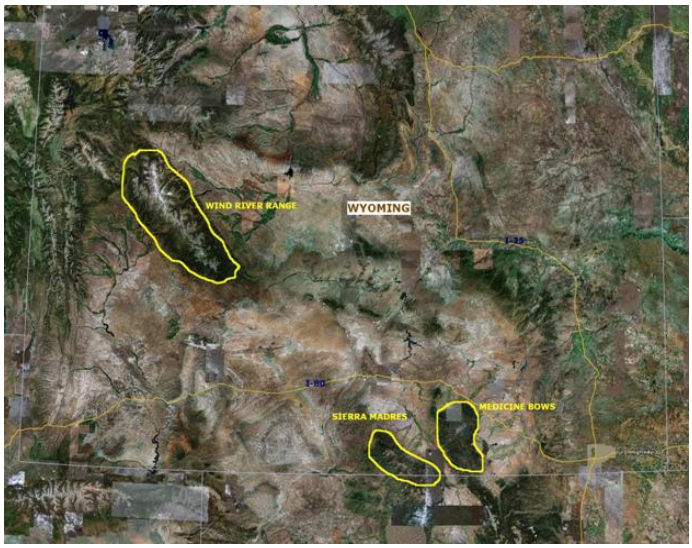
The Wyoming Weather Modification Pilot Program (WWMPP), funded by the State of Wyoming through the Wyoming Water Development Commission (WWDC), has established an orographic cloud seeding research program in three target areas (the Medicine Bow Range, Sierra Madre Range and Wind River Range). It is unique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

Background

Natural precipitation in winter storms occurs when clouds: a) contain supercooled liquid water (SLW); b) exist in a temperature range where small particles, ice nuclei, will cause some of the SLW to freeze, forming ice particles; and c) persist long enough for the ice particles to grow and fall to the ground. Many clouds are naturally inefficient in producing snow because there are few ice nuclei active at the temperatures in the cloud where significant SLW is found. Such clouds may be induced to precipitate by supplying artificial ice nuclei in the regions of SLW. This is the essence of cloud seeding.

Programs 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 research experiments, but the technology still has many skeptics. Few operational programs have peer-reviewed evaluation plans, and the majority of scientific experiments have ended without conclusive results. Because of the large natural variability of precipitation, and the relatively small seeding effect expected, multiple layers of evidence, both statistical and physical, are required to provide a consistent picture of the effect of cloud seeding.



The evaluation of the WWMPP is based on two avenues: a) a statistical experiment to collect a randomized set of seeded and unseeded cases, and b) exploratory observations to investigate the different physical processes in cloud seeding to show that the seeding hypothesis is physically-based. Collaborations with other scientists, particularly those at the University of Wyoming, have led to "piggy-back" studies applicable to the assessment of seeding impacts on precipitation formation and eventually on streamflows.

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

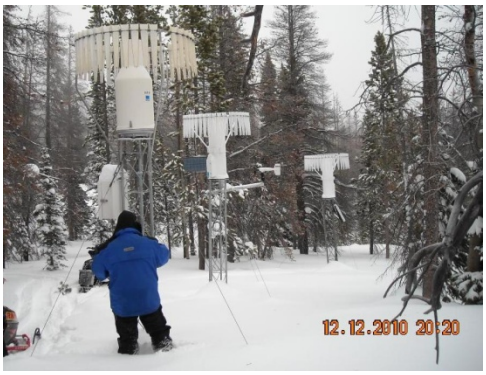
The Randomized Experiment

At the end of 2007, after initial measurements and required permits were obtained, the Medicine Bows and Sierra Madres were established as targets for a randomized winter time cloud seeding experiment, using ground-based seeding generators, with an annual seeding period from 15 November through 15 April. High-resolution

precipitation gauges were deployed for snowfall measurements, along with auxiliary instruments to assist in determining seeding conditions and seeding impacts. Non-randomized seeding was planned for the Wind River Range, with evaluations based on SNOTEL data and numerical modeling.

The randomized seeding experiment (RSE) design includes the following: 1) target areas near the crests of the Medicine Bows and Sierra Madres; 2) a cross-over design in which one range is randomly seeded and the other acts as the control, resulting in paired cases; 3) a seeding period of four hours with a "buffer" period of four hours to clear the areas of seeding material; 4) high-resolution precipitation gauge measurements within each target area; 5) two control gauge sites (unaffected by seeding) in each range to help describe the natural variability in precipitation between target areas, and between snowfall events; 6) seeding conditions occurring in each range simultaneously (i.e., cold enough temperatures for the seeding material to work, wind flow of the right direction for the seeding generators to affect snowfall in the target areas, and the presence of SLW); and 7) enough cases to provide quantifiable results with statistical significance (i.e., high level of confidence in the results).

Resources used for carrying out the experimental design include 16 ground-based seeding generators (8 in each range), 20-23 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 (balloon-borne instrument 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. The precipitation gauge network, one radiometer, and forecast model are operated by RAL/NCAR.



Preliminary Results ~ May, 2012

The design of the RSE included estimates of the number of cases required to achieve a statistically significant conclusion on the effect of seeding, based on several assumptions regarding precipitation characteristics (from SNOTEL data) and a range of possible seeding effects. As the experiment has progressed, estimates of the required sample size are able to be refined, based on the measured precipitation characteristics. These characteristics include the quality of the precipitation data, the correlation in target areas between the ranges, and the variability of precipitation amounts during the 4-hr periods of the cases. These new estimates and the cases sampled thus far can then be used to address the two main questions regarding the progress of the program: How many cases are needed, and what are the seeding effects to date?

Updated sample size estimates were recalculated, and indicate that roughly 50-60 more cases are needed to reach a statistically significant conclusion, assuming a seeding effect of 10% or more. This implies that two more seasons are needed, at the current rate of ~25-30 cases per season, to complete the experiment. Funding for the final two seasons was recently approved in an extension of the WWMPP by the 2012 Wyoming State Legislature.

Analyzing the cases collected thus far, the results of a seeding effect are not yet statistically significant, and thus no conclusions should be drawn regarding any effect. Preliminary analysis of the data, however, shows that the significance of the results has increased with each successful year of the program. While this is a promising trend, the number of cases is still too small to reach a credible conclusion concerning the effect of seeding. To achieve that result requires the additional 50 or so cases indicated above, or two more operational seasons. At that point the WWMPP, if the experiment progresses as it has been, would be uniquely successful in completing such a randomized statistical experiment testing the efficacy of winter-time cloud seeding from ground-based generators.