"REVIEWED"

THE BRIDGER RANGE, MONTANA, 1986-1987 SNOW PACK AUGMENTATION PROGRAM

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Abstract

A winter orographic snow pack augmentation program was conducted for the benefit of a ski resort near Bozeman, Montana, during the winter of 1986-87. The operational goals were to help ensure a timely opening of the resort and to increase the snow pack, especially for the Christmas-New Year's holiday season. Seeding was from a single surface-based AgI generator located well up the west slope of the Main Bridger Ridge. Three hundred and eighty five hours were seeded during the period of 11 Nov. to the end of Feb. A research program was "piggy-backed" upon the operations to test the targeting effectiveness, to document the existence of supercooled liquid water, to examine the microphysical aspects of the seeding and to determine if the seeding increased the seasonal snow pack. Supercooled liquid water was documented and AgI was verified as crossing the Main Ridge by an acoustical ice nucleus detector. Analysis of sedimentation plate images suggested that aggregation and riming were important contributors to the rapid growth of crystals falling on the ski resort, the center of which was 4 km SE of the generator. Target-control analysis of snow course data suggested 35 to 50% additional seasonal snow pack within the target.

1. INTRODUCTION

The winters of 1984-85 and 1985-86 had low snow pack accumulations at the Bridger Bowl ski resort near Bozeman, Montana (MT). At the request of the local non-profit ski area, Montana State University planned and implemented a snow pack enhancement project using cloud seeding during the winter of 1986-87. The project's goal was to increase the snow pack, especially early in the winter to provide a timely opening of the ski area, and to have abundant snow for the Christmas-New Year's holiday season. The operations were based on research done in the same area from 1968 through 1972 during the randomized exploratory Bridger Range Experiment (Super and Heimbach, 1983, hereafter SH), and again in 1985 when physical experiments were conducted (Super and Heimbach, 1988).

SH found strong statistical evidence of a seeding signal over the Bangtail Ridge target area (see Fig. 1) for 700 mb and ridge top temperatures $\leq$-9C. Super (1986), in further a posteriori analyses of the Bridger Range Experiment data, found the largest seeding signals occurred in the 700 mb wind range of 240-300 deg. Precipitation data were not collected in support of the Bridger Range Experiment within the ski resort boundaryμ however, target-control analysis of independently collected snow course data indicated anomalously high snow water equivalents in the ski area at the end of the two winters the northern seeding site was operated.

During Jan. 1985 airborne measurements of microphysical parameters were made in seeded storms over the Bangtail Ridge to test hypotheses previously unaddressable due to budget and technical constraints (Super and Heimbach, 1988). Seeding in 1985 was from the southern of two sites used in the earlier experiment. Measurements confirmed targeting of the silver iodide (AgI) ice nuclei, and indicated increased ice crystal concentrations with greater estimated precipitation rates within seeded portions of some storms which had supercooled liquid water present.

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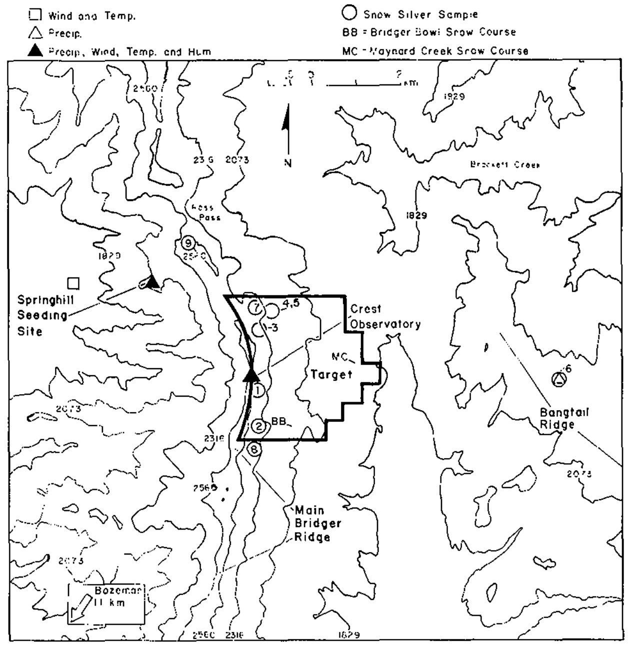

Fig. 1. Operations area for the 1986-87 Bridger Range winter orographic weather modification project. Elevations are in meters MSL.

2. OPERATIONS

Seeding during the 1986-87 winter was done with a single ground-based modified Skyfire generator burning a mixture of 3% by weight AgI complexed with NH_4I-acetone-water in a propane flame. About thirty grams of AgI were burned per hour. At -10C, a common temperature at the Main Ridge, the efficiency of the aerosol was found by Garvey (1975) to be 6×10^{13} ice nuclei g^{-1} AgI. The complex and generator were identical to those used in the Bridger Range Experiment and the 1985 experiment. The seeding site was the northern of two sites used in the earlier experiment and is labeled "Springhill Seeding Site" in Fig. 1. It was well up the west slope of the Main Ridge at an elevation of 2121 m. The seeding generator was manually operated, requiring an operator on site 24 hours per day during any potentially seedable conditions.

The seeding criteria used during 1986-87 were:

1. Winds from 240-300 deg. true as measured at the Crest Observatory (Fig. 1), by pilot balloons released from the seeding site, or from observing the cloud base motion.

2. The Main Ridge Crestline had to be obscured in cloud.

3. After 1 Jan. the seeding site temperature had to be below -5C.

The first criterion was determined to be the optimal wind direction range for seeding from the 1970-72 randomized experiment. The second criterion assumed that supercooled liquid water would most likely be present when cloud base was below the crestline. The third criterion assumed that the utilized AgI complex becomes active in significant concentrations at or below -9C at crestline elevations as suggested by SH. Under average conditions this would correspond to below -5C at the seeding site elevation.

Seeding operations commenced on 11 Nov. 1986 and ceased 28 Feb. 1987, with the last seeded day being 24 Feb. To ensure the public welfare was maintained, suspension criteria were imposed. Seeding would have stopped if the Bridger Bowl snow course (see Fig. 1) showed 200% or more of normal snow pack (normal plus 100%) during Nov. and Dec. 1986, 125% in Jan. and normal in Feb. 1987. These criteria were not invoked due to the unusually low frequency of storms during the winter.

For the months Nov. through Feb. 94, 84, 99, and 107 h were seeded, respectively. November and the first ten days of Dec. had frequent storm conditions. From 10 Dec. to the end of that month precipitation events were limited. January and Feb. produced far less than the normal snow pack over the area. Fifteen days in Jan. had measurable precipitation at the seeding site, but many of these events could not be seeded due to inappropriate winds. February was dry until the thirteenth, and thereafter several good seeding periods occurred. By 1 Mar., Snow Survey measurements showed the snow water equivalent of several snow courses in southwestern Montana as low as 50% of normal.

3. ASSOCIATED RESEARCH PROGRAM

Four goals were addressed by an adjunct research program.

1. Test whether the resort area was targeted with AgI.

2. Document the occurrence of supercooled liquid water above the Main Bridger Ridge just upwind (west) of the ski area.

3. Examine the near-source microphysical characteristics of seeding.

4. Determine any departure from normal in the ski area snow water equivalent.

Because of the limited resources available for the research program, only surface observations were made, and some of these were limited to several storms in Jan. and Feb. Instrumentation at the Crest Observatory, located on the crestline forming the west boundary of the target area, consisted of the following:

(1) A National Center for Atmospheric Research (NCAR) acoustical ice nucleus counter (Langer, 1973) was used to monitor ice nuclei at -20C. Because background concentrations were consistently 0-1 L^{-1}, the acoustical counter was essentially an AgI detector.

(2) A Rosemount 871CB1 icing rate meter was mounted 8 m above the crestline. This device had a 0.64 cm diameter probe of 1.75 cm^2 cross-sectional area. An accumulation of 0.07 g ice (derived through wind tunnel tests) on this probe triggered a melting cycle which was logged on a strip chart. These icing events and the wind speed were used to estimate supercooled liquid water content, assuming unity collection efficiency. Because the actual collection efficiency will be less than unity for small cloud droplets and light winds, some underestimation of supercooled liquid water content can be expected.

(3) Wind speed and direction were measured at 10 m above the crestline by an anemometer and vane defrosted by heat lamps.

(4) Vertical ice particle flux was measured by a device described by Langer (1970). Ice particles were drawn isokinetically down a 3 mm capillary tube from a 2.5 cm diameter intake. The particles (or sometimes clumps of particles) were counted and continuously recorded in the manner of the acoustical ice nucleus counter.

(5) For selected storms, a photographic device produced 35 mm slides of ice particles collected on glass sedimentation plates exposed for known time intervals. Crystal images were manually sized and assigned habits. Contributions of the various habits to crystal concentrations and estimated precipitation rates were derived following the procedures of Holroyd (1987). The minimum discernable size was 0.12 mm. Smaller particles could be confused with dust and they contributed negligibly to the estimated precipitation.

(6) Air temperature and humidity were measured by a hygrothermograph in a weather shelter.

Besides the Crest Observatory measurements, ambient temperature and humidity, precipitation, surface wind, and winds aloft (from pilot balloons) were observed at the seeding site. The silver content of the snow pack was sampled soon after the seeding program terminated (see Sec. 6).

4. CASE STUDIES OF NEAR-SOURCE MICROPHYSICAL EFFECTS

Portions or all of ten seeded storms were sampled at the Crest Observatory during Jan.-Feb. Two case studies will be presented in detail to examine the presence of AgI, supercooled liquid water and microphysical (ice particle) characteristics. Microphysical characteristics are of particular interest because of concerns about limited time for ice particle nucleation, growth and fallout since the center of the intended target area was only about 4 km southwest of the seeding site (Fig. 1). The snow course analysis of SH strongly suggested that prior seeding from that site significantly increased snowfall in the ski area. However, the physical mechanisms involved were not well understood.

Recent work by Finnegan and Pitter (1987) indicates that ice nucleation can sometimes commence immediately downwind of the AgI generator at temperatures below -6C due to supersaturation produced by combustion of acetone and propane. Conditions required for this rapid nucleation often existed at the Springhill seeding site so high concentrations of tiny ice crystals may have formed essentially at the seeding site. Further, Takahashi et al. (1986) suggest that aggregation of small crystals could provide precipitable particles within several minutes.

4.1 13-14 February 1987

On 13 Feb. a storm started at approximately 1430 (all times Mountain Standard) and lasted until 0600 on the 14th. During its course, nine of the Crest Observatory hourly averaged wind directions were classed as variable (≥180 deg. range over the hour). The other hours had averaged wind directions which ranged from 277 to 282 deg. true. The supercooled liquid water content could not be estimated because the anemometer cups were rimed during most of the storm in spite of the heat lamps focused upon them. However, the icing rate meter cycled more frequently between 0200 and 0300 than during any other hour sampled throughout the winter. The winds at the seeding site were variable or southeasterly, and 0 to 2 $m\ s^{-1}$ during this storm.

The top portion of Fig. 2 shows a plot of ice nucleus concentrations derived from the acoustical counter and the seeded period for this case. The calculated concentrations (effective at -20C) include a x10 multiplication suggested by Langer (1973) to account for crystal losses in the cloud chamber. The peak concentrations reached 5×10^3 L^{-1}. The jagged appearance of this plot is due to the logarithmic ordinate exaggerating the low concentrations. The discrete appearance over most of the plot corresponds to one count per minute, the digitizing interval, which converts to slightly over one ice nucleus L^{-1}. On this plot a concentration of zero corresponds to "0.3" L^{-1}. A total filter was put on the intake at 1940 and again at 2007 to insure the counter was working properly, i.e., not generating false counts. It was removed after a significant drop in ice nucleus detection rate was observed.

It is noteworthy that AgI was clearly detected at the Crest Observatory less than 4 h during the approximate 16 h seeded period. It was typical of the storms sampled that AgI was clearly at the Observatory only a fraction of the seeded period. Of course, the AgI plume may have been above or to either side of the single observing point when AgI was not being monitored. A much more elaborate sampling program would be required to test this supposition.

The bottom portion of Fig. 2 shows the vertical ice particle flux data which does not show a close correlation with the ice nucleus trace. This is likely because supercooled liquid water, which is believed necessary for the seeding to be effective, was not present until after 2000. Thereafter there is some correspondence with high ice nucleus concentrations although high vertical ice particle flux continued after the ice nucleus concentration decreased to background levels. It is unknown whether AgI existed at levels above the Crest Observatory after about 2220 or the high flux was a natural phenomenon. Unfortunately, vertical flux data are missing for the AgI plume registered between 1830 and 1900. The high ice nucleus concentrations corresponded with winds slightly north of west.

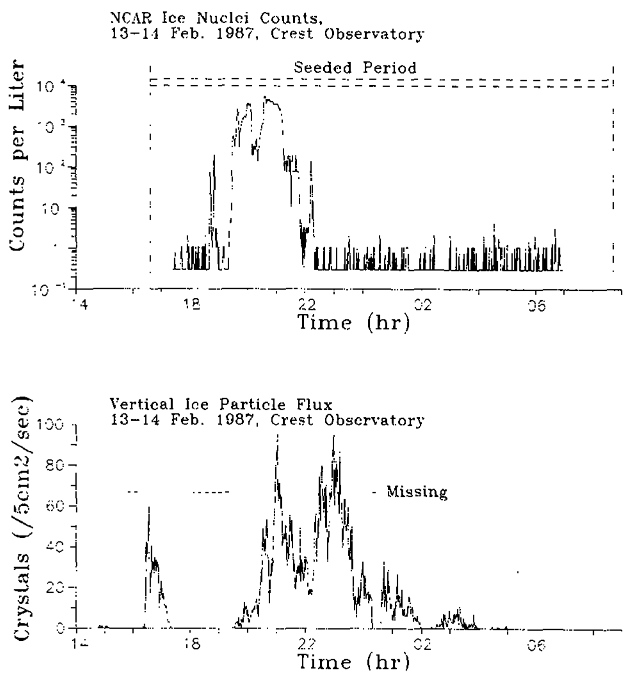

Fig. 2. Ice nucleus and vertical ice particle flux measurements for case of 13-14 Feb. 1987.

Figure 3 shows the results of analyzing the photographed sedimentation plates. The photography did not start until 1853 because warm temperatures during the earlier portion of the storm caused melting of the crystals on the plates. "Compact/hex" particles (plates) had the highest concentrations as would be expected from the ambient temperatures, which ranged from-2, at the start of the storm, to -7C on the Crest Observatory. It should be noted that previous airborne plume tracing over the Main Ridge Crest (Super, 1974) indicated that AgI often reached about 400-500 m above the crestline, where temperatures should be about 3C colder than at the Crest Observatory. One would expect plates and/or needles in this regime (Magono and Lee, 1966), and during portions of this relatively warm storm higher concentrations of linear crystals were seen than in any other storm sampled. Aggregates contributed most of the precipitation (see bottom of Fig. 3). These aggregates were made up of plates and linear particles, with aggregates of the latter being observed in the later portions of the storm.

Although the Crest Observatory was successfully targeted for part of this storm, the AgI may not have been highly effective for two reasons. First, supercooled liquid water was not evident during much of the plume impactµ and second, the temperatures were warmer than considered optimum for ice nucleation with the AgI complex used. Aggregation of small particles was observed during AgI plume detection, giving greater terminal velocities. This aggregation supports the concept of a near-source seeding signal.

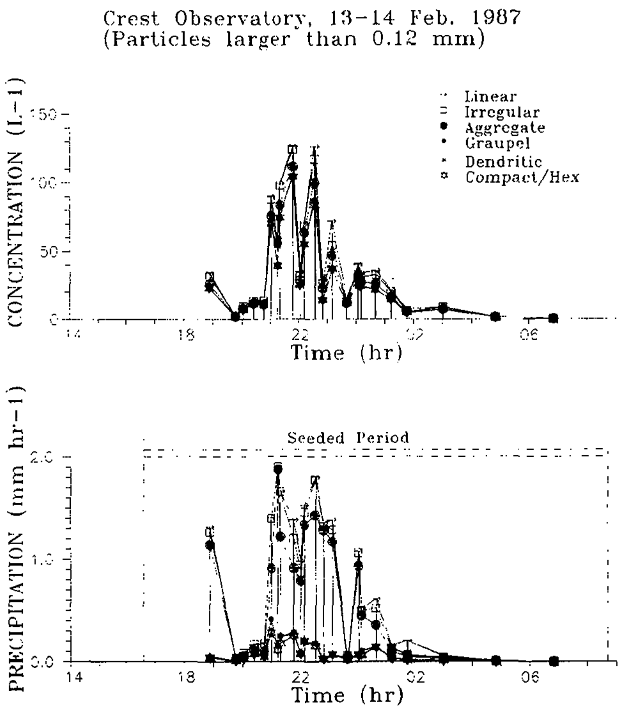

Fig. 3. Ice crystal concentrations and estimated precipitation contributions from six habit classes for 13-14 Feb. 1987.

4.2 22 February 1987

A storm which was observed at the Crest Observatory during its entire lifetime started in the early morning of 22 Feb. Associated with this storm was northwesterly flow aloft which steered a weak frontal system over Montana. Four hours had variable winds at the Crest Observatory, and the remainder were west to west-northwesterly. The hourly speeds ranged from 4 to 9 m s^{-1}, lower than typical. Very high ice nucleus concentrations were detected for over an hour. Figure 4 shows a time plot of ice nuclei and the seeded period. After the time of highest concentrations, there was a lingering period of relatively high ice nucleus counts which could represent a residual or a limited transport from the generator.

Supercooled liquid water was observed from approximately 0830 to 1200. The peak hourly liquid water content according to the Rosemount device was 0.04 g m^{-3} between 0900-1000. Two Rotorod samples (see Rogers et al., 1983) gave contents of 0.07 and 0.06 at 0910 and 1016 respectively. Rimed particles were seen prior to 0830, indicating supercooled liquid water existed above the Crest Observatory.

Figure 4 also shows the vertical ice particle flux trend during the storm. The flux was variable as was characteristic of all the storms sampled. In spite of this variability, some covariability with ice nuclei is apparent, with the highest flux corresponding to the period of AgI plume detection.

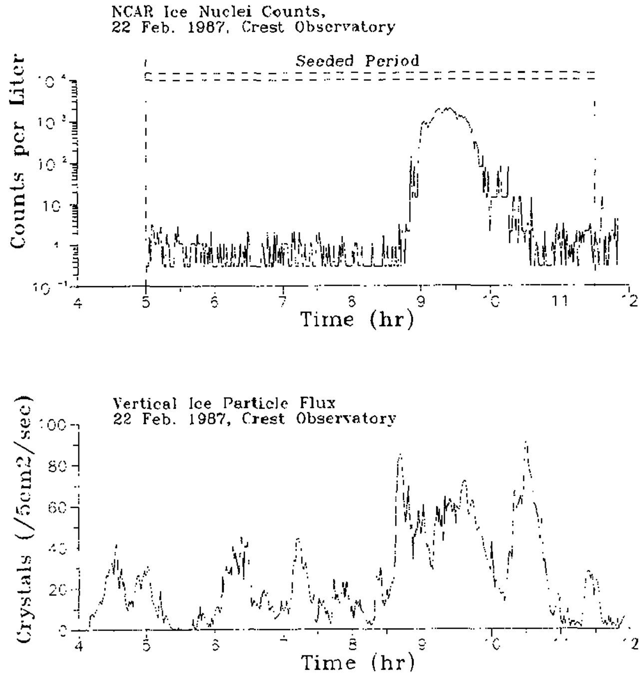

Fig. 4. Ice nucleus concentrations effective at -20C and vertical ice particle flux for 22 Feb. 1987.

Figure 5 shows the concentrations and estimated precipitation rates derived from the 14 photographs taken during the course of the storm. Both plots show an apparent response to the seeding although there is some natural variability. The highest ice particle concentrations and precipitation rates occurred between 0830-1030, in close agreement with the elevated ice nucleus counts of Fig. 4. The Crest Observatory temperature averaged -10C during the seeded period which would be in the plate growth zone (Magono and Lee, 1966). The greatest concentrations were in the "compact/hex" category meeting the expectation that the ice particles grew at temperatures near those observed. During the period when high ice nucleus concentrations were detected, higher plate concentrations were found, and though not evident from Fig. 5, the aggregates contributing most of the precipitation were made up mainly of plates and irregular crystals.

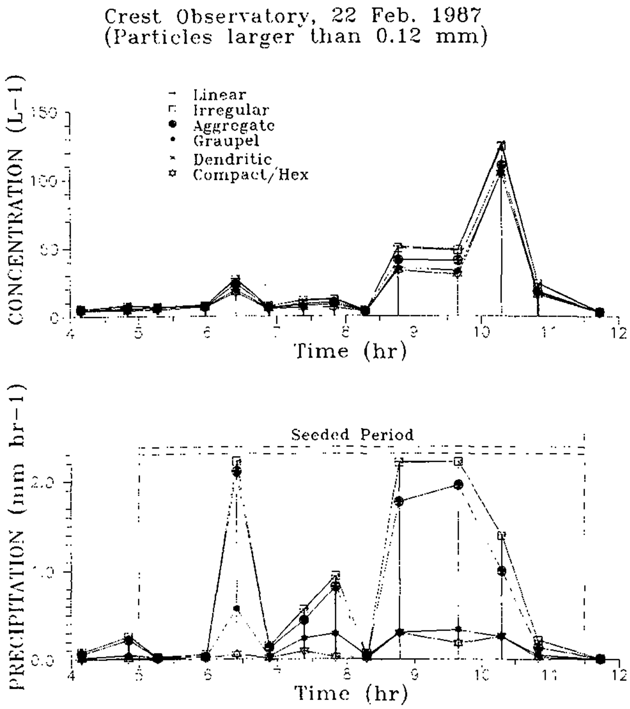

Fig. 5. Ice crystal concentrations and estimated precipitation contributions from six habit classes for 22 Feb. 1987.

4.3 Summary of Microphysical Observations

For a majority of the cases sampled at the Crest Observatory, temperatures were in the range which would produce plates or needles, i.e. -4 to -12C (ibid.). Targeting of the AgI at the Crest Observatory was not always successful, but in those cases when it was, increased ice particle fluxes were often associated with the AgI plumes. Photographic evidence showed increases in plates and/or tiny (<0.3 mm) particles. There were not enough needles or columns observed to give any conclusions regarding their production by AgI. In some instances there were increases in the number of aggregates associated with the AgI plume, and these had a high proportion of plates.

The two microphysical hypotheses for increasing precipitation over the target area were: 1) more ice particles would be generatedμ and 2) though not necessarily large enough to fall out individually, aggregation of these crystals would produce particles large enough to fall within the target area. The hypotheses appear to have been borne out for at least some of the seeded periods. Photography showed that during periods of significant snowfall rates, there was riming of the crystals, indicating that even with seeding, not all the available supercooled liquid water was being processed and some accretional growth was helping the precipitation process. Accretional growth was not anticipated as being significantμ however in one case, 16 Feb., precipitable particles were associated with the production of many small graupel-like particles (0.5-1.5 mm). Above background ice nucleus concentrations were detected on the 16th with the highest concentration occurring during the initial portions of the storm.

5. SUMMARY OF SEASONAL SUPERCOOLED LIQUID WATER CHARACTERISTICS

Out of a total of 2310 hours sampled by the Rosemount device from 21 Nov. through 28 Feb., 155 hrs or 6.7% had supercooled liquid water detected. One hundred and nine hours, or 70% of the hours having liquid water, had ridge top winds between 240-300 deg. true, which was the range of winds specified for seeding. Twenty-seven hours, or 17%, had winds with an easterly component. Reference to Fig. 1 shows that upward motion and associated liquid water production might be expected for both easterly and westerly flow over the Main Ridge. Eighteen hours, or 12% of the hours having supercooled liquid water, had variable winds at the Crest Observatory.

Most hourly mean values of supercooled liquid water content at the Crest Observatory were 0.05 g m^{-3} or less with occasional values up to 0.10 g m^{-3}. As previously noted these are believed to be underestimates due to the assumed unity collection efficiency for the Rosemount probe. Also, one might expect larger contents at higher elevations since the lower levels could be affected by riming on surface features. Such a vertical gradient was suggested in computer simulations for the Park Range of Colorado (Rauber and Grant, 1981).

6. SAMPLING OF SNOW SILVER CONTENT

Nine snow samples were taken from eight snow pits during 6 to 12 March 1987, soon after seeding terminated. Trace silver analysis was done by the Desert Research Institute, Reno, Nevada. Table 1 lists the results in the order of collection, with the locations keyed on Fig. 1. Background from Table 1 is about 10^{-11} g Ag mL^{-1} which is similar to that found earlier in the Bridger Range Randomized Experiment. Samples 4 and 5 corresponded to snow layers that fell during Nov.-Dec. and Jan.-Feb., respectively, as identified by a snow and avalanche expert who monitored the ski area snow pack throughout the winter.

Table 1. Results of snow silver analyses (10^{-12} g Ag mL^{-1}).

Sample	Silver Content	pH	Elev. (m)	Remarks
1	19.4	4.9	2451	
2	40.4	4.9	2393	
3	91.3	4.6	2323	
4	78.8	4.9	2265	Nov.-Dec. layer
5	69.0	4.2	2265	Jan.-Feb. layer
6	48.9	4.9	2216	
7	41.3	5.1	2423	
8	13.0	4.9	2438	Detection limit
9	13.0	4.7	2423	Detection limit

Reference to Fig. 1 shows that the lowest (detection limit) values occurred on the ends of the N-S sampling line. The highest values were essentially ESE-SE of the seeding site, but even sample 2 in the southern portion of the target was well above background as was the single sample on the Bangtail Ridge. The relatively low value of sample 1, taken just below the Crest Observatory, is puzzling. However, it should be noted that this snow pit was on a very steep slope, sheltered by trees upslope and to the south. The other pits were in areas having less slope and were more exposed.

7. TARGET-CONTROL ANALYSIS OF SNOW COURSE DATA

Two snow courses are maintained by the Soil Conservation Service Snow Survey in the ski resort target area. These were used in the analysis presented by SH. One is named Bridger Bowl, indicated as "BB" in Fig. 1, with an elevation of 2210 m MSL. Unfortunately, in 1986, extensive logging was carried out to the edge of this course. There was visible evidence of snow scouring and deposition on the course during early 1987 due to the increased exposure. Analysis of the 1 March point-by-point variability of the ten sampling point course revealed that in 1987 individual sampling points had much greater departures from the course mean than ever observed since the snow course was first sampled in 1965. Accordingly, in the authors' opinion, the Bridger Bowl snow course is no longer suitable for evaluation of cloud seeding. The other snow course within the target is Maynard Creek ("MC" in Fig. 1), located at 1893 m MSL. This site has been sampled since 1968 but was moved prior to the winter of 1974-75. Only post-1974 measurements are used in the analysis to follow to avoid the uncertainties of adjusted data.

The target-control analysis used arithmetic mean snow water equivalent data from groups of snow courses outside the range of seeding influence to predict that of Maynard Creek. Linear least-squares fits, and correlation coefficients between target and control data were derived using nonseeded winters. Estimates of what would have occurred naturally over the target were derived from the regression line. Table 2 summarizes the target-control analysis for the 1 Mar. measurements, the first made following the last day of seeding, 24 Feb.

Table 2. Highlights of 1 Mar. Maynard Creek target-control analysis. Control years are 1975-86.

Control Course(s)	Correlation Coefficient	Residual Inches SWE	Residual %
1,2,3,4	0.927	1.9	35.4
1	0.958	2.1	40.9
1,4,5,6	0.987	2.4	50.2

1. Sacajawea 3. New World 5. Four Mile
2. Shower Falls 4. S. Fork Shields 6. Grasshopper

Three sets of control courses are shown. Sacajawea alone and the means of the combined group Sacajawea, Shower Falls, New World and South Fork Shields are presented because these same courses were used in the analysis of SH. Figure 6 shows the results of the analysis using Sacajawea as the sole control. This suggests an additional 40.9% snow water equivalent due to seeding. This is the largest residual in Fig. 6 and amounts to an additional 2.1 inches snow water equivalent. Sacajawea, the nearest available control course, is approximately 6.2 km NNW of Maynard Creek. Both of these courses are on the east slope of the Main Bridger Ridge and are about the same altitude: 1996 m MSL for Sacajawea and 1893 m MSL for Maynard Creek.

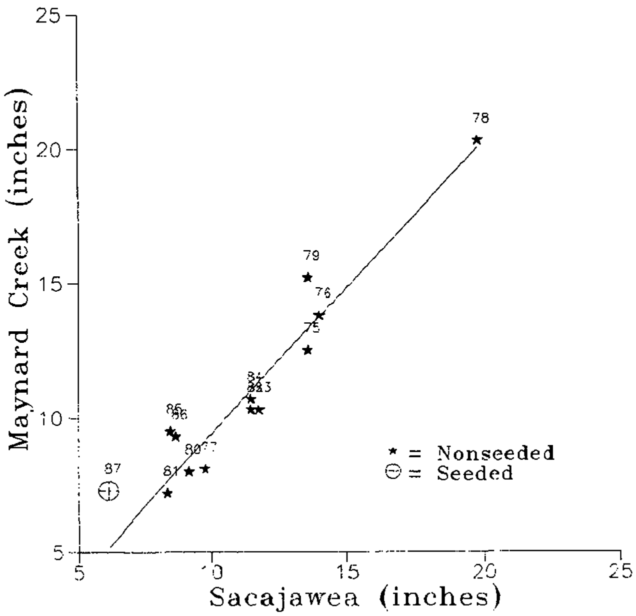

Fig. 6. Maynard Creek versus Sacajawea snow course snow water equivalent accumulations for 1 Mar., 1975-87.

Figure 7 shows a target-control analysis for 1 Mar. using the group of controls whose average snow water equivalent was best correlated with Maynard Creek out of all possible combinations of snow courses within 100 km. There is less scatter than in Fig. 6 indicating a better predictability as quantified by the correlation coefficients in Table 2. Figure 7 suggests a 50.2% snow water equivalent increase due to seeding, corresponding to 2.44 inches additional snow water equivalent.

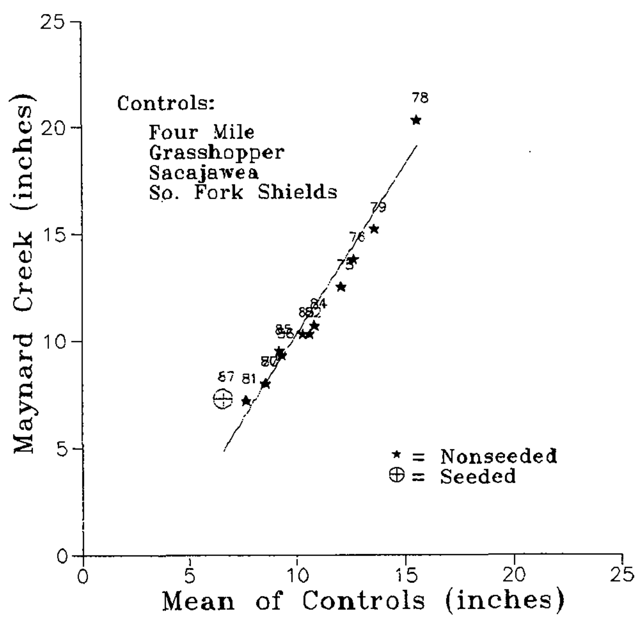

Fig. 7. Maynard Creek snow course snow water equivalent accumulations of 1 Mar. 1975-87 versus the average of Sacajawea, South Fork Shields, Four Mile, and Grasshopper.

It is noteworthy that 1 Mar. 1986 had the second lowest snow pack recorded at Maynard Creek. A number of snow courses in the area had the lowest snow pack of record. The suggested increase associated with the 1986-87 winter seeding is particularly encouraging in view of the exceptionally dry winter.

8. DISCUSSION

The 1986-87 seeding operation attempted to target the Bridger Bowl ski resort which was limited in size, existing on parts of four sections. It's center was only 4 km SE of the seeding site. Previous research detected a strong seeding signal further downwind over the Bangtail Ridge 5 to 20 km E of the Main Ridge. Analysis of snow course data from the period of randomized seeding strongly suggested a seeding signal was also present in the ski resort for the two winters an AgI generator was operated from the same site used during the 1986-87 winter.

Although previous research gave reason for optimism regarding the potential success of the 1986-87 operations, there were questions concerning the targeting of the resort, the frequency of seedable conditions, and how ice particles resulting from seeding could grow to precipitable sizes so close to the seeding site. Measurements made during the 1986-87 winter documented targeting of the AgI and the existence of supercooled liquid water above the Crest. Evidence was found of small seeding-induced particles aggregating to larger particles. Also, it was observed that particles sometimes became rimed enough to enhance their fall speed.

The winter of 1986-87 produced anomalously low snow packs over all of Montana, and several snow courses had record lows late in the winter despite good accumulations in Nov. and Dec. In view of the regionally low snow water equivalent, the increase suggested at the Maynard Creek snow course within the target area is very encouraging. Unfortunately, the logging next to the Bridger Bowl snow course rendered that site unsuitable for a historical target-control analysis. The use of Sacajawea, the nearest snow course, as a control suggested about a 40% increase at Maynard Creek due to seeding. This indicated percentage increase is approximately double that found in the Bridger Range Experiment which employed 50:50 randomization.

Targeting of the AgI was shown to be effective for at least part of the operations by the ice nucleus detector. The snow silver analyses indicated silver concentrations well above background in the ski area and at the single point sampled downwind. The snow silver samples showed a pronounced north-south gradient with the highest silver contents being east-southeast to southeast of the generator. Increased silver content doesn't prove that the seeding modified snowfall as scavenging of AgI by natural snowfall can enhance the snow silver content. However, lack of enhanced silver levels in the target area would indicate failure to target the seeding material.

The periods with highest ice nucleus concentrations detected at the Crest Observatory were associated with some northerly wind component or variable directions. West through west-southwest winds were often found to have several ice nuclei per liter effective at -20C, well above background levels which ranged from 0 to 1 L^{-1}. The elevated ice nucleus concentrations could have been from limited transport from the generator, or residuals from previous seeding. This made control periods difficult to define. Targeting assumed low-level terrain forcing unless northwesterly winds were present. During several experiments, the time from generator start to first detection of ice nuclei at the Crest Observatory, just 3 km from the seeding site, was found to be 15 to 25 min.

The photography of 22 Feb. suggests that an abundance of plates was associated with AgI seeding with a Main Ridge temperature of -10C, a typical value during winter storms. Aggregates of these plates provided a large proportion of the estimated precipitation accumulation. On 13-14 Feb. a similar aggregation of plates was associated with high ice nucleus concentrations. Later in this case the aggregates were of linear particles. Another mechanism which could allow seeding to provide precipitable ice particles within a few kilometers of the generator could be growth by riming. This mechanism was observed on 16 Feb. when many small graupel-like particles with diameters from 0.5 to 1.5 mm were collected on the sedimentation plates.

In summary, the limited research program yielded several indications supportive of the hypothesis that seeding increased the target area snow pack. The AgI plume was detected on the Main Ridge just upwind of the target on several occasions. Increased ice particle concentrations and snowfall rates were sometimes associated with the AgI plume at the Crest Observatory. Cross-wind sampling of the snow silver content revealed high levels downwind (ESE and SE) of the generator in the target area, decreasing to background levels on the north and south ends of the sampling line. Most important, target-control analysis of seasonal snow course measurements indicated approximately 40% more snow water equivalent in the target than predicted from nonseeded winters.

ACKNOWLEDGEMENTS

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REFERENCES

Garvey, D.M., 1975: Testing of cloud seeding materials at the Cloud Simulation and Aerosol Laboratory, 1971-1973. J. Appl. Meteor., **14**, 883-890.

Finnegan, W.G. and R.L. Pitter, 1987: Rapid ice nucleation by acetone-silver iodide generator aerosols and implications to winter orographic seeding strategies. Proceedings of 11th Conf. on Weather Modification, 6-9 October, Edmonton, Alberta, Canada, 9-10.

Holroyd, E.W., 1987: Some techniques and uses of 2D-C habit classification software for snow particles. Accepted for publication in J. Atmos. Ocean. Tech., **4**.

Langer, 1970: Counter for number of snowflakes falling per unit area. Proceedings of Conf. on Cloud Physics, Ft. Collins, CO, Aug. 24-27, 105-106.

_____, 1973: Evaluation of NCAR ice nucleus counter. Part I: Operation. J. Appl. Meteor., **12**, 1000-1011.

Magono, C. and C.W. Lee, 1966: Meteorological classification of natural snow crystals. J. Fac. Sci., Hokkaido Univ. 2:321-325.

Rauber, R.M. and L.O. Grant, 1981: Microphysical processes and weather modification potential of two stably stratified orographic storms. Extended abstracts, Eighth Conf. on Inad. and Plan. Wea. Mod., Oct. 5-7, Reno, NE, 58-59.

Rogers, D.C., D. Baumgardner and G. Vali, 1983: Determination of supercooled liquid water content by measuring rime rate, J. Clim. Appl. Meteor., **22**, 153-162.

Super, A.B., 1974: Silver iodide plume characteristics over the Bridger Mountain Range, Montana. J. Appl. Meteor., **13**, 62-70.

_____, 1986: Further exploratory analysis of the Bridger Range winter cloud seeding experiment. J. Clim. Appl. Meteor., **25**, 1926-1933.

_____, and J.A. Heimbach, Jr., 1983: Evaluation of the Bridger Range cloud seeding experiment using control gages. J. Clim. Appl. Meteor., **22**, 1989-2011.

_____, and _____, 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., submitted.

_____, B.A. Boe, and J.A.Heimbach, Jr., 1988: Microphysical effects of winter cloud seeding with silver iodide over the Rocky Mountains. Part I: Experimental design and instrumentation. J. Appl. Meteor., submitted.

Takahashi, T., C. Inoue, Y. Furukawa, T. Endoh and R. Naruse, 1986: A vertical wind tunnel for snow process studies. J. Atmos. Ocean. Tech., **3**, 182-185.