Microphysical Effects of Wintertime Cloud Seeding with Silver Iodide over the Rocky Mountains. Part II: Observations over the Bridger Range, Montana

ARLIN B. SUPER
U.S. Bureau of Reclamation, Denver, Colorado

JAMES A. HEIMBACH, JR.*
Montana State University, Bozeman, Montana

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ABSTRACT

During January 1985 six aircraft sampling flights were made in cloud over the target area of an earlier randomized exploratory cloud seeding experiment in the Bridger Range, Montana. One of the two silver iodide (AgI) generator sites used in the earlier experiment was operated well up the west (windward) slope of the north-south oriented Main Ridge. Crosswind aircraft sampling was done to within 300 m above the secondary ridge target area about 17 km downwind of the AgI generator.

The AgI plume was detected over the target area on each of the six missions and was generally 5-8 km wide. Three of the missions detected supercooled liquid water (SLW) in the region of the AgI plume. The ice particle concentration (IPC) averaged about an order of magnitude higher in the seeded zone in these cases, and the estimated precipitation rate was greater, as compared with crosswind control zones. Most seeded ice particles were small hexagonal plates, appropriate for the prevailing temperatures and moisture conditions. The AgI generator was deliberately turned off in one of the experiments, and the seeding effects decreased with time beginning about one hour later.

The other three missions sampled negligible SLW in the seeded region over the target area. Observations did not indicate detectable changes in ice particle concentrations, sizes or habits.

The results of this series of physical experiments are in agreement with statistical suggestions from the earlier randomized experiment. It appears that seeding the stable orographic clouds over the Bridger Range sometimes caused marked increases in IPC, presumably leading to more surface snowfall. The physical observations indicate that enhanced IPC was largely dependent upon the availability of SLW when temperatures were cold enough for AgI nucleation.

1. Introduction

The Bridger Range Experiment (BRE) was a randomized exploratory single-area cloud seeding experiment conducted in southwestern Montana during the winters of 1969–72. Super and Heimbach (1983; hereafter SH) presented strong statistical suggestions from the BRE that seeding with silver iodide (AgI) released well up the west slope of the Main Ridge sometimes increased the downwind snowfall. This was supported by transport and dispersion investigations and airflow studies. The latter suggested that supercooled liquid water (SLW) should often have been produced near the windward slopes of the Main Ridge during orographic storms with westerly flow.

SH also indicated that some of the SLW should have been nucleated by the AgI when Main Ridge crest temperatures were lower than about −9°C, and that resulting ice particles should have been transported toward the Bangtail Ridge Target Area (BRTA) located between 10 and 20 km east of the seeding sites.

Further exploratory analysis by Super (1986) suggested that the AgI seeding had little or no effect on BRTA snowfall during most periods, but caused very marked increases during a small proportion of the storm events. Shallow storms with warm cloud top temperatures appeared to be particularly favorable seeding candidates, but some deep storm systems with cold tops also had suggested precipitation increases. No evidence was found of decreased snowfall due to seeding.

Although the post hoc statistical analysis of the BRE was very encouraging, SH recommended caution in its interpretation because of its exploratory nature and the limited physical observations obtained during the

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* Present Affiliation: University of North Carolina at Asheville, Asheville, North Carolina.

Corresponding author address: Dr. Arlin B. Super, Bureau of Reclamation, Code D-3720, Denver Federal Center, Denver, CO 80225.

experiment. They also recommended that a limited program of airborne measurements be carried out over the BRTA as the most appropriate next step.

During January 1985, physical experiments were conducted over the Bridger Range with a well-instrumented aircraft used primarily to search for evidence of ground-released AgI and associated in-cloud microphysical changes over the BRTA. The absence of nearby higher terrain to north and south, and the presence of a radio navigation station a short distance east, made it possible to fly north–south (N–S) in-cloud passes safely within 300 m of the highest BRTA terrain. Six successful instrument flight rules (IFR) missions were flown on four different dates. This paper describes those missions and the results of the airborne observations as well as some supporting measurements from surface sites. More detailed discussion of the physical hypothesis, instrumentation, observational procedures and evaluation techniques is included in Part I (Super et al. 1988).

2. Experimental area and operations

The southern AgI seeding site used in the BRE was reestablished for January 1985. Prior aircraft tracking under visual flight rules (VFR) conditions showed that the ground-released AgI plume from that site was routinely transported over the Main Ridge and BRTA and that its top was about 600 m higher than the latter (Super 1974; Super et al. 1974). The seeding site was on a ridge almost 5 km west of the Main Ridge (Fig. 1) at an elevation of 2.2 km (all elevations are MSL) and in a small depression well sheltered by trees from W through N through E. Since access was by a difficult climb from the 1.5 km level, the small personnel shelter and supplies had to be brought into the site by helicopter. Propane was used for heat and AgI generation, and for a thermoelectric generator, which powered communication radios. Winds were measured on an exposed knoll 100 m west of the AgI generator. Single theodolite pilot balloon (pibal) measurements were made at the seeding site prior to and during aircraft missions.

East of the seeding site, the Main Ridge crest averages approximately 2.6 km and is oriented almost north–south, forming an abrupt isolated barrier to the predominately westerly flow during winter storms. Approximately 6 km to the NE of the seeding site, on top of the Main Ridge at 2.6 km, wind sensors were maintained on a 10 m tower at the Crest Observatory (Fig. 1). On the same tower a Rosemount icing detector was used to monitor SLW. Temperature was recorded in a nearby weather shelter.

The experimental design assumed that the surface-released AgI would pass over the Main Ridge during periods of westerly flow. The AgI plume tracing during January 1985 investigated in-cloud plume characteristics further downwind over the BRTA, where the highest elevation is 2.4 km. The intent was to sample the seeded cloud volume and, nearly simultaneously, the natural cloud on either side during N–S passes through the plume. The crosswind natural cloud regions served as the control, or basis for comparison of seeded and nonseeded microphysical characteristics. Because of the N–S uniformity of the Main Ridge and limited instantaneous width of the plume, differences between treated and control cloud regions were expected to be readily detectable if they existed. Each N–S flight line extended from about 30 km north of the seeding site latitude to about 20 km south of it (high terrain prevented sampling further south). This insured that seeded zones would be detected for winds from SW to NW.

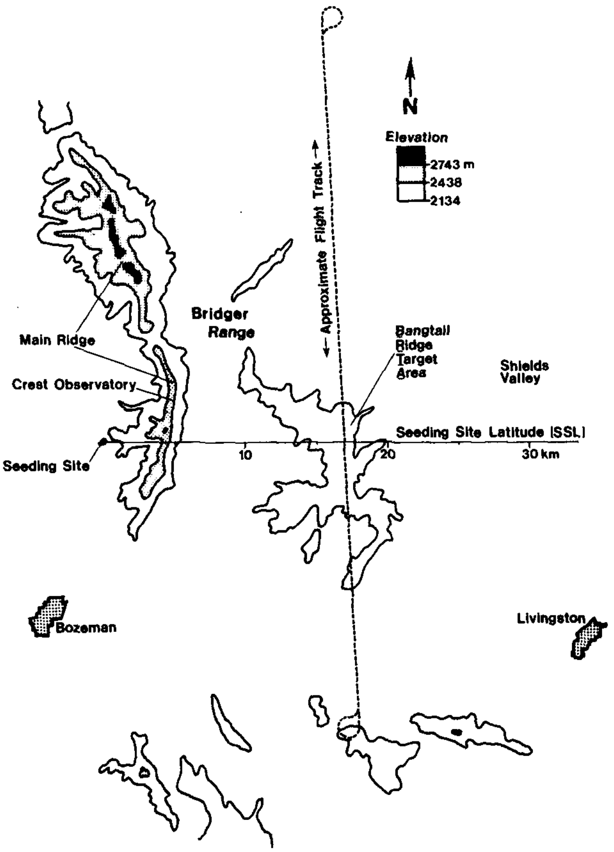

FIG. 1. Map of Bridger Mountain Range showing locations of seeding site, Main Ridge, Bangtail Ridge Target Area and primary aircraft sampling track.

The statistical indications of SH, and the expected nucleation activity for the AgI complex used, suggested that seeding effects should be observable at temperatures lower than about −9°C. Main Ridge crest temperatures are frequently below −9°C during January. The seeded clouds with SLW present were expected to have higher concentrations of ice particles, particularly those types characteristic of the temperature and moisture regime encountered by the AgI plume. Further, seeded ice particles should tend to be smaller than older natural crystals, and a decrease in the SLW content of the seeded volume might be anticipated. For these reasons, measurements of ice particles and SLW were critical to the conduct of the experiment. Observations of ice nuclei (effectively of AgI; see Part I) were also necessary to verify the targeting and approximate extent of the seeded cloud volume.

The lowest IFR sampling over the BRTA was at 2.7 km, 300 m above the highest terrain and approximately the same level as the crest of the Main Ridge. Results of previous VFR plume tracing indicated that this low flight level was necessary for the successful conduct of the experiments. It should be noted that IFR sampling this near to the barrier, made possible by a fortuitous combination of light air traffic, a nearby navigational station, and low terrain crosswind of the target, is not practical in most mountain locations. As will be shown, monitoring at normal terrain clearance altitudes of 600 m agl usually detected little of the seeding material that was consistently present nearer the BRTA surface.

Prior to 0900 (all times MST) of each operational day, a forecast was prepared using National Weather Service products as well as pibal and surface observations from the seeding site. If a westerly wind component and substantial clouds existed or were forecast, a technician was instructed to start the AgI generator approximately an hour prior to aircraft takeoff.

At the start of most research missions, the aircraft entered a holding pattern over the Bozeman Airport (BZN), 13 km west of the seeding site, while a sounding was made to about 5.2 km, or to above the cloud deck, whichever was lowest. Following the sounding, a west-to-east pass was made over the seeding site to the Shields Valley (Fig. 1). The aircraft then returned to the BRTA and conducted a series of N–S passes descending from 3.9 to 2.7 km in 300 m intervals to 3.0 km, and 150 m steps below. The flight to the Shields Valley and the descending profile were to test for unmanageable turbulence.

Following the BRTA traverses, a sounding was often made over the Shields Valley, after which the aircraft returned to BZN along the SSL (see Fig. 1). The flight plan was generally adhered to, excepting variations imposed by the flight controller due to other aircraft traffic.

3. Determination of seeded and control zones

Most results presented in this paper are from the analysis of N–S passes made over the BRTA. The segment of each pass with an enhancement in ice particle concentration (IPC), presumably due to AgI seeding (hereafter enhanced IPC zone), was determined in the following manner. The natural background IPC was established for the sampling level by examining the regions well north and south of any obvious enhanced IPC zone. The upper values of the natural background IPC were used to determine the edges of the high IPC zone by examining the buffer-by-buffer listing of IPC from the 2D-C probe. The north (south) edge of the enhanced IPC zone was considered to be that distance from the SSL where travel further north (south) would encounter no greater than natural maximum IPC levels for several kilometers.

Once the enhanced IPC zone was defined for each pass, attention was given to determining the entire seeded zone and the neighboring nonseeded cloud regions that would serve as control zones. Each side of the seeded zone was considered to be bounded by the enhanced IPC zone or by the estimated AgI plume edge position nearest in time for that side, whichever resulted in greater crosswind extent. Most commonly, the enhanced IPC zone boundaries determined both edges of the seeded zone, probably due to the errors in estimation of the AgI plume edge position discussed in Part I. However, on a few passes, AgI was detected up to a few kilometers further crosswind, which may be because the AgI did not encounter SLW in these limited regions.

Control zones of 2.5 km width were finally designated both north and south of the seeded zone using 1.0 km "buffer zones" between the seeded zone and each control zone. The purpose of the buffer zones was to minimize the effects of any underestimates of AgI plume width and the "tails" of the seeding-caused ice particle plume that might have IPC values just below the background selected.

The above procedures might seem unduly complicated, since in practice, defining the seeded zone was usually straightforward, because of abrupt increases in IPC and because the enhanced ice particle region was wider than the estimated AgI plume width. However, on a limited number of passes the seeded zone was not obvious and an objective means of handling these "problem cases" was considered desirable.

The seeded zones were subdivided into thirds for more detailed examination. If, for example, the IPC had a Gaussian distribution, the center of the seeded zone would exhibit the highest concentration. If ice particles settled to the sampling level in the presence of vertical wind directional shear, the seeded zone could have a skewed distribution, with the highest IPC on the side overlain by the falling particles. North–south gradients in SLW could also cause variations across the seeded zones.

4. Results of six in-cloud sampling missions

January 1985 was colder and much drier than usual; the average monthly temperature at the Bozeman Airport was 2.7°C below the normal. The 1 Feb 1985 snowpack water equivalent at the highest altitude Bridger Range snow course was only 63% of the long-term average. The colder periods of the month were usually dry.

Rosemount icing rate detector data were obtained during 659 h of January 1985 (85 h data are missing due to equipment malfunctions). Icing events were recorded during 9% of all hours with data (the corresponding percentage values for February and March 1985 were 8% and 7%, respectively). The January median calculated SLW content for hours with icing on the Main Ridge was 0.035 g m^{-3}. As discussed in Part I, observations from this type of sensor are often underestimates. Main Ridge temperatures ranged from −3° to −11°C during icing events, with a median of −8.5°C.

Most January icing occurred when winds were westerly at the Crest Observatory. However, during these periods, light and either northerly or variable winds were usually observed at the seeding site. This suggests either a general dispersion of the AgI prior to transport over the Main Ridge and/or southward drift of portions of the plume. Either would result in enhanced horizontal dispersion.

Six successful in-cloud research flights were flown in a wide variety of SLW conditions: one on 10 Jan (in limited SLW), two on 15 Jan (in abundant SLW), another on 19 Jan (with SLW only above the AgI plume), and the final two on 28 Jan (in virtually all-ice clouds).

The afternoon mission of 15 Jan is presented in detail to illustrate evaluation techniques and results. Other missions, although analyzed in similar fashion, are discussed more briefly. Section 5 summarizes the results of all six missions and presents for each mission supporting information, including atmospheric stability, cloud top height and temperature, and Main Ridge temperature. Further supporting information on winds is given in section 6.

a. 15 Jan, p.m.

At 50 kPa a low was centered over northern Hudson Bay, and the associated trough extended southward to Florida. A second deep low lay over the Baja Peninsula. The resulting flow aloft over the Bridger Range was northwesterly, with weak positive vorticity advection.

Snow began early in the morning over the Bridger Range and gradually decreased during the afternoon. A pibal released from the seeding site at 1223 was lost within cloud only 100 m aboveground as it drifted toward the Main Ridge. The obscured ceiling over the seeding site gradually improved to overcast by the end of the mission.

The Main Ridge crest remained in cloud for the mission duration. The aircraft was also in cloud over both the BRTA and Main Ridge up to 3.6 km altitude, the highest flown during this mission. A complete upwind sounding was precluded by other air trafffic, but cloud tops were observed at 4.6 km (−21°C) over the BRTA on the morning mission.

Mean hourly SLW values of 0.04–0.05 g m^{-3} were derived from the icing rate detector atop the Main Ridge during this mission, greater than all but one January day. Winds at the Crest Observatory were 8–10 m s^{-1} from 270°, and the temperature was −9°C. According to SH, significant nucleation should have occurred within the AgI plume over the Main Ridge in these conditions, and the resulting ice crystals, along with any remaining AgI, should have been transported toward the BRTA.

After taking off at 1241, the aircraft climbed around the south end of the Bridger Range to Livingston (Fig. 1). Winds of 290° at 10 m s^{-1} were observed at the seeding generator altitude (2.2 km). The wind increased to 14 m s^{-1} from 285° at 3.0 km. Slight stability was indicated by $d\theta_e/dz$ of 0.8 K km^{-1} through this layer, where θ_e is the equivalent potential temperature.

Supercooled liquid water of about 0.05 g m^{-3} was encountered on climbout from 2.2 km altitude and 9 km south of the seeding site until leveling out at 3.3 km over the south end of the BRTA. Amounts were then generally 0.1 to 0.2 g m^{-3} approaching the Livingston area.

The first N–S pass over the BRTA began at 1258 at 3.3 km altitude and −13°C. Almost continuous SLW in the range 0.05–0.15 g m^{-3} was found from 20 km north to 16 km south of the seeding site latitude (SSL) shown in Fig. 1. Limited zones of similar magnitude were found further north. The only significant ice was encountered south of the SSL in concentrations less than 4 L^{-1}, and no AgI was detected. However, the seeding generator had been on for only 0.5 h, which was probably inadequate for the plume to have traveled the 17 km downwind.

Pairs of passes were next flown at 3.0 and 2.85 km altitudes. Nine additional passes followed at 2.7 km between 1350 and 1515, as will be discussed.

A sounding was made in the Livingston vicinity about 1520. Cloud base was at 2.8 km, and SLW was recorded from that level to the top of the sounding at 3.6 km. The sounding was stable, as indicated by a mean lapse rate $d\theta_e/dz$ of 2.3 K km^{-1} through the layer. As much as 0.20–0.25 g m^{-3} SLW was measured between 3.3 and 3.5 km, which may have resulted in part from upslope flow against the mountains SE of Livingston.

The aircraft returned to base along the SSL at 3.6 km altitude until 9 km east of the seeding site, where descent commenced. From 45 to 26 km east of the seeding site, SLW on the order of 0.05–0.10 g m^{-3} was encountered, after which no SLW was found until 18.5 km east, almost to the N–S sampling track over the BRTA. Marked downdrafts on the order of 2–4 m s^{-1} were found in this dry region just to the lee of the Bangtail Ridge. A second dry region existed from 10 km east of the seeding site to the Main Ridge, probably also associated with lee subsidence. Between the dry regions, i.e., over the windward slope and top of the

Bangtail Ridge, abundant SLW up to 0.35 g m^{-3} was recorded.

Liquid water in the 0.05–0.10 g m^{-3} range was again encountered above the west slope of the Main Ridge, and continued during the descent until passage through cloud base at 2.8 km about 9 km west of the seeding site. Clearly, SLW was widespread during this mission.

The mean SLW contents and IPC observed during the pairs of passes made at 3.0 and 2.85 km altitude are shown in Fig. 2, along with those of the first six

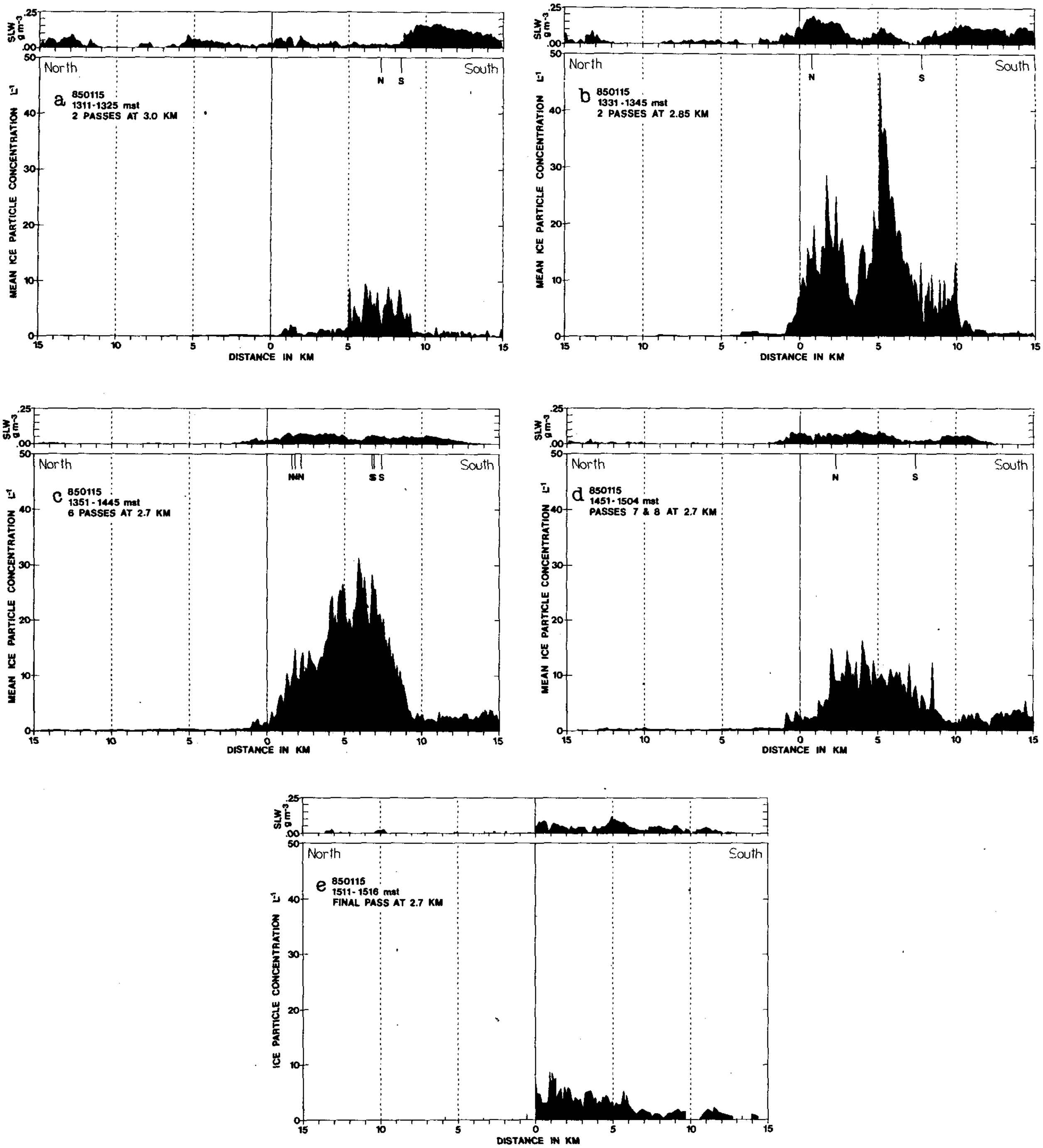

FIG. 2. North–south mean distributions of IPC and SLW content, with the origin 17 km east of the seeding site, for indicated numbers of passes and altitudes on 15 Jan 1985. The north (N) and south (S) edges of the AgI plume are shown by vertical lines at the top of each IPC plot.

passes at 2.7 km. Estimates of the north and south edges of the plume derived from acoustical counter data are shown by vertical lines at the tops of the IPC plots. The means of passes 7 and 8 at 2.7 km, as well as the final pass, are shown separately to illustrate the diminishing of IPC with time after generator shutdown at 1355.

Figure 2 shows that SLW persisted at the sampled levels over the BRTA throughout the mission, with highest amounts found south of the SSL (the origin in Fig. 2) at 2.85 and 3.0 km altitudes. The SLW was very limited north of the SSL at 2.7 km, the lowest level sampled. It is not obvious that seeding markedly reduced the SLW content. The mean vertical velocity within the seeded zones for the 9 passes at 2.7 km altitude was +0.3 m s^{-1}. Calculations by Rauber and Grant (1986) show that even lesser updrafts can produce sufficient condensate for growth of high concentrations of small crystals.

Evidence of seeding was apparent in both the IPC and AgI measurements as high as the 3.0 km level. Total AgI counts per pass were 14 and 18 at 3.0 km, and 71 and 113 at 2.85 km, and ranged between 73 and 120 for the first four passes at the 2.7 km altitude. Total counts subsequently decreased to 64 on pass 5, 66 on pass 6, 28 on pass 7 (at 1454), 17 on pass 8, and only 1 on pass 9. Peak IPC in excess of 50 L^{-1} continued at the lowest sampling level until about 1450. The rapid decrease of both AgI and IPC after that time is further evidence that the enhanced IPC was due to seeding. The observed IPC was almost down to background levels by the ninth and final pass (at about 1515), indicating that about 1.5 h was required for the AgI plume to "flush out" after generator shutdown.

A convenient method of characterizing the concentration of large cloud droplets is the threshold diameter, D_t (Hobbs and Rangno 1985). This is defined as the size where droplets $\geqslant D_t$ have a concentration of 3 cm^{-3} as measured by the FSSP instrument described in Part I. The mean D_t calculated for the wettest nonseeded 1 km interval of each 2.7 km altitude pass averaged 14 μm, and the mean concentration of all droplets was 140 cm^{-3}. The Hallett-Mossop (1974) ice multiplication process would not be expected to be active in these clouds, due to the scarcity of droplets >24 μm diameter, and indeed, Fig. 2 shows that the IPC was quite low outside the seeded regions.

Figure 3 summarizes ice particle concentrations, sizes, and habits, as well as estimated precipitation rates for the seeded (target) zone and two crosswind (control) zones, all averaged for the first six 2.7 km altitude passes. As noted in section 3, the seeded zone was further subdivided into equal zones designated N-S (North-Seeded), C-S (Central-Seeded), and S-S (South-Seeded). The crosswind control zones, designated N-C (North-Control) and S-C (South-Control), were each 2.5 km wide and were separated from the seeded zones by 1.0 km buffers. The approach of Holroyd (1987) was applied to the 2D-C probe images to estimate the vertical flux of ice particles through the aircraft sampling level, hereafter referred to as precipitation or snowfall, although these terms are usually reserved for surface measurements. The size scale of Fig. 3 is logarithmic (log 0.10 = −1.0, log 0.16 = −0.8, log 0.25 = −0.6, etc.).

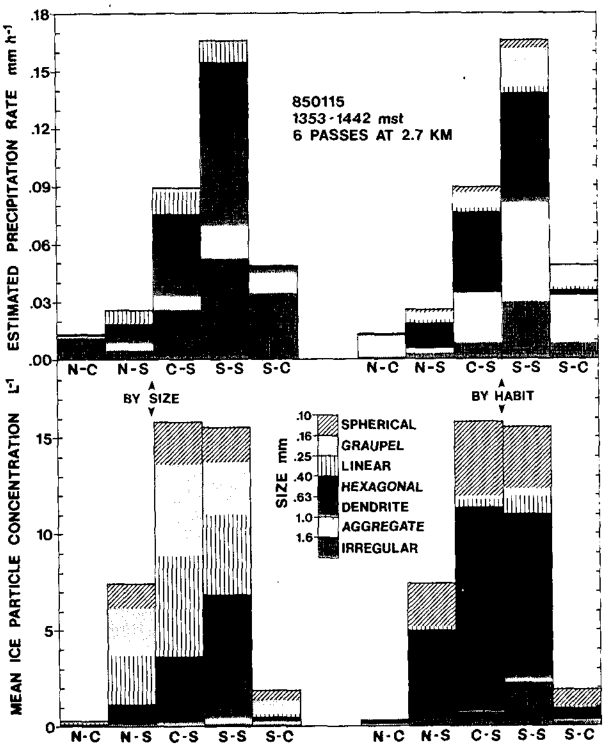

FIG. 3. Ice particle concentrations and estimated precipitation rates for the seeded zone subdivided into thirds (N-S, C-S, S-S), and north and south control zones (N-C and S-C), shown by ice particle size and habit. The particle size/habit shadings apply to both top and bottom panels. Values are means for the first six passes at 2.7 km during the afternoon of 15 Jan 1985.

The average IPC in the seeded zones exceeded by several times that in either control zone. The maximum IPC was near 16 L^{-1} in Zones S-S and C-S, while the maximum in the controls was 2 L^{-1}.

Figure 3 shows that most of the enhanced IPC was due to particles smaller than 0.6 mm, generally classified as hexagonal or spherical. Visual examination of the latter suggested that they were usually tiny plates too small to classify precisely within the limitations of the 2D-C probe's resolution and the processing software. Temperatures recorded over the BRTA ranged from −10° to −12°C at 2.7 and 3.0 km altitudes, respectively, so that growth of seeding-generated crystals in the observed plate habits is reasonable (Magono and Lee 1966). The limited sizes of these crystals suggests that growth in a water-saturated environment had lasted for only a few hundred seconds (e.g., Ryan et al. 1976; Holroyd 1986). Though these crystals were most probably nucleated while passing over the windward (west) slope of the Bangtail Ridge, they may also have formed over the Main Ridge, ceased growing or even partially sublimated in the lee subsidence, and resumed growth in the ascending SLW-rich air approaching the BRTA.

While seeding clearly enhanced the IPC, such enhancement will not necessarily result in greater precipitation. If, for example, smaller seeded ice particles were created at the expense of some natural particles rather than in addition to them, seeding might result in less snowfall. Even if small seeded crystals were present in addition to the natural background level of ice particles, their contribution to precipitation might be insignificant. Most snowfall mass tends to be concentrated in the largest particles, which often comprise a small fraction of the total population.

North–south gradients in SLW and natural snowfall existed, with both being greater to the south. While the estimated snowfall rate in Zone N-S was about twice that of the adjoining Zone N-C, it was less than in Zone S-C. However, Zone C-S had a mean snowfall rate nearly twice that of Zone S-C and several times that of Zone N-C. Zone S-S had even a higher rate, near 0.17 mm h^{-1} (all snowfall rates are for melt water equivalents). Particles greater than 1.0 mm, generally classified as aggregates, accounted for most of the snowfall in Zone S-C. In contrast, though some aggregates and graupel-like particles were observed in the seeded zones, much of the snowfall resulted from particles smaller than 1.0 mm classified as hexagonal.

The mean precipitation rate of 0.09 mm h^{-1} in the seeded zones was three times the mean rate for the two control zones, so it appears that the AgI seeding markedly increased the snowfall. However, the precipitation rates calculated from 2D-C probe images are believed to be underestimates (Part I). Consequently, it is likely that actual precipitation rates were greater at the 2.7 km level than is indicated in Fig. 3.

Recent observational evidence from a number of mountain ranges, some supported by numerical modeling, indicates that SLW is often concentrated above the windward slope and crest of the barriers in stable winter storms (e.g., Boe and Super 1986; Rauber and Grant 1986). These regions should contain greater vertical velocities and water vapor contents than colder regions further aloft. Though it was not possible to monitor SLW between the lowest flight level and the surface over the Bridger Range, it seems likely that some SLW existed below the 2.7 km level. Even if only ice saturation was exceeded, ice crystal growth could continue, possibly resulting in greater snowfall at the surface than at 2.7 km. However, no surface observations were made during the January 1985 experiments to test this conjecture, although it was practical to obtain such measurements over the Grand Mesa, Colorado, as reported in Part III (Super and Boe 1988).

b. 15 Jan, a.m.

The climbout sounding over the Bozeman Airport revealed very light amounts of SLW from 2.6–2.8 km, and concentrations of 0.05–0.15 g m^{-3} in the 3.5–3.9 km layer. A zone of SLW was encountered near cloud top while flying at 4.5 km toward the Main Ridge. The icing rate detector at the Crest Observatory measured hourly mean values of 0.03–0.04 g m^{-3} throughout the mission.

Single N–S passes were made at 3.9 and 3.3 km over the BRTA. Supercooled liquid water amounts were near 0.1 g m^{-3}, and only 1–2 L^{-1} IPC were found, with the exception of a 1.5 km wide region at 3.3 km centered about 9 km south of the SSL, which peaked at 20 L^{-1}. It coincided with a weak (6 counts) AgI plume.

Pairs of passes were made at 3.0, 2.85 and 2.7 km. The SLW content increased with altitude, with a two-pass mean of 0.06 g m^{-3} at 2.7 km and 0.17 g m^{-3} at 3.0 km. The threshold diameter, D_t, averaged 15 μm for the wettest nonseeded 1 km at the 2.7 km level, and the mean droplet concentration was 130 cm^{-3}.

A zone of very marked increase in IPC was evident on each of the six passes in the 2.7–3.0 km layer, with peak concentrations from 28–48 L^{-1}. These enhanced IPC zones were in spatial agreement with the AgI plumes. Total counts per plume transit from the acoustical counter ranged from 31–83.

Figures (not shown) similar to Fig. 2 were examined for evidence of decreased SLW in the seeded zone. Any such decrease was not obvious with the N–S gradient and the considerable spatial and temporal variability that were present.

The seeded zone for the mean of the two 2.7 km sampling passes was again subdivided into three equal segments and compared with the nearby 2.5 km wide control zones. The mean IPC in the seeded segments ranged from 6 L^{-1} in Zone N-S to 12 L^{-1} in Zone C-S, while that in the controls was under 1 L^{-1}. Most of the increase was in the smaller size ranges, generally less than 0.6 mm. As during the afternoon mission on this date, most of the enhanced ice particle population was classified as either hexagonal or spherical. Since the temperature over the BRTA ranged from −10.5°C at 2.7 km to −12.5°C at 3.0 km, production of hexagonal plates would be expected from AgI nucleation.

The estimated natural precipitation rate showed about a threefold increase from Zone N-C to S-C, associated with a N–S gradient in SLW as during the afternoon mission. A similar N–S gradient existed in the seeded zones, with Zone N-S greater than the north control but less than the south control and the other two seeded zones above both controls. The south control had a low concentration of large (>1.6 mm) aggregates that produced most of its snowfall. The natural N–S gradient complicates interpretation of any precipitation change due to seeding. However, the mean of the entire seeded zone was 0.06 mm h^{-1}, while that of the controls was 0.03 mm h^{-1}, suggesting that seeding increased the snowfall by about a factor of two.

c. 10 Jan

Ridging along the Pacific Coast and a deep trough over the central states placed the project area in strong NW flow. The sky was obscured most of the day with light snowfall at the seeding site. A pibal released at 0934 indicated WNW flow before it disappeared into the clouds about 300 m above the seeding site at 2.5 km altitude.

The seeding generator was turned on at 1040 and operated continuously until 1447. At 1212 the aircraft scientist observed cloud all along the Bridger Main Ridge and lenticular clouds east of the Main Ridge below 5 km. The icing rate detector at the Crest Observatory indicated the presence of SLW during most of the flight. The first sensor cycle of the day was at 1205. Thereafter, hourly mean SLW contents of 0.03–0.04 g m^{-3} were observed. At 1444 the aircraft scientist visually observed a liquid water cap cloud on the Main Ridge below the aircraft, which was flying at 3.4 km on its return to base. A zone of SLW (Maximum 0.05 g m^{-3}) of about 1 km east–west extent was detected at the same approximate time and altitude 2 km east of the Main Ridge. These observations confirm the icing rate detector indications that some SLW was present over the Main Ridge during this flight.

Single N–S passes were made at 3.9, 3.6 and 3.0 km and two were made at 3.3 km. No SLW was detected over the BRTA on any of these passes. Essentially, no AgI was detected by the acoustical counter during the passes from 3.9 km down to and including 3.0 km. The maximum IPC was less than 5 L^{-1} throughout the 3.9–3.0 km layer.

The first pass at 2.85 km detected a weak AgI plume a few kilometers south of the SSL. This position was appropriate for the 295° wind direction at that altitude and location; however, no SLW was detected and almost no ice particles were observed.

A series of four passes was then made at 2.7 km. Each detected limited zones of SLW with peak amounts near 0.1 g m^{-3}. The mean value of D_t was 14 μm for the wettest nonseeded 1 km of each pass with corresponding mean droplet concentration of 250 cm^{-3}. Markedly enhanced IPC was found downwind of the seeding site on each pass. Peak IPC values ranged from about 20 to 40 L^{-1}, and the enhanced IPC zone widths were approximately 5–8 km.

Two final passes were made at 2.85 km, which had total counts of 48 and 23 from the acoustical counter, about 10%–20% of the values detected 150 m lower. With the exception of one very narrow zone of ice particles peaking at 20 L^{-1}, the IPC was no more than a few per liter. Liquid water contents were also very low. Therefore, the effects of the AgI seeding were generally limited in altitude to the lowest flight level possible.

The IPC in both control zones was 0.5 L^{-1} with an estimated mean precipitation rate of only 0.01 mm h^{-1}. In contrast, the IPC in the subdivided seeded zone ranged from 3 to 7 L^{-1} with precipitation rates from 0.02 to 0.05 mm h^{-1}. Zone C-S in the center of the seeded zone had the highest IPC and precipitation rate.

Most of the enhanced IPC was due to hexagonal and spherical (compact) crystals less than 0.6 mm across. However, the increased snowfall rate in the seeded zone was primarily due to particles larger than 1.0 mm.

d. 19 Jan

Northwesterly flow persisted aloft, as a slow-moving arctic cold front approached from northeast of the project area. Though aircraft-observed cloud tops were −19°C at 5.0 km altitude just west of the Bridger Range, satellite imagery showed tops less than −45°C only 45 km east of it. Liquid water of 0.05–0.20 g m^{-3} was found on aircraft climbout from 1.7 to 4.2 km altitude, with additional ice cloud above. The highest SLW contents of the month (0.05–0.06 g m^{-3}) were recorded at the Crest Observatory prior to 1300 with west winds. Thereafter no SLW was detected as the wind direction became variable and the wind speed decreased.

Dry arctic air behind the front was overridden by moist northwesterly flow aloft, while the 500 m layer immediately above the BRTA was very stable.

North–south passes from 3.9 to 2.7 km altitude were made over the BRTA beginning at 1254. Some SLW was found along the entire 3.9 km pass, but only well north of the BRTA on subsequent 3.6, 3.3 and 3.0 km passes. No SLW was detected on any of six 2.7 km passes. The AgI plume was detected only at the 2.7 km level (no passes were made at 2.85 km). Total counts per pass were high, ranging from 240 to 1860, suggesting very limited vertical extent. Meandering of the plume within the stable layer resulted in more variable plume width estimates than on the other days, ranging from 0.3 to 12.5 km. Reduced AgI plume spreading and increased meandering are both characteristic of strong atmospheric stability (Holroyd et al. 1988).

Rather uniform IPCs were recorded at 2.7 km, usually from 2–10 L^{-1}, but occasionally higher. No differences were noted between high AgI zones and natural cloud sampled crosswind. The lack of an IPC enhancement was probably due to the dearth of SLW within the stable arctic airmass. Considering the strong stability, it is remarkable that the AgI was even transported over the Main Ridge and the BRTA.

e. 28 Jan, a.m.

A trough embedded in zonal flow aloft was entering Montana. Satellite imagery showed the storm extending over the entire state and beyond, with some cloud top temperature below −50°C near the Bridger Range. Snow began in the early morning and diminished during the afternoon. Throughout the morning, skies were obscured over the seeding site. Ice crystal clouds over the BRTA permitted intermittent visual ground contact from the aircraft.

Due to air traffic restrictions, the morning climbout sounding reached only the 3.7 km level (−19°C). Particle concentrations recorded by the 260X probe varied from a few to 20 L^{-1} up to 3.7 km. No icing rate data were available at the Crest Observatory on this day due to an equipment malfunction. The AgI generator suffered from slag formation in the combustion chamber throughout the mission, so AgI output was reduced by an unknown amount.

North–south passes over the BRTA detected no SLW at the 3.6 and 3.0 km levels, and the IPC generally varied from 2 to 10 L^{-1} with peaks of 15 L^{-1}.

Mean SLW amounts detected within 5 km of the SSL on the first six passes at 2.7 km altitude were zero, while four subsequent passes averaged 0.01–0.02 g m^{-3}. Narrow, transitory peak values of 0.1 g m^{-3} were recorded near the SSL (over the highest Bangtail Ridge terrain) during the latter passes. Observed AgI counts at 2.7 km altitude were lower than usual, probably due to the generator difficulties, and totals ranged from 12 to 83 on the ten passes. A single pass at 3.0 km altitude recorded only 5 counts. Plume position was consistent with the observed westerly flow.

The seeded zone could not be defined by enhanced IPC as on 10 and 15 Jan, but a central seeded zone was defined by the mean AgI plume edge positions at 2.7 km. It was compared with control zones from 3 to 6 km crosswind. No significant differences in IPC, crystal sizes or habits were apparent, and it was concluded that seeding had no significant effect on the region sampled. This is not surprising in view of the essentially all ice crystal cloud that existed over the BRTA.

f. 28 Jan, p.m.

The aircraft climbout sounding observed cloud top at 4.7 km and −27°C. Trace SLW amounts were encountered from 3.6 to 3.8 km and 4.6 to 4.7 km. Ice particle concentrations from the 260X probe ranged from 1 to 10 L^{-1}.

No SLW was detected during BRTA passes at 3.4 and 3.0 km altitudes, but IPC varied from 10 to 40 L^{-1}, and once exceeded 60 L^{-1}. A weak AgI plume was observed at 3.0 km. During subsequent 2.85 km passes, AgI was detected 2–6 km south of the SSL, and IPC remained highly variable, ranging from 5 to 70 L^{-1}. Except for a very few transient SLW zones, the cloud consisted of ice crystals. Six passes at the 2.7 km level consistently found the strong AgI plume positioned where expected, considering the observed westerly wind. Infrequently, small SLW pockets were encountered but were transitory in the presence of natural IPC from 5 to 50 L^{-1}.

No microphysical changes were observed within the seeded cloud over the BRTA. At the levels sampled, the limited SLW was apparently being rapidly depleted by the high natural IPC. One can only speculate on what transpired nearer the windward slopes of the Main Ridge and Bangtail Ridge, where SLW production might have been greater.

5. Summary of physical observations and comparison with earlier statistical analyses

The six in-cloud sampling missions are summarized in Table 1, which shows that the atmosphere was absolutely stable in each case. As reported by SH, absolute stability was usually observed during the BRE. As will be shown in section 6, flow was W to WNW during the January 1985 experiments, which is also typical of the BRE.

The seeding material was routinely observed on all flights at the lowest 2.7 km sampling level over the target area but was rarely detected above the 3.0 km level. This is consistent with earlier VFR plume observations over the Main Ridge. Clearly, high altitude ground-based seeding is capable of providing AgI to clouds over both the Main Ridge and downwind Bangtail Ridge during westerly flow. Mechanical turbulence is believed to provide the dispersion mechanism in the stable atmosphere.

Table 1 shows that each of the six missions had a Crest Observatory temperature of −9°C or lower, thereby satisfying one criterion of SH for seeding to be effective. Three of the missions had SLW present in the seeded zone over the BRTA. Obvious seeding signatures were found in these cases with considerable enhancement of the IPC and apparent increases in precipitation. Any decreases in SLW that may have resulted were masked by spatial and temporal variability in SLW content. The other three cases, with virtually no SLW in the seeded zone, had no apparent microphysical changes associated with the AgI plumes. This is in agreement with the physical hypothesis discussed by SH and stated in Part I.

An abundance of hexagonal plates were found in the seeded zones of 10 and 15 Jan. These were appropriate for the temperature and moisture regimes observed, presuming they were caused by the AgI. Most of these ice crystals were less than 0.6 mm in size, but some grew to the 1.0–1.6 mm range.

Estimates of precipitation rates were made using Holroyd's (1987) computerized scheme applied to the 2D-C images, which should be used with caution because of the limitations discussed in Part I. However, the estimates suggest at least a doubling of precipitation due to seeding on 10 and 15 Jan. Such large percentage increases are consistent with the statistical findings of

TABLE 1. Summary of six seeding experiments.

Date (1985)	Period of N-S passes over BRTA (MST)	$\frac{\partial\theta_e}{\partial z}$ (2.2–3.0 km)* (K/km)	$\frac{\partial\theta_e}{\partial z}$ (3.0–4.0 km)* (K/km)	Cloud top height (km)	Cloud top temp. (°C)	Main Ridge mean temp. (°C)	Highest level of AgI detection over BRTA (km)	Highest level of SLW detection over BRTA (km)	Availability of SLW in seeded zone over BRTA	Obvious microphysical changes over BRTA due to AgI	Predominant ice crystal type associated with seeding	Mean IPC at 2.7 km (L^{-1}) Seeded zones	Mean IPC at 2.7 km (L^{-1}) Control zones	Mean precipitation rate at 2.7 km (mm h^{-1}) Seeded zones	Mean precipitation rate at 2.7 km (mm h^{-1}) Control zones
10 Jan	1228–1429	2.0	4.5	5.1	−23	−10	2.85	2.7	Some	Yes	Hexagonal plates	6	0.5	0.03	0.01
15 Jan a.m.	0858–1018	0.9	3.9	4.6	−21	−9	3.3	3.9**	Abundant	Yes	Hexagonal plates	9	0.8	0.06	0.03
15 Jan p.m.	1258–1517	0.8	n.a.	>3.6**	< −15**	−9	3.0	3.6**	Abundant	Yes	Hexagonal plates	13	1.0	0.09	0.03
19 Jan	1254–1550	10.5	1.4	5.0	−19	−9	2.7	3.9**	None	No	None	—	—	—	—
28 Jan a.m.	0833–1050	1.3	1.8	>4.3**	< −23**	−11	3.0	3.0	Very limited and transient	No	None	—	—	—	—
28 Jan p.m.	1439–1615	0.8	1.6	4.7	−27	−11	3.0	2.85	Very limited and transient	No	None	—	—	—	—

* Upwind of Bridger Range.

** Highest level sampled.

SH, which indicated that overall, about 50% more snow fell on the BRTA for the population of seeded experimental days with Main Ridge temperature $\leqslant -9$°C. It would seem likely that seeding was ineffective on many of the days, as suggested by Super (1986), so that larger than 50% increases must have occurred on some other days. The latter analysis further indicates that a doubling of the precipitation is reasonable during periods when seeding is particulary effective [see, e.g., Fig. 3 of Super (1986)].

Super (1986) also suggested that seeding was especially effective in some of the cases where the 70 kPa wind had a strong westerly component and cloud tops were warmer than about −25°C. He indicated that seeding was highly effective during a fraction of the cases, but had little or no effect most of the time. Furthermore, no decreases in precipitation due to seeding were suggested by the statistical analysis, and none were found in the January 1985 physical observations.

Of the three experiments with marked seeding signatures, the afternoon mission of 15 Jan had the most abundant SLW, and the highest IPC and estimated snowfall rate in the seeded zone. The least amount of SLW, and shallowest liquid layer, occurred on 10 Jan, which also had the lowest IPC and estimated snowfall due to seeding. The morning mission of 15 Jan had somewhat less SLW, IPC and snowfall than the afternoon flight, but was well above 10 Jan. Cloud tops on all three days were relatively warm (no aircraft observation was made on the afternoon of 15 Jan, but satellite imagery suggests a top temperature near −20°C). This places all three missions in the most favorable category suggested by Super (1986).

Section 6 shows strong westerly flow over the BRTA on 15 Jan and considerably less on 10 Jan, which was likely a major factor in SLW production, and, in turn, was apparently related to the effectiveness of the seeding. This occurred despite the fact that the 2.7 km temperature was −12°C on 10 Jan and −10°C on 15 Jan, which should provide less potential AgI ice nuclei on the latter day. The greater abundance of SLW appeared to be more important to seeding effectiveness, which is reasonable if, as expected, contact nucleation was the primary process (DeMott et al. 1983).

The three missions without apparent seeding effects all had temperatures cold enough for AgI nucleation. Although moderate westerly flow existed, little or no SLW was available for AgI nucleation over the BRTA. In the case of 19 Jan, this was due to the arrival of a dry arctic air mass in the lower layers. Cloud tops were warm, and SLW existed in the upper levels, but not where the shallow AgI plume passed. The two missions of 28 Jan had abundant natural ice, probably because of the relatively cold cloud tops (Cooper 1986). Any SLW production over the target was rapidly depleted by the natural snowfall.

The limited number of January 1985 aircraft missions is too few to be able to claim that the resulting physical observations completely verified earlier statistical findings based on a large number of storms. Yet there are no apparent inconsistencies between the physical and statistical approaches. The January 1985 seeding was effective in some but not all cases. The successful seeding was done with Main Ridge temperatures of −9°C or colder, moderate to strong westerly flow, warm cloud tops, and SLW present. This is in agreement with earlier statistical suggestions and current physical understanding.

6. Crosswind widths of the seeded zones

It is of interest to document the widths of the AgI seeding plumes and the associated ice particle plumes over the BRTA, because such information can suggest the appropriate crosswind distance for placement of AgI generators for any future seeding programs with terrain and clouds similar to those at the Bridger Range.

The width of the ice particle plumes caused by AgI seeding were determined as described for the enhanced IPC zone in section 3. These were estimated by examination of buffer-by-buffer IPC measurements from the 2D-C probe. Ice particle plumes clearly caused by seeding were apparent on the 10 and 15 Jan missions. The widths of these plumes are shown in Table 2 for each pass except for the last three of 15 Jan, which had decreased IPC due to earlier cessation of seeding. The mean IPC is also noted. Supporting wind and stability data can be found in Table 3.

The mean plume widths at the lowest sampling level (2.7 km) were 5.2 km for 10 Jan, 8.0 km for the morning of 15 Jan, and 8.4 km for the afternoon of 15 Jan. Comparison with Table 3 shows that the mean ice particle plume was narrower than the mean AgI plume in the 10 Jan case, presumably due to the limited crosswind extent of SLW. Table 2 also shows that the plume was narrower at 3.0 km than at 2.7 km on both the 15 Jan missions. Mean ice particle concentrations were remarkedly consistent, ranging only from 3 to 21 L^{-1}, with only two values below 7 L^{-1}. Table 3 lists AgI plume widths estimated with the acoustical counter for pairs of 2.7 km passes along the N–S sampling line over the BRTA. Also listed are wind and stability information, both upwind of the Bridger Range and over the BRTA. The mean concentration of AgI was estimated by dividing the mean adjusted total counts by the plume width. In this case the total counts per pass were multiplied by ten to adjust for chamber losses, as suggested by Langer (1973). The mean concentration is effective at −20°C, the acoustical counter cloud chamber temperature. Concentrations would be about an order of magnitude less at −10°C but only a factor of two less at −12°C, according to the AgI generator calibration of Garvey (1975). Comparison of 10 Jan IPC values in Table 2 with corresponding AgI concentration values in Table 3, adjusted downward by the factor of two for the prevailing temperature of −12°C, suggests that a small fraction of the available AgI nucleated ice crystals. This may be due to the long time dependence of contact nucleation, discussed by Demott et al. (1983), for the low water content cloud found on 10 Jan. Agreement between IPCs and ice nucleus concentrations was much better on the wetter 15 Jan missions if Table 3 values are reduced by a factor of ten for the warmer prevailing temperatures.

TABLE 2. Summary of ice particle plume widths and mean ice particle concentrations (IPC) for N–S passes with enhanced IPC due to seeding.

Date (1985)	Altitude (km)	Width (km)	Mean IPC (L^{-1})
10 Jan	2.7	2.1	12
	2.7	5.8	11
	2.7	4.9	8
	2.7	8.1	3
15 Jan (a.m.)	3.0	3.5	9
	3.0	3.3	14
	2.85	5.2	17
	2.85	3.3	15
	2.7	5.3	15
	2.7	10.7	7
15 Jan (p.m.)	3.0	4.1	6
	3.0	2.0	7
	2.85	7.7	18
	2.85	10.6	14
	2.7	7.3	19
	2.7	9.1	12
	2.7	8.6	14
	2.7	9.1	13
	2.7	9.0	21
	2.7	7.3	21

Excluding the apparently meandering plumes in the very stable atmosphere of 19 Jan, AgI plume width estimates ranged from about 2 to 8 km. The mean value for the 12 estimates in 5.2 km, which compares with a mean of 7.3 km for all 2.7 km ice particle plumes in Table 2. Tables 2 and 3 both suggest that the seeded zone at 2.7 km over the BRTA was infrequently less than 4.7 km wide. The range of conditions samples was somewhat limited, since five of the six missions had a moderately stable atmosphere over the BRTA. Wind speeds there varied from 6 to 15 m s^{-1} and directions from 268° to 299°. However, as shown by SH and by Super (1986), these were typical values during the BRE.

The BRE used two AgI generators with about a 6.4 km crosswind separation. The present work suggests that another generator between those two would have been advantageous, especially since time-averaged plumes tend to have Gaussian distributions with concentrations tailing off toward each edge. Although this was suspected from AgI plume tracing during the BRE, resources did not permit operation of a third seeding site.

TABLE 3. Summary of AgI plume measurements at 2.7 km with supporting information.

	Upwind Sounding		BRTA		2.7 km Plume		
Date	2.2 km dir./sp. (deg/m s^{-1})	3.0 km dir./sp. (deg/m s^{-1})	2.7 km dir./sp. (deg/m s^{-1})	2.7–3.0 km $\frac{\partial \theta_e}{\partial z}$ (K km^{-1})	Width (km)	Mean concentration (nuclei L^{-1}) (at −20°C)	Direction of transport (deg)
10 Jan	255/16	305/7	289/6	3.2	6.0	333	282
					6.2	231	279
15 Jan (a.m.)	305/17	315/13	298/15	1.7	8.2	57	287
15 Jan (p.m.)	290/10	285/14	299/13	2.0	4.8	154	284
					5.0	134	286
					4.8	88**	285
					4.8	30**	286
19 Jan	275/14	300/15	291/7	23.5	0.3*	20,000*	295
					5.0	1256	294
					12.5	28**	271
28 Jan (a.m.)	240/7	300/7	268/8	1.7	1.8	136	277
					2.0	275	265
28 Jan (p.m.)	250/7	275/10	277/10	1.4	6.9	110	277
					7.2	128	270
					4.7	185	273

* Doubtful due to plume meandering.
** Decreasing due to generator shut down.

7. Summary and conclusions

Several aircraft sampling missions were conducted during January 1985 in clouds seeded with AgI over the Bridger Mountain Range of Montana. The purpose of these flights was to make low-level crosswind observations of ice nuclei, ice crystals and supercooled liquid water (SLW) over the target area of a prior cloud seeding experiment, the Bridger Range Experiment (BRE). Earlier analyses of the BRE have provided strong statistical suggestions that AgI seeding sometimes markedly enhanced snowfall. If these suggestions are valid, it was reasoned that the in-cloud aircraft sampling should yield physical evidence that 1) the AgI was actually transported over the intended target area during storm events; 2) SLW sometimes existed in the region through which the AgI was transported; 3) the AgI interacted with the SLW to produce additional ice particles; and 4) detected enhancements in ice particle concentration (IPC) should also show evidence of increased snowfall rates.

Although the January 1985 observational period was abnormally dry, six successful in-cloud missions were flown on four days. In each case, AgI was released from the southern seeding site used during the BRE, which was located at 2.2 km elevation well up the windward (west) slope of the Main Ridge. On each mission, the AgI was consistently detected over the Bangtail Ridge Target Area (BRTA) about 17 km east of the seeding site.

The estimated AgI plume widths were usually in the range of 5 to 8 km and maximum plume tops ranged from 2.7 to 3.0 km. The atmosphere was absolutely stable in each case, as evidenced by the fact that θ_e increased with height. Absolute stability is typical of winter storms over the Bridger Range. Mechanical mixing is believed to have produced the observed dispersion.

Also typical was the mean W to WNW flow over the range during each mission, which transported the AgI over the southern portion of the BRTA. This was the region of suggested snowfall increases due to seeding during the 1969–70 winter, when only the southern seeding site was used (see Fig. 4 of SH).

The finding that AgI targeting can be successful is quite important. While many winter orographic projects have used ground-based seeding, there is surprisingly little direct evidence that the seeding material was routinely transported into the intended clouds. In fact, evidence from several projects seems to show that this was not the case. Failure to use adequately high elevation sites so that clouds were actually seeded may be responsible for the inconclusive results of a number of past experiments.

Supercooled liquid water contents varied widely among the six aircraft missions. Moderate and widespread SLW contents were found on the two missions of 15 Jan. Liquid water was found upwind of the Bridger Range and well above the BRTA on 19 Jan.

However, a dry arctic air mass existed in the lower levels above the BRTA where the AgI was transported. A shallow liquid cloud with limited SLW content was found over the BRTA on 10 Jan, when a liquid cap cloud was seen on the Main Ridge as well. The missions of 28 Jan were flown in a deep storm with cold top temperatures. Small, transient amounts of SLW were observed that were quickly depleted in the high concentrations of natural ice particles.

The three missions of 19 and 28 Jan, with negligible SLW at AgI plume levels over the BRTA, produced no detectable changes in IPC, ice particle sizes, or habits in the seeded zone. Conversely, the response of the clouds to the AgI seeding was very noticeable on the three flights of 10 and 15 Jan. During these three missions, the AgI clearly encountered SLW at temperatures of $-10°C$ or lower, resulting in severalfold increases in IPC, typically from $<1 \text{ L}^{-1}$ natural background levels to mean values near 10 L^{-1}. Values of the threshold diameter, D_t, were near the low value of of 15 μm at the 2.7 km level on each of these flights. Therefore, indications of ice multiplication by the Hallett-Mossop process were neither expected nor observed. Mean widths of the enhanced IPC zone on these three flights were 5.2–8.4 km about 17 km downwind of the seeding site.

The ice particles caused by seeding on 10 and 15 Jan were generally hexagonal plates mostly less than 0.6 mm across, although some grew to the 1.0–1.6 mm range. The estimated seeded zone precipitation rates were approximately twice that of the mean of the crosswind control zones.

Because the small sizes of the ice particles imply limited growth times, it is probable that most of the observed seeded crystals nucleated over the windward slopes of the BRTA. It is also likely that they grew near aircraft sampling levels due to their small settling velocities. Ice crystals that formed further upwind over the windward slope and crest of the Main Ridge, which is known to have frequent SLW, most likely settled to the surface upwind of, or below, the aircraft sampling line at 2.7 km. It is speculated that much of the effect of AgI seeding was nearer the Main Ridge and at lower levels, where aircraft sampling was not practical.

The physical observations of January 1985 lend considerable support to the previously reported statistical results. Clouds over the target area routinely contained an AgI plume several kilometers wide within 300 m of the highest terrain. Supercooled liquid water was observed on the Main Ridge crest from 7% to 9% of all hours from January through March 1985, an unusually dry period. During three of six in-cloud missions, the AgI intercepted SLW over the target area, and consequently, severalfold increases in IPC were found in the seeded zone. The crystal habits were appropriate for growth at the temperature of the sampling level. Most crystals in the seeded zone were small, implying recent nucleation. Estimated precipitation rates were greater in the seeded zones than in the crosswind control zones. While the limited physical sampling of January 1985 obviously does not completely verify the earlier statistical findings, which were based on a large number of cases, there is no obvious disagreement between the two approaches. It is recommended that a confirmatory statistical seeding experiment be designed and conducted in the Bridger Range. A strong physical component should be part of the design to test that the key steps in the hypothesis are routinely met. The advantages of this particular mountain range include 1) a relatively simple and isolated N–S Main Ridge lying across the prevailing westerly flow with a broad secondary ridge as the downwind target; 2) a reasonably high frequency of stable orographic clouds containing SLW cold enough to be nucleated with AgI near crestline levels; 3) a demonstrated ability to routinely target the clouds with ground-based generators; 4) the existence of an apparently successful exploratory statistical experiment; and 5) the existence of the physical evidence contained in this paper. The authors are not aware of any mountain barrier that would appear to offer more promise for a successful confirmatory seeding experiment with winter clouds.

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