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# IMPLICATIONS OF EARLY 1991 OBSERVATIONS OF SUPERCOOLED LIQUID WATER, PRECIPITATION AND SILVER IODIDE ON UTAH'S WASATCH PLATEAU

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Abstract. The Utah/NOAA Atmospheric Modification Program conducted an observational program in early 1991, with additional support from the Bureau of Reclamation. A summary is presented of observations obtained on the Wasatch Plateau of central Utah which includes SLW (supercooled liquid water), precipitation, AgI (silver iodide ice nuclei), air and dewpoint temperature, and wind velocity. With the exception of AgI ice nuclei, measurements were made on 20 days with storm conditions. Silver iodide was monitored during part or all of a subset of 12 days when valley AgI generators were being operated.

It is shown that abundant SLW existed during many hours, and a large fraction of these hours did not have precipitation observed on top the Plateau. The SLW flux over the Plateau-top's windward edge exceeded the average precipitation on top the Plateau. These findings suggest significant seeding potential may exist.

Acoustical ice nucleus counter observations were adjusted to temperatures typical of AgI plume tops. Aircraft measurements showed the plume tops were usually less than 1 km above the Plateau. The adjusted ice nucleus observations suggest effective AgI ice nuclei concentrations were too low for productive seeding much of the time when SLW was present. The main problem appears to be the warm temperatures of the SLW during most storm periods. Effective concentrations of AgI ice nuclei are not expected at such temperatures with the generators and release rates used in the Utah operational seeding program. However, these estimates were based on a 1981 generator calibration in a cloud simulation laboratory which may not be totally representative of winter orographic clouds. Direct observations are needed of ice particle concentrations caused by seeding orographic clouds for the range of conditions typical of winter storms.

The challenge is to develop means of routinely targeting the SLW zone with adequate concentrations of seeding-caused ice crystals which can start the precipitation formation processes in naturally inefficient clouds. A number of approaches are suggested which could make the Utah operational seeding program more effective.

## 1. INTRODUCTION

Observations of SLW (supercooled liquid water), precipitation, AgI (silver iodide) IN (ice nuclei), wind velocity, and air and dewpoint temperature were made on the Plateau (Wasatch Plateau) of central Utah between mid-January and mid-March 1991. This observational program was part of the Utah/NOAA (National Oceanic and Atmospheric Administration) Atmospheric Modification Program.

Overall purposes of the Utah/NOAA Atmospheric Modification Program are:

(1) To physically evaluate the effectiveness of the Utah operational cloud seeding program in enhancing the mountain snowpack.
(2) To suggest means of improving operational program effectiveness.

The project design of the operational program and the general seeding hypothesis are discussed by Griffith et al. (1991). Briefly, the program uses a widespread network of manual AgI generators operated upwind (west) of major mountain barriers. The generators are located mostly at valley sites with some generators near canyon mouths. The seeding hypothesis states that SLW is present in Utah storms which can be reached by the AgI, and that growth times and trajectories of augmented precipitation can impact the intended target areas. Special weather forecasts are made to determine whether storms meet stated seeding criteria and which, if any, generators should be operated in attempts to affect particular target areas.

The early 1991 Utah/NOAA observational program emphasized the transport and dispersion of ground-released AgI over the Plateau. Most AgI releases were made from valley and canyon mouth locations, but some were made from a high altitude site on the Plateau's windward slope as discussed further by Super and Holroyd (1994). Other discussion of the transport and dispersion of AgI over the Plateau includes Griffith et al. (1992), Heimbach and Super (1992) and Super and Huggins (1992).

This paper does not directly address the transport and dispersion of ground-released AgI except as monitored at a single Plateau-top observatory. Rather, this paper's purpose is to consider and relate particular variables of interest to winter orographic cloud seeding in an "overview" sense for the period of measurements. The SLW observations were summarized by Huggins et al. (1992). This paper expands upon their work in that precipitation observations are considered in more detail, and Plateau-top observations of AgI are discussed for periods of valley generator operation. Estimates of per-storm SLW flux over the Plateau during early 1991 have been presented by Super and Huggins (1993). Sassen and Zhao (1993) discuss the cloud seeding implications of a related data set collected over the Tushar Mountains of southern Utah.

## 2. OBSERVATIONS

Twenty days were selected for analysis of SLW and precipitation. Seeding was conducted during some of these days but any effects of seeding on SLW and precipitation measurements are not known. These 20 days (midnight to midnight - all times are LST) had almost complete measurements of the types noted above as well as significant SLW and/or precipitation. Amounts of SLW and precipitation outside these days were very limited during the late January to mid-March 1991 period. A few periods with significant SLW and precipitation occurred during the period January 14-27, but some precipitation data are missing.

Observations of IN were made on top the Plateau during part or all of a subset of 12 of the 20 days when valley seeding was being conducted from a network of 8 AgI generators (shown on Fig. 1 of Super and Holroyd, 1994). A total of about 164 h of seeding was carried out during these 12 days.

The days selected for analysis are listed below. Underlined dates had valley seeding and IN observations during at least part of the day.

January: <u>28</u>
February: <u>3</u>,12,13,14,<u>16</u>,<u>17</u>,18,19,<u>28</u>
March: <u>1</u>,<u>2</u>,3,<u>4</u>,<u>5</u>,<u>6</u>,7,<u>10</u>,<u>11</u>,14

Vertically-integrated SLW measurements were available from the Bureau of Reclamation's microwave radiometer. This type of instrument and its data retrieval have been discussed by Hogg et al. (1983). It was located at 2700 m (all elevations above mean sea level) near the Plateau-top's west edge at the head of a major canyon (the DOT site on Fig. 1 of Super and Holroyd, 1994).

Ambient temperatures at the radiometer were less than 0 °C for the large majority of hours with detectable liquid water, so all liquid was supercooled during such periods. A blower continuously directed a large volume of air over the outside reflector to keep it clear of snow and, to a lesser extent, occasional melted precipitation. The latter is not believed to have significantly affected measurements because melted precipitation was rare during above freezing hours, and the reflector was periodically checked and wiped dry if needed.

Twenty-five hours of radiometer data are missing from the 20 selected days, 6 of which are after 1800 on March 14 because of termination of the field program.

Wind speed and direction were measured by heated sensors (to prevent rime ice accumulation) which were located 7.5 m above ground level on a tower at the radiometer site. Air and dewpoint temperatures were measured on the same tower using an aspirated, chilled-mirror device and calibrated thermistors. These observations are complete for all 20 days with the exception of the last 6 h of March 14.

Ice nuclei concentrations were measured with a semiquantitative NCAR acoustical IN counter (Langer 1973, Super and Holroyd 1994) at the radiometer site. The unit was reconditioned by the system's inventor (G. Langer) just prior to the field program.

The NCAR IN counter rarely indicated a concentration as high as 1 IN $L^{-1}$ unless seeding was being conducted. This is not meant to suggest what the natural IN concentration was because the accuracy of the NCAR IN counter in measuring natural IN is not well known, as is true of most IN monitoring devices. However, experience with the counter indicated that IN concentrations above about 1 IN $L^{-1}$ at -20 °C, the cloud chamber temperature, were effectively AgI IN concentrations.

The NCAR IN counter was routinely checked for proper operation. Filtered air was periodically sampled to insure that IN count rates would decrease to very low levels. Flow checks insured against system air leaks. Several comparisons were made with a similar truck-mounted NCAR IN counter parked nearby when AgI was present. The two counters produced similar IN concentration values. Few problems were encountered with the radiometer site NCAR IN counter during the course of the field season.

Precipitation was measured by three shielded, weighing Belfort gauges on top of the Plateau. These gauges were located in protected clearings in the conifer forest just west of the radiometer site, near the center of the Plateau top, and near the Plateau-top's east edge (see Fig. 1 of Super and Holroyd, 1994). These measurements are complete for all 20 days.

## 3. PRECIPITATION AND SLW DISTRIBUTIONS

### 3.1 General

A sorting program counted and listed the hours with measurements between any specified minimum and maximum hourly average values of SLW, wind speed and direction, air temperature and dewpoint temperature, and hourly precipitation averaged for the three gauges. Hours with missing SLW measurements were ignored. A total of 455 h with complete data exists, which was used in the analysis to be presented. An exception is that a separate shorter data file was used for periods with IN measurements discussed in Sec. 8. No attempt was made to examine these data on a storm-by-storm basis. Rather, all data were considered together as a single set in a first step toward a "climatology." Of course, 20 days with storm activity from about 1.5 mo of a single winter do not begin to approach a climatology. However, because such observations are limited, in particular of SLW and AgI, it is of interest to consider an overview of the Plateau observations that do exist.

To place the observations in perspective, 179 h (39 pct) of the available 455 h had detectable precipitation, meaning at least one of the three gauges recorded at least 0.01 in. of precipitation. A total of 333 h (73 pct) had an hourly average SLW amount of 0.01 mm or greater. The radiometer's slight baseline drift was conservatively adjusted so that it is highly likely that all 333 h had SLW present, even when the hourly average was only 0.01 mm. A total of 169 h (37 pct) had simultaneously detectable SLW and precipitation. Only 10 h had measurable precipitation with no SLW observed. These 10 h were cold (average -11 °C at 2700 m), and were mostly associated with postfrontal, northwesterly flow.

### 3.2 Distribution of Precipitation

Hourly precipitation and SLW amounts are both known to have highly skewed frequency distributions in winter orographic storms. Table 1 lists the precipitation frequency distribution for the 179 h with detectable amounts in any of the gauges. (All precipitation observations were made in English units and are so reported.) The median hourly precipitation rate (snow liquid water equivalent) was about 0.015 in. Ninety pct of all hours had 0.06 in. or less. But 4 h exceeded 0.10 in. and the maximum observed hourly rate was 0.177 in.

Table 1 shows that the 41 pct of precipitation hours which received an average of 0.01 in. or less contributed only 10 pct to the total precipitation for all hours. Conversely, the 2 pct of precipitating hours with amounts exceeding 0.10 in. accounted for 11 pct of the total precipitation. About half the total precipitation fell during the 83 pct of the precipitating hours with average rates of 0.05 in. $h^{-1}$ or less. The 17 pct of hours with higher rates produced the other half of the total precipitation.

### 3.3 Distribution of SLW

The hourly frequency distribution of SLW amounts listed in Table 2 is also highly skewed. The median of all hours with SLW of 0.01 mm or greater was 0.06 mm. Almost 90 pct of all hours had 0.30 mm or less average SLW. However, 20 h exceeded 0.50 mm and 7 h exceeded 1.00 mm. The maximum recorded hourly mean was 1.50 mm.

Nineteen of the 20 h in excess of 0.50 mm occurred during a single storm event between the evening of March 3 and noon of March 5. All 7 h above 1.00 mm occurred between 1900 on March 4 and 0800 on March 5, an unusually warm and windy period.

The surface temperature at the radiometer was between 0 and +2 °C during portions of the 7 h with above 1.0 mm SLW. This raises the possibility of measurement errors caused by melting snow on the outside reflector. However, such errors are believed minor because of air blown across the reflector and periodic manual checks. Moreover, precipitation rates were light during the above freezing, high SLW periods, and much of the precipitation consisted of graupel which bounced off the reflector. Similar amounts were recorded by the nearby Desert Research Institute radiometer which effectively shed water drops with a spinning reflector. It is possible that some presumed liquid cloud water observations were elevated by a liquid film on falling ice particles above the radiometer. However, SLW hourly mean values continued to exceed 1.0 mm after the surface temperature reached and fell below 0 °C.

## 4. PRECIPITATION RATES EQUIVALENT TO SLW AMOUNTS

Based on aircraft observations and upwind rawinsonde measurements during winter storms, a westerly component of 10 m $s^{-1}$ is typical for the

**Table 1. - Frequency distribution of 179 h with observed precipitation.**

| Hourly Precip. (inches) | Percent | Cumulative Percent of hours | Cumulative Percent of total Precip. |
|---|---|---|---|
| 0.003-0.010 | 41 | 41 | 10 |
| 0.011-0.020 | 20 | 61 | 22 |
| 0.021-0.030 | 12 | 73 | 34 |
| 0.031-0.040 | 5 | 78 | 41 |
| 0.041-0.050 | 5 | 83 | 49 |
| 0.051-0.060 | 7 | 90 | 66 |
| 0.061-0.070 | 5 | 95 | 79 |
| 0.071-0.080 | 2 | 97 | 85 |
| 0.081-0.090 | 1 | 98 | 89 |
| 0.091-0.100 | 0 | 98 | 89 |
| 0.101-0.177* | 2 | 100 | 100 |

* change in interval size

Table 2. - Frequency distribution of 333 h with observed SLW.

| Hourly SLW (mm) | Percent | Cumulative Percent |
|---|---|---|
| 0.01-0.05 | 47 | 47 |
| 0.06-0.10 | 18 | 65 |
| 0.11-0.15 | 10 | 75 |
| 0.16-0.20 | 7 | 82 |
| 0.21-0.25 | 4 | 86 |
| 0.26-0.30 | 3 | 89 |
| 0.31-0.40* | 2 | 91 |
| 0.41-0.50 | 3 | 94 |
| 0.51-1.00* | 4 | 98 |
| 1.01-1.50 | 2 | 100 |

* change in interval size

lowest 600 m above the Plateau, believed to contain most of the SLW. Let it be assumed that the layer containing the SLW had a wind speed component normal to the Plateau of 10 m $s^{-1}$. The vertically integrated SLW, multiplied by the representative wind speed for the layer containing the SLW, provides a first approximation estimate of the SLW flux. The flux represents the upper limit for cloud seeding potential. While it is impractical for seeding to convert all available SLW to precipitation, total downwind precipitation caused by seeding cannot exceed the SLW flux.

To put the SLW flux values into perspective, their equivalent precipitation amounts were calculated by assuming the flux was totally converted to precipitation which fell uniformly over a 10-km distance, approximately the width of the Plateau top. A precipitation rate equivalent to this data set's observed median rate of 0.015 in. $h^{-1}$ would require a SLW value in excess of 0.10 mm for these assumptions. Table 2 shows that 65 pct of all hours with SLW had amounts of 0.10 mm or less above the west (windward) edge of the Plateau top. Some of this SLW flux was naturally converted to precipitation farther downwind. Therefore, even if seeding was capable of converting all the remaining "excess" SLW flux to additional precipitation, hourly rates would be quite limited for the majority of SLW hours. On the other hand, this 65 pct represents a large number of hours (216) with SLW amounts of 0.10 mm or less. If seeding could provide, on average, even an additional rate of 0.002 in. $h^{-1}$ during these many hours, the resulting precipitation accumulation would be 0.43 in. This figure represents 9 pct of the total which fell on the Plateau top during the 20 storm days comprising this data set. Therefore, beneficial precipitation could result from even minor seeded precipitation rates <u>if</u> the seeding was effective for many hours over the course of a winter.

Table 3 lists the precipitation rate equivalent to the midpoint of each SLW range in Table 2 with the assumptions that the SLW-layer wind speed normal to the barrier was 10 m $s^{-1}$ and all SLW flux was converted to precipitation of uniform intensity over a 10-km distance. The frequency of each range listed in Table 2 was used to estimate the percent of the total SLW flux (or equivalent precipitation) contributed by that range. The cumulative frequency of SLW flux is also listed.

Table 3 indicates that the many hours with SLW amounts less than or equal to the median of 0.06 mm have limited precipitation production potential. For example, approximately half of all hours with SLW (169 h) had amounts ranging from 0.01 through 0.06 mm with an average SLW value of 0.026 mm. Multiplying this average SLW value with an assumed representative wind speed of 10 m $s^{-1}$ provides an estimated total SLW flux for the 169 h. If this estimated flux was converted to uniform precipitation over the approximate 10-km width of the Plateau top, the equivalent precipitation would be about 0.6 in. For comparison, the total precipitation for the 20 days in question averaged 4.7 in. on top of the Plateau, a figure 8 times as large.

In contrast, the average SLW amount was 0.267 mm for the 164 h with values of 0.07 mm or greater. For the same assumptions, that is equivalent to 6.2 in. of precipitation. Therefore, to a first approximation and ignoring other factors, the wetter half of all SLW hours had the potential to contribute ten times as much precipitation as the drier half.

The estimated contributions of SLW flux listed in Table 3 suggest that one-third of all flux occurred with SLW amounts less than about 0.18 mm, one-third with amounts between 0.18 and about 0.55 mm, and one-third with higher amounts. Table 3 underestimates the importance of the higher SLW amounts because they tend to be associated with stronger winds resulting in greater fluxes than estimated with a constant 10 m $s^{-1}$ wind speed.

Tables 2 and 3 show the potential importance for seeding of the relatively few hours with high SLW amounts. Although only 6 pct of all SLW hours exceeded 0.50 mm, their SLW flux is estimated at 37 pct of the total. Seeding operations obviously should make every effort to successfully seed the wetter hours. But it may be difficult to convert a large fraction of this

**Table 3. - Precipitation rates equivalent to the midpoints of the listed SLW ranges if the mean wind speed normal to the barrier was 10 m $s^{-1}$ in the layer containing the SLW, and the SLW flux was converted to uniform precipitation over a 10-km distance. The contribution of SLW flux (or equivalent precipitation) is expressed as a percent of the total flux for all cases. The cumulative frequency is also listed.**

| Hourly SLW (mm) | Hourly precip. (mm) | (in) | Percent of total SLW flux | Cumulative percent of total SLW flux |
|---|---|---|---|---|
| 0.01-0.05 | 0.11 | 0.004 | 10 | 10 |
| 0.06-0.10 | 0.29 | 0.011 | 10 | 20 |
| 0.11-0.15 | 0.47 | 0.019 | 9 | 29 |
| 0.16-0.20 | 0.65 | 0.026 | 8 | 37 |
| 0.21-0.25 | 0.83 | 0.033 | 6 | 43 |
| 0.26-0.30 | 1.01 | 0.040 | 6 | 49 |
| 0.31-0.40* | 1.28 | 0.050 | 5 | 54 |
| 0.41-0.50 | 1.64 | 0.065 | 9 | 63 |
| 0.51-1.00* | 2.74 | 0.108 | 20 | 83 |
| 1.01-1.50 | 4.54 | 0.179 | 17 | 100 |

* change in interval size

abundant flux to precipitation, at least with common seeding approaches. The high flux hours are characterized by stronger winds and higher temperatures. Strong winds provide limited time for ice crystal formation, growth to snowflake or graupel sizes, and fallout to the surface. Ice crystal mass growth rates tend to be slower at higher temperatures (Redder and Fukuta 1989). Moreover, temperatures nearer freezing may make it impractical to create significant IN concentrations with AgI (see Sec. 9).

## 5. COMPARISON OF DRIER AND WETTER SLW HOURS

The wetter and drier SLW hours are further compared in the following tables. Table 4 lists them according to whether or not precipitation was detected. Tables 5 and 6 list a number of variables of interest for the wetter and drier hours, respectively.

Table 4 shows that for the drier half of the SLW hours, precipitation occurred during 70 h but was not detected during 99 h. The frequency was reversed for the wetter hours, which had precipitation during 99 h and no precipitation during 65 h. In either category, a large fraction of hours with SLW present had no precipitation. It is particularly encouraging that 40 pct of the wetter hours were not precipitating (at least not at detectable rates at the three Plateau-top gauges). Economically important cloud seeding potential may exist during some similar periods. Of course, cloud seeding potential also may exist when natural precipitation is occurring but is insufficient to convert all SLW to precipitation.

The 65 wetter hours without precipitation had significantly less SLW on the average than the 99 wetter hours with precipitation (0.150 vs 0.344 mm). The nonprecipitating hours were slightly warmer and noticeably drier (larger temperature-dewpoint spread) on the Plateau top, and had lighter wind speeds. Lighter winds and a drier atmosphere at mountain-top altitudes would be expected to result in less condensate production and is consistent with the lower SLW. These conditions would be expected to be associated with less dynamic storm phases, unlikely to produce as much precipitation. Nevertheless, the average of 0.15 mm SLW for the wetter nonprecipitating hours could represent significant seeding potential, if sufficient ice crystal concentrations can be created by seeding and if adequate time (distance) exists for ice crystal growth and fallout. These nonprecipitating hours have the advantage that more time is available with the lighter wind speeds.

As might be expected, the 99 drier hours without precipitation were warmer, drier, and less windy than the 70 drier hours with precipitation. The hours with precipitation had an average Plateau-top wind direction of 265°; all other categories had average winds near 245°. This observation suggests the precipitating hours with limited SLW were more likely to be postfrontal. Winds aloft generally shift to northwesterly after frontal passage while Plateau-top winds shift from southwesterly to westerly or northwesterly.

The 164 h with SLW of 0.07 mm or greater (wetter hours) occurred within a narrow range of wind direction as shown in Table 5 and the lower panel of Fig. 1. It can be seen that 75 pct of these hours had Plateau-top winds between 210 and 270°. Moreover, the average SLW amounts and wind speeds associated with this wind direction range were significantly higher than for other directions, which should result in greater SLW flux. Most of the precipitation was associated with the same 60° sector, likely as a consequence of the higher frequency of SLW occurrence and presumed higher flux amounts. An additional 11 pct of the SLW hours had winds between 270 and 300°. Limited SLW and precipitation occurred outside the 90° sector between 210-300°.

Table 6 is similar to Table 5 but lists observations for the 169 h which had average SLW values between 0.01 and 0.06 mm inclusive. Most of these drier SLW hours were also associated with westerly flow, but were somewhat less

Table 4. - Summary of average wind, temperature, moisture, and total precipitation partitioned by median SLW amount and whether precipitating or not.

| SLW range (mm) | Precip. | Hours | SLW (mm) | Temp (°C) | Dewpt. (°C) | Speed (m/s) | Dir. (deg) | Precip. (inch) |
|---|---|---|---|---|---|---|---|---|
| 0.01-0.06 | Yes | 70 | .028 | -6.9 | -7.6 | 4.4 | 265 | 1.56 |
| 0.01-0.06 | No | 99 | .025 | -4.0 | -8.6 | 3.1 | 242 | 0.00 |
| 0.07-1.50 | Yes | 99 | .344 | -2.5 | -3.2 | 6.4 | 246 | 3.08 |
| 0.07-1.50 | No | 65 | .150 | -1.9 | -6.1 | 4.3 | 243 | 0.00 |

Table 5. - Distribution of 164 h with SLW values of 0.07 mm or greater vs wind direction. The average SLW, air temperature, dewpoint temperature, wind speed, and average total precipitation on top the Plateau are given for indicated wind direction sectors.

| Wind Direction (degrees true) | Pct of hours | SLW (mm) | Temp. (°C) | Dewpt. (°C) | Wind Speed ($m\ s^{-1}$) | Total Precip. (inch) |
|---|---|---|---|---|---|---|
| 150-179 | 5 | .13 | -2.6 | -8.2 | 3.0 | 0.05 |
| 180-209 | 4 | .19 | -0.7 | -5.0 | 4.6 | 0.06 |
| 210-239 | 30 | .30 | -0.7 | -3.2 | 6.6 | 0.97 |
| 240-269 | 45 | .31 | -2.7 | -4.4 | 5.6 | 1.56 |
| 270-299 | 11 | .15 | -3.0 | -3.6 | 4.0 | 0.34 |
| 300-329 | 5 | .11 | -6.8 | -7.5 | 5.3 | 0.10 |
| 330-149 | 0 | N/A | N/A | N/A | N/A | N/A |

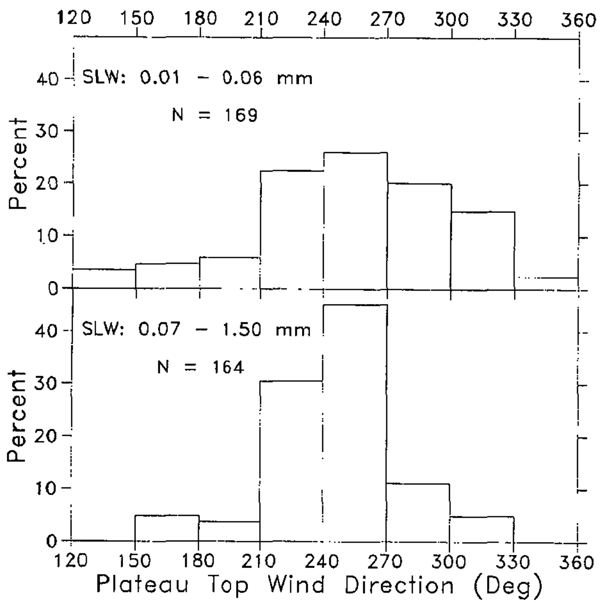


Fig. 1. Distribution of wind direction at the 2700-m microwave radiometer site for 169 drier hours (upper panel) and 164 wetter hours (lower panel).

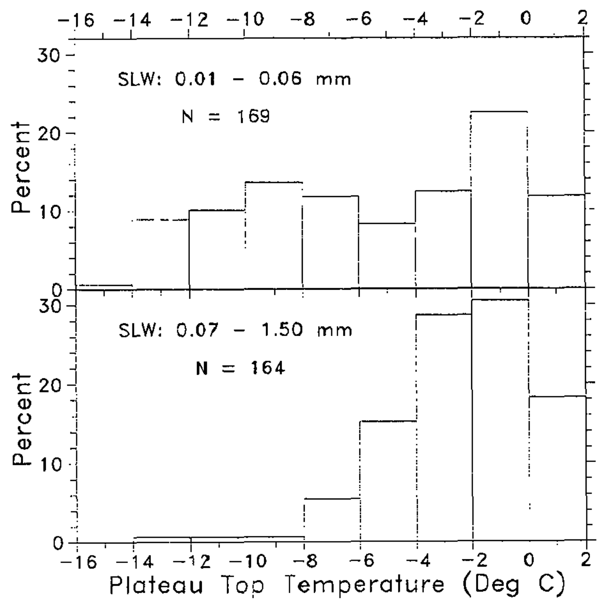


Fig. 2. Distribution of temperature at the 2700-m microwave radiometer site for 169 drier hours (upper panel) and 164 wetter hours (lower panel).

**Table 6. - Distribution of 169 h with SLW values from 0.01 to 0.06 mm vs wind direction. The average SLW, air temperature, dewpoint temperature, wind speed, and average total precipitation on top the Plateau are given for indicated wind direction sectors.**

| Wind Direction (degrees true) | Pct of hours | SLW (mm) | Temp. (°C) | Dewpt. (°C) | Wind Speed ($m\ s^{-1}$) | Total Precip. (inch) |
|---|---|---|---|---|---|---|
| 120-149 | 4 | .01 | -6.8 | -8.2 | 1.1 | 0.00 |
| 150-179 | 5 | .03 | -2.9 | -7.2 | 3.1 | 0.15 |
| 180-209 | 6 | .02 | -3.6 | -10.7 | 3.1 | 0.02 |
| 210-239 | 22 | .03 | -1.0 | -6.3 | 4.8 | 0.41 |
| 240-269 | 26 | .03 | -5.4 | -8.0 | 3.7 | 0.59 |
| 270-299 | 20 | .03 | -7.8 | -8.7 | 3.5 | 0.25 |
| 300-329 | 15 | .02 | -8.2 | -9.4 | 3.5 | 0.13 |
| 330-359 | 2 | .01 | -9.7 | -10.7 | 1.8 | 0.01 |
| 000-119 | 0 | N/A | N/A | N/A | N/A | N/A |

concentrated than the wetter hours as shown on the upper panel of Fig. 1. For example, although 86 pct of the wetter hours were in a 90° sector (210 to 300°) in Table 5, 83 pct of all hours of Table 6 were in a wider 120° sector (210 to 330°). The many cases between 270 and 360° are likely postfrontal because Plateau-top winds generally shift to the northwest quadrant after cold frontal passage.

Wind speeds with the drier SLW hours were lighter for all wind direction ranges with a westerly component than for the wetter SLW hours of Table 5. The strongest winds of Table 6 were associated with wind directions between 210 and 270°, similar to Table 5. The SLW amounts in this range were as high as found with any other wind direction range so it is presumed that the greater SLW fluxes occurred with southwest to westerly flow.

The drier hours tended to be colder and had greater temperature-dewpoint differences, indicating less atmospheric moisture at Plateau-top levels. The average air temperature and dewpoint temperature for the 164 wetter hours of Table 5 was -2.2 and -4.3 °C; the averages for the 169 drier hours of Table 6 were -5.2 and -8.2 °C.

Figure 2 shows hourly frequency distributions of air temperature measured at the 2700-m microwave radiometer site during the wetter and drier SLW hours. The drier hours, shown in the upper panel, did not have a marked temperature dependence for temperatures above -14 °C. In contrast, the wetter hours were concentrated between -6 and +2 °C, with almost 60 pct of all hours between -4 and 0 °C. Aircraft observations from early 1991 suggest that most of the SLW was within 1000 m of the Plateau top, and limited ground-released AgI reached that altitude. If it is assumed that the top of the SLW zone was always 1000 m above the surface with a typical moist adiabatic lapse rate, only about 1 in 5 of the wetter hours had any SLW colder than -11 °C. Most of the SLW was at lower altitudes with warmer temperatures. The implications for cloud seeding are discussed in Sec. 9.

Finally, the airflow was examined in the canyon leading from the valley west of the Plateau to the radiometer site. Hourly mean wind velocity observations were made about 3 km above the canyon mouth at an elevation of 2230 m. Wind speeds were usually between 1 and 3 $m\ s^{-1}$ during storms, and either upcanyon or downcanyon in direction.

The airflow was approximately evenly divided for the drier hours between 91 h with upcanyon flow and 78 h with downcanyon flow. When the wetter hours were considered, upcanyon flow existed for 125 h, and downcanyon flow for 39 h. This suggests a higher likelihood of valley-released AgI being transported to cloud levels during wetter episodes.

## 6. RELATIONSHIPS BETWEEN SLW AND OTHER PARAMETERS

The 333 h with SLW values of 0.01 mm or greater were used to calculate the amount of the SLW variance explained by various other parameters. A number of curve-fitting routines were attempted, but none explained more variance than simple linear least-squares regression. No single parameter was highly associated with SLW amounts; however, some definite trends and limits did exist.

Table 7 shows the percent of SLW variance explained by simple linear regression with each of several variables. As previously discussed, Fig. 1 showed a strong association of higher SLW values with southwesterly and westerly winds. However, the relationship is not well expressed by a simple linear regression equation. The variance explained by the absolute departure of the wind direction from 240° (near the SLW highest values) is only 9 pct. The highest amounts of SLW variance were explained by wind speed (27 pct) and dewpoint temperature (24 pct). Other relationships were quite weak.

Figure 3 plots SLW amounts for all 333 h with detectable SLW against wind speed. As discussed by Huggins et al. (1992), radiometer site winds were markedly slower than free atmosphere winds near the same altitude. (However, they showed that the radiometer wind direction was a reasonable approximation of free atmosphere flow). Figure 3 shows considerable scatter but a general trend; higher SLW amounts

Table 7. - Percent of SLW variance explained by linear least-squares regression with indicated variables. All but precipitation were measured at the 2700 m-radiometer site.

| Variable | Percent Variance |
|---|---|
| Wind direction departure from 240° (absolute value) | 9 |
| Wind speed | 27 |
| Air temperature | 14 |
| Dewpoint temperature | 24 |
| Temperature minus dewpoint | 1 |
| Average precipitation | 12 |

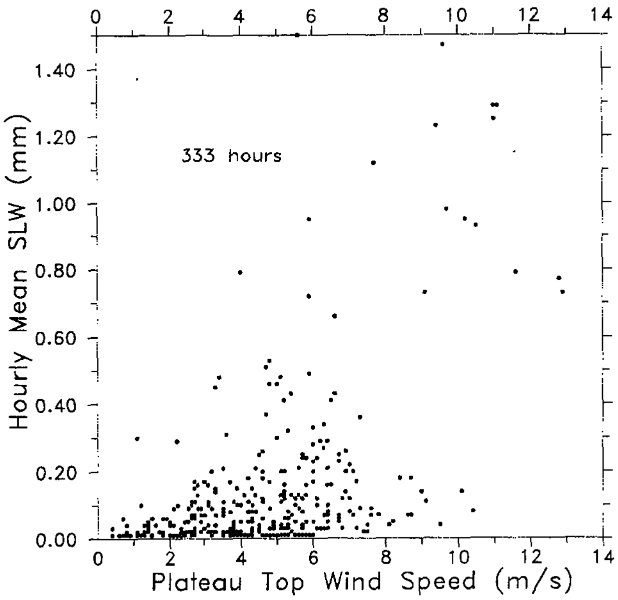


Fig. 3. Plot of hourly mean SLW amounts vs wind speed at the 2700-m microwave radiometer site for hours with detectable SLW.

tended to be associated with higher wind speeds. It might be expected that stronger winds would result in higher forced ascent rates up the windward slopes of the Plateau, resulting in greater liquid condensate production (more SLW). Although 35 pct of the 164 wetter SLW hours had wind speeds in excess of 6 m $s^{-1}$, only 9 pct of the drier 169 h had wind speeds that strong.

Table 7 shows little linear relationship between SLW and air temperature. However, only 2 pct of the 164 wetter SLW hours had temperatures less than -7 °C, whereas 37 pct of the 169 drier SLW hours were that cold. No hour with an average SLW amount exceeding 0.20 mm was colder than -5 °C on the Plateau top.

## 7. RELATIONSHIPS BETWEEN PRECIPITATION AND OTHER PARAMETERS

The distribution of the 179 h with measurable precipitation is given vs wind direction in Table 8. Again, a strong dependence between frequency of precipitation and wind direction is evident. The 90° sector between 210-299° contains 80 pct of all hours with precipitation and 88 pct of the total precipitation. Expanding the sector to 120° by adding the 300-329° range accounts for 92 pct of all precipitation hours and 94 pct of the total precipitation. Little precipitation fell on the Plateau during the 20-day study period unless the Plateau-top wind had a westerly component, orthogonal to the north-south oriented barrier.

Table 9 is similar to Table 7 but for the 179 h with detectable precipitation. It shows that little variance was explained by linear regression with any of the indicated variables. The dewpoint temperature was the best predictor, explaining 18 pct of the variance in precipitation.

Finally, both ordinary (Pearson product-moment) and tie-adjusted rank (Spearman) correlation coefficients were calculated between precipitation and SLW for the 169 h with both detected. The ordinary coefficient was 0.23, and the rank coefficient was 0.40. The latter is more appropriate because the highly skewed distributions of both precipitation and SLW violate the assumption of a normal distribution. Although a relationship exists, significant at the 1-pct level, the association between precipitation and SLW is weak.

The weak but significant relationship between SLW and precipitation is positive, with higher precipitation rates tending to be associated with higher SLW amounts. This relationship, based on hourly data, is similar to that found by Super and Huggins (1993) between SLW flux and precipitation for entire storm episodes. The hourly relationship further discredits the view that winter storm periods tend to be either efficient, with abundant precipitation and little or no SLW, or inefficient, with little precipitation but abundant SLW. Instead, the tendency is for higher precipitation rates to accompany periods with greater SLW. But the SLW was measured above the Plateau-top's windward edge while precipitation was averaged across the entire Plateau top. Therefore, the hourly relationship may simply follow from the natural conversion of SLW into precipitation.

## 8. MEASUREMENTS OF AgI ICE NUCLEI REACHING THE PLATEAU TOP

### 8.1 Summary of AgI Observations

As previously noted, an NCAR IN counter was operated at the 2700-m radiometer site during part or all of 12 days that were seeded with 8

Table 8. - Distribution of 179 h with detectable precipitation at one or more of the three gauges on top of the Wasatch Plateau. Average SLW, air temperature, dewpoint temperature and average total precipitation on top of the Plateau are given for indicated wind direction sectors.

| Wind Direction (degrees true) | Percent of hours | Ave. SLW (mm) | Ave. temp. (°C) | Ave dewpt. (°C) | Total precip. (inch) |
|---|---|---|---|---|---|
| 150-179 | 4 | .10 | -3.0 | -4.3 | 0.20 |
| 180-209 | 2 | .07 | -5.4 | -6.8 | 0.07 |
| 210-239 | 26 | .29 | -1.1 | -2.1 | 1.38 |
| 240-269 | 36 | .29 | -3.7 | -4.3 | 2.16 |
| 270-299 | 18 | .06 | -8.5 | -8.8 | 0.61 |
| 300-329 | 12 | .04 | -8.8 | -9.1 | 0.26 |
| 330-359 | 2 | .01 | -11.1 | -11.8 | 0.03 |
| 000-149 | 0 | N/A | N/A | N/A | 0.00 |

Table 9. - Percent of precipitation variance explained by linear least-squares regression with indicated variables, all measured at the 2700-m radiometer site.

| Variable | Percent variance |
|---|---|
| Wind direction departure from 240° (absolute value) | 11 |
| Wind Speed | 6 |
| Air temperature | 13 |
| Dewpoint temperature | 18 |
| Temperature minus dewpoint | 2 |
| Average SLW | 7 |

AgI generators located along the valley floor west of the Plateau. The generators were sited along a 38 km north-south distance, and each released about 8 g $h^{-1}$ AgI (Griffith et al. 1992).

In order to take a "first look" at the targeting of valley-released AgI, a computer file was developed which contained hourly mean values of vertically integrated SLW and AgI concentration. Observations were included in the hourly summary file only if the 8 valley AgI generators had been on for 2 h or more to allow for transport time to the Plateau top, hourly mean SLW values were 0.01 mm or greater, and the NCAR IN counter log did not indicate any problems with the instrument's operation. Hours with suspect data were rejected. Hours after AgI generators were turned off were not included. These criteria resulted in 144 h of valid data from 7 storm episodes from January 28 through March 11, 1991.

The NCAR IN counter was operated at a cloud chamber temperature near -20 °C with a sampling volume of about 10 L $min^{-1}$. Raw "counts" were multiplied by a factor of ten to account for known ice crystal losses to the counter's glycol-covered walls and bottom cone (Langer 1973). Resulting IN $L^{-1}$ were estimated at two additional temperatures, -10 and -15 °C, using a 1981 Colorado State University CSL (Cloud Simulation Laboratory) calibration of the Utah operational seeding generators presented by Griffith et al (1991). This procedure assumes that NCAR IN counter observations of AgI concentration at -20 °C are reasonably accurate. Super and Holroyd (1994) present some evidence and refer to other evidence that suggest this may be a reasonable assumption for a properly maintained and operated NCAR IN counter and AgI from a different type of generator. However, the accuracy of NCAR IN counter observations of the particular AgI seeding agent used in the Utah operational program is not known.

The procedure further assumes that CSL observations of the temperature dependence of effective AgI IN are reasonably accurate for the Utah operational AgI seeding agent in winter orographic cloud. The validity of this assumption is not known.

It would be desirable to obtain a new AgI generator calibration because of improvements in the simulation laboratory over the years. But even with a new calibration, there would be the concern about how representative any laboratory test is for AgI nucleation in orographic clouds. These uncertainties should be borne in mind in the discussion to follow, and conclusions to be drawn should be considered tentative. However, placing winter orographic cloud seeding on a firmer scientific footing requires use of the best measurements and knowledge at hand, even when they are known to have limitations.

The 1981 NAWC (North American Weather Consultants) AgI generator effectiveness values (ice crystals per gram of AgI) at -10 and -15 °C were approximately 1 and 25 pct of those at -20 °C for natural tunnel draft conditions. These values will be used because winds near the valley generators were light during most 1991 storms. (Percentage values were similar for maximum tunnel flow conditions). The stated percentage values were used to develop Figs. 4 and 5 which summarize estimated AgI IN concentrations at temperatures more typical of the SLW zone top than the NCAR IN counter's -20 °C.

Figure 4 shows IN $L^{-1}$ at -10 °C estimated from the NCAR IN counter observations for the available 145 h. The top panel is for the drier 59 h between 0.01 and 0.06 mm, while the lower panel is for the wetter 85 h between 0.07 and 1.5 mm. It is seen that for a temperature of -10 °C about half of the wetter hours had less than 2 IN $L^{-1}$ while 73 pct of the drier hours were in that range. The tendency for wetter hours to have somewhat higher IN concentrations is presumed to be caused by stronger dynamics (higher wind speeds up the Plateau's windward slopes) and more frequent embedded convection. Both processes can enhance the vertical transport of valley-released AgI to Plateau-top levels.

Figure 5 shows that about half the wetter hours had estimated concentrations less than 50 IN $L^{-1}$ at a temperature of -15 °C. The distributions are more skewed than indicated by Figs. 4 and 5. For -10 °C half the hours in the 0-2 IN $L^{-1}$ range were below 0.3 IN $L^{-1}$ in each panel of Fig. 4. The corresponding value is 7.5 IN $L^{-1}$ for -15 °C shown in Fig. 5. None of the drier hours exceeded 10 IN $L^{-1}$ in Fig. 4 (250 IN $L^{-1}$ in Fig. 5) and only 6 pct of the wetter hours were between 10-20 IN $L^{-1}$ (250-500 IN $L^{-1}$ in Fig. 5).

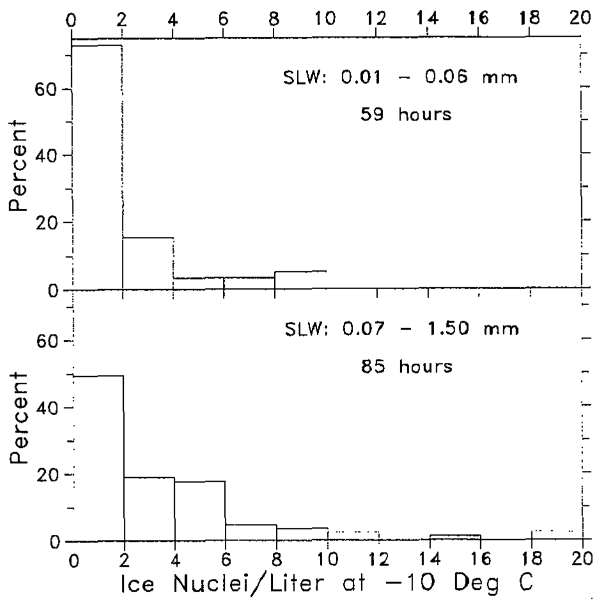


Fig. 4. Distribution of ice nuclei per liter, effective at -10 °C, based on NCAR counter measurements at the 2700-m microwave radiometer site. The upper panel is for 59 h with SLW between 0.01 - 0.06 mm while the lower panel is for 85 h with SLW between 0.07 - 1.50 mm.

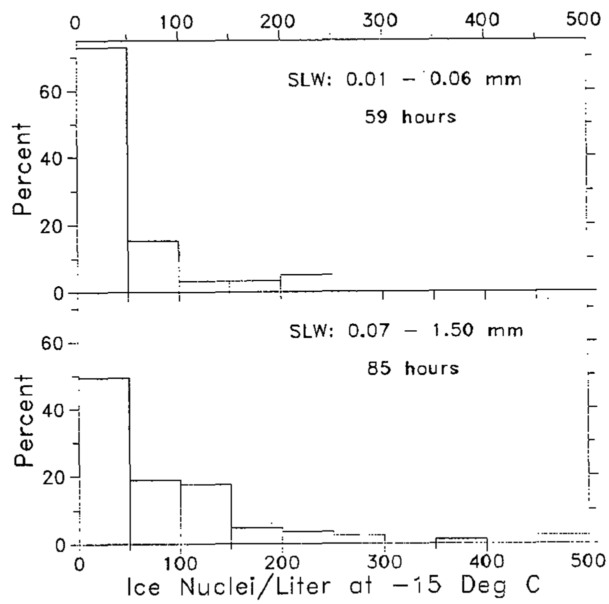


Fig. 5. Distribution of ice nuclei per liter, effective at -15 °C, based on NCAR counter measurements at the 2700-m microwave radiometer site. The upper panel is for 59 h with SLW between 0.01 - 0.06 mm, while the lower panel is for 85 h with SLW between 0.07 - 1.50 mm.

### 8.2 Artificial IN Concentration for Effective Seeding

The appropriate IN concentration for effective cloud seeding has received limited discussion in the scientific literature, perhaps because of the uncertainties involved. There is, of course, no single "correct" IN concentration because cloud conditions and growth processes vary widely. But cloud seeding operators and experimenters must choose AgI release rates and these should be based on physical reasoning. The following discussion attempts to provide an order-of-magnitude estimate of the appropriate AgI IN concentration for effective precipitation enhancement in winter orographic clouds in the intermountain West.

Observations of natural precipitation reveal highly skewed distributions with most ice particles having limited mass and only a "fortunate" fraction encountering a growth environment which allows them to become relatively large. Ice crystals nucleated by AgI might be expected to result in similar skewed distributions under most circumstances. Even when heavy riming produces graupel (snow pellets), masses are typically 0.1-0.2 mg with 150 cm $s^{-1}$ fall speeds (Locatelli and Hobbs 1974).

For the sake of illustration, let it be assumed that 10 pct of effective AgI IN produce graupel of mass 0.15 mg and 150 cm $s^{-1}$ fall speed. Because contact nucleation proceeds slowly, and the IPC (ice particle concentration) during most graupel showers is low, we will assume that the remaining AgI IN produces relatively small crystals or does not nucleate ice. Then for 10 AgI IN $L^{-1}$ the resulting snowfall rate is approximated by one graupel particle $L^{-1}$. The liter volume can be imagined to be a vertical cylinder of 150 cm height and 6.67 $cm^2$ cross-sectional area with one particle falling through the cylinder each second. The resulting snowfall rate is 0.15 mg per 6.67 $cm^2$ per second, equivalent to 0.8 mm $h^{-1}$ (0.03 in. $h^{-1}$). Table 1 shows that 73 pct of the observed Plateau-top precipitation was at this rate or less, which contributed about one-third of the total precipitation. Therefore, this rate can be considered typical. However, early 1991 observations suggested that most Plateau-top precipitation does not result from graupel but rather from snowflakes with riming ranging from none to moderate.

Fukuta et al. (1988) presented average ice particle masses observed during winter storms in the Tushar Mountains of southern Utah. These were calculated from the mass precipitation rate and the photographically-determined number flux. Both single crystals and aggregates were counted in determining the number flux. Mass calculations were presented for 18 time segments, each several hours in length. Average masses for these segments ranged between about 0.02-0.30 mg. The median of all averages was about 0.05 mg which should represent a "typical" snowflake. However, since many of the snowflakes were aggregates of individual crystals, typical crystal mass must be significantly less. A typical value for individual crystals appears to be less than 0.02 mg from the Tushar Mountain observations and other investigations cited by Super and Huggins (1992). Seeded ice crystals might be anticipated to have less average mass than naturally-nucleated crystals under most conditions because the latter often have longer growth times.

Using an average ice crystal mass of 0.02 mg, a fall velocity of 75 cm $s^{-1}$ and an effective AgI IN concentration of 10 $L^{-1}$ results in a precipitation rate of 0.5 mm $h^{-1}$ (0.02 in. $h^{-1}$). This example optimistically assumes that each potential AgI IN actually nucleated an ice crystal.

Both the calculations based on graupel and those based on typical individual crystals result in relatively low precipitation rates of 0.5 to 0.8 mm $h^{-1}$ (0.02 to 0.03 in. $h^{-1}$). It can be argued that seeding should produce at least 10 ice crystals $L^{-1}$ in order to result in noticeable precipitation increases. For example, if seeding produced only 1 ice particle $L^{-1}$, the seeding would need to be effective for a large number of hours each winter to significantly affect the seasonal snowfall. At 1 seeded ice crystal $L^{-1}$, the precipitation rate corresponding to the above examples would be about 0.065 mm $h^{-1}$ (0.0026 in. $h^{-1}$). It would take almost 1000 h of such seeding to provide a 10 pct increase in the normal Wasatch Plateau April 1 snowpack water equivalent. But the operational program usually seeds no more than a few hundred hours per winter and it is unlikely that seeding is effective for more than some fraction of those hours. Therefore, a precipitation rate corresponding to 1 ice crystal $L^{-1}$ in the above example would provide limited additional snowpack.

Further evidence that 10 IN $L^{-1}$ generally may be a marginal rate for effective seeding exists from observations within seeded clouds. Super and Heimbach (1988) presented measurements from aircraft ice particle imaging probes indicating mean seeded IPCs near 10 $L^{-1}$ over the Bridger Range of Montana (see their Tables 1 and 2). Natural IPCs were 1 $L^{-1}$ or less. Calculated precipitation rates at aircraft levels were less than 0.1 mm $h^{-1}$ (no ground measurements were available). Super and Boe (1988) presented similar observations of 5-20 $L^{-1}$ IPC within seeded cloud over the Grand Mesa, Colorado, where natural IPCs were 0.2-2.6 $L^{-1}$ (see their Table 2). The mean estimated precipitation rates at aircraft levels were somewhat higher over the Grand Mesa, between 0.1-0.4 mm $h^{-1}$. Ground precipitation observations were available which showed mean precipitation rates similar to aircraft level estimates, and peak precipitation rates of about 1 mm $h^{-1}$. These limited examples suggest that IPCs of about 10 $L^{-1}$ usually corresponded to less than 0.25 mm $h^{-1}$ (0.01 in.$h^{-1}$) precipitation production for the sampled conditions. Table 1 shows that such low rates accounted for little of the total precipitation. Therefore, it can be argued that effective seeding should produce at least 10 $L^{-1}$ ice crystals in similar conditions.

While seeding-enhanced IPCs were evident over both the Bridger Range and Grand Mesa, associated reductions in cloud liquid water were not discernible. The lack of a clear reduction in liquid water was probably partially caused by natural spatial and temporal variability, but might be evidence that seeding-caused IPCs were lower than optimum for precipitation enhancement.

If at least 10 IN $L^{-1}$ are required for winter orographic cloud seeding, Figs. 4 and 5 show that the temperature of the SLW zone reached by AgI is crucial. It appears unlikely that valley seeding would often be effective unless the AgI was transported to SLW cloud at temperatures lower than -10 °C. Moreover, it should be recalled that Figs. 4 and 5 are based on Plateau-top IN observations. Aircraft measurements made near AgI plume tops, usually within 1000 m of the Plateau top, revealed significantly lower IN concentrations. Therefore, Figs. 4 and 5 may markedly overestimate AgI IN concentrations when their indicated temperatures (-10 and -15 °C) are near aircraft sampling altitudes. Aircraft-observed plume top temperatures were usually higher than -15 °C as discussed further in Sec 9.

### 8.3 Representativeness of Periods with AgI Ice Nuclei Measurements

The 144 h of AgI IN measurements discussed in this section may be atypical of hours with SLW present. Over 100 h were from a series of storms, observed to have frequent embedded convection, which passed the Plateau between February 28 and March 11. The 144 h subsample was relatively wet, with 59 pct of its hours in the wetter (0.07 mm and above) SLW category as compared to 50 pct of the total 333 h sample in the wetter category. Only 12 pct of the wetter hours had downcanyon flow as compared to 24 pct for the 333 h sample discussed in Sec. 5. Twenty-two pct of the drier hours had downcanyon flow in the 144 h subsample as compared to 46 pct of the 333 h sample. These values suggest that Figs. 4 and 5 may be somewhat optimistic of winter storms in general. That is, the frequency with which valley-released AgI reaches SLW cloud levels cold enough to nucleate ice crystals may be even less than suggested in Secs. 8.1 and 8.2.

## 9. IMPLICATIONS FOR CLOUD SEEDING

As previously discussed, precipitation-producing potential was limited for the drier half of all hours with observed SLW. Nevertheless, it was shown that the seeding potential of such hours should not be ignored because even minor precipitation increases become important when accumulated over many hours.

Table 5 shows the most frequent and wettest SLW hours were concentrated between 210-270°. These hours also had the highest average wind speeds. All else being equal, these hours should have the most seeding potential. However, their average temperature at 2700 m on top of the Plateau was a relatively warm -1.9 °C, which makes successful AgI seeding a challenge.

Ongoing analysis of 1991 AgI and $SF_6$ plume measurements over the Plateau is revealing that the seeding material was usually found only at the lowest aircraft sampling altitudes, in the 3170 to 3750 m (10,400 to 12,300 ft) range. Moreover, the highest concentrations of both AgI and $SF_6$ were found at the lower, warmer end of this altitude range. Often, no AgI or $SF_6$ was found as high as 3750 m, and sometimes not at 3170 m. The finding that ground-released seeding plumes were concentrated in a layer less than 1 km above the terrain is in agreement with earlier investigations over other barriers in the intermountain West (e.g., Holroyd et al. 1988; Super et al. 1989).

With typical in-cloud temperature lapse rates, the average 2700-m temperature of -1.9 °C for the wetter SLW hours corresponds to temperatures of about -5 °C at 3170 m and -9 °C at 3750 m. Figure 2 shows few hours colder than -7 °C at 2700 m had much SLW. Corresponding 3170 m and 3750 m temperatures would be about -10 °C and -14 °C, respectively. These values are in agreement with the 12 in-cloud aircraft sampling missions flown during the 1991 field program. Their average 3750-m temperature was -11.3 °C and only 2 missions were colder than -15 °C at the altitude. Similar warm temperatures for the SLW zone were reported by Sassen and Zhao (1993) for the Tushar Mountains of southern Utah.

Figure 4 suggests that AgI concentrations measured <u>on top the Plateau</u> were insufficient for effective seeding (assumed to require 10 IN $L^{-1}$) unless the AgI reached SLW colder than about -12 °C. But AgI IN concentrations measured at aircraft levels, where such temperatures were found, were markedly below those measured on the Plateau top. The evidence suggests that the operational seeding program may be effective in only a fraction of the cases with seeding potential.

The evidence presented suggests that the Utah operational seeding program cannot be expected to significantly increase precipitation during warmer storm periods. However, in addition to concerns already raised about the NAWC AgI generator calibration and NCAR IN counter measurements, two caveats should be attached to this tentative conclusion. It is possible that AgI is more effective in creating ice crystals at relatively warm temperatures in mountain orographic clouds than in cloud simulation laboratory clouds. It is possible that AgI-nucleated ice crystals sometimes are involved in one or more significant ice multiplication processes that increase precipitation production.

The effective IN concentration estimates presented in this paper may be improved by obtaining a new CSL calibration of the Utah operational seeding generator, and by further comparing an NCAR IN counter with the CSL. In view of the modest costs involved, this laboratory work should be accomplished, and the calculations herein repeated with the newer data. However, the best (although difficult and costly) approach is to obtain more observations of seeding-caused IPCs from winter orographic clouds over typical ranges of temperatures and liquid water contents. It is important that seeding-caused changes in the cloud microphysics be documented to insure that such changes are significant, at least under favorable conditions.

Aircraft and Plateau-top observations planned for the early 1994 Utah field campaign will attempt to document seeding-caused IPCs in orographic clouds. Moreover, attempts will be made to follow seeding-caused crystals to the surface to document precipitation rates caused by seeding. Experience has shown that only a limited number of successful physical "direct detection" experiments should be expected from a 2-mo field effort. But the importance of such physical demonstrations cannot be overstated. The physical basis for winter orographic cloud seeding needs to be significantly enhanced for the field to gain credibility and for the technology to be improved.

## 10. CONCLUSIONS AND RECOMMENDATIONS

The 1991 data set is encouraging in that many hours had abundant SLW over the west edge of the Plateau top. A large fraction of the wetter hours had no detectable precipitation, suggesting significant seeding potential may exist if ice crystals can be produced in the SLW cloud. The average SLW amount during the wetter hours with precipitation was even higher than during the wetter hours with no precipitation, again suggesting seeding potential.

Huggins et al. (1992) presented estimates of SLW flux per storm episode for the 1991 field season. For the 20 days discussed herein, the estimate of total SLW flux exceeded 2100 Mg per meter of crestline. If that amount of water was converted to precipitation of uniform intensity over the width of the Plateau (about 10 km), the average precipitation would be 8.3 in., almost twice the observed amount. This calculation suggests that a substantial amount of excess SLW was transported over the Plateau as has been found over other mountain barriers in the intermountain West (e.g., Super and Huggins 1993). The portion of excess SLW that cloud seeding can convert to precipitation has yet to be demonstrated. However, the "raw material" needed for seeding to be effective certainly exists in relative abundance. The availability of abundant SLW has been assumed for decades but has been verified only in the past several years.

The 1991 data set also raises questions about the effectiveness of the Utah operational seeding program. Physical reasoning was presented that suggested seeding rates may be too low, at least for warmer storms. Admittedly, the estimates of effective IN may be flawed by instrumentation limitations and possible unrepresentativeness of CSL generator calibrations for winter orographic clouds. However, in the absence of better information, the observations and calculations presented in this paper indicate there is reason to be concerned. Production of adequate concentrations of seeded ice particles is basic to successful seeding. This topic deserves further investigation in the Utah operational program in particular, and in seeding programs in general.

The main problem for the Utah operational seeding program appears to be the relatively warm SLW temperatures combined with the strong temperature dependence of AgI as an effective IN. This problem could be partially remedied by increasing the source strength of potential IN using improved seeding generators and solutions and higher AgI output rates. However, the SLW is probably too warm for effective seeding with any practical AgI solution and seeding rate some of the time. Even transporting the AgI to higher, colder altitudes by aircraft seeding would frequently be ineffective because the AgI would then be above the SLW needed to nucleate ice crystals.

This is not to suggest that more effective AgI solutions and higher output generators should not be employed. Anything done to increase the output of effective IN should help seeding effectiveness. However, practical limits exist regarding what can be done with AgI. A large fraction of the winter storms, tending to be those with highest SLW amounts, likely cannot be effectively seeded with present AgI solutions because the SLW is simply too warm.

The problem of seeding warm SLW with AgI is not unique to Utah. The statistical analysis of Super and Heimbach (1983) strongly suggested that the warmer, wetter half of Montana winter orographic storms did not respond to AgI seeding, but the colder, drier storms (< -9 ° at 2600 m) clouds did respond. The State of California has been developing a propane seeding technology because the warm SLW problem is severe there (Reynolds, 1991). Propane seeding can create high concentrations of ice crystals at temperatures colder than 0 °C. Remote-controlled propane dispensers are much more economical than remote-controlled AgI generators, and are more reliable because they are much simpler devices. However, they must be located in or very near cloud to be effective.

It is recommended that the State of Utah pursue a number of approaches aimed at increasing the effectiveness of the operational seeding program. High output generators and more effective AgI solutions should be considered. Higher altitude release sites would increase the frequency of targeting SLW clouds. The possibility of high altitude releases from mountains upwind from the target areas deserves further exploration. Ongoing analysis suggests that AgI releases above canyon mouths may be more effective than AgI releases from valley floor locations. Finally, propane seeding should receive serious attention because even warm storms can be seeded as long as the propane dispensers are located at high altitudes within the orographic cloud.

The 1991 field program measurements have confirmed for the Wasatch Plateau of central Utah some of the earlier findings from the Tushar Mountains of southern Utah. Namely, abundant SLW is available during phases of many winter orographic storms which should provide frequent seedable opportunities. Most of the SLW is within 1 km of the mountain crestlines at relatively high temperatures. The challenge is to develop the means to routinely target the SLW zone with adequate concentrations of artificially nucleated ice crystals which can start the precipitation formation processes in naturally inefficient clouds.

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