Literature Review and Scientific Synthesis on the Efficacy of Winter Orographic Cloud Seeding

A Report to the U.S. Bureau of Reclamation

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1.0 Introduction

1.1. Introduction to Winter Orographic Cloud Seeding

In its most basic form, artificial seeding of clouds for precipitation enhancement can be divided into two broad categories: 1 – cloud seeding to enhance rainfall i.e. summer convection, 2 – winter orographic cloud seeding to enhance snowfall. The scope of this paper is only concerned with the latter. Winter orographic cloud seeding occurs when very small particles, typically silver iodide, are introduced into a cloud which is below freezing. The cloud moisture collects onto the small particles, freezing the moisture into tiny ice crystals which continue to grow until they become too heavy to remain in the cloud and then fall out as precipitation (typically snow). This process can happen rapidly on the windward slopes of mountains allowing the snow to fall near the crest of the mountain which causes a local enhancement to the amount of precipitation that would have fallen naturally (Figure 1.1).

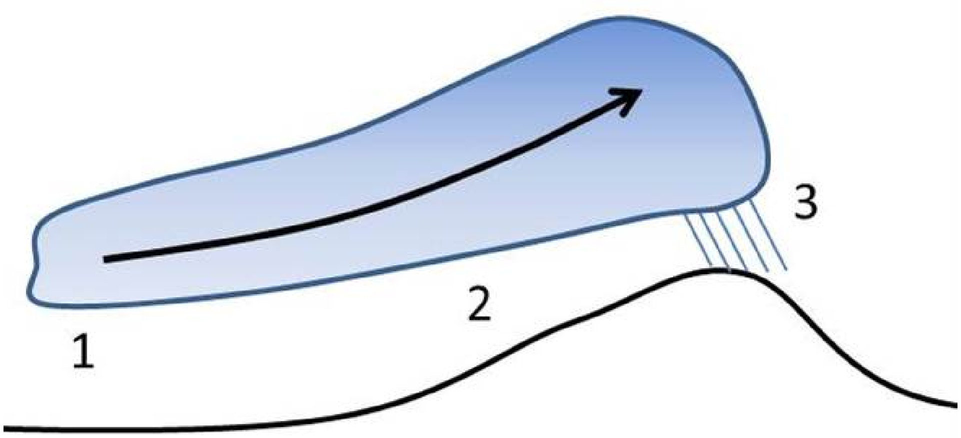

Figure 1.1 - Simple model of winter orographic cloud seeding. 1 - Introduction of seeding material, 2 forced ascent due to topography, 3 - enhanced precipitation falling out of cloud.

Winter orographic seeding has been attempted by Government organizations, the scientific community and private industry. Currently there are many private companies actively involved in both winter orographic cloud seeding and summer convective cloud seeding. The Bureau of Reclamation was active in cloud seeding in the past, mentioned in detail later, but currently does not support or have any active cloud seeding operations with the exception of a few recent research opportunities.

1.2 Purpose of this Study

Recently Reclamation has been interested in understanding whether scientific and legal issues have changed substantially over the decade since the National Research Council (NRC) paper Critical Issues in Weather Modification Research was published out in 2003. The purpose of this paper is to research the current state of the science concerning weather modification and Reclamation's position concerning winter orographic cloud seeding. This science synthesis will then inform considerations about developments in scientific efficacy that will be captured in a position paper to be written in the future.

This paper is broken down into 5 sections: 1 – Introduction, 2 – Review of weather modification since NRC 2003, 3 – Studies of efficacy of winter orographic cloud seeding, 4 – Compilation of statistical analysis of previous studies, and 5 – Summary and conclusions.

All of the information accumulated in this paper is aimed towards answering 3 questions which will drive the conclusions reached in the position paper. First, has there been progress in understanding the key uncertainties of NRC 2003? Second, have there been significant demonstrations of cloud seeding benefits since NRC 2003? Lastly, do these findings combine to suggest significant developments in regard to scientific efficacy?

1.3 Relevance and Need for a Reassessment of the Role of Winter Orographic Cloud Seeding to Enhance Water Supplies in the West

Weather modification is most commonly conducted through "cloud seeding," the introduction of chemical agents with the intent of affecting precipitation processes. A number of academic and private entities exist that offer services to states and local governments with the aim of increasing water supplies through inducing precipitation volumes above which would occur naturally. From the 1960s through the 1980s, Reclamation was involved in a variety of weather modification initiatives in the west under Project Skywater. This project included the Colorado River Basin Pilot Project, the High Plains Experiment (summer only), and the Sierra Cooperative Pilot Project. Project Skywater was terminated in 1988, but Reclamation continued to be involved with weather modification efforts. Reclamation participated in the development of the California Department of Water Resource's design and conduct of the Oroville Reservoir Runoff Enhancement Project from 1988 until 1994. Reclamation also supported other efforts through the mid-2000s, including the Weather Damage Modification Program.

Based upon scientific literature through 2006 and discussions with experts in the field, the efficacy of weather modification appears to be unsettled. In 2003, the National Research Council (NRC) report "Critical Issues in Weather Modification Research" (NRC 2003), concluded that "there is still no convincing scientific proof of the efficacy of intentional weather modification efforts". The NRC goes on to state that new technology allows for potential new research to help understand the process of precipitation and if weather modification is a viable means to increase water supplies.

In 2002-2003, Reclamation funded, through earmarks, weather modification studies in the states of Nevada, Utah, California, North Dakota, and Texas. The studies did not provide convincing scientific evidence that weather modification reliably generates additional water. However, there are a number of studies, including from within Reclamation (Hunter 2004 – cited within LBAO (Lahontan Basin Area Office) EA discussed later), that indicate that cloud seeding can significantly increase precipitation amounts for targeted locations.

In 2005, Reclamation primarily stopped involvement in weather modification efforts at the program level. As identified within Q&As developed by the Research and Development Office explaining Reclamations abandonment of the practice:

- Weather modification is not an operational function of Reclamation.
- In a letter dated December 13, 2005, sent to then-Texas Senator Kay Bailey Hutchison (R), the White House Office of Science and Technology Policy (OSTP) said there are significant concerns about liability and legal ramifications of weather modification, including whether weather modification can be demonstrated to actually be effective.

Since 2006, continuing drought conditions, and a strong interest amongst some Reclamation stakeholders, Reclamation engaged in two research projects related to weather modification in support of cold-season snowfall enhancement.

- In 2010 the Mid-Pacific Region's LBAO finalized an Environmental Assessment (LBAO EA) proposing to provide $1.35 million from Reclamation's Desert Terminal Lakes Program to the Desert Research Institute (DRI) for a cloud seeding project in the Walker River Basin.
- At a March 12, 2014 meeting of the Upper Colorado River Commission, weather modification was specifically identified as one of three activities that the Upper Basin states propose to include within their drought contingency plans. The Upper Basin states asked that Reclamation provide partial support for Wyoming's eighth year (2014) of an ongoing weather modification study / program being conducted with the National Center for Atmospheric Research (NCAR). This request resulted in Reclamation's Upper Colorado Region obligating $200,000 to the State of Wyoming for weather modification research and development efforts conducted by NCAR, with these monies obligated through an amendment to an existing cooperative agreement between Reclamation R&D and Universities Corporation for Atmospheric Research.

The Upper Basin states have noted that state and private entities in Colorado and Utah spend over $1M and $500,000 respectively on weather modification, and estimate efficacy between 6% and 20%. At the low end, the Upper Basin states identify that a benefit of 6% is inexpensive water within the Colorado River Basin. The Upper Basin states have argued that Reclamation's documents from the 1960s – 1980s have identified the positive results of weather modification.

These recent precedents of Reclamation supporting weather modification science activities sets up community interest in future investments toward weather modification science and operations. However, questions remain about how effective weather modification is and the remaining legal and liability issues. Responding to this community need, Reclamation has initiated an effort to

- prepare a supplemental science synthesis (this report) following from the efficacy questions and conclusions of NRC 2003.
- host a perspectives-gathering workshop from scientist and engineers who've conducted weather modification research and operations since 2003, and
- work with Reclamation's solicitor to learn whether there's been significant developments concerning potential legal and liability issues.

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The supplemental science synthesis will only focus on just weather modification to enhance cold-season orographic snowfall in the western U.S., which is just one of the weather modification applications addressed in NRC 2003 (along with warm-season rainfall enhancement and hail suppression).

1.4 NRC 2003 Report on Critical Issues in Weather Modification – Critical Issues Concerning Winter Orographic Cloud Seeding –

Box 2.2 of NRC 2003 report listed critical unresolved issues with regard to weather modification. Those issues pertinent to winter orographic cloud seeding will be the focus of this literature review and scientific synthesis. These are listed in Table 1.1 with reference back to the NRC 2003 identified critical issues.

BOX 2.2
Summary of Key Uncertainties
The statements in boldface type are considered to have the highest priority.

1.0 Cloud and precipitation microphysics issues

A. **Background concentration, sizes, and chemical composition of aerosols that participate in cloud processes** (see section 1.3.1)

B. Nucleation processes as they relate to chemical composition, sizes, and concentrations of hygroscopic aerosol particles (see sections 1.3.1)

C. Ice nucleation (primary and secondary) (see section 1.3.1)

D. Evolution of the droplet spectra in clouds and processes that contribute to spectra broadening and the onset of coalescence (see section 1.3.1)

E. Relative importance of drizzle in precipitation processes

2.0 Cloud dynamics issues

A. Cloud-to-cloud and mesoscale interactions as they relate to updraft and downdraft structures and cloud evolution and lifetimes

B. Cloud and sub-cloud dynamical interactions as they relate to precipitation amounts and the size spectrum of hydrometeors

C. Microphysical, thermodynamical, and dynamical interactions within clouds

3.0 Cloud-modeling issues

A. Combination of the best cloud models with advanced observing systems in carefully designed field tests and experiments (see section 3.4)

B. Extension of existing and development of new cloud-resolving models explicitly applied to weather modification (see section 3.4)

C. Application of short-term predictive models including precipitation forecasts and data assimilation and adjoint methodology in treated and untreated situations (see sections 3.4. 5.0)

D. Advancement of the capabilities in cloud models to simulate dispersion trajectories of seeding material (see section 3.4)
E. Evaluation of predictive models for severe weather events and establishment of current predictive capabilities including probabilistic forecasts

F. Use of cloud models to examine effects of cloud seeding outside of seeded areas (see section 3.4)

G. Combination of cloud models with statistical analysis to establish seeding effects (see section 2.2)

4.0 Seeding issues

A. Targeting of seeding agents, diffusion and transport of seeding material, and spread of seeding effects throughout the cloud volume (see sections 1.3.2, 2.1, 2.2, 3.1, 3.2, 3.4)

B. Measurement capabilities and limitations of cell-tracking software, radar, and technologies to observe seeding effects (see sections 1.3.2, 3.3)

C. Analysis of recent observations with new instruments of high concentrations of ice crystal (see sections 3.1, 3.2, 3.3)

D. Interactions between different hydrometeors in clouds and how to best model them

E. Modeling and prediction of treated and untreated conditions for simulation

F. Mechanisms of transferring the storm-scale effect into an area-wide precipitation effect and tracking possible downwind changes at the single cell, cloud cluster, and floating target scales

Table 1.1 - Key questions relating to winter orographic clouds

	Winter Orographic Cloud Seeding: Key Questions/Uncertainties	**NRCS 2003 Box 2.2 Reference**
1	**Favorable and Unfavorable Seeding Conditions**	
A	What are the location, duration and degree of supercooling of cloud liquid water?	**1A-E 2B**
B	Are their man-made pollutants or natural aerosols/particulates impacting the target clouds that could modify the cloud droplet spectra/IN concentrations to impede seeding effectiveness?	**1A**
C	Are their significant enough differences in maritime influenced winter orographic clouds versus continental orographic clouds that strongly influence the natural precipitation process?	**1B 1C 1D 1E**

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	Winter Orographic Cloud Seeding: Key Questions/Uncertainties	**NRCS 2003 Box 2.2 Reference**
D	Are there numerical models that can be run in real-time utilizing project filed observations to guide seeding decision making?	**3C 3D 4D**
E	If seeding occurs during unfavorable conditions i.e. insufficient SLW, inappropriate temperatures for the seeding agent, or improper targeting, are there unintended impacts in the target area or extended areas?	**3F**
2	**Seeding Delivery Methodology**	
A	What is the best seeding agent to use based on (1A) and what is the best way to deliver the seeding agent?	**1B 3D 4E**
B	What is the necessary density and location of ground-based dispensers and what is the dependency on seeding agent used?	**3D 3G**
C	What are the performance characteristics necessary for aerial seeding and to what extent can we determine number of aircraft needed to impact the total target watershed?	**4A**
3	**Targeting**	
A	What observing systems are needed and at what spatial and temporal frequency to adequately target seeding impacts?	**3C 4A**
B	What are the observing systems, either in-situ or remote sensing, that can observe and track a seeding plume from initiation to fallout? What are the benefits and limitations of each?	**4C 4B**
4	**Quantifying Seeding Impacts on Precipitation over a Target Area**	
A	What is the resolution and spacing required of recording snow gauges within the intended target area and downwind target area?	**3G 4B**
B	If silver iodide is the seeding agent, what are the benefits and limitations of sampling the silver concentration in the snow prior to spring melt to validate that a significant portion of the winter seeding impacted the target area?	**4A**
C	What is the best design of the seeding program to reduce uncertainty and insure meaningful statistical results?	**3G**
D	What are the best statistical methods to apply to achieve statistical significance and reduce Type I and II errors?	**3G**
E	Benefits and limitations of a reanalysis of operational cloud seeding projects	**3G 4E**

1.4.1 Response to NRC Report from Weather Modification Community

Shortly after the NRC report was issued, the Weather Modification Association issued a written response with their key issues as relates to winter orographic cloud seeding listed below (WMA, 2004).

- We support the NRC recommendation that there be a renewed commitment to advancing our knowledge of fundamental processes that are central to the issues of intentional and inadvertent weather modification.
- We support the NRC recommendation that a coordinated national program be developed to conduct a sustained research effort in the areas of cloud and precipitation physics,

cloud dynamics, cloud modeling, laboratory studies, and field measurements designed to reduce the key uncertainties that impede progress and understanding of intentional and inadvertent weather modification. *But, we argue that the coordinated national program should also support exploratory and confirmatory field studies in weather modification. It should capitalize on operational cloud seeding programs, and use them as a basis for testing models, and developing new statistical methods for evaluating the efficacy of those operations.*

- We support the NRC conclusion that a coordinated research program should capitalize on new remote and in situ observational tools to carry out exploratory and confirmatory experiments in a variety of cloud and storm systems.
- The Board on Atmospheric Sciences and Climate workshop report (BASC, 2001) recommended that a "Watershed Experiment" be conducted in the mountainous West using all of the available technology and equipment that can be brought to bear on a particular region which is water short and politically visible from a water resource management perspective. We strongly support this earlier recommendation that was not then included in the NRC report. Such a "Watershed Experiment" should be fully randomized and well equipped, and be conducted in the region of the mountainous West of the U.S. where enhanced precipitation will benefit substantial segments of the community, including enhancing water supplies in over-subscribed major water basins, urban areas, and Native American communities, for ranching and farming operations, and for recreation. This research should include "chain-of-events" investigations using airborne and remote sensing technologies, along with trace chemistry analysis of snowfall from the target area. Model simulations should be used to determine optimum positioning and times of operation for ground-based and aircraft seeding. The work should include evaluations of precipitation, run-off, and recharge of ground water aquifers. Also, it should include environmental impact studies including water quality, hazard evaluations such as avalanches, stream flow standards and protection of endangered species. Research is also recommended on seeding chemical formulations to improve efficiencies and on improving technology used in seeding aerosol delivery systems.
- We recommend the application of existing and newly developed numerical models that explicitly predict transport and dispersion of cloud seeding agents and activation of cloud condensation nuclei, giant cloud condensation nuclei, and ice nuclei, as well as condensation/evaporation and collection processes in detail, to the simulation/modification of clouds. We concur with the need to improve and refine models of cloud processes, but existing models can be used as a first step to examine, for example, the possible physical responses to hygroscopic seeding that occur several hours following the cessation of seeding. In addition, existing models can be used to replicate the transport and dispersion of ground-based and aircraft-released seeding agents and the cloud and precipitation responses to those seeding materials in winter orographic clouds. Existing models can also simulate static and dynamic seeding concepts for fields of supercooled convective clouds. Moreover, existing models can be used to improve the efficiency of the operation of weather modification research projects and operational programs, and be deployed in the assessment of those programs.
- We recommend that a wide range of cloud and mesoscale models be applied in weather modification research and operations. This includes various microphysics techniques (both bin and bulk-microphysical models have their uses) and various approaches in the

dynamics (all dimensionalities - one, two, and three dimensional models - offer applications).

- We recommend that support be given for the development of innovative ways to evaluate operational cloud seeding projects. This is particularly important for the establishment of the physical basis of various cloud seeding methods and for establishing the possible range of cloud seeding effects.
- We recommend that evaluation techniques presently being applied to operational programs be independently reviewed, and as necessary revised to reduce biases and increase statistical robustness to the extent possible. Recognizing that randomization is not considered to be a viable option for most operational seeding programs, we acknowledge that there is much room for improvement in most present evaluations, many of which are presently done in-house.

Given the strong response from the operational weather modification community, it should be kept in mind that there are two overriding issues being discussed by the NRC and the WMA. The NRC report is very focused on the understanding of the fundamental physical processes taking place in clouds that lead to precipitation. The WMA sees the problem more as an engineering problem. That is how to get the right amount of seeding agent into the right portions of the cloud to allow enough time for the seeded crystals to grow and fallout with sufficient mass to increase water on the ground that is economically viable. The science of quantitative precipitation forecasting does suffer from a lack of understanding of the complexities of the scales of interaction from the synoptic mesoscale down to the turbulent eddy and microphysical scale. This has been a focus of the scientific community for many decades. Over the years the research into winter orographic cloud seeding has provided a wealth of knowledge and understanding into the basic principles of seeding winter orographic clouds. It will be shown that one of the major impediments to a successful winter orographic cloud seeding program has been actually seeding the intended target clouds sufficiently. This relates specifically to why one can refer to this as more of an engineering problem than a fundamental science problem. Hopefully the following sections will make this more clear.

1.5 Brief History of Federal and State Authorizations for Weather Modification

The following is taken from Chisolm and Grimes (1979):

> In 1968, the Colorado River Basin Project Act of 1968 (Public Law 90-537) was passed by Congress to provide for the further comprehensive development of water resources of the Colorado River Basin and for the provision of additional and adequate water supplies for use in the upper as well as lower Colorado River Basin. Under Title II of this Act, the Secretary of the Interior was authorized to prepare and implement an augmentation plan to meet the water requirements of the new projects created by the Act (Central Arizona Project and Colorado River Storage Project), existing projects and water allotments, and the 1944 water treaty with Mexico.

Augmentation was one of the main issues in the deliberation on the Act. The Act defines augmentation as, “ ‘augment’ or ‘augmentation’ when used herein with reference to water means to increase supply of the Colorado River system or its tributaries by introduction of water into the Colorado River system, which is in addition to the natural supply of the system." The Statement of the Managers on the part of the House with regard to augmentation stated "all possible sources of water must be considered, including water conservation and salvage, weather modification, desalinization and importation from areas of surplus."

The Colorado River Basin Pilot Project (CRBPP) was the Bureau's first major effort on weather modification in Colorado under the auspices of Project Skywater and P. L. 90-537. The purpose of the Colorado River Basin Pilot Project was to provide for scientific and economic evaluation of precipitation augmentation technology and to increase precipitation. The specific objectives to be achieved were (l) to establish and operate a ground-based meteorological network in and near the San Juan Mountains of Colorado to provide data input in the selection of suitable storms for seeding, and (2) to establish and operate a ground-based silver iodide seeding system to increase snowfall in the project target area. The field phase of CRBPP began with the winter of 1970-71 and ran through the 1973-74 operating season. At about the time of completion of CRBPP in Colorado, the Bureau began funding Project Snowman in Utah. Project Snowman was conducted for the Bureau by Utah State University's Water Research Laboratory.

The objective of this four-year project was to develop cold-cloud seeding technology using airborne generators and ground-based generators located in the northern portion of the Wasatch Mountains. The Bureau's early work on precipitation augmentation in Colorado was based on a fairly extensive background of research activities. Three major research efforts in winter seeding contributed directly to the Bureau's CRBPP project in the Upper Colorado River Basin. These were:

1. The National Science Foundation sponsored research experiments by Colorado State University at Climax, Colorado, during the 1960's.
2. The operational research funded by the State of Colorado during the 1960' s at several mountain passes, particularly Wolf Creek Pass in the San Juan Mountains, and
3. The Bureau sponsored experiments in the Park Range near Steamboat Springs, Colorado during the late 1960's.

The results of the Colorado River Pilot Project indicated the need for further verification and improvement in technology before a large augmentation program could be undertaken. Thus, the Bureau's research program continued. Winter experiments were conducted outside of the Colorado River Basin at:

Elk Mountain, Wyoming (University of Wyoming)
Bridger Range, Montana (Montana State University)
Jimenez Mountains, New Mexico (New Mexico State University)
Pyramid Lake Pilot Project (University of Nevada)

In addition, the Bureau continued to provide supplemental funds to Colorado State University's NSF research and to Utah State University's state -sponsored research project. Through the Emergency Drought Act of 1977 the Bureau granted over $2 million to six states for supplemental support of their cloud seeding projects including over $1 million to the States of Colorado and Utah for cloud seeding in the Colorado River Basin.

1.6 Current Policy Statements from American Meteorological Society and World Meteorological Organization on Efficacy of Winter Orographic Cloud Seeding

The two leading organizations representing the atmospheric science scientific establishment, the World Meteorological Organization and the American Meteorological Society, have both issued policy statements on the efficacy of winter orographic cloud seeding. These are relevant to review given the NRC 2003 conclusions.

The current statement from the World Meteorological Organization (WMO 2010) on weather modification in general and relating specifically to winter orographic cloud seeding efficacy is stated below.

> “The scientific status of weather modification**,** while steadily improving, still reflects limitations in the detailed understanding of cloud microphysics and precipitation formation, as well as inadequacies in accurate precipitation measurement. Governments and scientific institutions are urged to substantially increase their efforts in basic physics and chemistry research related to weather modification and related programmes in weather modification. Further testing and evaluation of physical concepts and seeding strategies are critically important. The acceptance of weather modification can only be improved by increasing the numbers of well executed experiments and building the base of positive scientific results.”

> “Cloud seeding has been used on both cold clouds, in which glaciogenic seeding aims to induce ice-phase precipitation, and warm clouds, where hygroscopic seeding aims to promote coalescence of water droplets. There is statistical evidence, supported by some observations, of precipitation enhancement from glaciogenic seeding of orographic supercooled liquid and mixed-phase clouds and of some clouds associated with frontal systems that contain supercooled liquid water. “

The current AMS policy statement (AMS 2010) does not address specifically the efficacy of winter orographic cloud seeding but much like the NRC 2003 report identifies uncertainty and risk with much the same conclusions. These are listed below.

UNCERTAINTY - Planned weather modification programs benefit from a comprehensive understanding of the physical processes responsible for desired modification effects. Recent improvements in the composition and techniques for dispersion of seeding agents, observational technology, numerical cloud models, and in physical understanding of cloud processes permit evermore detailed design and targeting of planned weather modification effects, and more accurate specification of the range of anticipated responses. While effects are often immediately evident in simple situations, such as when cloud seeding is used to clear supercooled fog and low stratus cloud decks, in more complex cloud systems it is often difficult to determine a seeding effect on a cloud-by-cloud basis. In these more complex situations, large numbers of events must be analyzed to separate the response to cloud seeding from natural variability in cloud behavior. Rigorous attention to evaluation of both operational and research programs is needed to help develop more effective procedures and to improve understanding of the effects of cloud seeding. Research and operational programs should be designed in a way that will allow their physical and statistical evaluation. Any statistical assessment must be accompanied by physical evaluation to confirm that the statistical results can be attributed to the seeding through a well-understood chain of physical events. It should be noted, though, that in practice large potential benefits can warrant relatively small investments to conduct operational cloud seeding despite some uncertainty in the outcome.

RISK MANAGEMENT - Unintended consequences of cloud seeding, such as changes in precipitation or other environmental impacts downwind of a target area, have not been clearly demonstrated, but neither can they be ruled out. In addition, cloud seeding materials may not always be successfully targeted and may cause their intended effects in an area different than the desired target area. This brings us to the ethical concern that activities conducted for the benefit of some may have an undesirable impact on others; weather modification programs should be designed to minimize negative impacts.. At times unintended effects may cross political boundaries, so international cooperation may be needed in some regions. Precipitation augmentation through cloud seeding should be viewed cautiously as a drought-relief measure because opportunities to increase precipitation are reduced during droughts. A program of precipitation augmentation is more effective in cushioning the impact of drought if it is used as part of a water management strategy on a long-term basis, with continuity from year to year, whenever opportunities exist to build soil moisture, to improve cropland, and to increase water in storage. From time to time methods have been proposed for modifying extreme weather phenomena, such as seeding severe thunderstorms with aerosols to diminish tornado intensity, or seeding tropical cyclones to cause changes in their dynamics and steer them away from land and/or diminish their intensity. Some experimentation has taken place in these areas, but current knowledge of these complex weather systems is limited, and the physical basis by which seeding might influence their evolution is not well understood. Weather modification techniques other than cloud seeding have been used in various areas of the world for short periods of time to achieve goals similar to those of cloud seeding. Much less is known about the effects of these other techniques, and their scientific basis is even further from being demonstrated, either statistically or physically, than it is for cloud seeding. Application of weather modification methods that are not supported by statistically positive results combined with a well-understood physical chain of processes leading to these results, and that can also be replicated by numerical cloud modeling, should be discouraged.

Other organizations such as the North American Interstate Weather Modification Council, The Weather Modification Association, the American Society of Civil Engineers, and the Western States Water Council have also adopted policy statements or adopted resolutions relating to the use of weather modification for increasing snowpack and water supply. These are referenced in Ryan (2005) and will not be repeated here. Most if not all of these statements are much more positive in their support of the application of weather modification for enhancing snowpack and runoff.

1.7 Generalized Concepts of Winter Orographic Cloud Seeding

It is useful to review the general principles of winter orographic snowfall and whether this process could be modified or enhanced by artificial means. The basic physical concepts associated with seeding winter orographic clouds are not debated even though there is considerable debate over weather modification and its efficacy. These basic physical concepts are reviewed in the following section. There are several text books and encyclopedia articles available for a more in-depth discussion or broader overview of the physical basis of cloud seeding (Hess 1974; Dennis 1980; Dennis 1987; and Heymsfield 1992).

Figure 1.2 from Ludlam (1955), reproduced below, describes the process that remains to this day the fundamental conceptual model associated with winter orographic cloud seeding. Figure 1.2 shows a shallow orographic cloud, where the liquid condensate produced by forced assent over a mountain barrier is unable to be converted to snowfall before the air descends and evaporates in the lee of the mountain. During wintertime the freezing level (height of the 0C isotherm) varies dependent on the origin of the air mass impinging on the mountain barrier. This varies from north to south with the freezing level being lower in altitude at the northern latitudes of the western US and the inter-mountain west where the air masses that impact this area are usually modified maritime polar or continental polar. Freezing levels are usually below ground level in mountainous regions except in the warmest storms. In the Ludlum model, it is assumed the orographic cloud has a significant depth of cloud below 0 ^{o}C and thus the cloud moisture is said to be supercooled. The critical uncertainty with regard to successful conversion of the unused cloud condensate to snowfall prior to passing over the crest is the location, duration, temperature and concentration of the supercooled liquid water (SLW). As Ludlum describes it may take as much as 1500 seconds once artificial ice crystals are initiated to grow and fall out before passing to the lee of the mountain crest. This can vary by several tens of minutes based on SLW concentration, temperature vertical profile and winds. So the critical factors for achieving success are getting the seeding agent into the cloud at the right location where it will generate enough ice embryos such that they will utilize the available SLW prior to passing over the crest. There are many complex interactions that have made it very difficult to demonstrate the efficacy of winter orographic cloud seeding to the satisfaction of the scientific community. These factors are described in the following paragraphs.

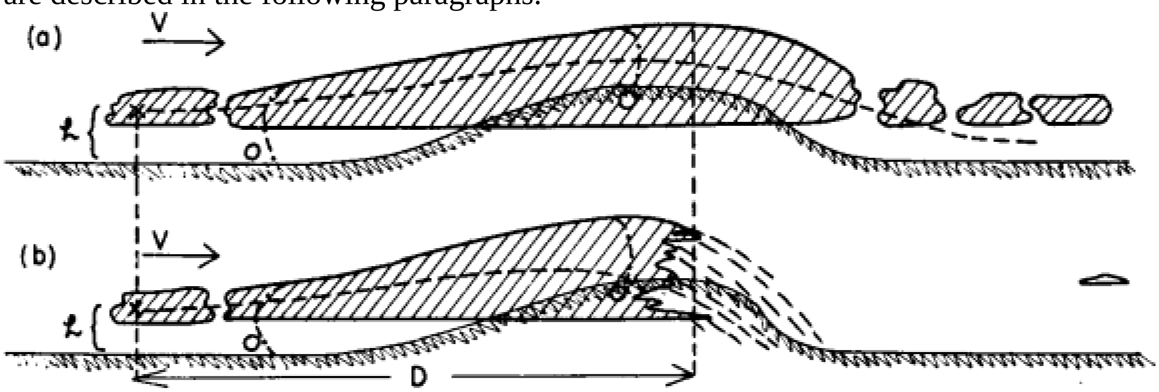

Figure 1.2 From Ludlam (1955) showing the formation of snow in mountain clouds. a) depicts an inefficient cloud where the natural precipitation process was not able to utilize all the available cloud water which is transported over the crest of the mountain and dissipates in the lee. b) shows where additional ice is introduced into the cloud at the appropriate distance

and height allowing the crystals to grow at the expense of the cloud water that in (a) was lost to the lee, bringing this moisture down on the windward side of the mountain.

1.7.1 The Initiation, Growth and Fallout of Snow in Winter Orographic Clouds

1.7.1.1 Converting Supercooled Liquid Water (SLW) to Snow

Supercooled liquid water (SLW) in the atmosphere is made up of tiny cloud droplets that are colder than 0 ^{o}C. There are two processes in nature by which SLW in the atmosphere can freeze to initiate snowfall: 1. Heterogeneous nucleation or 2. Homogeneous nucleation. Heterogeneous nucleation occurs when the supercooled liquid drop comes in contact with what is called an ice nucleus (IN) that emulates the crystalline structure of ice and causes the droplet to freeze. These can be dust particles, biological particles or a combination of the two. These aerosols can come from as far away as Asia and Africa initiating cloud ice in orographic clouds in the western US (Cremean et al. 2013). They are made of very small particles of tenths of microns in size. They are most active at cloud top and tend to activate the growth of snowflakes from the top of the cloud down. The warmer the cloud top the less percentage of ice makes up the cloud (Cremean et al. 2013). When clouds are dominated by warm rain processes, the aerosol makeup of the cloud is more sea salt and biological particles which act as condensation nuclei producing larger cloud droplets which grow to raindrops via collision coalescence. Homogeneous nucleation occurs when the air temperature drops below -40 ^{o}C and the water droplet spontaneously freezes without the aid of a nucleating agent. The most basic hypothesis in winter orographic cloud seeding is that in the presence of SLW droplets, ice crystals will grow at the expense of the drops. This means the drops will convert back to vapor allowing the crystals to grow by vapor deposition. The driver for crystal growth is related to the concentration of SLW and the temperature regime of the SLW (Ryan et al. 1976; Heymsfield 1992; Pruppacher and Klett 1978). In the presence of moderately high concentrations of SLW and with somewhat preferred growth temperatures (Ryan et al. 1976, Figure 1.3) enough of the initial ice crystals can grow and then begin to aggregate into larger flakes leading to higher fall speeds and earlier fall-out. If these artificial crystals encounter additional SLW as they fall back toward the mountain crest, the individual crystals or aggregates may collect these SLW drops (called riming) which will also increase the crystals fall-speed. If the naturally created ice crystals are unable to utilize all the available SLW, and some SLW evaporates to the lee of the mountain, the cloud is said to be less than 100% efficient. This provides the opportunity for the artificial injection of a nucleating agent to create the additional ice crystals necessary to bring the residual cloud water to the ground before it is lost to the lee of the mountain. This is the basic principles described in Ludlam's model.

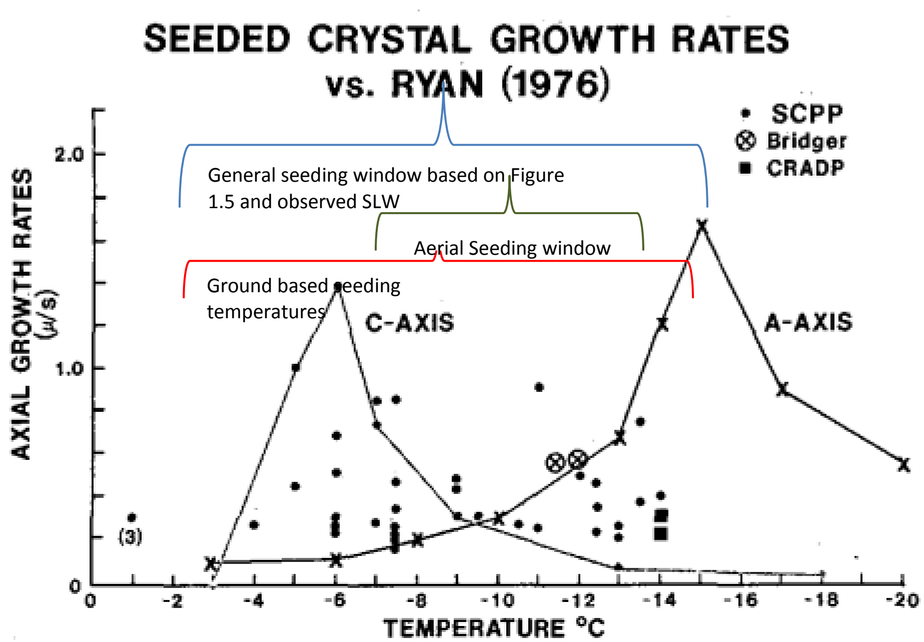

Figure 1.3 - A and C axis growth rates with respect to temperature. From Ryan et al 1976. The temperature where most orographic cloud seeding occurs is annotated. Actual seeded crystal growth rates are shown from three different winter cloud seeding studies (see Figure 1.4b). From Reynolds (1988).

As Super and Heimbach (2005) noted, the frequency of occurrence of SLW is temperature dependent with higher frequencies and amounts at warmer supercooled temperatures. This is true for all mountain ranges where SLW has been observed. There are two main reasons for this. First, the amount of water vapor in the atmosphere can be higher at warmer temperatures. Second, as the atmosphere cools and clouds form and reach temperatures colder than -10 °C, and especially at -20 °C, an abundance of natural ice can occur that depletes the supercooled cloud water. Thus, there is less SLW available for cloud seeding to enhance the natural precipitation process as the air approaches these temperatures.

It should be noted that studies (Reinking et al. 2000; Super 2005) have found significantly higher amounts of SLW (.5 to 1 mm integrated SLW) in wave clouds during winter storms and noted that others had observed such amounts during brief periods in other western mountain locations. However, the overwhelming amount of observations utilizing microwave radiometers (Heggli and Rauber 1988; Huggins 2009; Super and Heimbach 2005), in-situ aircraft observations, and mountain top icing rate meters indicate that SLW is concentrated in the lowest 1000m along the windward slopes of mountain ranges during passing winter storms. The primary SLW zone rapidly dissipates downwind of the crest because of warming produced by subsidence, and by depletion from conversion to snowfall (Boe and Super 1986; Rauber et al. 1986; Huggins 1995; Super 2005; Huggins 2009). Again these observations confirm the conceptual model espoused by Ludlam. The location of many of the research studies referenced in this report along with other locations that will be referenced later in this report are shown in Figure 1.4b. One can compare these locations to Figure 1.4a which shows the location where operational winter orographic cloud seeding is conducted circa 2006 per Griffith et al. 2006. Coastally influenced areas would be west of the Sierra Nevada and Cascades while the intermountain region refers to areas east of these two ranges.

The actual temperature relationship to SLW occurrence varies geographically. For the intermountain west, where the cloud drop size distributions are more numerous at the smaller drop sizes (10 to 15 microns; what is referred to as a continental drop size distribution), colder temperatures are reached before a sufficient number of natural ice crystals develop to utilize the available SLW. Thus, SLW can exist at temperatures as cold as -15 to -20 ^{o}C. Super and Heimbach (2005) provide a comprehensive review of SLW climatology in the intermountain west.

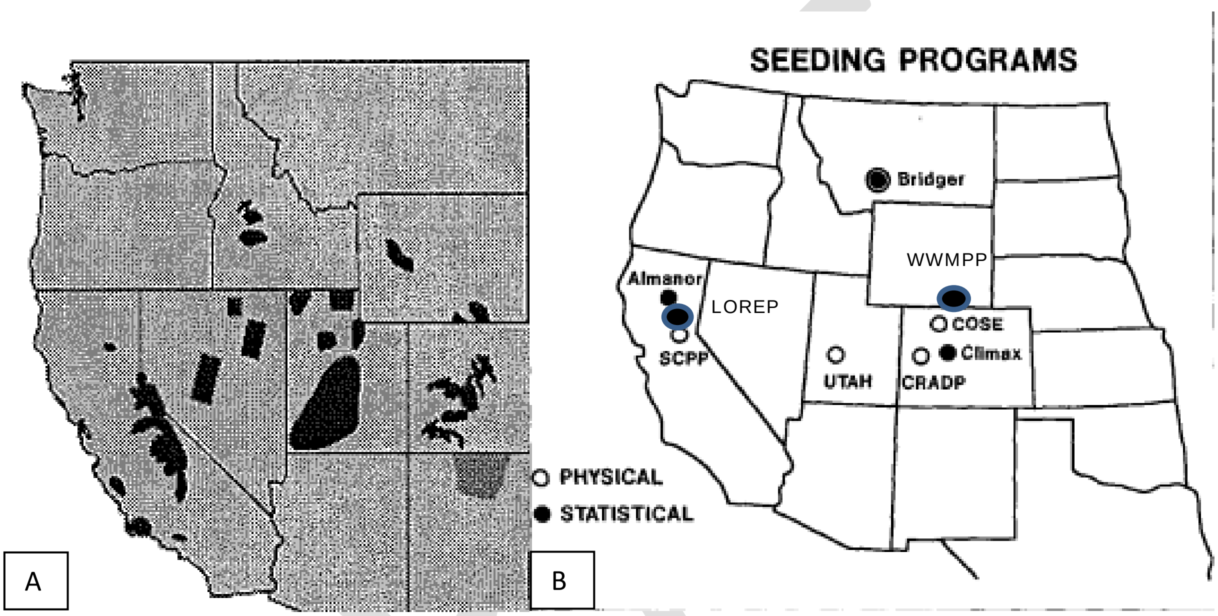

Figure 1.4 - a) Operational winter orographic cloud seeding programs circa 2006. From Griffith et al, 2006. b) Locations of winter orographic operational/research projects referred to in text (from Reynolds, 1988).

In more coastal regions, such as the Sierra Nevada and Cascades, the drop size distribution can be broad (what is referred to as a maritime drop size distribution). The drops can begin to collide and coalesce because of the varying fall speeds of the drops with a broader distribution of cloud droplets (extending into and above 30 microns). This leads to larger cloud drops (approaching drizzle size) that can be carried upslope into coastal mountains like the Cascades and Sierra Nevada ranges where just a few of these droplets can freeze leading to rime splintering or secondary ice-crystal production (Hallett and Mossop 1974; Dong and Hallett 1989; Mossop 1985). This can, and has been observed to lead to high concentrations of ice crystals with cloud temperatures warmer than -10 ^{o}C (Reinking 1978; Cooper 1986; Marwitz 1986; Rangno 1986; Rauber 1992).

Other factors (Rango 1986) can lead to high ice crystal concentrations with relatively warm cloud top temperatures. Mixing of very dry air into cloud tops can initiate cloud droplet freezing (Koenig 1968; Hobbs and Rangno 1985). This has been observed in the Cascades, Sierra Nevada and southern Utah. In the post-frontal airmass, where most of the shallow orographic clouds exist, very dry air can exist above cloud top. This is caused by sinking air parcels in the region behind the upper-level jet-stream that usually passes just ahead of the surface cold front

(Heggli and Reynolds 1985). Thus the coastal mountain clouds will have a lesser degree of supercooling, meaning that the clouds will be only marginally supercooled as natural ice production will utilize the available SLW within moderately supercooled clouds. Reynolds (1995) documented that over an 8 year period in the northern Sierra Nevada, 80% of the hours reporting SLW from mountain-top icing rate meters were at temperatures warmer than -4 ^{o}C. Reynolds (1996) also reported that 70% of the hours with precipitation had icing reported. Approximately 300 hours of icing were reported per season. However, some seasons had average temperatures during icing warmer than -2 ^{o}C which may be too warm for any known seeding agent to work effectively unless seeded aloft using aerial seeding. Studies examining mountain top temperatures in Colorado and Utah revealed that SLW in clouds is mildly supercooled in a large portion of all storm passages, which means clouds are too warm for effective AgI seeding (Super 2005). Refer to Figure 1.5 for activation levels of the various cloud seeding agents currently used or proposed.

There are many studies (Heggli et al. 1983; Boe and Super 1986; Rauber and Grant 1986; Heggli and Rauber 1988; Super and Huggins 1993; Super 2005; Huggins 2009) that state SLW within a cloud varies rather rapidly with time over any given point. Due to this variability in SLW, identifying seeding potential within winter orographic storms will require identification of the proper seeding agent and delivery technique and applied at the correct time and location (Hunter 2007; Huggins 2009). Huggins (2009) suggests that any cloud seeding program will necessarily be treating clouds that at any given time may not have sufficient SLW given its variability. This begs the question as to whether seeding in these situations may have negative impacts on snowfall production. This will be further discussed in Section 1.7.4.

Even though the location of SLW concentrations is known, the exact lower threshold for SLW concentrations to be sufficient for enhancing snowfall has not been quantified. It is believed to be greater than .05 mm integrated in the vertical derived from microwave radiometers (threshold used by Super and Heimbach 2005 and Manton et al 2011). However, Murakami (2013) used .2 mm as the lower threshold for determining cloud seeding feasibility and theorized that .3mm was probably the minimum threshold for viable increases in orographic precipitation enhancement. This is a critical question as frequency distributions of SLW concentrations from radiometer data (Reynolds 1988) indicate that 85% of the SLW reported were at concentrations below .2 mm (Figure 1.5).What constitutes a necessary and sufficient concentration of SLW for effective cloud seeding is still in debate.

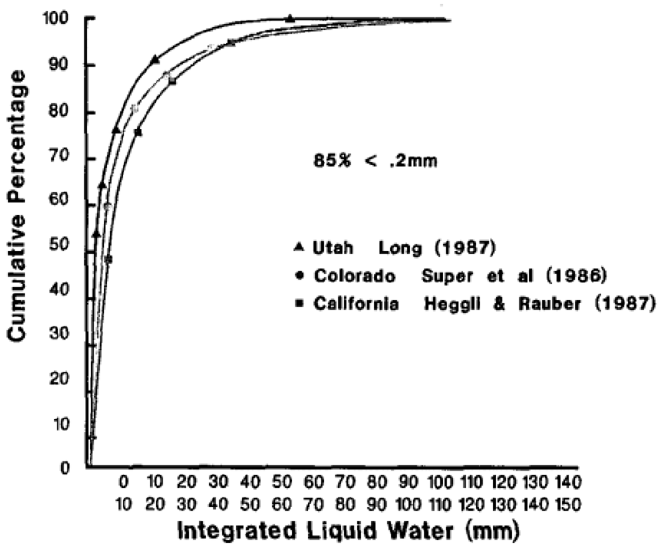

Figure 1.5 - Frequency distribution of SLW from Reynolds (1988).

1.7.1.2 Impacts of Pollution on Precipitation

Several studies (Rosenfeld 2000; Givati and Rosenfeld 2004; Rosenfeld and Givati, 2006; Griffith et al. 2005; Hunter 2007) have described decreases in orographic precipitation due to pollution. This specifically impacts the collision coalescence process and what is called warm rain, i.e. no ice processes involved. These studies discuss that pollution can slow down the collision coalescence process by narrowing the drop-size distribution. This, in turn, slows down the warm rain process and would have the largest impacts in the low-elevation coastal ranges along the west coast where the freezing level is well above the elevations of the coastal mountains, i.e. around Los Angeles where it has been proposed to reduce precipitation. Typically the decrease in orographically enhanced precipitation is greatest downwind of a major metropolitan area that is producing pollution. Givati and Rosenfeld (2004) showed precipitation losses near orographic features downwind of coastal urban centers corresponding to 15-25% of the annual precipitation. This loss of precipitation can be greater than the gain claimed by precipitation enhancement techniques in portions of California (Hunter 2007). Hindman et al (2006) noted that the trend over the past 20 years, from cloud droplet measurements at Storm Peak in the northern Rockies, has shown a decrease in CCN and an increase in cloud drop size. The conclusion was a decrease in upwind CCN concentrations (less pollution) but no relationship was found with precipitation rate. Thus, the change in cloud droplet spectra was not impacting riming growth efficiency (Borys et al 2003). It was noted by Creamean (2013) that pollutants, such as from human activity, were found mostly in the boundary layer and with frequently higher concentrations preceding surface cold fronts. The pollutants become trapped in the stable air as the air warms aloft and surface flows tend to be from the southeast to east tapping polluted sources from the central valley of CA. Once the front passed, the air-mass off the ocean did not contain these pollutants. It is the post–frontal cloud systems that have been identified as the most seedable in the northern and central Sierra (Heggli and Reynolds, 1985). It

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is not anticipated that pollutants play a significant role in these post-frontal shallow orographic clouds.
It should be noted that a more recent survey article by Tanre' et al (2009), reviewed the impact of aerosols on precipitation and concluded: "Even though we clearly see in measurements and in simulations the strong effect that aerosol particles have in cloud microphysics and development, we are not sure what is the magnitude or direction of the aerosol impact on precipitation and how it varies with meteorological conditions. Even the most informative measurements so far on the effect of aerosols on precipitation do not include simultaneous quantitative measurements of aerosols, cloud properties, precipitation and the full set of meteorological parameters." The current CALWATER II experiment running this winter in California is an attempt to provide such information.

The main limitation is very similar to the problems inherent in quantifying the impacts of artificial seeding of winter orographic clouds. That is the observing systems that we apply to quantifying the impacts have large measurement uncertainties and are of a magnitude similar to the expected aerosol influence on precipitation. Tanre' notes that satellite and radar measurements have 20-30% errors in the measurement of aerosol optical depth, while aircraft sampling in-cloud can introduce changes in the cloud that can compromise the utility of the aircraft observations. In-deed measurements of surface precipitation, especially snowfall water equivalent can have 10-15% measurement uncertainty given gauge location and thus exposure to wind, minimum threshold/resolution, and such problems as capping. These types of measurement uncertainties require longer term on-going statistical analyses to reduce the random noise in the observations much like is required for cloud seeding experiments, thus reducing the influence of measurement uncertainty so as to extract the small signal that might exist.

1.7.1.3 Artificial Stimulation of Snowfall by Seeding Agents

Artificial stimulation of snowfall is conducted through the application of aerosols that mimic natural ice nuclei to enhance the heterogeneous freezing of available SLW or by chilling the air below -40 ^{o}C to initiate homogenous nucleation. It is well known that the effectiveness of the heterogeneous seeding agent is highly temperature dependent. Artificial cloud nucleating substances (AgI, CO_2, Liquid propane, SNOWMAX) are dependent on the presence of SLW at temperatures slightly below 0 ^{o}C for CO_2, propane, and SNOWMAX (Ward and Demott 1989) or below -5 C to -8 ^{o}C for AgI mixtures (Figure 1.6).

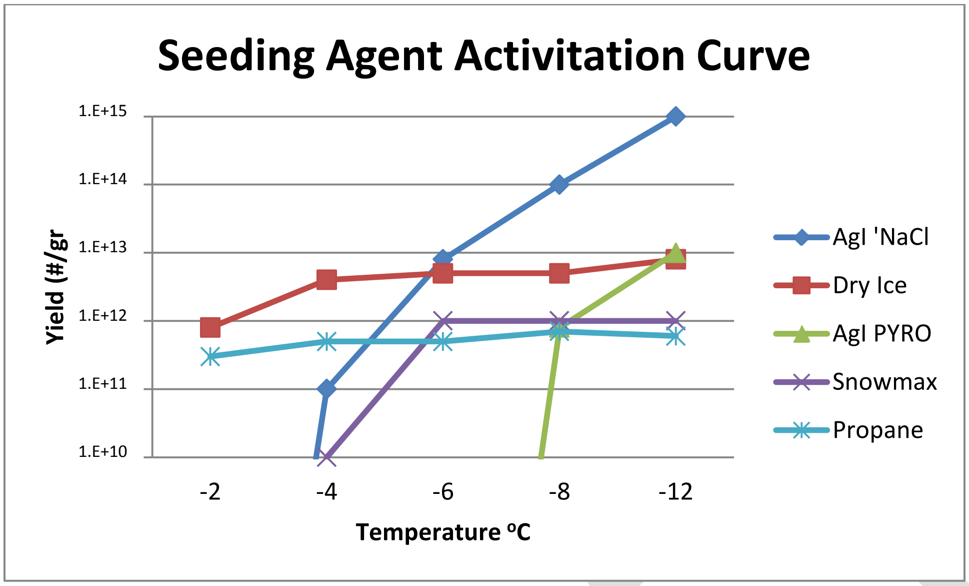

Figure 1.6 - Seeding activation versus temperature for seeding agents that have been used or proposed

These seeding agents act in different ways. Solid or liquid CO2 and liquid propane work by homogenous nucleation. These seeding agents need to be directly released in the presence of SLW for them to be effective. AgI and SNOWMAX work by heterogeneous nucleation, meaning they mimic the structure of natural ice nuclei. They do not have to be released directly into cloud or SLW. The aerosol can be carried aloft into clouds and when it encounters SLW at the right temperatures will begin generating ice crystals by contact nucleation. As shown in Figure 1.6, SNOWMAX works at the warmer end of the SLW temperature spectrum and its effectiveness does not vary greatly with temperature. To the author's knowledge, SNOWMAX is not used in any operational seeding program but is used almost exclusively for snowmaking at ski resorts. The effectiveness of AgI to nucleate ice crystals increases by orders of magnitude from -5 ^{o}C to -12 ^{o}C (Super 2005). It should be noted that under transient water supersaturations, AgI can activate more rapidly and at temperatures near -5 ^{o}C through the condensation freezing mechanism (Pitter and Finnegan 1987). Chai (1993) explained the only way AgI could have been an effective seeding agent in the Lake Almanor seeding experiment (Moony and Lunn 1969) was through the fast activating condensation freezing process. If the AgI is burned below cloud base or at temperatures warmer than -5 ^{o} C, the aerosol will not produce sufficient ice embryos until temperatures colder than -8 ^{o}C are reached (Super and Heimbach 2005). Huggins (2009) found the best temperatures for SLW in the Bridger Range Experiment occurred at $\leq$ -9 ^{o}C using AgI, which suggests the AgI acted through contact or deposition nucleation.

The central reason to explore propane seeding is its characteristic to be effective in mildly supercooled clouds that would be too warm for AgI. Propane dispensers tend to be more reliable, less complicated and less expensive than AgI generators. SLW temperatures in CO frequently range from -4 to -13 ^{o}C depending upon location and elevation (Boe and Super 1986; Rauber and Grant 1986; Huggins 1995; Super 2005; Huggins 2009). Due to the mildly supercooled nature of some CO locations, propane could be a useful alternative to AgI generators (Boe and Super 1986; Hindman 1986). The cloud base in California is often warmer than 0 ^{o}C while the top of the SLW near the mountain crest is usually $\geq$ -12 ^{o}C (Heggli et al. 1983; Heggli and Rauber 1988; Huggins 2009). This is why propane was adopted by Reynolds (1995) as the seeding agent of choice in the Lake Oroville Runoff Enhancement Program (LOREP) in northern California (see Figure 1.4b).

Cloud base altitude is an important consideration when siting propane dispensers which must be in-cloud or just below cloud base (at ice saturation) to be effective (Super 2005). Super and Heimbach (2005) indicate that even in the intermountain region, a significant number of hours with SLW are at temperatures where the release of AgI at elevations below -5 ^{o}C and out of cloud would not reach elevations cold enough to activate a sufficient quantity of the AgI to effectively "seed" the cloud and produce meaningful increases in snowfall. Thus, the 300 to 600 hours of reported SLW over the intermountain region during the 5 month snowfall season would require a mixture of seeding delivery methods including a mixture of high elevation ground released AgI and liquid propane or seeding from multiple aircraft.

1.7.2 Transport and Dispersion of Seeding Material

1.7.2.1 Ground Releases

Flow over complex terrain is not a simple and straightforward problem therefore making targeting a challenge. Trying to disperse AgI from ground based generators has proven to be very difficult (Super and Heimbach 2005). There are two critical issues here. One is whether a parcel of air starting out near the foothills or a valley location will be carried over the mountain in the prevailing wind direction or whether it will flow around the mountain. This is determined by the static stability of the air mass and the strength of the flow perpendicular to the mountain, often noted by the Froude number. When the velocity of the flow is strong enough to overcome the air parcels static stability, a Froude number greater than 1 is produced, meaning the parcel of air will pass over the mountain and not flow around the mountain. The depth of the boundary layer is also very important as ground based cloud seeding efforts are located within this layer. If AgI is released below cloud or at temperatures warmer than -5 ^{o}C, the aerosol will have to be carried up into the cloud to a level where the temperature is colder than -8 ^{o}C. If the boundary layer is shallow and does not allow the aerosol to reach the appropriate temperature level or that level is reached very near the crest of the mountain, there will be no impact on the windward slopes of the mountain. The depth of the boundary layer is a function of low level wind shear (Xue 2014), which is the change in direction or velocity of wind with height. The stronger the wind shear, the greater the depth of the boundary layer. Strong low level flow perpendicular to the mountain, along with strong wind shear and at times weak embedded convection, will provide the mechanism for lifting the aerosol up the mountain. This allows dispersal of the aerosol to seed more cloud volume. If the temperatures are cold enough and SLW is continuous, an increase in snowfall will occur on the windward slopes and increase the precipitation efficiency of the orographic cloud. The targeting issue has been described by many weather modification researchers (Super and Heimbach 2005; Reynolds 1988; Warburton et al. 1995a and b) as the single most critical issue that has compromised the success of both operational as well as research field projects. Again, reason to emphasize that effective cloud seeding is an engineering problem.

It has been shown that ample seeded crystals with sufficient concentration need to be dispersed so that a substantial volume of cloud over the target is treated for more than trace snowfall rates to occur (Super 2005; Huggins 2009). The seeding material must be injected into the SLW in sufficient quantities to generate 50 to 100/L or more initial ice embryos. This will then utilize the available SLW and fall out of the cloud prior to the snowflakes passing over the summit of the mountain and sublimating in the lee of the mountain.

An example of the use of a rather simple targeting model (GUIDE, Rauber et al , 1988) used in the Lake Oroville Runoff Enhancement Project (LOREP) to target ground-based liquid propane seeding effects is shown in Figure 1.7. This project used the tracer SF_6 co-released with the propane from two sites to validate the GUIDE and assure accurate targeting. The GUIDE plumes as shown both horizontally and vertically along with the vertical motion field from a locally released rawinsonde.

1.7.2.2 Seeding from Valley Locations

Many operational cloud seeding projects have placed AgI generators in valley locations as they are easily accessible and can be manually ignited when needed. However, a considerable body of evidence indicates valley released AgI plumes are often trapped by stable air (high static stability), especially when valley-based inversions are present (Langer et al. 1967; Rhea 1969; Super 2005). Often times in past projects AgI plumes from valley located generators were not tracked sufficiently to determine exactly where the aerosol plumes drifted (Smith and Heffernan 1967; Super 2005). As noted earlier, this is a recurring issue that has been raised in many winter orographic cloud seeding review articles (Rango 1986; Reynolds 1988; Super 2005; Hunter 2007; Huggins 2009). The aerosols may pool in the valley or may move in a direction around the mountain, only to be carried aloft when the static stability of the airmass decreases and low level winds increase. This usually occurs near and behind the surface cold fronts associated with winter storms. Thus, the AgI aerosol may travel far distances from the intended target and have unintended effects farther downwind.

1.7.2.3 Seeding from High Elevation Locations

Many studies suggest that seeding plumes released between half-to-two-thirds up the windward slope of the barrier routinely transport the seeding material over the mountain crest given favorable winds (Super 1974; Holroyd et al. 1988; Super and Heimbach 1988; Holroyd et al. 1995; Super and Heimbach 2005a). Super (1970) reported that AgI generators need to be placed at least halfway up the windward slope to be above the inversion commonly found in the Bridger Range of MT. The Bridger Range Experiment (Super and Heimbach,1983) proved successful in routinely seeding clouds by placing AgI generators two-thirds of the way up the windward slope (Super 1974; Heimbach and Super 1988; Super and Heimbach 1988). This however does reduce the time available for the crystals to grow and fallout prior to passing over the intended target. If the AgI generators are in cloud or above ice saturation, then the AgI will be fast acting in terms of nucleation and reduce the lag time between release and ice crystal formation (Pitter and

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Finnegan 1987). The best ground seeding situation occurs when 2 parallel ridges exist approximately 10-15 km apart as evidenced in the Bridger Range Experiment in southwest Montana (Super and Heimbach 1983; Super and Heimbach, 2005; Huggins 2009).

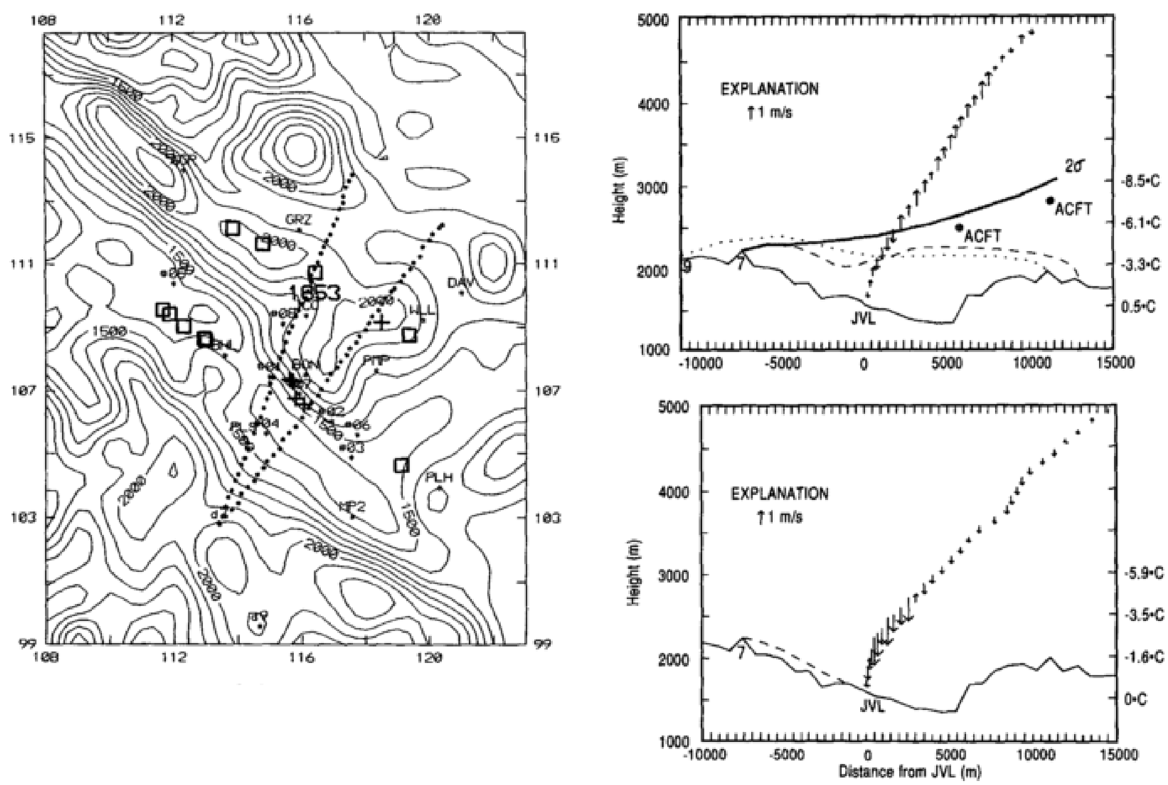

Figure 1.7 - a) GUIDE model predicted propane seeding plume overlaid on terrain contours for a propane transport and dispersion study conducted during LOREP. Aircraft measured tracer gas SF6 are annotated. b) GUIDE model predicted trajectories from two propane d

1.7.2.4 Seeding from Airplanes

Seeding by aircraft can be an alternative mechanism in locations where there is insufficient time to activate the seeding agent and grow the crystals to sufficient size for fallout to occur on the windward slopes of the barrier. These situations mainly occur within coastal mountains where the SLW near the crest of the mountain is only slightly sub-cooled. Typically the clouds extend up to a kilometer above and well upwind of the crest such that cloud top temperatures are -6 ^{o}C to -8 ^{o}C or colder. In these situations, the aircraft can fly in the tops of the clouds and either drop crushed dry ice, AgI droppable flares, or ignite AgI wing-tip generators or stationary flares that will directly inject the seeding material into the cloud. Using crushed dry ice or droppable flares will create a curtain of ice crystals some 1000 m below the aircraft. This will spread at a rate of 1-2 m/s dependent upon the amount of vertical wind shear (Hill 1980; Reynolds 1988). For these seeding curtains to merge together over the intended target area, the length of the seed line cannot be more than 30 to 40 km long (Deshler et al. 1990). However, the watershed of a large river basin can be several hundred kilometers wide. One aircraft will treat only a small portion of the watershed (see Figure 1.8). In addition, the duration of the seeding aircraft is usually about 2 to 4 hours, with the possibility of the aircraft having to descend to deice several times during the seeding mission. Aircraft operations are also expensive. For these reasons, many operational seeding programs use ground based seeding platforms, even if they are only viable a small percentage of the time.

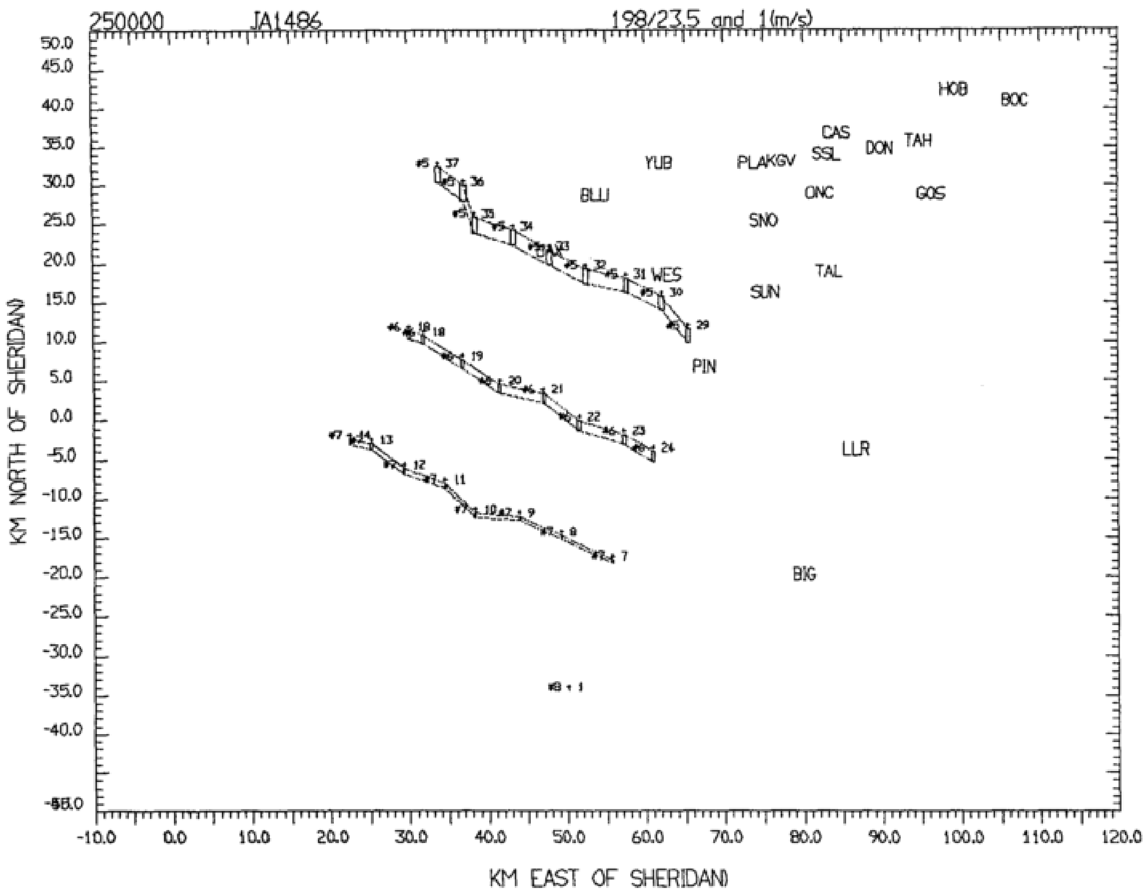

Figure 1.8 - Aircraft seedline positions and width from 10 to 30 min after seeding assuming a 23.5 m s-1 wind speed and a 1 m s-1 dispersion rate. Note the rather small volume of treated cloud. From Reynolds (1988).

1.7.3 Silver in Snow Concentrations and Other Targeting Validation Methods

It is possible to take samples in the spring snowpack to determine if silver concentrations exceed normal background levels when AgI is used as the seeding agent (Warburton 1969; Warburton 1996).The method takes a vertical profile of 2 cm samples in various locations throughout the intended target area. The depth of the sample can be related back to particular precipitation events utilizing a nearby snow gage precipitation record. Samples associated with seeding events can be analyzed for silver content above a background level determined for samples taken prior to seeding occurring. If silver is found above background levels it only indicates that silver from the seeding fell out in the target area. It does not differentiate as to whether the silver acted as active ice nuclei or was simply scavenged by natural snowflakes and precipitated out in the target area. Silver in snow analyses performed over many different geographic locations in the western US after seasonal seeding with ground-based AgI generators have shown just a small percentage, 10-20%, of the samples having silver content above natural backgrounds (Warburton 1995 a,b; Reynolds et al . 1989; Long 1984; Super et al. 2003). Samples taken during a winter season (Warburton, 1995b) within PG&Es Lake Almanor project, where Mooney and Lunn (1969) had reported statistically significant increases in snowfall during what was classified as “cold-westerly” wind cases, found 42% of the westerly wind cases had silver in snow above background levels. However, 80% of all seeded cases lacked evidence of silver in snow. There are three projects that stand out as having been successful in targeting ground based AgI: McGurty (1999) for the So Cal Edison project near Bear Creek in the San Joaquin drainage; Huggins (2006) for the Tahoe-Truckee and Walker river basins; and Manton et al (2011) for the Snowy Mountains of Australia. These projects reported between 70% and 100% of the 2 cm samples taken within the target area had AG above background levels.

A non-nucleating aerosol can be co-released with the AgI ground generator plume in order to determine if the AgI seeding agent actively participated in the precipitation process. The tracers tested have been rubidium and indium susquioxide. This has been done in the Walker Carson basin of Nevada, the upper American in California and in Australia’s Snowy Mountain project. The results of the Snowy Mountain project will be discussed in a later section of this report.

Other sampling methods to determine successful targeting have utilized an ice nucleus counter mounted either in a vehicle or, most commonly, on an aircraft (Super and Heimbach 2005 Appendix B). The most important conclusions reached in this analysis state that AgI generators located halfway-to-two-thirds up the windward slope of the intended mountain will be much more successful in impacting the target area.

When AgI is not used as the seeding agent, other tracers may be utilized to determine the transport and dispersion of the seeding agent. Sulfur hexafluoride, SF_6 , has proven to be a very effective tracer when propane has been released from the ground (Reynolds 1996). Samples can be taken either using sequential syringe samplers at surface locations within the intended target area, (Krasnec et al. 1984), or a continuous SF_6 sampler can be mounted on an aircraft (Stith et al. 1987; Reynolds 1996) that can fly downwind of the release points to monitor the vertical and horizontal dispersion of the trace gas that acts as a proxy for the seeding produced ice crystals.

Another method that has been used to try to tag air parcels that would emulate the seeding plume is the use of chaff (Reinking et al. 1999). Chaff are very small aluminum particles that are highly reflective to weather radars. Chaff is used routinely by the military as a countermeasure to radar surveillance. The chaff particles are suspended in the air and carried with the wind, similar to a seeded volume of air. While this has not obtained wide-spread use, it was identified in the NRC 2003 report as a potential tracer for transport and dispersion studies.

1.7.4 Extended Area Effects from Winter Orographic Cloud Seeding

Hunter (2009) prepared an extensive literature review of the current state of knowledge on extra or extended area effects from winter orographic cloud seeding. The main impetus for this report was to present any documented evidence that determined that seeding on one mountain barrier resulted in a possible reduction of the amount of precipitation downwind. This has been coined

"Robbing Peter to pay Paul". Hunter provided the following table which is reproduced here (not all references are included in Section 6). In every case, the seeding agent was silver iodide. These results indicate that once the AgI nuclei are released into the atmosphere, they can remain active for many hours, if not several days. If pooled in high concentrations, the AgI nuclei can seed areas well away from the intended target areas. However, the impacts of these extra-area effects are just as uncertain as the increase documented in the primary target areas. That is, without strong physical observations to compare with rigorous statistical analyses, there is still a significant level of uncertainty as to the efficacy of seeding with AgI to increase precipitation within large areas outside the intended target area.

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Table 1.2 - With permission from Hunter (2009. Please see this paper for all references.

Project	Extent of Positive Seeding Effects* Beyond Target Area (miles)	Comments (including magnitude of effects, statistical significance etc.)	Reference
Coeur d'Alene, Idaho	100-160	Low probability these positive precipitation anomalies could have occurred by chance	Keith J. Brown,in Elliott, Robert D., Keith J. Brown, and Lewis O. Grant (Eds.), 1971
Rogue River, Oregon	40-100 beyond the target area	1.2-1.5 seed vs. no-seed ratios with strong statistical confidence	Keith J. Brown,inElliott, Robert D., Keith J. Brown, and Lewis O. Grant (Eds.), 1971
Bear River, Wyoming	150-200	Similar pattern to the previous two areas, but greater downwind distances	Keith J. Brown,inElliott, Robert D., Keith J. Brown, and Lewis O. Grant (Eds.), 1971
Southern Sierra Nevada, California	100-250	Patterns complicated by multiple seeding projects. High ratios (1.2 to 1.6)	Keith J. Brown,inElliott, Robert D., Keith J.
South Cascades, Oregon	60-100	Citation of other sources	Berg, Neil H., and James L. Smith, 1980
Rogue River, Oregon	100-250	Citation of other sources	Berg, Neil H., and James L. Smith, 1980
Utah	150-200	Citation of other sources	Berg, Neil H., and

			James L. Smith, 1980
South Sierra Nevada, California	50-250	Citation of other sources	Berg, Neil H., and James L. Smith, 1980
Idaho	100-160	Citation of other sources	Berg, Neil H., and James L. Smith, 1980
Multiple areas	60-120	Summarizing other works	Dennis, Arnett S., 1980
Santa Barbara II, California	100-130	Found extensive areas of statistically-significant ratios of ≥ 1.5 seeded to non-seeded cases mainly downwind of AgI generators, but only for “warm” cloud tops (T500 ≥ -20°C).	Elliott, R.D., K.J. Brown, 1971
Climax, Central Colorado	50-150	Large positive extra-area precipitation anomalies from seeding, statistically significant	Grant, L.O., C.F. Chappell, P.W. Mielke, Jr., 1971
Uinta Mountains, Utah	25-100	Historic precipitation and snow course data analyzed statistically for seed and no-seed periods. Precipitation increases were generally greater for downwind areas than for intended target areas.	Grant, L. O. and P. W. Mielke, 1990
Northeast Utah and Southwest Wyoming	N/A	No statistically significant extra-area effects from seeding.	Grant, Lewis O., Mark D. Branson, and Paul W. Mielke, Jr., 1992
Central & Eastern Utah	~60-130	Historical target-control regression showed about 15% precipitation excess from seeding in “downwind” areas, but at slightly less than commonly accepted statistical significance levels.	Griffith, Don A., John R. Thompson, and Dan A. Risch, 1991
Pyramid Lake, Nevada	~100	Pyramid Lake Pilot Project found silver concentrations in snow that whose origins were from upwind cloud seeding in the American River Basin (California), pointing out the	Harris, Edward R., 1981

		difficulty of separating downwind effects from targeted effects (so-called “contamination”). Liquid tank (physical) modeling and transport and diffusion (numerical) models both corroborated these onsite measurements.	
Tahoe Basin, Nevada	>45	Numerical model of transport and diffusion of seeding material indicates contamination of Tahoe Basin by seeding on other site of Sierra Nevada crest line	Huggins, Arlen W., 2006
Climax, Central Colorado	50-150	Extensive positive seed/no-seed precipitation ratios on northeast Colorado plains, across the Continental Divide from target area. High statistical confidence, especially for certain meteorological conditions (e.g. relatively warm cloud tops).	Janssen, D.W., G.T. Meltesen, and L.O. Grant, 1974
Southern Idaho	180 maximum (no decrease in precipitation in Idaho from California seeding - too distant)	Not a field study -mainly a summary of literature on the subject of extended area effects. Found that these effects are the same as those in the target area, in general. Research indications of extra-area effects characterized as “weak, contradictory, and inconclusive.”	MacCracken, J.G., and J. O’Laughlin, 1996
Central and Northern Colorado	80	Seeding effects from upwind project (Park Range) were very evident, with low probability of chance, in experimental area (Climax) on non-seed days at Climax; so much so that those effects	Paul W. Mielke, Jr, inElliott, Robert D., Keith J. Brown, and Lewis O. Grant (Eds.), 1971

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		were comparable to the effects of the Climax seeding generators.	
Colorado	68-150	Aircraft sampling of ice nuclei concentrations and aerosol silver concentrations; findings of extra-area seeding effects were supported by silver-in-snow measurements and numerical cloud modeling.	Mulvey, Gerald J., 1977
Utah	To 100, then drastic decrease of effects.	Traditional target-control regression of long-term precipitation data. Average increase was 14% out to 75 miles.	Solak, Mark E., David P. Yorty, and Don A. Griffith, 2003
Bridger Range, Southwest Montana	>20	No effect found beyond 20 miles from target, but these areas were much lower in elevation than target	A.B. Super and V.L. Mitchell, in Elliott, Robert D., Keith J. Brown, and Lewis O. Grant (Eds.), 1971
Southwest Montana	>18	Randomized experiment; statistically analyzed precipitation and snow course data. Downwind increases evident on lee slope and valley beyond, especially for (Bridger Range) crest temperature < -12°C.	Super, Arlin B., and James A. Heimbach, Jr., 1983
Central Utah	~50-140	Post-hoc statistical analysis of long-term precipitation records in and around operational seeding projects. Downwind increases were evident but not as statistically significant as increases in targets.	Thompson, John R., and Don A. Griffith, 1981
Lake Tahoe Basin, Nevada	30-75	Silver-in-snow concentrations, not precipitation, measurements. Doubling of concentrations over background attributed to upwind operational seeding projects	Warburton, J.A,in Elliott, Robert D., Keith J. Brown, and Lewis O. Grant (Eds.), 1971

Tahoe-Truckee in the Sierra Nevada, Park Range of Colorado, and Lake Erie region of NY State	50-150	Silver-in-snow sampling of 25 winter storms, some seeded and some not. Found 5-30 times background silver levels in diverse regions, associated with either aircraft of ground seeding. Concludes that seeding effectiveness analysis would be complicated by projects separated by less than 100 miles.	Warburton, J.A., 1971
Most of the Sierra Nevada, California	~100	Statistical analyses of long-term streamflow data, not precipitation, showing increases contemporaneous with operational seeding projects upwind	Merlin Williams, in Elliott, Robert D., Keith J. Brown, and Lewis O. Grant (Eds.), 1971

1.7.5 Statistical Analyses

Statistical analyses have been a key part of assessing past cloud seeding experiments. Credence has usually only been given to those experiments that have been randomized and run as a confirmatory experiment. Key historical projects such as Climax and the series of Israeli cloud seeding experiments run as confirmatory, and meeting or exceeding the level of statistical significance set out in the experimental design, have come under further scrutiny and found to suffer from what is called Type 1 errors (Rhea 1983; Rangno and Hobbs 1993; Rangno and Hobbs 1995b; Rosenfeld 1997). In statistical testing there are two types of errors: Type I errors and Type II errors. Type I errors are false positives. This occurs when a relationship is thought to exist when in fact it does not. Type II errors are failing to find an effect that is present. This occurs when a relationship does exist but is not detected. Type I and Type II errors can be minimized by choosing an appropriate significance level for the statistical test being performed. Scientific convention typically uses a significance level between 1 to 15%. This means there is a 1 to 15% probability that the result was due to chance. Significance levels minimize error but do not completely remove them. A significance level of 1% means there is a 99% chance the outcome is not due to randomness, i.e., chance. To test whether the statistical analysis meets the significance level used, a p-value is calculated. The p-value compares the real outcome of the statistical analysis to the expected outcome of the statistical analysis. If the calculated p-value is less than the significance level, then the result is said to be statistically significant. For example, if a significance level of 1% is used and the results prove to be significant by calculating a p-value less than 1%, there is a 99% probability that the results of the statistical analysis are not caused by chance.

It is stated in the IPCC report that scientists err on the conservative side of attribution of anthropogenic causes of extreme weather thus favoring Type II errors over Type I errors (Table

1.3 from Anderegg et al. 2014). This is typical in scientific statistical testing. It is considered less incorrect to not detect a relationship when one exists rather than detect a relationship when one does not exist. Other statistical methods, such as the use of covariates, can be useful in determining the statistical success of seeding operations (Dennis 1980; Mielke et al. 1981; Gabriel 1999; Gabriel 2002; Huggins 2009). A problem common to the statistical method of historical regression is the assumption that climate has been stable over many decades (Hunter 2007) which is called stationarity.

Table 1.3 - from Anderegg et al. 2014

	Null hypothesis is TRUE	Null hypothesis is FALSE
Reject null hypothesis	Type I Error (False positive)	Correct outcome! (True positive)
Fail to reject null hypothesis	Correct outcome! (True negative)	Type II Error (False negative)

1.8 Summary

From the information summarized above it is worth reviewing the key questions as outlined for winter orographic clouds as listed in Table 1.1.

What is the location, duration, and degree of supercooling of cloud liquid water in winter orographic clouds?

- Concentrated in the lowest km on the windward slopes of mountain (Super and Heimbach, 2005)
- Highly variable in space and time given fluctuations in wind speed/direction and natural precipitation processes.
- Higher concentrations and higher frequency of SLW at warmer temperatures for all mountain ranges
  - SLW >.05 mm vertical integrated has been used as lower threshold for cloud seeding initiation.

Are their man-made pollutants or natural aerosols/particulates impacting the target clouds that could modify the cloud droplet spectra/IN concentrations to impede seeding effectiveness?

- Pollutants acting as CCN can narrow the droplet spectrum and slow down the collision coalescence process (warm rain) reducing rainfall downwind of major pollution sources. (Rosenfeld 2000; Givati and Rosenfeld 2004; Givati and Rosenfeld 2005,)

- It was found in SCPP that SIP (secondary ice production) produced high ice concentrations at relatively warm cloud top temperatures (-5 to -10 oC)
- If pollutants narrow the droplet spectrum, then pollutants in theory should reduce SIP.
- If high concentrations of pollution produce high concentration of cloud droplets in a narrow size range, this could reduce riming and reduce snowfall on the windward slopes of narrow mountain ranges where growth times are critical.
- A more recent survey article on the role of pollution on clouds and precipitation (Tanre', 2009) concluded it was still uncertain as to the magnitude of the impact of pollution or whether pollution increases or decreases precipitation based on the meteorological setting.
- Dust (Saharan and Gobi desert) and aerosols (bacteria) acting as IN can enhance natural snowfall when present on West Coast (CalWater I)
- When not present there should be more favorable conditions for orographic cloud seeding?

Are their significant enough differences in maritime influenced winter orographic clouds versus continental orographic clouds that strongly influence the natural precipitation process?

- Yes. Maritime clouds with broader drop size distributions are subject to SIP and thus clouds are more efficient at warmer temperatures.
- Continental clouds have relatively more SLW at colder temperatures given the lack of SIP.
- Evidence of this is well-documented when one compares SCPP and Washington studies with interior mountain studies.

Are there numerical models that can be run in real-time utilizing project field observations to guide seeding decision making?

- Demonstrated in SCPP that with frequently updated three dimensional winds (single or better yet valley and crest rawinsonde launches at 3-hr intervals) the GUIDE model could be used for targeting both ground –based and aerial seeding operations.
- Numerical models are not yet capable of forecasting the hourly magnitude and hour by hour variability of SLW over a given barrier. Thus scanning microwave radiometers within the intended target area can be used to monitor the presence of SLW. Mountain-top icing rate meters are a less expensive but also less representative alternative to monitor SLW. Rawinsonde data can be used to determine SLW temperatures.

What is the best seeding agent to use based on SLW temperature regime and what is the best way to deliver the seeding agent?

- If 1) SLW is found at temperatures colder than -5 oC, and 2) is within the lowest 1000m on windward slopes of the mountain and 3) there are locations where ground-based generators can be placed mid-way up the mountain slope to assure aerosol reaches activation temperatures quickly and reliably and 4) there is sufficient time to grow crystals (~1500 s) before they pass to

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the lee of the mountain, AgI with a compound that promotes condensation freezing would be the preferred method.

- If the SLW is found at temperatures warmer than -6 oC, but clouds extend vertically to the -10 to -15 oC range well upwind of the crest, aerial seeding with AgI wingtip flares or crushed dry ice is the preferred method.
- Liquid propane dispensers located within SLW cloud sufficiently upwind of the crest or on a ridge upwind of a second ridge where subsidence is minimized between ridges can be a good alternative to aerial seeding. Again, there has to be sufficient time for crystal growth and fallout to produce any meaningful snowfall enhancement.

What is the necessary density and location of ground-based dispensers and what is the dependency on seeding agent used?

- One should assume an approximate 10 o to 15o spread of ground based seeding aerosols. Given a minimum of 15 to 30 min to fallout, the generators should be placed sufficiently close to assure complete coverage of the intended target and positioned to take advantage of a spectrum of wind directions that can produce SLW over the mountain thus maximizing seeding events per season.
- Again, the location of the dispensers should be sufficiently high on the barrier to assure adequate nucleation and targeting of the seeding agent and fallout of the seeded crystals before passing to the lee of the crest.
- One has to consider whether the dispenser is located within cloud and below temperature thresholds for which a sufficient number of ice nuclei will activate to produce say 50 to 100 L-1 of ice crystals. AgI dispensers with a mixture allowing condensation freezing and liquid propane which produces ice crystals immediately will have fallout closer to the dispensers. The plumes will thus be narrower and have a smaller impact footprint. One needs to then make sure the dispensers are close enough together to have plume overlap within 15 to 30 min of transient time downwind.

What observing systems are needed and at what spatial and temporal frequency to adequately target seeding impacts?

- Rawinsondes launched within or just upwind of the intended target area provide the most useful observations of the vertical profile of wind and temperatures. They should be launched at least every three hours to assure adequate capture of changing wind and temperature conditions. If the barrier is of sufficient length and width an upwind sounding may not represent the winds over the crest and thus a rawinsonde may need to be launched near the mountain crest at a similar frequency to the upwind site. This sampling is necessary for both ground-based an aerial seeding.

What are the observing systems, either in-situ or remote sensing, that can observe and track a seeding plume from initiation to fallout? What are the benefits and limitations of each?

- To date the most useful observing systems have been ice crystal particle probes onboard aircraft combined with an NCAR ice-nucleus counter when AgI has been used as the seeding agent. This is most useful for aerial seeding as most aircraft are restricted from flying to within 1000m of the highest terrain which is the depth to which most of the seeding agent is concentrated from ground releases. It is most effective for tracking of aerial seeding plumes.

- These same probes can be mounted on a tower or vehicle and combined with a wind sensor to adequately determine the sampling volume and crystal concentration. Again an NCAR ice-nucleus counter can be operated with the particle probe to assure the sampling is being done within the seeded plume if ground-based AgI seeding is being conducted.
- The above sampling methods are compromised by naturally occurring snowfall that can mask the seeding effects. Also, the AgI aerosol and seeded crystals will soon begin to separate as the seeded crystal fallout and the AgI aerosol continues to be lifted by the orographic forcing.
- X- band or C-band radars have been used with limited success for monitoring seeded plumes from both aerial and ground based seeding. However natural ice severely compromises the radars ability to see a high concentration of small increase if there are naturally occurring large crystals within the seeded volume.

What is the resolution and spacing required of recording snow gauges within the intended target area and downwind target area?

- The resolution of recording snow gauges is a function of the duration of the seeding and the expected effects. Based on observed seeding effects that average about .25 mm/hr, the gauge resolution should be about twice this or near .1 mm/hr. This requires careful siting of the gauges within sheltered locations of the target area. Having high quality gauges with sheltered locations is more important than the number of gauges. This is true for the primary and downwind target area as well as any control area that is being used for statistical analysis. However one must consider that given the narrow plume width from ground-based seeding, unless the ground generators are placed close enough together to assure complete coverage of the target area, gauges may not be within the seeded volume at all times when seeding is conducted and thus may not provide an adequate measure of seeding effects.

If silver iodide is the seeding agent, what are the benefits and limitations of sampling the silver concentration in the snow prior to spring melt to validate that a significant portion of the winter seeding impacted the target area?

- Measuring silver in snow is a very tedious and necessarily sophisticated effort as one is trying to detect concentrations in parts per trillion above a background of 3-5 ppt. Thus it takes very careful sampling and the area should be away from possible contamination by dust that can advect in and contaminate the site. Observing Ag in snow above background levels will only determine that there was adequate targeting, but unless a non-nucleating agent is released with a similar mass concentration, it is impossible to tell if the additional Ag is removed from the cloud by scavenging or primary nucleation.

What is the best design of the seeding program to reduce uncertainty and insure meaningful statistical results?

- If a project is going to evaluate the seeding effectiveness, then randomized seeding should be used. That is, some seeding opportunities should be left unseeded, and the seeding decisions should not be communicated to those doing the evaluation. The number of cases needed to reach a level of statistical significance will be based on the expected seeding effect. If one assumes a 10% increase in seed over no-seed, and one has a long historical climatology of target area precipitation, the number of samples can be computed. The sample size can be reduced if a highly correlated (r value > .8 is best) control area can be determined that will not be impacted by the seeding. A further reduction in sample size is possible if a cross-over design is used. That is, that the target area alternates in a randomized fashion between the two areas with an equal distribution of seed no-seed between the two. It is expected that one should plan on at least a 5 year period of randomized seeding with a buffer of several more years if seedable conditions are lacking for several of those years.

What is the best statistical method to apply to achieve statistical significance and reduce Type I and II errors?

- The best method to avoid false positives (Type I errors) or false negatives (Type II errors) is to establish a-priori response variables that are sensitive to the seeding. The primary response variable will most likely be snow water equivalent for the target and control sites. Secondary response variables such as integrated SLW, or Ag in snow, or ratio of Ag to a non-nucleating agent, can also be used. The more physical evidence of seeding effects that help document the links in the chain from seeding agent release to seeded crystal fallout the less chance of Type I or Type II errors.

Benefits and limitations of a reanalysis of operational cloud seeding projects?

- Seeding outcomes of historical operational cloud seeding projects based on target control statistical analyses can only be considered suggestive. Because they are not randomized and the selection of the data set to be analyzed can be subjective, the results, even though shown to be statistically significant, cannot be evaluated in the same manner as a fully randomized, blind or double blind, confirmatory seeding experiment. Because of changing conditions between the primary target and the chosen control (also subjective), there is certainly the possibility of bias in any results such as these.

In the next sections of this report more detailed analyses of recent (post NRC 2003) winter orographic cloud seeding studies will be reviewed. At the end of these reviews, a final summary addressing these same questions will be provided incorporating any significant findings from these studies.

Review of Relevant Winter Orographic Cloud Seeding Research Projects Since NRC 2003

2.1. Introduction to Winter Orographic Cloud Seeding

The Snowy Precipitation Enhancement Research Project (SPERP) was undertaken from May 2005 to June 2009 in the Snowy Mountains of southeastern Australia with the aim of enhancing snowfall in westerly flows associated with winter cold fronts (Manton et al. 2011; Huggins et al. 2008). Building on earlier field studies in the region, SPERP was developed as a confirmatory experiment of glaciogenic static seeding using a silver-chloro-iodide material dispersed from ground-based generators. Seeding of 5-h experimental units (EUs) was randomized with a seeding ratio of 2:1. Only the generator operators and maintenance personnel were privy to the seeding decision. A total of 107 EUs were undertaken at suitable times, based on surface and upper-air observations. Indium (III) susquieoxide was released during all EUs for comparison of indium and silver concentrations in snow in seeded and unseeded EUs to test the targeting of seeding material. A network of gauges was deployed at 44 sites across the region to detect whether precipitation was enhanced in a fixed target area of 832 km^2, using observations from a fixed control area to estimate the natural precipitation in the target. Additional measurements included integrated supercooled liquid water at a site in the target area and upper-air data from a site upwind of the target.

It is useful to review the maximum snow pack depth for this watershed and the trends in snow depth for the period of record. Figure 2.1 shows the trend in maximum snow depth since 1954 and the accumulated snow depth for three of the five years of the experiment as provided by Huggins et al, 2008). Note that the maximum depth has been trending downward since records began as well as the 3 years (2004 was not part of the confirmatory experiment) shown were below average. The snowpack accumulation period lasts for about 2.5 months.

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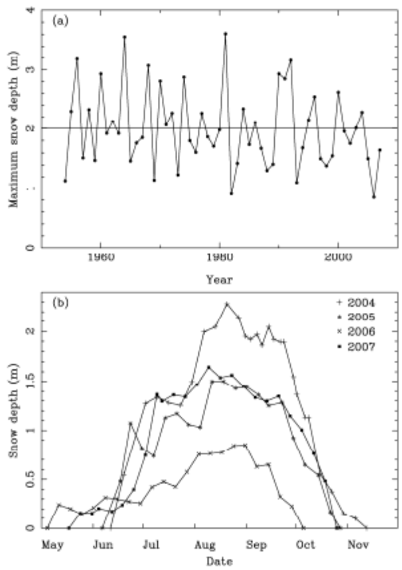

Figure 9.1 Trends in winter snowpack in the SPERP target area and the seasonal trends during a portion of the randomized confirmatory experiments. (Huggins et al. 2008)

The SPERP confirmatory experiment built off several decades of exploratory research studies conducted as far back as the 1950s and extending into the mid-90s over various regions of the Snowy Mountains. In particular Long and Huggins (1992) and Warburton and Wetzel (1992) reported observing many hours of supercooled liquid water over the Baw Baw Plateau (Figure 2.2a) during the passage of winter cold fronts. It was inferred by the researchers of SPERP that fronts passing over the Snowy Mountains were the same fronts that passed over Tasmania, where decades of seeding had demonstrated statistically significant rainfall increases when seeding these frontal clouds (Ryan and King 1997). The SPERP may have been the first confirmatory experiment that utilized direct field observations of SLW and real-time vertical temperature and wind information to initialize a numerical targeting model (GUIDE, Rauber et al. 1988), developed during the Sierra Cooperative Pilot Project, to determine when seeding should be initiated. In addition, real-time chemical samples were taken in the target area at Blue Cow (Fig. 2.2b) and additional samples taken after an Experimental Unit (EU) at 16 sites (14 in the target area and 1 each in the control and extended area). These samples consist of 2 cm layers taken at each of the 16 sites. The samples are processed for silver content in individual seed/no-seed events along with the non-nucleating aerosol (Indium III) co-released with the ground-based silver iodide generators or released alone on no-seed events. The silver in snow samples would address whether targeting was successful while the ratio of silver to indium ratio would indicate whether the silver acted as a nucleating agent rather than simply being scavenged and precipitated out by natural snowfall. This project was therefore patterned very much after the research conducted during SCPP. This makes sense since Huggins and Warburton both were active participants in the SCPP.

The project area is shown in Figure 2.2b along with the control and extended monitoring area. The target area is approximately 15 to 30 km from the ground based seeding generators. An upwind sounding was taken at Khancoban and a microwave radiometer was operated at Blue

Cow. A cross section of the project terrain and a simulation of the trajectory of the AgI plume along with nucleation and fall-out as output from the GUIDE model are shown in Figure 2.3. Soundings were taken at Khancoban every 3 hours to initiate the GUIDE model. Seeding criteria required snowfall in the target area, or freezing levels at 1600 m or lower, that at least one of the 13 generators demonstrate proper targeting of seeded crystals in the target area from GUIDE model runs, that the cloud-top temperature be less than -7 ^{o}C and there must be at least 400m of cloud above the -5 ^{o}C level. The latter two were to assure the AgI would activate and have enough cloud to grow to a sufficient size to fallout in the target area. In addition, the radiometer at Blue Cow had to observe at least .05mm of integrated SLW for a minimum of 30 min and that this is projected to last for a minimum of 3 hours. As stated, EUs were 5 hours long. A one-hour purge period was used before another EU could be called. This was determined from GUIDE model runs indicating when the plumes would pass out of range of the target. Based on previous AgI sampling studies using an NCAR ice nucleus counter (Super and Heimbach 2005) this would seem to be a very short period to assure the AgI agent is completely removed. In fact Huggins notes that there were observations of Ag in snow samples taken 1 hour after seeding ended. Give this one hour purge, there could, in one storm event, be several EUs. Huggins et al (2008) reports on a series of 5 EU during one storm event.

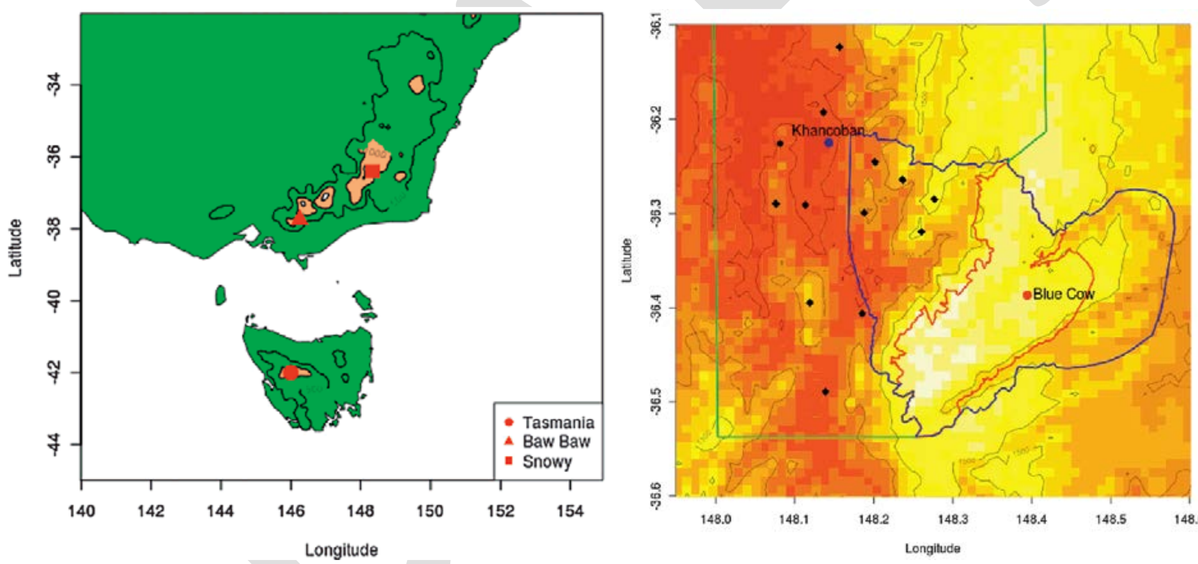

Figure 2.2 a) various locations of seeding trials in southern Australia and Tasmania. b) SPERP project area showing primary target area in red, extended target area in blue and control area in green. Diamonds denote ground generators and blue dot the rawinsonde location. Elevation contours at 500, 1000, and 1500m shown. From Manton et al. 2011.

The SPERP used thirteen pairs of seeding generators, located along the western perimeter of the target area at altitudes ranging from 439 to 1662 m (five above 1000 m), to disperse the seeder and tracer aerosols into the atmosphere. The seeding aerosol is specifically AgCl0.22I0.78·0.5NaCl, reported on by Feng and Finnegan (1989), with an activity of 1.2 x 10^{14} nuclei gm-1 at -10^{o} C and approximately 10^{12} nuclei gm-1 at -6^{o} C. The mass release of the Ag and In and thus there ratio in a snow sample would be 1 if both were being removed by scavenging. The activity spectra of this solution drops off exponentially below -6° C. As noted in Huggins (2008), this AgI NaCl solution can nucleate by condensation freezing if released in water saturated conditions at temperatures below -5° C. However this temperature level was well above all of the ground based generators in almost all EUs thus it is unlikely that this process occurred very often if at all. It would be expected that the nucleation was by contact or deposition freezing once the aerosol reached activation temperatures.

A key measurement is snow water equivalent. A question that arises in any evaluation of a winter cloud seeding project is, "What is the snow gauge resolution, placement density and sensitivity to wind?" As Huggins (2008) reports, the project did a very good job of addressing this issue by testing various gauge types and testing various wind fences to minimize under-catch. Figure 2.4 from Huggins shows examples of the gauge testing and the degree of under-catch when fencing is not used. The type of gauge used was the ETI gauge developed during SCPP with a resolution of .25mm and many of the target gauges used the half-fence to minimize under-catch. Gauge precision issues, as well as gauge random biases, contribute to gauge snowfall measurement uncertainty with regards to winter orographic cloud seeding. With short EUs and possibly sporadic targeting as the plumes drift back and forth over a target gauge, it has and remains a challenge to resolve seeding effects using gauges. Thus the reason for long term randomized seeding programs that can reduce this uncertainty.

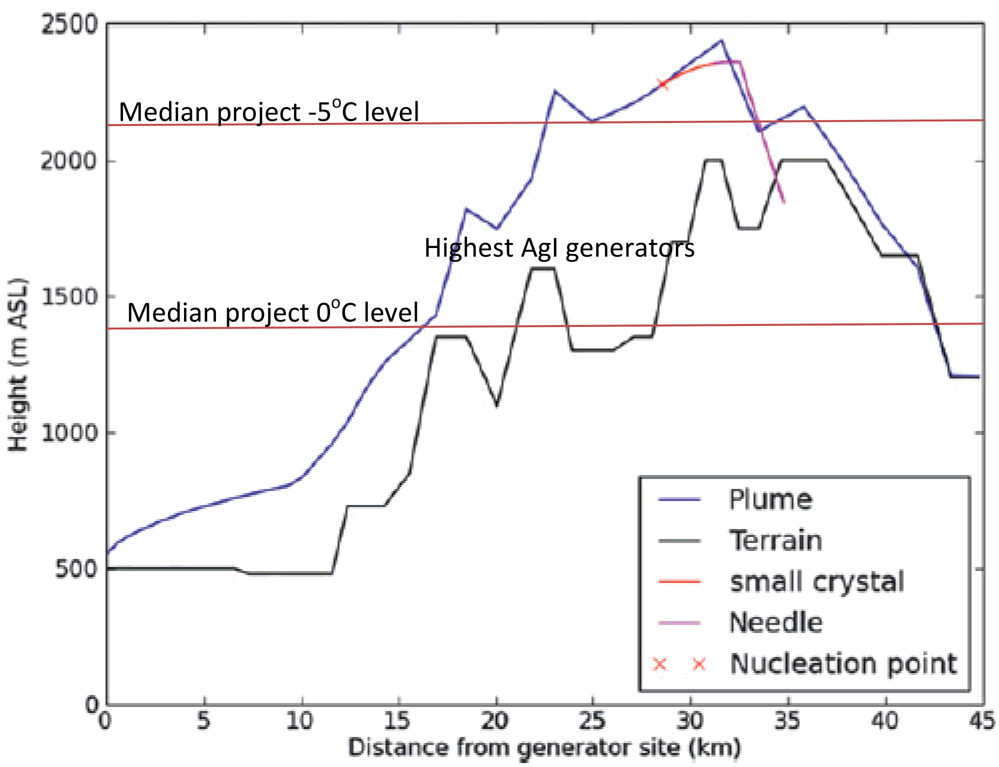

Figure 2.2.10 GUIDE model output showing AgI plume trajectory, primary nucleation location and crystal fallout. Also annotated are the median values of the freezing level and -5 °C used as the threshold of activation for the AgI solution used for this project. Also noted is the highest AgI generators used in the project. From Manton et al. 2011.

Huggins et al (2008) presented some very interesting preliminary physical studies not presented in Manton et al (2011). First, he showed the percentage of Ag to indium ratios in snow samples taken during the first year of the confirmatory experiment at greater than 1. In 2004 testing of the generator sites were performed but were not part of the confirmatory experiment, Figure 2.5a. As Huggins noted the targeting improved during the second year after generators were repositioned, Figure 2.5b,c. The background concentration of Ag in snow in this area was determined to be 4PPT although later analysis by Manton questioned whether some contamination may have occurred. He reported that in the overall confirmatory experiment, in 26 unseeded EUs where chemical sampling could isolate a specific EU, the average maximum Ag was 9.59 ppt or over twice the background level. These may mean that the seeding agent was not purged adequately during the one-hour purge period or another source of silver was contaminating the samples. This discovery will be discussed further below. Figure 2.5b indicates that seeding impacts appeared to occur not only in the target area but upwind of the main target area and upwind of the generators in what is part of the control area.

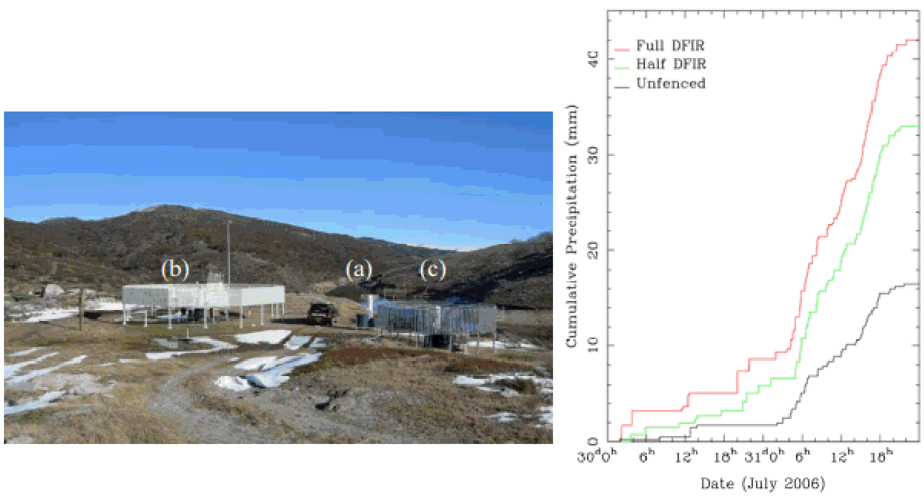

Figure 3. Left: The pluviometer comparison site at Guthega Dam, consisting of an unfenced gauge (a) and identical gauges fenced with a full DFIR (b) and a half DFIR (c). Right: The cumulative precipitation measured by the gauges over a two day period in July 2006.

Figure 2.2.11 Snow gauge comparison studies performed using the various gauge measuring systems on SPERP. An example of the observed precipitation for a two day period is shown. From Huggins 2008.

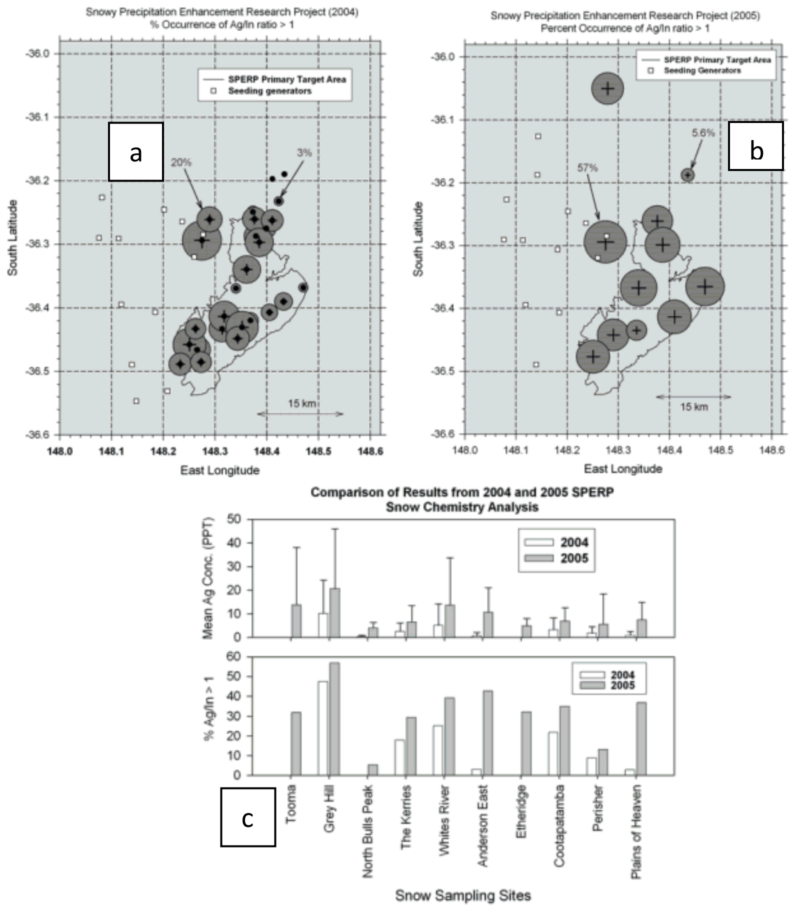

Figure 2.5 a) Trace chemistry results from 2004 (prior to confirmatory exp.) and 2005 (b) of Ag to Indium ratios both spatially (a and b above) and (c) at individual sampling sites. From Huggins 2008.

In addition to chemical sampling and SLW samples taken at Blue Cow, icing rate meters were installed to determine that low level SLW was present. Cloud and precipitation imaging probes were used to monitor ice crystal concentrations, sizes, and habit. As has been reported in Section 1, projects that successfully monitored seeding impacts using AgI, utilized mobile or aircraft mounted ice nucleus counters or other tracers like SF_6 or even chaff to track the plumes of seeded material. This project was only able to utilize the chemistry information to assume the seeding plume not only passed over the target area but that the AgI participated in the precipitation process by initiating additional ice crystals. Over a 4 day period from July 29 to August 1, 5 EUs were conducted. At the time the seeding decisions for each EU had not been divulged as the experiment had at least another year to reach completion. However, the silver in snow provided information that could determine if seeding had been initiated during any of the 5 EUs. The results showed several periods of above background Ag as well as ratios of In to Ag higher than 1. Manton (2011) showed background Ag with a range of 5 to 10 PPT as determined from unseeded cases. During the 5 cases, the icing rate meters and radiometer data indicated sufficient SLW for seeding to have positive effects. The GUIDE model was used to determine when seeding effects would arrive at Blue Cow. In general, the arrival were quite close to expected times when measured by the Ag in snow concentrations.

Of the 5 EUs observed, 2 appeared to be seeded ((units #38 and #40).). Both showed Ag in snow samples of 15 to 30 PPT and approximately 3 to 1 Ag to indium ratios. Unit #38 had only marginal SLWSLW as reported from the radiometer and icing rate meters. Unit #40 had substantial SLW with peak values over 10x the required .05mm. Temperatures at Blue Cow were running -3 to -5 ^oC so the AgI should have activated well upwind of the target. For EU #38,there was no significant difference in the ice crystal concentrations between the seeded period and the preceding and post 2-hour period. There were some suggestions of ice crystal habit changes and some increase in particle concentrations but nothing definitive even though chemistry data indicted Ag nucleated additional ice. This may be due to the low background levels of SLW and rather high background ice crystal concentrations that varied from 20 to up to 100 L^{-1}. There were no definitive seeding effects noted for EU #40 even though background SLW was significantly higher than EU #38 and Ag to Indium ratios were between 4 to 1 and 3 to 1. There were spikes in ICC (ice crystal concentrations) to 80-100 L^{-1} from background levels of 20-30 L^{-1} but similar spikes were noted before and after the seeded EU period. The Huggins paper was the only published paper on physical studies for this 5 year experiment to the author's knowledge. In the following paragraphs the statistical results of the confirmatory experiment will be reviewed.

Results of the confirmatory experiment are reported in Manton and Warren (2011). The randomized seeding design was built on a target control regression relationship. The control was used to predict what the target area precipitation would be had seeding not occurred. It was estimated that it would take 100 EUs using 5 hour increments over a 5 year period applying a 2 to 1 seed no-seed ratio to obtain a p-value of 10% for a 10% increase in snowpack water equivalent (SWE) (Manson et al. 2011). This was based on a correlation coefficient of .82 between the target and control area. However, the probability of obtaining this was only 42%. The probability of obtaining a 20% increase was 77%. Normally the target p-value for minimizing a type I or type II error is 5%. So at the outset of the experiment there was some pessimism of obtaining statistically significant results. The criteria established in the confirmatory design were two-fold. First, that a p-value of 10% was required for establishing seeding increases in the primary target area. Secondly, the silver concentration in the seeded EUs had to be higher than the non-seeded EUs with a p value of 5% or less for all EUs with tagged chemistry samples of indium concentrations above 1 PPT. This assured that adequate targeting was occurring during seeding. As was mentioned in Section 1, this problem had plagued many other ground seeding programs in the past. The Ag/I ratio information was not a primary response variable because of the possibility of contamination of Ag in non-seeded events as well as from other sources like silver mining. From the chemistry analysis it was estimated that over 90% of the seeded EUs had adequate targeting. The median observed SWE in the target area for seeded EUs was 2.5 mm or .1 inches. Using a 10 to 1 snow water equivalent this would be 1 inch of snow over 5 hours. The median control 5 hour SWE was 1.7 mm. The average SLW during all EUs was .07 mm and the median CTT for all EUs was -13.6 ^oC meaning the AgI should have nucleated as clouds existed at sufficiently cold temperatures above the -5 ^oC level.

There were at total of 107 EUs with 71 seeded and 36 unseeded. There was a maximum of 65 generator hours possible per seeded EU because there were 13 generators available. There was a median of 53 generator hours per seeded EU with 80% having over 45 generator hours. The median height of the 0 ^{o}C level was 1440m or above for a majority of the seeding generator hours. The median -5 ^{o}C level was 2160m or near the summit of the target area. Thus, the seeded agent was most likely released at temperatures warmer than 0 ^{o}C, had to rise to an altitude above 2100 m, activate, then the crystals grow and fallout prior to passing over the target area. The terrain in this portion of the Snowy Mountains has a rise of 1800m in about 15 km. Given a median wind speed of 10 m/s upslope this could induce a vertical motion of 1.2 m/s, which is substantial. So this in theory does provide adequate lift for the seeded plume to rise above the -5 ^{o}C level for generators within 15 km or farther from the target area. For example, a generator located 15 km from the target at an elevation of 1000m and using the median 10m/s upslope wind and median 2160 -5C level, the plume would reach the -5 ^{o}C level in 1000 seconds. In 1000 seconds the plume would have traveled 10 km in the horizontal. So in the next 5 km and 500 seconds, the crystal would have to grow and fallout or would pass over the target area. In looking back at the growth rates of crystals at -5 to -6 ^{o}C, in 500 seconds the crystal would grow to 500 um and be most likely a column or needle habit. ItIt may also be slightly rimed due to the SLW over the crest. ItIt is very plausible that seeding could have a positive impact on SWE over the target area given over 90% of the EUs had proper targeting and the median values of temperature, wind and SLW were within acceptable values.

The results of the statistical analysis showed that there was a 7% increase in SWE in seeded versus unseeded cases but a 24% probability this was a chance occurrence. The statistical design required a 10% threshold. As noted, the targeting response variable, Ag/In, ratio was significant at the 5% level. The range of possible seeding impacts ranged from -16% to +32%. The results showed a 9% increase but with a p-value of 13% if the entire target area is used instead of just the primary area where the correlation was .9 with the control gauges. Regardless, the calculated p-values are above the required 10% level required to obtain significance with a range of possible effects of -16% to +31%. Further post stratification analysis was done for the entire target area because of the improvement seen in the overall target area results. This would not be considered as part of the confirmatory experiment.

The EUs were partitioned into divisions having at least 45 generator hours. This was to assure multiple generators were impacting the target area as determined by the GUIDE model and as substantiated by the Ag/In ratios. The more generator hours per EU the more impact would be expected. The number of EUs dropped to 84 with 53 seeded and 31 unseeded. The results of the Ag/In ratios and the SWE observed for the seeded and unseeded cases are shown in Figure 2.6 (a,b) from Manton and Warren. The analysis of these cases yielded a 14% increase significant at the 3% level. Applying the 45 hour criteria for just the primary target area as specified in the original design, the analysis showed a 14% increase at the 8% level. Thus, the 14% increase is consistent between the primary target and the entire target area. This result again highlights the engineering aspects of conducting a successful winter cloud seeding program. To be successful the clouds need to be seeded!

Other physical studies were performed on response variables that were not selected as part of the primary analysis but considered a secondary response variable because they add physical credibility to the statistical results (see Table 2.1). The first secondary response variable analyzed was SLW. It was found that the higher the mean SLW in the one-half hour prior to seeding correlated to higher fractional increases in SWE for seeded cases (r=.35 significant at the

1% level). The threshold where significant positive results occurred was at an integrated liquid water value of .2mm. In Section 1, Murakami found .3mm to be a minimum threshold for increased snowfall. There was a negative correlation for the unseeded cases. That is, the natural precipitation process was inefficient in the unseeded cases. It was also found that mean SLW for the duration of the EU showed a negative correlation between SLW and fractional precipitation increases for mean SLW below .1 mm. This suggests that when the mean SLW is lower for the entire seeded EU, the seeding impact is greater. Thus, the seeding is utilizing the available SLW. No such relationship was observed for the unseeded cases.

Wind speed and direction were also secondary response variables. It was found that the fractional increase in seeded precipitation was best correlated with winds north of west or greater than 270 degrees. This makes physical sense as the target barrier is oriented NE to SW such that a northwest wind would be perpendicular to the barrier. It was also observed that more SLW was observed in northwest flow. There was a positive correlation between wind speed and seeding of .48 at the 3% significance level. Thus, the higher the wind speed the higher the condensate supply and higher SLW and better seeding effects. There was also a positive correlation for the unseeded cases of .32 at the 8 % significance level but lower than for the seeded cases. There was an optimum speed observed of 8 -18 m/s. Lower winds would have lees condensate and lift while winds above 20 m/s would not allow adequate time for the crystal to rise grow and fallout prior to passing over the crest (about 15minutes for mean generator distance from the target area).

The fractional seeding increases were also compared with cloud-top temperature (CTT), cloud height, cloud base, and height of the 0 and -5 ^{o}C levels. Fractional increases in seeding were noted up to CTT's to -20 ^{o}C with colder cloud tops indicating a negative impact from seeding. The importance of CTT was described in Section 1 so this finding is not surprising. The height on the -5 ^{o}C level was somewhat confusing in that the higher it was the higher the fractional seeding increases. This may indicate there is a deeper cloud between the 0 and -5 ^{o}C level as the 0 ^{o}C level had to be higher than 1600m for an EU to be called. The deeper this warmer cloud section the more SLW is available.

Finally, the data were analyzed for absolute precipitation amounts falling during a 5-hr EU. A positive correlation was found between the control 5-hr precipitation and fractional seeding increases. The higher the natural snowfall rate the higher the seeding impacts. The relationship tails off above 2 mm per 5 hr EU. Thus, as the rate gets above 2 mm, the natural precipitation process becomes more efficient and less opportunity for seeding to enhance precipitation. Given the 14% increase discussed and a median seeded EU of .4 mm/h, the absolute value of the seeding increase is about .06 mm/hr or .002 in/hr times 5 hr EU or .01 inches in 5 hours or ~.1 inches of snow per 5 hours. This would amount to about 5 inches of snow for the 56 seeded EUs. As Manton concluded in his paper, a separate economic impact has to be run to determine the benefit cost ratio for such a seeding increase.

It can be stated that the secondary analysis shows a statistically significant (probability by chance of 3%) increase (14%) in seeded vs non-seeded EUs and that the secondary response variables indicate strong physical plausibility for the statistical results. These results are also consistent with Super (1986) for the Bridger Range experiment. It could be stated that the Snowy

Mountain Confirmatory Experiment indicates transferability of the Bridger Range results to another continent and hemisphere. The question to address is does this constitute the “proof’ required by the NRC 2003 report? Again because both projects have not met the criteria established for a successful confirmatory experiment, these results are very suggestive of a positive seeding effect but cannot be considered “proof”.

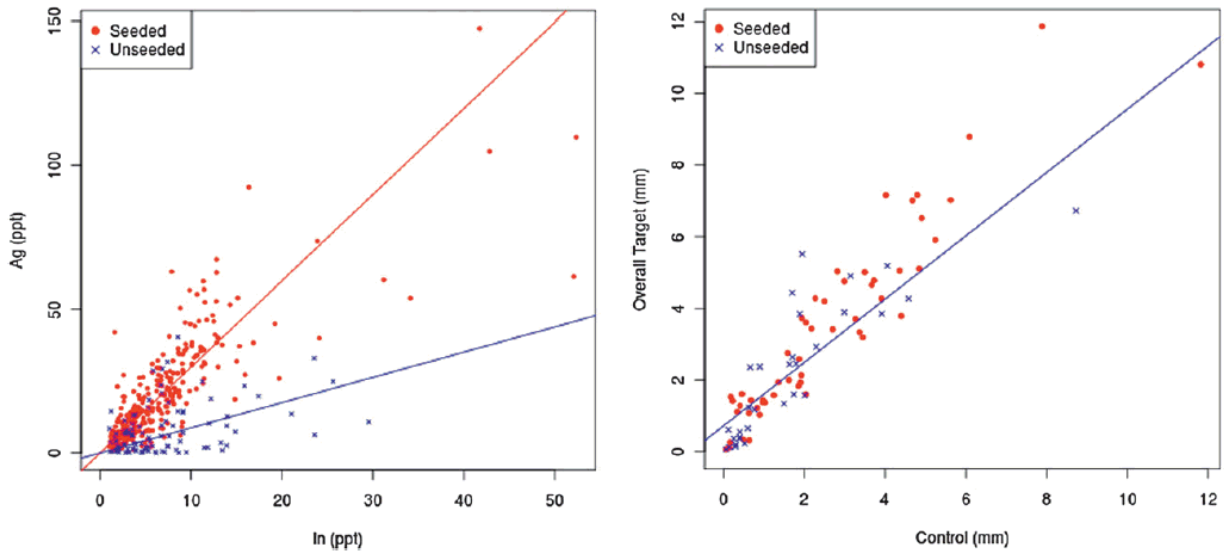

Figure 2.6 Scatterplot on left (a), shows the concentration of Ag to In for seeded (red) and unseeded (blue) EUs;Lines pass through the origin with slopes of the median values of the Ag:In ratio. The scatterplot to the right(b), shows the SWE in the overall target and control areas for seeded (red0 and unseeded(blue) EUs with more than 45 generator hours; the regression line for unseeded line for unsedded cases is shown in blue. From Manton and Warren (2011).

Table 2.1 Correlation between independent variables and seeding impact, represented by precipitation residual.

Variable	Correlation with precipitation residual for seeded EUs (significance level)	Comment
Generator hours	0.20 (9%)	Seeding impact increases with amount of seeding material released
SLW at start of EU (SLWS)	0.35 (1%)	Seeding impact increases with available SLW
Mean SLW over EU (SLWM)	0.64 (0.00%)	There are few seeded EUs with SLWM greater than 0.1 mm; i.e., seeding impact is associated with low values of SLWM
SLWS − SLWM (DSLW)	−0.71 (0.2%) for DSLW < 0	For SLWS < SLWM, seeded EUs behave like unseeded EUs; for SLWS > SLWM, there is no correlation for seeded EUs, suggesting that SLW is consumed when seeding is effective
Wind direction at −5°C level	0.32 (2%)	Seeding is most effective for northwesterly winds, perhaps owing to the optimization of the alignment of the wind with the main range in the target area
Wind speed at −5°C level	0.48 (0.03%)	The correlation seems to be associated with a window between about 8 and 18 m s^{-1}, such that winds too low do not generate substantial amounts of SLW and winds too high do not allow sufficient time for microphysical effects to occur
Cloud-top temperature (CTT)	No significant correlation	For unseeded EUs, there is a correlation of −0.37 at the 4% level between CTT and the precipitation residual; this is lost for seeded EUs, when high residuals do not occur at very low CTTs
Cloud-top height (HGTCT)	No significant correlation	For unseeded EUs, there is a correlation of 0.31 at the 9% level between HGTCT and precipitation residual; this is lost for seeded EUs
Height of −5°C level (HGT5C)	0.26 (6%)	The higher HGT5C is, the deeper the layer for ice particles to sweep up cloud particles below
Diff between cloud-top height and −5°C level (DHCT5C)	No significant correlation	For unseeded EUs, there is a correlation of 0.35 at the 6% level between DHCT5C and the precipitation residual; this is lost for seeded EUs
Precipitation in control area	0.47 (0.04%)	Seeding effect is essentially multiplicative

2.1.1 Follow-on three year randomized seeding

Following the Snowy Precipitation Enhancement Research Project (SPERP) described by Manton and Warren (2011), a randomized snowfall enhancement project was carried out over the winters of 2010 to 2013, Manton et al (2015). The original target area was extended to the north along the mountain ridges, and the control area was adjusted appropriately, Figure 2.7. The target was split into north and south areas to account for differences in orography and to allow comparison with SPERP. The start criteria for seedable events were refined, Table 2.2, yielding 54 seeded and 43 unseeded events over the four winters. A key change in the design was the addition of 10 generators to the original 13 making a total of 23 available for seeding. In addition, the seeding criteria required at least 15 generators had to affect the target based on the GUIDE model runs. These additional criteria followed from the results of SPERP that more seeding material getting into the clouds over the target area leads to more snowfall. No trace chemistry was performed for this second randomized experiment. A similar analysis of seeding impact from these cases, assuming a linear relationship between target and control precipitation as per SPERP , yielded small but statistically insignificant increases in precipitation. A formal model selection analysis was then performed, using the Bayesian information criterion (BIC) (Bayesian statistics was a key recommendation of NRC 2003 to reduce uncertainty), found that the optimal predictors of target precipitation are the control precipitation (pcon) and wind speed at the -5 °C level (wsp5). Structural equation modelling confirmed the physical basis of the relationship between target precipitation and environmental variables. Using pcon and wsp5 as predictors led to statistically significant increases in precipitation in both target areas. The impacts are comparable with those found by Manton and Warren (2011) after detailed screening of events with little dispersed seeding material. The results were confirmed by alternative analyses: an independent analogue method, and a resampling regression method which provided conservative estimates of uncertainties in the regression coefficients. These are described in more detail in Manton et al (2015). The techniques were then applied to both the present experiment and the earlier SPERP data as described below.

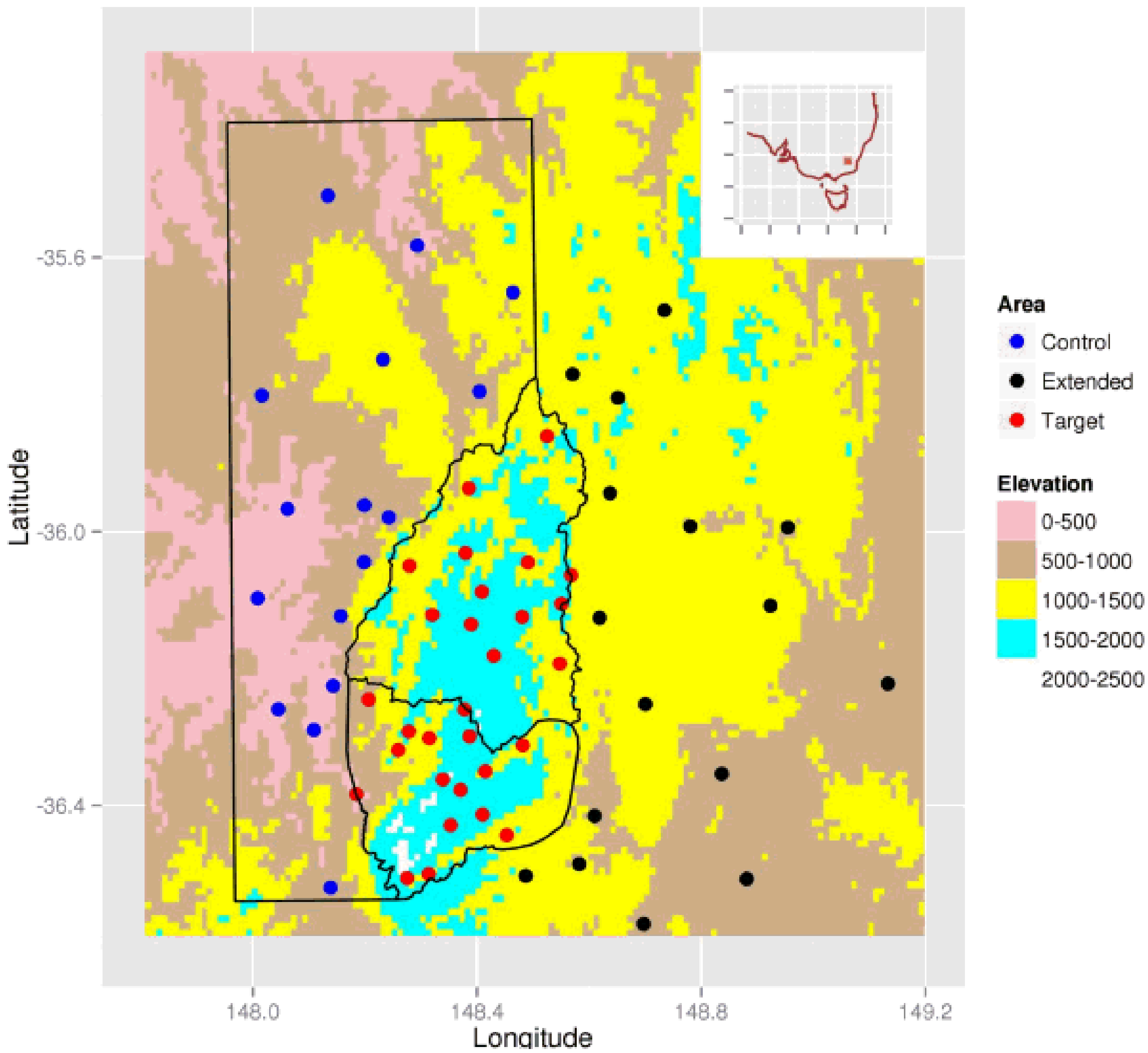

Figure 2.7 Modified Snowy Mountain randomized seeding experiment run from 2010- 2013. Locations indicate gauges within the primary target (red) the extended area (black) and the control area (blue).

There have been some changes in cloud seeding operations in the Snowy Mountains during the period since 2005. The SPERP experiment was run consistently from May 2005 to June 2009 (project A). Seeding continued over the rest of winter 2009 (project B) while seeding strategies were modified based on the results of project A and while infrastructure was added to the network. The current project commenced in 2010 with a seeding ratio of 1:1 and was run consistently for three years (project C). In 2013 the decision was taken by Snowy Hydro Ltd to increase the seeding ratio to 7:1 (project D). The effect of this decision was somewhat offset by the occurrence of 7 seedable events in early May 2013 that were unseeded owing to delays in seeding operations but for which the key variables were observed. A total of 232 seedable events have occurred since 2005: 107 for project A (SPERP), 28 for project B, 66 for project C, and 31 for project D. The results of these various projects are provided in Table 2.3. These results have removed one suspended case and two cases where the cloud-top-temperatures were colder than -35 ^{o}C (assumed clouds already very efficient).

Table 2.2 Start criteria for commencing an event suitable for seeding; the second column identifies criteria that were introduced after the analysis of SPERP

Criterion	Commenced	Reason
Freezing level ≤ 1600 m with snow below 1400 m	2005	Government legislation
At least 0.005 mm SLW	2005	Sufficient SLW for seeding (Manton et al. 2011)
Cloud depth > 400 m above -5 ° C level	2005	Sufficient cloud depth above activation temperature of silver iodide (-5 ° C) for ice crystal growth (Manton et al.. 2011)
Cloud top temperature ≤ -7 ° C	2005	Silver iodide is several orders of magnitude more active below -7 ° C than -5 ° C (Manton et al. 2011)
Cloud top temperature ≥ -35 ° C	2013	Natural ice particles are likely to be present and so reduce cloud seeding efficiency (Section 6)
At least 15 generator plumes over target area	2010	Ensure adequate seeding material over target (Manton and Warren 2011)
At least one generator plume indicates fallout within target area	2005	Ensure nucleation is possible and seeded precipitation falls in target area (Manton et al. 2011)
Seeding material must exit target area within 160 minutes	2010	Remove very low wind speed events when vertical mixing is likely to be poor (Manton and Warren 2011)
Purge time from GUIDE model has elapsed from start of event	2005	Ensure target area is purged of seeding material before no-seed event commences
At least 0.2 mm of precipitation in 30 minutes before start of event	2010	Ensure there is precipitation to be enhanced
Suitable conditions are forecast to continue for at least 5 hours	2010	Reduce likelihood of suspended events; before 2010, the forecast period was 3 hours

The change in strategy between projects C and D needs to be investigated to ensure the validity of the overall results. Table 2.3 compares the computed impacts of seeding using the multi-variate regression method for projects CD, C and BCD. For the south target, it is clear that the effect of the additional events in project D is simply to reduce the uncertainties in the estimated impact of seeding: the mean and fractional increases are very similar for projects C and CD, but the statistical significance of the results for CD are much higher. It is also seen that even including the transition year (project B) yields a positive and consistent impact of seeding over the period 2009 to 2013 (project BCD).

On the other hand, the estimated impacts and associated significance for project C in the north Target are much less in C than in CD. Manton has suggested that low-precipitation events can mask the impact of seeding, and one consistent difference between the precipitation in the north target versus the south target is that there are more low-precipitation events in the north. This difference may therefore be the cause of the low seeding impacts computed for the north target in project C when the total number of events is small.

Table 2.3 Impact of seeding for projects between 2009 and 2013, with suspended events and events with cdtt < -35 C removed, and using pcon and wsp5 are predictors of natural target precipitation in a resampled regression

Project	Target	No. Events	Mean Precipitation Increase (mm)	Fractional Increase in Precipitation	Statistical Significance
CD	North	94	0.50	0.15	0.05
C	North	63	0.19	0.05	0.32
BCD	North	118	0.30	0.09	0.15
CD	South	94	0.45	0.12	0.07
C	South	63	0.46	0.11	0.12
BCD	South	118	0.25	0.07	0.16

In summary, this second randomized experiment, CD, once the suspended event and the two events with cdtt < -35 ^{o}C were removed, yielded a fractional increase of about 0.13 for both targets with a statistical significance of about 6%. This is similar to the impact found by Manton and Warren (2011) for the SPERP after detailed screening of events having little dispersed seeding material.

Analysis of different subsets of all seedable events since 2009 shows that there is a consistent and positive impact of seeding in both targets. These results should be considered very encouraging as to the efficacy of ground based seeding. Although the hourly seeding increases are small, .1mm/hr or less, these are consistent with the fact the natural precipitation rates for these 5-hour periods are only 2-4 mm, (.4 to .8 mm/hr), which is very light but also consistent with the clouds being mostly shallow orographic clouds. It has been discussed that since these clouds are mostly post-frontal, there may be weak convection within the clouds helping to loft the seeding agent up quickly to the -5 to -7 ^{o}C level. Given the activation levels of the AgI are one to two orders of magnitude lower than at -9 ^{o}C, which is what the Wyoming project used as described in the next section, even with stratifying by generator hours to assure adequate seeding, it would appear that even higher seeding rates per generator may be in order. Modeling studies as presented by Xue (2015) showed that there is little chance of over-seeding even with an order of magnitude higher seeding rates even at the colder -9 ^{o}C threshold.

2.2 Wyoming Weather Modification Pilot Project

A thorough description of the design of the WWMPP (Wyoming Weather Modification Pilot Project) is described in Breed et al (2014). WWMPP was a 6-year randomized ground–based AgI seeding program (assumed to be run as a confirmatory seeding project based on many years of physical studies (see Section 3) done in this area and utilizing results of decades of research in the Rocky Mountains) to determine the efficacy of cloud seeding to increase snowfall and subsequent runoff in the Sierra Madre and Medicine Bow Mountains of south-central Wyoming. Two barriers were chosen to allow a cross-over seeding design to be used (Dennis 1980). The cross-over design minimizes the length of the experiment by reducing the number of EUs needed to reach statistical significance if the two areas are well correlated in terms of precipitation. The design calls for 4-hr EUs with a 4-hr purge period between EUs. This purge period was chosen to allow the seeding material to be flushed from the area, especially if the Sierra Madre were seeded and the AgI aerosol could subsequently seed the Medicine Bow's. This concern was raised during AgI tracer studies using the NCAR ice nucleus counter onboard the Wyoming King Air (Boe et al. 2014). Which barrier is treated is determined randomly with the randomization set so there would be an equal number of cases for each barrier and that no one barrier could be seeded more than 4 times consecutively. The seeding decisions were kept by the seeding contractor (Weather Modification Inc.) and were released to the researchers (NCAR) after completing the statistical analyses. The seeding criteria utilized the 700 mb wind (210 to 315^{o}) and temperature (<-8 ^{o}C derived from an upwind sounding). SLW must be detected on both ridges using a microwave radiometer located just upwind of the seeding generators. All generators were activated except in certain cases where the wind direction would obviously not allow a specific generator to impact the target. The WWMPP project layout is shown in Figure 2.8. The project had suspension criteria that were established to avoid any possible hazardous situations that might be perceived to be aggravated by seeding. This included above normal snowpack and the threat of flooding. During the six winters of the randomized seeding experiment, suspension criteria were met only three times totaling 70 days.

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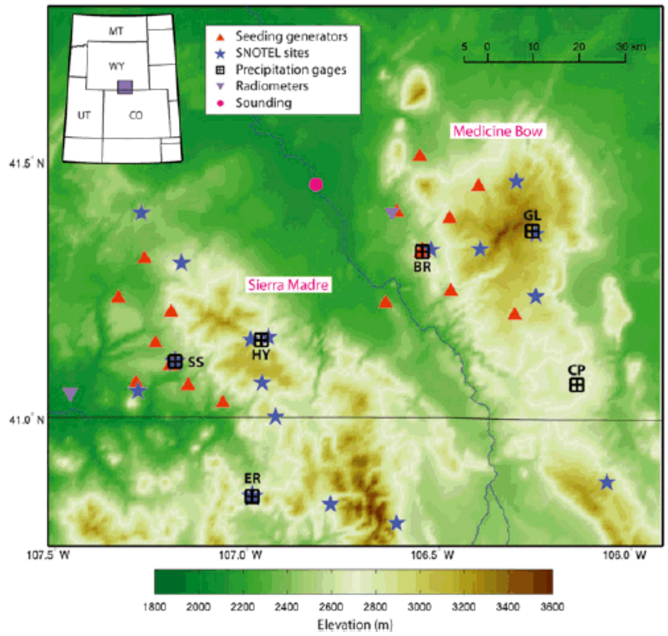

Figure 2.8 WWMPP terrain map and project equipment layout. Extended area control sites are shown as ER and CP in the figure and the near control sites are SS and BR.

The final location and number of ground based generators was determined using the WRF numerical model with an AgI ground based seeding module that tracked the release and dispersion of the AgI as well as the growth and fallout of the seeded ice-crystals (Xue et al. 2013).

Physical studies such as trace silver in snow and the use of the NCAR ice nuclei counter were conducted during all or a portion of the 6-year study. Only Ag was sampled in the snow as no other non-nucleating seeding agent was co-released with the AgI. Thus one could not surmise whether the Ag observed in the snowpack was deposited by nucleation or scavenged by the naturally occurring snow. There were issues with the samples with respect to dust containing silver being deposited in the snowpack between storms, as well as rather low concentrations compared to what has been observed in projects like the Snowy Mountains. However results indicated that enhanced silver in the snowpack could be related to the randomized seeding but many seeded cases showed no Ag at the specific target site where the target gauge was located (Tilly 2015). Sampling of soils and streams within the target area indicated that the AgI seeding had no impact on soil or water quality within the target area. Ground-based NCAR counter results during the first three years of the randomized seeding experiment near the Medicine Bow target gauge showed the seeding agent was hitting the target area when the Medicine Bows were being treated. These data also indicated that on some occasions, the Medicine Bows were being treated when seeding was conducted for the Sierra Madre. This might compromise the seeding results and was considered before the seeding experiment was even begun. Even though this might reduce the magnitude of the seeding impacts in the statistical analysis it was not thought significant enough to redesign the experiment. As mentioned earlier, these reasons were the reason for extending the purge period between EUs to 4 hours.

The primary response variable used in the statistical analysis was the 4-hr accumulated precipitation from the primary precipitation gauge sites shown in Figure 2.8. There were three gauges located at each of the sites shown. An average of the gauges that met quality control criteria at each site was used for the data for each EU. A total of 154 EUs were conducted during the 6 winters. In the final analysis of the randomized seeding results, a combination of physical, statistical, and modeling results were used to accumulate a body of evidence to determine the final outcome of the seeding. This follows the recommendation from the NRC 2003 report. *However one should remember that for a formal confirmatory experiment to be validated it must follow the original design and meet the formal criteria set.* The primary statistical analysis first required a careful review and quality control of the gauge data. As mentioned the three gauges at the primary target site within each target provided redundancy and a method to QC the data. From this analysis, 23 EUs were eliminated from the statistical analysis. In addition, 13 cases were removed as they did not have the required ground-based generators working. Thus a total of 118 EUs were used in the final statistical analysis.

It should be pointed out that in a rigorous confirmatory experiment, where one has staked a claim on the primary response variable showing a statistically significant increase in precipitation for the seeded cases (in this case a one-tailed P value of .05 and power of .8), the project would be unable to override the null hypothesis (seeding has no impact on precipitation) if the P value comes out higher than .05. Once the data is *a posteriori* stratified, the results can no longer be considered part of the confirmatory experiment. Thus the results may be considered suggestive of a seeding effect but not statistically "proven".

The primary statistical analysis used the Root Regression Ratio (Gabriel 1999; List et al. 1999) to determine the seeding effect. This statistic is a variant of what Silverman used and is described in Section 4.0. The RRR makes use of extended area control sites in addition to the difference in the target and control seeding differences. The controls are used to predict what the target would have expected if seeding had not been performed. This assumes a strong correlation between the target and control. For the WWMPP, the correlation between the target and the control sites was .5 historically. The correlation for the actual seeding EUs has not yet been provided. A more complete discussion of the RRR and how it is derived is provided in Breed et al (2014). It should be noted that in the experimental design, it was estimated that it would take somewhere between 110 and 236 EUs to detect a 15% (10%) seeding effect. This is based on correlations between target to target and near control to controls (Sierra Madre and Medicine Bows) of .5-.7 and a correlation to the far controls of .4-.5. So there was some doubt whether the confirmatory experiment could obtain enough EUs during a 6-yr period to detect a 10% or maybe even a 15% increase.

The primary statistical analysis of the WWMPP yielded an RRR of 1.03 with a one-tailed P value of .28. This implies a 3% increase in the seed over the no-seed cases with a 28% probability of this occurring by chance. ***Thus the primary statistical analysis showed no significant seeding effects***. As mentioned earlier, any post-stratification that is done that was not part of the formal experimental design can only be suggestive of a seeding effect. No significance value can be associated with the confirmatory experiment but can be computed *a-posterior*.

Modeling studies using the WRF model with the AgI module indicated 18 cases where the Medicine Bows might be impacted when seeding was conducted over the Sierra Madre.

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Eliminating these cases increase the RRR to .09 with a p-value of 8%. Direct observations using the NCAR counter yielded 21 cases where silver reached the Medicine Bows when seeding was conducted over the Sierra Madre. When these 21 cases were eliminated, the RRR only increased to 1.04. The differences in RRR values between the 18 cases versus the 21 cases, may suggest that the presence of Ag in the NCAR counter does not necessarily suggest that the Ag participated in the precipitation process. The model simulated cases indicated that the AgI enhanced precipitation over the Medicine Bows from Sierra Madre seeding, while the NCAR counter only indicated the presence of AgI but no information on precipitation changes due to seeding.

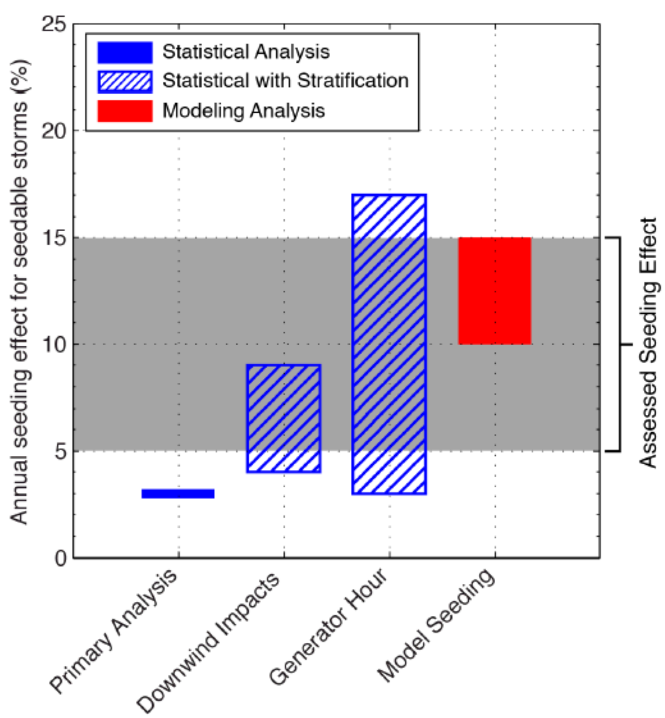

Figure 2.9 WWMPP estimated seeding impacts as determined from the primary and a posteriori analysis along with modeling simulations. The gray shaded region is the range of seeding impacts that NCAR concluded is the appropriate range of seeding impacts for seedable cases based on the accumulated body of evidence accumulated during the exploratory and confirmatory seeding experiments. Again these can only be considered suggestive.

It was observed during the Australian Snowy Mountain experiment that the number of seeding generators operated on any given EU was a major factor in determining whether an increase in precipitation for seeded cases could be observed. Again this was determined *a posteriori*, and could not be made a part of the confirmatory experiment but strongly suggested that at least 45 generators hours (9 generators operating for 5 hours) was required to provide a seeding impact (14% increase). For the WWMPP it was found that the number of generators operated per EU varied based on seeding generator operational status. Thirteen cases had already been eliminated from the original confirmatory experiment due to generator status. Additional cases were removed if there were less than 27 generator hours per EU (7 of 8 generators x 4 hours) impacting the target area. This implies that the amount of seeding agent delivered is critical to impacting precipitation. A total of 56 cases were eliminated from the 118 original leaving a total of 62 EUs. The RRR increased to 1.17. Although the P value indicated only a 3% probability that this increase occurred by chance, it can still be considered only suggestive of seeding increases. Figure 2.9 is a graphical depiction of the primary plus the *a posteriori* stratifications. The modeling analysis results shown in red were based on running one-half of the EUs (2009, 2011, 2013) through the WRF model using the AgI seeding module simulator that showed between a 10% and 15% increase in target precipitation from seeding.

A climatological analysis was performed (Ritzman 2013; Ritzman et al. 2015) using a high-resolution climate model forced with re-analysis meteorological data to determine the frequency of seedable clouds using the seeding criteria established for the WWMPP. A second condition was established that precipitation must be occurring over the target areas as well. The results indicated that about 30% of the winter snowpack in the target areas would fall during seedable events. If one assumes a 10% increase over 60% of the North Platte River Basin (NPRB) of 390 sq-mi it was estimated that 7,100 ac-ft of additional runoff could be generated. This was derived using the Variable Infiltration Hydrologic Model (VIC). The model was used to predict the natural snowmelt runoff for an 8 year period and came within 1 % of the observed snowmelt-driven streamflow. It was thus assumed it could be used to estimate the seeding induced augmented runoff. The 7100 ac-ft constitutes about a 1.8% increase in streamflow. If one assumes on average about 22 4-hr seeding periods per season (what was observed during the 6 year project) the hourly increase in precipitation over the project area would be .16 mm/hr. This is well within the range of observed seeding effects as will be shown in Table 5.1.

A cost-benefit analysis was computed based on various cost estimates of an operational seeding program. The costs varied based on contracted versus an in-house run project as well as a yearly evaluation program. Costs varied from $375,500 to $526,400/year. Figure 2.10 shows the various costs break-outs depending on the cost scenario used, along with a range of seeding impacts. The cost of water for the NPRB was estimated at $75 ac-ft. One can see the break-even point for a contracted seeding program without evaluation is at 10%. An in-house run project would have a break-even point at about 8% seeding effect.

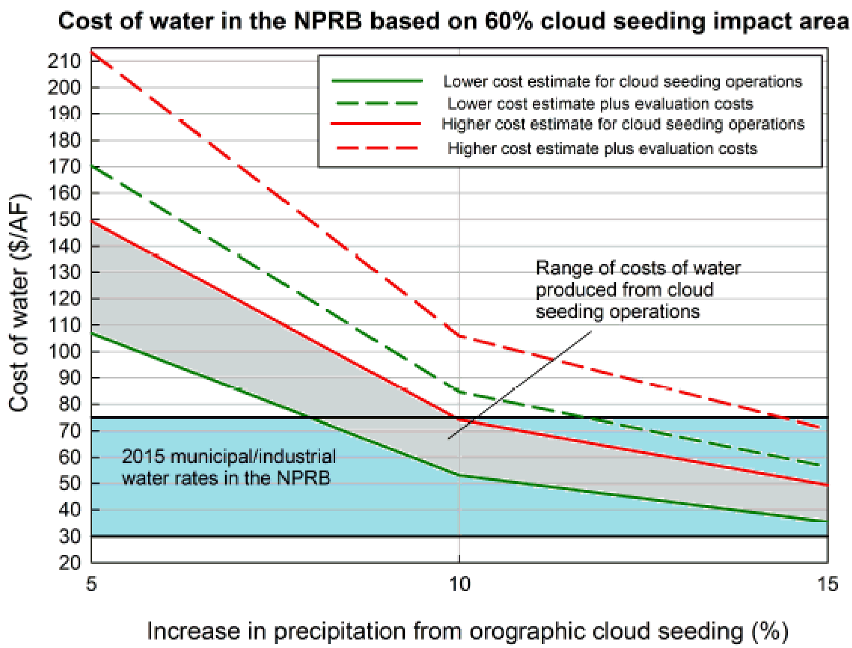

Figure 2.10 Range of costs per acre-ft of water produced by cloud seeding for the various estimated levels of seeding effect.

It was concluded by the NCAR analysis of the WWMPP that the Wyoming Water Development Commission undertakes an operational cloud seeding program that could yield a 5 to 15% increase in precipitation over a targeted watershed if properly designed. This would require significant initial investments if new barriers were to be included in the program, basically reproducing the level of effort that was needed to design the WWMPP over the Sierra Madre and Medicine Bow Mountains. A strong modeling component including a climatology of annual seedable cases to be expected, high resolution modeling to determine the number and location of ground-based seeding generators and placement of observing equipment like radiometers and precipitation gauges, and new environmental impact studies to obtain permits for installing the equipment would be required. A period of evaluation should be built into the program, at least in the early stages to verify targeting using the WRF adapted targeting model.

These results of the WWMPP were reported in an Executive Summary posted to the Wyoming Water Development Board website (http://wwdc.state.wy.us/weathermod/WYWeatherModPilotProgramExecSummary.html) and by Rasmussen et al (2015). A comprehensive final report is being drafted and will be made available after a formal review process is completed. This is expected to be completed by late spring. Additional physical and statistical studies are reported on in Section 3 of this report.

3.0 Short-term Physical Process Studies of Efficacy of Winter Orographic Cloud Seeding

3.1 Utah Exploratory Propane Seeding Trials

During mid-January to mid-March of 2003-4 an exploratory randomized cloud seeding program was conducted on the Wasatch Plateau in Utah to test the efficacy of liquid propane to enhance ice crystal production and subsequent snowfall within mildly supercooled winter orographic clouds (Super and Heimbach 2005a,b). As was described in Section 1, liquid propane released at temperatures just below 0 ^{o}C can generate sufficient ice crystals by homogenous nucleation when in the presence of SLW to enhance precipitation. It is a viable alternative to AgI which requires temperatures of at least -5 ^{o}C before sufficient ice crystals will be generated when released in cloud. The target area was approximately 5 km downwind from the propane dispensers. High resolution precipitation gauges (.05-.06 mm) were placed both upstream of the primary target and downwind of the primary target but no farther than 6.5 km from the dispensers as well as in a highly correlated cross-wind location to be used as a covariate in the statistical analysis. The experimental unit was 2 hrs. Each unit contained one hour with the propane dispenser on (40 minutes of actual dispensing and 20 minutes of purge time) and one hour off. Which hour was treated or left as a placebo was randomized. An experimental unit was automatically declared when a co-located icing-rate meter indicated SLW was present above a pre-defined concentration. A total of 98 EUs were conducted. A brief description of the project and a summary of the statistical results are provided below.

Figure 3.1 shows the project layout. This site had been used in earlier studies of both AgI and propane seeding experiments by Super et al (1995) and Holyrod and Super (1998). The primary response variables in the statistical analysis were the 4 recording gauges located along the pre-determined seeding plume center-line given predominately SW prevailing winds during passing winter storms. The gauge known as GRD was located in an unprotected clearing and determined to be inferior for inclusion in all but a few preliminary statistical analyses. GNO was used as the control gauge and was shown to correlate with the three target gauges used in the final analysis (R=.89). An automated 2D-C probe was operated at the TAR site to monitor changes in ice crystal concentrations from which precipitation rates were derived. Surface wind measurements were located at the HAS and TAR sites to determine the wind direction for targeting purposes and stratifying EUs for the statistical analysis. The icing detector was located at TSO in Figure 3.1. Three propane seeding generators were used with 6 nozzles each releasing 3.5 gallons per hour.

The conduct of the experiment was first determined by the presence of SLW. This was determined by the Goodrich icing meter that monitored the changing frequency of the instrument probe with a change of 35 Hz in 10 minutes indicating approximately .005 in of ice had accreted on the probe. There were some problems with this sensor in high icing conditions and with NW wind flows. A second icing meter, the Rosemount icing-rate meter was also used as needed for backup. Its location was moved from the SIR site to the HAS midway through the experiment as the SIR was determined to be a poor site. The TAR site was fully automated and power provided by a propane powered generator. Power issues were observed at the TAR causing some missing data which would include the 2-D probe system which ran 24/7 during the experimental period. Also, there were periods of missing icing information from two of the icing monitoring stations. This did not compromise the seeding experiment.

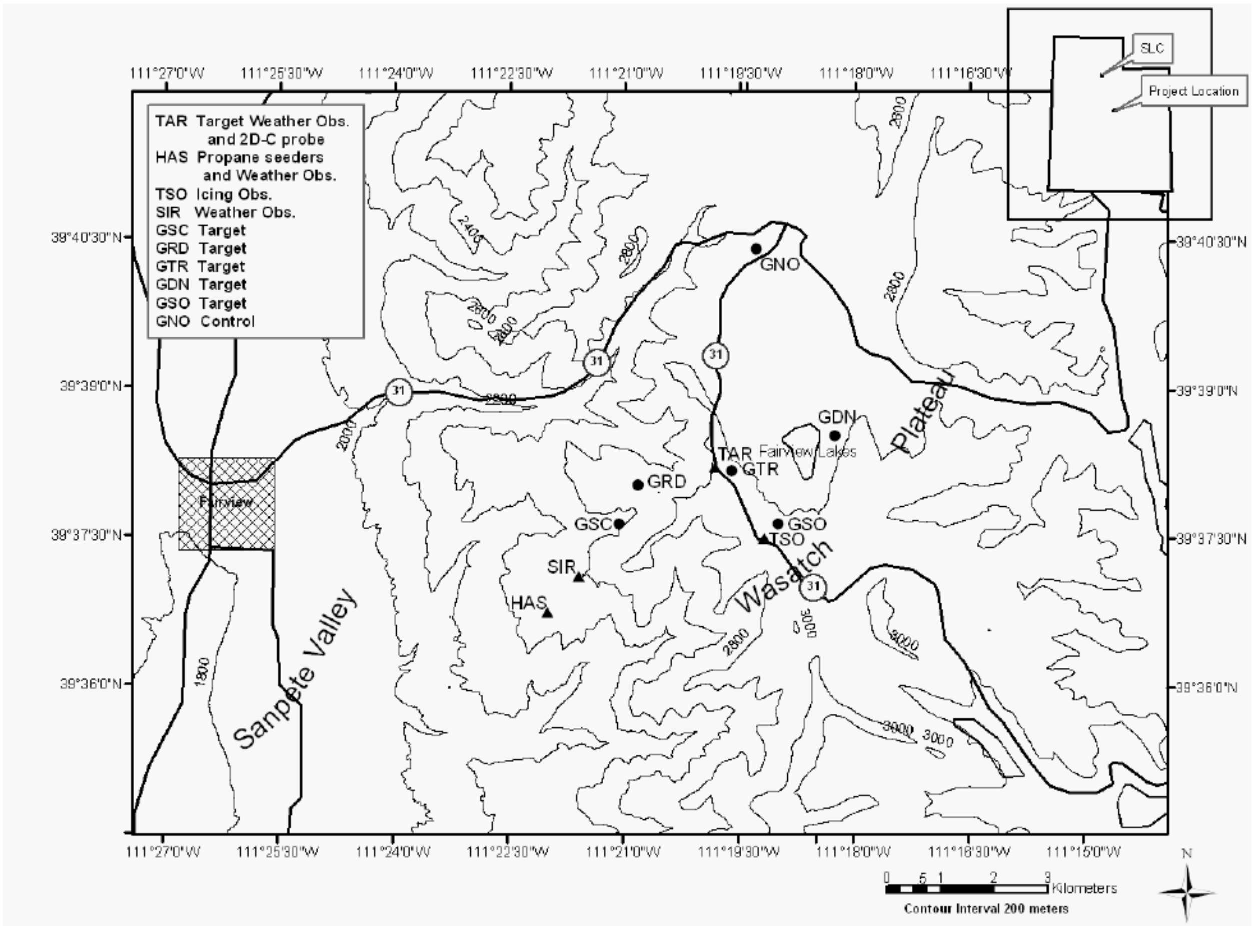

Figure 3.1 Map of the experimental area for the Utah 2003-2004 propane seeding experiment. The contour interval is 200m. Key equipment locations are noted. Propane was release from the HAS site. The TAR site was equipped with an automated 2D-C ice crystal probe slaved to a wind sensor to observe ice crystal concentrations.

Four statistical tests were applied to the EUs. These were composed of regression analysis, pairs analysis of seeded minus non-seeded residuals, the Wilcoxon test and ratio analysis. The regression analysis compares the difference in slope or Y intercept between the regression line of the target estimated precipitation based on the control site for seeded and unseeded samples. A higher Y intercept or larger slope would indicate positive seeding effects. The pairs test first computes a regression line forced through 0 between the control gauge precipitation and the target precipitation. Residuals are then calculated from this line for the seeded and unseeded pairs within each EU. The mean of the difference of these residuals is assumed to be from seeding. Rerandomization, or what is called permutations, using the Monte Carlo technique (1000 rerandomizations switching the seeded period with the unseeded period) was performed as described by Dennis (1980). A one-tailed significance value, or p–value, having a low value, preferably .05 or less, between the mean seed no-seed residual and the rerandomized residual mean would indicate a statistically significant positive seeding effect. The Wilcoxon, or nonparametric test, used frequently in weather modification analyses, was used to determine the significance between the rank sum of residuals of seeded and non-seeded SWEs from that predicted from the control target regression, and that of the rank sum of the null distribution. Finally, the ratio statistic using the mean double ratio as defined by Gabriel (1999) was applied to the seed no-seed individual cases (not paired). The double ratio uses the sum of the seeded SWEs divided by the sum of the non-seeded SWEs to the estimated seeded using the control site divided by the sum of the SWEs of the non-seeded cases estimated from the control site. Rerandomization was required since there were only 89 EUs instead of 100 as recommended by Gabriel. The p-value is inferred by the number of cases where the rerandomized MDR's (Mean Double Ratios) are ≥ the sample MDR. If 60 out of 1000 meet this test the p-value would be .06. The double ratio test allows one to calculate the possible magnitude of the seeding effect using a 95% confidence interval and a two-tailed parametric test. That is, if the range of the effects are both positive, there is a 95% chance the real effect is within this range. If one of the ranges is ≤ 0, this implies a greater uncertainty and there is a 95% chance that there may have been no, or a negative effect, from the seeding.

The final selection of EUs to include in the analysis was determined by the wind speed from the HAS site. The wind had to be strong enough to be able to calculate the seeding window for each downstream gauge. If the wind was too low to calculate the impact window the case was removed from further consideration. Out of the 102 cases, 51 seeded and 51 non-seeded, 98 samples remained, 50 seeded and 48 non-seeded. Using the wind speed from the TAR and HAS site, the time window for seeding impact at each gauge was calculated and this was the information used in the statistical analysis.

The regression analysis was applied to all 5 gauges independently by regressing them to the control gauge. Two regressions were done for each pair, one for the seeded and one for the non-seeded sample. Mean double-ratios were calculated with all target gauges showing values greater than 1.2 except for GRD. It was mentioned earlier that GRD had site issues causing it to have a serious undercatch. The 1.2 ratio indicates a 20% increase in SWE for seeded versus non-seeded samples. The one-tailed t-test ranged from .02 to .23. The p-value was lowest for GTR, the primary target gauge, and .10 for GSC, with higher p-values for the other three gauges. One can infer that positive seeding impacts were strongly suggested at two gauges and inconclusive at the other three sites. The results from the Pairs, Wilcoxon and Ratio tests are shown in Table 3.1 from Super and Heimbach (2005a). The following paragraphs are taken directly from Super and Heimbach (2005a).

"The first entry in Table 1 (Table 3.1) is for target gauge GSC. Interpretation of its testing results is as follows: The second column has the mean S-NS residual in the pairs analysis equal to 0.006, suggesting that on average, seeded units received 0.006 inch more precipitation per 40 min period than the non-seeded units based on residuals calculated using GNO as a covariant. The third column indicates a p-level of 0.04 was obtained for this S-NS residual using rerandomization. Column 4 lists the target control linear correlation coefficient for the 98 pooled S and NS units. The Wilcoxon nonparametric test in the fifth column gives the rank-sum p-value of 0.05, also strongly suggesting statistical significance by meeting the often used 0.05 α -level to denote "significance." Column 6 lists GSC's MDR as 1.22, indicative of a 22% SWE increase due to treatment. The MDR was derived from the 50 seeded and 48 non-seeded units, not the 47 pairs. Using rerandomization to derive the statistical inference of this MDR gave a P-level of

0.06, somewhat suggestive. The confidence interval in column 8 indicates a 1-tailed 95% confidence that the actual MDR lies somewhere between +2% and infinity, assuming that seeding can only increase, not decrease, precipitation. No upper boundary can be specified with that assumption. ”

Results for GRD are inconclusive and its correlation with the control gauge is well below the other correlations. As discussed in Sec. 3, that gauge site proved to be too windy for reliable measurements. The primary intended target gauge, GTR, and the GSO site 1 km due south of GTR, both had significant P-values by the pairs and MDR ratio tests. Their Wilcoxon P-values were 0.10, somewhat suggestive of a seeding effect. Gauges GSC, GTR and GSO are within 3 km or less of one another and will be referred to as the "core gauges." Taken together, the evidence is strong for a seeding effect at the core gauges with MDRs near 1.22 implying a 22% SWE increase for seeded EUs over nonseeded EUs. The 95% confidence intervals for the core gauges indicate minimum increases of 2, 4 and 6%, respectively. The pairs residuals are all 0.006 inch per 40 min, equivalent to 0.009 inch h-1(~.23 mm/hr) mean snowfall increases. While only light snowfall, it is near the median value for all hours at GTR, found to be just above 0.010 inch h-1 by Super and Heimbach (2005b). Although the downwind GDN gauge MDR was 1.21, P-values were 0.27, 0.12 and 0.09. The latter two values might be considered somewhat suggestive of a seeding effect but, overall, the results must be considered inconclusive for GDN. Failure to detect a significant seeding effect at GDN may be related in part to its having the second lowest correlation, with only the windy GRD ridge location having a lower value. A relatively low association with the control gauge results in the statistical testing being less sensitive, all else being equal.”

Given the almost .01 in/hr suggested seeding increase noted above for the three primary target gauges, it is useful to put this in perspective to the climatology of the area. The following is again taken from Super and Heimbach (2005a).

“Average S-NS residuals are 0.006 inch for each gauge, suggesting that much additional SWE fell on average per 40 min EU, equivalent to an hourly rate near 0.01 inch h-1. That may seem a limited amount until it is realized that median natural rates for all significant snowfall days were just above 0.01 inch h-1 for the sensitive GTR gauge used in this study (see Super and Heimbach 2005b). The large majority of hours with snowfall in the Intermountain West have similar light rates, and significant accumulations result because so many hours are involved. Obviously, 100 hours with a rate of 0.01 inch h-1 results in one inch of SWE. For reference, the long term average April 1st snowpack at the Mammoth-Cottonwood SNOTEL located near GNO is 19.9 inch, so a 1.0 inch increases represents a 5% seasonal increase from 100 hrs of seeding. At least 150 hours with SLW available at the HAS can be expected during a normal winter, and that estimate is likely low given the tendency of the tower-type Rosemount sensors to underestimate during light and/or brief icing episodes. “

Super and Heimbach (2005a) went on to partition (stratify) the EUs by wind direction, snowfall rate at the control site, by SLW observations, by HAS temperature, and by HAS wind speed. The statistical results were somewhat compromised because these partitions reduced the overall sample sizes. The partitioning of wind direction to $< 270^{o}$ provided the most useful and strongly suggestive results. These are shown in Table 3.2. It is encouraging to see these results based on wind direction since this partitioning reflects on better targeting. Thus, even with a reduced sample size the statistics strongly suggest a positive seeding impact of 22 to 26% over the non-seeded cases.

Table 3.1 Summary for 98 available EUs with no partitioning:47 pairs, 50 seeded and 48 nonseeded EUs.

Target Gauge	Sample S-NS Residual (inch)	S-NS 1-tailed P-value	Pooled Target – GNO Correlation	Wilcoxon 1-tailed P-value	Sample MDR	Re-randomized 1-tailed P-value	1-tailed 95% Confidence Interval
GSC	0.006	**0.04**	0.85	**0.05**	1.22	**0.06**	1.02 - ∞
GRD	0.000	0.43	0.75	0.26	1.08	0.32	0.81 - ∞
GTR	0.006	**0.05**	0.88	**0.10**	1.22	**0.04**	1.04 - ∞
GSO	0.006	**0.04**	0.89	**0.10**	1.23	**0.03**	1.06 - ∞
GDN	0.001	0.27	0.84	0.12	1.21	**0.09**	0.98 - ∞

Table 3.2 – HAS wins direction partition from 169 to 270 deg inclusive: 32 pairs, 35 seeded and 34 nonseeded.

Target Gauge	Sample S-NS Residual (inch)	S-NS 1-tailed P-value	Pooled Target – GNO Correlation	Wilcoxon 1-tailed P-value	Sample MDR	Re-randomized 1-tailed P-value	1-tailed 95% Confidence Interval
GSC	0.010	**0.02**	0.82	0.13	1.22	**0.09**	1.00 ~ ∞
GRD	0.001	0.34	0.70	0.45	1.02	0.46	0.74 ~ ∞
GTR	0.009	**0.04**	0.85	0.15	1.24	**0.05**	1.05 ~ ∞
GSO	0.008	**0.05**	0.86	0.11	1.26	**0.03**	1.07 ~ ∞
GDN	0.002	0.25	0.80	**0.09**	1.27	**0.06**	1.05 ~ ∞

A detailed physical study was presented by Super and Heimbach (2005a) for one EU that was conducted during very light natural snowfall. The study showed propane seeding effects similar to those that have been observed in other physical studies using either AgI or propane and ground 2D probes to sample the seeding plume 15 to 30 minutes downwind. This case showed within the expected seeding plume, significant increases in ice crystal concentrations of predominately uniform size crystals. Using the 2D probe concentrations and sizes to approximate SWE gave a value of .011 in/hr. This value is very close to the randomized statistical results. The three gauges in line with the seeding plume observed .01in/hr, .013in/hr, and .019 in/hr with increasing distance downwind. The physical studies provide credibility to the statistical results. A summary of observed seeding impacts for those EUs observed using the 2D probe was provided. These are shown in Table 3.2.

Table 3.3 – Distribution of mean IPCs for 21 seeded and 22 nonseeded EUs with available 2D-C observations and HAS median wind directions between 169 to 270 deg. Noted percentiles are given for all ice crystal sizes and for small crystals from 100 to 600 um. Differences per liter between seeded and nonseeded are shown next to their corresponding percentages of the nonseeded concentrations.

Percentile	Seeded Cry. L^{-1} All sizes	Nonseed Cry. L^{-1} All sizes	Seeded Difference # (%)	Seeded Cry. L^{-1} Small	Nonseeded Cry. L^{-1} Small	Seeded Difference # (%)
25%	27	20	7 (35)	20	15	5 (33)
50%	51	37	14 (38)	36	27	9 (33)
75%	84	66	18 (27)	66	47	19 (40)
90%	104	81	23 (28)	77	61	16 (26)

Super and Heimbach (2005a) summarized the randomized propane seeding experiment by doing a calculation of the seasonal increase in snowpack based on the statistical results discussed above. The area impacted from the seeding was estimated at 22 km^2 with a 1 in water equivalent increase from seeding over this area equates to 450 ac-ft. This estimate is only for the duration of the seeding conducted, 3.5 months, during a dry winter. Given that the MDR values shown that had a strong suggestion of a 27% increase in seeded vs nonseeded samples and applying this over a season, an 8% increase could be assumed. If an 8% increase is assumed on the seasonal SWE as observed at the closest SNOTEL site observing 20.5 in on April 1, the seasonal increase would be closer to 740 ac-ft. It is not clear from the paper whether if this calculation is from one dispenser or from the three dispensers utilizing 6 release nozzles. Since the numbers are based on the statistical results that used the 6 nozzles, one must assume this is from the combined output from the three dispensers. It is interesting to note that the .01 in/hr implied from the statistical results matches perfectly with the calculations performed by Reynolds (1996) Appendix D for propane seeding from, however, 1 dispenser with a seeding rate of 2.5 gallons per hour. So the magnitude of the seeding impacts are consistent with the hourly seeding induced precipitation rate increase that will be presented in Table 5.1 of Section 5.0 of this report and thus seem very credible.

3.2 Exploratory Physical Process Studies in Winter Orographic Clouds in Japan

From 1994 -2011 the Meteorological Research Institute and the Japanese Meteorological Agency conducted exploratory cloud seeding and physical process studies in wintertime orographic clouds over a watershed in central Honshu Island of Japan where snowmelt runoff supplies the main water supply for Tokyo. The Japanese Cloud Seeding Experiment for Precipitation Augmentation (JCSEPA) deployed a very sophisticated array of in-situ and remote sensing observing systems to study the microphysical and precipitation mechanisms in natural and seeded winter orographic clouds over the Echigo Mountains. In addition, a sophisticated modeling effort was run in parallel with the observations. First, the Clark (1977) non-hydrostatic model with improved microphysics and the ability to simulate seeding from ground and aerial releases was used. Next, the Japanese Meteorological Agency's non-hydrostatic model with bin microphysics (Saito 2006) was incorporated. The information presented here was obtained through conference proceedings and presentations and one referred Journal article (Murakami et al. 2003; Hashimoto et al. 2008; Murakami et al. 2011). In correspondence with Dr. Murakami, he mentioned there are no detailed papers to date that summarize in any detail the large amount

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of data and modeling efforts that have been done over this extended period. Thus, the summary provided here will be limited in scope.

Figure 3.2a shows the outer and inner domains used for the JMA model runs and 3.2b shows how the study area sits with relation to the Sea of Japan and the cold continental area of eastern Siberia. Cold air moving off this area picks up moisture from the Sea of Japan and then is forced to rise up the steep terrain of the Echigo Mountains. The slope of terrain is about .04 so for a 10 m/s wind, the vertical motion would be about .4 m/s. This is about 10% steeper than the Sierra Nevada where SCPP operated. Extensive SLW observations were made at the foot of the Echigos and at the summit. It was described by Murakami (2003) that there were two types of clouds that have substantial SLW:a shallow stable orographic cloud with cloud-top-temperatures of -5 to -15 ^{o} C and more convective clouds with CTT's of -15 to -25 ^{o}C. When combined, these cloud types existed about 15% of the time during the cool season from November through April in the observed 8 year period. This would be about 650 hours per winter season. The convective orographic cloud existed about twice as much as the stable orographic cloud. These two cloud types were very similar to the two cloud types found in SCPP where seeding experiments were conducted, SCPP floating target experiment (convective clouds along the Sierra foothills) and the fixed target experiment on stable orographic clouds (Reynolds and Dennis 1986). In a subsequent analysis by Hashimoto (2008) the seedability of a cloud was determined by analyzing 1 hour output from the 1 km JMA model and averaging these to 6 hour periods for a location on the upwind side of the barrier. Wind speed and direction, integrated liquid water profile, mean weighted cloud water temperature, and ratio of cloud water to total condensate were each given scores from 0-4. The seedability of the cloud was then given a letter from A through E with A being the most seedable and E the least. The model was evaluated based on simulated seasonal SWE to those observed from a cross-section of gauges as shown in Figure 3.2. The model does have a low bias on the windward side of the mountain with respect to seasonal SWE and a slight high bias on the leeward slopes. The integrated LWP is quite good compared to observations for the 2005-2006 season. These values are somewhat higher than reported on by Reynolds (1988) for the three projects where LWP frequency distributions were available. In addition the model's simulated values of wind speed, weighted cloud water temperature, integrated SLW frequency distribution, and ratio of cloud water to total condensate are plotted for a location on the upwind side of the crest for the winter seasons 2005-06. It is useful to look at both these plots as shown in Figure 3.3. From these the seedability was computed as described above. In the 2006/07 winter, the ranks A to E had 11, 30, 61, 45, and 15 cases, respectively (each case corresponds to one 6-hour period). In total, 162 cases are expected to have a positive seeding effect if cloud seeding is conducted. In the 2005/06 winter, 200 cases were determined to be favorable. Thus, a total of 362 6-hour periods would be expected in the two year period observed and modeled, with 2006 being considered a drought year. These are considerably more hours (X10 per season) than in any other seeding project that has been reviewed in this survey and may be related to the unique location of the project.

Seeding simulations were conducted for the individual categories for the two winter seasons. The results are shown in the three figures (Figure 3.4 a-c). The authors implemented the aerial dry ice seeding module developed by Kopp et al (1983) at the South Dakota School of Mines. This module not only simulated the dry-ice seeding but the optimum location to dispense the seeding material. From this a calculation of seeding impacts on SWE for each seedability category and for each 6-hr unit could be computed. These are shown in Figure 3.4 b-c. Given category C had the highest frequency and ranged in score from 8-10, its hourly SWE rate enhancement was about .2 mm/hr. This is just under .01 in/hr which is what was observed in the propane seeding experiment reported by Super and Heimbach (2005a) in the previous section. The total seasonal impacts from seeding can be determined by looking at the observed seasonal snowfall shown in Figure 3.5. Because Japan sits in a location with much higher frequency of frontal passage and has a large body of water to its west, an approximate 110 mm increase would be about a 6% increase at the Shimizu site located in the primary target area.

Physical measurements were used to support these potential seeding impacts. Murakami (2011) presented aircraft microphysics and radar seeding signatures from the dry ice seeding trials and then did some simple linear regressions of within and outside the seeding curtain. These results are shown in Figures 3.6 and 3.7. From these observations Murakami (2011) described a sequence of physical links in the chain of effects from dry-ice seeding that are very similar to what was described by Deshler et al (1990) for clouds over the Sierra Nevada from aerial dry ice releases. Dry-ice seeding produced ICC of near 100 L^{-1} which began to aggregate and fall through SLW leading to riming. Precipitation size particles of near 1 mm developed which fell to the surface in 40 minutes while with slightly higher SLW concentrations 1-2 mm size particles developed and precipitated out in 20 to 30 minutes. Radar echoes associated with seeding curtains increased reflectivity of 3 to 10 dBZ. Precipitation measured at the surface was near .1 to 1 mm/hr. Given that both areas have a strong marine influence with broad drop size distributions which will promote riming it is not surprising results from these two projects are similar, especially for the colder cases observed in SCPP during late winter.

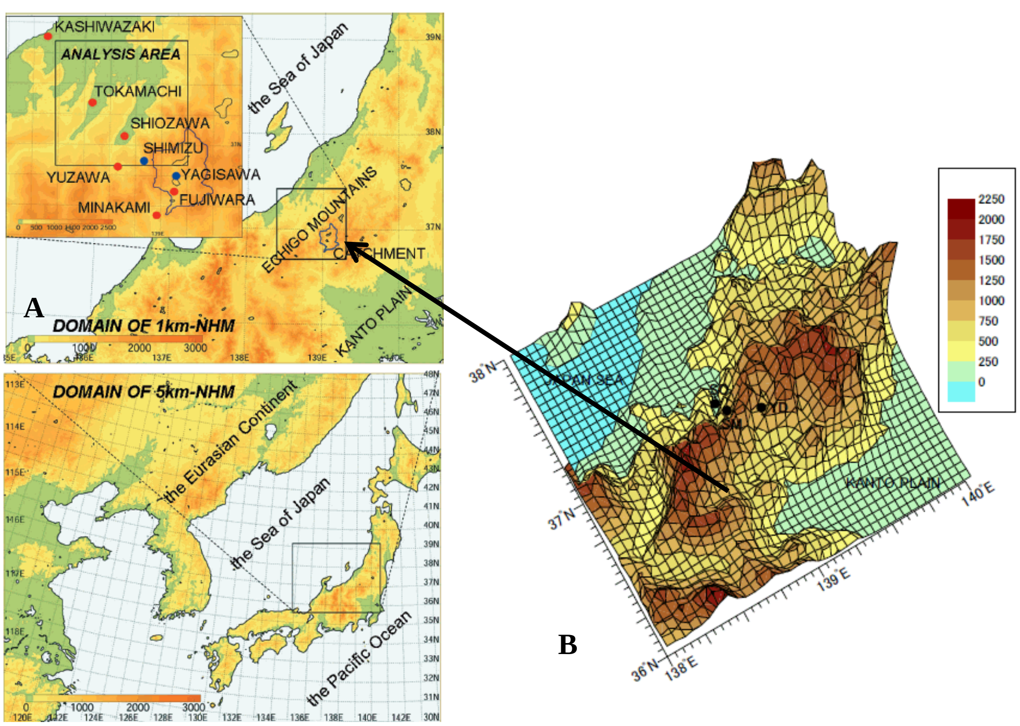

Figure 3.2 a) Japan Meteorological Agency 3-D cloud model outer and inner domains and b) the JCSEPA project area highlighted to the right.

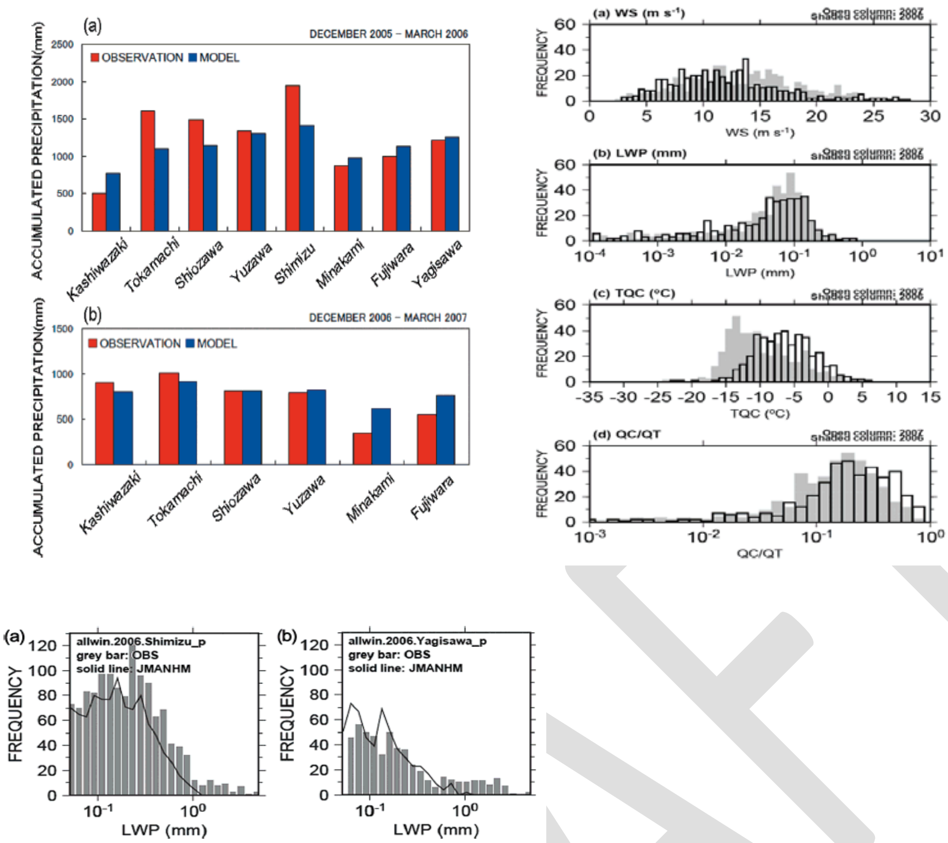

Figure 3.3 Comparison of JMA cloud model to observations for 2005-06 and 2006-07 winters. From Murakami (2011).

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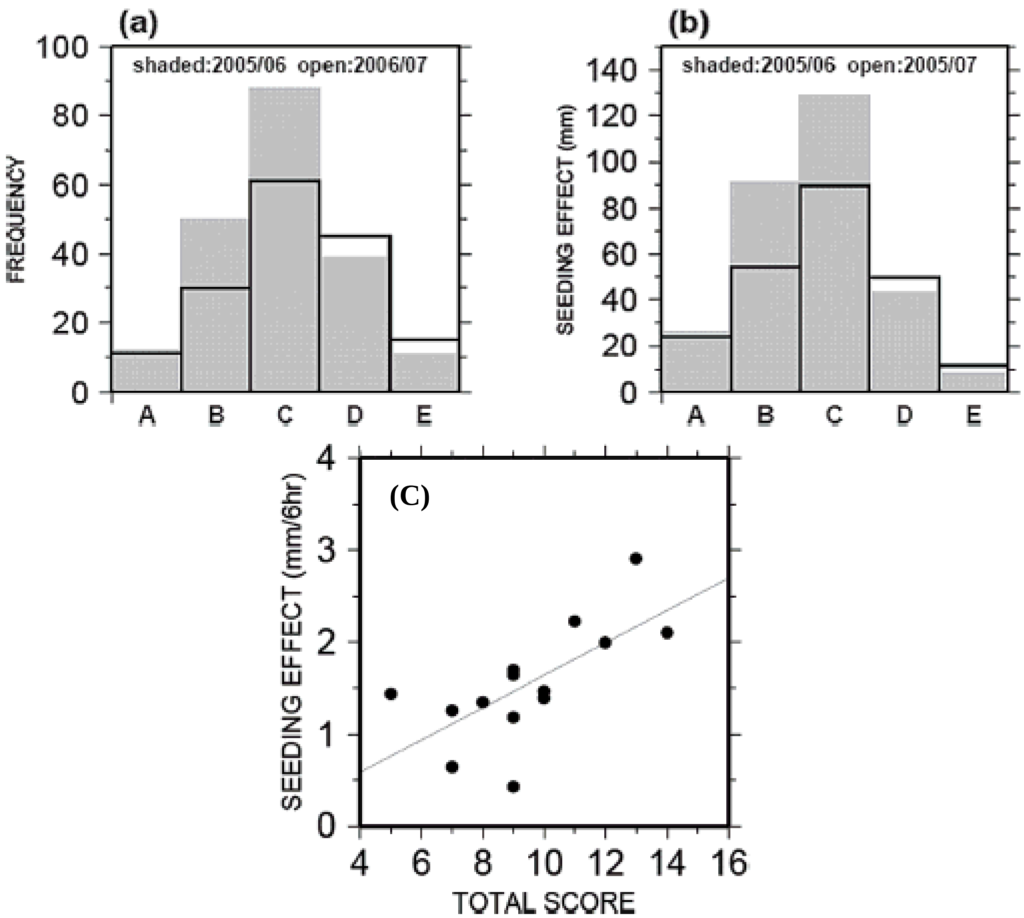

Figure 3.4 (a-c) Modeled seeding effects for various seeding categories as described in the text.

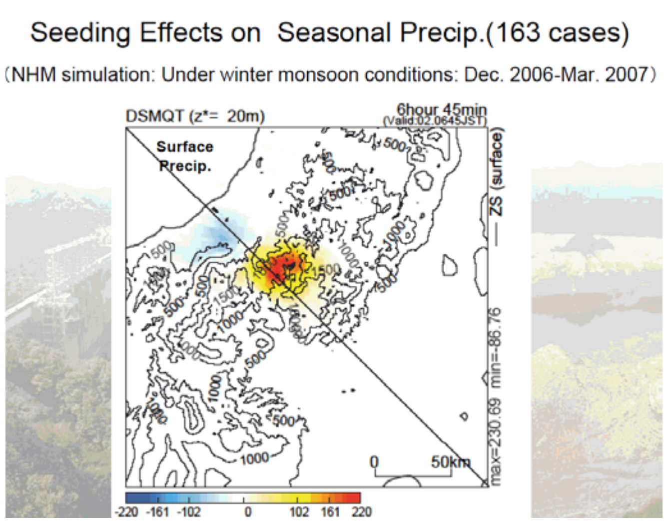

Figure 3.5 Seasonal increases projected by modeling simulations over the target area. Note there is some indication of redistribution with a negative area near the coast and a larger increase on the windward slopes. Murakami (2011).

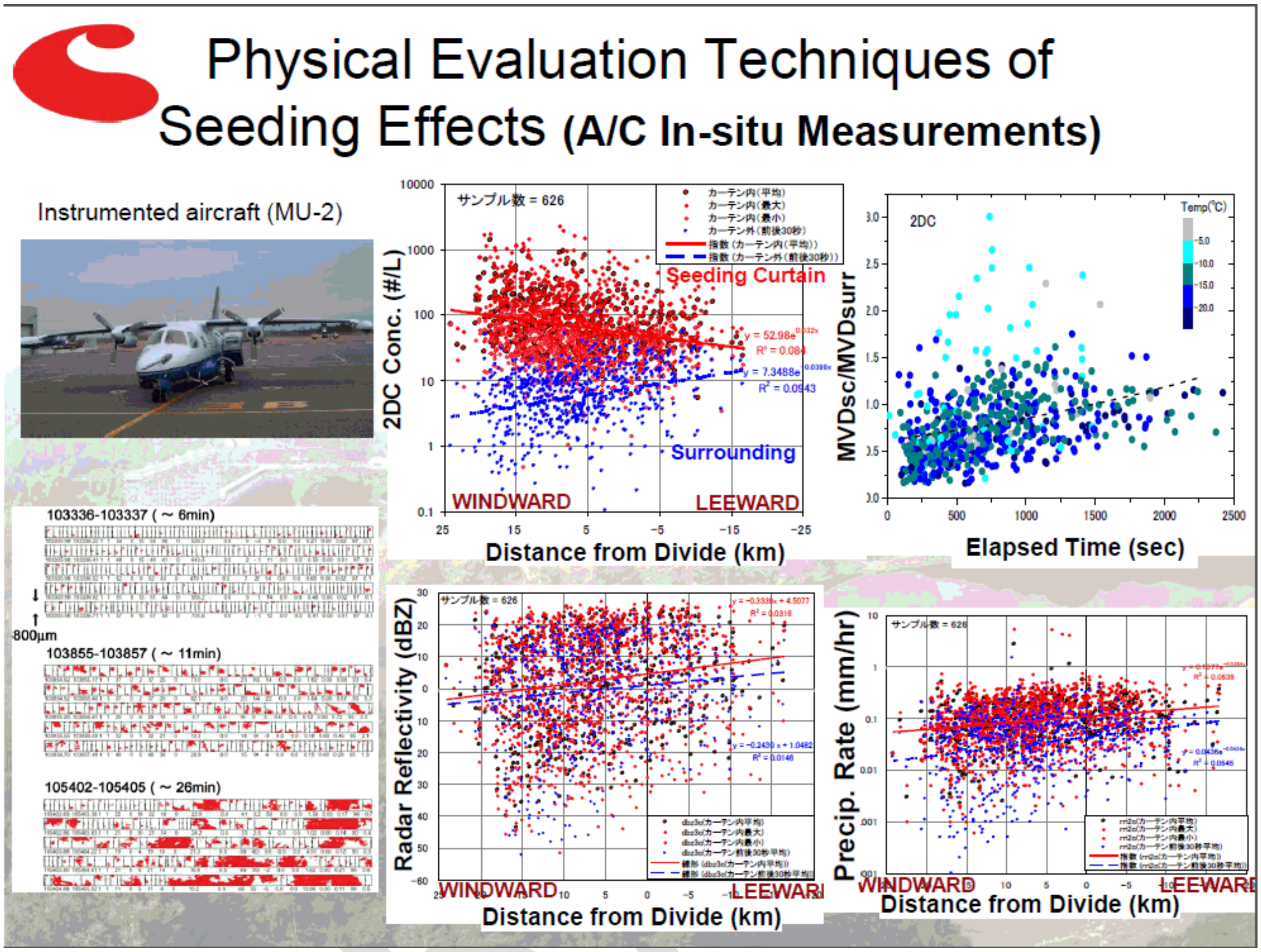

Figure 3.6 Seeding effects from aerial release of dry ice as observed from aircraft. These results are similar to the dry ice seeding experiments conducted during SCPP.

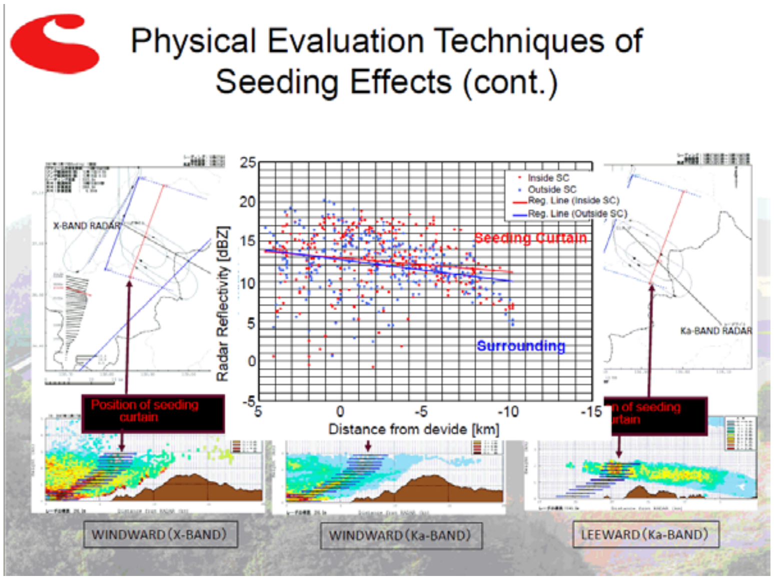

Figure 3.7 Radar analysis of dry ice seeding curtain as it passes upwind, over and downwind of the target area. Scatterplot shows slight increase in reflectivity within seeded volume versus surroundings. Murakami (2011).

3.3 Exploratory Physical Studies of AgI Ground Based Seeding in Wyoming

3.3.1 ASCII 12

During the 2008-2014 Wyoming Weather Modification Pilot Project (WWMPP) several field campaigns were conducted called the AgI Seeding Cloud Impact Investigation or ASCII project. ASCII 12 (Geerts et al. 2013) was conducted over the Sierra Madre Range while ASCII 13 was conducted over the Medicine Bow Range (Pokharel and Geerts 2014). Intensive multi-radar, radiometer, cloud physics and chemical tracer studies were included as part of these experiments. An overview of these results is presented here.

During ASCII 12 an unprecedented diversity of radar systems were deployed which included the W-band (3mm) profiling Wyoming Cloud Radar (WCR), a pair of Ka-band (1 cm) profiling Micro Rain Radars (MRRs), and an X-band (3 cm) scanning Doppler-on-Wheels (DOW) radar. The WCR was on board a University of Wyoming research aircraft flying geographically fixed tracks, the DOW was located on the main mountain pass in the target region, one MRR was at this pass, and the other was upstream of the ground based generators. The University of Wyoming King Air (UWKA) aircraft carried in-situ cloud probes which are of limited value for the purpose of ground-based seeding signature detection as the flight level (13 kft, the lowest permitted under instrument flight rule over the Sierra Madre, corresponding to 607 m above the highest terrain) was generally too high to sample boundary layer air and no independent tracer gas was released from the AgI generator sites. Potentially more revealing is the 95 GHz (3 mm) Wyoming Cloud Radar (WCR), a Doppler radar with fixed antennas pointing down and up from the aircraft. The nadir view provides radar data within ~30 m of the ground, whereas the commonly used ground-based scanning radars can only provide measurements above the crests of complex terrain. The ability to detect changes near the ground is important because the WWMPP AgI generators are ground-based and because a pilot project of seven flights in 2008-09 revealed that the target orographic clouds are generally rather shallow (radar echo tops 2-3 km AGL, ignoring elevated cloud layers not feeding the shallow orographic clouds).). A summary of twelve IOPs in ASCII 12 is given in Table 3.3. The UWKA had technical problems between 19 January and 12 February, which prevented its participation in three IOPs. The five across-wind tracks shown in Figure 3.8a constitute what is known as a "ladder". On all flights, two complete ladder patterns were completed in the SEED period, and two in the NOSEED period, except on 22 February, when the last (4th) ladder pattern was aborted after completion of track 3, *i.e*. tracks 1 and 2 were not flown a 4th time. The flight tracks are numbered as shown in Figure 3.8a.

In almost all cases, obvious radar seeding signatures are not present. Natural variability in background precipitation and radar's sensitivity to particle size versus radar wavelength make it difficult to observe impacts on a case by case basis. This is no different than what has been found in other projects that have utilized various radars to directly detect seeding signatures. A composite of the aircraft reflectivity profiles was created in what is called a frequency-by-altitude (FAD) profile referenced to above ground level (AGL) to determine if seeding had an impact on precipitation. These profiles are normalized by the number of samples available for each elevation. The difference in the FADs between no-seed and seeded periods can thus be performed even if the number of profiles was different for the two regimes. When all seven flights were composited for the no-seed periods and the seeded periods, which were by design two hours apart, there was noted a 2dBz decrease in reflectivity in the lowest.6km, the depth expected to be impacted by the ground based AgI seeding. However, a weakening of the storms was occurring during the two hour period between the no-seed and the seed periods as shown by an overall decrease in the upwind (of generators) reflectivity as detected by the aircraft profiles on leg 1. This decrease in overall storm intensity was confirmed using the two MRR Ka band radars, one upstream of the generators at MRR1 and one in the target area at MRR2. Given these results, a second series of FADs were developed utilizing a composite of the MRR1 and MRR2 data. Nine IOPs were used in these composites, seven matching the composites used for the aircraft vertical sampling including the same noseed -seed sampling periods. The 2 additional cases where no aircraft data were available used a similar two hour window prior to the seeding period with an assumed 1 hour buffer built in as well. Figure3.9 shows the difference in seed no-seed composites for both the upwind MRR(1) and the target MRR(2). For the control the decrease in reflectivity between the seed and noseed periods can be seen as was described above. However, when looking at the target MRR(2) profile differences there is an increase in low level reflectivity in the lowest 1 km above ground. This is inferred to be the results of the ground based seeding and indicate an increase of 2-3 dBZ. The data from both the aircraft and the MRRs were further stratified by 700mb temperature removing 7 cases of the 12 where the temperature was warmer than -8 ^{o}C. For the aircraft profiles this showed a "slightly more positive" seeding effect in the lowest km AGL. For the MRR data, an even stronger seeding effect emerged.

A second more detailed case study was done for the 13 February 2012 case (Pokharel et al. 2014b). This case again emphasized the radar data available during ASCII 12. Additional data were utilized during this case that was not included in the summary of ASCII 12 described above. For this study, the mobile Doppler radar (DOW) was available along with snow chemistry samples taken at the target site (Battle Town) along with a Parsivel disdrometer capable of recording ice particle concentrations (IPC) and 1-D size estimates as well as particle fall-speed. Also included was the precipitation recorded at two high-resolution ETI gauges within the target area. In addition4 snow samples were collected during the case-study to validate that AgI targeting was occurring. Each sample was analyzed for Ag along with 4 non-nucleating tracer elements co-released with the AgI burners, such that a ratio of >1 between Ag and the 4 tracers indicates that the AgI was participating in the ice nucleating process and not just scavenged as the other elements would be. Refer to Figure 3.8b for the siting of equipment.

The SLW values for this case were below .1 mm averaging only .03 mm. Temperatures at the DOW were between -6 and -8 ^{o}C meaning AgI should have reached at least -10 to -11 ^{o}C and winds were consistent at about 10 m/s upslope. The cloud was rather shallow with tops averaging around 4 km or a cloud depth of 1.7 km. Again, this case consisted of two hours of no-seed cloud conditions followed by a two hour period of seeding.

First it was noted that the near one-hour trace chemistry samples indicated that Ag was above background during the seeded portion of the storm with the ratio of Ag to the trace elements of 3 indicating the AgI was nucleating ice crystals that fell out near Battle Pass. Precipitation rates measured at the target site were running under 1 mm/hr during the entire period of the experiment but rates did increase slightly during the seeding window expected at the target gauge.

A similar analysis was done for the aircraft nadir pointing radar data (WCR) as was described for the composite ASCII 12 data. A direct analysis of the reflectivity downwind of the generators showed no apparent seeding signatures. The FAD analysis was then done for the no-seed control leg and downwind flight legs and differenced from the seeded control and downwind seeded period. These analyses indicated that the cloud was shallowing-out during the transition from no-seeded to seeded conditions and that weak embedded convection developed which was stronger over the target area due to forced ascent up the mountain barrier. These complicating factors made it difficult to assess seeding effects from the WCR radar data even when the FADs were further stratified to tracks 4 and 5 to allow more time for seeded crystals to grow. It was noted that with the weak convection, cloud tops penetrated the flight level of the aircraft where up to 600 L^{-1} IPC were observed in what should have been the seeded volume of cloud. There was also a noted difference in low level reflectivity within the main seeded plume as determined by a 20 degree cone encompassing the ground based generators. There was an indication of a 3 dBZ increase in reflectivity in the lowest 1 km in the seeded plume when compared to observations in the lateral control boundaries. These observations along with the enhanced IPC observed by the aircraft suggest a possible seeding effect.

Further analysis was done using the MRR radars. The MRR1 site saw virtually no echoes during the no-seeded period and weak echoes during the seeded period associated with the developing weak convection. There were continuous weak echoes over the MRR2 target radar during the same time frame. Figure 3.9 a-c show the MRR2 data for the entire experiment and the difference between the seeded and no-seed periods for MRR2. There is almost a 10 dBZ difference in low level reflectivity between the two periods. However, a good portion of this difference is from the snow shower that occurs during a period when the Ag sample indicated no silver above background (2100 to 2200 UTC).

The DOW radar data was analyzed for this case as well. The sampling volume was divided into sectors based on the location of the seeding generators to the radar. This is shown in Figure 3.10. Two parameters were computed based on differences in reflectivity measured by the DOW for the area called the control versus that called the target. ZIP is the difference in reflectivity between the target seed versus no-seed and the control seed versus no-seed. PIP is the reflectivity converted to precipitation rate then a ratio is calculated between precipitation rate of the seeded target over the no-seed target precipitation rate divided by the same ratio only for the control. ZIP and PIF were calculated for all three radars using each radars target and control regions as previously described. The PIP and ZIP values are shown in Figure 3.11 computed for all three radars. The horizontal line in the figure is the height of the boundary layer where below this, seeding effects should be concentrated. The bottom figure shows the absolute differences in reflectivity for the three radars between the target seed and noseed. All three show absolute increases. However, these differences are associated with the convection that develops toward the end of the seeding period. The PIP and ZIP values are shown in the top half of Figure 3.11. As mentioned there were no echoes over the upwind MRR radar so it is not included in this figure. The differences are all positive except for the upwind DOW control region. This ZIP value is most likely due to a convective cell that passed through the DOW control area. The differences shown between the upwind control and target indicate a seeding effect but natural convective processes cannot be ruled out given that the lift over the barrier was releasing the convective instability in the parcels of air. However, it is also likely that seeding material was ingested by these convective parcels and thus may have contributed to the increases seen. It is however less likely that the increases in PIF in the DOW lateral controls are solely due to the natural convection since both are within the region of the natural convection.

Past analysis of the use of radar for identifying seeding signatures has proven difficult and this case appears to be no different. There are suggestions of seeding increases but not convincing evidence. Because the effects of AgI seeding should be to increase the IPC in the cloud the authors looked at both the aircraft particle probes and the ground based Parsivel disdrometer data. Since the weak convection lifted the cloud depth to a height that intersected the aircraft flight level it was possible to analyze the probes for seeding effects. An analysis of the particle probes showed distinct increases in particle concentrations within the expected seeding plume which were much higher than observed just outside the expected cone. The increased concentrations were contributed to by particles in the .1 to 1 mm range which is consistent with glaciogenic seeding effects. Without an NCAR counter onboard the aircraft it is not possible to assure the aircraft was sampling within the AgI plume. Given it was not expected that the aircraft would often be able to observe ground seeding plumes at its altitude, this instrument was not flown. In fact there was no room left on the aircraft (Geerts personnel communication).

Since the trace chemistry analysis confirmed the AgI targeted the Battle Pass site and the R factor was 3 (Ag to inert tracer), seeding effects should be observed at the site. Figure 3.12 shows the trace of the Parsivel disdrometer data during the noseed seed period. The ETI gauge data along with the trace chemistry information is shown in Figure 3.13. There is a distinct shift to smaller but more numerous particles during the expected arrival time of the seeded volume. An increase of 5 to 10 L^{-1} is seen for particles under 1 mm. This is again consistent with the glaciogenic seeding hypothesis. The largest and heaviest snowfall of the entire sampling period occurred just after the expected end of the seeding period. Given this is well within the purge period of the AgI to pass through the target area based on other projects reported on by Super that AgI could take up to 4 hours to completely clear the area, it is certainly possible the snow shower that is observed after 2300 is enhanced by the seeding.

Another intensive case study was published by Pokharel et al (2014a) for the 21 February 2012 case. The meteorological factors for this day are shown in Table 3.3. This day was again a rather shallow orographic cloud with generally light precipitation. Eight generators were operated for this case which was 5 more than on the 13 February case. Liquid water values averaged .2 mm, significantly higher than the previous case. Temperatures were cold enough for good activation of the AgI in cloud. This case was run with a longer seeding period than the last case with a 4-hour seed period preceded with a 2-hr non-seeding period. All three radars were again available for analysis of seeding signatures however sampling of each was done at different times within the seeding window. Also the target MRR radar was not functional during the first half of the seeding window. The Battle Pass site had the Parsivel disdrometer data as well as the ETI gauge available. Snow chemistry samples taken at Battle Pass were inconclusive with respect to silver in snow and for the non-nucleating tracers. Although modeling studies using the 2-D WRF indicated at least one of the 8 generators passed over the target, the chemistry data could not support this. This observation points out a fundamental weakness in the design of the WWMPP in having one focused target site. Even with 8 generators operating for 4 hours, a standard EU for WWMPP, the AgI apparently did not impact the target. This certainly compromises the statistical analyses using the difference in target versus control precipitation.

Again there were no obvious seeding signatures in looking at the raw WCR flight legs downstream of the 8 generators. However the seed no-seed FAD differences between the upwind control leg and the four downwind tracks show what appears to be a distinct increase in low level reflectivity (<1 km AGL). Individual FAD differences were done combining legs 2&3 (~10 min downstream from generators) and legs 4 &5 (~20 min downstream). The results are shown on the right hand side of Figure 3.14. There is a distinct increase in low level reflectivity for legs 2-3 and an even stronger reflectivity increase for legs 4&5. The MRR radar data although available only for the second half of the seeding period, also showed increase in the low level reflectivity as seen on the right side of Figure 3.14. However this is only minor as the upwind MRR shows that reflectivities increases during the seeded period over the non-seeded period indicating natural snowfall rates increase upwind during the seeded period. This does not agree with the aircraft WCR data which showed a decrease in reflectivity over the upstream flight track #1 between the no-seed and seeded periods. Since different sampling windows and locations were used for each of these upstream or control areas, this simply indicates the complexities of natural snowfall in mountainous terrain. The DOW data also indicated seeding effects when examining the immediate downwind area of the generators, the target area and the downstream area just to the lee of the crest. There are indications of reflectivity increases just downstream of the southernmost generators as well as larger increases to the lee of the crest which substantiates the increases seen in the aircraft WCR data. These DOW difference plots are shown in Figure 3.15.

Finally the same types of plots were created for reflectivity and precipitation impacts as for the previous case study. Profiles of ZIP and PIF for the three radars are shown in Figure 3.16a. All three radars show positive ZIP values (and PIF) near the surface, but they disagree about the magnitude: the WCR has the largest ZIP values, followed by the DOW and the MRR pair. The corresponding PIF values imply increases in the snowfall rate of 250%, 70%, and 10% for the WCR, the DOW, and the MRR pair, respectively, at their lowest data level. Differences are expected of course, since different seed–no-seed periods and different control–target areas are used for the three radars. While the ZIP values in the lowest 600m (the average turbulent BL depth, according to WCR vertical velocity data) may be attributable to AgI seeding, which cannot be the case in the free troposphere, as it is very unlikely the AgI aerosol released at the ground could be carried above the BL. The positive ZIP values aloft indicate non uniform temporal changes and actually reduce the confidence in the validity of the glaciogenic seeding attribution within the BL. The simple temporal change in the target area (not compared to that in a control area) actually is more consistent among the three radars (Figure 3.16b).

The surface Parsival IPC data and ETI gauge data are shown in Figure 3.17a-c. The data show significant increase in IPC and an increase in all size bins with most in the smaller bins. It is noteworthy that the increases occur in the latter half of the seeding window an continue beyond the expected time period. If this is a seeding effect it is occurring almost 2 hrs later than the generators were ignited. It is very unfortunate that the chemistry data were not available for this period. The precipitation rates observed during the latter half of the seeding window infer about a 1-1.5 mm/hr increase in precipitation. These are consistent with the low level PIF values of 1-2 mm/hr. Attribution to AgI seeding of this magnitude is difficult without confirmation of targeting. Given the delay in the effects and the lack of any Ag measurements reduces the confidence in surface impacts. However given the radar impacts and that the modeling showed good targeting one cannot rule out seeding impacts in the target.

One can see that even with what was considered to be a rather shallow simple orographic cloud observed using some of the most sophisticated remote-sensing and in-situ observing systems documenting seeding effects, when there is background natural variability in precipitation, it is difficult to categorically state seeding impacts have been observed. Certainly there is a strong suggestion for seeding effects from the ground based IPC information and trace chemistry. This is also true for the aircraft IPC data. However, for the radar data, it is much more difficult to sort out seeding effects.

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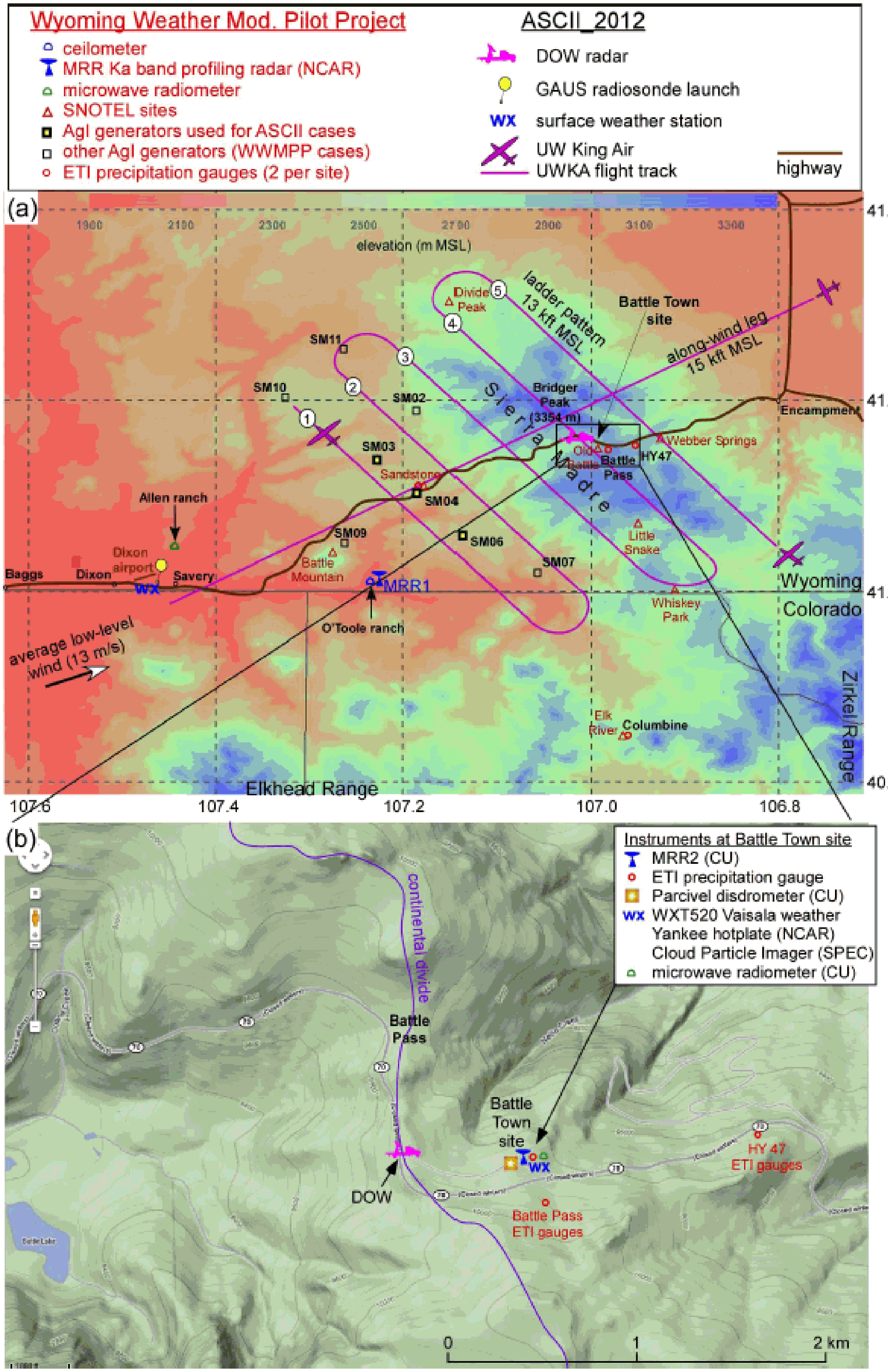

Figure 3.8 a) ASCII 12 field campaign over the Sierra Madre of southern Wyoming. Equipment layout and terrain map are shown along with key locations referred to in the write-up. b) Primary target area with locations of DOW and MRR radars as well as microphysics site identified.

Table 3.3 *Summary of the upstream environment for the 12 ASCII_12 IOPs. The number of AgI generators activated was either three (shown in bold in Fig. 3.8) or eight (all generators over the target range). The UWKA did not participate in the three IOPs highlighted in grey. Insufficient MRR data were available to assess seeding impact for the three IOPs in italics. Most information in this Table is derived from a series of radiosondes released from Dixon (Fig. 3.8), during the IOPs. Average values are shown, based on 3-4 soundings. The Brunt-Väisälä frequency N is the dry (moist) value below (above) the cloud base (LCL). The Froude number Fr is calculated as the wind speed divided by N and the height of Medicine Bow Peak above Saratoga. The elevation of the three generators ranges between 2431-2551 m, Battle Pass is at 3034 m (~700 mb). The LWP in the penultimate column is inferred from a dual-frequency passive microwave radiometer (MR), located at Savery (Fig. 3.8), but with an antenna pointing such that it captures clouds in the direction of the Sierra Madre's highest point, Bridger Peak (elevation 3354 m). This slant path is converted to a zenith one, i.e. it represents the vertically integrated liquid water. The PBL depth in the last column is the depth of the turbulent layer estimated from the WCR vertical velocity along tracks 1-4, following the technique in Geerts et al. (2011). From Geerts et al (2013).*

data source:						upstream radiosondes							up stream MR	air borne WCR
date in 2012	**time (UTC)**				**# AgI generators**	**700 mb T**	**cloud base (LCL)**		**average values from the surface to mountain top**				**average liquid water path**	**PBL depth**
	NOSEED		**SEED**				**T**	**altitude**	**N**	**Fr**	**wind speed**	**wind dir**		
	start	**end**	**start**	**end**		**°C**	**°C**	**m MSL**	**10^{-2} s^{-1}**	**-**	**m/s**	**deg**	**mm**	**m**
18-Jan	*0025*	*0130*	*0130*	*0331*	*3 SM*	*-6.3*	*-10.4*	*3593*	*0.9*	*1.7*	*19.5*	*240*	*0.085*	*740*
19-Jan			*1811*	*2018*	*3 SM*	*-2.6*	*-4.9*	*3331*	*0.9*	*1.7*	*18.9*	*237*	*0.15*	
10-Feb			0445	0750	8 SM	-5.5	-1.9	2537	0.9	1.0	12.6	268	0.065	
12-Feb			2300	300	3 SM	-6	-3.9	2471	1.2	0.9	7.7	279	0.022	
13-Feb	1922	2015	2015	2215	3 SM	-8.2	-4.2	2418	0.4	0.9	5.1	249	0.026	631
14-Feb	*2258*	*0005*	*0005*	*0205*	*3 SM*	*-8*	*-4.9*	*2513*	*0.6*	*1.4*	*9.5*	*278*	*0.065*	*449*
21-Feb	1957	2120	2120	0118	8 SM/MB	-8.4	-7.4	2917	0.7	1.8	15.9	251	0.218	594
22-Feb	1405	1510	1510	1710	3 SM	-4.6	-3.2	2870	0.9	1.8	20.5	260	0.308	643
28-Feb	1358	1504	1504	1700	3 SM	-7.2	-3.1	2336	0.4	2.9	12.9	240	0.173	506
28-Feb	1951	2056	2056	2300	3 SM	-9.1	-6.5	2624	0.4	4.1	15.3	283	0.073	713
29-Feb	0158	0310	2130	0000	3 SM	-7.7	-8.0	3012	0.5	3.0	18.3	213	0.116	663
3-Mar	1816	1930	1930	2330	8 SM/MB	-11.4	-9.1	2767	0.7	2.2	14.6	266	0.08	519

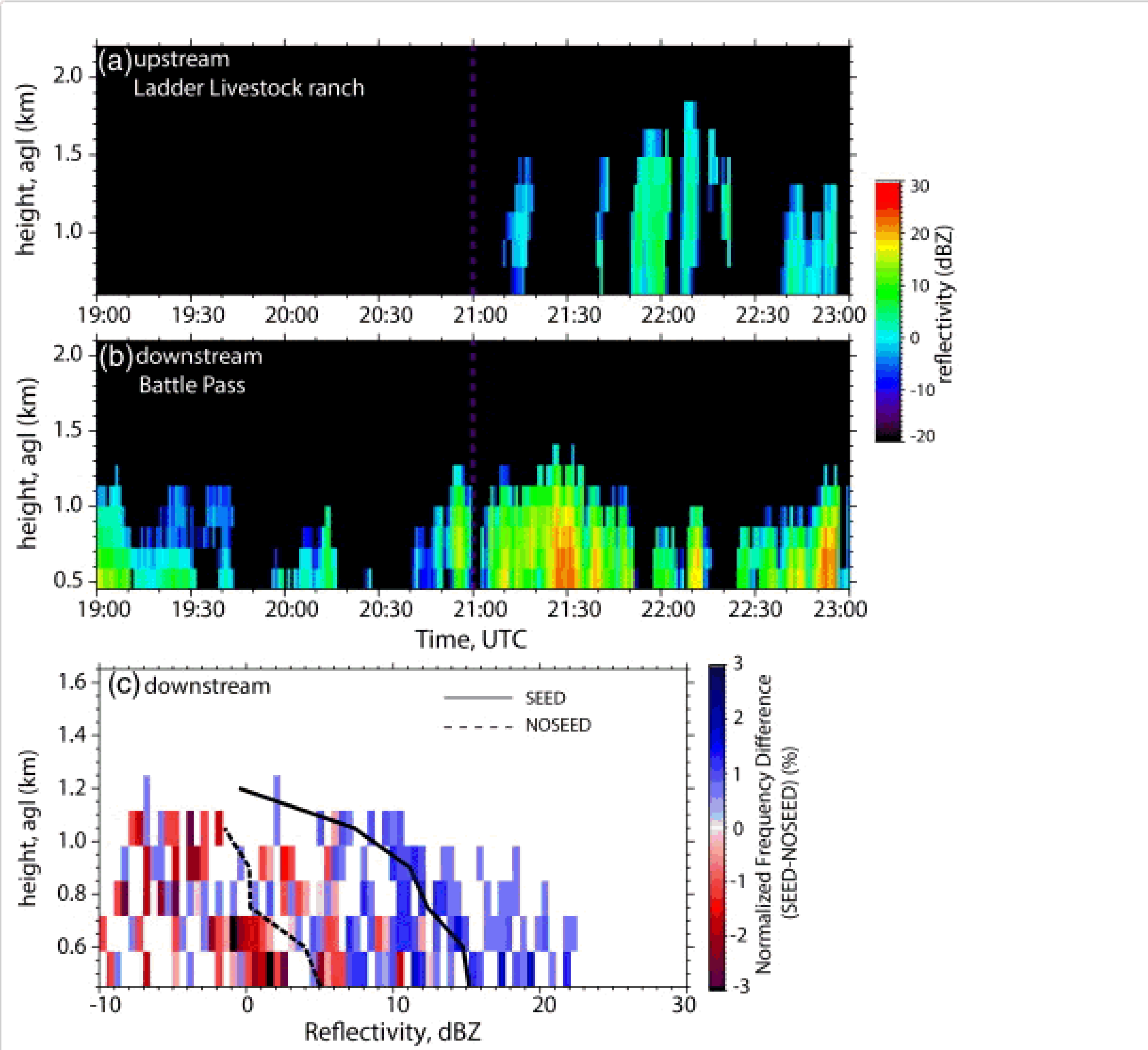

Figure 3.9 MRR measured reflectivity data from (a) the control site (Ladder Livestock ranch) and (b) the target site (Battle Pass) during the experiment period. The vertical line in both panels shows the start of the SEED period at Battle Pass (Table 1). (c) Difference in normalized reflectivity FAD (SEED–NOSEED) for the target MRR, plus the mean reflectivity profiles for the two periods.

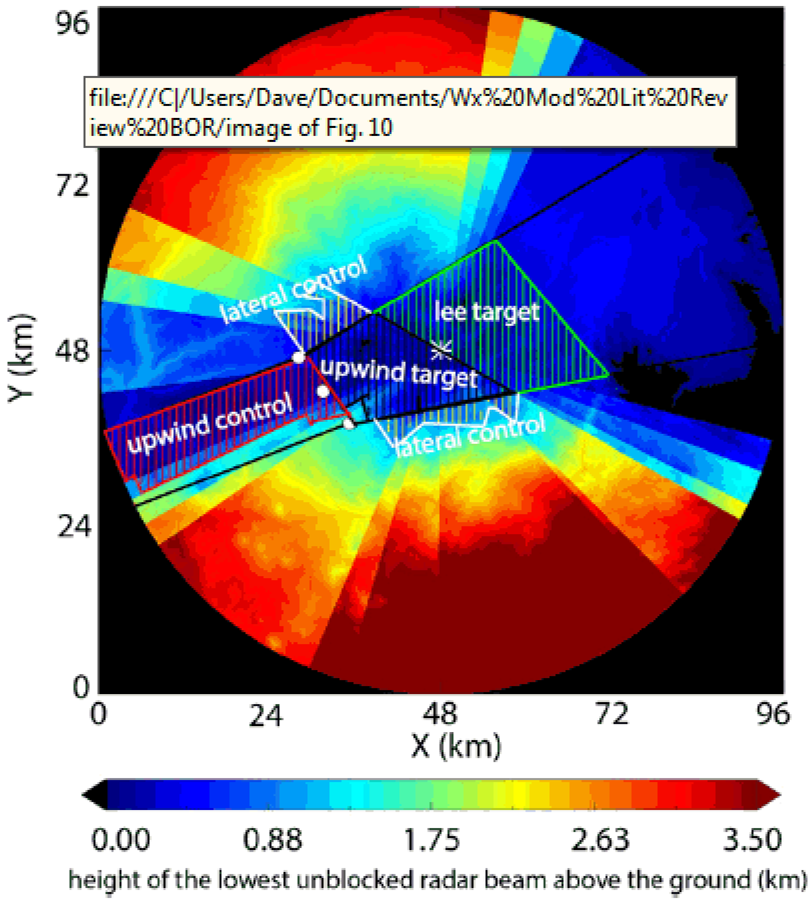

Figure 3.10 Height (km AGL) of the lowest unblocked beam from the DOW radar, located at Battle Pass (Fig. 1). Also shown are four vertically hatched regions used in the analysis of the seeding impact: the upstream control region (red), the lateral control regions (white), the "close target" region (black) upwind of the mountain crest, and the "lee target" region (light green) in the lee. The control area is defined as a region mostly upstream of the AgI generators where the lowest unblocked DOW beam is no more than 1 km above the terrain.

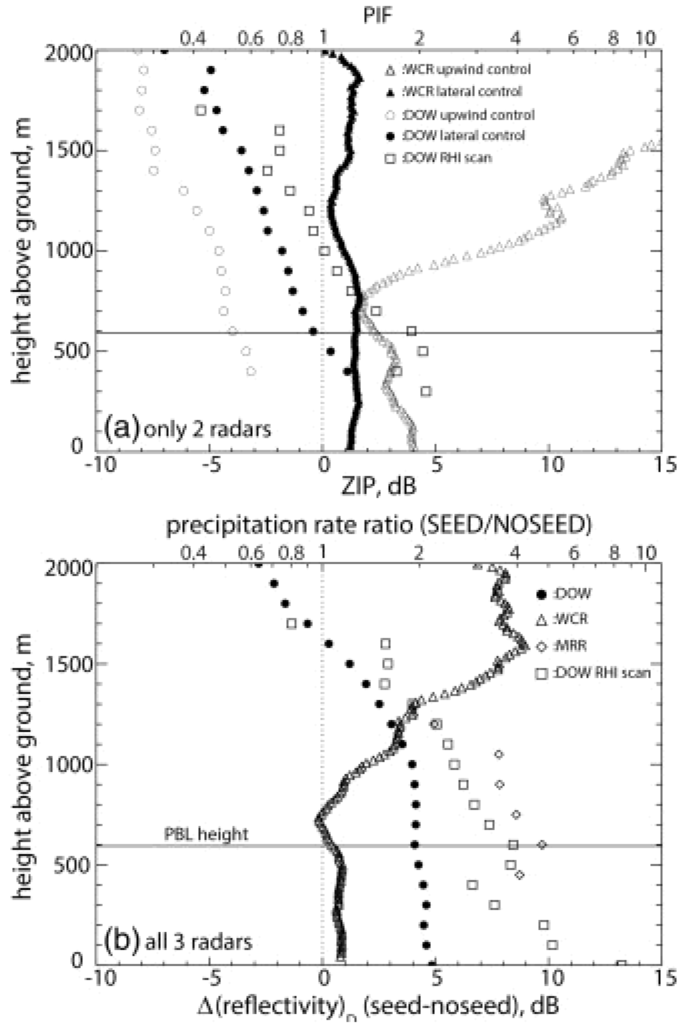

Figure 3.11 Vertical profile of reflectivity change, according to three radar systems. (a) The reflectivity change (SEED–NOSEED) in the target region relative to the same change in control regions, i.e. the reflectivity impact parameter (ZIP) and the precipitation impact factor (PIF) as defined in the text. For the WCR, the upwind control is track #1 (with as target tracks #2–#5), and the lateral control is out-of-cone flight section (Fig. 8d) (with as target the in-cone sections, Fig. 8c). For the DOW volume scans, the upwind (lateral) control is the upwind (lateral) control area, and the target in both cases consists of both the upwind and lee target regions (Fig. 10). For the DOW RHI scans, the control is an upwind control only, and the target combines both the upwind and lee target regions (Fig. 13f). (b) The absolute change in reflectivity and derived precipitation rate between SEED and NOSEED in the target region. The horizontal solid line in both panels is the WCR-derived average PBL depth.

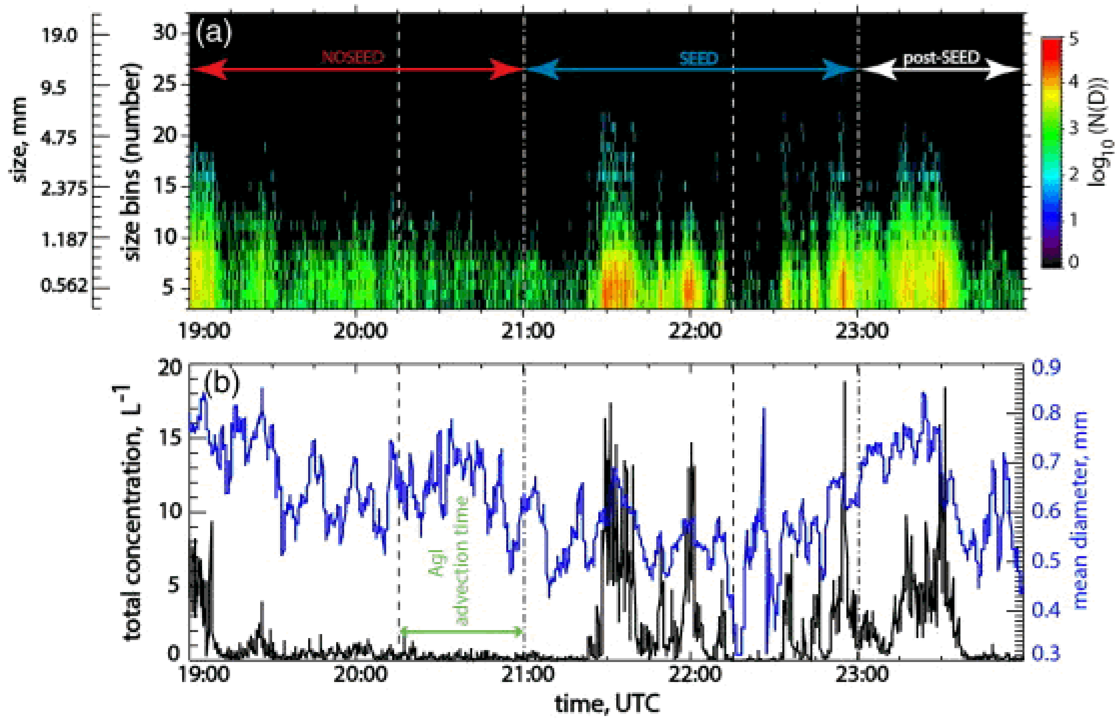

Figure 3.12 Time series of Parsivel disdrometer measurements at Battle Town site: (a) snow size distribution and (b) total snow concentration (black line) and mean diameter (blue line). The vertical dashed lines in both panels mark the period of AgI generator operation and vertical dash-dot lines indicate an equally long period starting at the estimated arrival time of the AgI plume at Battle Pass.

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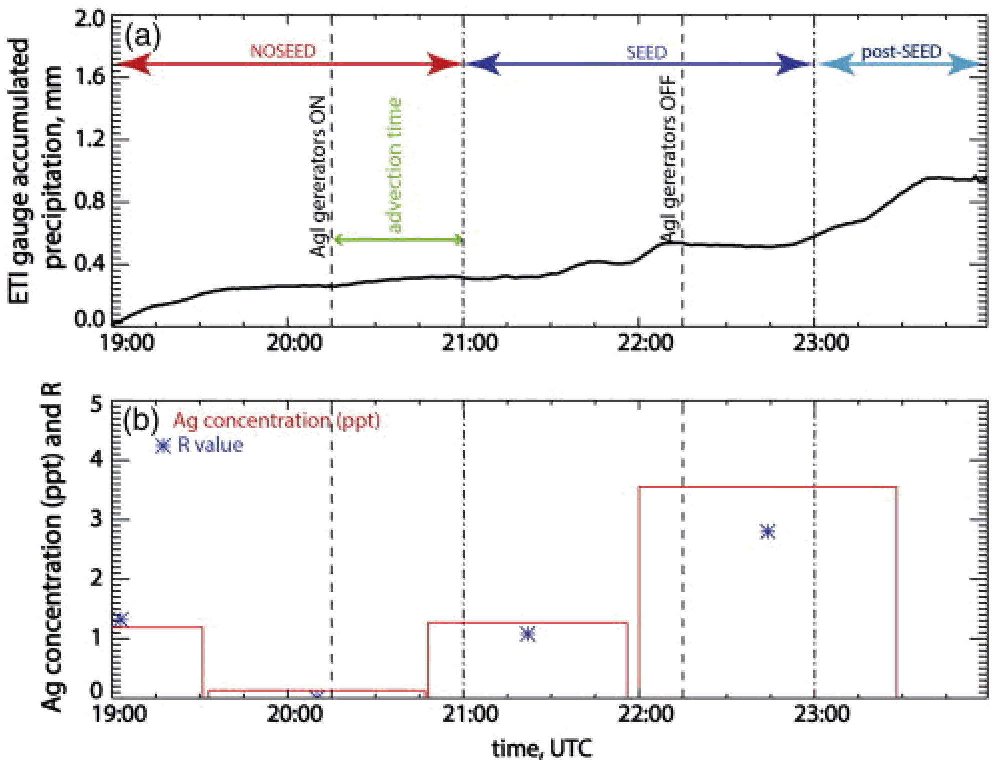

Figure 3.13 Time series of (a) accumulated precipitation measured by (a) ETI snow gauge, and (b) silver concentration, Ag, in parts per trillion (ppt) and the factor R from four snow samples collected during the IOP. The width of the histogram shows the duration of snow sample collected. The first snow sample collection started at 18:35 UTC. The measurements are from Battle Town site. Pokharel et al, 2014b)

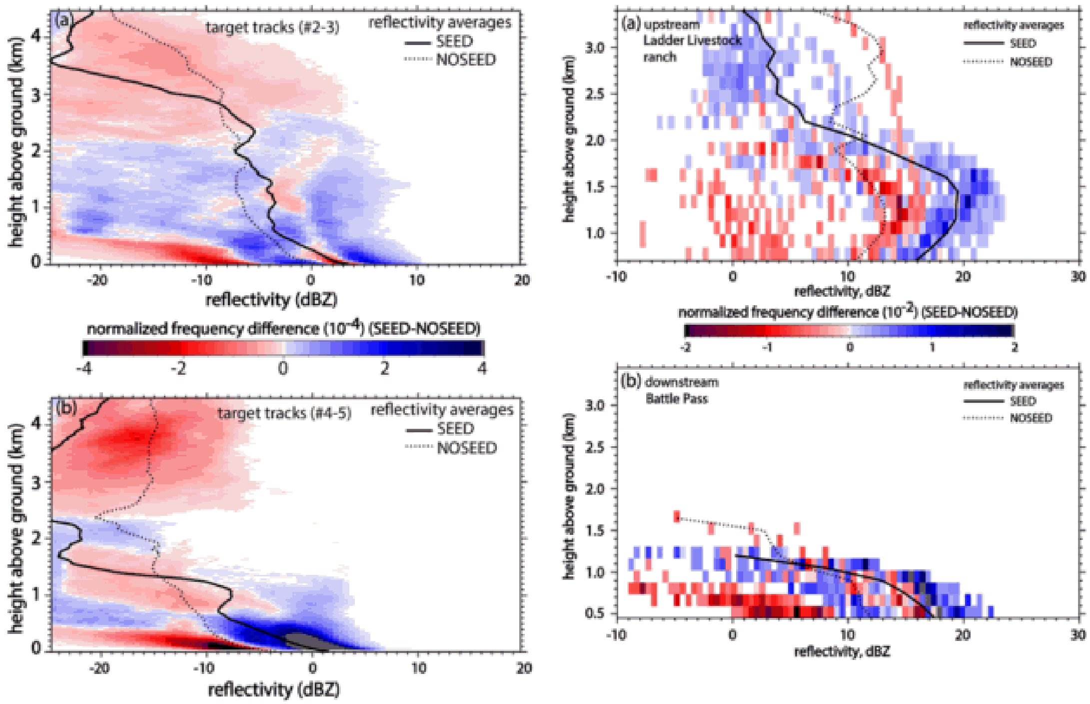

Figure 3.14 Left - Difference in normalized FAD (SEED2NOSEED) for WCR reflectivity for (a) the two target tracks just downwind of the generators (tracks 2 and 3) and (b) the two more distant flight tracks (4 and 5). Right - Difference in normalized FAD (SEED 2 NOSEED) for (a) the upstream MRR (control) and (b) the downstream MRR (target). The NOSEED and SEED periods are defined in Table 3.1. From Pokharel (2014 JAM)

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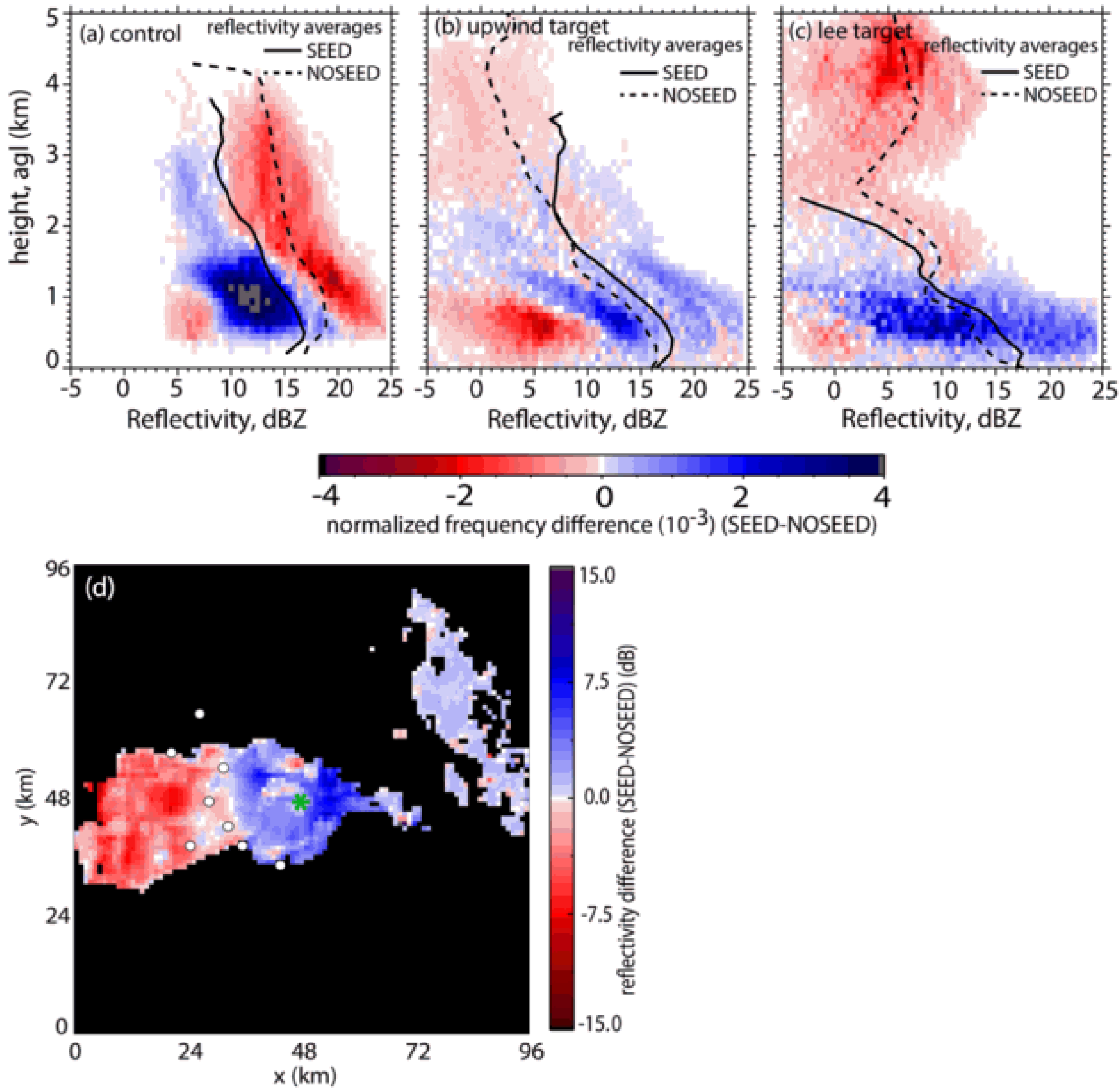

Figure 3.15 DOW radar reflectivity difference FADs SEED 2 NOSEED) measured in the (a) control region, (b)upwind target region upwind of the mountain crest, and (c) lee target region. Solid and dashed lines show the average values during SEED and NOSEED, respectively. (d) The horizontal distribution of 0–1-km AGL averaged reflectivity difference SEED-NOSEED) over the same domain as in Fig. 3.10. The green asterisk shows the DOW location, and white circles indicate the locations of the AgI generators. The far-range region to the ENE is affected by ground clutter. (from Pokharel et al. 2014 JAM)

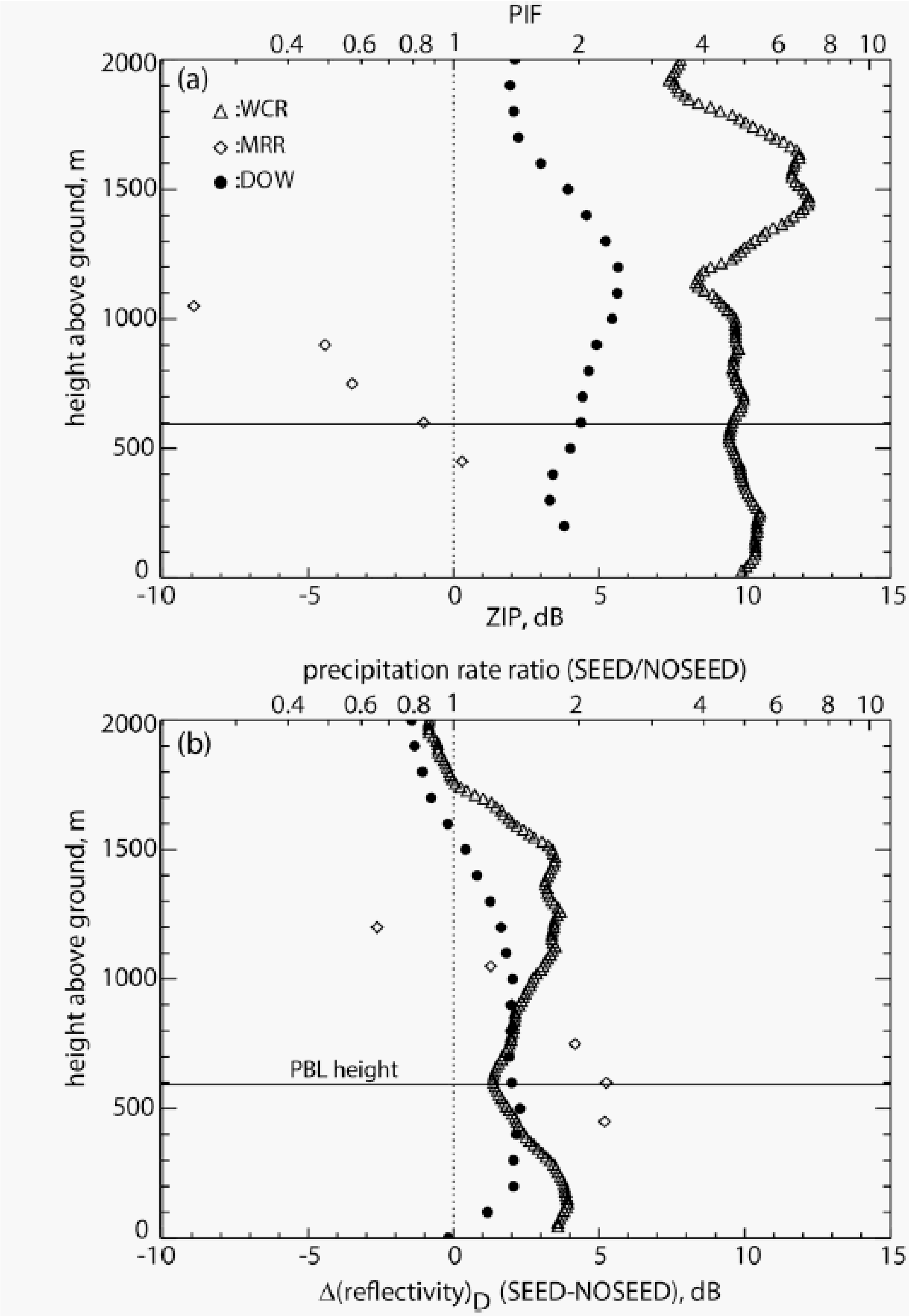

Figure 3.16 Vertical profiles of seeding impact parameters for the WCR (triangles), MRR (diamonds), and DOW (circles) data, each with different control and target regions. (a) The seeding impact parameters ZIP and PIF (defined in the text). (b) Change in reflectivity and derived precipitation rate between SEED and NOSEED in the target region. The vertical dotted lines in (a) and (b) separate a positive effect to the right from a negative effect to the left. The horizontal solid line is the WCR-derived average PBL depth.

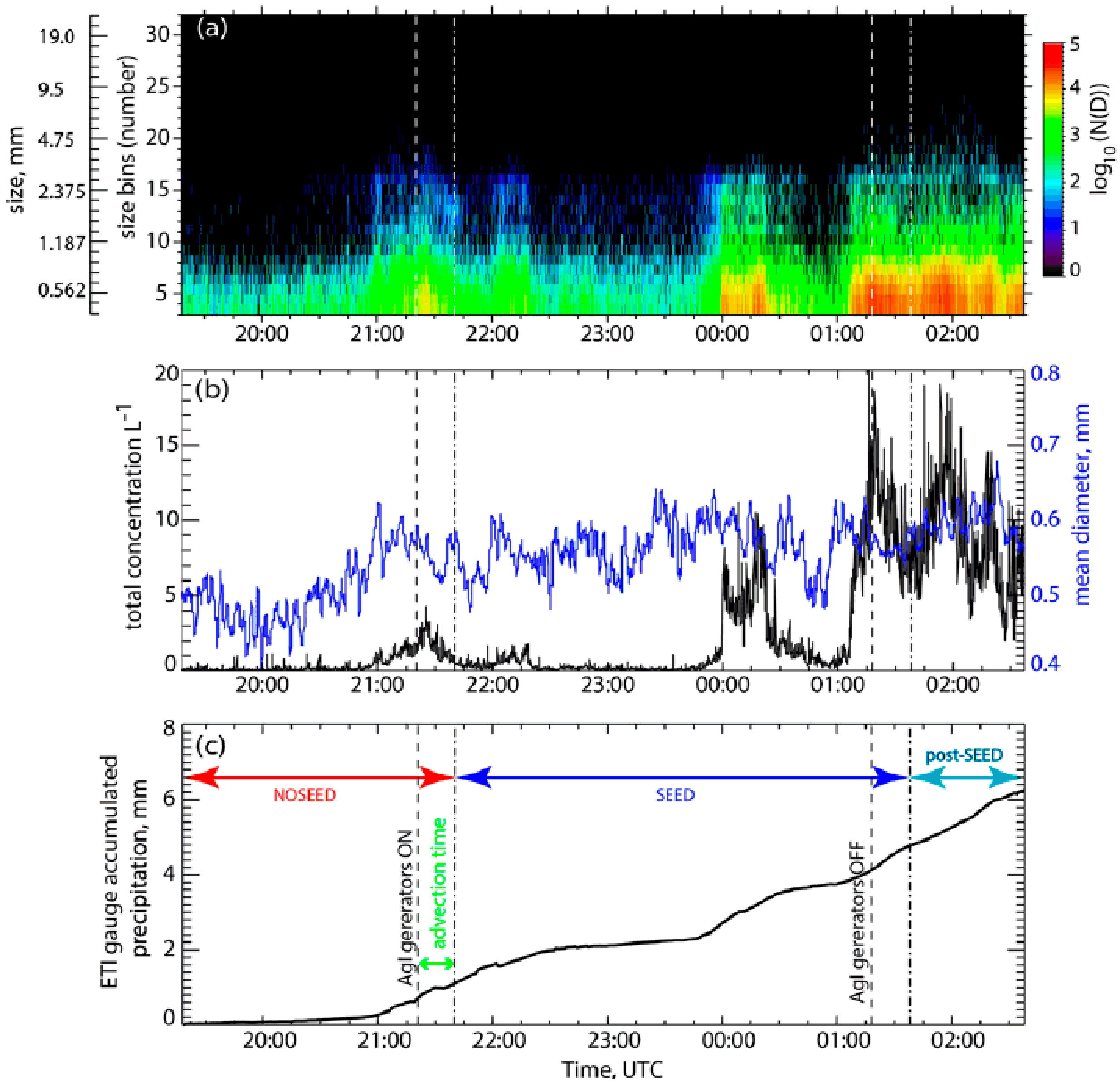

Figure 3.17 Time series of snow measurements at Battle Pass. The vertical dashed lines in all panels mark the period of AgI nucleus dispersion from the ground-based generators, while the dashed–dotted lines delineate the NOSEED, SEED, and post-SEED periods at Battle Pass. (a) Parsivel disdrometer snow size distribution, (b) Parsivel total snow concentration and mean diameter, and (c) accumulated precipitation measured by ETI gauge.

3.3.2 ASCII 13

ASCII 13 was a follow-on physical study of ground-based AgI seeding impacts patterned after ASCII 12 but conducted over the Medicine Bow Mtns, the second of the two target areas of the WWMPP. Preliminary to ASCII 13, exploratory radar observations utilizing the Wyoming King Air Cloud Radar (WCR) were conducted on 7 days spanning the winters of 2008 and 2009 over the Medicine Bows. The results of these observations will be briefly highlighted and can be placed in perspective with the results shown for ASCII 13.

The orientation of the Medicine Bow are slightly different than the Sierra Madre. They are more aligned to the SSW to NNE meaning winds from north of west would be the prevailing upslope flow. Figure 3.18 shows the terrain and the location of the seeding generators, the layout of the flight legs, as well as other ground based equipment available. However for the exploratory studies of Geerts et al (2010), the analysis will be restricted to the WCR data. The 7 flights flown all had temperatures at the seeding generators very close to or colder than the -8 ^{o}C threshold of activation of the AgI solution used. SLW values were almost all below .1mm except for one case that showed .12 mm. Background snow water-equivalent rates were .22 to 1.17 mm/hr or light snow. The generators are located about 11 km from the crest of the mountain and about 15 km upwind of flight leg 5. Thus given a nominal 10 m/s wind in the layer transporting the seeding plume, these locations are approximately 18 and 25 min downstream. This will vary from flight to flight in an approximate range of 10 min (crest) to 30 min (leg #5).

A total of 70 seeded flight legs and 44 noseed flight legs were flown. As was the case in ASCII 12, no apparent seeding effects could be seen in the raw WCR reflectivity profiles over the downwind seeded legs within the expected seeded plumes. A simple calculation was done to determine the height reached by the AgI aerosols given dual-doppler vertical velocities observed by the aircraft and the computed height of the planetary boundary layer (PBL). It was estimated that the aerosols would reach the top of the PBL (~800 m on average) near flight leg #5 or about 20 min downwind. However this height is normally below the level of the aircraft making the aircraft in-situ observations of seeding effects less useful and thus the focus on the remote WCR data. Results from all seven flights comparing seed versus no-seed FAD profiles showed that the downstream seeded flight legs were 36% more likely to have > 10dBZ reflectivity values in the PBL. Using a computed Z-S (reflectivity to snowfall) calculation based on in-situ observations of particle size spectra, shape and fall-speed, the increase in reflectivity translates into a .3 mm/hr increase in SWE in the seeded cases versus the non-seeded cases. This is very close to the mean increase observed by Holyrod et al (1988) over the Grand Mesa and a factor of ten higher than Super and Heimbach (1988) reported over the Bridger Range although their observations were at aircraft flight altitude. A further refinement in the analysis was to match the number of seeded and non-seeded flight leg FADs to determine the difference in Z and a larger increase was observed (2.6 dBZ). This translates to a doubling of the precipitation rate in the seeded cases. A statistical random sampling methodology was used to determine the significance of the reflectivity difference observed. Utilizing this technique it was determined there was only a 2% probability that the reflectivity increases due to seeding >10 dBZ was by chance.

It was found that in segregating the downwind flight legs to the two closest (legs #2-3), that most of the reflectivity increase occurred closest to the seeding generators. These two lines are only 5-10 min downwind of the generators. Given the temperatures at the generators average near -8 ^{o}C and near if not in cloud, the nucleation process is most likely condensation freezing, meaning ice crystals formed near the generators and fell out before they reached flights legs 4-5. This is consistent with what has been observed by Holyrod et al (1995) and discussed by Finnegan and Pitter (1991) and Chai and Finnegan (2003). If in fact this is what is occurring, this brings up two issues. One is that the dispersal of the seeding material would be limited, meaning the plumes would be narrow this close to the generators so the areal coverage of the seeding effects may be limited. Secondly it would argue that under these situations there would be little downwind effects as the AgI would be rapidly converted to ice which falls out quickly. These key points have an impact on the WWMPP statistical results reviewed in Section 2.2.

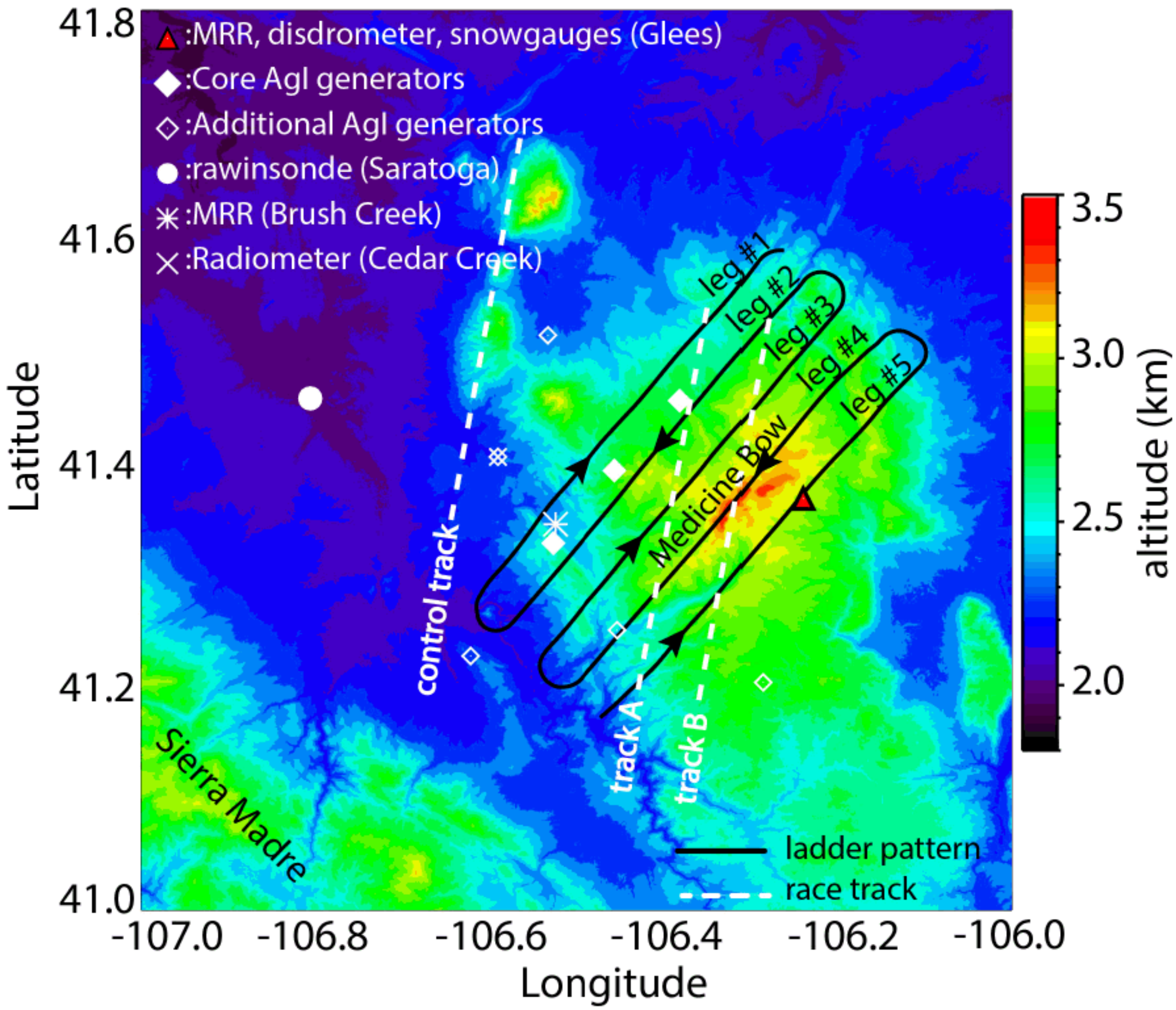

Figure 3.18 *The ASCII-13 experimental design map, showing UWKA flight tracks over the Medicine Bow range. Two types of flight patterns were flown: a) a five-rung ladder pattern (solid lines), used on the 13 flights where only the core AgI generators (filled diamonds) were used; and b) a racetrack and control track (white dashed lines), used on the two flights where the other five generators (hollow diamonds) were used as well. The terrain is shown in the background.*

During ASCII 13 (Pokharel and Geerts, 2014) and additional 8 flights were conducted in the same manner as discussed above. The WCR data collected from these flights were combined with the flights from 2008-09. Two days during the 2013 campaign, 8 generators were operated instead of just the three that had been used in 2008-09. Conditions were similar for the 8 flights to the earlier flights with temperatures at cloud base at or colder than -8 ^{o}C, SLW values of .05 - .15 mm, and mean transport winds of 10 – 15 m/s. The PBL averaged around 800 m.

The FADs from the various seed no-seed flights were averaged and sampled using various methodologies as has been described earlier including by flight legs, for inside the expected seeding cones of influence and outside the cones used as control etc. A summary figure was provided, Figure 3.19, that shows the difference in reflectivity and computed precipitation rate for seeded and non-seeded flight legs for all 13 flights looking only at the lowest 500m. The figure would indicate a trend in seeding impacts with respect to 700 mb temperatures with colder temperatures indicating a larger impact. However the authors identified this trend as most likely due to a natural increase in precipitation between the non-seeded legs and seeded legs during a given flight. That is that non-seeded legs always precede seeded legs and there appeared to be an intensification of the snowfall over the entire region during seeded legs versus non-seeded legs.

To remove this trend the ZIP and PIF values were computed utilizing the control portions of the flight legs to the seeded portion of the flight legs. ZIP and PIF were described earlier. These results are shown in Figure 3.20a. These values were compared to ASCII12 results over the Sierra Madre. These results are shown in Figure 3.20b. The results suggest that there are positive seeding effects for the Sierra Madre but little if any over the Medicine Bows. The authors had no good explanation of why the results were positive over the Sierra Madre and weak to non-existent over the Medicine Bows.

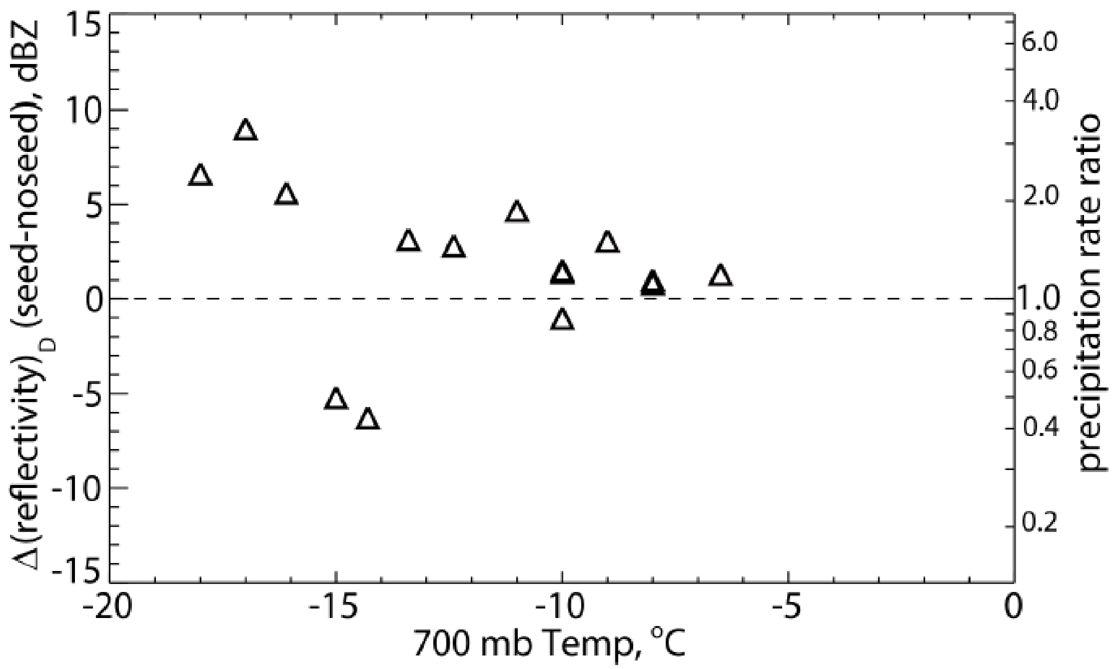

Figure 3.19 The difference (SEED – NOSEED) in mean WCR reflectivity from target legs below 500 m above the ground according to the 15 flights over the Medicine Bow range. The resulting change in precipitation rate (S) assumes the relation $S=0.39Z^{0.58}$.

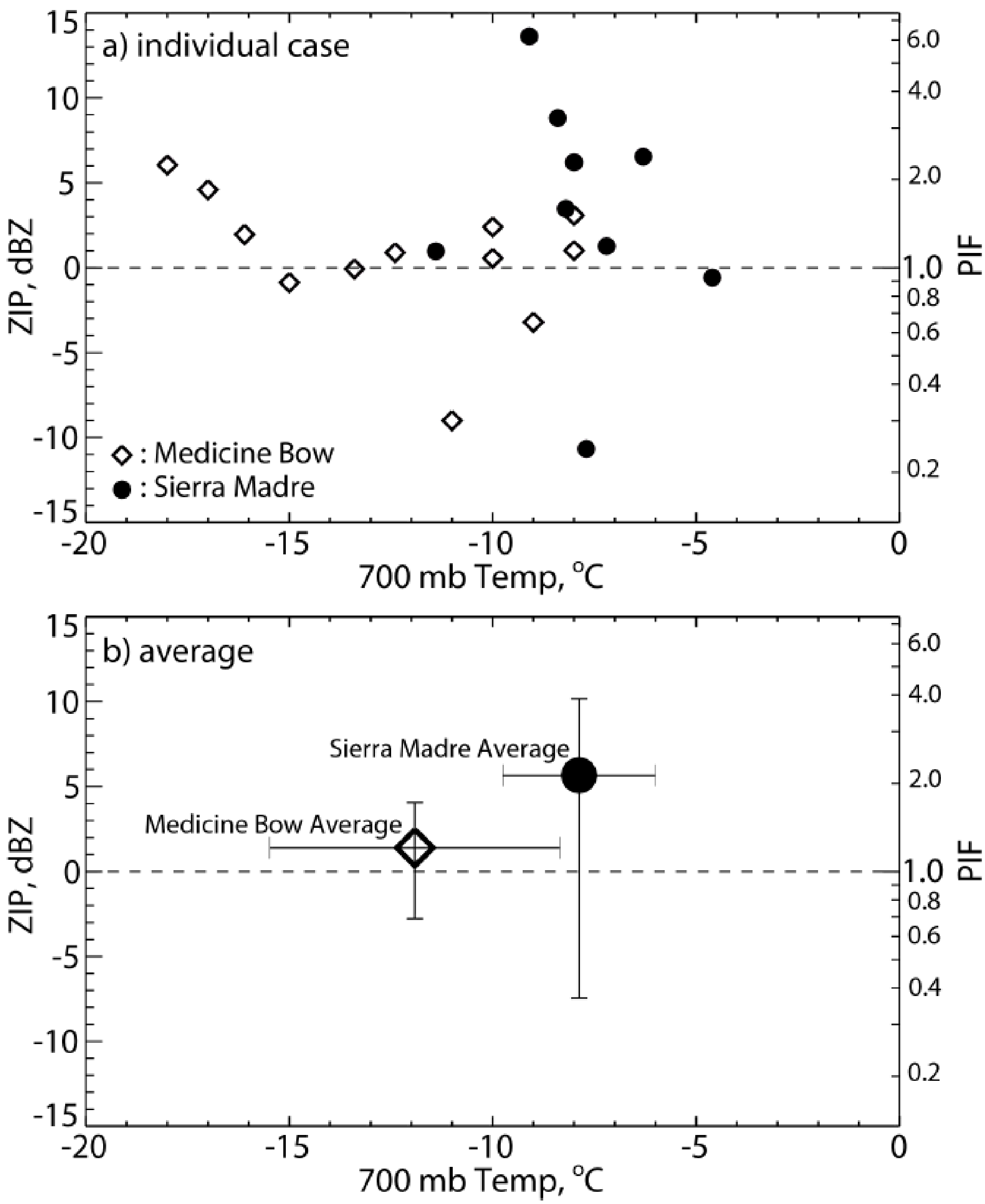

Figure 3.20 (a) The reflectivity impact parameter (ZIP) and precipitation impact factor (PIF) calculated from the mean WCR reflectivity below 500 m AGL from 21 flights over two mountain ranges (12 flights over the Medicine Bow range and nine flights over the Sierra Madre). (b) As (a), but showing the average value over the two mountains with error bars corresponding to one standard deviation. From Pokharel and Geerts, 2014.

3.4 Application of Numerical Modeling in the Conduct and Evaluation of Winter Orographic Cloud Seeding

Application of numerical models to the simulation of seeding effects in winter clouds has been an ongoing effort for decades. Kopp et al (1983) and Oroville and Kopp (1994), describe the use of 2-D cloud models to simulate orographic and convective cloud processes as well as simulate the effects of dry-ice seeding on convective clouds. Several winter cloud seeding projects have used the Clark model (Clark and Gall, 1982) as part of the development of a winter cloud seeding project (Bruintjes et al. 1994). These studies highlighted that every ridge and valley within the complex terrain of western mountains has updrafts and downdrafts as well as mountain waves that strongly impact the location and duration of SLW, Figure 3.21. The Japanese Meteorological Agency has also developed a 3-D modeling system called the Non-Hydrostatic Modeling System (NHM) that has been used to determine the seedability of and the potential seeding impacts on winter orographic clouds over the Echigo Mountains (Hashimoto et al, 2008) of Japan. This project was described in Section 3.2. Section 3.4.1 will review the most recent work of Xue et al (2013) that describes the development of a cloud seeding module emulating the treatment of winter orographic clouds by ground-based and aerial seeding. Much of this information was presented by Dr. Rasmussen at the Bureau of Reclamation's Winter Orographic Cloud Seeding Workshop held in November 2014 at the Denver Federal Center.

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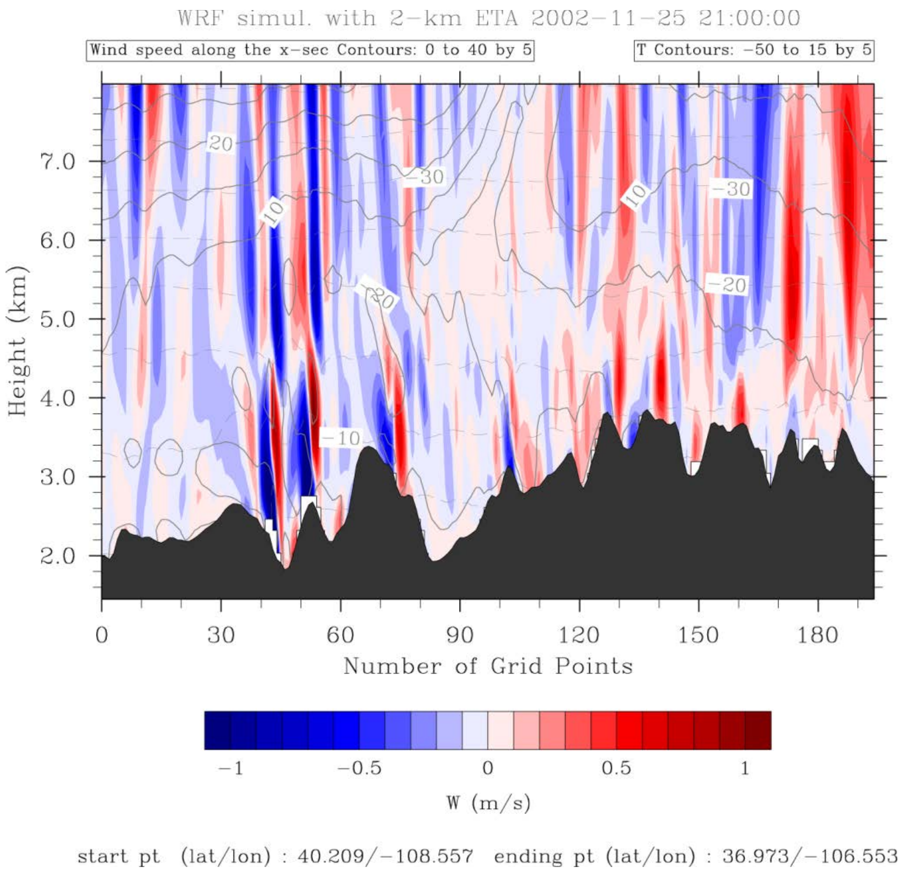

Figure 3.21 Vertical motion field over a transect of the Colorado Rockies showing the complex vertical motion associated with each ridge and valley. One can also see the vertical propagation of the motions in the lee of the ridges due to mountain waves. Courtesy Roy Rasmussen .

3.4.1 NCAR WRF Modeling for Winter Orographic Cloud Seeding

The Weather Research and Forecast Model (Skamarock et al. 2008) is the basis for NCAR's winter orographic cloud seeding modeling effort. This model is used widely by researchers and a 4 km resolution version of this model is run operationally at NCEP. Many National Weather Service Forecast Offices run a high resolution version of this model covering all or a portion of the offices forecast area usually at 1 or 3 km resolution. (Rozmulaski, http://strc.comet.ucar.edu/software/newrems/userguide/emsguide_preface.pdf). The WRF is a refinement and improvement of the Mesoscale Model version 5 (MM5) developed by the Pennsylvania State University and NCAR. Rasmussen et al (2002) adapted this model to identify the microphysical growth processes leading to freezing drizzle. This was a key study in that it lead to a much improved parameterization of cloud supercooled liquid water and how cloud drop size and size distributions were critical to the development of supercooled drizzle drops that can be extremely hazardous to aircraft. The Thompson microphysics scheme is now widely used in WRF applications and has been demonstrated to produce realistic SLW profiles over mountain barriers in the west. Liu et al (2011) tested the sensitivity of the model utilizing the ARW dynamic core to various microphysics, planetary boundary layer, land surface, and radiative schemes to assess the models applicability in simulating precipitation over the Colorado Rockies over a winter season. Rasmussen et al (2011) then ran this version of the model to simulate multi-winter-season snowfall as shown in Figure 3.22. This study provided the basis for demonstrating that the WRF could reproduce annual snowfall at various SNOTEL sites in the complex terrain of the Rockies and noted the importance of model resolution. The higher the resolution the better the model simulated the precipitation. These preliminary studies showed that the WRF could be adapted for use in determining the feasibility of conducting winter orographic cloud seeding such as those being conducted in Wyoming and Idaho. The basis for this is that if the model can simulate very well the seasonal SWE one assumes it has a good handle on the cloud microphysics and the natural precipitation processes. If the model can then emulate the process of injecting AgI into the cloud and activating and dispersing the aerosol properly, there is hope the model can guide seeding operations and estimate seeding effects.

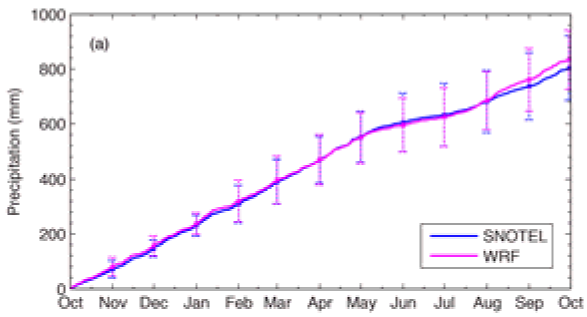

Figure 3.22 Simulated snow water equivalent as determined from the WRF model for a combined seven seasons at a SNOTEL site in the Colorado Rockies.

Xue et al (2013a) describes the AgI parameterization that was developed for the WRF. The logic flow is shown in Figure 3.23. It is critical that the model is evaluated against observations to make sure it is delivering the AgI to the cloud and dispersing it properly. This has to be done in a realistically simulated winter orographic cloud. The WRF was further tested to determine the best data assimilation and initialization scheme for running the model. It was determined that the model performed better when using a Real-Time Four Dimensional Data Assimilation (RTFDDA) then using the North American Regional Reanalysis (Figure 3.24). The RTFDDA makes better use of in-situ observations to nudge the model's first guess field to the observations. This well described in Xue et al (2013a).

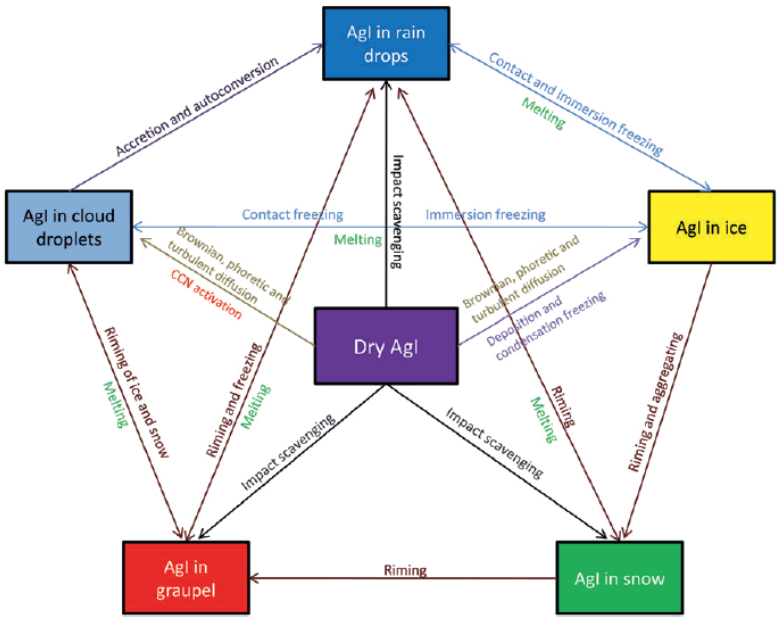

Figure 3.23 AgI parameterization logic used in the WRF model as described by Xue, 2013a

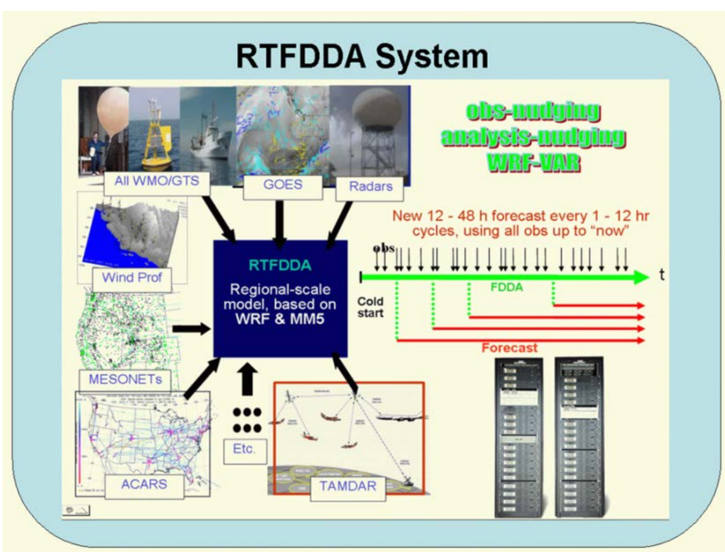

Figure 3.24 Real-time Four Dimensional Data Assimilation used in the WRF to improve model initialization.

Once the model has been configured it must be evaluated with observations of critical observed features such as the location duration and magnitude of SLW. It must disperse ground based AgI realistically into the cloud and forecast the proper trajectory of the plumes, both vertically and horizontally. As in the Rockies the model was shown to reproduce to a first order the SLW located on the upwind edge of the Sierra Madre and the Medicine Bow's and to simulate the SWE at SNOTEL sites within both ranges target areas.

As had been pointed out by the NRC 2003 report, targeting has been a critical weak link in past AgI ground based seeding programs. Thus it is critical that the modeling framework be evaluated against in-situ observations of the transport and diffusion of the AgI. Boe et al (2014) described in-situ AgI plume tracing during the winter 2011, using both an aircraft-mounted NCAR ice nucleus counter and a ground-based ice nucleus counter. These plume tracing experiments performed from the aircraft-mounted unit had to be conducted in seeding-like conditions in that flight rules prohibit flights within 600m of the terrain when the mountain is engulfed by clouds. The ground based counter was located in the Medicine Bows (MB) within the WWMPP target area and was operated for three winter season, 2008-2011. These three seasons of ground based sampling of AgI noted that when seeding was being conducted over the Sierra Madre, for several hours after seeding terminated, AgI was still being observed over the Medicine Bows. It was discussed in Section 2.2 that this was thought to dilute the seeding impacts from seeding what was to be the unseeded control. It was discovered that during these three seasons, plumes could not always be observed when seeding was occurring over the MB. This could be for several reasons, but most likely the plumes from the generators were narrow and missed the location of the counter. Given that the statistical evaluation found that the number of generators was critical to observing a seeding impact, these results are not surprising. Figure 3.25 shows several examples of plumes observed.

The aircraft sampling was done using three different experiments. One with a single generator on, one with five generators that would mimic a real randomized seeding experiment, and one where the aircraft tried to sample the plume downwind of the Sierra Madre. This last experiment proved unsuccessful. In all cases the aircraft flying just downwind of the generators at low altitudes, 150m, picked up the AgI plumes and with subsequent downwind flights at incremental altitudes and flying perpendicular to the wind direction picked up the plumes to altitudes of 500 to 700 m above the generator release elevations and to IPC's above 10 L^{-1} (assumed corrected to altitude temperature and not -20 ^{o}C chamber temperature of counter) which would be sufficient to effect snowfall rates. The plumes measured aloft were of higher concentrations then measured at the surface sampling site. Thus it appears that it is possible that weak plumes measured at ground site or meandering plumes may not represent what is going on above the sampling site within the clouds. The inability to find the plumes downwind of the Sierra Madre in the direction of the MBs for this case may represent poor flight paths as it is known the plumes can and do effect the MBs when seeding the Sierra Madre.

The 16 February transport and dispersion experiment was simulated using the WRF large-eddy simulation (LES) with 100 m grid resolution and the AgI seeding module to try to replicate the observations. The in-situ aircraft measurements are shown in Figure 3.26 indicating the flight path downwind of the generators and the vertical concentrations observed. Figures 3.27 and 3.28 represent a 3-D view of the plumes as simulated by the 100m LES model runs and a vertical cross-section along the plumes. Both shows the AgI is concentrated in the lowest 500-700 m above the generators with rather narrow plumes showing weak horizontal dispersion.

The key findings of the study were: Qualitative and quantitative comparisons between the LES results and observed AgI concentrations were conducted. Analyses of turbulent kinetic energy (TKE) features within the planetary boundary layer (PBL) and comparisons between the 100-m

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LES and simulations with 500-m grid spacing were performed as well. The results showed the following: 1) Despite the moist bias close to the ground and above 4km AGL, the LES with 100-m grid spacing captured the essential environmental conditions except for a slightly more stable PBL relative to the observed soundings. 2) Wind shear is the dominant TKE production mechanism in wintertime PBL over complex terrain and generates a PBL of about 1000-m depth. The terrain-induced turbulent eddies are primarily responsible for the vertical dispersion of AgI particles. 3) The LES-simulated AgI plumes were shallow and narrow, in agreement with observations. The LES overestimated AgI concentrations close to the ground, which is consistent with the higher static stability in the model than is observed. 4) Non-LES simulations using PBL schemes had difficulty in capturing the shear-dominant turbulent PBL structure over complex terrain in wintertime and thus the vertical and horizontal dispersion of the AgI. Therefore, LES are recommended for simulating winter orographic clouds using grid spacings close to 500m or finer. Running this model is computationally expensive and most likely would not be practical for operational seeding programs.

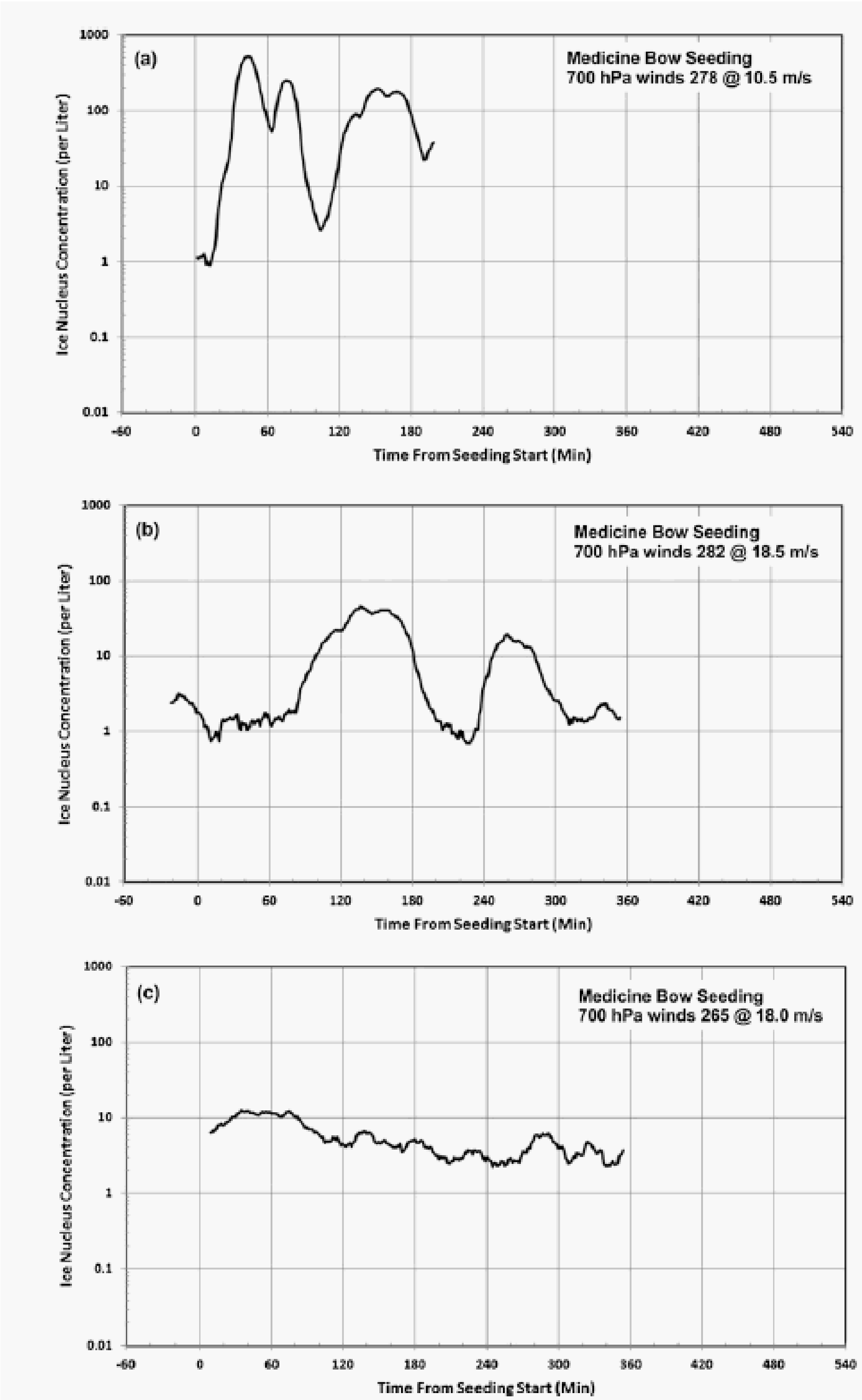


Figure 3.25 AgI plumes observed at the Medicine Bow sampling site the depict top: strong plume of AgI observed infrequently, center: a more typical plume (s) showing that a weak plume did not arrive until almost 1 hr after seeding started and either meandered away for an hour then meandered back over the site lasting almost an hour after seeding ended. Bottom: very weak plume with low concentrations. This sort of plume was not observed very often.

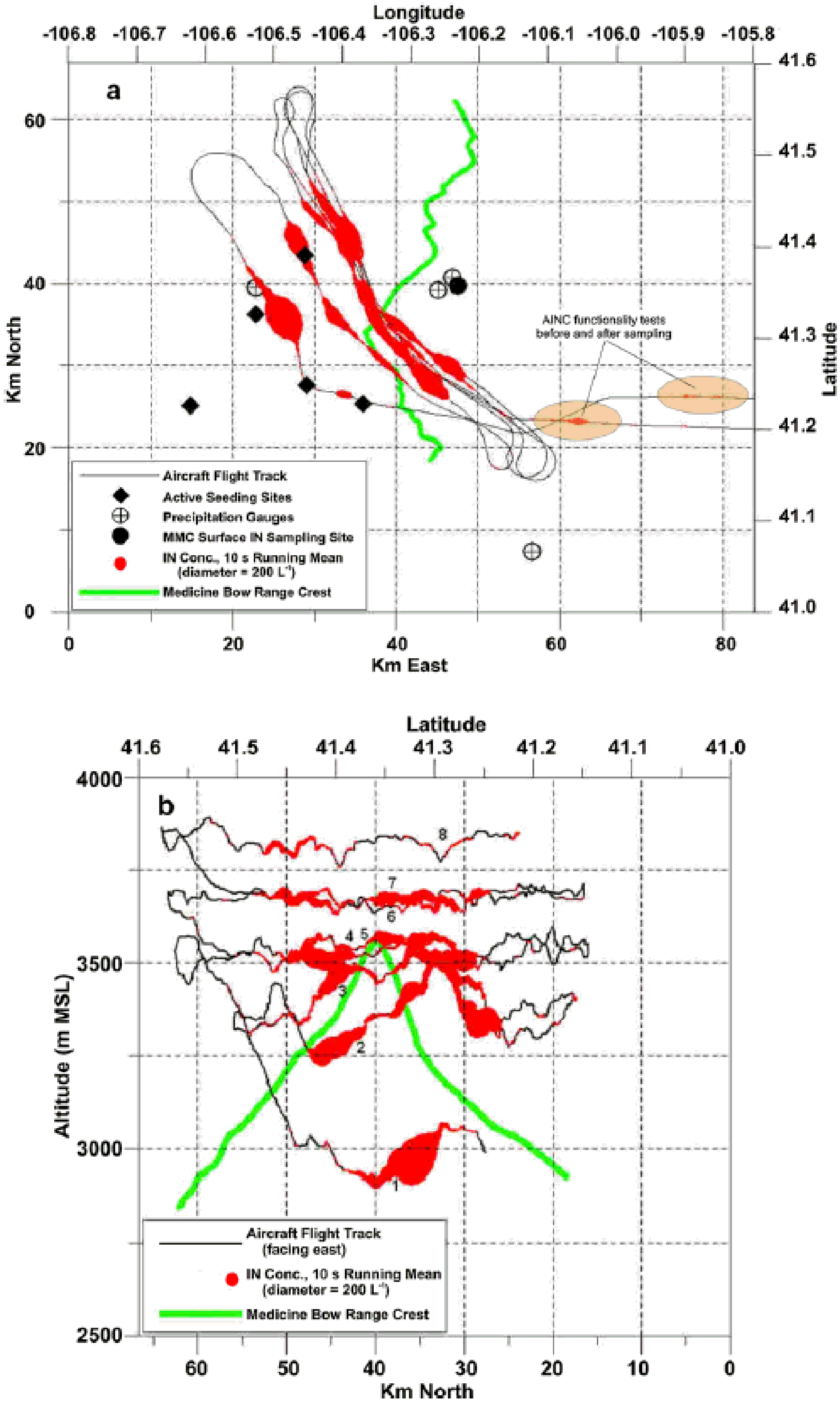


Figure 3.26 Aircraft sampled AgI concentrations both in plan view and in vertical cross-section over the Medicine Bow's for 16 February 2011.

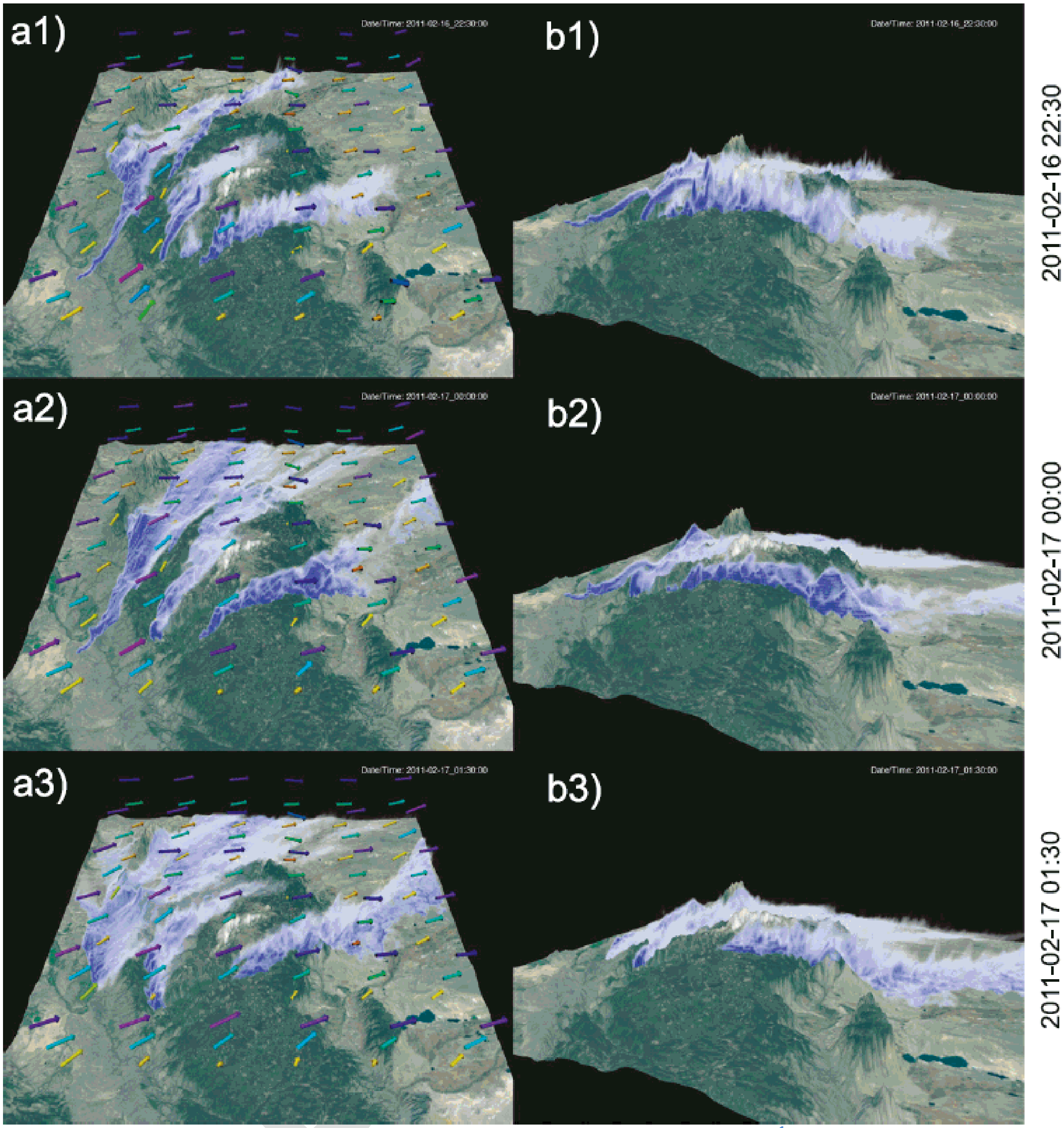


Figure 3.27 3D depictions of the topography, AgI number concentration (greater than 100L^{-1} for visible plumes), and wind vectors; (2800 m—yellow,3600 m—blue, and 4400 m—purple MSL). (a) Bird's-eye view perspective from the south and (b) side views from the southeast. Three snapshots are shown at times (top) 2230 UTC 16 Feb, (middle) 0000 UTC 17 Feb, and (bottom) 0130 UTC 17 Feb.

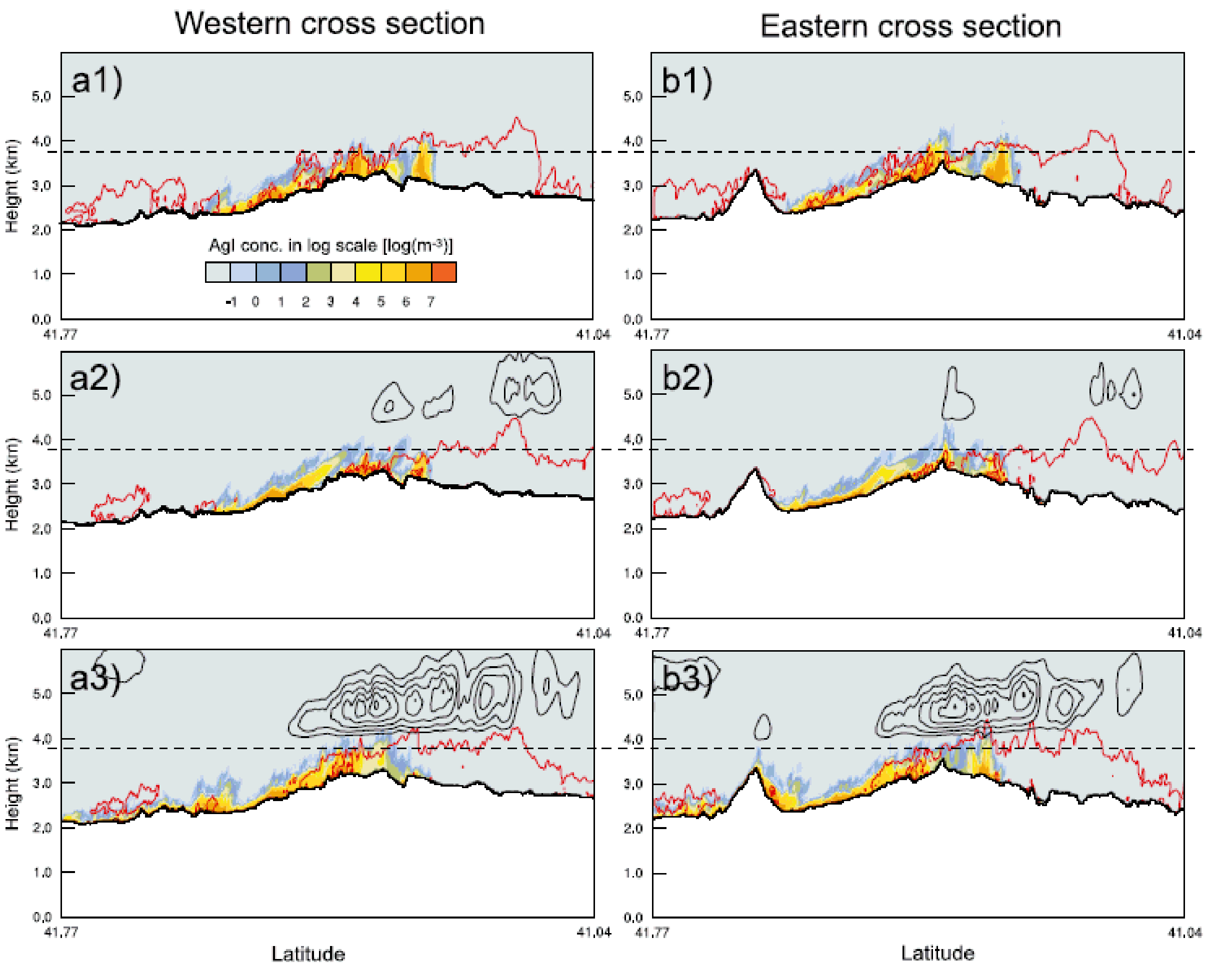


Figure 3.28 Cross sections of AgI concentration [logarithmic scale and color shaded: log(m^{-3})], isoline of TKE 5 1m2 s22 (red outlines), and cloud water mixing ratio (black contours in intervals of 0.1 g kg^{-1}). (a) The western cross section and (b) the eastern cross section. Valid at (top) 2230 UTC 16 Feb, (middle) 0000 UTC 17 Feb, and (bottom) 0130 UTC 17 Feb. The black dashed lines indicate the highest level at which the in situ measurements were taken (around 3800m MSL).

The next step in the process is to simulate the actual impact of the AgI seeding on precipitation. In Xue et al (2013b) four seeding experiments were run. Three being ground-based and one being aircraft seeding. These simulations were run over the operational target areas of the Snake River basin in Idaho operated by Idaho Power. These areas are shown in Figure 3.29. The A baseline run and various sensitivity tests were run with the 3-D WRF using RTFDDA including varying the seeding rates, using different PBL schemes, varying the seeding generator locations varying ice-nuclei concentrations and cloud water droplet concentrations, and adjusting the aircraft flight tracks. These are listed in Table 3.5.1.

The baseline runs indicated that for ground based seeding, nucleation by deposition followed by diffusional growth dominated with more vapor being utilized in the crystal growth process than SLW. This mainly because the crystals begin to aggregate and fall out sooner if they are not lofted high enough over the barrier to be able to consume more of the cloud SLW. It could not be determined if the generators used in the simulation were in cloud and below say -6 ^{o}C. If so there is a possibility that condensation freezing versus deposition would have been observed. This would in essence speed-up the growth of the crystals and may have led to fallout even sooner. Since both processes are part of the AgI nucleation simulation, it can only be assumed that the condensation freezing wasn't expected in these cases. For aerial seeding, the crystals also grow by diffusion but because they are aloft longer and fall into the SLW region close to the barrier, riming growth occurs and more mass is brought to the ground leading to a more efficient precipitation process. Since aerial seeding is emulating more closely the natural precipitation process, nucleation occurs near cloud top rather than in lower region of the cloud, aerial seeding is more efficient in removing cloud SLW.

The results of these sensitivity tests are shown in Table 3.5.2 as both increases in ac-ft over the target area and as a percentage increase. It can be seen that the largest increases come with increased seeding rate whether from ground-based or aerial seeding. It was also shown that switching the 0216 case from ground based to aerial seeding and increasing the seeding rates had a large impact on seeding efficiency and effect. This was concluded to be that aerial seeding does a better job of targeting the SLW in the cloud and bringing this water to the ground.

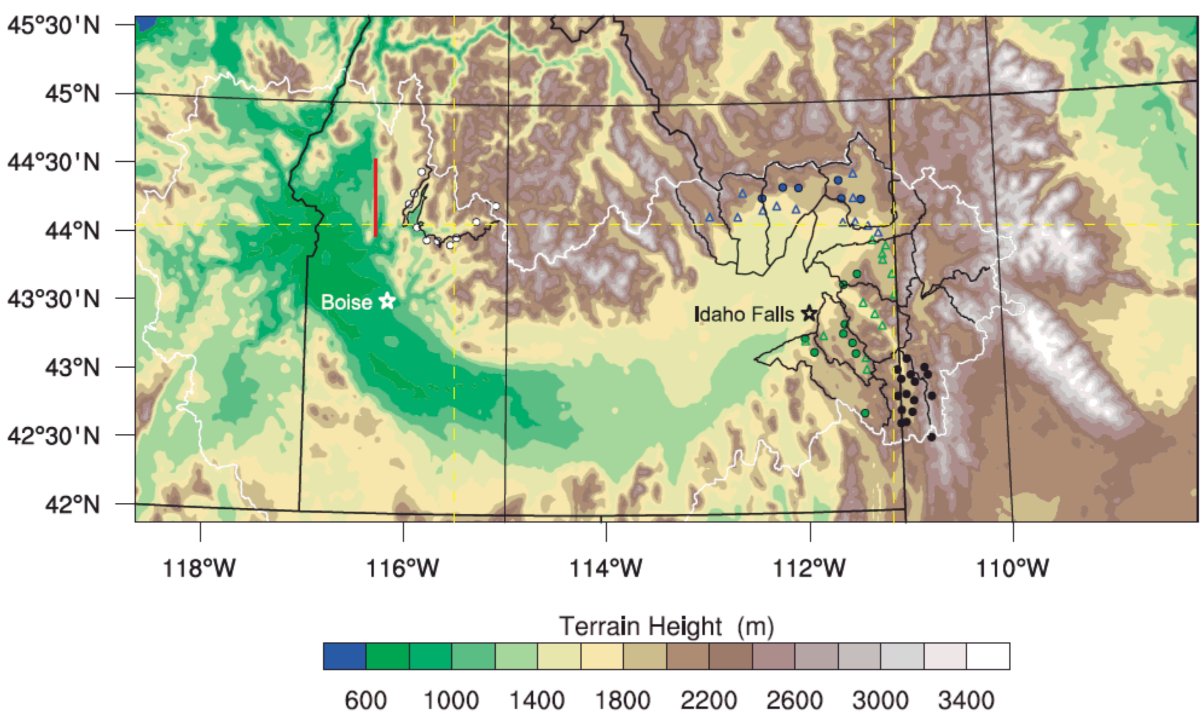


Figure 3.29 Domain of the simulations. Terrain height (m) is color shaded. The Snake River basin is outlined in white. The Payette watershed and the eastern Idaho watersheds are outlined in black. Generators are indicated by circles (automatic generators with seeding rate of 20 g h^{-1}) and triangles (manual generators with seeding rate of14 gh^{-1}). Generators over the Payette region are in white. Blue generators consist of the northern group over the target area in eastern Idaho. Green is the southern group. Black is the Wyoming group. White and black stars indicate the cities of Boise and Idaho Falls, respectively. Flight track is represented by the red segment on the western side of the Payette watershed.

Table 3.5.1 Sensitivity tests run for the four cases.

Case[a]	1127_PAY	1202_PAY	1219_EID	0216_EID
YSU	X	X	X	X
N+O	X	—	X	X
Track[b]	—	A2B	AB	AB
SR05	X	X	X	X[c]
SR2	X	X	X	X[c]
SR5	X	X	X	X[c]
E30m	X	—	—	—
L30m	X	—	—	—
IN001	X	—	—	—
IN100	X	—	—	—
CN200	X	—	—	—
CN800	X	—	—	—

[a] YSU cases used the YSU PBL scheme instead of the MYJ scheme. N+O were seeding cases with new and original generators (see Fig. 7). Track indicated whether a new or alternative flight track was used in the test. SR05, SR2, and SR5 were cases with 0.5, 2, and 5 times the original seeding rates, respectively. E30m and L30m were cases in which seeding occurred 30 min earlier and later than the original starting time, respectively. IN001 and IN100 were cases with 1% of and 100 times the background IN concentrations, respectively. CN200 and CN800 were cases with cloud droplet concentrations of 200 and 800 cm^{-3}, respectively.

[b] For the 1202_PAY case, A2B was tested instead of A4B. For the 1219_EID and 0216_EID cases, the northern group of ground generators was replaced by an imaginary flight track (see Fig. 7).

[c] The 0216_EID seeding-rate cases were tested for the airborne-seeding scenario.

Table 3.5.2 Simulated precipitation changes due to seeding for the sensitivity experiments listed in Table 3.5.1 (af = acre ft).

Case	Domain (af)	Domain (%)	Basin (af)	Basin (%)	Target (af)	Target (%)
			1127_PAY			
BASE	682	0.24	281	0.12	282	2.06
YSU	614	0.21	293	0.13	273	1.96
N+O	807	0.28	384	0.17	341	2.49
SR05	448	0.16	175	0.08	178	1.30
SR2	977	0.34	416	0.18	421	3.07
SR5	1463	0.51	651	0.28	652	4.75
E30m	705	0.25	267	0.12	306	2.23
L30m	635	0.22	274	0.12	257	1.87
IN001	713	0.25	288	0.13	289	2.11
IN100	523	0.18	205	0.09	235	1.70
CN200	737	0.26	324	0.14	311	2.27
CN800	900	0.32	446	0.20	389	2.85
			1202_PAY			
BASE	805	0.29	385	0.22	392	2.89
YSU	836	0.30	376	0.22	399	2.91
A2B	425	0.16	305	0.18	206	1.52
SR05	611	0.22	273	0.16	290	2.14
SR2	1002	0.37	493	0.29	494	3.64
SR5	1257	0.46	625	0.36	606	4.47
			1219_EID			
BASE	6330	0.41	1023	0.11	1044	0.39
YSU	2674	0.17	241	0.03	239	0.09
N+O	6935	0.44	1219	0.14	1098	0.41
AB	4961	0.32	1051	0.12	992	0.37
SR05	4335	0.28	850	0.09	796	0.30
SR2	9388	0.60	1855	0.21	1742	0.65
SR5	13 481	0.86	2630	0.29	2477	0.92
			0216_EID			
BASE	451	0.08	64	0.02	68	0.04
YSU	217	0.04	8	0.00	12	0.01
N+O	544	0.10	83	0.03	106	0.06
AB	544	0.10	209	0.08	201	0.11
ABSR05	366	0.06	149	0.05	140	0.08
ABSR2	698	0.12	249	0.09	256	0.15
ABSR5	932	0.17	318	0.11	321	0.18

Another interesting result was that by increasing the cloud droplet concentration to 800 cc^{-1}, which simulates a heavy pollution influence, the cloud seeding could not overcome the reduction in the natural precipitation from the pollution. When the droplet concentration was increased to only 200 cc^{-1}, the seeding compensated for the reduced natural precipitation as indicated by Givati and Rosenfeld (2004).

These modeling studies indicate that the seeding impacts are small, mainly in response to the small volume of cloud seeded, the dominate growth mechanism being diffusional growth, and the small residence time of the crystals in cloud, especially from ground-based generators. The relative increases for the four baseline experiments are shown in Figure 3.30.

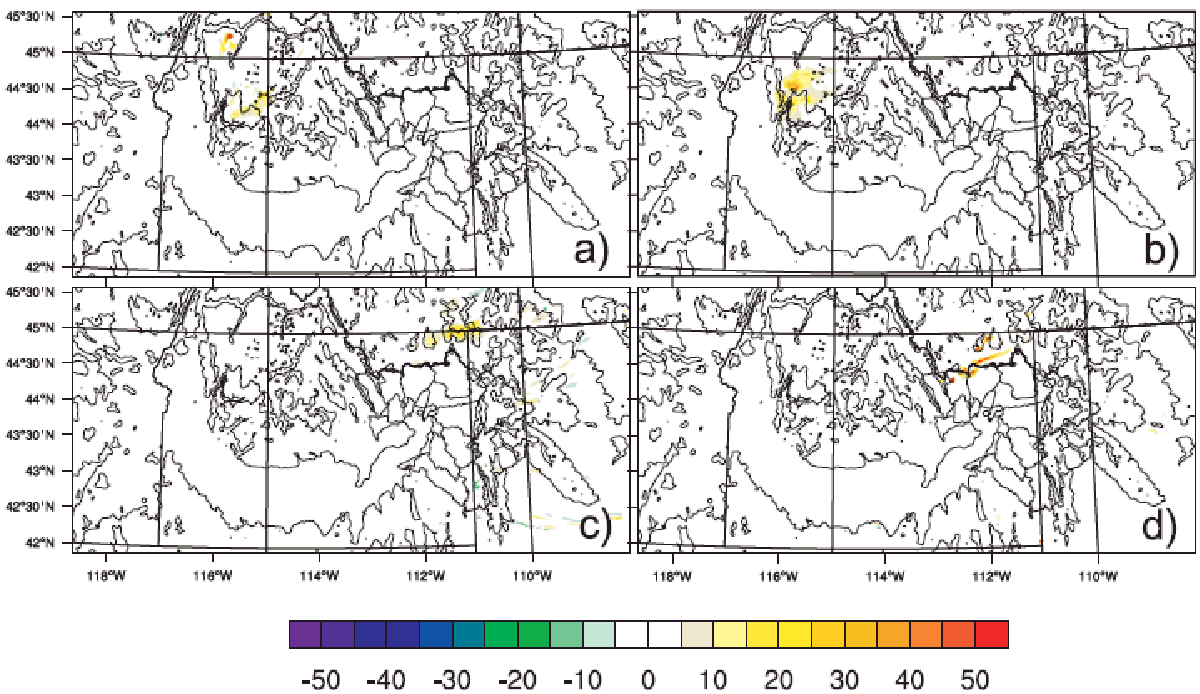


Figure 3.30 The local relative precipitation difference (%) between seeding cases and control cases at the end of simulations for (a) 1127_PAY, (b) 1202_PAY, (c) 1219_EID, and (d) 0216_EID.

Similar modeling studies were run for a case from the WWMPP using various resolutions of the WRF LES (Chu et al. 2014). The modeling domain is shown in Figure 3.31. The purpose of this study was two-fold. First was to validate the model using in-situ observations of thermodynamic and kinematic fields. There are differences in the model fields versus what was observed using even the highest model simulation of 100m. These differences could be significant when attempting to emulate the effects of seeding. These include slight differences in wind speed and direction, cloud moisture, cloud base height, and storm dissipation rate. Figure 3.32 compares observations from the ground-based radiometer scanning to the east and southeast at 9^{o} elevation from its location upwind of the MB range with model simulations along these slant paths. One can see that the model underestimates by a substantial amount the LWP. The second focus of this paper was to simulate the vertical profile of reflectivity from the Wyoming King Air as reported by Geertz and reviewed in Section 3.3. The simulation of the vertical reflectivity profile and the simulation of the effect of seeding on this profile were discussed. Qualitatively the model simulation of the seeded case matched with the observations. The seeding signal is weak an accounted for only .8 dBZ difference between the seeded and control run. The natural variability both in nature and in the model depiction showing a decrease in clouds and natural precipitation during the seeding portion of the simulation dwarfed the effects of seeding. This case points out the fact that in a general sense, the very high resolution LES model run can emulate the general conditions of a shallow orographic cloud formed over complex terrain. It provides useful information on the mechanisms that disperse the seeding agent into the clouds and can represent the general microphysical processes. However the specific details that would impact the specific seeding event can be sufficiently inexact as to misrepresent the targeting, the crystal growth properties and the fallout of the seeded crystals. Given these limitations, there is really no question that the seeding impacts are very small and difficult to differentiate from the natural variability both in the real world and the model simulations (Figure 3.33 and Figure 3.34 for the 100m LES) .

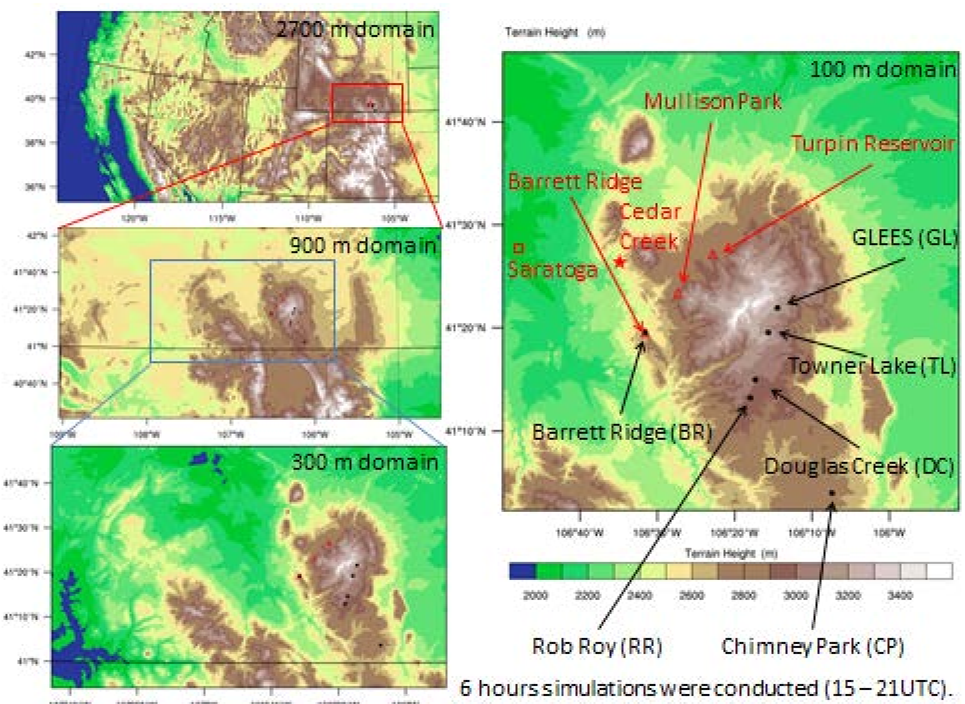


Figure 3.31 WRF Model outer and nested domains for the WWMPP simulations of AgI seeding impacts.

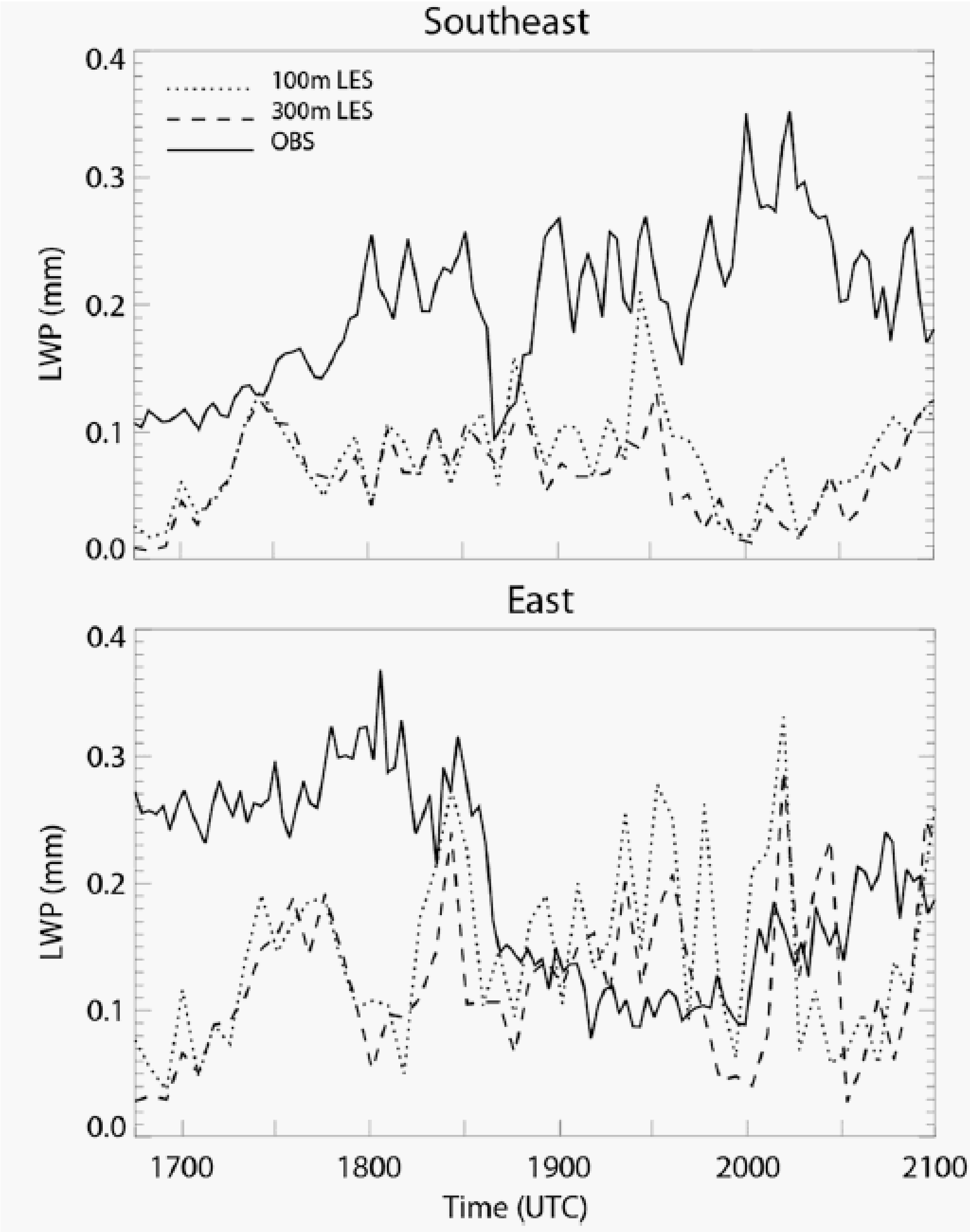
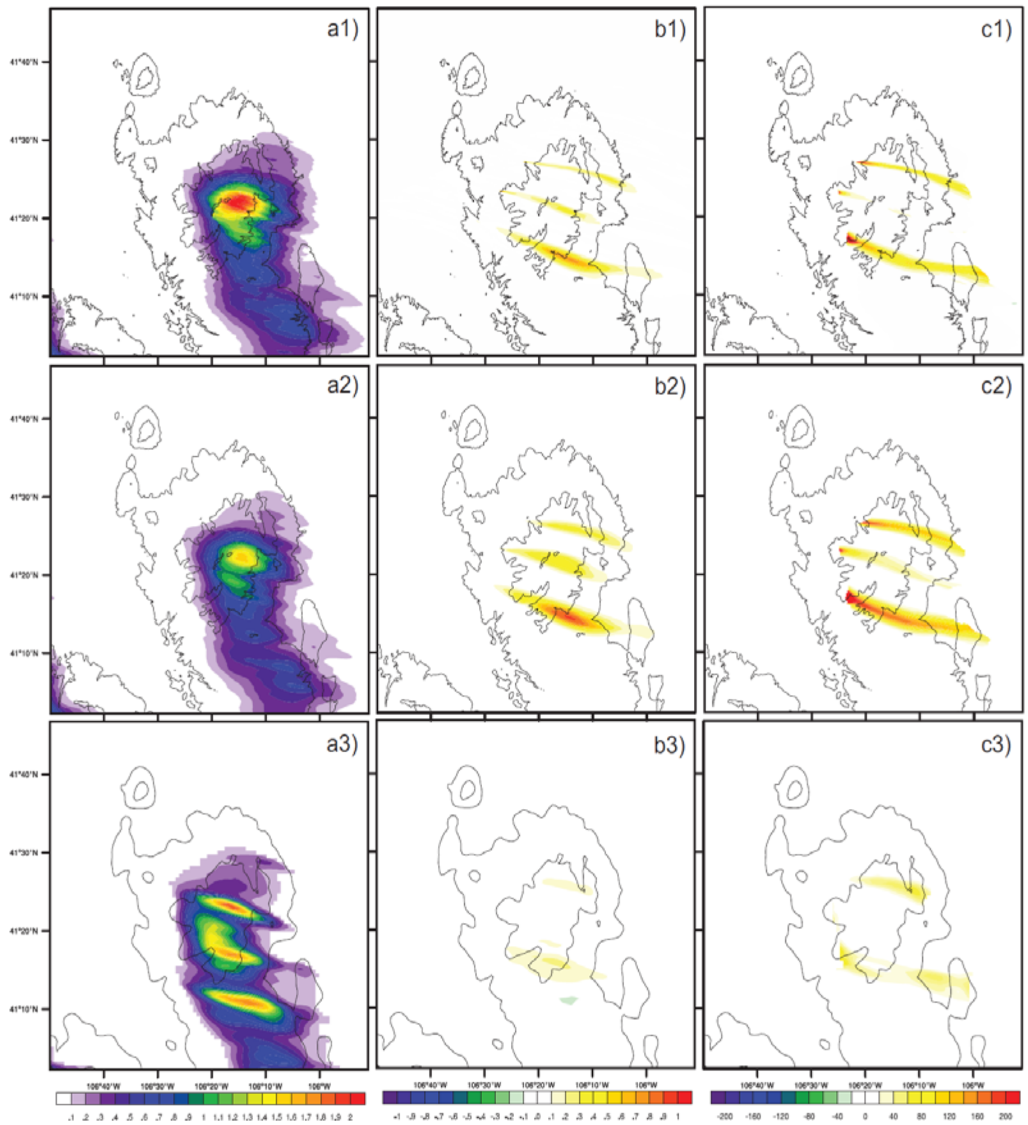


Figure 3.32 LWP trend as observed by the radiometer and as simulated by the 300- and 100-m WRF LES.



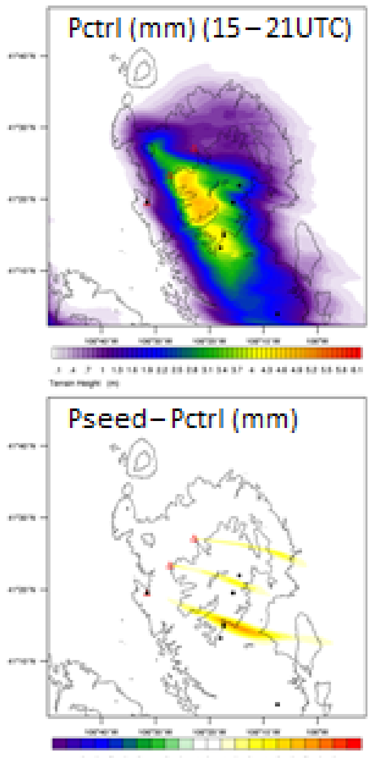
100-m LES simulated precipitation, seeding effect and relative seeding effect

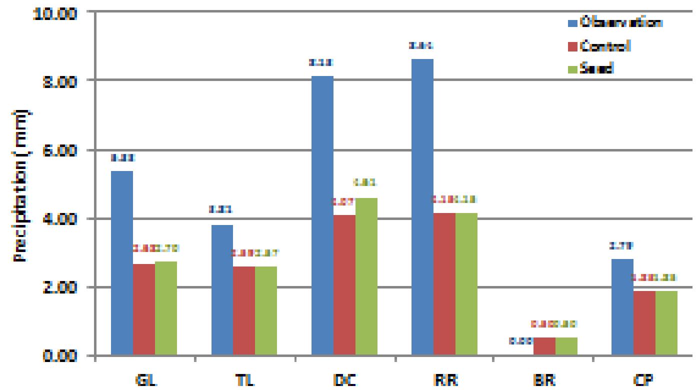
300-m LES simulated precipitation, seeding effect and relative seeding effect

900-m non-LES precipitation, seeding effect and relative seeding effect

Figure 3.33 WRF model 6-hr simulations at various resolutions showing the model simulated precipitation, the additional precipitation from seeding, and the relative difference.

Precipitation and seeding effect





100 m precip. comparisons

Site	Delta Precp. (%)
GL	0.75
TL	-0.77
DC	13.27
RR	0.00
BR	0.00
CP	0.00

Figure 3.34 100m WRF with LES simulation showing details for individual sampling points within the target area. Note that for a 6-hr simulation the area showing seeding effects is quite limited. (Courtesy Rasmussen (2014).

3.4.2 Modeling and Observations over the Tahoe Truckee and Walker River Basins in Nevada

This study was conducted by the Desert Research Institute as part of the Bureau of Reclamations' Weather Damage Modification Program carried out using FY 2002 and 2003 funding. The Nevada studies had five main focus areas. 1) Frequency, duration and distribution of SLW over and downwind of the Sierra Nevada and compare this to mesoscale model results. 2) Conduct model simulations of the transport and dispersion of ground-based aerosol releases and evaluate the appropriateness of generator locations used in the Nevada operational program. 3) Trace chemistry analysis within the Nevada seeding target areas to evaluate the effectiveness of targeting and determine possible impacts of targeting through snow sampling. 4) set up a hydrologic modeling system to evaluate the increased runoff possible from seeding. 5) collect airborne microphysics to document natural cloud seedabilty, provide verification to modeling studies, and evaluate airborne or ground based seeding plumes. The complete project is reported on in Huggins (2005). A brief review of just some of the results is presented here.

3.4.2.1 Modeling studies of transport and dispersion

The model used by DRI was the MM5, a precursor to the WRF model. A 1 km nest was centered over the Tahoe basin. A Lagrangian random particle dispersion model (LAP) developed by DRI was used to model the transport and dispersion of seeding aerosol in complex terrain. LAP can track multiple seeding sources which make it very useful for simulating the coverage of a target area from ground-based seeding as well as simulating aerial seeding lines. For the Tahoe and Walker Basins, four to six point sources were used using 27 grams/hr AgI release rates. Several cases were simulated. One was for a case in December 1996 and another well-documented SCPP case in December1986. The third case was for a case in February 2004 for the Walker basin. The first case simulated the transport and dispersion of 6 generators operated by the Sacramento Municipal Utility District (SMUD). The SMUD target area is the windward side of the Sierra just south of Lake Tahoe. However modeling studies indicated that the seeding plumes were more effective at seeding the Tahoe basin due to low level south to southwest winds then the SMUD target area. This is a similar result to what was reported by Reynolds et al (1988). By the time the plumes reached the Tahoe basin, the plumes are merged and were well dispersed given the strong vertical motions to the lee of the main Sierra Nevada crest. This implies unintentional downwind effects from the SMUD seeding and emulates what was observed in the Wyoming project where the Sierra Madre generators seeded the Medicine Bows.

The second SCPP case was for several days in December 1986 indicating that the higher elevation generator sites of the Nevada program located on the windward side of the Sierra and generators operated by PGE in the Mokolume were passing mostly to the north of the Tahoe basin. These results were similar to Reynolds (1988) indicating the southerly barrier jet is effectively carrying seeding plumes well north of the intended locations. Silver sampling done shortly after the seeding concluded on these days showed almost all the Ag was found in snow to the north of the Tahoe basin, validating both the LAP model and the GUIDE used by SCPP.

The third case was for the Walker basin simulating seeding from both aircraft and ground based generators. Figure 3.35 is the layout of the generator locations and aerial seeding line and the location where SLW measurements were made along with snow chemistry. It should be noted that this layout is very similar to the LOREP project discussed earlier using propane seeding. It would be expected that this project would be impacted by mountain waves bringing the seeding agent from ground release quickly down into the Walker basin allowing little time for crystal growth. Given the radiometer location, it was possible for this case to compare SLW and vapor observations to the model simulated values for the 48-hr simulation. These results are shown in Figure 3.36. It is interesting to note that in this case the highest SLW came with the highest precipitation rates associated with the front that was not modeled well by MM5. It has been pointed out by Rasmussen that the microphysical parameterization is critical to handling the SLW right. Ground seeding did commence about 15z. Thus even though these were very deep cold clouds, the clouds were still inefficient given the radiometer was located near the crest indicating this water would most likely pass east and maybe be lost to subsidence. The model did fairly well in tracking the rates of precipitation for a gauge located on the windward slopes but underpredicted what fell to the lee of the crest (not shown). This is not unusual in cases where there is a very high condensate supply rate and the condensate cannot be removed quickly by subsidence so there is a great deal of carryover of precipitation into the lee of the mountain. Aircraft sampling for this case also showed an underestimate of the SLW both over the crest and downwind of the crest out to 35 km east of the crest. Again the condensate supply was large enough that subsidence was not able to deplete the SLW until many km downstream of the crest. This phenomena was observed in a few cases for the WWMPP.

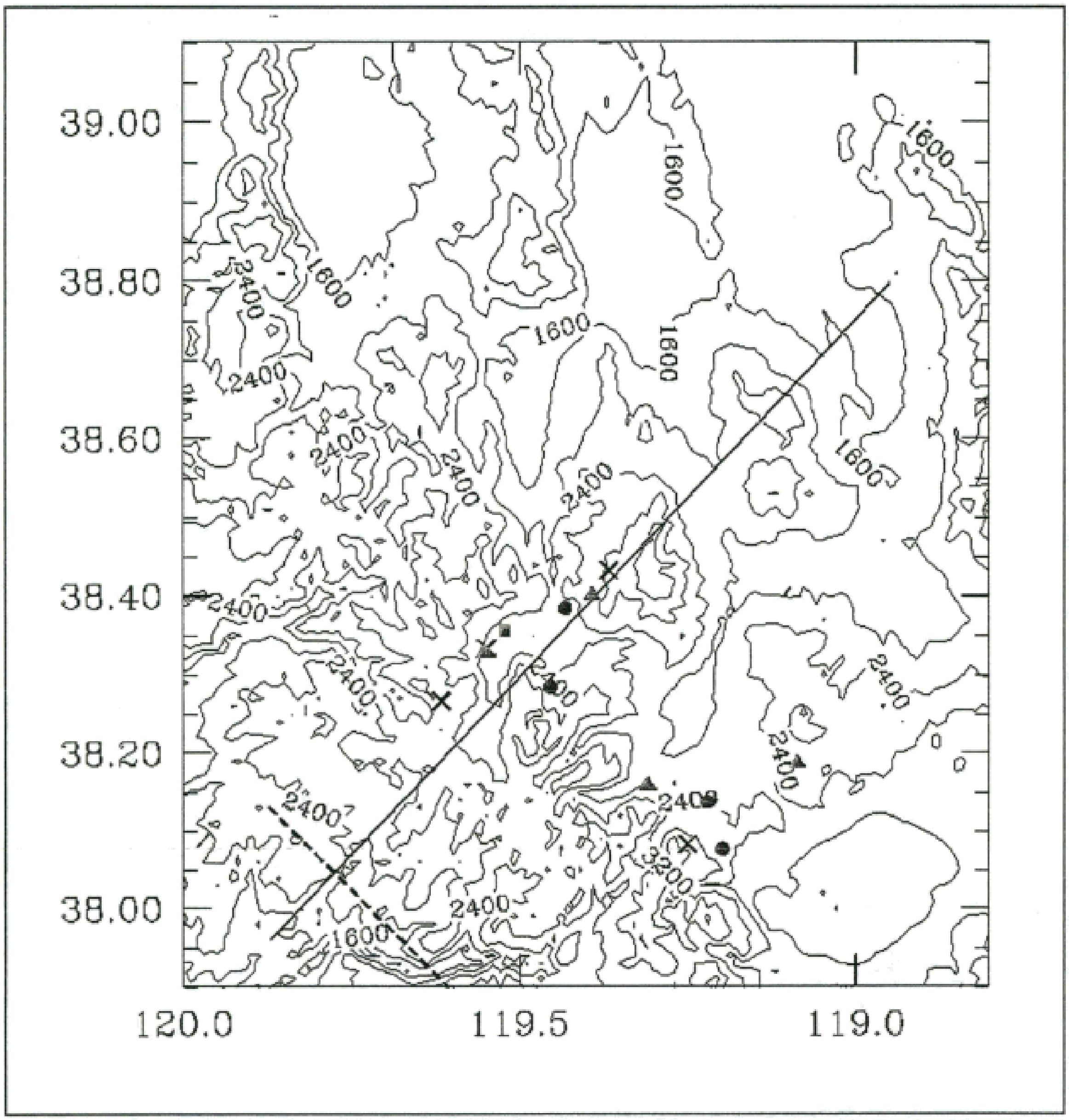


Figure 3.35 Walker basin seeding experiment for 2004 showing locations of ground generators (circles), snow sampling sites (triangles) for trace chemistry, SNOTEL sites (X's, and radiometer site (square). Aircraft seeding track for this case is dashed line. Black line is location of model cross-sections but none will be shown.

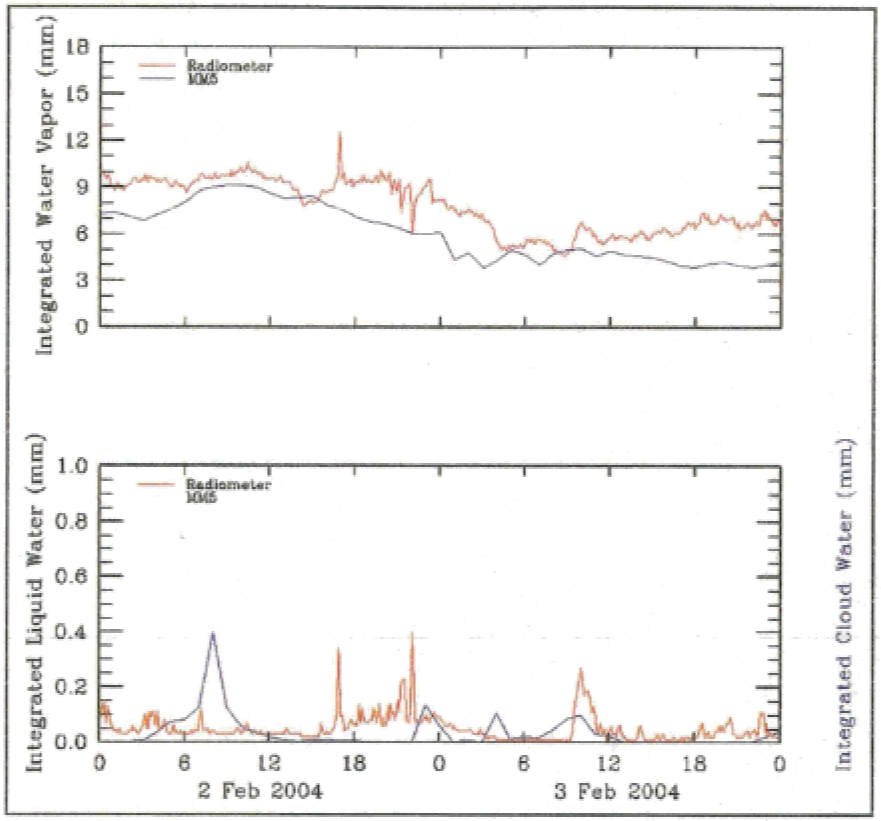


Figure 3.36 Top panel is integrated water vapor from radiometer (orange) and bottom is SLW with same color scheme. AgI generators were activated at 15z. Front passed about 23z.

LAP plume traces showed a complicated mix of plume trajectories based on generator elevation and time relative to frontal passage. Plumes were shown to be caught up in the mountain waves and vertically dispersed while at other times plumes would be channeled away from the Walker target area and down into valleys. Given the proximity of the generators to the crest these results are again not surprising based on the experience in the LOREP reported by Reynolds (1995).

LAP was also able to simulate aerial seeding along the path shown in Figure 3.34. The seeded volume is depicted after various legs have been flown. The southern end of the lines just passed over the two northern trace chemistry sites.

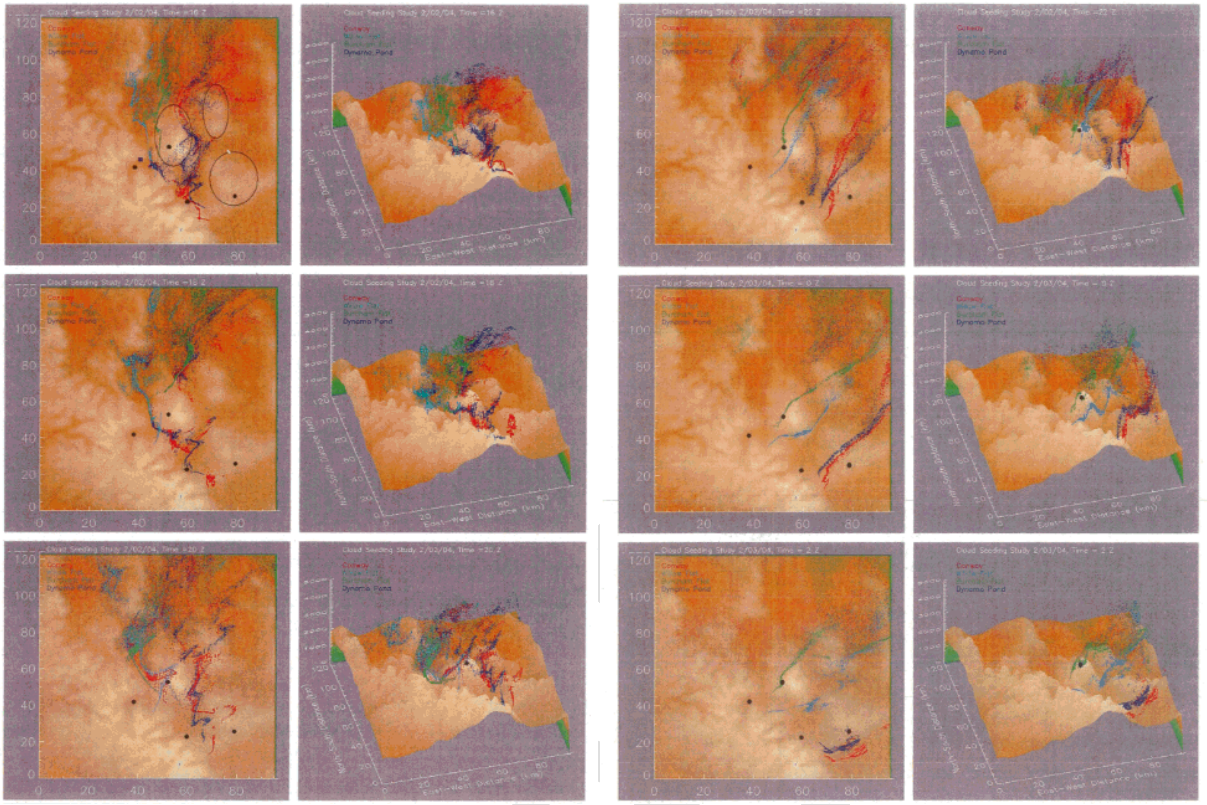


Figure 3.37 Left is LAP plan view and perspectives view of seeding plumes for 2 Feb for 4 ground generators for 16, 18 and 20z. Upper right shows circles indicating target areas within the Walker basin. Black circle are trace chemistry sites. On right is same but for 22z 2 Feb and 00 and 02z 3 Feb.

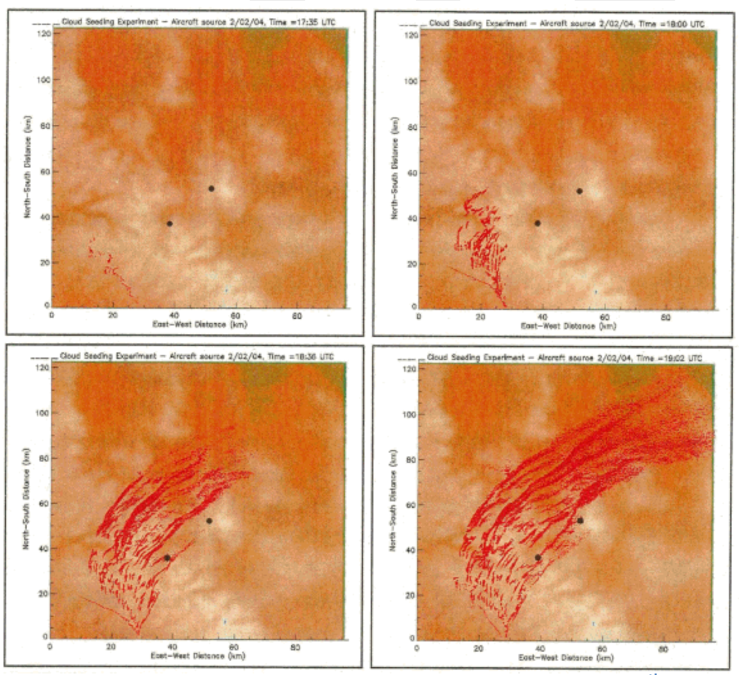


Figure 3.38 Aerial seed lines shown after the first leg, upper left, 4th leg upper right, 8th leg lower left and 11th leg lower right. Seeded volume passes over the two northern trace chemistry sites but most of seeded volume moves north of these.

3.4.2.2 Trace chemistry results

The trace chemistry sampling used the same methodology as has been used in other projects including the Snowy Mountain and WWMPP seeding programs. Thus it will not be described in detail here other than to say other trace chemicals were sampled to assure dust and other contaminates may not have compromised the silver sampling. No inert trace gas was released to determine whether Ag in the snow came from nucleation or scavenging. Samples were done periodically after seeding cases but not in real-time. There was an effort to try to tag the individual seeding samples by depth to individual events and to determine if the snow density may have been impacted. However this proved to be very difficult given rapidly changing snowpack conditions. The sampling results for the 4 sample sites in the Tahoe Basin are show in in Table 3.6. These percentages are very high and indicate that for all but one site Ag plumes are passing over the target area indicating at least good directional targeting. One cannot say exactly how much of the Ag came from the Nevada generators or the SMUD generators to the south and west of Tahoe.

Table 3.6 Trace chemistry for 4 sampling sites in Tahoe basin target area for 2003-04. Key parameter is % Ag above 10 ppt.

	TMDW	PLTO	CSSL	SGHC
Samples	94	70	46	38
Mass (gm)	116.4	119.7	37.6	79.6
Density	0.29	0.30	0.15	0.20
Al (PPT/500)	22.6	36.5	25.0	11.0
Ag (PPT)	30.0	36.2	14.5	11.8
% Ag ≥10 PPT	87.5	100	71.1	27.8
In (PPT)	2.8	4.4	0.7	0.2
Cs (PPT)	2.3	3.3	9.5	2.9
Rb (PPT)	-	-	-	25.7

For the Walker basin the results are shown in Table 3.7. There is some indication of contamination in the samples given the high Al concentrations, especially at the LEAV site. However there does appear to be strong indications of effective targeting of the basin by ground and aerial seeding.

Additional trace chemistry was conducted during 2004-5 winter but only at two sites in the Tahoe-Truckee basin. The results show less effective targeting but still well above what was reported on from studies done in the 80s. Again these results do not indicate the efficacy of the seeding on snowpack but do at least indicate that the silver is getting into the snowpack from seeding whether by nucleation or scavenging.

Table 3.7 Same as 3.6 but for the Walker basin sampling sites for 2003-04.

	TWIN	LEAV	BODI	LBLK
Samples	37	44	13	19
Mass (gm)	117.0	102.9	145.2	107.3
Density	0.28	0.23	0.34	0.21
Al PPT/500	24.5	47.6	10.7	4.3
Ag PPT	33.8	62.4	28.7	18.9
% Ag ≥10 PPT	100	100	100	89.5
In PPT	3.5	7.2	0.2	1.1
Cs PPT	6.1	4.7	4.1	2.6
Rb PPT/10	31.6	30.0	48.8	28.7

Table 3.8 2004-5 trace chemistry results for two sites in the Tahoe basin.

	TMDW	PLTO
Samples	59	59
Snow Density	0.36	0.37
Ag (PPT)	9.7	13.8
In (PPT)	0.02	0.00
Cs (PPT)	10.1	9.5
Rb (PPT/10)	14.6	7.0
% Ag ≥10 PPT	34.0	52.5

3.4.2.3 Radiometer studies in Walker basin

As noted earlier a scanning radiometer was located above the Walker basin along the crest of the Sierra Nevada during December 2003 through March 2004. It is useful just to note the climatology of SLW occurrence although these numbers do not indicate all hours would be seedable given temperatures, wind direction etc. These results are shown in Table 3.9. On average only about half or less of the hours were actually seeded due to either criteria out of bounds or missed forecasts.

Table 3.9 Radiometer statistics for the Walker Basin for Dec-Mar 2003-04. A storm is defined as any precipitation observed in the Walker basin. Both values of .05 mm and .005 mm have been used in winter cloud seeding programs using radiometers to identify the presence of SLW and deemed sufficient to initiate seeding.

Month	Total Storm Hours	Hours of LW ≥ 0.025 mm	% of Hours ≥ 0.025 mm	Hours of LW ≥ 0.05 mm	% of Hours ≥ 0.05 mm
Dec 2003	395.6	322.5	82.0	209.5	53.0
Jan 2004	264.7	146.0	55.2	83.4	31.5
Feb 2004	326.9	293.8	89.9	217.2	66.4
Mar 2004	192.0	167.9	87.5	58.9	30.7

3.4.2.4 Hydrologic modeling studies

The Precipitation Runoff Modeling System (PRMS) was adapted for use in this study. The model was setup for the entire Walker basin and the basin was divided into hydrologic response units (HSU). The effects of cloud seeding were simulated by choosing those units considered to be most impacted by the seeding based on tracer and modeling studies. Two cases were run for the 2004 water year, one with no seeding, and the other assuming a 10% increase in 5 of the HSUs. The results indicated that the additional water added to evaporation and runoff but had little impact on soil moisture and ground water. The added precipitation that went into the streamflow increased runoff from 49% to 89% in the five different HSUs. It was stated that there is a large uncertainty in these results.

4.0 Statistical Analyses of Non-randomized Operational Seeding Programs

4.1 Introduction

The historical regression method, used with target and control area measurements, has long been employed in evaluation of cloud seeding projects intended to increase precipitation. Measurements of seasonal snow accumulation, rainfall or streamflow are compared between the intended target area and upwind and crosswind locations (control areas) unlikely to be affected by the seeding. Several non-seeded seasons are needed to establish a historical relationship by linear regression analysis. Control area observations during seeded seasons are used with this relationship to predict expected target area amounts in the absence of seeding. Departures from these predictions are examined for evidence of cloud seeding effectiveness. It is generally assumed that the stronger the target-control relationship, the more successful the method can be in detecting relatively small departures possibly caused by seeding. A linear correlation coefficient (R-value) is typically calculated to express the degree of relationship, or association, between target and control station means, while R^2 is considered the variance explained.

Dennis (1980) discussed the historical regression method in detail, pointing out possible sources of uncontrolled variance and bias. Dennis (1980) also warned that the most serious difficulty with the historical regression method has to do with the lack of stability of the target-control relationship. One cannot eliminate bias if the controls used in the analysis are chosen after the seeding has occurred. This is why the scientific community has required a-priori selection of target and control areas prior to seeding commencing and strongly encourages randomization and single or double-blind studies so the analysts are not aware of the seeding decisions until after the statistical analysis is complete. In the policy statements referenced in Section 1 of this report, it was emphasized that any statistical results of seeding efficacy must be combined with detailed physical studies to validate the statistics. Most operational projects do not employ rigorous physical studies or randomization as these are costly and reduce the amount of seeding that takes place during a given season. Thus, any results of operational projects that show a strong statistical signal, low p-values, should be considered only suggestive of a seeding impact.

Gabriel and Petrondas (1983) also point out that the validity of the statistical inferences based on the historical regression method depends on two assumptions: (1) all differences between the historical and operational periods are due to either the effect of seeding or to random year-to-year variation and there are no other effects confounded with these differences, and (2) the variability of streamflow between the two periods behaves like variability of two independent random samples of years. These assumptions are highly suspect for streamflow data that are subject to some year-to-year dependence, cycles, and/or trends, especially since there are no exact models of this behavior available.

4.2 Historical Evaluation of 11 Operational Winter Seeding Programs in California

To try and minimize these limitations and produce more meaningful statistics, Gabriel (1999) described a technique called regression ratios. This technique has been applied by Silverman (2007) in the evaluation of several operational non-randomized cloud seeding projects in the west (Silverman 2010). The key to the use of this statistic is the requirement for a well suited control that has a high correlation coefficient and explains a significant amount of the variance between the target and control. Also, a long record prior to seeding as well as a long period of seeded years to compute the historical relationship is required. The regression ratio (RR) is given by the relationship, RR = SR / SRPRED where the single ratio (SR) is the ratio of the average target streamflow during the operational seeding period (TSO) to the average streamflow for the seeding target during the historical period (TSH), i.e., SR=TSO/TSH , and SRPRED is the SR as predicted by the target-control regression relationship. By dividing the SR by SRPRED, SR is adjusted for effects due to natural differences in streamflow between the target and control and, by taking advantage of the high correlation between the target and control streamflows over the entire period of analysis (including both the historical and operational periods), the variance of the regression ratio is reduced with respect to the variance of the single ratio for the target station only. This enables the detection of smaller effects due to seeding with greater probability. A least-squares linear regression is used for the prediction of the specific target stream gauge(s) utilizing the selected control site(s). The RR is biased corrected to try to minimize the bias associated with *a posteriori* evaluations. This is accomplished by doubling the computed P-value as suggested by Gabriel and Petrondas (1983).

Silverman (2010) utilized a Monte Carlo non-parametric permutation method (10,000 re-randomizations) to obtain confidence intervals. Nicholls (2001) points out that in an exploratory hypothesis testing, the significance of the difference in sample means provides little useful information. Confidence intervals provide much more useful information on the strength of the signal and are the motivation for Silverman to focus on the two-tailed confidence interval so one can evaluate its economic impact. A project is considered to have a statistically significant result if the 90% confidence interval (two sided test) does not include the null hypothesis, i.e. 0 or less. The 11 projects evaluated are shown in Figure 44.1. Table 4.1 lists the project watershed, the sponsor, the operator, and the year seeding began. The parameter used for the target and control is the observed or calculated water-year Full Natural Flow or FNF. There were found 6 control sites that were determined by Silverman not to be impacted by seeding but in close enough proximity to be highly correlated with the target (R values of >.9). One and possibly two control sites were used as predictors for the target site in the RR evaluation. Silverman (2011) emphasizes that these results should be viewed as exploratory and used with caution since these are *a posteriori* evaluations of non-randomized seeding projects. Thus,, the results are only suggestive of a possible seeding effect and require a fully randomized statistical evaluation with strong physical studies to validate the statistics.

The Silverman (2010) results our shown in Table 4.2. He notes that the only statistically significant results are for projects located on the windward side of the Sierra. No projects that are located on the eastern side of the Sierra suggested seeding impacts annual stream flows. Note that a majority of these projects augmented ground based seeding with aerial seeding. However of the 6 projects with positive seeding indications, two were ground-based only, two were aerial seeding only and two were a mixture. Thus, it is somewhat inconclusive as to the benefits of aerial versus ground-based seeding to augment annual stream flow. The general conclusion is that there is a suggestion of a ~5% increase in average annual stream flow where a seeding impact was implied. This translates to various amounts of runoff depending on the seasonal FNF for that watershed. For those showing positive impacts from seeding, the estimated runoff increase assuming a 5% annual increase are: Kern – 32k ac-ft, Kings – 8k ac-ft, San Joaquin – 3.6k ac-ft, Toulomne – 37k ac-ft, Upper American - 8k ac-ft, and Lake Almanor – 10.5k ac-ft. Note that the Kern and Toulumne are both aerial seeding only and have a factor of ten higher estimated seeding impact on runoff. It is also noteworthy that the Kaweah basin, located between the Kings and Kern, shows no impact from aerial seeding. It is not clear why this is given the same contractor seeded using the same aerial seeding methodology for both the Kings, Kern, and Kaweah target areas. This does highlight that these results are only suggestive of possible seeding impacts and further evaluations are necessary.

Figure 4.1 Map of California showing the watersheds of the Sierra Nevada Mountains that are subject to operational seeding programs. Map Scale 1 cm=80km. From Silverman (2011).

Table 4.1 – Sierra operational cloud seeding programs

Sierra watershed	Sponsor	Seeding operator(s)	WY start seeding
Sierra Southwest			
Kern	North Kern Water Storage District (NKWSD)	AI, RHS	1977
Kaweah	Kaweah Delta Water Conservation District (KDWCD)	AI	1976
Kings	Kings River Conservation District (KRCD)	AI, NAWC	1955
San Joaquin	Southern California Edison (SCE)	NAWC, AI, RHS	1951
Sierra Northwest			
Tuolumne	Turlock and Modesto Irrigation Districts (TID & MID)	AI, WMI	1991
Upper Mokelumne	Pacific Gas & Electric (PG&E)	PG&E	1954
Upper American	Sacramento Municipal Utility District (SMUD)	SMUD	1969
Lake Almanor	Pacific Gas & Electric (PG&E)	PG&E	1954
Sierra East			
Eastern Sierra	Los Angeles Department of Water & Power (LADWP)	AI	1987
Carson–Walker	Desert Research Institute (DRI)	DRI	1980
Tahoe-Truckee	Desert Research Institute (DRI)	DRI	1978

AI = Atmospherics Inc.; NAWC = North American Weather Consultants; RHS = RHS Consulting; WMI = Weather Modification Inc.

Table 4.2 – Summary of the statistically significant results of the evolution of the Sierra operational cloud seeding programs.

Sierra watershed	Seed mode	N_T	N_{SS}	90% confidence interval
	(1)	(2)	(3)	(4)
Sierra Southwest				
Kern	A	3	3	KRK(2.4, 12.9); KRI(5.3, 15.2); KRB(3.0, 10.9)
Kaweah	A	1	0	None
Kings	G+A	3	3	KGC(0.0, 7.5); KGP(2.2, 9.2); KGF(1.3, 6.6)
San Joaquin	G+A	4	2	MNO(2.1, 8.9); PIT(1.5, 9.4)
Tuolumne	A	2	1	THH(2.4, 7.5)
Sierra Northwest				
Upper Mokelumne	G	2	0	None
Upper American	G	7	4	ALO(5.6, 11.9); AUO(2.7, 8.6); ABO(8.8, 24.4); ASO(1.8, 7.9)
Lake Almanor	G	4	2	FTP(2.5, 12.6); FTO(2.3, 7.0)
Sierra East				
Eastern Sierra	A	4	0	None
Carson–Walker	G+A	3	0	None (5)
Tahoe-Truckee	G+A	1	0	None

(1) Seed mode: G = ground-based seeding; A = aircraft seeding.
(2) N_T = number of target sub-basins evaluated.
(3) N_{SS} = number of target sub-basins having a statistically significant seeding effect.
(4) 90% confidence interval = 90% confidence interval for target sub-basins having a statistically significant seeding effect; XXX(LB,UB) where XXX is the target station code, LB is the lower bound (%) and UB is the upper bound (%).
(5) There was evidence of a seeding effect at WWR(1.5, 8.3) but it was apparently due to contamination from an upwind seeding program.

4.3 Historical Evaluation of the Vail Colorado Operational Seeding Program

It should be noted that Silverman did a similar analysis for the Vail ski area cloud seeding program for the period 1977 through 2005. The historical record for 8 stream gauges providing annual FNFs within the target area dates back from 1948 to 1967. Correlation coefficients between the target gauges and the "Best" control site were .775. This was significantly lower than observed for the Sierra target and controls used. Figure4.2 is a map of the Vail area showing the target areas, the generator locations, the target gauges within the white outlined area and the control used, FRR, to the south of the generators. The results of his analysis are shown in Figure 4.3. For those gauges showing a statistically significant result, the cumulative annual runoff increase is 9,497 ac-ft or about 15% increase for the entire target area.

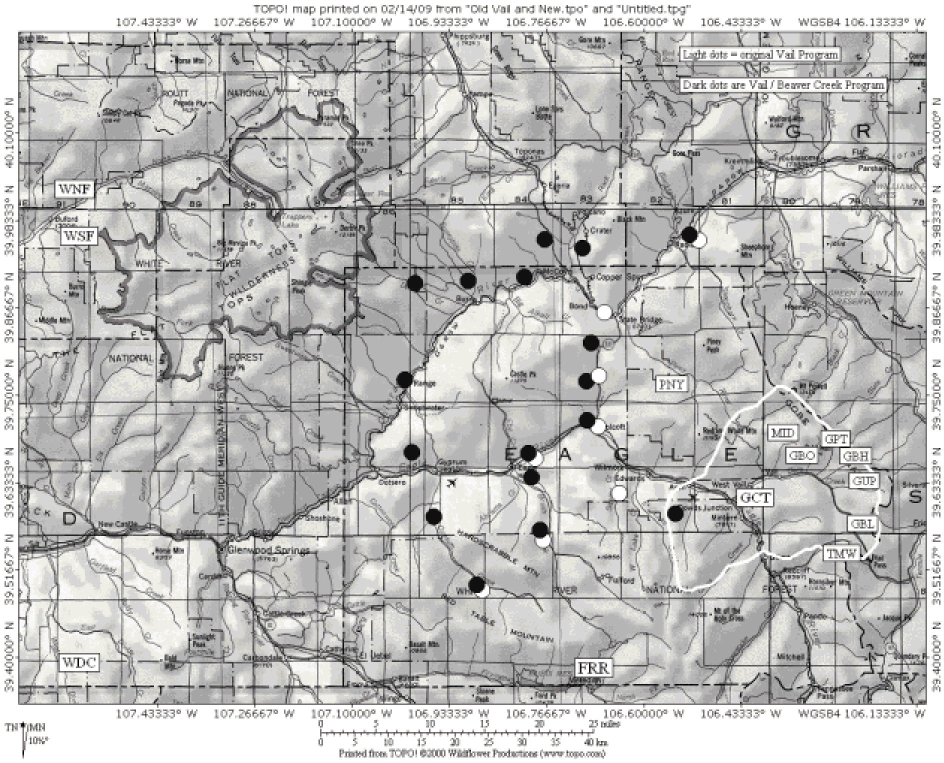


Figure 4.2 Map of the Vail region showing the location of all the targets and controls, and the location of the ground generators used for the original Vail program 9Blanl circles) and for the Vail-Beaver Creek program (shaded circles). The white "circle' encompassing the target stations is the intended target area.

DRAFT

Table 4.3 Vail statistical results showing seeding increase, lower and upper confidence interval and P value for snow gauges within the target area.

Target	δ	CI90L	CI90U	ρ
PNY	**+6.3**	**+0.4**	**+12.5**	0.910
GBO	**+9.3**	**+1.1**	**+18.1**	0.836
MID	+7.9	-0.2	+16.7	0.909
GPT	**+18.5**	**+7.3**	**+30.9**	0.812
GBH	**+28.8**	**+16.6**	**+42.2**	0.775
GUP	**+11.1**	**+4.7**	**+18.0**	0.837
GBL	+4.6	-0.6	+10.1	0.918
TMW	-2.0	-11.5	+8.3	0.871

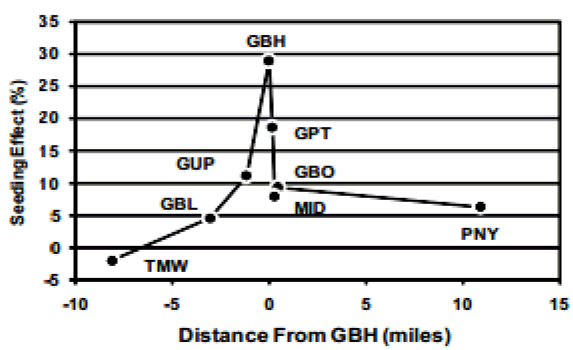


Figure 4.3 Graphical plot of seeding increases showing effects are focused on the center of the target area.

5.0 Summary and Conclusions

In Section 1.3 the key uncertainties as outlined in Table 1.1 were reviewed based on the information presented in Section 1. We will review these uncertainties again after having reviewed the most recent research as provided in Sections 2 through 4, all post NRC 2003. The key questions will be addressed again providing what could be considered the "state of the science" as of this writing (references not repeated here). Table 1.1 is repeated here but with an additional category noting whether there has been an increase in understanding and reduced uncertainty with regard to the key question being addressed. These subjective categories are rated with a score of 1 to 5 with 1 indicating little increase in understanding in the science or reduction in uncertainty to 5 being a significant increase in understanding or improvement in the science and reduction in the level of uncertainty.

	Winter Orographic Cloud Seeding: Key Questions/Uncertainties	**NRCS 2003 Box 2.2 Reference**	**Change since NRC 2003**
1	**Favorable and Unfavorable Seeding Conditions**		
A	What are the location, duration and degree of supercooling of cloud liquid water?	**1A-E 2B**	**4**
B	Are their man-made pollutants or natural aerosols/particulates impacting the target clouds that could modify the cloud droplet spectra/IN concentrations to impede seeding effectiveness?	**1A**	**2**
C	Are their significant enough differences in maritime influenced winter orographic clouds versus continental orographic clouds that strongly influence the natural precipitation process?	**1B 1C 1D 1E**	**2**
D	Are there numerical models that can be run in real-time utilizing project filed observations to guide seeding decision making?	**3C 3D 4D**	**5**
E	If seeding occurs during unfavorable conditions i.e. insufficient SLW, inappropriate temperatures for the seeding agent, or improper targeting, are there unintended impacts in the target area or extended areas?	**3F**	**3**
2	**Seeding Delivery Methodology**		
A	What is the best seeding agent to use based on (1A) and what is the best way to deliver the seeding agent?	**1B 3D 4E**	**4**
B	What is the necessary density and location of ground-based dispensers and what is the dependency on seeding agent used?	**3D 3G**	**4**
C	What are the performance characteristics necessary for aerial seeding and to what extent can we determine number of aircraft needed to impact the total target watershed?	**4A**	**3**
3	**Targeting**		
A	What observing systems are needed and at what spatial and temporal frequency to adequately target seeding impact	**3C 4A**	**4**
B	What are the observing systems, either in-situ or remote sensing, that can observe and track a seeding plume from initiation to fallout? What are the benefits and limitations of each?	**4C 4B**	**3**

	Winter Orographic Cloud Seeding: Key Questions/Uncertainties	**NRCS 2003 Box 2.2 Reference**	**Change since NRC 2003**
4	**Quantifying Seeding Impacts on Precipitation over a Target Area**		
A	What is the resolution and spacing required of recording snow gauges within the intended target area and downwind target area?	**3G 4B**	**4**
B	If silver iodide is the seeding agent, what are the benefits and limitations of sampling the silver concentration in the snow prior to spring melt to validate that a significant portion of the winter seeding impacted the target area?	**4A**	**4**
C	What is the best design of the seeding program to reduce uncertainty and insure meaningful statistical results?	**3G**	**3**
D	What are the best statistical methods to apply to achieve statistical significance and reduce Type I and II errors?	**3G**	**2**
E	Benefits and limitations of a reanalysis of operational cloud seeding projects	**3G 4E**	**2**

5.1Developments in Understanding Key Uncertainties

5.1.1 What is the location, duration, and degree of supercooling of cloud liquid water in winter orographic clouds?

- Detailed 3-D modeling using LES simulations and very high resolution (100m) has demonstrated that SLW within orographic clouds is highly variable given slight variations in wind speed and direction within the complex flow of the boundary layer (~ lowest 1000m) over complex terrain. Each ridge and valley can be a source and sink of SLW. Modeling can help define when and where SLW may be located, but the models ability to forecast the location, amount, and duration of SLW within any given period within a winter storm is still a challenge.
- Modeling indicates that diffusional growth is the dominate growth mechanism for ground based seeding. This is certainly true for clouds modeled in the inter-mountain west. It is not clear that this would necessarily be the case for coastal mountains. It also indicates that based on the amount of seeding material getting into the clouds using current seeding rates and generator density, it is difficult to over-seed the cloud. The Snowy Mountain SPERP experiment had shown some correlation to when seeding was conducted and a reduction in radiometer SLW. However, in the follow-on three year experiment and when the entire period of seeding was combined, even though there was shown to be a statistically significant positive seeding increase, there was not a strong signal in the reduction of SLW. These results would indicate that as long as nucleation occurs by the seeding agent and the crystals remain in a slightly supersaturated environment with respect to ice, they will continue to grow until their terminal velocity overcomes the orographic lift. Thus even small amounts of SLW appear to be sufficient to produce some positive seeding increase, albeit small increases.
- Aerial seeding, both from modeling studies and observations would indicate that this is a more efficient seeding method if one is to affect a larger portion of the SLW. This better

mimics the natural precipitation process known as seeder feeder, where the nucleation occurs near the top of the cloud and crystals grow by diffusion and aggregation and fall-out on the windward slope of the barrier sweeping out the low-level SLW by riming.

- It appears that SLW can occur during almost all portions of a storm, including when clouds have very cold tops and precipitation rates are high such as within a frontal band. If the condensate supply rate is sufficiently high, precipitation rates may not be able to completely use all the available SLW. These types of cases also lead to large carry-over of precipitation into the lee of the mountain as has been seen in the Sierra and Sierra Madre of Wyoming. These maybe rather transient cases and much harder to predict than in the post-frontal shallow orographic clouds that have been the focus of most winter cloud seeding operations in the past 30 years. These deep cold clouds have been avoided as they have very high natural high crystal concentrations. However, there are periods that may contribute many hours of icing as would be reported by mountain top icing rate meters. Thus these periods should be evaluated for seeding opportunities from ground-based generators since over-seeding appears to be difficult according to modeling studies.
- The range of SLW temperatures seems to span the range of available seeding agents currently being used. SLW has been observed from just below 0 ^{o}C to -20 ^{o}C . However the magnitude and duration of the SLW is higher as cloud top temperatures warm and the natural nucleation process becomes minimal. Thus there are many hours where SLW is present at temperatures warmer than AgI is effective at treating. An area that needs more research is to develop an aerosol seeding agent that acts through heterogeneous nucleation but activates at just below 0 ^{o}C. SNOWMAX is currently not a viable agent as its aerosol size distribution is too large and can be removed too quickly by dry deposition. As we move into an era of warmer temperatures, this will become a more important issue for winter orographic cloud seeding.

5.1.2 Are their man-made pollutants or natural aerosols/particulates impacting the target clouds that could modify the cloud droplet spectra/IN concentrations to impede seeding effectiveness?

- It is not clear that any of the most recent or even past winter orographic cloud seeding experiments conducted in the western US have observed significant impacts from pollution. The impacts would most likely occur in locations having a maritime influence and a broad or bi-modal drop-size distribution. Certain types of pollution act as cloud condensation nuclei and thus can produce many more droplets with a much narrower size distribution but higher number concentration. This can act to slow down the ice initiation process (if by contact or immersion freezing) which in an orographic cloud could lead to more SLW passing over the mountain unused.
- From the discussion concerning SLW, ground-based seeding, driven mostly by deposition nucleation and diffusional growth, is not impacted greatly by drop size or concentration. However when riming is a major contributor to particle growth, the drop size and number concentration is important. Aerial seeding should then be more impacted by any pollution that affects the number and size of cloud droplets. Modeling studies indicate that seeding may negate the decreases caused by pollution, but if pollution is significant, seeding may not compensate.
- Results from CalWater I are limited but do suggest that IN (dust from the Sahara and Gobi deserts) traveling across the Pacific can positively impact primary ice nucleation in

western US winter storms. Some winter storms may not be impacted by these natural IN and thus may not be as efficient as those that are. Using CALIPSO and MODIS satellite data may provide some information on the transport and concentrations of dust coming across the Pacific and may provide an opportunity to recognize more seedable events.

- CalWater II will be conducted during the winter of 2014-15 and may provide additional documentation on the importance of dust transport across the Pacific and its impact on winter orographic precipitation.
- Quantifying the impacts of man-made pollutants on clouds and precipitation processes is as difficult a task as quantifying the impacts of artificial seeding of winter orographic clouds. No long term statistical analyses of pollution impacts have been conducted in a manner similar to winter cloud seeding and thus there is more likely a greater uncertainty on the role of pollution on precipitation within winter orographic clouds then to artificial seeding of these same clouds.

5.1.3 Are their significant enough differences in maritime influenced winter orographic clouds versus continental orographic clouds that strongly influence the natural precipitation process?

- 3-D modeling studies with detailed microphysics and AgI seeding simulations indicate that drop size distribution is important to the growth of both natural and seeded crystals. This is significant in that maritime clouds have a broader bi-modal drop-size distribution while continental clouds have a much narrower distribution and greater number of smaller drops. The broader the drop size the more efficient the collision coalescence process for riming growth. Thus any significant changes in drop size distributions could impact the growth rate and mechanism of winter precipitation if riming is important. Again, this has been documented in field studies comparing coastal mountain range precipitation processes with interior mountain precipitation processes. In the intermountain region where continental orographic clouds are more prevalent, unless embedded convection occurs or very high amounts of SLW occur, usually in the warmer storms where AgI may not be effective, riming growth is not significant especially with regards to AgI ground-based seeding.
- In maritime regions where cloud-base temperatures are warm, say near 10 ^{o}C but clouds extend up through the freezing level, large cloud drops and even supercooled drizzle drops can form. When these freeze they can produce large numbers of ice crystals through the Hallet-Mossop process and mimic what seeding could produce. This reduces the benefit that artificial seeding could produce. Again this occurs mostly along the US West Coast and has not been frequently observed in places like Japan or Australia in winter orographic clouds as cloud base temperatures are near or below freezing.

5.1.4 Are there numerical models that can be run in real-time utilizing project field observations to guide seeding decision making?

- High resolution 3-D models run with at least 1 km spatial resolution and using four-dimensional data assimilation and project rawinsondes can provide short-term guidance on when to seed and which generators may be used to effect accurate targeting. However the timing, location, and duration of the SLW as well as the accuracy of the hour by hour winds may be lacking. It is still necessary to have high frequency (1-3 hours) in-situ vertical winds and temperatures over the project area to guide seeding operations. Wind profilers with RASS and S-Prof freezing level sensors (White et al, 2013) could provide near continuous measurements of the necessary parameters to feed simple models like GUIDE that could be very useful for operational programs. The HRRR model (High Resolution Rapid Refresh http://ruc.noaa.gov/pdf/ESRLRAPHRRRchanges2014.pdf) run nationally at 3 km and updated hourly run out to 15 hours (became operational late September 2014) could be a very useful model for operational seeding decision makers.

- Given model limitations, it is still necessary to operate scanning microwave radiometers to measure the amount and horizontal distribution and if possible obtain a vertical distribution of SLW (Serke et al 2014).
- The GUIDE model, if initiated with representative topography, winds, temperatures and SLW has been used operationally with some success. It is an inexpensive alternative to running a sophisticated model like the WRF.

5.1.5 What is the best seeding agent to use based on SLW temperature regime and what is the best way to deliver the seeding agent?

- If SLW is found at temperatures colder than -5 ^{o}C, and is within the lowest 1000m on windward slopes of the mountain and there are locations where ground-based generators can be placed mid-way up the mountain slope to assure the aerosol reaches activation temperatures quickly and reliably, and there is sufficient time to grow crystals (~900-1500 s) before they pass to the lee of the mountain, AgI with a compound that promotes condensation freezing would be the preferred method.
- If the SLW is concentrated at temperatures warmer than -5 ^{o}C, but clouds extend vertically to -10 to -15 ^{o}C, extend well upwind of the barrier crest, and are saturated with respect to ice, aerial seeding with AgI wingtip flares, acetone burners or crushed dry ice is a viable alternative. Based on a 1 m/s horizontal spread rate, one should limit the length of the flight leg per seedline to maximize line merging prior to passing over the target area.
- Liquid propane dispensers located within SLW cloud sufficiently upwind of the crest or on a ridge upwind of a second ridge where subsidence is minimized between ridges, can be a good alternative to aerial seeding when SLW is concentrated in a layer with temperatures -5 ^{o}C or warmer. Again there has to be sufficient time for crystal growth and fallout to produce any meaningful snowfall enhancement (~900-1500s).

5.1.6 What is the necessary density and location of ground-based dispensers and what is the dependency on seeding agent used?

- One should assume an approximate 10 to 15^{o} horizontal spread for ground based seeding aerosols. Given a minimum of 15 to 30 min to fallout, the generators should be placed sufficiently close to ensure complete coverage of the intended target and positioned to take advantage of a spectrum of wind directions and speeds that can produce SLW over the mountain thus maximizing seeding events per season.

- Again the location of the dispensers should be sufficiently high on the barrier to avoid trapping by low level inversions and to ensure adequate nucleation and targeting of the seeding agent and fallout of the seeded crystals before passing to the lee of the crest. Whereas AgI compounds can be released below cloud and through turbulence and weak convection be lofted up into the cloud to cold enough temperatures to activate large numbers of nuclei, propane must be released in-cloud or above ice saturation and at temperatures just below freezing for it to work effectively.
- The number and spacing of ground based generators is probably the single most important factor if winter orographic cloud seeding is to be successful. Both the Snowy Mountains and Wyoming experiments have demonstrated that to produce meaningful additional snowfall, one must ensure the clouds are being treated over the entire volume of the target area for the duration of the time clouds are within seedable criteria. Most programs have suffered from both poor siting of ground-based generators and to an insufficient number of generators.
- It is a fact that when AgI aerosols are injected into SLW at temperatures colder than -5 ^{o}C, ice crystals will form. Thus winter orographic cloud seeding is just as much an engineering problem as a scientific challenge. How does one effectively seed the cloud to ensure sufficient ice is produced and can grow and fallout within the intended target area when cloud moisture and temperatures are sufficient? The second Snowy Mountain experiment in Australia has addressed this issue by increasing the number of ground based generators and taking measures to assure at least a majority of the generators are targeting the desired area of impact. If a project is to be successful, it must be designed to assure the clouds over the target are effectively treated. This has not been the case for many programs in the past.

5.1.7 What observing systems are needed and at what spatial and temporal frequency to adequately target seeding impacts?

- Rawinsondes launched within or just upwind of the intended target area provide the most useful observations of the vertical profile of wind and temperatures. They should be launched at least every three hours to assure adequate capture of changing wind and temperature conditions. If the barrier is of sufficient length and width an upwind sounding may not represent the winds over the crest and thus a rawinsonde may need to be launched near the mountain crest at a similar frequency to the upwind site. This sampling is necessary for both ground-based and aerial seeding to ensure good targeting.
- Wind profilers with RASS and S-band vertically pointing radars that detect the snow-level (S-Prof) could provide very useful observations at 15 min frequency. A combined system of wind profiler, S-Prof, gps integrated water vapor and surface weather and precipitation measurements are called Atmospheric River Observatories. These are now being installed along the California coast (White et al 2013). The ability to assimilate these data into the WRF and HRRR models could be very useful to seeding operations in the Sierra Nevada. White describes how the ARO data can be combined with high resolution model data to produce what has been called a “flux tool” that provides the decision maker with how well the model has been performing during the past 12 hrs and the model forecast for the next 12 hours. See Figure 5.1 for further information.

Knowing the vertical profile of SLW (and thus its degree of supercooling) is also very critical. Current scanning radiometer technology can indicate the presence of SLW. It still lacks the capability to provide meaningful vertical profiles although research in this area is continuing. A revised vibrating-wire technique incorporated into the rawinsonde package is one means to obtain a profile of SLW but would be infrequent given times between launches. NASA is apparently developing an icing remote sensing system that combines a microwave radiometer, a K-band cloud radar and lidar ceilometer to obtain a vertical profile of SLW (R. Rasmussen personnel communication).

- Mountain-top icing rate meters can provide indications of locally produced SLW but they do not provide any information on the horizontal or vertical distribution. These have been used in an automated fashion to initiate seeding when co-located with propane dispensers. This ensures that nucleation will occur but does not provide information on the fate of these nucleated crystals once they move away from the local source of SLW.
- Again it should be mentioned that for ground-based seeding, the entire initiation and growth process occurs within the boundary layer created by the turbulent motions of wind over complex terrain. Strong up and downward motions will impact the trajectory and fallout of these artificial crystals leading to large variability in seeding impacts within a given target area both within a given storm and from storm to storm. Thus it is imperative that if one is to observe the seeding effects it is necessary to have a network of observing systems (accurate snow gauges) spread out through the target area as any given point in the target may or may not be impacted continuously within an event.

5.1.8 What are the observing systems, either in-situ or remote sensing, that can observe and track a seeding plume from initiation to fallout? What are the benefits and limitations of each?

- To date the most useful observing systems have been ice crystals particle probes onboard aircraft combined with an NCAR ice-nucleus counter when AgI has been used as the seeding agent. This is most useful for aerial seeding as most aircraft are restricted from flying to within 1000m of the highest terrain which is the depth to which most of the seeding agent is concentrated from ground releases.
- These same probes can be mounted on a tower or vehicle and interfaced to a wind sensor to adequately determine the sampling volume and crystal concentration. Again an NCAR ice-nucleus counter can be operated with the particle probe to assure the sampling is being done within the seeded plume if ground-based AgI seeding is being conducted.
- If propane is used as the seeding agent, sulfur-hexaflouride (SF_6) has been used as a tracer that can be co-released at the propane generator site to tag the seeded volume.
- The above sampling methods are compromised by naturally occurring snowfall that can mask the seeding effects. Also the AgI aerosol and seeded crystals will soon begin to separate as the seeded crystal fallout and the AgI aerosol continues to be lifted by the orographic forcing. The same will hold true when using SF_6 as the crystals initiated at the propane nozzle will grow and begin to fallout while the trace gas moves with the air parcel.
- K-band or X-band radars have been used with limited success for monitoring seeded plumes from both aerial and ground based seeding. However natural ice severely compromises the radars ability to see a high concentration of small crystals especially if there are naturally occurring large crystals within the seeded volume. These radar

systems are becoming more and more compact and have been demonstrated to operate unmanned in harsh winter conditions, especially as shown in the WWMPP. However there is a need to statistically post-process the data to extract any seeding signature that is hidden by the large natural variability.

- Downward looking radars as flown on the Wyoming King Air during the WWMPP have shown dramatically how complex the flow is over mountain barriers. Although this in itself is very informative and has helped scientists to understand the complexities of mountain flows and has provided validation to numerical models, the radar data itself is still overwhelmed by the natural variability. The radar data has to be statistically post-processed to extract any seeding effects. These results themselves should be subject to statistical significance tests.

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5.1.9 What is the resolution and spacing required of recording snow gauges within the intended target area and downwind target area?

- The resolution of recording snow gauges required is a function of the duration of the seeding and the expected effects. Based on observed seeding effects (see Table 5.1) that average about .25 mm/hr the gauge resolution should be about twice this or near .1 mm/hr. This requires careful siting of the gauges within sheltered locations of the target area. Wind can have a large impact on gauge catch efficiency leading to under catch of 10-20%. Thus siting in a forest clearing or making sure the gauges are properly shielded is critical. This was discussed in Section 2.1 for the Australia seeding program. Random noise within the gauge measurement systems will introduce bias and uncertainty. These types of errors are minimized by having a large number of experimental units and using statistical techniques to remove these types of biases. Multiple gauge sites should be installed within the intended target area and in the downwind and control sites if one is going to validate the seeding effects and determine if the effects are moving beyond the intended target. Again assuming a 10-15^{o} spread of the seeding plume and assuming fallout of crystals of from 15 to 30 min downwind and a mean wind speed of 15 m/s the gauges would need to be from 3 to 7 km apart.
- If enough ground generators are installed to ensure that the entire volume of air passing over the target area is seeded, one could reduce the number of gauge sites as it would be expected that those gauges in the target area would be representative of seeding impacts across the target area.
- Modeling studies previously discussed in this report using reanalysis data as input could be used to both site ground generators and determine the optimum locations for surface snow gauges as part of the project design study.

5.1.10 If silver iodide is the seeding agent, what are the benefits and limitations of sampling the silver concentration in the snow prior to spring melt to validate that a significant portion of the winter seeding impacted the target area?

- Trace chemistry samples taken at various locations within the target area for Ag can be useful for determining if the target was impacted by the seeding plume. If real-time samples can be taken using a sequential sampler (ferris–wheel sampler being developed by Idaho Power) one could monitor both the presence of Ag above background and the sample density to determine seeding impacts when Ag is observed (seeded sample) and when it is not (control sample). It would also be useful to release a non-nucleating agent like indium or cesium to determine if the Ag acted as an ice nucleating agent or was scavenged out of the cloud. This methodology would be useful for both ground-based and aerial seeding. Care should be taken to monitor for natural contamination by dust. It is critical that samples be taken of snow prior to any seeding occurring and measured for background levels of Ag and other naturally occurring trace elements so that a baseline is established and one can determine if levels are above background and if contamination may be occurring.

5.1.11 What is the best design of the seeding program to reduce uncertainty and insure meaningful statistical results?

- If a project is going to evaluate the seeding effectiveness, randomized seeding should be used. That is, some seeding opportunities should be left unseeded and the seeding decisions should not be communicated to those doing the evaluation. The number of cases needed to reach a level of statistical significance will be based on the expected seeding effect. If one assumes a 10% increase in seed over no-seed periods, and one has a long historical climatology of target area precipitation, the number of samples can be computed. The sample size can be reduced if a highly correlated (r value > .8 is best) control area can be determined that will not be impacted by the seeding and that this correlation is well behaved. A further reduction in sample size is possible if a cross-over design is used. That is that the target area alternates in a randomized fashion between the two areas with an equal distribution of seed no-seed between the two.
- In addition, it has been shown for the follow-on SPERP experiment in Australia, finding good predictors of the precipitation in the target area can reduce the uncertainty (smaller residuals). Reducing the residual errors in the regression analysis using predictors will enhance the statistical analysis and should improve the confidence that the signal observed is statistically significant. It is expected that one should plan on at least a 5 year period of randomized seeding with a contingency of several more years if seedable conditions are lacking or suspension criteria reduced experimental units during several of the target years. If one is designing a new randomized seeding experiment, detailed statistical studies identifying control sites that are highly correlated and would not be impacted by seeding is desirable, as well as having additional predictors of target precipitation to reduce the regression residuals. It has been suggested that as numerical models improve and can be demonstrated to accurately predict precipitation for a given experimental unit (4-6 hrs), that the model can be used as the predictor of what the target would have received had it not been treated. In fact if the models were to become good enough, randomization may not be needed. However this certainly is not the current state of the science in numerical modeling.

5.1.12 What are the best statistical methods to apply to achieve statistical significance and reduce Type I and II errors?

- The best method to avoid false positives (Type I errors) or false negatives (Type II errors) is to establish *a-priori* response variables that are sensitive to the seeding. The primary response variable will most likely be snow water equivalent for the target and control sites. Secondary response variables such as integrated SLW, or Ag in snow, or ratio of Ag to a non-nucleating agent can also be used. It is also imperative that during the seeding experiment detailed physical evidence of seeding effects that help document the physical links in the chain of events from seeding agent release to seeded crystal fallout in the target area will reduce the chance of Type I or Type II errors.

5.1.13 Benefits and limitations of a reanalysis of operational cloud seeding projects?

- The seeding outcomes of historical operational cloud seeding projects based on target control statistical analyses can only be considered suggestive. Because they are not randomized, and the selection of the data set to be analyzed can be subjective, the results, even though shown to be statistically significant, cannot be evaluated in the same manner as a fully randomized, blind or double blind, confirmatory seeding experiment. Because of changing conditions between the primary target and the chosen control (also subjective), there is certainly the possibility of bias in any results such as these.
- It should be noted that very little has been documented in determining the impact of small increases in seeded precipitation and increases in seasonal runoff. Because it has been difficult to quantify the seeding impacts, these secondary studies can only be considered speculative. However the recent results from the Wyoming project and the Australia second statistical analysis are now providing some insight as to what the magnitude of seasonal snowfall increase from seeding might be over a given watershed. Again the numbers can be rather small percentages (~5%) seasonally and this will make it very difficult to quantify how this additional water impacts runoff. This is certainly an area that needs research.

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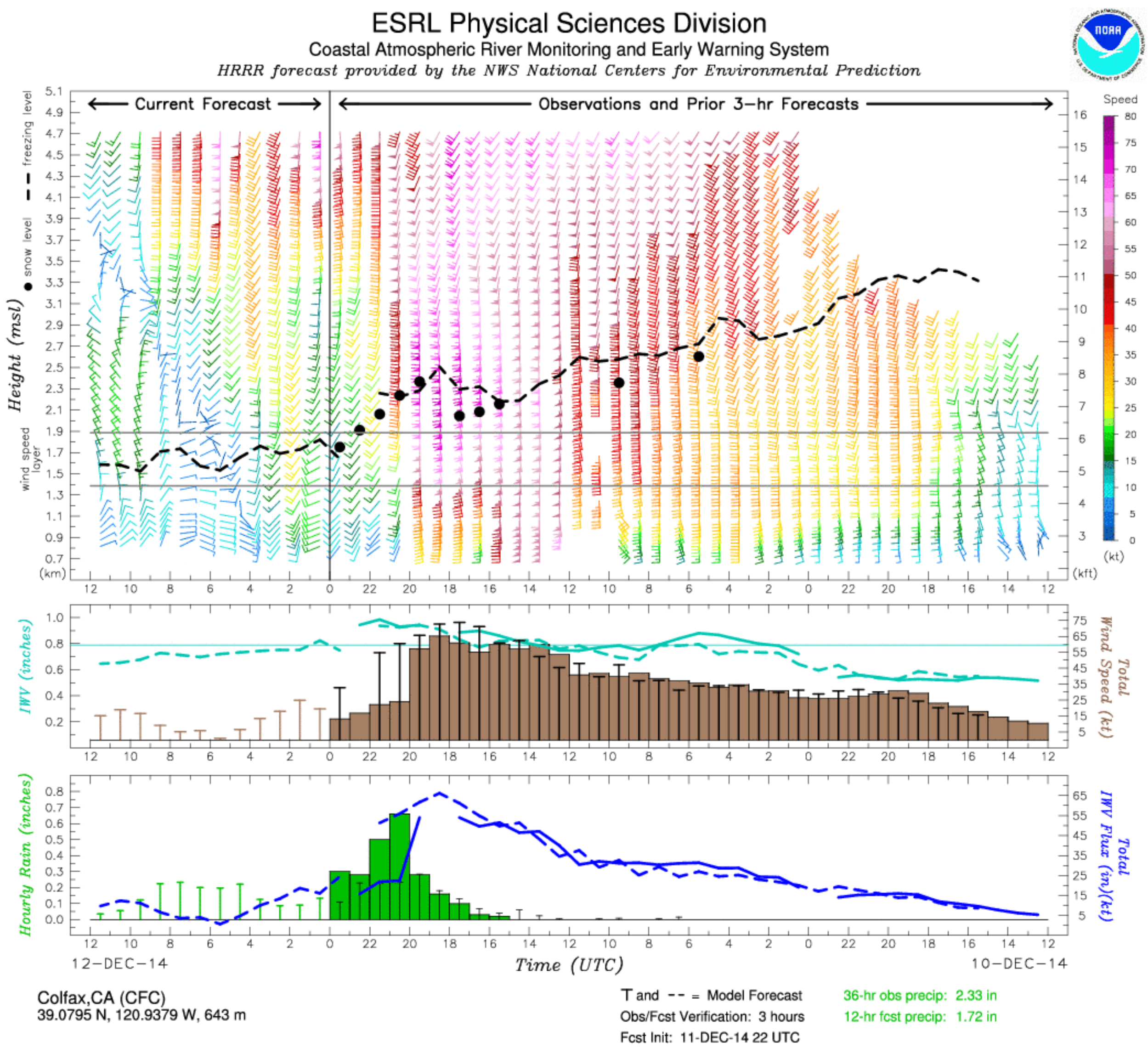

Figure 5.1 Example from 10 to 12 Dec 2014 of the AR water vapor flux tool applied to sites in Northern California (Colfax). (top) Wind profiler hourly averaged observations of the snow level (bold dots) and retrospective hourly HRRR model forecasts of the freezing level (dashed line) at 3-h verification time along with time–height section of hourly averaged wind profiles (flags =50 kt ; barbs = 10 kt; half-barbs =5 kt; wind speed color coded), observed by the ARO at Colfax. (middle) Time series of hourly averaged upslope flow (kts) observed (histogram) and predicted (T posts) in the layer between 1400 1900 m MSL (bounded by the dashed lines in the top panel), and IWV (cm) observed (solid line) and predicted (dashed line) by the HRRR (bottom). Time series of hourly averaged IWV flux (in kt) observed (solid line) and predicted (dashed line) by the HRRR and hourly rainfall histogram from Colfax (inches green). Time moves from right to left along the x axis. The current time is indicated by the vertical line in the top panel. Data plotted to the left of this line in each panel show the current HRRR forecast only (i.e., no observations), whereas data plotted to the right of the line in each panel are a combination of observations and model output. Minimum thresholds of IWV in atmospheric river conditions are indicated by the thin horizontal lines in the middle panel.

5.2 Effectiveness of Winter Orographic Cloud Seeding

The NRC 2003 report emphasized the need to document the physical links in the chain of events from seeding release to enhanced snowfall on the ground. This has proven to be a major challenge to weather modification researchers. There are but a limited set of locations where researchers have attempted to monitor the complete chain of seeding events from nucleation to fallout. Although not a complete list there have been many papers that have documented seeding plume locations, ice particle enhancement and precipitation increases from artificial seeding of winter orographic clouds (Deshler et al. 1990; Reynolds 1996; Holroyd et al. 1995; Super and Holroyd 1997; Holroyd et al. 1998; Huggins 2007; Huggins 2009; Murakami 2013; Geertz et al. 2012, 2015; Pokharel 2014). These are summarized in Table 5.1.

Table 5.1 – Compilation of Physical Seeding Effects

Location	Seeding Agent	Plume Width (°)	Plume Height	Distance from Seeding Location	Nucleation temperature	IPC	Precip Rate if Detected	Radar Detected Reflectivity Increases	Author
Bridger Range MT	$AgINH_4I$ 30g/hr	10 to 30 avg 17	600	17 km	- 9C	6 to 13 L^{-1}	.03 to .09 mm/hr		Super and Heimbach, 1988
Grand Mesa CO	$AgINH_4I$ 30g/hr	15	500-800 m AGL	0-20 km	-5C	7-20 L^{-1}	.1 mm/hr		Super and Boe 1988
Snowy Mtns Australia	AgCl.8I0.5NaCl	?	800 – 1500m	15-30km	- 5C	?	.06m/hr		Manton and Warren 2011
Snowy Mtns II	AgCl.8I0.5NaCl	?			- 5C		.1 mm/hr		Manton et al, 2015
Wasatch Plateau UT	Propane	25	sfc Obs	6km	- 4C	15-19 L^{-1}	.1 to 0.25 mm/hr		Super 2003-04
Wasatch Plateau	$AgINH_4I$ 30g/hr	10-20	1200m	4-23 km	-5C	10-50 L^{-1}	1 mm/hr Convect	5-10 dBZ	Huggins, 2007
Medicine Bow WY	AgI0.8Cl 0.2-NaCl		600	15-30 km	-5C to -8C		.2 - .3 mm/hr	1-5 dbZ W Band Aircraft	Geerts 2010 Geerts 2014
Sierra Madre Range WY	AgI0.8Cl 0.2-NaCl		600 to 1000m	15 to 30 km	-8C to -10C	5 to 15 L^{-1}	.3 to ..4 mm/hr	1-10 dBZ	Pokharel et al 2014
Sierra Nevada CA	AgNH4II	10 to 15	500 to 1000 m	20 to 30 km	-6 C				Reynolds et al 1989
Feather River CA	Propane	10 to 15	500m	17 to 20 km	0 to -8 C	10 to 30 L^{-1}	.05 to .15 mm/hr		Reynolds, 1996
Aerial Releases		Plume Spread m^{s-1}	Rate of Rise	Length of seed line to fill target volume					
Grand Mesa CO	$AgINH_4I$ 30g/hr	2	.	30 km	- 9 to -14C	10-20 L^{-1}	.3 -.4 mm/h		Holyrod 1988 JAM
Wasatch Plateau UT		.5 to 1 m/s	.1 m/s	30 km					Hill (1980)
Snake River ID	AgI				- 20 to - 8 C				Xue et al Model only
Sierra Nevada CA	AgI and CO2	1-2 m/s	.3 m/s	37 km or less	-3 to -15 C	10-20 L^{-1}	.1 to 1 mm/h	3-10 dbZ	Deshler et al 1990
Japan	CO2	1 m/s		30-50 km	- 8C	15-100 l^{-1}	.5 to 1.5 mm/hr	3-5 dbZ Ka band 2D-C est.	Murakami 2013

Increases in the precipitation rate observed from ground-based seeding are remarkably consistent. Because the seeded crystals remain in the lower portion of the cloud and are growing

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at temperatures where diffusional growth is rather slow, -7 to -10 ^{o} C (see Figure 1.5) particle mass would be expected to be small after 15 to 30 min of growth. Thus the .1 to .3 mm/hr precipitation rates noted from ground-based seeding are very reasonable. It should be noted that results shown in the table are a mix of direct observations (gauge or radar) and inferred from statistical analysis (Australia). Precipitation rates observed from aerial seeding are shown to be higher than ground-based seeding. Model simulations support these higher rates in that crystals can more effectively sweep out the low level SLW by riming much like the natural precipitation process.

It is still a challenge to translate these hourly seeding rates or even the results of randomized seed no-seed percent increases to seasonal snowpack and runoff enhancements over a given watershed. Attempts have been made at this, as was done for the WWMPP based on the assumption of seeding all available "seedable" events based on climatology. There were examples also given for the Walker Basin in Nevada, again based on assumptions of a 10% increase in SWE over 5 hydrologic service units, and Silverman looked directly at runoff as a possible indicator of long term winter orographic cloud seeding programs in California. These results can only be considered suggestive of possible seasonal increases but certainly not what one should consider reliable.

5.3 Summary and Conclusions about Scientific Efficacy

Sections 5.1 and 5.2 have reviewed what has been identified as the key questions/uncertainties in winter orographic cloud seeding for snowfall enhancement and what the current state of knowledge is and how much we may have progressed since NRC 2003. Although there have been significant improvements in our ability to model winter orographic clouds and to observe these clouds, especially with downward looking aircraft mounted radars and lidars, the complexity of even the simplest orographic clouds are daunting. The turbulent motions and up and downdrafts associated with each ridge and valley that make up the complex terrain of any mountain have and still make direct observations of seeding effects on a routine basis a significant challenge. It is well understood that the presence of SLW in these winter clouds is critical for producing snowfall increases from seeding. As noted in Section 5.1.1, SLW is concentrated in the lowest layers of the cloud and can vary considerably from hour to hour over any given location along the windward slopes of the mountain. This implies that seeding effects will be non-continuous at any given point within the target area and thus complicates quantification of the seeding effect. Although there have been studies of the impact of pollutants and other aerosols in the formation of and impact on orographic precipitation as reviewed in Section 5.1.2, it is not clear that there is a significant impact on the cloud properties such that it reduces the potential for seeding winter orographic clouds.

It is true that along the west coast, where there is a strong maritime influence (section 5.1.3), that natural processes like secondary ice production through rime splintering can actively compete for the available SLW and the ability to increase snowfall through seeding. Although this is a more common observation along the west coast, it has been observed even in inter-mountain regions of the west, but rarely. Of more significance is the temperature of the SLW in west coast winter orographic clouds. There are many hours of SLW observed at temperatures warmer than -5 ^{o}C. It was also described that there are many hours of only slightly supercooled

clouds in the intermountain west. To treat these louds will require either the use of ground-based propane generators or aerial seeding to effectively convert the SLW to snowfall. Finding effective locations for propane dispensers, in that they have to be in-cloud and within the SLW region of the cloud, is a challenge as was noted in the LOREP. Aerial seeding has been shown to be more effective in sweeping out the low level SLW but one aircraft has very limited flight duration and a limited ability to effectively treat a large volume of cloud (Section 5.1.5).
The WWMPP project along with the Idaho Power seeding program are the first to use sophisticated numerical modeling with parameterized AgI seeding to both inform the design of the programs as well as inform seeding decision makers as to when to seed. Section 5.1.4 noted however that even with sophisticated modeling, there is uncertainty in the models ability to accurately forecast in the near term the winds and thus SLW distributions that relate directly to knowing where the seeding impacts may occur downstream. Without very sophisticated modeling using LES and resolutions down to 100m, which are impractical in real–time, modeling will only provide a general idea of when, where and how much additional snowfall can be expected from ground-based or aerial seeding. Although it has been suggested by NCAR scientist that numerical modeling may someday provide this capability, it has yet to be demonstrated that modeling will replace direct observations and statistical analyses for detecting seeding increases on an annual basis. This is demonstrated by the fact that the WWMPP used state-of-the art numerical modeling to not only design the project, but to help in the real-time decision making as to when to seed. Even with these tools the program was unable to demonstrate a positive seeding effect in the confirmatory experiment. In hind-sight having one sampling point in the center of the target may have been a weakness in the experimental design (Section 5.1.7).

As described, recent confirmatory experiments in Australia as well as Wyoming, although failing to meet or exceed the statistical significance threshold set out in the experimental design, have through *a posteriori* analysis, strongly suggested that both projects may have succeeded had more generators been operated to assure more effective targeting and more continuous impacts within the target. Both projects showed statistically significant results when it could be established that more generators were effectively seeding the target area. As was discussed by Reynolds (1988) in his survey article referenced many times in this report, and the conclusions of Super and Heimbach (2005) in there review article on the feasibility of snowpack enhancement in the Colorado Rockies, the inability to seed clouds effectively either through poor targeting, or placing enough seeding material (and active for the cloud temperatures being treated) in the cloud to fill a large volume with sufficient ice crystals, has led to this lack of statistical “Proof”. Simple seeding experiments such as conducted by Super and others in Montana, Colorado, and Utah have demonstrated using both AgI and propane, that if targeting is assured, seeding impacts can be observed directly with particle probes and over a period of time in snow gauges with statistically significant results (section 5.1.8). These seeding effects can be further corroborated by the use of real-time operation of an ice nucleus counter, Ag in snow measurements with an added non-ice nucleant to assure scavenging was not the primary method of Ag deposit, and by the use of tracers such as SF_6 co-released at the seeding generator or aircraft to tag the seeded volume (Section 5.1.10). It has been shown that radar observations using 5 cm to millimeter wavelengths have a difficult time directly observing seeding effects. This is because seeding generates many small crystals that are more difficult to observe when any natural and larger ice crystals exist in the cloud. Only through statistical analyses were weak signals from seeding able to be identified during the ASCII projects. When nature allows a glimpse of seeding effects, the magnitude of the effects in terms of augmented precipitation rates are quite consistent as shown in Table 5.1. Given these augmented rates are near the threshold of current snow gauge measurement technology (Section 5.1.9), it makes it imperative that to prove seasonal increases in snowpack through seeding, randomized seeding trials over a significant number of winter seasons must be conducted and must demonstrate success through meeting or exceeding a pre-determined statistical level of significance, specifically a 90 to 95% confidence level (Section 5.1.12).

Although many operational projects have been operating for decades and have a large sample of seeding seasons to perform target-control statistical analyses, these analyses can only be considered suggestive of possible seeding effects (Section 5.1.13) There are just too many subjective issues such as the choice of controls *a posteriori* that compromise the significance of these types of studies. It however must also be recognized that the sponsors of these long-term projects have continued to conduct seeding annually based on these types of analyses and thus should not be ignored. Physical studies that have been performed in cooperation with these operational seeding programs, especially Ag in snow analyses with non-nucleating agents, provide some credible physical evidence that seeding may be effective under certain conditions.

Winter orographic cloud seeding, to have any success, comes down to proper design. As highlighted in Section 5.1.11, one must factor meteorological as well as engineering issues into the design:

1) there is a good understanding of the characteristics of the winter clouds over the given barrier as to depth, duration, and temperature structure, and seasonal climatology of the SLW in the cloud, 2) that strategically located ground-based seeding generators appropriate for the temperature of the SLW can be installed with assurance the agent will activate and increase ICC by 10-100 L^{-1} and there is time available for the artificial crystals to grow to a meaningful size to effect seasonal snowpack water content within the desired watershed, 3) that aerial seeding is considered when ground based sites are not available.

Enhancing winter snowpack through artificial seeding is both a science problem and an engineering problem. From the science perspective, it is understanding the meteorology of the given mountain barrier and having the tools such as the right observations and modeling capability, as has been outlined above, to know when it is appropriate to seed. From the engineering perspective, it comes down to seeding the clouds effectively with enough nuclei (AgI) or with embryonic ice crystals (propane) to effectively fill the volume of cloud over the target area with enough ice to deplete the available SLW and bring it to the surface before the seeded volume passes to the lee of the barrier and may be lost to subsidence. The weather modification community has spent decades trying to get the engineering right and not with great success, at least from the scientist perspective. As seen with both the WWMPP and SPERP, each acknowledged that they did not *effectively* seed the clouds on all seedable occasions which produced insignificant statistical results in each’s confirmatory experiments.

5.3.1 Next Steps

Numerical modeling has really been the major scientific advancement since NRC 2003. It has helped the science to understand the observations made during former field studies: 1) why radiometer data shows high temporal and spatial variability in SLW, 2) why seeding plumes are narrow and concentrated in the lowest 1000m over the windward slopes of the terrain, 3) that it is really difficult to over-seed and in almost all cases downwind effects are either neutral or positive, 4) aerial seeding is more efficient at getting more SLW out of the cloud but logistically is a much more difficult platform to operate compared to ground-based seeding. 5) why the impacts of seeding on precipitation rate are small but consistent over many different barriers in the west given that seeding is controlled by diffusional growth, and 6) it is difficult to quantify the magnitude of seasonal snowpack increases one might expect given the variability of SLW, complexities in targeting, and the spatial variability of seeding impacts, and hydrologically how this additional snowfall might impact seasonal runoff, based on antecedent soil moisture, timing of snow melt and other factors that influence the normal spring runoff. Modeling will continue to improve and utilizing more in-situ observations such as the 21st Century observing network such as California has almost completed, we can more rigorously evaluate and verify the models. Verification will improve our confidence in the models ability to simulate the spatial and temporal variability observed in winter orographic clouds and what the impacts of seeding these clouds will have on seasonal snowpack. Combining these atmospheric models with distributed hydrologic models should then allow one to determine the impacts of this additional snowpack on seasonal runoff. The science is not there yet and history has shown it will progress slower than we would like. However it is an absolute necessity that we continue to invest in both the modeling and the observations if we are to finally achieve “Proof” that artificial seeding of winter orographic clouds increases seasonal snowpacks by 10-15%.

5.3.2 Final Conclusion

Based on both the historical evidence and the last decade of research, it is reasonable to conclude that artificial enhancement of winter snowpack over mountain barriers is possible. It is very difficult to quantify the seasonal increases to be expected both in snowpack and subsequent spring runoff. This is because each target area has to be investigated as to the meteorology of the winter clouds and their seedability, and the engineering aspects of effectively seeding the clouds to maximize increases. Winter orographic cloud seeding should thus continue to be supported both from the scientific and operational community working together to further the science and operational outcomes. It must be stated however, that as of yet, no rigorous scientific study conducted as a randomized confirmatory seeding experiment with pre-defined primary response variables and requiring an established threshold of statistical significance has demonstrated that seeding winter orographic clouds increases snowfall. As such, the “proof” the scientific community has been seeking for many decades is still not in hand.

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