Evaluation of the Bridger Range Winter Cloud Seeding Experiment Using Control Gages

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ABSTRACT

A randomized exploratory single-area cloud seeding experiment was carried out in the Bridger Range of southwestern Montana during the winters of 1969–72. Seeding was accomplished using ground-based silver iodide (AgI) generators located more than midway up the west (windward) slope of the north–south Main Ridge, thereby avoiding trapping by lower stable layers. A secondary ridge from 5 to 20 km east of the Main Ridge was the expected target. An extensive airborne plume tracing program provided strong evidence of successful targeting of the AgI seeding material, with further evidence furnished by tracking of pibals and silver-in-snow analysis.

The experimental unit was 24 h beginning at local noon, a natural diurnal minimum in precipitation intensity. The response variable was daily precipitation amount as measured by a dense network of recording gages. Locally-launched rawinsondes and a thermograph atop the Main Ridge provided data for partitioning the experimental days.

A *post hoc* statistical analysis was conducted utilizing upwind and crosswind control gage data. Results from both the Wilcoxon rank-sum test and the recently developed multiresponse permutation procedure (MRPP) strongly suggest that increased target area snowfall resulted from seeding when AgI plume temperatures were colder than approximately −9°C. Double ratios yielded estimates of ~15% more seasonal target area precipitation than predicted by control gages on nonseeded days, while a target-control analysis of independent snow-course data strongly suggested seeding enhanced the seasonal snowpack by more than 15%.

Consideration of plume tracing findings and AgI generator calibration results suggest that the artificial ice nuclei concentration in the seeded volume would be quite limited at temperatures warmer than approximately −9°C. This provides a plausible physical explanation for the results suggested by the statistical investigations.

1. Introduction

Researchers at Montana State University (MSU) conducted an experimental winter orographic cloud seeding program in the late 1960s and early 1970s. This was one of a number of winter cloud seeding investigations conducted in several states under the auspices of the Bureau of Reclamation's Project Skywater. These programs were intended to evaluate the potential for precipitation augmentation in mountainous regions with differing topographies and climates. They were partially motivated by the apparent success of the Climax I experiment reported by Grant and Mielke (1967) and Mielke *et al.* (1970) and (1971).

The Bridger Range Experiment (BRE) was conducted in southwestern Montana, near Bozeman. This site was chosen because of the relatively simple topography and good access. The Main Ridge of the Bridger Range rises abruptly to the east of an ~60 km wide valley, and is oriented approximately perpendicular to the prevailing westerly wind (see Fig. 1). It was hypothesized that seeding clouds above the Main Ridge with silver iodide (AgI) could sometimes affect snowfall farther downwind, particularly on the broad Bangtail Ridge ~5 to 20 km east of the Main Ridge crestline.

The BRE was an exploratory experiment in which a single target area was either seeded or not seeded, based on a randomized decision (~50% seeded). A 24 h experimental unit was used. Daily precipitation, as measured by a network of weighing gages, was the only response variable. Radiosondes were launched ~10 km west of the Main Ridge crest line, and a thermograph was maintained on the crest line. The upper air and thermograph measurements were to provide for partitioning of the precipitation measurements in *post hoc* statistical analysis.

In addition to the randomized experiment, several supporting investigations were carried out. These included airborne tracing of AgI plumes, airflow investigations, analysis of snow silver content and attempts to directly detect the effects of short-period seeding episodes through a variety of physical measurements.

The BRE and several of the other experiments previously noted were terminated earlier than planned due to a major reduction of the sponsoring agency's

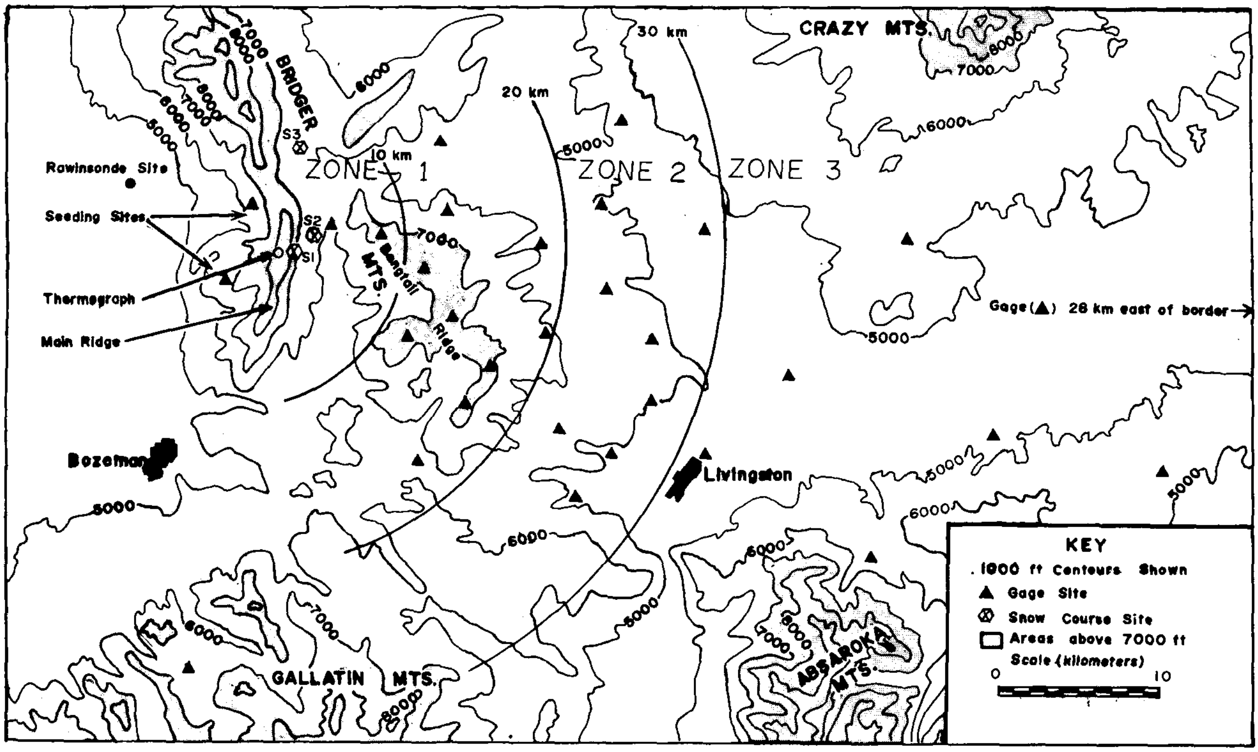

FIG. 1. Map of Bridger Range experimental area showing locations of precipitation gages and snow courses.

budget for fiscal year 1973. This resulted in fewer experimental days than anticipated and decreased resources for analysis. Nevertheless, considerable analyses were completed and reported in a two-part final report[1] (Super *et al.*, 1972, 1974, hereafter referred to as Part I and Part II). These reports also contain detailed discussions of experimental design, field facilities, operations, all supporting investigations and a complete listing of the precipitation, Main Ridge thermograph and upper-air data used in the analysis reported herein. These reports were provided to many interested individuals and organizations at the time of their publication.

Previous statistical analyses of the BRE, noted below, gave strong indications of type I statistical errors—i.e., rejection of a true null hypothesis. This means that some meteorological partitions yielded distributions of seeded and nonseeded days for which the statistical testing suggested significant changes in precipitation due to seeding when, in fact, no logical cause and effect relationship was evident. Changes were generally in the sense that seeding apparently decreased precipitation although some were also in the opposite sense. The suggested type I errors occurred even with rather large populations.

The first indication of a type I error was reported in early 1971 by Super and Mitchell (1971) in a preliminary analysis of data from the 1969–70 winter and first half of the 1970–71 winter. After completion of the BRE, type I errors in both positive and negative sense were reported by Super (1975). These showed apparent increases in snowfall at several target gages associated with a limited number ($n = 33$) of experimental days with thin clouds. Similar apparent increases were found at each seeding site and at the control gage well to the south. More strikingly, 162 days with clouds thicker than 1000 m and with westerly winds indicated significantly less snowfall on the seeded days, not only at several target gages, but also at the control gage and at the Billings Airport 185 km to the east. Both these changes are believed to be type I errors.

Super and Heimbach (1974) summarized the BRE statistical analysis which was fully presented in Part II. They gave further evidence of a serious type I error using National Weather Service (NWS) precipitation probability forecasts for each experimental day. However, they also presented some partitions which suggested that real precipitation increases were associated with seeding. In these cases, snowfall increases were not apparent at the control gage, at gages near the seeding sites, or often even at gages at the crosswind edges of the intended target.

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[1] Copies of the BRE Final Reports and magnetic tape copies of data used herein are available at cost from the Division of Atmospheric Resources Research, Bureau of Reclamation, DFC, P.O. Box 25007, Denver, CO 80225.

Once an apparent type I error was detected by examining Wilcoxon test statistics at gages both in and outside the expected target area, there was no known objective scheme to overcome it. Since a major portion of the BRE was apparently subjected to type I errors, there seemed to be limited additional information to be gleaned. Moreover, due to cutbacks in the funding agency's budget, resources to pursue further analysis were curtailed.

The problem of type I errors is common in randomized seeding experiments; the Whitetop project may have suffered from it (Decker *et al.*, 1971), as well as the Grand River experiment in South Dakota (Gelhaus *et al.*, 1974). Neiburger and Chin (1969) discussed the problem in relation to a Swiss hail suppression project. Mielke (1979) reported that the Climax I and II experiments were influenced by type I errors.

Recently, objective procedures have been developed to overcome the type I error using upwind control gage precipitation measurements (Mielke *et al.*, 1981a, 1982). The analysis reported herein was largely inspired by the availability of these procedures, which have been applied to the BRE. Use of control gages greatly increases the effectiveness of statistical designs over the single-area approach as shown by Neumann and Shimbursky (1972).

Because the BRE was clearly an exploratory experiment according to the nomenclature of Gabriel (1981) and its analysis is of *post hoc* nature, the reader is cautioned that problems of multiplicity of analyses exist. This should be borne in mind in interpreting probability values to be presented. The statistical results cannot be considered scientifically conclusive without a confirmatory experiment which has not been conducted. Thus, they should be considered no more than suggestive.

The remainder of this paper is structured in the following manner. Section 2 discusses the general physical hypothesis envisioned at the time of the BRE and more recent findings which suggest that the hypothesis requires revision. The equipment and measurement systems employed in the BRE are considered in Section 3, followed by a discussion of the evidence for successful targeting of the seeding material in Section 4. Section 5 summarizes the experimental design; statistical analysis procedures are the topic of Section 6. Results of data partitions are shown and discussed in Section 7. Section 8 considers supporting evidence from snow courses while Section 9 gives a general summary and recommendations.

2. Physical hypothesis

The BRE experimental design was strongly influenced by the Colorado State University (CSU) Climax I statistical results and CSU's physical studies and modeling efforts associated with the then ongoing Climax II experiment. It was envisioned that the BRE would test the concepts emerging from the CSU work in a higher latitude and over simpler topography. It was assumed that the abruptly rising Bridger Range (see Fig. 1) would provide strong uplift to moist eastward-flowing air, thereby producing liquid water condensate. It was also assumed that the concentration of natural ice nuclei and resulting ice particles was sometimes less than optimum for conversion of the condensate to snowfall. The latter assumption was based on ice nuclei measurements made with both a Schaefer-type mixing cold chamber and a NCAR ice nucleus counter, on the Bangtail Ridge prior to the BRE. Both instruments generally indicated less than one ice nucleus per liter at −20°C (Super *et al.*, 1969).

These ideas follow the classic paper by Ludlam (1955). Chappell (1967) expanded on Ludlam's concepts for the specific Climax situation and later modeled the cold orographic cloud (Chappell, 1970). A proposed physical explanation of the Climax statistical results by Grant *et al.* (1969) followed similar reasoning. It was believed that cloud top temperature was very important because ground-based measurements of natural ice nucleus concentrations were observed to be highly temperature dependent. Cold cloud tops were, therefore, expected to result in high concentrations of ice nuclei and resulting crystals, which would settle through the cloud effectively converting the available condensate to snowfall. Conversely, as suggested by the Climax I results, cloud tops warmer than approximately −20°C were expected to produce limited natural ice nucleus concentrations, in which case AgI seeding might increase snowfall.

This physical concept has been questioned by Hobbs and Rangno (1979). They point out that "direct airborne measurements in winter clouds over the Rockies have since shown that the ice particle concentrations bear little or no relation to the measured ice nucleus concentrations, and that the ice particle concentrations often exceed Grant *et al.* (1969) optimum concentrations even at quite high temperatures". Cooper and Saunders (1980) also note that ice nucleus measurements were much lower than ice particle concentrations measured in storms over the San Juan Mountains of southern Colorado. However, in a companion paper, Cooper and Marwitz (1980) suggest that seeding potential may well exist in some storm stages where ice particle concentrations were generally $\leq 10\ \mathrm{L}^{-1}$ and 1 $\mathrm{m\ s}^{-1}$ updrafts were common.

Other recent observations also give cause to question the importance of cloud top temperature. Rauber and Grant (1981a) present results of aircraft measurements from two stably stratified storms over the Park Range in northern Colorado. The liquid water was confined to a narrow region over the windward slope and barrier crest. Further, single ice crystals were horizontally stratified, with their habit appropriate to their environmental temperature and their limited fall velocities apparently in approximate balance with the general upward motion approaching the barrier. Crystal concentrations of 5–20 L^{-1} were found upwind of the barrier with almost no temperature dependence. Rauber and Grant (1981b) also present model results in good agreement with their observations. More recent observations from several more storms gave further evidence that most of the liquid water was located over the crest and upper slopes of the Park Range (Rauber *et al.*, 1982).

Hill (1980a), in discussing winter orographic storms in northern Utah, noted that, "our data indicate that the production of supercooled water is closely associated with vertical air motion which in turn is found primarily at or near mountain-top levels". Thus, it appears that liquid water concentrations may generally be quite low in stable orographic clouds. The only region of significant liquid water may be within ~1 km of the ground above the upwind slope of the barrier, over the ridge and perhaps for a short distance beyond. This likely corresponds to the region of most pronounced upward motion. In this situation, ice crystal growth may be very limited outside the zone of supercooled liquid water. Simple calculations of diffusional growth and subsequent ice crystal trajectories suggest that crystals formed at elevations well above the liquid water zone (e.g. near cloud top) are generally carried beyond a barrier the width of the Bridger Range without settling to the surface. The crystals most important to the snowfall processes may be those formed well below cloud top that are carried quasi-horizontally into the liquid water zone where rapid growth can occur.

While understanding of both natural and seeded snowfall process is still incomplete, the following general statements about artificial seeding can be made. In order for cloud seeding to increase snowfall from winter clouds over mountainous terrain, several links in a physical chain of events must exist. First, seeding material must be successfully and reliably produced. Second, this material must be transported into a region of cloud that has supercooled water or ice supersaturation in excess of that which can be converted to ice by naturally produced ice crystals. Third, the seeding material must have dispersed sufficiently upon reaching this region so that a significant volume is affected by the desired concentration range of ice nuclei or the resulting ice crystals. In the case of AgI seeding this requires, fourth, that the temperature be low enough for substantial nucleation to occur. Once ice crystals form, they must remain in an environment suitable for growth long enough to enable fallout to occur, generally prior to their being carried beyond the mountain barrier where downslope motion, cloud evaporation and ice crystal sublimation typically exist.

The BRE was not able to acquire direct physical evidence that each of these steps in the physical process occurred in a significant fraction of the orographic storms. Only AgI generator operation, precipitation measured by the gage network, certain other surface observations and upper air parameters were routinely monitored. However, the BRE did obtain evidence that the first four steps frequently occurred. Considerable uncertainties still remain concerning the entire physical process, particularly with regard to the growth and trajectories of ice particles. This *post hoc* statistical analysis is an attempt to reduce these uncertainties.

3. Experimental equipment

a. Precipitation gage network

A network of 31 precipitation monitoring sites was maintained during the 1970–71 and 1971–72 winters and is shown in Fig. 1. Twenty-eight of these sites were east of the Main Ridge, one was 28 km south of the southern seeding site and the other two were at the seeding sites. These latter three were used as control gages in the statistical analysis herein.

The mechanisms of standard Belfort weighing gages were used throughout the network. However, special gage shells were constructed with a 28.7 cm diameter orifice. This provided twice the sampling area of the standard 8 inch gage, which prevented "capping" by snow buildup, and doubled resolution on the gage chart. Each gage was equipped with an Alter-II type windshield (Warnick, 1956).

All gages were positioned in relation to local terrain features or forest cover so as to minimize wind effects. The higher elevation sites, including the control gages and gages on the Bangtail Ridge, were located in natural clearings in the forest. These would be classified as "overprotected" by Brown and Peck (1962). It is not known how well measurements in such sites represent the absolute snowfall amount over the larger, mostly forested area. However, as shown in Part I, comparisons between gages and snowboards showed excellent agreement within such sites ($r = 0.99$) and correlation coefficients of approximately 0.95 were common for 24 h totals between sheltered gage sites located ~4 km apart. Thus, at least in a relative sense, the gages appeared to provide reliable estimates of precipitation.

All precipitation charts were manually reduced to the nearest 0.01 inch by two independent teams of data clerks. Any differences were then reconciled by a third examination. Approximately 96% of all possible precipitation data was retrieved from the gage charts. About three-fourths of the remaining 4% had total precipitation known but time distribution unknown, usually due to clock stoppages. All missing data were estimated with the aid of a series of maps, similar to Fig. 1, which were prepared for all consecutive 6 h periods with missing data. All available precipitation totals were noted by each gage site, and information on "amounts known but time distribution unknown" was also noted. However, each map was coded and nothing on it indicated the date in question, whether the day was seeded, or even if the period was from an experimental day. The first author then subjectively estimated the missing data, insuring that the sum of the 6 h estimates agreed with any precipitation total of unknown time distribution for the period in question. It is believed that this procedure did not introduce human bias into the experiment because of the estimator's ignorance of the status of each period. It is again emphasized that 96% of all possible data was measured. All precipitation data were reported in Part II in 1974 and the same data are used in this analysis.

b. Rawinsonde system

A Weather Measure 1680 MHz RD-65 rawinsonde system was operated about 10 km west of the Main Ridge crest during the 1970–71 and 1971–72 winters. While data were occasionally lost due to system problems, reliability was generally high. All launch preparations were made and data recorded in accordance with procedures contained in *Federal Meteorological Handbook* No. 3(1969).

c. Main Ridge thermographs

Two recording thermographs were maintained in the same standard weather shelter atop the crest of the Main Ridge at 2595 m (see Fig. 1). A precision mercury-in-glass thermometer was also in the shelter with its bulb thermally lagged to closely correspond to that of the thermographs. The thermometer was read immediately upon opening of the shelter door for each weekly servicing. The mean difference in readings between the thermometer and each thermograph for the winter season was used to establish the final calibration for the chart readings. Chart temperatures were extracted at 1 h intervals and then averaged for the 6 h means reported in Part II. With the use of two thermographs, a complete data set was obtained without any missing temperature measurements.

While shelter temperatures are known to be influenced by solar radiation, this effect should be limited by the cloud cover during storms and by the well ventilated exposure of the Main Ridge site. Moreover, the snow-covered terrain should reduce the effects of the underlying surface.

d. Seeding generators

The first attempts to seed clouds over the Bridger Range took place during the winter of 1968–69 with AgI generators at two foothill locations at 1550 m, well below the 2600 m crestline. However, measurements obtained that winter revealed the presence of a persistent stable layer during snowfall that often extended from the upwind valley floor to about midway up the west or windward slope of the Bridger Range (Super *et al.*, 1970). Consequently, there were no apparent means for the AgI to be transported into the intended orographic cloud region during a large portion of the seeded periods. Because of this, generator sites were later established at two remote sites located about two-thirds of the way up the slope of the Bridger Range, near the 2150 m level (see Fig. 1). These sites were difficult to maintain, with winter access limited to foot travel and helicopter. However, they were judged necessary for achieving reliable transport and dispersion of the AgI into the orographic clouds.

The Montana State University AgI generators used during the 1970–71 and 1971–72 winters were among the highest output ground-based units tested at the CSU Simulation Laboratory as reported by Garvey (1975). They were particularly effective at warmer temperatures. Fig. 2 shows their effectiveness values, as reported by the CSU Simulation Laboratory, for two wind speeds past the burner: natural draft (~1–2 m s^{-1}) and maximum fan (~10 m s^{-1}).

Wind speeds were measured at generator stack height during all seeded periods of the 1971–72 winter. Average speeds at the northern and southern sites were only 1.3 and 1.8 m s^{-1} respectively, as both generators were in relatively sheltered locations to minimize flameouts. Since average wind speeds seldom exceeded 3 or 4 m s^{-1} it is probably appropriate to use the natural draft curve in Fig. 2 to approximate field conditions. It can be seen that generator output increases very rapidly as temperature decreases until about −12°C. At lower temperatures the output reaches only about twice the −12°C value. However, the values at −8°C and −10°C are factors of approximately 150 and 5 less than the −12°C output respectively. This

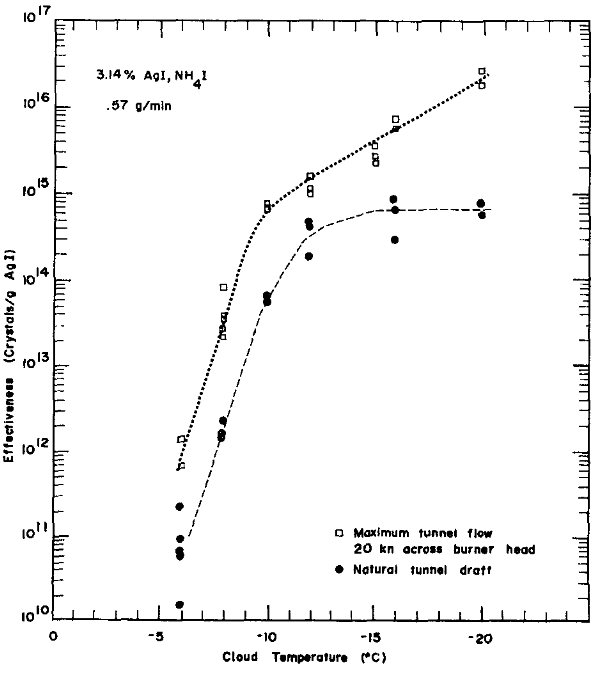

FIG. 2. Calibration of Montana State University Silver Iodide Generator.

marked temperature dependence is believed to partially explain the results of the statistical analysis to be discussed.

The generator at each seeding site was operated at approximately 30 g AgI h^{-1}. A 3% (by weight) solution of AgI in acetone, complexed with NH_4I, was used. Calibrated flowmeters, pressure settings and flame condition were monitored and recorded at 3–4.5 h intervals, day and night. The reliability of the seeding operations was high as the total downtime was only 9 and 24 h for the northern and southern generators respectively, out of a total of over 700 seeded h during the winter of 1970–71. Downtimes for the 1971–72 winter were estimated as less than 6 h at either site.

4. Transport, dispersion and deposition of the AgI

The BRE gave particular attention to the generation, dispersion and transport of silver iodide (AgI) seeding agent. The question of proper targeting of desired concentration of AgI has been, and continues to be, a serious uncertainty in most winter orographic seeding programs. For examples see Rottner *et al.* (1975), Reid (1979) and Miller and Hill (1981). It is believed that the BRE has some of the most convincing evidence of successful targeting obtained in a winter orographic program. This evidence will now be reviewed because of its importance in consideration of the suggestions of the statistical analysis.

a. Silver iodide plume tracing

Silver iodide plume characteristics over the Bridger Range have been reported by Super (1974). Some additional observations were reported in Part II. Consequently, only a brief summary of the plume tracing program and results will be given here.

An NCAR ice nucleus counter was flown in a light twin aircraft on over a dozen different days, about half during February–March, 1971 and the rest during February–March, 1973. Flight passes were usually above the Main Ridge, but sometimes over the Bangtail Ridge as well. The counter was very similar to that described by Langer (1973) who reported quite good agreement between it and the CSU isothermal cloud chamber. All sampling missions were, of practical necessity, flown under visual flight rule (VFR) conditions, usually while the atmospheric layer of interest was slightly stable.

Diffusion would be expected to be greater than sampled under VFR conditions during storms with convection present. In order to assess the frequency of convection during Bridger storms, the convective instability $\partial\theta_e/\partial z$ of the 750–700 mb layer has been calculated from the BRE rawinsonde data. This layer should have been lifted with westerly flow over the Bridger Range. Therefore, cases with $\partial\theta_e/\partial z < 0$ and cloud present at the bottom of the layer should result in embedded convection which would enhance plume dispersion.

Of the total of 363 available soundings examined, 80% were stable between 750–700 mb as indicated by $\partial\theta_e/\partial z > 0$. Further, when the averages of all available soundings for each experimental day were considered, only 10% were convectively unstable. It appears that convection was only present infrequently to increase the plume dispersion. Thus, the observations made under VFR conditions and in a slightly stable atmospheric layer should be a reasonable first approximation of actual plume conditions in most winter storms. It is believed that mechanical mixing was primarily responsible for the plume dispersion.

Pairs of passes in opposite directions were normally made directly above the Main Ridge at pressure altitude increments of ~150 m (500 ft). These were flown from just above the surface to above the maximum altitude reached by the AgI plume(s). The known time delay in the counter's first response encountering AgI was used to estimate the plume edge position for each entrance into it. All passes in a given vertical plane across the plume were sometimes used, together with wind data from pibals, to estimate the flux of AgI.

Major findings of the AgI plume tracing program were as follows: 1) AgI plumes from both generators were usually identified moving over the Main Ridge and toward the intended target—the Bangtail Ridge. In fact, the plume from the southern site, located further upwind, is believed to have been detected on practically every pass ever made in the lowest 400 m above the Main Ridge, i.e., during 42 passes over 13 different days. 2) the AgI was largely confined to within ~450 m (1500 ft) of the Main Ridge crestline, which placed the plume top at about the 700 mb level. 3) Plume widths from the southern generator were usually in the 10–30° range over the Main Ridge, corresponding to a crosswind distance of 1.7–2.7 km. Limited observations over the Bangtail Ridge (see Part II) indicated further crosswind broadening of the AgI with widths between 4 and 5 km, but with little additional vertical ascent evident. Little data are available to calculate plume widths from the northern generator. 4) Measured ice nucleus concentrations above the Main Ridge typically ranged from 100 to 1000 per liter, effective at −20°C. The values represent the NCAR counter raw data increased by a factor of 10 to compensate for known instrument losses (Langer and Weickmann, 1971). This was estimated to correspond to 10 to 100 per liter at the warmer temperatures prevalent within 450 m of the crestline. (5) Estimates of ice nuclei flux over the Main Ridge were in very good agreement with generator output as calibrated at the CSU Cloud Simulation Laboratory.

It is also noteworthy that the AgI produced by the Montana State University generators appeared to retain its ice nucleating ability for periods from one to a few hours even in bright sunlight, as discussed by Super *et al.* (1975).

b. Pibal investigations

Further evidence of proper targeting of the AgI was gained by dual-theodolite tracking of pibals released from the seeding sites. As discussed more fully in Part I, pibals of known ascent rate were simultaneously tracked from the two seeding sites on many occasions. These data were used to estimate average vertical and horizontal wind speeds between the launch sites and Main Ridge. This was done for each pibal for which data existed within the zone from the crestline to 0.9 km west of it and withn 450 m above it. Correlation coefficients and linear regression equations were calculated between all pairs of vertical wind speed (VWS) and the component of the horizontal wind speed normal to the Main Ridge (HWS). These are given in Table 1. A correspondence between vertical motion and the horizontal cross-barrier flow is evident. A similar correspondence has been shown by Hill (1980a) for a north–south oriented barrier in Utah.

The ratio of change in ground elevation with horizontal distance between the seeding sites and Main Ridge is 0.09 and 0.28 for the southern and northern sites respectively. These are reasonably close to the slopes of their regression lines suggesting that, to a first approximation, the terrain slope determined the vertical air motion. The average VWS for the data of Table 1 was 0.6 m s^{-1} for the southern seeding site, located 4.7 km west of the Main Ridge and 1.6 m s^{-1} for the northern site, only 1.5 km west of it. Updrafts of this magnitude can be expected to produce abundant condensate from air saturated with respect to water.

The positions of the pibals were noted at 1 min intervals. Eighty and 90% of the resulting 1 min changes in balloon position indicated an updraft component between the southern and northern sites, respectively and the Main Ridge.

The pibals were also examined to determine how well the 10 000 ft wind represented the mean wind in the layer from the seeding sites to 10 000 ft, i.e., the layer in which the AgI was generally transported until beyond the Main Ridge. As discussed in Part II, it was found that the 3050 m (10 000 ft) wind direction was a very good predictor of the mean wind direction for this entire layer, with mean differences of less than 5°. With this in mind, it is instructive to consider the distribution of 700 mb (approximately 3050 m) wind directions. All 359 available rawins were considered and it was found that 80% of the cases were between 240 and 320°. Winds in this range should transport AgI toward the intended target area (see Fig. 1). Only 6% of the 700 mb wind observations had an easterly component.

TABLE 1. Correlation coefficients and regression equations for vertical wind speed (VWS) versus horizontal wind speed (HWS).

Launch site	Number of pairs	Correlation coefficient	Regression equation (m s^{-1})
Southern AgI generator	55	0.64	VWS = −0.25 + 0.10 HWS
Northern AgI generator	134	0.70	VWS = −0.47 + 0.39 HWS

In summary, the pibal data are quite consistent with the concept that the AgI was transported rapidly up the west slope of the Bridger Range, crossed the Main Ridge and moved toward the intended Bangtail Ridge target area. Further, they suggest that substantial liquid water should be produced by saturated air flowing up the west side of the Main Ridge in the probable region of the AgI plumes.

c. Silver concentrations in snow

Warburton and Young (1968) discussed a neutron activation procedure for analysis of the silver in precipitation. Snow samples from the Bridger Range were sent to Warburton who supervised their silver analysis. Samples collected prior to any known seeding on the Bridgers and near the Gallatin Range control gage during the BRE, revealed background silver concentrations that were approximately 1×10^{-11} g ml^{-1}. Seasonal samples were obtained from snowpits dug during March 1971 and 1972 at seven sites on the Bangtail Ridge as described in Part I. Values for these ranged from 3 to 10 times the average background value. These data and snowpack water equivalents were used to estimate the total amount of silver in the Bangtail Ridge snowpack above the 1800 m (6000 ft) elevation contour, an area of 218 km^2. The estimates suggest that, of the total silver emitted by both generators only during periods with snowfall occurring near the center of the Bangtail Ridge, about 70% and 40% of the silver was in the snowpack during March 1971 and 1972 respectively. Comparable figures for all hours of generator operations are 18 and 14%.

Increased silver in the snow is not proof that seeding altered the snowfall amount. Scavenging by natural snowfall or direct deposition could also explain increased silver concentration. However, failure to find increased silver would indicate that proper targeting was not being achieved. The increased silver concentrations found on the Bangtail Ridge lend further support to the evidence of proper targeting previously discussed.

5. Experimental design and operations

The BRE had been planned to commence on 1 November 1969, using radio-controlled generators at two remote sites on the west slope of the Bridger Range.

However, due to late delivery of the generators, and subsequent operational problems, it was decided by early December to commence seeding with manual generators from a single location. Limited resources did not permit manual operation of the planned second seeding site during the winter of 1969–70, and it was recognized that coverage by a single generator site might often be inadequate. Nevertheless, as all other equipment and personnel were operational, it was decided to proceed so that at least a complete operational "shakedown" of all equipment and procedures might be achieved.

Additional resources and improved technology made several significant advances possible prior to the 1970–71 winter. These were also carried through the 1971–72 winter season. By November 1970 both high elevation seeding sites were operational. Each was equipped with an improved AgI generator system compared with the commercial versions of the Colorado State University (CSU) modified Skyfire generator previously used. Another important change was that NH_4I was used to complex the AgI rather than NaI. This improved the ice nucleation in the laboratory at higher temperatures (Donnan *et al.,* 1970). Precipitation gages were installed at each seeding site. Also, while radiosonde observations were made during 1969–70, rawinsonde capability was added before the 1970–71 winter, providing information on local winds aloft. For these reasons, the 1970–71 and 1971–72 dataset is considered superior to and not totally compatible with the 1969–70 data. Therefore, except in Section 7f, only the 1970–71 and 1971–72 dataset is analyzed herein. This consists of 185 experimental days.

The BRE used the 24 h day beginning at local noon, a known minimum in Bridger Range winter precipitation, as the basic experimental unit. Experimental days were declared whenever a special forecast, issued each morning by the National Weather Service Office at Helena, Montana, indicated the probability of precipitation at the Bozeman Airport exceeded 20% during the 24 h beginning at noon. Forecasts were made for the airport located 17 km west of the Bridger Range rather than the Range itself because the forecasters routinely predicted the weather for this location, and had verification observations available from the Federal Aviation Administration office there. The forecasters were not aware of the consequences of their forecast on each day's activity for the BRE. The purpose of the forecast was to attempt to exclude days with little likelihood of precipitation from the experiment in order to give field personnel time off.

Before the AgI plume tracing and pibal investigations discussed in Super (1974) and Section 4 were completed, it was considered important to provide a buffer period between seeded and nonseeded days to reduce possible contamination by the AgI. During the winters of 1969–70 and 1970–71, a buffer period of at least 3 h was provided in the following manner. Cloud and snowfall observations, obtained prior to the BRE, indicated that snowfall was unlikely for at least 3 h following an observation of cloud base higher than 3000 m and cloud cover less than $^6/_{10}$. These cloud base and cover criteria were designated Potential Storm Conditions (PSC). It is noteworthy that the highest peak in the Bridger Range is just under 3000 m, providing a convenient visual reference for cloud base.

On each experimental day, whether or not seeding had taken place, PSC observations were made at 0900 (all times MST), 3 h prior to the end of the experimental unit. If PSC did not then exist, a new random decision was used for the next experimental day and if clouds had been seeded during the present day, AgI generators were immediately turned off. If PSC existed at 0900, another observation was made at 1200. If PSC still existed, the prior random decision was carried over to the new 24 h period starting at that time, which was considered an experimental day regardless of the NWS special forecast. If PSC existed at 0900 but not at 1200, a new random decision was made for the next experimental day, that is, the next day with a greater than 20% precipitation probability forecast. Thus, in this case, the next experimental day would start immediately at 1200 if, and only if, the forecast probability exceeded 20%. These procedures were identically applied for nonseeded and seeded experimental days.

Whatever the period of actual treatment, the sole response variable in the analysis herein was the 24 h noon-to-noon precipitation amount as measured by the gage network shown in Fig. 1.

Random decisions were obtained by the opening of sealed envelopes which had been prepared under the supervision of Dr. Paul Mielke of CSU, statistical consultant to the BRE. A simple block randomization scheme was used during the 1969–70 and 1970–71 winters in which no more than four seed or nonseed decisions were allowed to occur in sequence.

To summarize for the 1969–70 and 1970–71 winters, experimental units and the precipitation amount response variable were always for 24 h, beginning at local noon. The treatment period, however, was sometimes shorter if PSC didn't exist throughout the 24 h experimental unit. Individual random decisions were sometimes carried over to an additional day or even days if PSC continued to exist during the last 3 h (0900 and 1200 observations) of an experimental unit. This procedure was intended to minimize possible AgI contamination of nonseeded days following seeded days by providing a minimum 3 h buffer period without treatment between all experimental units based on a new random decision. Appendix A of Part I contains a complete listing of hours of AgI generator operation and the basis for each day's treatment decision, whether new random decision, or carry-over due to continued PSC.

By the final winter season (1971–72), plume tracing and airflow observations suggested there was little need for the buffer period. A random decision was then assigned to each calendar date prior to the start of the season by Dr. Paul Mielke of CSU. The randomization was restricted to no more than three seed or nonseed decisions in a row. With the exception that some blocks of days were set aside from the randomized experiment for special experiments at least 6 days in advance (see Part I), each experimental day was declared solely on the NWS special forecast. That is, each day forecast to have a greater than 20% probability of precipitation at the Bozeman Airport was an experimental day.

Rawinsonde launches were scheduled four times per experimental day, at 1500, 2100, 0300 and 0900. However, available resources required compromise with the ideal of 4 launches per day whatever the weather. Instead, rawinsondes were launched when PSC, as defined above, existed approximately 1 h before the scheduled release time.

A total of 364 usable rawinsonde observations were obtained during the two winters being considered. Most 6 h periods with snowfall in the intended target area have accompanying rawin data. To illustrate, let it be assumed that at least 3 of 12 gages in Zone 1 of Fig. 1 must register $\geqslant 0.02$ inches for a significant snowfall event to have occurred in a 6 h period centered on a potential rawin launch time. This should largely eliminate cases with apparent but questionable snowfall episodes. Such occurrences may be due to gage mechanism expansion/contraction, snow adhering to the inside orifice wall and finally falling off, etc. A total of 319 6 h periods met these criteria out of the total of 740 possible (185 × 4). Soundings exist for 253 (79%) of these 319 periods. Considering the entire experimental day, only 9 had a significant snowfall event as defined, but no rawinsonde observations. Thus, the procedures used were reasonably successful in providing upper air data for partitioning the experimental units.

6. Statistical techniques

Earlier analysis of the BRE, referenced in Section 1, suggested that type I errors existed in the data pool. In that analysis, the seeded and nonseeded precipitation accumulations at each individual gage were compared using the Wilcoxon rank-sum (Mann and Whitney, 1947) and the squared-rank-sum tests (Noether, 1967).

Mielke, *et al.* (1981a) applied a nonparametric inference technique in a reanalysis of Climax I and II. In their study, rank-ordered residuals from a linear least-squares line ($y = bx$) fitted to paired target-control observations, were input to two-sample rank-sum tests. This approach compensated for covariate data. However, Mielke *et al.* (1982), noted that the least-squares inference can place undue weight on the outlying data pairs and there is potential for distortion in the Wilcoxon rank-sum test due to its non-Euclidean geometry. They applied a new nonparametric inference technique to the Climax data to reduce distortions. Residuals were found using the median regression line and testing was through the multiresponse permutation procedures (MRPP).

In the analysis herein both the well-known Wilcoxon rank-sum and the MRPP are used to test for differences in the rank-ordered target residuals determined from the median regression line. Following Mielke *et al.* (1982), the median regression line is forced through the origin to minimize the impact of "busted" forecasts and the number of cases when either the target or control, but not both, had zero precipitation. The seeded and nonseeded target control pairs were pooled to define the median line. Only those pairs meeting partition criteria were applied. Although the possibility of distortion apparently exists for the Wilcoxon test (Mielke *et al.*, 1982), it is kept in this analysis because it is particularly well-known. The MRPP is a new approach which has yet to stand the test of time; however, since it is able to perform multiresponse analyses efficiently, its utilization will likely increase with time.

A complete description of MRPP and efficient computation techniques is given by Mielke *et al.* (1976) and an easily understood example is presented by Mielke *et al.* (1981b). For this study, there is only one response variable which is the residual from the median line. The statistic δ is found using the differences between the residuals to the unit power; i.e., Euclidean distance ($k = 1$ of Mielke *et al.*, 1976) is inferred. There are two groups, of sizes n_s and n_n, corresponding to seeded and nonseeded samples. The effect of outlying residuals is minimized by substituting a score function for the residuals in MRPP. The Ith score function s_I, is derived from the tie-adjusted ranks of the residuals

$$s_I = \text{rank}_I - (n_s + n_n + 1)/2. \tag{1}$$

This was applied by Mielke *et al.*, (1981a) and Mielke *et al.* (1982).

A generalized Fortran program to apply MRPP was provided by P. Mielke and adapted to a Perkin-Elmer 3220 computer. Running this test required that large amounts of data be input and output to a temporary disc file. The resulting long run-times forced the use of the Wilcoxon as a screening test for preliminary analysis.

In this analysis partitions yielding less than $n_s + n_n = 20$ samples were not considered because the null distributions of the test statistic may not be adequately approximated by a standardized variable. For example, Mann and Whitney (1947) suggested that about eight samples for each of two random variables are required in the Wilcoxon rank-sum test for the ranks of observations to be approximately normal.

It is of obvious interest to consider the magnitude of the precipitation differences between the seeded and nonseeded cases. Toward this end, estimates were calculated using the "mean double ratio" defined by $(T_s/T_{ns})/C_s/C_{ns})$ where T and C refer to target and control mean precipitation amounts and s and ns refer to seeded and nonseeded experimental units. However, as pointed out by Mielke *et al.* (1981a), double ratios can be dominated by a few large precipitation events. This depends upon the distribution of precipitation amounts yielded by a particular partition. But, in general, the lower the association between the target and control and the smaller the subpopulation being examined, the more unstable the double ratios tend to become. Hence, they should be interpreted with care, especially for small populations and for Zones 2 and 3 which have a lesser association with the control gages than Zone 1, as will be shown.

In an attempt to reduce the impact of a few large storms on the mean double ratio, a second double ratio was calculated, as suggested by a reviewer, by substituting median target and control precipitation amounts for mean amounts. This "median double ratio" has a shortcoming in that it can become unstable with subpopulations containing a relatively high frequency of zero precipitation amounts. It becomes indeterminate if more than half the cases have zero precipitation. This problem is again greatest in Zones 2 and 3, particularly in the latter. These zones are in the lee of the Bridger Range and sometimes have zero precipitation during days with significant snowfall amounts in Zone 1.

Both the mean and median double ratios will be presented with the caveats noted above. It is not known which is most appropriate in any particular partition. This would presume knowledge about whether seeding effects (if any) are proportionally greater for large or small storms, as well as whether seeding causes precipitation during naturally non-precipitating periods. The double ratios do provide an indication of the magnitude of any seeding effect—a matter of obvious interest.

7. Results of partitioning experimental units

Except where noted, precipitation data were grouped into three zones for all statistical testing. This was done by the simple expedient of averaging data from all gages less than 20 km, from 20 to 30 km, and beyond 30 km from the midpoint between the two generator sites (see Fig. 1). This resulted in 12 gages on or near the intended Bangtail Ridge target area designated as Zone 1. Nine gages were in Zone 2, the lee slope of the Bangtail Ridge and seven gages were in Zone 3, more than 30 km downwind of the generators.

a. Partitioning by Main Ridge temperature

Since the AgI generator calibration illustrated in Fig. 2 shows a marked temperature dependence in effective ice nuclei, it is reasonable to partition experimental days by plume temperature. The AgI plume measurements of Super (1974), together with the generator calibration of Fig. 2, indicate that the artificial ice nuclei concentrations would not exceed more than a few per liter until plume temperatures decreased below about −8°C.

The evidence from airborne tracing of AgI plumes indicated that the seeding material was usually in the lowest 400–500 m above the Main Ridge. Thus, the temperature measured by thermograph on the Main Ridge crest is a convenient estimate of plume temperature. For typical in-cloud lapse rates, the plume top should have been no more than 3°C below the Main Ridge temperature (hereafter called Ridge temperature), assuming the plume ascended less than 500 m above the Main Ridge. The average of the 24 hourly Ridge temperature measurements was used to partition each experimental unit.

In order to search for possible seeding effects in a consistent manner, the following scheme was applied to the population of Ridge temperatures and to all other parameters used to partition the experimental days into subpopulations. This approach avoided some of the multiplicity involved in continued searching for those particular ranges that yield the lowest probabilities. The entire available population of experimental days was subdivided, as closely as possible, into halves, thirds and quarters. These fractions of the whole population, as well as the entire population, were then subjected to the statistical tests discussed in Section 6. The resulting one-tailed probabilities for Ridge temperatures are shown in Table 2. It can be seen that values for both statistical tests suggest that the colder portion of the total population had significant differences between seeded and nonseeded subpopulations. No significant differences are evident for the warmer half of the total population.

The colder portion of the population was examined further, by testing the subpopulations indicated in Table 3 using 2°C intervals. Mean and median double ratios are also shown. It is seen that except for the coldest and warmest subpopulations shown, probabilities are 0.01–0.02 by both tests for Zone 1, the intended target. The highest mean and median double ratios are 1.90 and 2.35, respectively, both for temperatures of −13°C and colder, which suggests an approximate doubling of the precipitation in that partition. Low probability values are also seen in the other two zones for temperatures lower than about −11°C. The highest mean double ratios in Zones 2 and 3 exceed 2.0 and are for those cases $\leqslant$ 13°C. The median double ratios are much larger than the mean double ratios in Zone 3, especially for the colder cases. This was due to very low median values for nonseeded days in Zone 3. For example, for the 27 nonseeded days with Ridge temperatures $\leqslant -13°$, the median precipitation

TABLE 2. Ridge temperature partitions: fractions of all days. Wilcoxon (W) and MRPP one-tailed probabilities are for 3 zones of Fig. 1.

Range (°C)	Experimental days		Zone 1		Zone 2		Zone 3	
	All	s[1]/ns[2]	W	MRPP	W	MRPP	W	MRPP
−26.0/+5.0	185	90/95	0.17	0.22	0.35	0.36	0.12	0.12
−9.4/+5.0	93	48/45	0.31	0.36	0.22	0.30	0.50	0.50
−26.0/−9.5	92	45/50	0.01	0.01	0.09	0.11	0.07	0.05
−7.3/+5.0	62	29/33	0.33	0.34	0.42	0.50	0.45	0.50
−11.5/−7.4	61	32/29	0.30	0.41	0.10	0.11	0.34	0.21
−26.0/−11.6	62	29/33	0.02	0.02	0.02	0.02	0.03	0.02
−6.0/+5.0	47	22/25	0.33	0.36	0.33	0.30	0.26	0.24
−9.4/−6.1	46	26/20	0.35	0.25	0.08	0.12	0.22	0.24
−13.3/−9.5	47	24/23	0.11	0.15	0.24	0.31	0.11	0.14
−26.0/−13.4	45	18/27	0.01	0.01	0.01	0.02	0.01	0.01

[1] seeded.
[2] nonseeded.

amount in Zone 3 was only 0.15 mm as compared with 0.40 mm for the 22 seeded days. Obviously, precipitation amounts were often limited in this zone for both seeded and nonseeded days. Interestingly, only two seeded and four nonseeded days had zero precipitation at all gages for the partition. Thus, snowfall usually occurred on these experimental days, but it was very light at these gages, which were generally located in a dry valley to the lee of the Bridger Range (see Fig. 1).

A number of partitions were examined with the highest temperature set at −9°C but with the lowest temperature limit varied. These showed no improvement over inclusion of all the cases colder than −9°C. This suggests that the apparent seeding effect was maintained for the coldest portion of the available cases; however, the range in question is not large. Of the 100 days with mean Ridge temperature ≤ −9°C, 82 were in the range of −16 to −9°C. It is noteworthy that this contains the dendritic ice crystal range around −15°C where growth rates are maximum. It should also be noted that few cases with temperatures colder than −20°C existed so these data are not appropriate for testing the cold side of Grant and Elliott's (1974) conceptual cloud seeding temperature window, which should be applied to AgI plume top rather than cloud top in the particular situation of the Bridger Range.

The total population of 185 days in Table 2 was further divided by consideration of data from each of the two winters separately. It was reasoned that increased credibility could be given to the results if they were similar for each winter. This is a demanding test, since the population size is approximately halved.

Table 4, Part A for the 1970–71 winter indicates probabilities of 0.06 or less in all 3 zones by both statistical tests for temperatures ≤ −11°C. Part B of Table 4 shows the results for the winter of 1971–72. Probabilities of 0.05 or less were achieved by both tests in Zone 1 for the 24 days with temperatures colder than or equal to −13°C. Probability values for Zone 2 are 0.05 and 0.08 for the Wilcoxon and MRPP, respectively with higher values in Zone 3. While these

TABLE 3. Ridge temperature partitions: colder days by 2°C increments. Probabilities and double ratios are for 3 zones of Fig. 1.

Range (°C)	Experimental days		Zone 1				Zone 2				Zone 3			
			Probability		Double ratio		Probability		Double ratio		Probability		Double ratio	
	All	s/ns	W*	MRPP	Mean/Median		W	MRPP	Mean/Median		W	MRPP	Mean/median	
≤ −7.0	131	65/66	0.04	0.04	1.35	1.37	0.33	0.25	1.11	1.08	0.20	0.13	1.17	2.15
≤ −9.0	100	44/56	0.01	0.01	1.56	1.29	0.13	0.14	1.38	1.46	0.09	0.08	1.43	3.35
≤ −11.0	68	31/37	0.01	0.02	1.69	2.02	0.06	0.08	1.78	2.01	0.02	0.02	1.90	5.45
≤ −13.0	49	22/27	0.01	0.01	1.90	2.35	0.01	0.01	2.93	3.40	0.005	0.004	3.24	5.96
≤ −15.0	26	10/16	0.30	0.15	1.06	1.18	0.05	0.09	2.02	2.81	0.02	0.02	2.08	7.86

* Wilcoxon.

TABLE 4. Ridge temperature partitions: Wilcoxon (W) and MRPP probabilities for each winter tested separately.

Range (°C)	Experimental days		Zone 1		Zone 2		Zone 3	
	All	s/ns	W	MRPP	W	MRPP	W	MRPP
Part A					1970–71 data			
≤ −7.0	61	27/34	0.10	0.05	0.47	0.46	0.20	0.09
≤ −9.0	46	18/28	0.06	0.05	0.31	0.46	0.16	0.12
≤ −11.0	30	12/18	0.03	0.02	0.05	0.06	0.004	0.003
≤ −13.0	25	9/16	0.04	0.04	0.03	0.05	0.004	0.003
Part B					1971–72 data			
≤ −7.0	70	38/32	0.21	0.29	0.33	0.46	0.35	0.40
≤ −9.0	54	26/28	0.07	0.12	0.17	0.28	0.20	0.26
≤ −11.0	38	19/19	0.08	0.11	0.28	0.34	0.24	0.34
≤ −13.0	24	13/11	0.04	0.05	0.05	0.08	0.16	0.22

probability values are not as low as those of the former winter, the important point is that similar results were achieved in each of two separate winters.

The 100 days with mean Ridge temperatures of −9°C and below yielded low probability values in Zone 1, the intended target, while the partition of −13°C and below yielded low values by both tests in all three zones. These two subpopulations have consequently been chosen for more detailed illustration of results. Table 5 shows various statistics for the seeded and nonseeded populations for the three zones.

It can be seen that correlation coefficients are highest between the control gages and those of Zone 1, ranging from 0.75–0.85. Precipitation amounts are highest, and days with zero precipitation least frequent, at the control and Zone 1 gages—as would be expected with higher elevation sites. The frequency of precipitation, mean and median precipitation amounts and correlation coefficients generally decrease with the lower elevation sites further downwind in Zones 2 and 3. Therefore, the results there should be interpreted with more caution.

The mean and median precipitation amounts at the control gages are seen to be less for the seeded days than for the nonseeded. This difference is in the direction of the type I statistical error suggested in previous analysis of the BRE as discussed in Section 1. In contrast, mean and median precipitation amounts are similar for seeded and nonseeded days in Zone 1.

It is interesting to examine the spatial variation of the differences associated with seeding. This has been done by calculation of the Wilcoxon probability and mean double ratio for each gage and plotting of the results in Fig. 3. It should be expected that calculation of these statistics for individual gages will yield more "noise" in the results than use of the mean of all gages in a zone as done previously. Local topography and forest cover would be expected to increase the variance in single site measurements.

Figure 3 shows the spatial pattern for the 100 days with Ridge temperatures ≤ −9.0°C. It indicates that the lowest probability values and highest double ratios tend to be in the northern portion of Zone 1, the intended target. However, three additional gages have probabilities less than 0.05 along the southern edge of Zones 1 and 2 and one gage has a value of 0.05 far downwind in the foothills of the next mountain range. The highest probabilities and lowest double ratios tend to be in the central and northern portions of Zones 2 and 3, or east of the low probability gages in the northern portion of Zone 1. Thus, there does seem to be a general pattern in probability values with either high or low numbers usually grouped together. It would be disquieting to observe alternating high and low values in close proximity in a random fashion.

The AgI plume tracing results and generator calibrations previously cited suggest that mean ice particle concentrations should have ranged from about ten to several hundred per liter in the AgI plumes for the partitions ≤ −9°C. Concentrations at warmer temperatures would be expected to be much lower. This offers a plausible physical explanation for the statistical suggestions.

b. *Partitioning by 700 mb temperature*

As discussed in Section 4, the 700 mb temperature (hereafter noted by T_{700}) is believed to approximate the AgI plume-top temperature above the Main Ridge. The mean height of the 700 mb surface was 2950 m, so T_{700} was closely associated with the Main Ridge temperature measured at 2595 m. The reasoning for using T_{700} in addition to Ridge temperature to partition the experimental days is as follows. The Ridge temperatures are averages for the entire 24 h day. They indicate nothing regarding the presence of clouds suitable for snowfall formation. Often, however, storms lasted for only some fraction of the day. Therefore,

TABLE 5. Summary of statistics for two Ridge temperature partitions for seeded (s) and non-seeded (ns) cases.

Temperature ≤ −9°C	44 s 56 ns	Control (3 gages)	Zone 1 (12 gages)	Zone 2 (9 gages)	Zone 3 (7 gages)
Target–control correlation coefficients	All		0.75	0.66	0.66
	s		0.78	0.60	0.57
	ns		0.81	0.73	0.75
Mean precipitation (mm)	s	2.14	3.21	1.51	1.31
	ns	3.01	2.90	1.54	1.28
Median precipitation (mm)	s	1.27	1.98	0.65	0.49
	ns	1.73	2.10	0.61	0.20
Days with zero precipitation at all gages	s	6	2	9	7
	ns	6	3	11	10
One-tailed probabilities	Wilcoxon		0.008	0.13	0.09
	MRPP		0.01	0.14	0.08
Double ratio	Mean		1.56	1.38	1.43
	Median		1.29	1.46	3.35

Temperature ≤ −13°C	22 s 27 ns	Control (3 gages)	Zone 1 (12 gages)	Zone 2 (9 gages)	Zone 3 (7 gages)
Target–control correlation coefficients	All		0.77	0.53	0.42
	s		0.85	0.58	0.52
	ns		0.78	0.67	0.54
Mean precipitation (mm)	s	1.37	2.29	1.35	1.21
	ns	2.81	2.46	0.94	0.76
Median precipitation (mm)	s	0.51	1.86	0.62	0.40
	ns	1.10	1.71	0.40	0.15
Days with zero precipitation at all gages	s	3	0	4	2
	ns	4	0	5	4
One-tailed probabilities	Wilcoxon		0.009	0.008	0.005
	MRPP		0.007	0.01	0.004
Double ratio	Mean		1.90	2.93	3.24
	Median		2.35	3.40	5.96

inclusion of temperature observations for times without suitable clouds may dilute any "signal" in the data.

As discussed in Section 5, rawinsondes were launched only when potential storm conditions existed. Therefore, the use of T_{700} might be expected to "sharpen" the temperature partition. The average T_{700} from all available rawins for each experimental day was used to partition the day. Again the entire population was first subdivided into halves, thirds and quarters and these were subjected to the Wilcoxon and MRPP tests with the results given in Table 6.

Table 6 shows the coldest half, third and quarter of all days to have low probability values in Zone 1. Low values are also shown for the two colder quarters of the cases in Zone 2 and the second coldest in Zone 3. However, unlike all other low probability values shown in this table, the quarter with 39 cases between −13.8 and −10.5°C yielded mean and median double ratios below unity, both in Zone 2 and Zone 3. These double ratios ranged from 0.32 to 0.68 suggesting decreased snowfall on seeded days. The temperature range is low enough so that artificial ice nuclei concentrations should have been significant. It may be that snowfall which naturally would have fallen on Zones 2 and 3 was redistributed onto Zone 1 for this temperature range. This could have resulted if increased ice particle concentrations caused by seeding resulted in more aggregation and, thereby, increased snowflake fall velocities as found by Holroyd and Jiusto (1971).

The colder cases were tested at 2°C intervals in Table 7. Probabilities of 0.05 or less are seen for both tests in Zone 1 for all but the warmest partition shown. Both double ratios for Zone 1 are largest for T_{700} of ≤ -13°C. Probabilities less than 0.10 appear in Zones 2 and 3 only for T_{700} of ≤ -15°C.

The results of partitioning by T_{700} are similar to those obtained with Ridge temperature. This is probably because Ridge temperature did not usually change markedly over the course of the day. This resulted in a correlation coefficient of 0.90 between 24 h mean

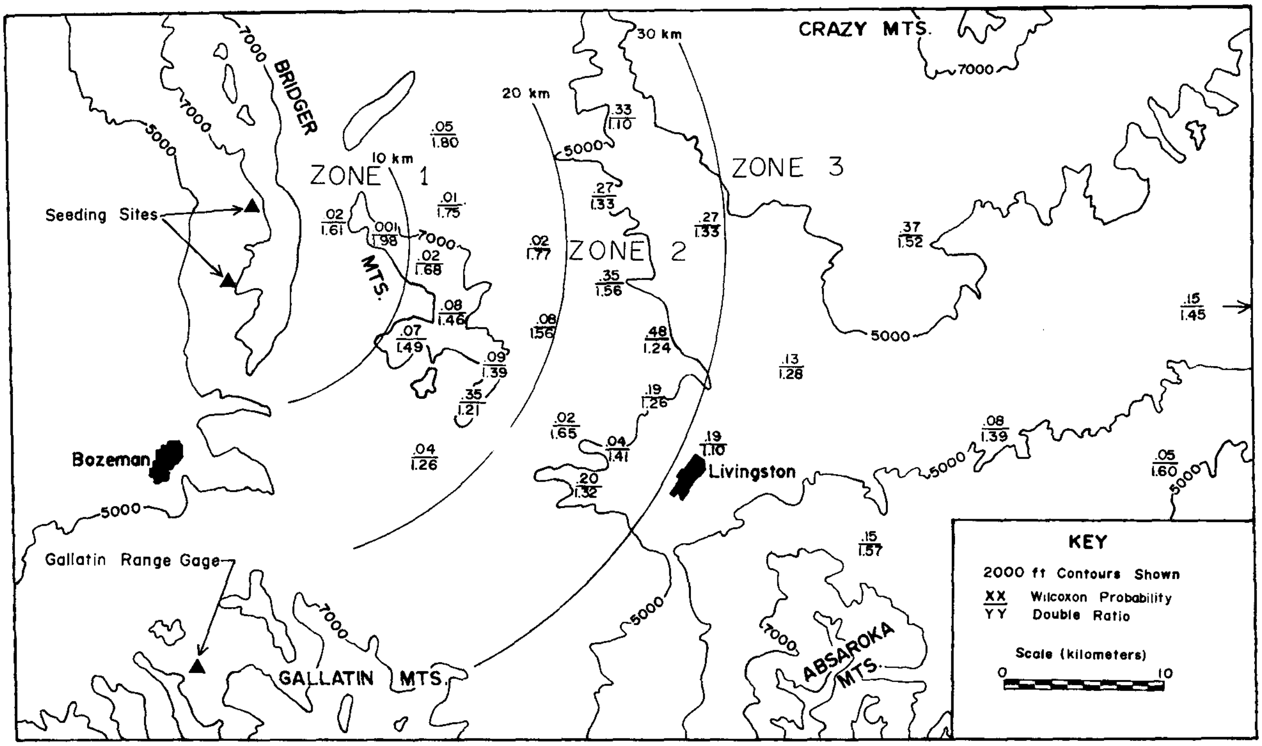

FIG. 3. Map of Wilcoxon probabilities and mean double ratios for 100 days with Ridge temperatures ≤ −9.0°C.

Ridge temperature and the daily mean of all available T_{700} observations. The mean of Ridge temperature and T_{700} were −12.2 and −13.4°C, respectively for the days with $T_{700} \leq -9°C$. This also helps explain the similarity in the results. One notable difference between the Ridge temperature and T_{700} partitions is that the latter sugggested decreased snowfall associated with seeding downwind of the intended target for temperatures between −10.5 and −13.8°C.

c. Partitioning by cloud-top temperature

It is of interest to partition the BRE precipitation data by cloud-top temperature because of the importance given this parameter in past analyses of cloud seeding experiments. For example, Grant and Elliott (1974) presented the concept of a cloud seeding temperature "window", based on a number of experiments. They argue that a cloud-top temperature window exists

TABLE 6. 700 mb temperature partitions: fractions of all days. Wilcoxon (W) and MRPP one-tailed probabilities are for 3 zones of Fig. 1.

Range (°C)	Experimental days		Zone 1		Zone 2		Zone 3	
	All	s/ns	W	MRPP	W	MRPP	W	MRPP
−26.0/+1.0	154	75/79	0.12	0.13	0.34	0.36	0.17	0.18
−10.4/+1.0	77	36/41	0.48	0.50	0.48	0.50	0.21	0.27
−26.0/−10.5	77	39/38	0.05	0.05	0.40	0.37	0.39	0.35
−9.0/+1.0	51	24/27	0.29	0.36	0.26	0.32	0.47	0.39
−12.8/−9.1	51	28/23	0.40	0.40	0.47	0.50	0.34	0.43
−26.0/−12.9	52	23/29	0.01	0.01	0.14	0.14	0.20	0.20
−7.9/+1.0	38	17/21	0.49	0.38	0.38	0.50	0.39	0.32
−10.4/−8.0	39	19/20	0.47	0.41	0.46	0.50	0.16	0.16
−13.8/−10.5	39	23/16	0.43	0.37	0.03	0.04	0.04	0.05
−26.0/−13.9	38	16/22	0.02	0.03	0.04	0.07	0.12	0.17

TABLE 7. 700 mb temperature partitions: colder days by 2° increments. Probabilities and double ratios are for 3 zones of Fig. 1.

Range (°C)	Experimental days		Zone 1			Zone 2			Zone 3		
			Probability		Double ratio	Probability		Double ratio	Probability		Double ratio
	All	s/ns*	W	MRPP	Mean/Median	W	MRPP	Mean/Median	W	MRPP	Mean/Median
⩽ −7.0	127	62/65	0.14	0.09	1.17/1.35	0.33	0.24	1.03/1.55	0.26	0.21	1.09/3.89
⩽ −9.0	104	52/52	0.02	0.02	1.37/1.00	0.24	0.24	1.14/1.12	0.17	0.15	1.23/2.94
⩽ −11.0	70	35/35	0.02	0.02	1.52/1.30	0.22	0.20	1.29/1.29	0.36	0.34	1.17/1.47
⩽ −13.0	50	22/28	0.02	0.02	1.74/1.76	0.10	0.13	1.77/2.07	0.12	0.11	1.57/2.06
⩽ −15.0	26	11/15	0.03	0.03	1.72/1.12	0.01	0.02	3.81/1.73	0.06	0.09	3.41/3.00

* s—seeded/ns—nonseeded.

from about −10°C to about −24°C within which seeding can lead to increased precipitation. Grant and Elliott appear to agree that for the particular circumstances of the BRE, temperatures near mountaintop levels should define seeding effectiveness better than cloud-top temperature. However, they suggest that the latter should be crucial in establishing the requirement for seeding.

Cloud top estimates are known to be crude when based on radiosonde units manufactured prior to development of a new humidity duct introduced into general use in about 1972 (Hill, 1980b). Montana State University researchers were aware of the humidity problems and obtained the new ducts for retrofitting to their store of radiosondes as soon as they became available. Records of the first use of the new duct no longer exist, but examination of temperature–dewpoint differences suggests it was near the beginning of the final winter season. This implies that cloud tops for 1970–71 were largely estimated from less reliable humidity data than the 1971–72 cloud tops.

The method used to estimate cloud top temperature from radiosonde data in the BRE is discussed in detail in Part II. Basically, the temperature–dewpoint difference was used and the difference was linearly increased with decreasing pressure such that a 3°C difference was used at 700 mb, a 4°C difference at 600 mb and 5°C difference at 500 mb, etc. The manner of handling such problems of multi-layered clouds is also discussed in Part II. While no claim is made for the accuracy of the cloud-top estimates due to lack of independent supporting data, all estimates were calculated in an objective and consistent fashion.

All available sounding data were averaged to estimate the mean cloud-top temperature for each 24 h experimental unit. The median value of the entire population of 149 days was −25.5°C, and 80% of all values were between −24.0 and −55.0°C. The whole population, and halves, thirds and quarters of the population, were subjected to the Wilcoxon test for each of the three zones of Fig. 1. None of the resulting 30 probabilities was <0.05. This suggests that cloud-top temperature,

TABLE 8. Cloud-top temperature partitions for fractions of all days with Ridge temperature ⩽ −9.0°C: Wilcoxon (W) and MRPP one-tailed probabilities are for the 3 zones of Fig. 1.

Range (°C)	Experimental days		Zone 1		Zone 2		Zone 3	
	All	s/ns*	W	MRPP	W	MRPP	W	MRPP
−55.0/−8.0	84	39/45	0.02	0.03	0.19	0.18	0.17	0.15
−29.5/−8.0	42	19/23	0.17	0.27	0.40	0.13	0.33	0.28
−55.0/−29.6	42	20/22	0.04	0.04	0.04	0.06	0.13	0.21
−25.5/−8.0	27	11/16	0.20	0.27	0.24	0.18	0.29	0.17
−34.5/−25.6	28	16/12	0.05	0.07	0.14	0.15	0.40	0.32
−55.0/−34.6	29	12/17	0.19	0.24	0.10	0.13	0.40	0.49
−22.7/−8.0	21	9/12	0.26	0.33	0.21	0.23	0.35	0.29
−29.5/−22.8	21	10/11	0.34	0.46	0.32	0.14	0.46	0.50
−37.9/−29.6	21	10/11	0.01	0.01	0.06	0.08	0.12	0.17
−55.0/−38.0	21	10/11	0.34	0.31	0.15	0.19	0.18	0.29

* s—seeded/ns—nonseeded.

as estimated from the radiosonde data available, had little if any association with suggested seeding effects.

An attempt was made to test Grant and Elliott's (1974) suggestion that cloud top temperature should be important in establishing the requirement for seeding in the BRE. Dual partitions were used such that only days with mean Ridge temperatures ≤ −9.0°C were included and further partitioning was by cloud top temperature. The results of partitioning this population into halves, thirds and quarters are shown in Table 8.

It can be seen that the lower half of the cloud top temperatures yielded relatively low probability values in Zones 1 and 2, while the warmer cases did not. The cases contributing to the low values appear to be concentrated from approximately −38 to −28°C. The mean double ratios associated with those probability values ≤0.05 ranged from 1.54 for all 84 cases in Zone 1 to 2.41 for the second coldest quarter in Zone 1. This does not support the notion that cold cloud tops, with presumed naturally high ice crystal concentrations, reduces or eliminates seeding potential near Bridger Range mountaintop levels.

It is worth recalling that the Bridger Range rises abruptly and is a rather narrow barrier (see Fig. 1). Ice crystals formed high above the surface would be expected to have greater influence on broad barriers where the crystals would more frequently have sufficient time for settling to the surface before being transported beyond the barrier.

d. Partitioning by 500 mb temperature

The temperature at 500 mb has been used to partition a number of winter orographic cloud seeding projects, often with the assumption that it is an approximation or index of cloud top temperature. The Climax experiments are a notable example of apparently successful partitioning by the 500 mb temperature (Mielke *et al.*, 1981a and Mielke *et al.*, 1982). The BRE was also partitioned by this parameter because of its widespread usage.

Once again, all available local sounding data were averaged to estimate the daily 500 mb temperature. The median value for the entire population of 152 days was −26°C, and 80% of all daily means were between −19.5 and −34.5°C. The Wilcoxon test was applied to the entire population, and halves, thirds and quarters of it, for the three zones of Fig. 1. Only one of the resulting 30 probability values was ≤0.05, which could be expected by chance. Therefore, partitioning the BRE data by 500 mb temperature alone did not suggest any changes in snowfall associated with seeding.

e. Partitioning by 700 mb wind speed

The component of the horizontal wind speed perpendicular to the Bridger Range might be expected to be quite important to the precipitation process, both for natural and seeded storms. Hill (1980a) argues that the cross-barrier flux of supercooled water is approximately proportional to the square of the cross-barrier wind speed. Further evidence to support this concept is given by Hill (1982). In addition, the amount of time available for ice particle growth and fallout at any downwind distance is largely dependent upon the cross-barrier wind speed.

The eastward component of the 700 mb wind speed was chosen to approximate the cross-barrier wind speed. This quantity was calculated for each available rawinsonde observation and the average of all available observations was used to partition each 24 h experimental unit.

The entire population of 148 experimental days with a measured positive eastward component of 700 mb wind speed was subdivided into halves, thirds and quarters. These and the whole population were tested by the Wilcoxon test for Zones 1, 2 and 3 of Fig. 1. Of the resulting 30 values of Wilcoxon probability, only one was ≤0.05. This is about what one would expect by chance indicating that normal wind speed alone was not strongly associated with suggested seeding effects. This should probably not be a surprising

TABLE 9. Ridge temperature partitions for colder days using the single Gallatin Range gage for control. Probabilities and double ratios (D.R.) are for 3 zones of Fig. 1.

Range (°C)	Experimental days		Zone 1			Zone 2			Zone 3		
	All	s/ns*	W**	MRPP	D.R.	W	MRPP	D.R.	W	MRPP	D.R.
≤ −7.0	131	65/66	0.08	0.09	1.34/2.67	0.20	0.10	1.11/2.10	0.28	0.26	1.16/4.20
≤ −9.0	100	44/56	0.06	0.09	1/51/1/65	0.11	0.10	1.33/1.87	0.11	0.11	1.39/4.30
≤ −11.0	68	31/37	0.08	0.08	1.34/1.66	0.25	0.34	1.42/1.66	0.11	0.16	1.52/4.50
≤ −13.0	49	22/27	0.05	0.03	1.50/3.62	0.02	0.02	2.31/5.24	0.04	0.05	2.55/9.17
≤ −15.0	26	10/16	0.30	0.25	0.95/0.86	0.11	0.17	1.82/2.04	0.05	0.06	1.87/5.71

* s—seeded/ns—nonseeded.

** Wilcoxon.

result in view of the marked temperature dependence of suggested seeding effects previously shown.

f. Further consideration of the Main Ridge temperature partitions

As noted in Section 3a, one of the three precipitation gages used as a control was located 28 km south of the southern seeding site in the Gallatin Mountain Range as shown in Fig. 1. This gage was always intended to serve as a control as stated in reports to the sponsoring agency at the beginning of the BRE. The type of analysis envisioned was the target-control using a gamma distribution and a parametric statistical test. As briefly described in Part II, such an analysis was attempted but yielded no apparent effects of seeding, possibly due to the relatively low variance in target area precipitation explained by the single control gage.

Some might object to use of the other two control gages located at the seeding sites because they were not specified as controls prior to the BRE and/or because of danger of contamination by seeding. The latter is believed improbable in view of the results presented in Section 4. At any rate, it was decided to repeat the analysis of the lower Ridge temperature partitions using only the Gallatin Range gage as control. Results are shown in Tables 9 and 10 which have the same formats as Tables 3 and 5 respectively.

Comparison of Tables 5 and 10 shows that the single Gallatin Range gage is less highly correlated with Zone 1 gages than is the mean of all 3 control gages. However, the difference is not great. For the downwind zones, the single control gage has practically the same correlation coefficients as the mean of three gages. While the probability values in Table 9 are not as low as those of Table 3, they still suggest a seeding effect for the colder cases in all 3 zones.

It will be recalled from the discussion in Section 5

TABLE 10. Summary of statistics for two Ridge temperature partitions using the single Gallatin Range gage for control.

Temperature ⩽ −9°C	44 s* 56 ns**	Control (1 gage)	Zone 1 (12 gages)	Zone 2 (9 gages)	Zone 3 (7 gages)
Target–control correlation coefficients	All		0.67	0.67	0.71
	s		0.65	0.60	0.63
	ns		0.74	0.74	0.80
Mean precipitation (mm)	s	2.30	3.21	1.51	1.31
	ns	3.13	2.90	1.54	1.28
Median precipitation (mm)	s	1.02	1.98	0.65	0.49
	ns	1.78	2.10	0.61	0.20
Days with zero precipitation at all gages	s	16	2	9	7
	ns	10	3	11	10
One-tailed probabilities	Wilcoxon		0.06	0.11	0.11
	MRPP		0.09	0.10	0.11
Double ratio	Mean		1.51	1.33	1.39
	Median		1.65	1.87	4.30
Temperature ⩽ −13°C	**22 s* 27 ns****	**Control (1 gage)**	**Zone 1 (12 gages)**	**Zone 2 (9 gages)**	**Zone 3 (7 gages)**
Target–control correlation coefficients	All		0.67	0.46	0.40
	s		0.66	0.40	0.42
	ns		0.68	0.61	0.50
Mean precipitation (mm)	s	1.58	2.29	1.35	1.21
	ns	2.55	2.46	0.94	0.76
Median precipitation (mm)	s	0.38	1.86	0.62	0.40
	ns	1.27	1.71	0.40	0.15
Days with zero precipitation at all gages	s	8	0	4	2
	ns	7	0	5	4
One-tailed probabilities	Wilcoxon		0.05	0.02	0.04
	MRPP		0.03	0.02	0.05
Double ratio	Mean		1.50	2.31	2.55
	Median		3.62	5.24	9.17

* seeded.
** nonseeded.

TABLE 11. Ridge temperature partitions for colder days during the 1969–70 winter using the single Gallatin Range gage for control. Probabilities and double ratios are for 3 zones of Fig. 1.

Range (°C)	Experimental days		Zone 1			Zone 2			Zone 3		
	All	s/ns*	W**	MRPP	D.R.	W	MRPP	D.R.	W	MRPP	D.R.
≤ −7.0	47	27/20	0.04	0.04	2.06/2.37	0.30	0.35	2.44/3.25	0.32	0.28	1.43/2.03
≤ −9.0	41	24/17	0.08	0.10	1.93/2.25	0.16	0.26	3.17/4.50	0.34	0.33	1.37/2.50
≤ −11.0	29	16/13	0.07	0.09	2.01/3.56	0.41	0.29	2.08/6.75	0.42	0.28	1.46/0.00

* s—seeded/ns—nonseeded.
** Wilcoxon.

that only the southern seeding site was operated during the winter of 1969–70, prior to the 1970–71 and 1971–72 seasons analyzed thus far. That winter's data set is not totally compatible with the two latter winters for other reasons as well; namely, the Gallatin Range gage was the only available control, somewhat different seeding generators were used, and AgI was complexed with NaI in 1969–70 rather than with NH_4I as used later. However, with the realization that the Gallatin Range gage appeared to be a suitable control by itself, it was decided to apply the previous analysis procedures to the 1969–70 winter's data. It should be noted that one less gage was operated during the 1969–70 winter in Zone 1 and also in Zone 3, reducing the number of gages in the respective zones to 11 and 6.

Table 11 shows the resulting probabilities and double ratios for the colder cases during 1969–70. It is seen that relatively low probability values occur in Zone 1, again suggesting a seeding effect in the intended target area. Low probabilities did not occur farther downwind. However, reference to Tables 4 and 11 shows that individual analysis of each of the three separate winters of the BRE sugggested increased target area precipitation associated with seeding when Ridge temperatures were ≤ −9°C.

It is interesting to examine the 1969–70 spatial distribution of probabilities across the three zones of Fig. 1, particularly since only one seeding site was used. This was done by calculation of the Wilcoxon probability and mean double ratio for each gage in the

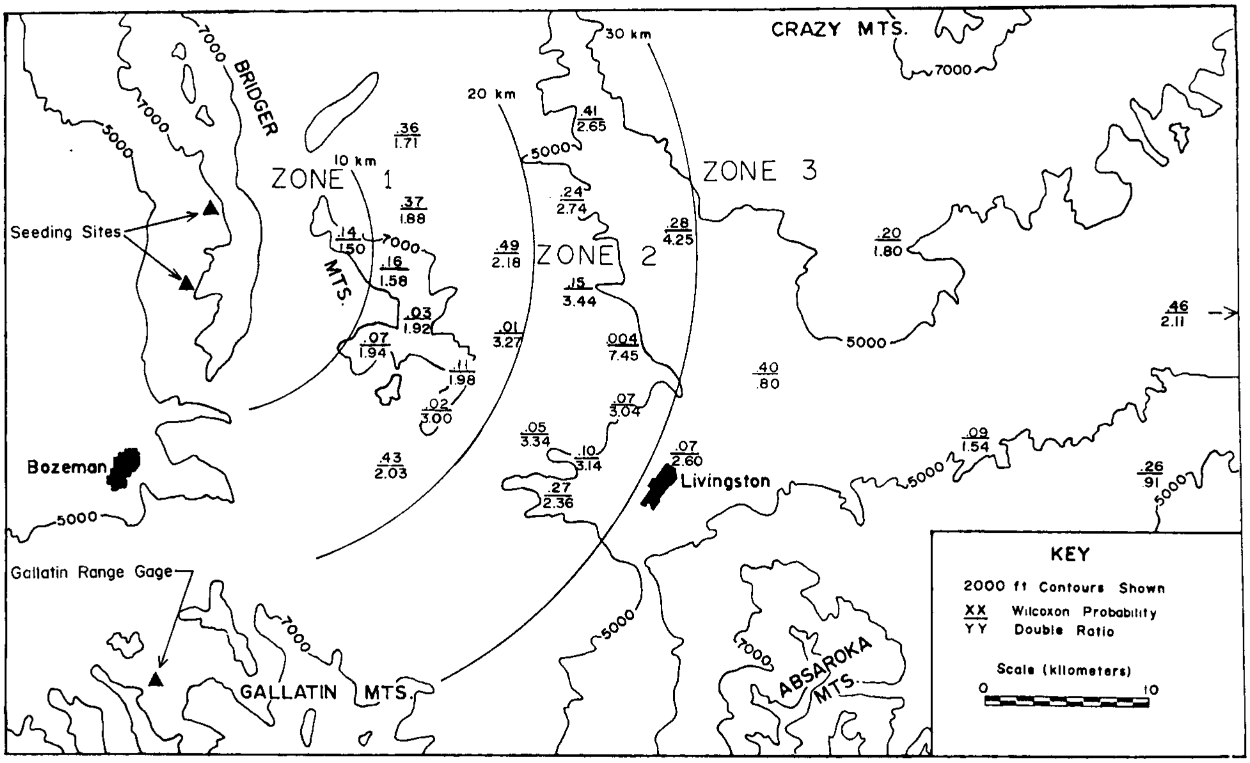

FIG. 4. Map of Wilcoxon probabilities and mean double ratios for the 41 1969–70 winter days with Ridge temperature ≤ −9.0°C.

network, using the Gallatin Range gage as control. These statistics are shown in Fig. 4, for Ridge temperatures ⩽ −9.0°C. It is seen that all probabilities ⩽ 0.10 are across the southern portions of the zones, roughly along an ESE line from the single southern seeding site. As 700 mb wind directions were generally WNW, this suggests a correspondence between the mean plume position and the lower probability values.

8. Supporting evidence from snow courses

The BRE did not operate gages on the east slope of the Main Ridge as it was assumed that any significant effects of seeding would be further downwind. That is, it was expected that small ice crystals that formed just upwind of or over the Main Ridge, would be carried several kilometers further east before growing sufficiently large to settle as snowflakes. However, aggregates of many small crystals with enhanced fall velocities were shown to result in the seeding attempts to redistribute lake-effect snowfall (e.g., Holroyd and Jiusto, 1971). It may be that high concentrations of ice crystals, presumably caused by seeding just upwind of the Main Ridge, sometimes resulted in aggregates which fell on the east slope.

The westernmost gage, aside from the control gages, was located in the valley between the Main Ridge and Bangtail Ridge (see Fig. 1). After the statistical analysis suggested increases at that gage, it was decided to compare data from the two snow courses sampled by the Soil Conservation Service (SCS) on the Main Ridge east slope (Bridger Bowl and Maynard Creek) with nearby courses in a target–control analysis. Both snow courses are approximately east of the midpoint of a line joining the two seeding generators, and are at 2210 and 1895 m in the locations noted by S1 and S2 in Fig. 1. The two courses have continuous records since 1965 and 1967 respectively. As a point of information, no snow courses have been maintained on the Bangtail Ridge.

A search was made of all other nearby SCS snow course data for any that might be highly associated with S1 and S2. Because large natural variations commonly occur in the percent-of-normal seasonal snowpack over distances of 100 km or more, it was considered desirable to limit the distance from target to control courses as much as practical. However, it was also important to consider courses in both crosswind directions (north and south), as well as upwind (generally west), to further minimize natural gradients across the region.

As a first step, all snow courses with the appropriate period of record within a 60 km radius of S1 and S2 were selected. The Bridger Range had one additional snow course probably suitable as a control. However, this course, designated by S3 on Fig. 1, was only 7 km north of S1. Therefore, it is possible that it may have been affected by the seeding under some wind regimes. Presumably seeding would affect S1, S2 and S3 in the same direction, so the use of S3 as a control snow course should be a conservative approach.

The Gallatin Range immediately south of the Bridger Range had six snow courses as potential controls, while the Crazy Mountain Range, northeast of the Bridgers, had three such courses. These latter three may have been occasionally influenced by seeding although a transport wind more southerly than 240 deg would have been required. Only 5% of all 359 rawins tracked

TABLE 12. Summary of snow course information.

Mountain range	Snow course name	Elevation (feet)	Direction from Bridger Bowl	Approximate distance from Bridger Bowl (km)	13 Season correlation coefficient*
Bridger	Bridger Bowl	7250	—	0	—
Bridger	Maynard Creek	6210	ENE	2	—
Bridger	Sacajawea	6550	N	7	0.92
Gallatin	Arch Falls	7350	S	45	0.84
Gallatin	Devils Slide	8100	S	47	0.89
Gallatin	Hood Meadow	6600	S	39	0.81
Gallatin	Lick Creek	6860	S	36	0.76
Gallatin	New World	6700	S	29	0.88
Gallatin	Shower Falls	8100	S	46	0.92
Crazy	Bald Ridge	7500	NE	50	0.79
Crazy	Porcupine	6500	NE	48	0.69
Crazy	So. Fork Shields	8100	NE	48	0.88
Castle	Elk Peak	8000	NNE	75	0.89
Big Belt	Boulder Mt.	7950	NNW	90	0.79
Tobacco Root	Branham Lakes	8850	WSW	92	0.70
Tobacco Root	Lower Twin	7900	WSW	87	0.65
Tobacco Root	Middle Mill Creek	7850	WSW	93	0.68

* See text.

during the BRE yielded a 700 mb (near plume top) wind direction between 180 and 240 deg. Thus, any impact of seeding on the Crazy Mountain Range courses is believed minimal.

In addition to the ten possible control courses noted above within 60 km of S1 and S2, five additional courses were considered at greater range in an attempt to select upwind courses and additional courses to the north (six were available within 60 km to the south). As shown in Table 12, three were ~90 km WSW in the closest upwind mountains, the Tobacco Root Range. The final two courses were the closest in a northerly direction, being ~75 and 90 km distant from S1 and S2. All other snow courses from a westerly through northerly direction of S1 and S2 were more than 110 km away and were not considered.

Table 12 lists the snow courses considered and shows the correlation each had with the March 1 mean water equivalent at S1 and S2 for 13 nonseeded seasons. March 1 was used rather than April 1 to reduce errors due to early spring snowmelt and because the 1970–71 seeding was suspended on March 1, one month earlier than planned, due to well above normal snowpack conditions. The means of S1 and S2 were used because, as might be expected, higher associations were found with other courses than when each of these two snow courses was considered separately. The data used were the entire period of record (1967–83), with the four winters of any seeding in the Bridgers excluded (1969–72). It is believed that no other cloud seeding took place within the time period and region considered.

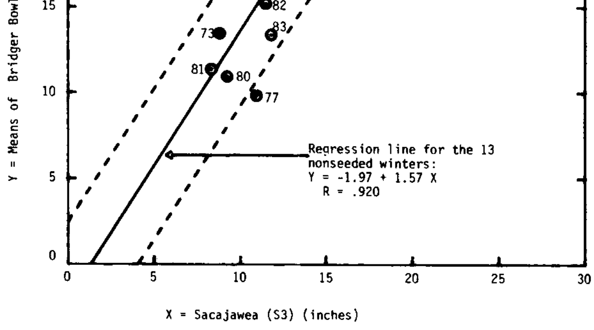

FIG. 5. Plot of 1 March mean water equivalents for indicated snow courses.

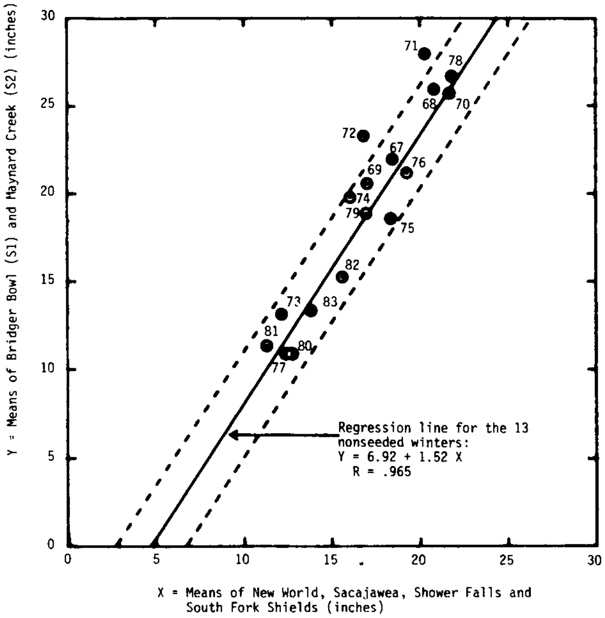

FIG. 6. Plot of 1 March mean water equivalents for indicated snow courses.

It is seen that six courses yielded relatively high correlation coefficients from 0.88 to 0.92 so that any one of them would explain more than 75% of the total variance in the mean target snow course data. All other courses yielded lower correlation coefficients, from 0.65 to 0.84. These snow courses were not considered further.

The most straightforward target–control analysis is to use the nearby Sacajawea (S3) course as the sole control with the realization that it may have been occasionally affected by seeding. Fig. 5 is a plot of March 1 snow course water equivalent data for individual seasons. The least-squares regression line of the form $y = a + bx$ is shown for the 13 nonseeded winters while the dashed lines show ±1.96 standard errors of estimate calculated for the same winters. (It would be expected that 95% of a nonseeded population would lie between the dashed lines.) It is seen that the 1968–69 winter is on the regression line and the 1969–70 winter is below it. It will be recalled that only low-elevation generators were used the former winter and that these were relocated after discovery of a persistent stable layer. Only the southern seeding site was operational in time for the latter winter and gages with low probabilities were confined to the southern portions of the three zones as shown in Fig. 4.

The observations from the 1970–71 and 1971–72 winters, which are the period of the main statistical analysis herein, are seen to depart markedly from the regression line. On an absolute basis, these data points depart farther from the line than any other points in either direction, (4.3 and 3.6 inches water equivalent respectively) and both depart in the direction expected if seeding increased snowfall at S1 and S2. Both the 1971 and 1972 data points are 18% above the values predicted by the regression line. However, the nonseeded 1974 data point has an even greater percentage departure from the regression line at 22%.

An effort was made to improve the predictability of the target–control relationship by including additional courses. Correlation coefficients were calculated for all combinations of 2, 3, . . . , 6 of the courses with individual correlation coefficients ⩾ 0.88 in Table 12. Of the 57 possible combinations, the highest coefficient achieved was 0.965 resulting from the means of Sacajawea, New World, Shower Falls and South Fork Shields correlated with the means of the two target courses. These seasonal means are plotted in Fig. 6 together with a least-squares regression line fitted to the 13 nonseeded winters and the ±1.96 standard errors of estimate (dashed) lines.

The data points for the 1968–69 and 1969–70 winters are near the regression line, suggesting little net change in snowfall due to seeding during those winters. However, the 1 March data points for the 1970–71 and 1971–72 seeded winters are 4.1 and 4.7 inches above the regression line, respectively, corresponding to percentage departures of 17 and 25%. These departures represent standard errors of 2.8 and 3.1, implying a significant positive deviation from the nonseeded winters.

The mean and median double ratios were calculated between the three control gages and the 12 gages of Zone 1, as well as for the single gage nearest the Bridger Bowl and Maynard Creek snow courses, for all experimental days of the 1970–71 and 1971–72 winters respectively. The same was done for the two winters combined. These values are given in Table 13.

It can be seen that the mean double ratio for the gage nearest the snow courses suggests twice as great an increase for the 1970–71 winter, and is in close agreement for the 1971–72 winter, when compared with the snow course estimates. The median double ratio estimates for the single gage depart markedly from the snow course estimates. Agreement is better when median double ratios are based on all 12 gages of Zone 1, but the 1970–71 value of 1.63, implying a 63% increase, is still far above the snow course estimate of a 17% increase.

TABLE 13. Single and two-winter double ratios.

Winter	Experimental days	Double ratio between 3 control gages and:			
		12 gages of Zone 1		Gage 1.5 km NE of Maynard Creek	
		Mean	Median	Mean	Median
1970–71	86	1.10	1.63	1.35	2.33
1971–72	99	1.26	1.19	1.24	0.69
Both winters combined	185	1.15	1.24	1.25	1.14

When the large data pool of 185 experimental days from both winters is considered, the zone and single gage double ratios, both mean and median, all fall in a range suggesting 15–25% increases. This should be considered somewhat of an overestimate because some storm days were not included in the randomized program (e.g., days with "busted" forecasts). These estimates are in good agreement with the snow-course estimates. Thus, both precipitation gage and snow course data suggest that seeding may have increased seasonal snowfall in Zone 1 by ~15%.

9. Summary and recommendations

The Bridger Range winter orographic cloud seeding experiment has been analyzed using upwind and crosswind precipitation gages as controls and recently developed statistical approaches. Because this was an exploratory experiment with *post hoc* analysis, the results cannot be considered scientifically conclusive. The probability values presented should be interpreted with caution due to potential multiplicity problems. At best, the results can be considered strongly suggestive.

The statistical analysis suggests that seeding increased snowfall in the intended target area and sometimes further downwind as well, when the temperature near the top of the Main Ridge was colder than about −9°C. This apparent increase was found in partitions using the 700 mb temperature from radiosondes, or the temperature measured by thermograph at 2595 m elevation.

The apparent increase in target area precipitation was found for the 100 experimental days with mean Ridge temperatures ⩽ −9°C during the 1970–71 and 1971–72 winters combined. It was also suggested in the same data but with each winter examined separately. Further, the same suggestion was found in the 1969–70 winter dataset which was not totally compatible with the two later winters (e.g., one rather than two seeding sites was used).

Single partitioning by estimated cloud top temperature, 500 mb temperature, or the component of the 700 mb wind perpendicular to the Main Ridge did not suggest that changes in precipitation were associated with seeding. A dual partitioning by cloud top temperature ⩽ −9.0°C suggested increased precipitation tended to be associated with colder cloud tops.

Double ratios suggest that, on a seasonal basis, ~15 percent more precipitation fell during the seeded days in the intended target than predicted by the control gage data. When the colder days were considered alone, double ratios suggested seeding-associated snowfall increases of 50 percent or more.

Suggested increases were also found on the lee slope and broad valley beyond the intended target area. These tended to be with Ridge temperatures colder than about −12°C. There was also a suggestion that seeding may have decreased downwind precipitation for 700 mb temperatures near the −10 to −14°C range.

Independent snow course data were examined for the two courses on the lee slope of the Main Ridge, located between the intended target and the seeding generators. These data show unusually high snowpack water equivalent values for the 1970–71 and 1971–72 seeded winters. Values for these winters depart from the values predicted by control snow courses by ~17 and 25% respectively.

The apparent increases in precipitation associated with seeding during the colder storms are believed to be consistent with current physical understanding, which admittedly still has serious limitations. The airflow and AgI plume tracing results from the BRE were reviewed. These are consistent with the hypothesis that the seeding agent generally was transported up and over the Main Ridge and toward the intended target, with sufficient diffusion for wide-area coverage by the AgI plumes. Also, the strong uplift above the windward slope of the Main Ridge should have produced considerable condensate in the zone through which the AgI was transported. Further, simulation–laboratory calibrations of the seeding generators used suggest that artificial nucleation should have been very limited until Ridge temperatures were colder than about −9°C.

In the opinion of the authors, the results presented herein are encouraging enough to justify further field efforts in the Bridger Range. However, a confirmatory statistical experiment is not advocated at this time. Rather, it is recommended that a limited program of airborne measurements, primarily downwind of the southern generator site, is the most appropriate next step. Several plume tracing flights have shown that the southern generator site is capable of routinely producing AgI plumes that are transported over both the Main Ridge and Bangtail Ridge target area, with tops about 600 m above the highest point in the latter ridge. Preliminary contacts with the Federal Aviation Administration have suggested that it should be practical to make north–south aircraft passes above the Bangtail Ridge during storms, while within 300 m of the highest terrain. This would place the aircraft well into the seeding plume. An NCAR ice nucleus counter and repeated flight passes in opposite directions would delineate the seeding plume boundaries. Simultaneous measurements of liquid water content and ice particle concentrations and size spectra should yield marked differences between in-plume observations and those made crosswind of the plume in nonseeded clouds. Analysis of such data, collected from several storms, should yield physical evidence that tends to either confirm or reject the suggestions of the statistical analysis presented. If the airborne physical observations appeared in accord with the statistical suggestions, a confirmatory statistical experiment with a strong physical component would appear to be justified.

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