the airplane's windscreen. The freezing level was at 8800 ft. Ten minute mean surface winds at Mount Pleasant were between 0.7-1.8 m s^{-1} during aircraft sampling with directions between northeast and southeast (downslope).

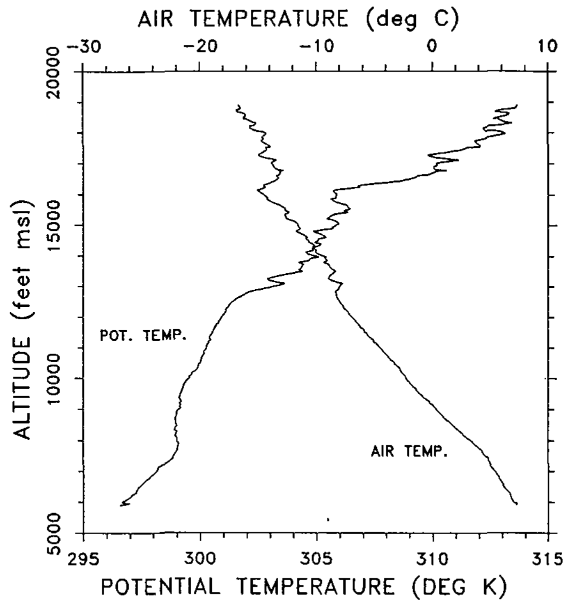

Fig. 9. Vertical distributions of potential temperature and air temperature from Airsonde released at 1533 on March 2, 1990, from Mount Pleasant, Utah.

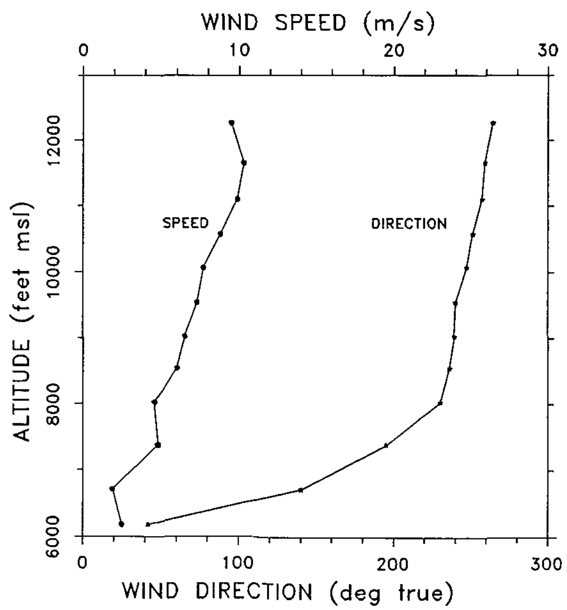

Fig. 10. Vertical distributions of wind speed and direction from Airsonde released at 1533 on March 2, 1990, from Mount Pleasant, Utah.

Conditions during the research period provided a fair representation of storm conditions. Clouds and moisture were present, and winds aloft were southwesterly, although weaker than during most storm situations. Light winds at the surface are, however, common in the valleys between mountain ranges. The 1987 and 1989 Utah/NOAA soundings showed that 50 percent were launched when surface winds were 1 m s^{-1} or less.

From 1420-1455 the aircraft circled the Mount Pleasant area, searching for the AgI and SF_6 from about 300-900 ft AGL. The first SF_6 detection occurred at 1455, at 6100 ft elevation about 2.5 miles southwest of the release site. Three more passes along the same northwest-southeast track detected high concentrations of the gas between 5950-6100 ft. Plume widths were up to 1.0 mile, and peak concentrations exceeded 10,000 ppt. A pass at 6200 feet barely detected the SF_6 and passes at 6500 and 6800 ft detected no gas.

AgI was also detected on the lower level passes but peak count rates were only in the 4-7 IN s^{-1} range. The checklist notations made each 20 minutes or so did not indicate acoustical counter malfunction. The AgI generator may not have been operating properly. At any rate, the AgI concentration was much lower than expected for a plume trapped near the surface.

A final aircraft pass was made from 1519-24 at low levels over the western foothills of the Wasatch Plateau. As expected, no SF_6 or AgI was found moving up the western slope.

In summary, the valley-released plumes were trapped in the stable lower atmosphere and drifting toward the southwest in the light down-valley wind. Although snow showers were occurring high on the Plateau, the observations indicate that seeding with valley generators would not be succeessful under the prevailing conditions.

2.5 Mission of March 8, 1990

The final flight of the 1990 research period took place from 1405 to 1535 in the vicinity of the Wasatch Plateau after an earlier sampling attempt was aborted. A significant upper air trough located west of Utah, with its north-south axis located along the coast of Washington and Oregon, progressed eastward between 0500 and 1700. The height gradient over Utah at 700 and 500 mb increased with time. By 1700, winds at 700 mb were southwest at 10 m s^{-1}, and 500 mb winds were west-southwest at 20-25 m s^{-1}. The strongest winds were still northwest of the research area. At 700 mb dewpoint depressions remained greater than 11°C through 1700, while the presence of altostratus and cirrus indicated midlevel and high level moisture over the central Utah area. From 0500 through 1700, warm air advection occurred over Utah from low through midlevels of the atmosphere. By 1700 the 700 mb temperature at Salt Lake City was a mild -1°C.

At the surface a cold front progressed from central Nevada at 1100 to near Salt Lake City by 1700. A high pressure region over southeast Utah, in combination with the advancing front, produced moderate southeast to southern winds over most of western Utah prior to and during the research flight. Over central Utah cloud bases were generally 12,000 ft AGL, with lower bases reported only near Salt Lake as the front approached between 1600 and 1700.

The research flight again took place in the prefrontal storm environment, where lower atmospheric layers were still relatively dry, but midlevel moisture and clouds were present. The 700 and 500 mb winds typified pretrough winds, and the surface flow also resembled that commonly experienced with low pressure to the west and a high pressure center in southeastern Utah. Warm temperatures existed at all levels, which is also common during the prefrontal stage of March storms in Utah.

The sampling aircraft arrived at the Mount Pleasant area at 1120 under a high, thick overcast. A haze layer observed at low levels suggested an inversion. The aircraft flew a "missed approach" over the Mount Pleasant Airport runway to obtain a temperature profile extending to the surface. The aircraft temperature profile showed an inversion based about 150 ft AGL, extending to 500 ft AGL, overlain by an isothermal layer. Airsondes released from Mount Pleasant at 0925 and 1015 indicated similar stability in the lower atmosphere. Surface winds were from the north at about 1 m s^{-1} at the time of the aircraft sounding. The 1015 Airsonde indicated light winds below 6500 ft (600 ft AGL), but increasing to 9-10 m s^{-1} from 210 degrees at Plateau top elevations.

In view of the low-level stability and light winds, the aircrew decided to postpone plume tracing until later in the day, hoping that low-level stability would decrease with time. The release of SF_6 gas, started at 1109 at 100 lbs h^{-1}, was stopped at 1127. AgI was produced from 0906-1127. The aircraft was flown to the Price Airport, east of the Wasatch Plateau, and remained there until early afternoon.

An Airsonde was released from Mount Pleasant at 1523. Figure 11 shows the variation of air temperature and potential temperature with altitude. Except for a very shallow surface-based layer, the atmosphere was stable throughout the layer measured, especially below about 8000 ft. A weak inversion is evident based at about 6200 feet. Figure 12 shows the distribution of wind speed and direction with altitude. Wind speeds were light below 7000 ft, drifting from the north-northeast to northeast. However, at Plateau top altitudes (9000-10000 ft), winds were from the southwest at almost 10 m s^{-1}. Such velocities typify prefrontal storm periods.

The aircraft returned to the Mount Pleasant area at 1407. The release of SF_6 commenced at 1412 from the north edge of Mount Pleasant, again at 100 lbs h^{-1}. Gas release continued until 1533. The AgI generator, located near the tracer gas release site, was presumably operated during the same period. However, the technician's checklist did not so indicate, and acoustical counter measurements, discussed later, were very low.

Aircraft sampling continued until 1535, about the time the supply of tracer gas was exhausted. A high, thick overcast persisted throughout the period. Many sampling passes and circles around Mount Pleasant took place during the almost 1.5 h sampling period summarized below.

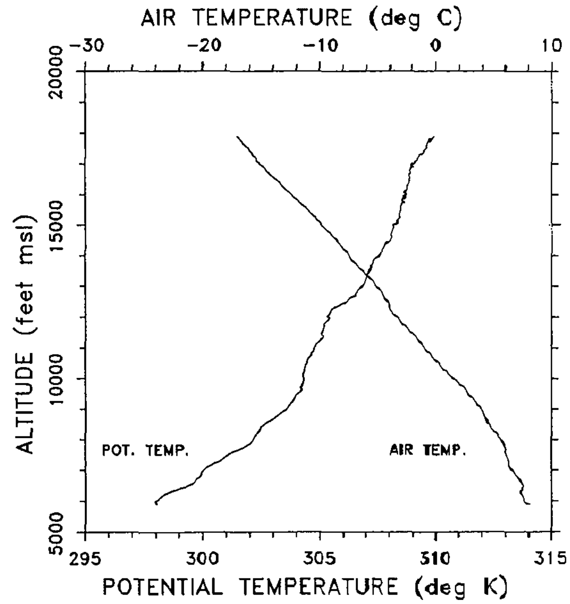

Fig. 11. Vertical distributions of potential temperature and air temperature from Airsonde released at 1523 on March 8, 1990, from Mount Pleasant, Utah.

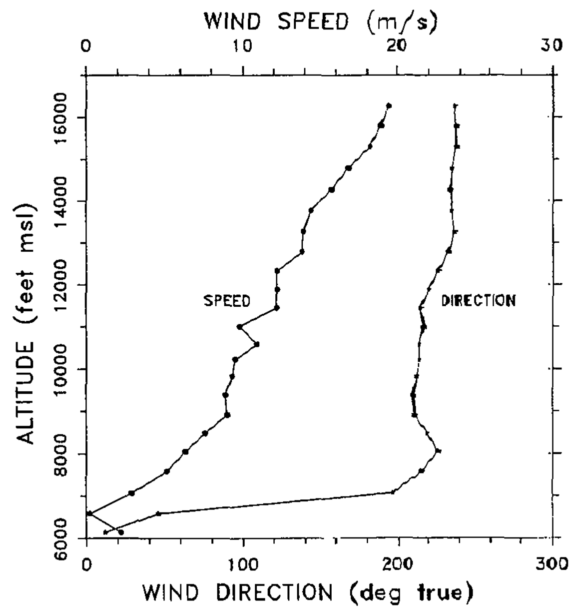

Fig. 12. Vertical distributions of wind speed and direction from Airsonde released at 1523 on March 8, 1990, from Mount Pleasant, Utah.

The tracer gas was first detected at 1412, 2 minutes before the start of the afternoon release. In fact, a wide area of SF_6 was found within 2-3 miles of the release site between 1412-1426, generally in the half-circle from east through south to west. The gas was found between 6500-6700 ft, but no SF_6 was detected at 7100 ft, so the gas was trapped in the lowest 1000 ft AGL. This widespread region of tracer gas had to be the residue from the morning release as surface winds had been about 1 m s^{-1} and variable in direction since the start of release at 1106. Peak gas concentrations were 600-800 ppt.

A pass was made at 7400 ft between 1430-1435, skimming the foothills of the Plateau from southeast to northeast of the gas release site. Pockets of tracer gas were detected during this pass, but peak concentrations were only 100 ppt. The smoothness of the low-level flight indicated light winds and insignificant mechanical turbulence over the rugged terrain.

Several circles were flown around the release site from 1436-1456, usually at a radius between 2-3 miles. Sampling levels ranged from 6000 ft (near the ground) to 7000 ft. As found earlier, the gas was widespread from east to south to west of Mount Pleasant, and peak concentrations reached around 600 ppt at 6500 ft and below. Limited regions of gas were found at 7000 ft with maximum concentrations near 100 ppt.

Two near-terrain passes were made over the foothills from northeast to south-southwest of Mount Pleasant between 1454-1507. The first pass, at 6700 ft, detected SF_6 concentrations up to 300 ppt southeast of the release site. The second, at 7500 ft, did not observe any tracer gas.

A series of five passes, along a northwest-southeast axis from 1510-1530 between 6200-6500 ft elevation, all detected an approximately 1-mile wide gas plume 3-4 miles southwest of Mount Pleasant. Peak concentrations exceeded 5000 ppt on three passes, 1000 ppt on one pass, and only 200 ppt on another pass. The high concentrations suggest these passes were detecting the afternoon release of SF_6 . Surface winds since the start of the afternoon release usually varied from 20-50 degrees and 1.1-1.8 m s^{-1}. The gas should have been transported about 3 miles southwest since the 1414 start of release at the average surface speed.

A final near-terrain pass made over the Wasatch Plateau foothills from 1531-1535 at 7000 ft detected no tracer gas.

AgI was frequently measured by the acoustical counter at low altitudes, but count rates seldom exceeded 3 IN s^{-1}, even when encountering high gas concentrations after 1510. As noted earlier, it is not certain that the generator was operated during the afternoon. There was no evidence of problems with the acoustical counter.

A missed approach flown over the Mount Pleasant Airport near 1511 indicated a temperature inversion between about 6200-6800 ft, which is the layer the tracer gas was usually confined to.

In summary, the plume tracing from this day once again indicated a stable layer based near the valley floor. Any seeding material released by valley floor generators would not be transported over the Wasatch Plateau under such conditions. Thus, during storm conditions simulated by the winds and stabilities of March 8, 1990, seeding from the valley floor would be ineffective.

3. SUMMARY

A series of five aircraft missions tracked AgI and SF_6 (simulating AgI releases) from valley and canyon mouth sites used in the Utah operational seeding program. All flights took place in VFR conditions to permit very low-level sampling over both mountainous terrain and within valleys. Each mission was flown under atmospheric conditions typical of prefrontal conditions during winter storms. In fact, snowfall was occurring at higher elevations during some sampling flights.

Four of the five aircraft missions found that real and simulated seeding material was transported along the mountain barrier rather than over it, or the material was trapped by low-level stability and was drifting about the valley.

The AgI and SF_6 were tracked over the Wasatch Plateau during part of one mission when the lower atmosphere likely had neutral stability. Ice nucleus concentrations were estimated based on the largest mean SF_6 amount above the Plateau and the characteristics of the AgI generators used in Utah. It was found that ice nucleus concentrations would be very limited at typical SLW temperatures in the prefrontal storm phase. Acoustical counter measurements of IN supported this conclusion. Thus, even in the single case where plumes were transported in the layer over the Plateau where SLW is known to concentrate, resulting IN concentrations appeared inadequate for effective seeding.

The present seeding approach may be effective during other storm conditions than those sampled. For example, the AgI may pool in the valleys for extended periods and then be transported into the SLW region in higher concentrations during frontal passage, a possibility that has not been adequately tested. Unpublished observations from early March 1991 showed that storms with embedded convection transported valley-released AgI to aircraft sampling levels well above the Plateau. It will be interesting to analyze the resulting ice nucleus concentrations.

The observations presented in this paper, together with those described in the Part I companion paper, strongly suggest frequent ineffectiveness in current cloud seeding methods in Utah. Steps should be taken to improve the frequency of targeting of the SLW region with AgI and to increase the concentration of seeded crystals when the SLW region is targeted. The technology exists to do both.

Repeating the strong recommendation made in Part I: winter orographic cloud seeding projects should follow Utah's example and physically examine their targeting if they have not done so already. This question is too important to ignore.

Acknowledgements:

Don Griffith of NAWC supervised the aircraft sampling program and scheduled flights during typical prefrontal conditions. The NAWC aircrew, consisting of George Wilkerson, aircraft scientist and SF_6 detector operator; Bill Hauze, acoustical counter operator; and Al Lisonbee, pilot; are to be commended for enduring considerable turbulence while tracking plumes at low levels over complex terrain. Evelyn Lees obtained Airsonde and other data to support the missions. Jack McPartland and Glenn Cascino of the Bureau of Reclamation helped with field equipment installation and maintenance. Jim Heimbach and Gary Langer contributed many helpful suggestions for the conduct of these investigations. Barry Saunders and Clark Ogden of the Utah Division of Water Resources provided overall management of the research program. John Lease provided overall management of Reclamation efforts.

This research was primarily supported by the Atmospheric Modification Program of NOAA, directed by Roger Reinking, with additional support from the Bureau of Reclamation.

4. REFERENCES

Benner, R.L. and B. Lamb, 1985: A fast response continuous analyzer for halogenated atmospheric tracers. J. Atmos. Oceanic Technol., **2**, 582-589.

Griffith, D.A., J.R. Thompson and D.A. Risch, 1991: A winter cloud seeding program in Utah. J. Weather Mod., **23**, 27-34.

Holroyd, E.W., J.T. McPartland and A.B. Super, 1988: Observations of silver iodide plumes over the Grand Mesa of Colorado. J. Appl. Meteor., **27**, 1125-1144.

Huggins, A.W., 1990: Investigations of winter mountain storms in Utah during the 1987 Utah/NOAA field program. Final Report to the Utah Dept. of Natural Resources, Division of Water Resources. Desert Research Institute, Reno, NV, 212 pp.

Langer, G, 1973: Evaluation of NCAR ice nucleus counter. Part I: Basic operation. J. Appl. Meteor., **12**, 1000-1011.

Long, A.B., B.A. Campistron and A.W. Huggins, 1990: Investigations of a winter mountain storm in Utah. Part I: Synoptic analyses, mesoscale kinematics, and water release rates. J. Atmos. Sci., **47**, 1302-1322.

Reynolds, D.W., 1991: Design and field testing of a remote ground-based liquid propane dispenser. J. Weather Mod., **23**, 49-53.

Sassen, K., A.W. Huggins, A.B. Long, J.B. Snider and R.J. Meitin, 1990: Investigations of a winter mountain storm in Utah. Part II: Mesoscale structure, supercooled liquid water development, and precipitation processes. J. Atmos. Sci., 47, 1323-1350.

Super, A.B. and J.A. Heimbach, 1988: Microphysical effects of wintertime cloud seeding with silver iodide over the Rocky Mountains. Part II: Observations over the Bridger Range, Montana. J. Appl. Meteor., **27**, 1152-1165.

Super, A.B. and A.W. Huggins, 1992: Investigations of the Targeting of Ground-released Silver Iodide in Utah. Part I: Silver-in-snow measurements and ground ice nucleus observations. J. Weather Mod., **24**, accepted.

Super, A.B., B.A. Boe, E. W. Holroyd and J.A. Heimbach, 1988: Microphysical effects of wintertime cloud seeding with silver iodide over the Rocky Mountains. Part I: Experimental design and instrumentation. J. Appl. Meteor., **27**, 1145-1151.