SIX HOUR ANALYSES OF THE BRIDGER RANGE RANDOMIZED WINTER OROGRAPHIC CLOUD SEEDING EXPERIMENT

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Abstract. The Bridger Range winter orographic cloud seeding experiment was conducted during the early 1970s. Published post hoc exploratory statistical analyses used 24 h experimental units. However, 6 h precipitation observations exist which have not been previously tested with non-parametric statistics. They should be better represented by available 6 h partitioning data. This experiment produced high quality precipitation data and was one of few with associated physical studies adding credibility to statistical suggestions. Use of control gauge data substantially reduces natural variance in target precipitation. Two independent statistical approaches were applied to the 6 h dataset. Results strongly suggest that seeding was effective when conditions were conducive to orographic cloud formation with near-crestline temperatures sufficiently cold for adequate nucleation with silver iodide. Specifically, the null hypothesis (seeding had no effect) was rejected with one-tailed P-values near 0.001 for the single partition of seeded zone temperatures less than the median. That subpopulation was further reduced by about 50% with the requirement of rawinsonde observations, launched only when clouds existed near or below crestline elevations. Similar very low P-values resulted from this dual partition with much reduced sample size, and for an even smaller population with 700 mb dew point depressions less than their median value. These results are physically reasonable. Partitioning by cloud-top temperature and cloud thickness suggested that seeding could be effective even when thick clouds with cold tops were present. It is stressed that these results are based on post hoc exploratory analyses so they can only be viewed as suggestive and not conclusive proof. Suggestions are given for future randomized winter orographic experimentation.

1. INTRODUCTION

Cloud seeding for mountain snowpack augmentation has been operationally applied for six decades but the field remains controversial (National Research Council 2003; Boe *et al*. 2004; Huggins 2009). The 1998 American Meteorological Society Policy Statement (AMS 1998) may be considered cautiously optimistic about future potential but does not indicate a proven technology. The Statement recommended, "Whereas a statistical evaluation is required to establish that a significant change resulted from a given seeding activity, it must be accompanied by a physical evaluation to confirm that the statistically observed change was due to the seeding."

The Bridger Range Experiment (BRE), conducted in southwestern Montana during the early 1970s, is described in detail by Super and Heimbach (1983), hereafter SH83. Review of the peer-reviewed literature indicates that no more recent randomized winter orographic experiment (RWOE) has met the above AMS statement recommendation as well as the BRE (Reynolds 1988; Huggins 2009). Given this state of affairs and continued lack of research funding, the authors decided to statistically analyze 6 h BRE data in an attempt to provide further insight beyond the 24 h analyses of SH83.

It is well established that randomized experiments are required to provide credible statistical inferences. Dennis (1980), Gabriel (2000), Super and Heimbach (2003) and others show that statistical results from historical target-control analyses or other non-randomized approaches can have serious potential sources of bias.

Credible short-term physical evidence of seeding effects over mountains was reported by Hobbs (1975b) with radar detection shown by Hobbs *et al*. (1981). Several more recent physical experiments which demonstrated seeding-caused snowfall were summarized by Huggins (2009). A detailed case study including apparent detection by radar was presented Huggins (2007). Such brief (~ 1h) experiments provide convincing evidence that some types of seeding can enhance snowfall under some conditions. However, they cannot provide credible estimates of *seasonal* changes. Therefore, randomized experimentation is emphasized herein.

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This paper presents post-hoc exploratory analyses of 6 h periods from the BRE, the shortest interval for which routine precipitation and rawinsonde (rawin) observations were collected. It also addresses whether resulting statistically significant results are physically credible. Statistical analyses of the original 24 h experimental units (EUs) were presented by SH83 along with considerable supporting physical evidence including AgI plume tracking, airflow studies and silver-in-snow analyses. Physical evidence obtained in the same area after the BRE was reported by Heimbach and Super (1988) and Super and Heimbach (1988).

Six-hour intervals should be better represented by associated partitioning data than was the case for the original 24 h EUs. A similar idea was proposed by Mielke (1995) who stated with respect to the Climax Experiments, “At the time the analyses were accomplished, it seemed important to have analysis and experimental units be identical (i.e., 24-h periods). I now feel this notion of identical units may have hindered improved analyses. A suggestion by L. O. Grant to imbed eight 3-h analysis units on each 24-h experimental unit would yield a vast improvement since the atmospheric conditions are more uniform during a 3-h period than a 24-h period.”

It is fundamental that certain conditions be satisfied for winter orographic cloud seeding with AgI to succeed. Supercooled liquid water (SLW) cloud, the necessary “raw material” for seeding to be effective, must exist in the spatial zone intended for treatment, upwind of and perhaps over the target area. The AgI must frequently be transported and widely dispersed into that zone in sufficiently high *effective* concentrations to produce meaningful snowfall rates. Silver iodide effectiveness is highly temperature dependent especially above about -10°C. Moreover, the rate of AgI nucleation varies significantly depending upon the specific formulation of the seeding solution and SLW cloud conditions (Chai *et al.* 1993; DeMott *et al*. 1995)

The BRE did not have instrumentation for direct measurements of SLW. Ice crystal observations were occasionally made on the target area which frequently showed riming. Later icing rate sensor observations atop the Main Ridge (MRO on Fig. 1) during the months of January, February and March 1985 detected SLW during 9, 8 and 7% of all hours with data, respectively, with a median Main Ridge temperature (MRT) of -8.5°C (Super and Heimbach 1988). An operational seeding project attempted to increase snowfall on a ski area immediately to the lee of the Main Ridge during the 1986-87 winter (Heimbach and Super 1988). The northern BRE seeding site, just upwind of the ski area (see Fig. 1), was reactivated for this purpose. Additional icing rate sensor observations detected SLW during 7% of all hours during that dry winter with locally record low snowpack. Heimbach and Super (1988) summarized microphysical observations from that crestline location and stated, “Photography showed that during periods of significant snowfall rates, there was riming of the crystals, indicating that even with seeding, not all the available supercooled liquid water was being processed

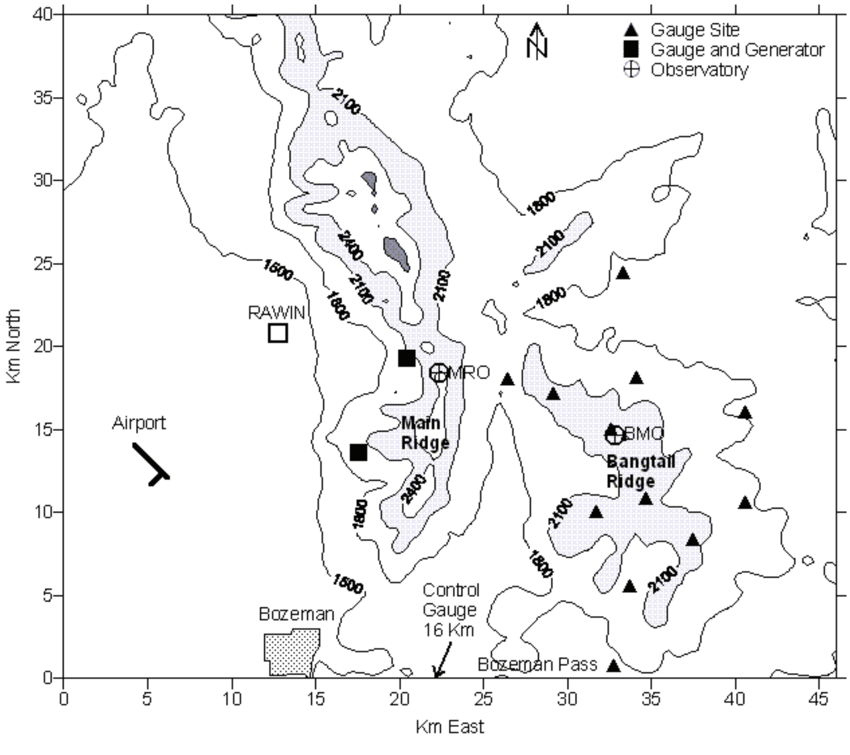

Fig. 1. Map of Bridger Range experimental area showing Main Ridge and Bangtail Ridge, location of gauges, seeding sites and facilities. Contours are meters MSL.

and some accretional growth was helping the precipitation process."

Observations of SLW cloud have been made over several mountain ranges since the BRE. Studies summarized by Huggins (2009) show that a common feature has been predominance of SLW over windward slopes and crests due to orographic lift with most SLW found <1 km above mountain crests. The SLW decreases further downwind due to conversion to precipitation and/or evaporation in descending air (Hobbs 1975a; Huggins 1995). Huggins (2009) noted that the overall conclusion of each study of SLW availability was that significant cloud seeding potential existed in winter storms over mountainous terrain if seeding could be properly applied. Availability of SLW cloud does not appear to be a limitation for seeding effectiveness over the course of many storms (Super and Huggins 1993; Super 1994). But measurements have consistently documented considerable SLW variability over periods of a few hours or less (Rauber *et al*. 1986; Boe and Super 1986; Super 1999).

2. OVERVIEW OF BRIDGER RANGE EXPERIMENTATION

Bridger Range experimentation was accomplished by Montana State University (MSU) researchers under the Bureau of Reclamation's Project Skywater. The MSU research and some contemporary projects were partially motivated by the apparent success of ongoing experimentation at Climax, Colorado. Funding for the BRE and other western state field research projects was unexpectedly terminated during 1972 when resources were concentrated on a large Reclamation "pilot project."

The randomized BRE was designed to test whether seeding could enhance the seasonal snowfall on a broad secondary downwind ridge by seeding clouds over the somewhat higher primary upwind ridge (see Fig. 1). The upwind Main Ridge and downwind Bangtail Ridge Target Area (BRTA) both have a generally north-south axis and are separated by a narrow mountain valley. Both ridges can be expected to produce near-terrain SLW cloud. Seeded crystals formed over the Main Ridge may encounter a secondary SLW zone upwind and over the target ridge, potentially enhancing the snow production process. Embedded gravity waves may sometimes have an important role in SLW production (Heimbach and Hall 1994; Reinking *et al.* 2000). The BRE design was unusual in that most experiments (and operational projects) have attempted to seed a single downwind barrier.

Available resources did not permit testing over a larger area and only two seeding sites were used. But the limited target area was sufficient to test the seeding hypothesis discussed in SH83. The BRE had two top field priorities: (a) insuring that orographically-enhanced (hereafter simply orographic) clouds over the upwind Main Ridge were actually seeded on a routine basis with AgI ice nuclei (IN) and, (b) observing melted snow water equivalent (SWE) as accurately as practical over and downwind of the expected target area. Super *et al*. (1972; 1974) produced a comprehensive two-part final report, hereafter Part I and Part II, which discussed Bridger Range experimentation in detail including design, field equipment and operations and several auxiliary studies such as radar observations, airflow and AgI plume tracking investigations and attempts to directly detect seeding effects. Printed or microfiche copies of Part I and Part II are available from the National Technical Informational Service. Part II contains listings of all data used in this paper, available in ASCII format upon request of either author.

Although the BRE was discussed by SH83, details of seeding operations and snowfall observation are presented herein because of their importance in conducting a successful RWOE and to have this paper stand alone. Large variations exist among various programs in the application of "cloud seeding" due to different release methods, rates, seeding agents and their transport and dispersion, and variations in topography. The resulting uncertainties, and those related to the difficulties in accurately measuring snowfall in mountainous terrain, are often not fully appreciated.

The BRE expended considerable effort and resources to insure seeding reliability by using improved silver iodide (AgI) generators monitored at 3 to 4.5 h intervals day and night. Field technicians climbed about 600 m vertically from the upwind valley to man the remote high elevation sites for 3-day shifts. All major supplies and equipment had to be lifted in by helicopter. Use of foothill generator sites was abandoned after initial testing during the 1968-69 winter. Wind and temperature profile observations showed a high frequency of persistent stable conditions below about midway up the west (windward) slope of the Main Ridge (Super *et al.* 1970) so seeding sites were later established about 2/3 of the way up that slope (Fig. 1). Commercially-obtained generators were used during preliminary testing but proved unsatisfactory. Improved "MSU Skyfire" generators were locally-fabricated in time for the BRE. Unlike the commercial generators, the MSU units permitted fine spatial adjustment of the hypodermic needle used to inject seeding solution into the propane jet permitting complete solution atomization upon entering the burner chamber. Wind shields were added to minimize flameouts although typical seeding site winds proved to be light. At the time the MSU generators were among the highest yield ground-based units tested by the Colorado State University Cloud Simulation Laboratory, particularly at warmer temperatures (Garvey 1975).

Considerable documentation exists that high elevation Bridger Range generators provided routine transport and dispersion of seeding plumes over the Main Ridge and downwind BRTA (Super 1974; Part II; SH83). Numerous aircraft missions documented AgI plumes over both the Main Ridge and BRTA during visual flight rules conditions, usually with a mid-level and/or high overcast to reduce solar heating. Acoustical counter sampling at the Bangtail Mountain Observatory (BMO) frequently detected AgI (Part I). In-cloud aircraft sampling during a January 1985 NSF-sponsored experiment detected AgI plumes over the BRTA during all six missions as well as co-located seeded ice crystals during the three missions with detectable SLW (Super and Heimbach 1988). Further evidence that seeding plumes frequently passed over the intended target was provided by seasonal snowpack samples which showed silver concentrations well above background over the BRTA for both BRE winters (SH83). Those observations combined with seasonal SWE data suggested that much of the silver emitted during snowfall ended up in the BRTA snowpack. Similar sampling for a 1986-87 winter operational seeding project demonstrated high silver levels on the ski area target just to the lee of the Main Ridge and near the previous BMO target location (Heimbach and Super 1988). Later sampling of plumes released from similar high elevation sites on the Grand Mesa of Colorado and Wasatch Plateau of Utah also showed routine transport and dispersion over the barriers (Huggins 2009).

Snow water equivalent was measured by a dense network of Universal (Belfort) weighing gauges then in common use by the National Weather Service (NWS) and other agencies. Initial testing with the standard 8-inch diameter gauge orifices revealed they were unsuitable for snowfall observations in protected clearings because of frequent partial or total snow bridging over the orifices, known as "capping." Replacement gauge shells were locally manufactured for the BRE with 11.3-inch diameter orifices providing twice the standard orifice area. The larger orifices eliminated capping and doubled the resolution from 0.01 to 0.005 inch SWE. This facilitated reading Universal gauge charts to the nearest 0.01 inch, the NWS standard, as did extraction at 6 h intervals rather than hourly as sometimes done by the NWS. The BRE practice was more realistic and less prone to false readings given the high frequency of hours with very light snowfall in the Rocky Mountains. For example, all nonseeded 6 h periods with rawin data and a westerly wind component at 700 mb were selected for examination of a representative target gauge, near the BMO shown on Fig. 1. Of the 138 periods with detectable SWE, 23% had 0.01 inch, the smallest value extracted from the gauge charts. The median 6 h amount was only 0.04 inches. Careful consideration should obviously be given to gauge characteristics and protection from wind-caused undercatch when measuring such low snowfall rates.

Gauge mechanisms were carefully calibrated with standard weight sets prior to each field season. After field installation each calibration was again checked and mechanisms were adjusted when outside of specifications. Prior to end-of-season gauge removal, a final weight set check was made. These revealed that all units stayed in calibration during each winter season. Gauge chart clocks were also carefully adjusted prior to field use. Start and stop times were marked on each 24 h rotation chart during approximately weekly service visits and clocks were soon replaced if needed. All gauges were operated in the field for at least a month prior to each season and the large majority of problems were resolved during those shakedown periods. These procedures minimized missing data.

Numerous publications over many decades have addressed the difficulties of obtaining accurate measurements of SWE, especially in the presence of wind. Brooks (1941) stated, "It has been generally recognized for more than a century that the more precipitation gages are exposed to the wind the less they catch; and that the catch of snow in an unshielded gage gives a very unreliable indication of the precipitation." He also pointed out the importance of using Alter wind shields to improve catch. All BRE gauges used Alter shields. But a 5 m s^{-1} wind speed will reduce the catch of even an Alter-shielded Universal gauge by 50% (Goodison 1978) with unshielded gauges having significantly poorer performances. Wilson (1954) reported results of a five winter comprehensive study of mountain snowfall measurements. He analyzed the catch of several gauges against snow course measurements and concluded that small protected clearings provided the best gauge sites. Brown and Peck (1962) compared seasonal gauge catch with snow course observations in the mountains of Utah and provided a subjective scheme for selecting sites with limited wind effects. Small clearings in conifer forest, which they called "overprotected," were sought out for BRE gauges. The 3 control gauges and 10 of 12 BRTA gauges were in such clearings where wind speed was minimal. For example, average wind speeds were 0.6 m s^{-1} in the BMO gauge clearing during days with snowfall. Agreement was excellent between that gauge and two nearby snowboards with a correlation coefficient of 0.99 for 54 daily SWE totals during the 1969-70 winter (Part I). The linear regression equation with the gauge as the dependent variable had a slope of 1.05 and intercept of -0.02 inch indicating minor undercatch by the gauge.

Two BRTA target gauges were on the lee slope below conifer forest but were shielded from wind as much as practical by terrain and brush. Gauges further downwind in the broad and windy Shields Valley are not analyzed in this paper. They had much greater exposure to wind effects due to lack of forest cover, and received substantially lower precipitation amounts due to the "rain shadow" effect. Valley gauges had a high frequency of 6 h periods with no precipitation detected. Use of 6 h totals becomes problematic under such conditions.

Ideally, collection and reduction of SWE data would have been contracted out to an independent agency to minimize human bias. This was not considered practical during conduct of the modestly-funded BRE for both operational and economical reasons. Data from each gauge chart was reduced twice by separate teams of MSU data clerks (work study students) who had no knowledge of seeded periods. Any differences were resolved by the data clerk supervisor. Approximately 96% of all data were complete. The remaining 4% were estimated by the first author as discussed by SH83, using all available data plotted on contour maps by data clerks. The maps were coded with no date or seeding information on them. It is believed that human bias was eliminated by these procedures.

Analyses of BRE 24 h EUs and associated studies are described in detail by SH83. Seeding during the 1969-70 winter, just prior to the BRE, used a single high elevation site with a different AgI generator and seeding solution. Only one control gauge south of the Bridger Range was operated that winter (Fig. 1) which provided a shakedown period for field procedures and equipment. A second high elevation seeding site was selected prior to the BRE, 6.4 km crosswind from the southern site (Fig. 1). Both generator sites were near 2150 m (all elevations MSL) where generators burned 3% by weight AgI in a solution of acetone complexed by NH_4I. The resulting rather pure AgI particles are known to nucleate by contact-freezing, a relatively slow process (DeMott *et al*. 1995) unless generators were within sufficiently cold SLW cloud enabling rapid forced condensation-freezing nucleation (Finnegan and Pitter 1988). BRE generators were often in cloud but the frequency of in-cloud seeding is unknown. Control gauges were installed in forest clearings near each seeding sites prior to the 1970-71 winter to supplement the original control gauge in mountains south of the Bridger Range (Fig. 1).

The intended target was the BRTA about 5 to 20 km east of the Main Ridge crestline (Fig. 1). The latter had an average elevation of 2600 m. Rawins launched about 10 km west of the Main Ridge crest indicated that 700 mb (about 3050 m) winds should have transported seeding plumes toward the BRTA in the large majority of cases. Aircraft tracking over both the Main Ridge and BRTA revealed AgI plumes were seldom transported higher than 3050 m so 700 mb wind directions approximate plume top transport but not necessarily lower plume portions.

Twenty-four hour EUs beginning at local noon were declared by the simple criterion of a special NWS precipitation probability forecast ≥ 30% for the upwind valley airport (Fig. 1). The main statistical suggestions of the 24 h analyses were that AgI seeding was effective when the MRT was less than about -9°C, and that operational seeding would likely increase target area seasonal snowfall by approximately 15%.

3. STATISTICAL TECHNIQUES

The natural variation of precipitation in RWOEs can be several orders of magnitude larger than the seeding signal requiring a large number of EUs to find probabilities (P-values) small enough to reject the null hypothesis that seeding is ineffective. The statistical convention used in this paper follows. A Type I error, i.e., erroneously rejecting the null hypothesis and claiming a seeded effect when none exists, is expressed as a probability level and is symbolized by α. An α-level of 0.05 has traditionally been used in weather modification and is termed *significance level* if expressed as a percentage. The P-value is the specific probability of a Type I error derived by a statistical test that is compared to the specified α-level to judge the null hypothesis. A Type II statistical error, which is the incorrect acceptance of a false null hypothesis, has its probability symbolized by β. Heimbach and Super (1996) used BRE 24 h SWE data show that the power of a test, i.e., the probability of not having a Type II error, (1-β), is difficult to quantify if response to seeding is variable among EUs. That seems likely given SLW variability and other factors.

The large natural variability of SWE, the primary response variable, makes it essential to use covariates that are strongly correlated with target snowfalls. Otherwise, the number of EUs and, therefore, seasons needed to detect a treatment effect can be prohibitive while the risk of undetected Type I errors remains. The best covariates are upwind and crosswind control gauges (Gabriel 2000). Properly sited control gauges appropriate for snowfall measurement can remove half or more of the natural SWE variance, improving the efficiency of detecting a treatment effect.

Early analyses of Bridger Range data in Parts I and II used control gauge observations only for detection of "bad draws." These were partitions for which the randomization procedure failed to provide similar distributions of *natural* SWE amounts for seeded and nonseeded EU populations as shown by comparison of control gauge amounts. Wilcoxon testing was applied to individual gauges. If P-values were low at control gauges as well as target gauges the particular partition was considered flawed by a bad draw. The authors of Part II concluded that, "It was found that portions of the total observed ranges for several of these parameters (used to partition) were subject to a bad draw. Therefore, nothing could be determined regarding seeding effects in these instances."

Evidence that the entire BRE had a bad draw is provided by SWE observations from the three available control gauges, all at mountain locations (Fig. 1). The BRE produced 185 experimental days, 90 seeded and 95 nonseeded. But even with this large population the randomization scheme produced dissimilar seeded and nonseeded distributions of natural SWE amounts. The control gauges' nonseeded mean and median daily amounts were 0.116 and 0.050 inch, respectively, while corresponding seeded values were 0.095 and 0.037 inch. Thus, the mean (median) SWE amounts on nonseeded days were 22% (35%) larger because of the bad draw, greater than typical claims of seeding-enhanced SWE. The bad draw was even more pronounced for the 44 seeded and 56 nonseeded days with MRT ≤ -9.0°C, suggested by SH83 as most affected by seeding. Control gauge nonseeded mean and median daily amounts were 0.118 and 0.067 inch, respectively, compared with seeded values of 0.084 and 0.043 inch. Without reference to control gauges or other covariates unaffected by seeding, analyses of target SWE could have produced a Type I error incorrectly suggesting that seeding decreased snowfall. Even with larger populations, Climax I and Climax II were each influenced by bad draws in the opposite sense with seeded days receiving more natural snowfall than nonseeded days (Mielke *et al*. 1981).

While the authors realized a bad draw had occurred, the techniques for incorporating control gauge data were not available until Mielke *et al*. (1981). That paper described a nonparametric inference technique which adjusted for such errors and applied it to the Climax Experiments. In this method, control gauge observations are used to predict target precipitation and the seed and nonseed residuals (departures) from the regression are input to one or more statistical inference tests. SH83 applied the techniques of Mielke *et al*. (1981; 1982) to the BRE 24 h data and found strong suggestions of a seeding effect with small P-values for partitions that were physically reasonable.

The high variability of meteorological conditions within the 24 h EUs warrants subdividing into 6 h periods, the shortest intervals for which BRE observations are available. The independence of 6 h periods was conservatively tested by calculating the lag correlation for all 339 available adjoining 6 h pairs of nonseeded target area precipitation, that is, each pair was from a continuous 12 h block. Calculations were based on averages of the 12 BRTA gauges, called Zone 1 by SH83. With 54 pairs of 0, 0 precipitation included (excluded), variance explained was only 8.5% (6.4%). These values suggest that the 6 h periods are not entirely independent; however, the amount of dependence is small. Conversely, the natural variance explained by the 6 h control data in the analyses herein is substantial, far overshadowing that explained by autocorrelation. Consequently, the 6 h SWE amounts can be considered independent for practical purposes, producing at most minor errors in probability estimation. Such errors have little consequence here as post-hoc analyses are being applied to an exploratory experiment so tests of statistical significance do not have the level of certainty provided by *a priori* rigorously controlled confirmatory experiment (Dennis 1980; Gabriel 2000). Given that caveat, some latitude is appropriate for exploratory analyses. Accordingly, adjectives like "suggestive" and "strongly suggestive" are applied to statistical results herein as the term "proof" would be inappropriate.

To form a basis of comparison, portions of the 6 h analyses described in this paper mimic those done earlier by SH83 to 24 h data by applying the well-known Wilcoxon non-parametric test. Another statistical technique is applied based on rerandomization of ratios (described below). Since there is no evidence that BRE seeding decreased precipitation (Super 1986 and this paper), only 1-tailed inferences are used.

3.1. Applying the Wilcoxon Test

The Wilcoxon test is also known as the Mann-Whitney test because ranks to the first power are summed. Residuals were calculated from the median regression line which minimizes the sum of absolute deviations and is of the form $\hat{T} = b\overline{C}$ where $\hat{T}$ is the predicted average of the 12 BRTA gauges, and $\overline{C}$ is the average of the three control gauges. The fit was forced through the origin to minimize the influences of periods when either the control or target SWE, but not both, were zero (Mielke *et al.* 1981). The seeded and nonseeded target-control pairs were pooled to define the median fit following Mielke *et al*. (1982) and SH83. The seeded ranks of the rank-ordered residuals were summed to give a test statistic (Mann and Whitney 1947). The test statistic's null distribution is approximately normal if N_S and N_{NS} are each 8 or more where "S" refers to seeded and "NS" to nonseeded. This was not an issue for the current paper because all reported partitions met this requirement. Handling tied residuals was described by Mielke (1967).

3.2. Rerandomized Ratio Test (RRT)

The simplest ratios are the mean (median) single ratio which is the mean (median) seeded divided by the mean (median) nonseeded SWE. Control data are not involved in single ratios. Therefore, inferences drawn from the single ratio can be misleading because there is no compensation for the inherent large natural variance. There are several double ratios which involve control data. These include the mean double ratio (MDR) and median double ratio (MedDR).

$$\mathrm{MDR} = \frac{\text{(Mean Target Single Ratio)}}{\text{(Mean Control Single Ratio)}}$$

$$= \frac{\overline{T}_S}{\overline{C}_S} \bigg/ \frac{\overline{T}_{NS}}{\overline{C}_{NS}} . \qquad (1)$$

The MedDR is Eq. (1) with "Median" substituted for "Mean".

The MedDR is affected less by outlying values than the MDR, but is unstable if there are a large number of zero precipitation accumulations, and undefined if half or more of the T_{NS}, C_S, and/or C_{NS} SWEs are zero. Only the MDR is presented herein as it has been widely applied and provides an estimate of the proportional increase due to seeding.

The MDR can have its null distribution derived analytically through a logarithmic transformation to produce an approximately normal distribution provided >100 EUs are in the sample (Gabriel 1999). This size criterion could not be met for several of the partitions in the current paper so rerandomization was applied. Gabriel (2000) discusses the importance of using rerandomization to provide valid statistical inferences without transformation or parameterization (Mielke *et al*. 1981).

The rerandomization process pooled the observed 6 h S and NS periods, and then the seeded status of each was randomly reassigned, keeping the number of S and NS the same as the actual sample. A rerandomized MDR (hereafter, MDR_j) was derived from this synthesized sample. This process was repeated to derive a total of 10,000 rerandomized double ratios, $MDR_{j=1,10000}$, for each partitioning. These were ordered to produce a null distribution.

A P-value was derived by comparing the sample MDR to the null distribution. For example, if 500 out of 10,000 MDR_js were ≥ the sample MDR, then the 1-tailed P-value was 0.05. P-values were interpolated when the sample MDR was between two ordered MDR_js.

The same rerandomized null distribution is used to derive confidence intervals. The null distribution is transformed into MDR_j' by centering it on the sample's MDR,

$$MDR'_j = MDR_j + (MDR - \overline{MDR_j}). \qquad (2)$$

The lower bound for the (1-α) = 0.95 1-tailed confidence interval is the point bounding the lowest 0.05 X 10,000 MDR_j's.

$$MDR'_{j=0.05*10000} \leq \text{1-tailed 0.95 confidence interval.} \qquad (3)$$

The upper 1-tailed limit is unbounded. For the 2-tailed confidence interval (not applied in the current paper), the 0.95 bounds are defined by (α/2) and (1-α /2) corresponding to the value of the ordered points in the null distribution,

$$MDR'_{j=0.025*10000} \leq \text{2-tailed 0.95 confidence interval} \leq MDR'_{j=0.975*10000}. \qquad (4)$$

Statistical significance can also be inferred through the application of confidence intervals. If the confidence interval includes MDR = 1 or 0% proportional increase due to seeding, i.e., the null effect, then the null hypothesis cannot be rejected at the specified α-level (Gabriel 2002). All 1-tailed confidence intervals reported in this paper use the 0.95 level meaning there are 95 chances out of 100 that the indicated MDR lower limit was achieved or exceeded.

The RRT and Wilcoxon test provide different approaches for statistical examination of the same data sets. Differences in the results can be expected because the Wilcoxon deals with linear ranks, whereas the rerandomization of target-control pairs involves the magnitude of the double ratios. The RRT is sensitive to outliers because of their influence on the magnitude of the MDR. Because the Wilcoxon test deals with ranks, not magnitudes of EUs, it reduces the distortion caused by outliers, i.e., is “resistant” (Wilks 2006). Low RRT P-values smaller than Wilcoxon P-values from the same dataset suggest the seeding signal may be dominated by periods with larger precipitation amounts.

4. STATISTICAL ANALYSES OF 6 H PERIODS

The 6 h analyses are limited to the 12 BRTA gauges and the 3 available control gauges (Fig. 1), all operated specifically for the BRE. The limited non-BRE gauges which existed in the general area are inadequate for the analyses herein. All but a few were at cooperative stations which provided only daily precipitation totals. The few with hourly data were operated in open valley locations, some without wind shields, and consequently subject to serious undercatch under windy conditions and numerous 6 h periods without detectable precipitation.

The 185 daily EUs produced a sample of 740 6 h periods. With the exception of Sec. 4.7, all analysis results are based on the Wilcoxon and RRT tests discussed in Sec. 3.

4.1. Partitioning by Main Ridge Temperature

The MRT distribution was used to subdivide the 6 h periods into halves, thirds, quarters and fifths shown in Table 1. As done by SH83, fractions are consistently used to partition populations throughout this paper in order to reduce bias by eliminating the possibility of “cherry-picking” results for more favorable (lower) P-values. One-tailed P-values less than or equal to α = 0.10 are in bold type in all tables to follow.

The Wilcoxon test provided a relatively low P-value of 0.06 for the entire population while the RRT had a somewhat suggestive value of 0.11. Both tests provided extremely low P-values of 0.001 or less for the colder half of the population with MRT ≤ -9.3°C, the 6 h median value. These results suggest only about one chance in a thousand of falsely rejecting the null hypothesis that seeding is ineffective in the colder temperature range. For comparison, corresponding values were 0.01 for both the Wilcoxon and the multiresponse permutation procedures tests applied to 24 h EUs in the SH83 study.

The presumed seeding signal in Table 1 is associated with colder temperatures, less than about -9 or -10°C. It is impractical to precisely estimate the higher MRT boundary for seeding effectiveness because each tested sample is made up of a range of temperatures. Low P-values are seen to exist for the coldest third, and two coldest quarters and fifths of the entire population. There is no indication of colder temperatures limiting seeding effectiveness. Only 4% of all periods had a MRT less than -20°C.

Table 1. Main Ridge temperature partitions by fraction of all 6 h periods. MDR is the mean double ratio.

MRT (°C)	N_s / N_{ns}	Pooled R	Wilcoxon P-value	RRT P-value	MDR	Confidence Interval
All Cases						
-35.6 ~ +5.8	360 / 380	0.75	**0.06**	0.11	1.15	0.98 ~ ∞
Halves						
≥-9.2	191 / 178	0.74	0.72	0.63	0.95	0.69 ~ ∞
≤ -9.3	169 / 202	0.78	**0.001**	**< 0.001**	1.54	1.33 ~ ∞
Thirds						
≥ -6.8	117 / 129	0.68	0.84	0.61	0.93	0.56~ ∞
-11.5 ~ -6.9	135 / 114	0.86	0.57	0.35	1.05	0.86 ~ ∞
≤ -11.6	108 / 137	0.79	**< 0.001**	**< 0.001**	1.91	1.66 ~ ∞
Quartiles						
≥ -5.6	91 / 94	0.69	0.66	0.66	0.88	0.45~ ∞
-9.2 ~ -5.7	100 / 84	0.87	0.77	0.36	1.06	0.83 ~ ∞
-13.2 ~ -9.3	88 / 98	0.77	**0.09**	**0.03**	1.44	1.15 ~ ∞
≤-13.3	81 / 104	0.79	**0.003**	**0.003**	1.70	1.41 ~ ∞
Quintiles						
≥ -4.7	71 / 75	0.60	0.60	0.49	1.00	0.45 ~ ∞
-7.8 ~ -4.8	69 / 76	0.81	0.88	0.70	0.88	0.55 ~ ∞
-10.6 ~ -7.9	88 / 66	0.86	0.18	0.17	1.16	0.92 ~ ∞
-14.2 ~ -10.7	70 / 80	0.73	**0.09**	**0.005**	1.84	1.49 ~ ∞
≤-14.3	62 / 83	0.77	**0.006**	**0.03**	1.44	1.14 ~ ∞

4.2. Partitioning by Control Gauge Detection of SWE

Table 2 documents the effect of requiring detectable 6 h SWE at none, one, two or all three control gauges, done to address concerns about the numerous periods without detectable precipitation at one or more control sites. Results are shown only for periods with MRT ≤ -9.3°C as no seeding signal was suggested for the warmer periods. Only partitions with both P-values ≤ 0.10 will be listed in this and the remaining tables with the single exception of Table 7.

A strong seeding signal is suggested by low P-values in each row of Table 2. The tendency for the P-values to increase with reduction in sample size would be expected. The decrease in correlation coefficient (R) with more control gauges receiving snowfall is related to the reduction of T=C=0 SWE cases. Table 2 suggests that seeding was effective no matter how many control gauges detected snowfall, if any.

4.3. Partitioning by Cloud Presence and 700 mb Westerly Wind Component

Rawins were released at the midpoint of each 6 h period only when broken to overcast cloud cover was observed over the Main Ridge with bases estimated below 3050 m. A total of 364 rawins provided usable data during the BRE with some observations missing due to equipment and other problems. All but 9 rawins had 700 mb wind observations. Directions (not speed) were estimated for those nine by reference to other data including synoptic charts. Estimates ranged from 235 to 320 deg (all directions referenced to true north), all typical of storm periods.

Table 3 presents statistical results for 700 mb wind direction partitions with and without the 6% of periods with an easterly wind component. The top row shows analyses using all 364 periods with rawins. Simply partitioning by having a rawin available, meaning cloud criteria were met, provided P-values of 0.03 and 0.05, respectively, with a mean double ratio of 1.24. This is an impressive result, given the strong temperature dependence of seeding effectiveness previously discussed. However, P-values for warmer periods with MRT ≥ -9.2°C were insignificant at 0.62 and 0.43, respectively, compared with ≤ 0.001 values for colder periods shown in Table 3. The suggested seeding signal is clearly associated with colder temperatures.

Results including or excluding easterly winds are very similar as might be expected since only 22 (16) periods had an easterly component for all temperatures (colder temperatures). It is physically implausible that easterly winds would transport AgI toward the BRTA so such periods are not considered in analyses to follow. The median 700 mb wind direction is 279° for periods between 180 and 360° (actual observations were from 192 ~ 359°).

The colder periods have smaller P-values, larger MDRs and tightened confidence intervals, compared with inclusion of all temperatures. These results would be expected with the previously demonstrated strong temperature dependence.

Partitioning was done with the 700 mb wind speed component normal to the north-south Main Ridge. This parameter might be expected to be correlated with SLW production. All 331 periods with rawin speed data and a westerly wind component were subdivided into halves, thirds and quarters. There was no indication of a seeding effect for any partition indicating the normal wind speed component had no detectable relationship with seeding.

4.4. Partitioning by Cloud-top Temperature and Thickness

A common opinion is that the most seedable orographic clouds are shallow with relatively warm tops, perhaps no colder than about -20°C, while deep cold-topped clouds are naturally efficient in converting SLW to snowfall. As a result, the latter are considered to have negligible seeding potential. Grant and Elliott (1974) presented the concept of a cloud-top "temperature window," arguing that seeding can increase precipitation when tops range from about -10 to -24°C. Analyses were based on simple seed/noseed precipitation ratios compared with estimated cloud-top temperatures from seven randomized experiments. Diverse cloud environments and seeding approaches were included ranging from all-season airborne seeding of convective and mixed clouds in Australia to ground pyrotechnic flare seeding of convective bands over California's low coastal ranges to ground-based AgI generator seeding over the Rocky Mountains. The authors of this paper believe there is good

Table 2. Statistical results with different numbers of control gauges detecting SWE and MRT ≤ -9.3°C.

Control Gauges w / SWE	N_s / N_{ns}	Pooled R	Wilcoxon P-value	RRT P-value	MDR	Confidence Interval
0 ~ 3	169 / 202	0.78	**0.001**	**<0.001**	1.54	1.33 ~ ∞
1 ~ 3	92 / 125	0.74	**0.006**	**0.003**	1.46	1.25 ~ ∞
2 ~ 3	61 / 96	0.72	**0.004**	**0.006**	1.41	1.20 ~ ∞
3	35 / 63	0.70	**0.02**	**0.02**	1.35	1.11 ~ ∞

Table 3. Statistical results for noted 700 mb wind direction and MRT ranges. Each period had rawin data implying clouds existed over the Main Ridge.

Wind Dir. Range (°)	N_s / N_{ns}	Pooled R	Wilcoxon P-value	RRT P-value	MDR	Confidence Interval
All Temperatures						
1 ~ 360	181 / 183	0.71	**0.03**	**0.05**	1.24	1.04 ~ ∞
180 ~ 360	169 / 173	0.70	**0.02**	**0.04**	1.28	1.07 ~ ∞
MRT ≤ -9.3°C						
1 ~ 360	88 / 102	0.74	**0.001**	**<0.001**	1.62	1.38 ~ ∞
180 ~ 360	79 / 95	0.74	**0.002**	**<0.001**	1.64	1.39 ~ ∞

reason to doubt the validity of the Grant and Elliott (1974) concept given the broad range of cloud types and seeding methods they included, the lack of controls in the analyses approach, and later published challenges to the Climax I, II and Wolf Creek Pass experiments.

Evidence certainly exists that shallow, warm-topped orographic clouds can have abundant SLW. Examples include Rauber and Grant (1986; 1987). But their 1986 article also presents conceptual models of deep stratiform and convective cloud phases having significant SLW over and upwind of mountain crest-lines, in agreement with Cooper and Marwitz (1980).

Instrumentation to routinely monitor SLW was not available to the BRE although several physical experiments discussed in Part I showed frequent rimed ice crystals on the target area. An icing rate sensor and microphysical observations of ice crystals showed evidence of SLW atop the Bridger Range Main Ridge during a later operational program (Heimbach and Super 1988). Measurements of SLW since development of the microwave radiometer have indicated abundant and frequent SLW during major storm passages at other Rocky Mountain locations. For example, two winters of microwave radiometer-sensing of SLW over the Grand Mesa of western Colorado were summarized by Boe and Super (1986). They noted that SLW production was usually linked to the passage of short-wave troughs or low-pressure centers, and that substantial SLW was often present even during periods with significant natural snowfall.

Super and Huggins (1993) presented SLW flux estimates, based on microwave radiometer and wind observations, and compared them with winter precipitation observations from four mountain ranges in Arizona, Colorado and Utah. None of the data sets supported the concept that large precipitation-producing storms are highly efficient in converting SLW flux to snowfall. The reverse was indicated; i.e., storms with larger precipitation totals tended to have greater SLW flux. This indication suggests that large SLW flux-producing storms may be efficient in snow production during some phases and inefficient during other phases. A case study of a moderate-sized Utah storm supported this conceptual picture.

Huggins (2009) described some important characteristics of SLW in winter storms. He noted that SLW is present at some stage of nearly every winter storm but it exhibits considerable temporal and spatial variability. A number of SLW periods may be interspersed with other periods with none during a given storm passage.

SH83 discussed use of radiosonde temperature-dew point differences for estimation of cloud base and top temperature and cloud thickness. The estimates were approximations at best, especially during 1970-71 winter daylight periods, because of improperly-shielded and ducted relative humidity sensors then in use (Hill 1980). The BRE began using improved humidity ducts as soon as they became available near the beginning of the final 1971-72 winter (exact date unknown). Partitioning of 24 h EUs by cloud-top temperature by SH83 found little if any correlation between suggested seeding effects and cloud-top temperatures. They concluded, “This (these results) does not support the notion that cold cloud tops, with presumed naturally high ice crystal concentrations, reduces or eliminates seeding potential near Bridger Range mountain-top levels.”

The influence of cloud-top temperature on seedability was revisited for the present 6 h analysis and cloud thickness was also considered. Original radiosonde data were discarded long ago and the only observations available to SH83 and this paper are listed in Part II. They are pressure level height, temperature, dew point, wind speed and direction at 800, 700, 600 and 500 mb, respectively; estimated cloud base and top temperature and cloud thickness (last three without reference to altitude or pressure level), 800 mb equivalent potential temperature and the lapse rate between the mean seeding site elevation and 700 mb.

All available 6 h periods with westerly flow and estimates of cloud-top temperature (CTT) and cloud thickness (CTH) were partitioned into halves, thirds and quarters. Results are shown in Tables 4 and 5. Since CTT and CTH are inversely related, with a correlation coefficient of 0.76 for the 315 periods with CTT available, results are similar. A total of 342 periods exist for CTH because 27 cases had no detectable cloud by the criterion used, i.e., estimated thickness was zero.

Tables 4 and 5 show P-values from 0.02 to 0.05 for the entire populations with MDRs of 1.25 and 1.28. These results could be anticipated from Table 3 since populations are the same or very similar. Other P-values near or below 0.05 by both tests were found for the coldest and thickest clouds in each partitioning with MDRs in the range 1.40 to 1.57. The single exception was the 2nd quartile for cloud thickness, from 1068 ~ 1970 m, which has P-values of 0.04 and 0.08 with a MDR of 1.64, suggesting relatively shallow clouds may be seedable. But the results also suggest that seeding was most effective during passage of deep, cold-topped cloud systems. Such results may be unanticipated as cold cloud regions can be expected to naturally nucleate ice crystals. Possible explanations may be that (1) natural crystals formed at high levels did not settle down to the near-terrain zone of orographically-produced SLW before being transported beyond the BRTA and/or (2) natural ice crystal production rates were insufficient to convert all the low-level SLW to snowfall.

Table 4. Cloud-top temperature partitions by fraction of all 315 six hour periods with a westerly wind component at 700 mb. Only partitions with both P-values ≤ 0.10 are listed.

Cloud Temperature (°C)	N_s / N_{ns}	Pooled R	Wilcoxon P-value	RRT P-value	MDR	Confidence Interval
All Cases						
-52.3 ~ -0.2	156 / 159	0.70	**0.05**	**0.05**	1.25	1.03 ~ ∞
Halves – (none qualified)						
Thirds						
-52.3 ~ -31.2	51 / 54	0.77	**0.06**	**0.02**	1.41	1.15 ~ ∞
Quartiles						
-52.3 ~ -35.2	36 / 42	0.79	**0.009**	**0.006**	1.53	1.26 ~ ∞

Table 5. Like Table 4 except cloud thickness partitions by fraction of all 342 six hour periods.

Cloud Thickness (m)	N_s / N_{ns}	Pooled R	Wilcoxon P-value	RRT P-value	MDR	Confidence Interval
All Cases						
1 ~ 5689	79 / 95	0.74	**0.002**	**<.001**	1.64	1.39 ~ ∞
Halves						
1 ~ 2119	40 / 47	0.77	**0.03**	**0.06**	1.52	1.13 ~ ∞
2120 ~ 5689	39 / 48	0.69	**0.02**	**0.005**	1.66	1.37 ~ ∞
Thirds						
1 ~ 1399	28 / 30	0.83	**0.02**	**0.02**	1.78	1.36 ~ ∞
2960 ~ 5689	23 / 35	0.71	**0.03**	**0.002**	1.94	1.59 ~ ∞
Quartiles						
1 ~ 1129	21 / 22	0.85	**0.01**	**0.05**	1.79	1.30 ~ ∞
3565 ~ 5689	15 / 29	0.74	**0.05**	**0.01**	1.91	1.53 ~ ∞

The results of partitioning by cloud thickness and MRT ≤ -9.3°C are presented in Table 6. Low P-values are apparent for all periods and for both the thinner and thicker halves, all with substantial MDRs. Examination of the thirds and quartiles (not shown) revealed insignificant P-values (inconclusive results) for the mid-thickness periods, possibly related to the unusually low target-control correlation coefficients for the middle third and two center quartiles. They ranged only between 0.42 and 0.56, well below more typical values ≥ 0.7. Table 6 suggests seeding was effective, if MRT was sufficiently cold, for both the thinner and thicker cloud periods. The results in this section do not support the view that seeding is necessarily ineffective if thick clouds with cold tops are present.

4.5. Partitioning by Dew point Depression

The 700 mb dew point depression might be expected to provide a better indication of cloud presence upwind of the Bridger Range than just the existence of rawin data. For typical winds and ascent rates rawins would reach the 700 mb level about 8 km upwind of the Main Ridge crestline. Cloud boundaries were estimated by a dew point depression of 3°C or less at 700 mb (Part II, p. 40). The accuracy of that approach is uncertain. However, it can be generally stated that smaller dew point depressions have a higher likelihood of cloud existing over the Bridger Range. For this analysis the median dew point depression of 2.7°C for the population of 342 rawins (easterly flow excluded) was used in Table 7. Results applying higher MRTs and greater dew point depressions are not listed because none were significant. Table 7 shows that partitioning only by the smaller half of dew point depressions results in P-values of 0.01 and 0.03 and a respectable MDR of 1.39, whatever the MRT. Although P-values are similar in the two upper rows, the sample size is halved in the second row suggesting the seeding signal was concentrated within periods with smaller dew point depressions. Additional partitioning by the colder MRTs reduces the P-values by an order of magnitude, increases the MDR to 1.90, and narrows the confidence interval to 1.58 ~ ∞. This dual partition strongly suggests a seeding effect primarily in the colder periods (as previously shown) but also associated with small dew point depressions indicative of moist air and/or clouds extending several kilometers upwind of the mountains where rawin sampling was done. This particular partition is likely the best approximation of the existence of cold SLW cloud over the Bridger Range that can be provided by existing observations. The low P-values of 0.002 by both tests are particularly impressive given the limited sample size. SLW cloud was not monitored during the BRE but later observations atop the Main Ridge detected SLW during 7-9 % of all hours as discussed in Sec. 1.

Table 6. Like Table 5 except by fraction of all 174 six hour periods with MRT ≤ -9.3°C.

Cloud Thickness (m)	N_s / N_{ns}	Pooled R	Wilcoxon P-value	RRT P-value	MDR	Confidence Interval
All Cases						
1 ~ 6231	169 / 173	0.70	**0.02**	**0.04**	1.28	1.07 ~ ∞
Halves						
1971 ~ 6231	84 / 87	0.68	**0.04**	**0.01**	1.42	1.18 ~ ∞
Thirds						
2754 ~ 6231	55 / 59	0.69	**0.05**	**0.01**	1.48	1.21 ~ ∞
Quartiles						
1068 ~ 1970	43 / 43	0.75	**0.04**	**0.08**	1.64	1.14 ~ ∞
3265 ~ 6231	36 / 50	0.69	**0.04**	**0.008**	1.57	1.28 ~ ∞

Table 7. Statistical results for noted dew point depression and MRT partitions.

Dew point Depression (°C)	MRT (°C)	N_s / N_{ns}	Pooled R	Wilcoxon P-value	RRT P-value	MDR	Confidence Interval
All	All	169 / 173	0.70	**0.02**	**0.04**	1.28	1.07 ~ ∞
≤ 2.7	All	79 / 95	0.67	**0.01**	**0.03**	1.39	1.12 ~ ∞
≥ 2.8	All	90 / 78	0.73	0.21	0.34	1.10	0.77 ~ ∞
≤ 2.7	≤ -9.3	40 / 51	0.59	**0.002**	**0.002**	1.90	1.58 ~ ∞

4.6. Partitioning by Individual Winters and Halves of Day

In addition to analyses of the combined two winters of the BRE, SH83 analyzed each winter separately for colder MRTs. This approach approximately halved the sample size, providing a demanding test. Analogous tests are presented here with 6 h periods providing larger sample sizes, but limited to periods with a westerly wind component. Table 8 shows results for MRT ≤ -9.3°C. The BRE was suspended during the month of March 1971 because of well-above normal snowpack, partially explaining the smaller sample size that winter.

Table 8 is divided into two portions. First considered is the upper portion which partitions the total sample by individual winters. It is shown that low P-values and high MDRs result for each winter. Target-control correlation coefficients were high with the control gauges explaining 55% of the natural variance in each winter. Finding strong statistical suggestions of effective seeding for separate winters adds to the credibility of the overall results. It is less likely that a Type I error occurred since each winter showed low P-values.

The lower portion of Table 8 examines 6 h populations split from the first and last half of each 24 experimental day. Partitioning by each 6 h time period (e.g., 1200 - 1800 MST) was attempted but the results were unstable with widely differing P-values and MDRs. This was likely due to small sample sizes, ranging from 34 to 48. It is seen that approximately halving the entire population, in this case by splitting 24 h days, again resulted in low P-values and high MDRs. This provides further evidence that a Type I error was unlikely for analyses of the overall population.

Comparison of the markedly lower P-values in the combined middle row with those by partitioning by individual winters, or by first and last half of each day, illustrates the sensitivity of statistical analysis to sample size.

4.7. Testing by Least-squares Regression

Given the previous discussion, a seeding effect should be evident in the relation between the target and control data. A widely-known and easily understood relation is the linear least-squares regression where for this application the target SWE, $\hat{T} = a + b\bar{C}$.

Table 8. Statistical results for partitioning by separate winters (upper 2 rows) and 12 h periods from the first and last half of each 24 h EU (lower 2 rows). The MRT was ≤ -9.3°C with the 700 mb wind direction

Winter	**N_s / N_{ns}**	**Pooled R**	Wilcoxon P-value	**RRT P-value**	**MDR**	**Confidence Interval**
1970/71	24 / 45	0.74	0.02	**0.08**	1.42	1.07 ~ ∞
1971/72	55 / 50	0.74	0.02	**0.004**	1.79	1.45 ~ ∞
Combined	79 / 95	0.74	0.002	**<0.001**	1.64	1.39 ~ ∞
Noon to Midnight	44 / 50	0.82	0.03	**0.02**	1.57	1.24 ~ ∞
Midnight to Noon	35 / 45	0.62	0.01	**0.01**	1.75	1.39 ~ ∞

The average control SWE is indicated by $\overline{C}$. If there is a positive seeding effect, the seeded slope, $b_{S,}$ will be greater than the nonseeded slope, b_{NS}. One way to test the null hypothesis of homogeneity among the slopes is to apply an analysis of variance (ANOVA) to find an F_s statistic (Sokal and Rohlf 1969),

$$F_s = \frac{MS_{\text{Variation Among Regressions}}}{MS_{\text{Unexplained by Regression}}}. \qquad (5)$$

F_s is compared to critical values of $F_{\acute{a}[1,s+ns-4]}$ to determine the P-value of a Type I error. Since an ANOVA cannot differentiate variance due to positive or negative effects, the test is 2-tailed.

Application of this ANOVA to the partitioned data of the last line of Table 3 produced a 2-tailed P-value of 0.042. The 1-tailed P-value is half this or 0.021, suggesting that the two slopes are not from the same population, i.e., there is a seeding effect. This simple regression analysis confirms the encouraging results from the more robust Wilcoxon and rerandomized ratio tests.

5. DISCUSSION

5.1. Summary of Statistical Suggestions

Post-hoc exploratory analyses of BRE 6 h data strongly suggest that AgI seeding was effective in enhancing snowfall in the sample population with MRT ≤ -9.3°C, the median value. This is essentially the same result reported by SH83 using 24 h EUs (N = 92) but the statistical significance is greater with the larger 6 h sample size (N = 371) and tighter association with weather parameters. It was impractical with the statistical testing to precisely estimate the warm temperature limit for *effective* seeding which, in any event, might only apply to the particular AgI complex, generator type, release rate, terrain configuration and cloud conditions of the BRE. But the best statistical evidence from Table 1 is that the limit was near -9°C. Seeding likely produced some effective IN at temperatures a few degrees warmer but in concentrations too low for meaningful snowfall production, unless AgI was released within SLW cloud ≤ -6°C allowing forced condensation-freezing to occur. It may not be coincidence that -6°C at the seeding sites corresponds to a MRT near -9°C for in-cloud lapse rates. Claims that AgI seeding with newer complexes can produce meaningful snowfall rates at higher temperatures may be true but have yet to be documented.

A seasonal SWE increase of 15% was suggested by the mean double ratio for all 6 h periods with a 54% increase indicated for the colder half. The mean (median) nonseeded target SWE for the colder half was 0.620 (0.178) mm per 6 h so a 54% increase is equivalent to a *hourly* rate of 0.056 (0.016) mm. Actual seeding increases per individual periods are unknown but could be expected to range from zero to several times the above rates. That range is in reasonable agreement with the survey by Huggins (2009) which indicated that short-term seeding experiments revealed precipitation rate increases of a few hundredths to >1 mm h^{-1}.

Analyses of periods with available rawin observations (cloud cover observed) produced low P-values by both tests regardless of temperature. The MDR for westerly flow component periods was 1.28 (28% increase). Including the requirement of MRT ≤ -9.3° indicated about one chance in a thousand of incorrectly rejecting the null hypothesis with a suggested 64% SWE increase from seeding. The associated 1-tailed confidence interval (1.39 ~ ∞) showed a 95% chance that the increase was at least 39% for this dual partition. It had a sample size of 174 or about half of the single partition of MRT ≤ -9.3°. This favorable dual partition was further tested by applying ANOVA to compare seeded and nonseeded slopes from least-squares regression. This simple approach resulted in a 1-tailed P-value of 0.02.

A reviewer raised the possibility of a natural sample bias (bad draw) for the colder periods in spite of substantially reducing (but not eliminating) natural variance with control gauges. Statistical testing cannot totally rule out that possibility. An attempt was made to address that concern by further testing the same dual partition by approximately halving the overall sample by (1) separately testing each winter and (2) testing the first and last half of each day. Impressive results were calculated for all four of these subdivisions, each with relatively small sample sizes. This stringent testing adds credibility to the hypothesis that suggested seeding effects were real and not the result of multiplicity or natural sampling bias.

Partitioning by estimated cloud-top temperature or cloud thickness suggested that presence of deep, cold-topped clouds does not necessarily rule out seeding effectiveness. A number of investigations have suggested that large SLW flux-producing storms may be inefficient in snow production during some phases but efficient during other phases (Huggins 2009).

Dual-partitioning by westerly wind component and 700 mb dew point depression ≤ the 2.7°C median resulted in P-values of 0.01 and 0.03 with a 1.39 MDR. Including the additional partition of MRT ≤ -9.3° decreased P-values to 0.002 by both tests with a MDR of 1.90. The sample size for the latter was limited to 91 periods, about half the 174 size of the dual partition and a quarter of the single colder MRT partition with N = 371. Consequently, the results suggest that seeding was especially effective if moist air and/or cloud was present just upwind of the Main Ridge, sufficiently cold for AgI nucleation. This would be expected from physical reasoning and thereby adds credibility to the statistical suggestions.

5.2. Physical plausibility

The most fundamental element for any RWOE should be a demonstrated capability to target clouds as intended. Yet, based on review of several other RWOEs and various plume tracing studies, it is the authors' opinion that most previous RWOEs had frequent failures to seed as planned. Orographic clouds have either been infrequently seeded (mistargeting, trapping, generator failures), seeded with effective IN concentrations too low for meaningful snowfall production (Super 1999), and/or seeded with generators too widely spaced resulting in untreated gaps between AgI plumes (Griffith *et al*. 1992). In discussing the results of a propane-seeding RWOE in the Sierra Nevada, Reynolds (1996) concluded, "Again, it would seem imperative that detailed transport and dispersion studies be preformed prior to the onset of any long-term snowfall enhancement program in order to confirm that successful targeting is possible for a majority of storm periods when liquid water is observed." The authors of this paper fully agree.

The most important physical evidence in support of the BRE is the considerable documentation that orographic clouds were regularly seeded. Moreover, sufficiently high concentrations of effective AgI IN resulted with colder seeded zone temperatures. As discussed by Super (1974) and SH83, many below-cloud aircraft passes over the Bridger Range showed AgI plumes were consistently transported over both the Main and Bangtail Ridges as detected by an acoustical IN counter. The AgI was largely confined to within ~ 450 m of the Main Ridge crestline. Such low level aircraft sampling over mountain peaks is not permitted within cloud because of safety concerns. Plume widths from the southern generator, 4.7 km upwind of the crestline, were usually in the 10-30° range over the Main Ridge. Long after the BRE, in-cloud sampling of AgI plumes from the southern generator site was done as low as 300 m above the highest (2433 m) BRTA terrain (Super and Heimbach 1988). Plume widths ranged between 5-8 km (16-26°) while tops were detected from 2.7 to 3.3 km on each of six aircraft missions. Orographically-produced SLW cloud is concentrated in this same zone, within 1 km over mountainous terrain, as shown by studies summarized by Super (1999) and Huggins (2009).

Further evidence of appropriate AgI targeting was discussed by SH83, and Heimbach and Super (1988). To briefly summarize, numerous pilot balloons (pibals) of known still air ascent rates were tracked by the dual-theodolite method from each seeding site. The observations demonstrated that the vertical wind speed just west of the Main Ridge crestline was essentially forced by the terrain slope. The 3050 m wind direction was a good predictor of the mean wind direction for the layer in which AgI was transported up the west slope of the Main Ridge. There was little indication of changes in wind direction near plume tops between the Main Ridge and BRTA. However, prevailing southwest winds were measured at the BMO which may have transported AgI and seeded crystals more northward than suggested by 700 mb winds.

End of season silver-in-snow analyses during the BRE (SH83), and later sampling reported by Heimbach and Super (1988), showed widespread Ag concentrations well above background levels over intended targets. Large fractions of the total Ag released during the BRE while snowfall was detected near the BMO were found in the BRTA snowpack. Scavenging by natural snowfall could explain an unknown fraction of the observed silver enhancement. But finding increased Ag in the seasonal snowpack provides further evidence that the AgI plumes were often transported over the target areas. Finally, acoustical ice nucleus counter observations at both the BMO and MRO observatories (see Fig. 1) frequently detected AgI plumes atop the Bangtail Ridge (Part I) and Main Ridge (Heimbach and Super 1988). There is no reason to doubt that AgI plumes were routinely transported over the BRTA with widths sufficient to affect much of the target area at any given time. Meandering winds and wind shear would be expected to further broaden the affected area.

The question remains whether *effective* AgI particle concentrations were sufficiently high to result in meaningful snowfall rates. On the Grand Mesa of Colorado (Super *et al*. 1986) and the Wasatch Plateau of Utah (Super and Heimbach 2005b) many hours with "trace" precipitation, < 0.13 mm (0.005 inch) or less, contributed only a few percent to the total seasonal SWE and can be considered trivial. Seeding-caused snowfall must often exceed trace rates to be meaningful, which leads to discussion of required seeded ice particle concentrations (hereafter IPCs).

Holroyd and Super (1998) used observations from a wind vane-mounted 2D-C optical array probe and nearby high resolution gauge on the Wasatch Plateau to show that most natural ice particle concentrations (IPCs) exceeded 10 L^{-1} when precipitation rates were more than trivial. The same instrumentation and location were later used by Super and Heimbach (2005a). They concluded that a minimum of 20 L^{-1} was probably a more realistic threshold for seeded snowfall to exceed hourly trace amounts. These threshold values are similar to the low end of the 10 to 100 L^{-1} effective seeding range calculated in the classic paper by Ludlam (1955). The BRE attempted to achieve that range for typical conditions as discussed by Super (1974). He showed that aerially-sampled AgI plumes passing over the Main Ridge would, for average conditions, be exposed to temperatures from about -13 to -10°C. Given AgI generator calibrations results and aircraft-observed AgI plume widths and depths over the Main Ridge, it was estimated that approximately 10 to 100 effective IN L^{-1} would result for typical temperatures during snowfall. Discussion in the 1972 Part I report stated, "A recent calibration of one of the generators used on the Bridger Range experiment has revealed that the number of effective nuclei per gram of silver iodide decreases rapidly as the temperature is increased above about -10ºC. Thus, little nucleation is to be expected for temperatures warmer than -10ºC." Statistical analyses done by SH83 and herein suggest that long-ago expectation was met.

Direct IPC observations with an aircraft 2D-C particle imaging probe were made over the BRTA in January of 1985 (Super and Heimbach 1988). Three missions had clear evidence that the AgI plume encountered SLW cloud over the BRTA when the MRT was between -9 to -10°C. Twenty crosswind passes showed AgI-caused IPC increases ranging from 3 to 21 L^{-1} with only two values below 7 L^{-1} and a median of 14 L^{-1}. These are very likely conservative values because a large fraction of seeded crystals should have fallen below safe aircraft sampling altitudes. These observations and the above estimates of effective AgI IN all suggest that BRE seeding should have produced sufficient IPCs for meaningful snowfall production when SLW cloud temperatures were less than approximately -10°C. These physical results are in excellent agreement with the statistical suggestions presented herein which indicate seeding was effective for MRTs colder than about -9°C, with corresponding AgI plume top temperatures below -12°C. This apparently effective seeding temperature range coincides well with the rapid ice crystal mass growth range, peaking between -11 to -17°C according to Redder and Fukuta (1989), providing further physical plausibility to the statistical suggestions.

A nucleation process unknown at the time of the BRE offers another plausible reason to expect effective BRE seeding during some storm conditions. The rapid "*forced*-condensation freezing" mechanism functions immediately downwind of AgI generators operated in ice or water saturated conditions if the ambient temperature is less than -6°C (Finnegan and Pitter 1988; Chai *et al*. 1993). Combustion of acetone and propane releases considerable water vapor resulting in a local zone of high supersaturation. The BRE seeding sites were often in-cloud during storms and had temperatures < -6°C when the MRT was ≤ -9°C. Ice crystals formed just above the generators should have been transported upslope in the SLW cloud production zone. Such early nucleation would significantly prolong the period available for seeded crystal growth and fallout, and might explain suggested near-source increases in snow on the lee slopes of the Main Ridge (SH83, Sec. 8; Heimbach and Super 1988).

Partitioning by availability of a rawin observation with a westerly wind component at 700 mb strongly suggested that seeding was particularly effective within the subpopulation with broken to overcast cloud cover over the Main Ridge and bases below 3050 m. Further partitioning by dew point depression provided even stronger evidence for the half of periods most likely to have moist air or cloud upwind of the Main Ridge. Such conditions could be expected to likely have SLW cloud production in forced uplift over the Bridger Range. These are physically plausible results since SLW cloud is the "raw material" necessary for seeding to be effective. When those partitions were combined with MRT less than or equal to the median of -9.3°C, even more significant P-values resulted as expected from the previously demonstrated temperature dependence of seeding effectiveness.

6. CONCLUSIONS AND RECOMMENDATIONS

The strong statistical suggestions from two independent analyses of BRE 6 h periods can be briefly summarized as follows:

- Seeding appeared to be most effective when atmospheric conditions favored orographic production of SLW cloud over the Bridger Range with crestline temperatures colder than the median of -9.3°C. Corresponding AgI plume top temperatures would be less than -12°C.

- There was no evidence that seeding decreased snowfall, even with the coldest temperatures experienced. Seeding apparently increased snowfall for both small and large storms since low P-values resulted no matter how many control gauges detected snowfall, how cold cloud tops were, or how thick the clouds.

- Mean double ratios and confidence intervals suggested the relative increase was larger for smaller storms.

- The seasonal increase to be expected from operational seeding was estimated as 15% by the MDR calculated for all 6 h periods.

It is strongly recommended that a relatively small RWOE be conducted using a simple design with EUs declared only by real-time observations of SLW cloud near the windward crest. Such observations make it practical to totally automate an experiment on a 24/7 basis as demonstrated by Super and Heimbach (2005a). The experimental area should be carefully selected to permit practical over-snow travel to a dense precipitation gauge network and other surface instrumentation sites. Sufficient conifer forest should exist to provide well-protected locations for snowfall observations. As a matter of practicality the target area should be limited in crosswind extent so that it can be regularly impacted by no more than four high elevation seeding sites spaced 4-5 km crosswind. A minimum of one target and one crosswind or upwind mountain observatory should be maintained for microphysical observations because cloud microphysics is still imperfectly understood even though it is fundamental to understanding variations in seeding effectiveness. Experimental unit duration should be no longer than about 3 h given known variability in SLW and natural snowfall. At least one winter should be devoted to a complete "shakedown" of all design and observational aspects, definitely emphasizing seeding plume tracking, prior to initiation of a randomized experiment.

Modern remote-sensing instrumentation and model simulations should, of course, be part of any future RWOE. But care should be taken so that the related high expense does not reduce funding needed to accomplish the fundamentals of proper seeding, monitoring transport and dispersion of seeding plumes and the primary response variable of snowfall on the ground. Scientists have a natural tendency to give a high priority to what is new, different, "cutting-edge," and of particular interest to them. The overall goal of some past RWOEs has not been met in part because of misplaced priorities with the fundamentals taken for granted.

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