EVALUATION OF THE WYOMING WINTER OROGRAPHIC CLOUD SEEDING PROGRAM: DESIGN OF THE RANDOMIZED SEEDING EXPERIMENT

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1. INTRODUCTION

The Wyoming Weather Modification Pilot Program (WWMPP) is funded by the State of Wyoming through the Wyoming Water Development Commission (WWDC), and is unique among state-sponsored programs in that it includes a substantial evaluation component. The main purposes of the WWMPP are to establish an orographic cloud seeding program in three target areas (the Medicine Bow Range, Sierra Madre Range and Wind River Range) and evaluate the feasibility and effectiveness of the cloud seeding. The logistics, infrastructure, and operations of the program are covered under a contract with Weather Modification Inc. (WMI), while the evaluation activities fall under a separate contract with the Research Applications Laboratory (RAL) of the National Center for Atmospheric Research (NCAR).

Figure 1. *Map of Wyoming with coarse representation of topography and land use. Red outlined areas denote the three mountain ranges selected for cloud seeding operations: Medicine Bow, Sierra Madre, and Wind River. The randomized seeding experiment involves only the two southern ranges, the Medicine Bows and Sierra Madres.*

Natural precipitation in winter storms develops and falls out when clouds: a) contain sufficient condensate (usually in the form of supercooled liquid water or SLW); b) exist in a temperature range for efficient ice nuclei (IN) activation and crystal growth; c) form in conditions conducive to snow development (riming or aggregation); and d) have sufficient time for ice particles to develop, grow, and fall onto the barrier (or target area in this case). Many storms are thought to be naturally inefficient in producing snowfall because they lack a sufficient number of IN active at the cloud temperatures where significant SLW is found. Such clouds may possibly be made more efficient by supplying additional IN in these regions of SLW – the essence of cloud seeding.

Attempts to increase snowpack by seeding clouds have been carried out for well over fifty years. Average increases of 10 to 15% have been reported in some experiments, but the topic remains controversial and many operational programs and scientific experiments have ended without conclusive results. Because of the large natural variability of precipitation and the relatively small seeding effect expected, it is generally believed that no single analysis can be convincing regarding the effect of seeding. Rather, it is necessary to build multiple layers of evidence, both statistical and physical, to provide a consistent picture of the effect of cloud seeding.

Two general approaches are guiding the evaluation of the WWMPP: 1) a randomized experiment that builds distributions of seeded and control (unseeded) cases, and 2) exploratory studies to investigate a wide variety of ideas on detecting seeding effects, including physical studies to document the precipitation formation events hypothesized to be important to snowfall production in orographic storms. This paper addresses the first approach – the design of the randomized seeding experiment.

2. DEPLOYMENT OF RESOURCES

Resources used for carrying out the experimental design include 16 ground-based seeding generators (8 in each range), 21 precipitation gauges at 8 sites (with redundancy at each site and some experimental gauges), 12 weather stations (at each gauge site and four at generator sites), two microwave radiometers for detecting SLW, a radiosonde unit ("weather balloon" for measuring temperature and winds at cloud heights), and a numerical forecast model cycling every three hours with updated observations. The seeding generators, radiosonde unit, and one radiometer are operated by WMI, and the precipitation gauge network, one radiometer, and forecast model are operated by RAL/NCAR. Figure 2 shows all of the resources deployed in the southern mountain ranges.

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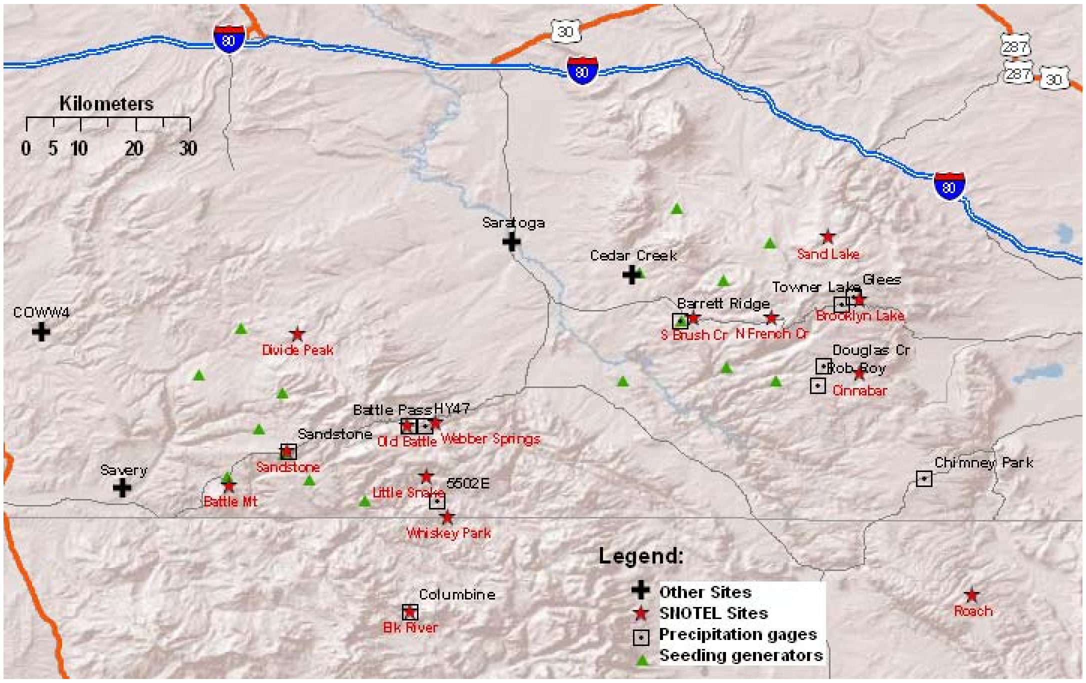

Figure 2. *Instrument sites and operational networks in the southern mountains of Wyoming (Medicine Bows to the east, Sierra Madres to the WSW). The precipitation gauge sites are indicated by a square; SNOTEL sites are indicated by red stars; AgI generator sites are indicated by green triangles; and other sites are indicated with bold crosses. Savery and Cedar Creek are radiometer sites, and the Saratoga site is where soundings are released. (COWW4 is the Cow Creek Remote Automated Weather Station site. The precipitation gauge sites 5502E, Douglas Creek, and Rob Roy are no longer active.)*

3. OVERVIEW OF THE DESIGN ELEMENTS

The following list highlights some details of the design elements of the randomized seeding experiment. These were established in 2007 and subsequent studies have modified some of the estimates, such as correlations, sample size, and annual number of cases, which are discussed in Section 4.

- Target areas have been identified near the crests of the Medicine Bows and the Sierra Madres, encompassing the existing SNOTEL sites at Brooklyn Lake and Old Battle (shown in Fig. 2). The SNOTEL data indicated that these target areas receive significant snowpack during a season [15 November – 15 April]. These sites were also chosen to take advantage of the existing instrumentation and historical precipitation and climate data.
- Seeding generator sites have been chosen to affect the target areas under predominant wind directions (roughly from the southwest, west, and northwest directions). Their location on Forest Service lands required long permitting lead time and acceptable forest clearings. The spacing of generators was roughly determined from results of past studies, taking into account practical siting considerations, and was further characterized with plume modeling.
- A majority of the storms in this region affect both ranges. This is evident from the relatively high correlations of ~0.5 for daily snowfall between the ranges using SNOTEL data from sites in or near the target areas within each range.
- A cross-over design is planned, in which one range is randomly determined to be seeded while the other becomes the control. This results in paired cases.
- The seeding treatment period will be kept short (4-hr) to strive for homogeneous conditions as well as to obtain a greater number of cases.
- A buffer time period of 4-hr will be used between consecutive treatment periods to clear the area of seeding material.
- High-resolution precipitation measurements will be made using gauges (resolution 0.1 mm, recorded in 5-min periods) at both target and control sites in each range.
- Two closely-spaced (~2 km apart) sites will be used in each target area in the respective ranges and averaged to decrease the variance in the precipitation measurement at each site.
- Two control sites, one largely upwind and one largely cross-wind, will also be used in each range and treated independently in the statistical evaluation. The control sites will be used to help describe the natural variability in precipitation between targets and between events.
- Case selection requires: temperatures that are cold enough for efficient AgI IN activation; wind

direction that is appropriate for some AgI generators to impact the target; and the presence of SLW. These criteria should be satisfied in both target ranges simultaneously.

- The primary statistical test will be based on ratios – summation of 4-hr accumulated precipitation at target gauges for seeded versus unseeded events, scaled by the ratio of 4-hr accumulated precipitation during seed/no-seed events at control gauges.
- A secondary statistical test (Wilcoxon-Mann Whitney) will be performed on residuals – difference between 4-hr accumulated precipitation at target gauges and an accumulation based on predicted response at the target area using control gauges. Other tests may also be performed.
- The ratio test will be used to evaluate the null hypothesis that the ratio of the total measured precipitation for seeded versus unseeded conditions is equal to 1. A ratio significantly greater than one would suggest evidence for the effectiveness of the seeding method (see Gabriel, 1999).
- An estimate of the number of paired cases to be expected in an average season is about 60-70.
- The number of samples needed for statistical significance is estimated to be of the order of 165 to 360 to detect a 15% to 10% precipitation increase.
- Aside from the primary uncertainty of whether seeded clouds will produce additional precipitation, the other uncertainties in this design relate to the dispersal of the seeding material and the subsequent dispersal of seeded snow crystals. Are the generators sited appropriately to affect the small area of the instrumented target sites? Will seeded snowfall contaminate the control gauges? Will AgI released from the upwind range, the Sierra Madres, affect the Medicine Bows? The issues of targeting uncertainty and contamination potential will be at least partially assessed through collection of silver-in-snow samples and occasional ice nuclei measurements in the Medicine Bow target area.

4. ESTIMATES OF SAMPLES NEEDED AND EXPECTED

The number of samples needed for statistical significance depends on several factors, as shown in the equation below (Gabriel, 1999; Eqn 6).

$$n_{RRR} = 2\sigma^2\left(1-\tau\right)\left(1-\left(\frac{\kappa-\gamma}{1-\tau}\right)^2\right)\left[\frac{Z_\alpha + Z_\beta}{\ln\left(1+\delta\right)}\right]^2$$

The first term, σ^2, refers to the relative variance of the precipitation amounts; the second term takes into account the correlation (τ) between the two target ranges; the third term includes correlations between control sites and the target ranges; and the fourth term contains variables dependent on the significance level, power, and the (assumed) effect or increase in precipitation. A range of significance levels and power of the statistical test (variables in the fourth term) were investigated using past experiments, and were used in the equation to determine sensitivity to various but appropriate values. The final design settled on a significance level of 0.95 (representing a guard against false positives) and a power of 0.80 (representing a guard against false negatives). Various levels of effects or precipitation increases (δ) can be assumed and used in sensitivity trials.

While the initial studies relied on historic data (e.g., from SNOTEL sites) to estimate the number of cases likely to be gathered in a season and the total number of cases needed for statistical significance (given some assumptions), data collected during actual cases have begun to refine those original estimates. Two key variables that directly affect the number of cases needed for the experiment are measurement variance (i.e., the variations of snow amounts that fell during cases) and correlation between ranges (i.e., how closely snowfall amounts in each range track each other for the cases).

The best estimates prior to the collection of any data in the target ranges were based on rather coarse measurements from SNOTEL sites, and showed correlations between target ranges of 0.60, with correlations to nearby controls of 0.80 and far controls of 0.54. Using the initial variance values and the uncertainty in the correlation estimates, the number of cases needed to detect a 15% increase in precipitation was calculated to be 166 (147-328). For 10%, the number of samples was 358 (315-704).

A variety of methods were used to estimate the seasonal number of cases that might be expected to meet the seeding criteria. These involved daily SNOTEL data, one season of WRF numerical model runs, and extrapolation from short periods of high-resolution precipitation data. (A major weakness in the estimate is that not all the seeding criteria variables were available or considered, such as temperature at 700 mb, for each snow event or case.) Without explaining all the details, the overall result suggested that 60-70 cases per season might be expected under ideal situations.

Following two seasons of precipitation data and case selections, a re-examination of the number of cases expected and updates on correlations and variances was done. This re-examination was performed only to validate or demonstrate variability in the initial estimates and was not used to alter the experimental design in any way.

First, the actual number of cases selected in a season (35-40 per season) was about half of what was expected. This is largely due to case selection criteria, particularly temperature at 700 mb, not considered in the initial estimate, as well as a variety of other factors (e.g., ending the season early due to high snowpack, a larger buffer period in the experiment than was used in the initial estimates, etc.).

Second, correlations and precipitation variance were calculated from cases during two seasons. The number of cases is still quite small, so there is the possibility for high variability in these values. The correlations are not much different than the initial estimates. Using only one season, the target-target correlation seemed to be higher (~0.7) than was initially estimated but precipitation in an additional season was less correlated such that the overall correlation of the two seasons was ~0.6. The same was true for the control-target correlations. The precipitation variance is lower than initially estimated: ~0.61 versus 1.12. That value has been steady from season to season, which might be expected given that winter orographic precipitation at the 4-hr time period is not highly variable (unlike convective precipitation). The initial estimate used coarse-resolution data over longer time periods, both of which contributed to a higher variance.

Using the more representative data to estimate variance and correlations, the number of samples needed to detect a 10% effect was calculated to be 209 (with a range of 77-282). This updated estimate is less than initially calculated, mostly due to the change in the precipitation variance. This suggests that the lower number of cases per season currently being experienced will not be as limiting as first thought. However, this exercise points out the necessity of collecting appropriate data prior to an experiment in developing a final experimental design. A recent example of this is the seeding experiment designed for the Snowy Mountains in Australia (Manton et al., 2011).

5. COMMENTS

Elements of the cross-over design for a randomized seeding experiment of winter orographic storms for two southern mountain ranges in Wyoming have been described. An updated estimate of the number of cases needed to detect a 10% increase in precipitation (snow water equivalent or SWE) suggests a number of ~200. Although the number of cases eligible in a season is less than expected (35-40), it appears that five years of seeding (on a randomized basis) will sample enough cases to provide an acceptable level of confidence in the results (assuming an effect of at least 10%). This is still in line with expectations when the program was originally funded, even though those expectations were based on very coarse estimates and assumptions.

A number of issues remain, particularly regarding effective targeting and potential contamination between ranges, which need to be assessed within the framework of the experimental design. The second path of the evaluation approach – exploratory studies – is addressing some of the issues as opportunities arise. For example, ice nucleus measurements have been made at ground-level within the Medicine Bow target area (about 15-30 km from the seeding generators). The results are mixed with most but not all Medicine Bow plumes identified and a significant number of AgI plumes from Sierra Madre seeding operations showing up in the Medicine Bows. An example of a Medicine Bow plume is shown in Figure 3. Airborne measurements are planned for February 2011 to better characterize seeding plumes and provide data for comparison to numerical model simulations.

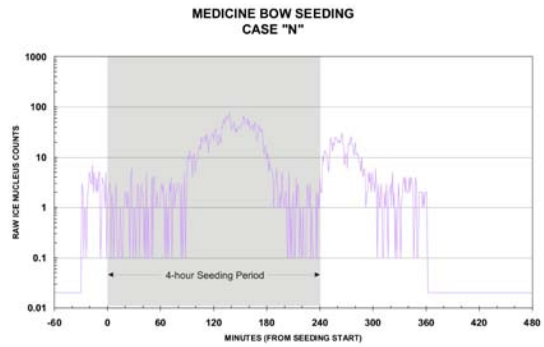

Figure 3. *An example of measurements (counts) from an acoustic ice nuclei counter located in the Medicine Bow target area. Time-series trace shows elevated counts 90 min after seeding started with a break in the plume from about 200-240 min.*

A precipitation process study by Geerts et al. (2010) showed seeding effects from airborne w-band radar measurements that are encouraging in their elucidation and validation of the conceptual model of AgI seeding in winter storms. However, the number of cases was very limited and another field campaign in 2012 is planned to extend the study with more airborne measurements in conjunction with ground-based measurements and remote sensors (K-band radar observations). This and other collaborative studies have proven very effective in enhancing the evaluation component of the WWMPP.

6. REFERENCES

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