SUMMARY OF THE NOAA/UTAH ATMOSPHERIC MODIFICATION PROGRAM: 1990-1998

by Arlin B. Super
Bureau of Reclamation
Denver Federal Center

Abstract. *This paper summarizes many previously published physical investigations into the artificial nucleation ("seeding") of winter mountain clouds in central Utah during 1990-1998. Program goals were to evaluate the effectiveness of the Utah operational cloud seeding program and to recommend improvements. Field programs employed a wide variety of instrumentation systems. Sophisticated numerical modeling was used in conjunction with the observational programs. Amounts and distributions of supercooled liquid water (SLW) cloud were investigated, as was transport and dispersion of ground-released seeding agents and tracer gases. Several experiments directly monitored ice crystals and snowfall rates resulting from either silver iodide (AgI) or liquid propane seeding. Results showed frequent SLW in excess of natural conversion to snowfall, suggesting significant seeding potential. The SLW was concentrated near the terrain where temperatures were relatively warm. When valley-released AgI was transported to cloud levels, resulting ice crystal formation was usually too limited for significant snowfall augmentation. However, marked enhancement of ice crystal concentrations and snowfall rates resulted from a number of high altitude releases of both AgI and liquid propane. Propane seeding was effective within even slightly supercooled cloud. Several recommendations were given for improving the operational seeding program's effectiveness.*

1. BACKGROUND AND INTRODUCTION

1.1 General Background

The purpose of this article is to summarize in one place the most important results of many previously published articles and conference papers. These resulted from a multi-year project investigating the effectiveness of winter orographic (mountain-induced) cloud seeding in Utah, with emphasis on the Utah operational seeding program. This applied research was primarily sponsored by the National Oceanic and Atmospheric Administration (NOAA) Atmospheric Modification Program (AMP), in cooperation with the Utah Division of Water Resources and the Bureau of Reclamation (Reclamation). Discussions of the multi-state AMP are given by Reinking (1992) and Golden (1995). While the Utah portion of the NOAA AMP (hereafter NOAA/Utah AMP) began several years earlier, the cooperative program discussed herein began late in 1989 when Reclamation became involved. Reclamation scientists continued to participate in the NOAA/Utah AMP through 1996, at which time NOAA AMP funding was terminated by the U.S. Congress. Some additional analyses were performed after 1996 as reflected in this article.

A total of 29 journal articles and conference papers were published under this program during 1992-1998. These publications resulted from research done by a number of groups involved in the program during this decade. In addition to Reclamation, those groups included the University of Nevada Desert Research Institute (DRI), the University of North Carolina at Asheville, the University of Utah, Utah State University, the National Center for Atmospheric Research (NCAR) and North American Weather Consultants (NAWC). The NOAA Environmental Research Laboratories in Boulder, Colorado, also had a major role in this program. This agency provided an instrumented cloud physics and plume tracking aircraft for two major field programs, including pilots and technical personnel needed to support the sophisticated instrumentation systems. Their support was crucial to the program's success.

1.2 Objectives and Research Reported

The research reported herein is based on the last several years of the NOAA/Utah AMP when field work was conducted on the Wasatch Plateau (Plateau) of central Utah, approximately between the towns of Fairview and Price. Earlier work was conducted on the Tushar Mountains of southern Utah. That work, which has its own large body of publications (e.g., Huggins and Sassen 1990), is not discussed in this report. The single exception is the article by Sassen and Zhao (1993) which is quite relevant to the Plateau findings and was published during the Plateau phase. A review of the earlier years of NOAA AMP work, with an extensive list of references, is given by Reinking (1992).

The NOAA/Utah AMP had two main objectives during the period in question. First, the program was designed to *physically* evaluate the effectiveness of the Utah operational seeding program which has been partially funded by the State of Utah. Second, the program was to recommend to the Utah Division of Water Resources any changes which might improve future effectiveness of the operational seeding program. The operational program's goal was to increase the high mountain snowpack, which should lead to spring and summer streamflow augmentation (Super and McPartland 1993). Numerous findings and recommendations which could improve the operational program are to be found in the articles and papers summarized herein. Any decisions to implement such recommendations are the responsibility of the Utah Division of Water Resources and cooperating local water management agencies which jointly fund the operational program.

The key physical questions addressed during the studies reported herein are listed below and repeated in section 7.2.

1. When, where, and in what quantities does SLW exist within orographic clouds in excess of that naturally converted to mountain snowfall?

2. When, where, and in what quantities does the seeding agent affect the SLW cloud, converting portions of it to embryonic ice particles? In Utah, the operational seeding agent has been AgI produced by valley generators using the acetone-silver iodide-ammonium iodide solution.

3. When, where, and in what quantities do the seeding-induced ice crystals grow to snowflake sizes and fall to the mountain surfaces?

Most of the investigations reported during the NOAA/Utah AMP addressed one or more of the above questions. Section 7.3 briefly states the key physical findings to these questions.

1.3 Problems with Statistical Evaluations

Three statistical evaluations of the operational program have been reported by Thompson and Griffith (1981), Griffith et al. (1991), and Griffith et al. (1997). The reader is referred to these articles for details of the operational program which used valley-based silver iodide (AgI) generators, typically spaced on the order of 16 km (Griffith 1996). A small minority of all generators were sited in or near canyon mouths which could help transport and dispersion over mountainous terrain.

While all three of the statistical evaluations have suggested seasonal snowfall increases in the 10-20 percent range, one should be very cautious about accepting such indications. Griffith et al. (1997) correctly point out their (statistical) techniques, "are not as rigorous or scientifically acceptable as is the randomization technique used in research." A sizeable body of literature exists which discusses the many difficulties of after-the-fact statistical analysis of operational seeding programs and why such attempts should be viewed with caution. Dennis (1980) and Gabriel (1981) discusses some of the many problems that can result from improperly applied statistical approaches. Most of these arguments will not be repeated here. However, a major problem is the lack of any randomization with operational seeding programs, considered by many statisticians and meteorologists as essential for valid statistical testing. Target-control analysis of the type applied to Utah's operational seeding program must assume that precipitation relationships are stable over decades. This assumption presents a major difficulty (Dennis 1980), especially in view of known climatic change. In the Utah analyses, these relationships are assumed stable over long distances, from central and southern Utah target precipitation gages well into Nevada and Arizona where control gages were selected. But it is well known that precipitation relationships can change over time and space for a variety of reasons ranging from large scale climatic changes to local changes in the environment of a precipitation gage (e.g., growth of vegetation affecting gage catch). Another problem with the cited Utah statistical analyses is that markedly different sets of control gages and target gages were used in each analysis. Some changes in gage selection may be necessary as gages are discontinued or relocated. But whatever the reason, any changes in target and control gages after the initial selection (which should have been made prior to any seeding) diminishes the credibility of statistical results.

Because of these and other problems with post-hoc statistical analysis of the Utah operational program, the Utah Division of Water Resources agreed that physical evidence was needed to evaluate the operational program. Accordingly, the NOAA/Utah AMP was heavily based on physical observations and reasoning, including sophisticated numerical modeling.

1.4 Selection of Wasatch Plateau Experimental Area

Soon after Reclamation became involved in the NOAA/Utah AMP, observational emphasis was shifted from the Tushar Mountains of southern Utah to the Wasatch Plateau of central Utah. This shift in the experimental area occurred because of several practical considerations, which significantly improved field observations. A winter field program was conducted during early 1990 on both the Wasatch Plateau of central Utah and the Wasatch Range just east of Salt Lake City (Super and Huggins 1992a, 1992b). Both are long north-south mountain barriers which should minimize transport of valley-released seeding material around them. However, the Plateau offered several advantages for field observational studies including less rugged terrain which permitted in-cloud aircraft sampling much closer to the barrier top, and all-weather roads across and along the Plateau, permitting widespread surface sampling by instrumented vehicles and access to fixed installations.

The importance of low-level instrumented aircraft sampling and instrumented vehicle sampling along the Plateau's all-weather highways, cannot be overemphasized. It has simply not been practical to obtain such observations for other mountain regions, with a few exceptions like the Grand Mesa of western Colorado (Super and Boe 1988). Aircraft sampling over the Plateau was conducted under special waivers from the Federal Aviation Administration. This procedure allowed flight to within 300 m of nearby *highest* terrain, while standard flight rules require 600 m minimum separation over mountainous terrain. Moreover, lowest sampling passes were made in a terrain-following mode, rather than flying at a constant altitude (Super 1995a), which required exceptional flying and navigational skills by the NOAA pilots. This practice and the special waivers resulted in lowest aircraft observations within 600 m of typical (not highest) Plateau top elevations. *In spite of the unusually low level sampling, the aircraft could not always descend into ground-released seeding plumes or significant SLW cloud because both were in shallow layers over the terrain.*

The relative uniformity of the Plateau, with the broad Sanpete Valley to the west and parallel San Pitch Mountains farther westward, provided simplicities for airflow trajectories and numerical modeling efforts compared with more complex and rugged terrain. Nevertheless, the Plateau is believed to be reasonably typical of most of Utah's north-south oriented mountains targeted by the Utah operational seeding program.

Figure 1 shows the frequently investigated portion of the Plateau. Highway 31 ascends the Plateau's west slope from the town of Fairview on the Sanpete Valley floor. It splits into two all-weather roads (31 and 264) at the western edge of the Plateau top. From that intersection highway 31 follows the Plateau top's west (upwind) edge for several kilometers to the south and southeast. This portion of highway was frequently sampled by instrumented vehicles, and significant fixed surface instrumentation was located next to the highway. One major aircraft track was generally above this portion of highway 31, and extended well north and south of it, following the Plateau top's west edge. Both highways cross the entire Plateau top permitting along-the-wind sampling.

1.5 Experimental Field Projects

During the years under discussion, three limited and two major field programs were conducted. The limited, early 1990 program was conducted on the Wasatch Range and Wasatch Plateau, as discussed by Super and Huggins (1992a, 1992b).

Major field programs were held on the Plateau from mid-January to mid-March of both 1991 and 1994. Major equipment used during these programs included:

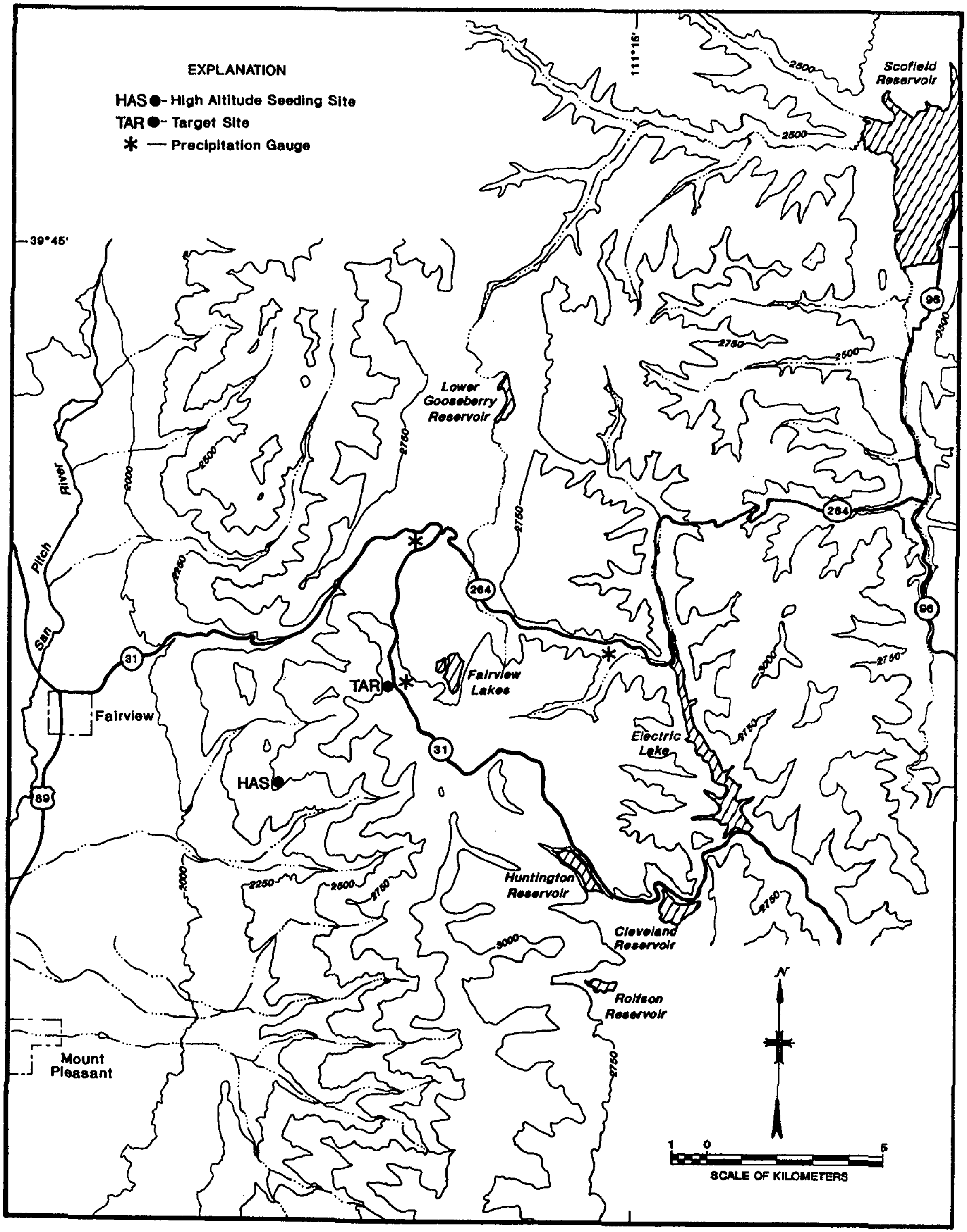

Fig. 1. Wasatch Plateau Experimental Area in central Utah showing terrain contours in meters above sea level. The towns of Fairview and Mount Pleasant are shown in the Sanpete Valley west of the Plateau. All-weather highways 31 and 264 provide access over the Plateau. The several kilometer portion of highway 31 just south and southeast of its intersection with 264 was used for frequent surface sampling along the Plateau top's west (windward) edge. The Target site (TAR) and High Altitude Seeding Site (HAS) were used in the 1994-95 and 1995-96 winter experiments.

- The NOAA Beechcraft King Air C-90 (N46RF) cloud physics and plume detection aircraft
- fixed and mobile microwave radiometers for monitoring vertically integrated liquid water and water vapor
- weather radar
- fixed and mobile ground-based detectors for silver iodide (AgI) and sulfur hexafluoride (SF_6) tracer gas
- valley and high altitude AgI seeding generators and SF_6 release equipment
- recording precipitation gage networks
- local rawinsonde releases in the Sanpete Valley
- automated weather stations

More information on these programs is provided in several articles summarized herein (e.g., Super 1994, 1995a).

Limited field programs took place on the Plateau during the 1994-95 and 1995-96 winters. These programs used a single, high altitude release site with AgI and SF_6 release capabilities and automated weather observations (HAS on figure 1). A single target to detect the effects of seeding was operated on the west edge of the Plateau top (TAR on figure 1), as discussed by Super and Holroyd (1997). The target station was equipped to observe AgI, SF_6, ice particle characteristics (by 2D-C laser probe), and supporting weather information.

1.6 Structure of Article

This article is made of 7 sections followed by references. This first section presents an introduction and background information. Section 2 discusses the availability of supercooled liquid water while section 3 concerns the transport and dispersion of ground-released seeding agents and tracer gas. Section 4 presents the results of physical cloud seeding experiments and section 5 discusses numerical modeling investigations. Miscellaneous associated work is found in section 6 and, finally, section 7 contains a summary and several recommendations for improving the operation seeding program.

The original published form of the 29 articles and papers summarized herein would total hundreds of pages of text and figures, for it is a significant body of work. In addition, numerous project reports and field program operations plans were produced during the NOAA/Utah AMP. This additional information is not discussed here.

2. AVAILABILITY OF SUPERCOOLED LIQUID WATER

2.1 Background Information

It is well known that a necessary (but not sufficient) condition for winter orographic cloud seeding to be effective is the availability of SLW in excess of that naturally converted to snowfall. Successful seeding also requires transport and dispersion of seeding agents into the SLW clouds in sufficient concentrations to convert significant quantities of SLW to ice particles. Moreover, the conversion must take place where sufficient time and distance permit ice particles resulting from seeding to grow to snowflakes sizes which settle to the mountain surface before sublimating in the lee subsidence zone. All of this must happen in an ever-changing and complex airflow and cloud environment. While it is sometimes convenient to consider winter orographic clouds as quasi steady-state entities, they actually change rapidly over a wide range of spatial and temporal scales.

Many operational winter orographic cloud seeding programs and a number of experimental projects have assumed the presence of abundant SLW. However, few programs have made significant efforts to test this *crucial assumption*. The NOAA/Utah AMP put considerable effort into investigating spatial and temporal SLW distributions, using both observations and sophisticated numerical modeling. Indeed, documentation of SLW was the program's first major scientific objective.

Several of the studies summarized herein dealt with the important topic of SLW. These include Huggins (1992), Sassen and Zhao (1993), Super and Huggins (1993), Super (1994), Huggins (1995), Super (1995a), Huggins (1996), and

Wetzel et al. (1996). Observations of SLW were made by tower-mounted icing rate meters, sensors carried by the NOAA instrumented aircraft, and by both fixed and mobile microwave radiometers. A mobile microwave radiometer was first deployed in the field during the NOAA/Utah AMP, as discussed by Huggins (1992, 1995) and Wetzel et al. (1996). It proved invaluable in mapping SLW distributions over the Plateau.

The general portrayal of SLW over the Plateau in the articles just noted is similar to findings from other mountainous regions, as reviewed by Super (1990). He noted that, "There is remarkable similarity among the research results from the various mountain ranges. In general, SLW is available during at least portions of many storms. It is usually concentrated in the lower layers, and especially in shallow clouds with warm tops. Average integrated amounts are normally limited implying low cloud liquid water contents, in agreement with aircraft observations."

The articles cited herein agree with the Super (1990) portrayal and expand upon it. Seasonally, a significant portion of the SLW flux is not converted to snowfall during passage over the Plateau. This finding suggests the availability of sufficient "raw material" for seeding to have an important impact on snowfall, *provided that seeding can convert a significant portion of the SLW flux to snowfall.* The seasonal SLW flux is concentrated in a few large storms that are efficient snowfall producers during portions of their passages but inefficient during other phases. Super and Huggins (1993) considered the SLW flux across a number of mountain barriers. They concluded that seeding may be appropriate both when SLW is abundant and when it is more limited. The relatively rare hours with large SLW amounts produce significant flux. But the numerous hours with small SLW amounts also produce significant flux over the course of an entire winter.

2.2 Field Observations of SLW

Huggins (1995) presented seasonal average portrayals of the cross-barrier SLW distribution over the Plateau. That work and other articles herein demonstrate the expected formation of SLW by forced orographic uplift over the west (windward) slope of the Plateau. Embedded convection, usually weak, enhances SLW production during some storm phases, and maximum SLW amounts are found above the windward slope. The gravity wave mechanism can also enhance SLW production as discussed in section 5. Snowfall often begins to reduce SLW amounts by the time cloudy air reaches the Plateau top's west edge, and the reduction continues as air flows eastward across the top (Huggins 1995). Both snowfall and subsiding airflow during passage across the Plateau lead to substantial SLW reduction. The SLW is largely depleted by the Plateau top's east (downwind) edge, approximately 10 km from the west edge, as a result of both snowfall and subsidence of the cloudy air.

Sassen and Zhao (1993) used lidar, microwave radiometer, and other observations to investigate SLW over the Tushar Mountains, about 175 km southwest of the Plateau experimental area. They demonstrated that SLW was usually found at barrier levels in the 0 to -10 °C range. Sassen and Zhao (1993) concluded that SLW cloud thickness was often only 500 to 800 m, with some SLW clouds nearly 1,000 m thick. That finding, along with layer temperature observations, led to their important conclusion that there was only a limited "window" for AgI seeding success. This window involved the upper portions of relatively warm SLW clouds with base temperatures warmer than -7 °C. Clouds with tops colder than -12 °C appeared to efficiently convert SLW to ice particles. Silver iodide is not effective for ice particle formation for temperatures warmer than -6 °C even when high AgI concentrations are present. With the in-cloud AgI concentrations resulting from operational seeding, effective concentrations at prevailing temperatures are often too low for the seeding to produce significant snowfall.

Super (1994) discussed the implications of almost continuous observations during the early 1991 two-month field program. Measurements included SLW by microwave radiometer, gage precipitation, AgI by acoustical ice nucleus counter and supporting observations. Super (1994) concluded that the SLW flux over the Plateau top's windward edge well exceeded the average snowfall over the Plateau top, suggesting that seeding might have the potential to convert some of the "excess" flux to additional snowfall. Moreover, many of the wetter hours had no detectable snowfall. These findings indicated significant seeding potential *if a large fraction of the excess SLW flux could be* *converted to snowfall.*

To put microwave radiometer vertically-integrated hourly amounts of SLW into perspective, Super (1994) compared them with observed hourly snow water equivalents. Accumulations for all 179 h with at least 0.01 inch observed by one or more of the three Plateau top gages provided the median hourly accumulation value of 0.015 inch. Half the total snowfall fell during the 83 percent of the precipitating hours with hourly accumulations of 0.05 inch or less. These data illustrate that mountain snowfall usually occurs at light rates over numerous hours as has been shown at a number of Rocky Mountain locations. Super (1994) calculated the equivalent snowfall rate if all SLW flux was converted to snowfall which fell uniformly across the 10 km wide Plateau top with a typical cross-barrier wind speed of 10 m s^{-1}. He showed that a vertically-integrated hourly SLW amount in excess of 0.10 mm was needed to produce the median hourly snowfall accumulation of 0.015. Sixty-five percent of all hours with detectable SLW over the Plateau top's west edge had average SLW amounts less than 0.10 mm. A significant portion of the SLW will be naturally converted to snow. Therefore, it follows that even when AgI seeding is successful, typical hourly accumulations would be limited. Moreover, hours with SLW amounts less than about 0.05 mm have very limited potential for snowfall production by seeding.

Super (1995a) presented the results from all six early 1991 experiments during which valley-released AgI was detected at lowest aircraft sampling levels over the Plateau. Observations of SLW were presented from a Plateau top microwave radiometer and from aircraft sensors. Temperatures of SLW cloud reached by the AgI were usually only mildly supercooled, and estimated effective AgI ice nucleus concentrations were quite small. Aircraft measurements of ice particle concentrations and gage observations of snowfall indicated that any snowfall increases caused by seeding were at limited rates and occurred only when seeded clouds were colder than -9 °C at aircraft sampling altitudes.

2.3 Summary of SLW Findings

In summary, SLW not utilized in snowfall production often existed over the Plateau during at least portions of storm passages. During the early 1991 and early 1994 major field programs, SLW existed during pre-frontal southwest flow and typically disappeared after frontal passage, as soon as Plateau top winds shifted to northwest. The SLW was confined to a shallow layer less than 1000 m thick (often considerably less) above the Plateau where temperatures were typically mildly supercooled. For example, when vertically-integrated SLW amounts were significant (exceeding 0.07 mm), Plateau top temperatures were colder than -4 °C during less than 25 percent of the hours (Super 1994). The corresponding temperature 1000 m above the Plateau would be about -10 °C for in-cloud lapse rates. These temperature, SLW cloud thickness and percentage values illustrate that effective ground-based AgI seeding of the SLW layer is limited a fraction of the hours when significant SLW is present.

This general portrayal of SLW availability implies that effective seeding must create significant ice particle concentrations in the SLW cloud very soon after condensate is produced during transport of moist air up the Plateau's windward slope. Otherwise, growth times will be too limited for much snowfall production before the SLW is depleted. Accomplishment of ground-based seeding under these circumstances presents a significant challenge, especially with AgI, because the condensate is formed at only slightly supercooled temperatures. This challenge is not limited to the Plateau, as much of the Rocky Mountain region has similar shallow, slightly supercooled liquid water zones as reported by a number of authors.

3. TRANSPORT AND DISPERSION OF GROUND-RELEASED SEEDING AGENTS AND TRACER GAS

3.1 Background Information

Once the generalized distribution of SLW is known over a mountain barrier, it is of obvious interest to consider the transport and dispersion of seeding material to determine when, where, and in what concentrations the seeding material creates ice particles within the SLW cloud. Such transport and dispersion investigations were the second major research objective of the NOAA/Utah AMP.

The Utah operational seeding program has used

AgI for many years, and that seeding material was given priority in the Plateau experiments. Liquid propane seeding, which can create ice crystals at higher temperatures than AgI, was also given serious attention, since it was found that SLW was often too warm for AgI to be effective. Sulfur hexafluoride tracer gas was frequently used to simulate seeding material transport and dispersion because it can be detected in small concentrations by fast-response instruments.

Unless otherwise stated, AgI in this report refers to the aerosol produced by burning AgI-NH_4I-acetone-water solutions in seeding generators. This solution has been used in the Utah operational seeding program, and it was used during the experiments discussed herein, including use of high altitude generators. This aerosol is known to operate by the contact-freezing nucleation mechanism (DeMott et al. 1995), known to be a relatively slow process in typical orographic clouds that have limited cloud droplet concentrations, often between 50-200 droplets cm^{-3} (Rauber and Grant 1986).

3.2 Field Investigations of Transport and Dispersion

Super and Huggins (1992a, 1992b) considered the targeting of ground-released AgI during the early 1990 field program from three different approaches. Silver-in-snow analysis was done with bulk snow samples from 10 sampling sites within the operational seeding program's target area. There was little evidence that silver concentrations in snow from seeded periods were greater than from nonseeded periods. These results were similar to earlier findings from the Tushar Mountains, but quite different from some projects in other states where seeding clearly increased snow silver concentrations by about an order of magnitude (e.g., Super and Heimbach 1983).

Real-time ice nucleus sampling was conducted well up Big Cottonwood Canyon while AgI releases were made with two generators in and above the canyon mouth. The AgI was routinely observed at the surface sampling location, which was about 500 m higher in elevation than the highest AgI generator. However, estimated AgI concentrations were small at prevailing SLW cloud temperatures.

The third approach reported by Super and Huggins (1992b) used aircraft sampling of ground-released AgI and SF_6 during near-storm prefrontal conditions. Sampling was done during times when visual flight rules (VFR) operations were permissible, allowing sampling near the terrain. Four of the five aircraft missions of this type showed the AgI and tracer gas were confined to the boundary layer above the valley floor and were not transported over the Plateau. Plumes were found over the Plateau during part of the fifth mission, but estimated ice nucleus concentrations active at the observed cloud temperatures were quite limited.

Griffith et al. (1992) reported on instrument flight rules (IFR) aircraft sampling during the early 1991 program. Two case studies were selected for detailed discussion. Tracer gas released at the mouth of a major canyon was found over the Plateau during the two aircraft missions at temperatures near -12 to -17 °C, respectively. Ice particle concentrations, calculated from SF_6 measurements, were sufficient for seeding to have been effective. However, it is suspected that natural cloud processes were quite efficient during the unusually cold cloud temperatures of one (March 6, 1991) of the two missions, as very little SLW existed above the Plateau top's west edge or at aircraft levels. Moreover, Super (1995a) reported that the maximum snowfall accumulation for the three Plateau top gages was only 0.01 inch during the entire 3 h experiment. Therefore, even if seeding increased the snowfall from this cold, weak storm, any enhancement was at the trace level.

The Plateau top snowfall during the second mission of March 2, 1991, was also quite limited, even though all eight valley AgI generators had been operating for many hours, and AgI was abundant at relatively cold temperatures where SLW was plentiful. Super (1995a) reported two of the three Plateau top gages detected snowfall during the experiment, but only at trace levels, in spite of a noticeable increase in the aircraft observed ice particle concentration (IPC) within the AgI plume(s). This finding is not encouraging for the valley seeding mode of operation. Even though the March 2 mission was flown under conditions apparently ideal for seeding, and the valley-released AgI was transported to sufficiently cold SLW levels, any resulting snowfall was insignificant. It is speculated that AgI nucleation occurred too late for snowflake growth and fallout to occur on the Plateau.

Super (1994) examined SLW, snowfall, and AgI during 12 experimental days of the early 1991 season when valley seeding was being conducted. Using the then most current 1981 calibration of the NAWC generator Super (1994) concluded that the AgI concentrations measured on top the Plateau were insufficient for effective seeding unless the AgI reached SLW colder than about -12 °C. Even using the more optimistic AgI generator calibration reported by DeMott et al. (1995), estimated effective ice nucleus concentrations were too low as discussed by Super (1995a).

3.3 Analyses Based on Recent Laboratory Studies

A subset of the early 1991 data reported by Super (1994) has been reexamined for this paper using the latest calibration data for the NAWC AgI generator from DeMott et al. (1995). Values were used for "natural draft" conditions typical of light valley winds during seeding. An even 100 h from seven different relatively wet storm episodes met the following criteria: The eight valley AgI generators had been on for at least 2 h to allow for transport time, microwave radiometer SLW equaled or exceeded 0.05 mm above the Plateau top's west edge, and the co-located NCAR acoustical ice nucleus counter operated properly with its cloud chamber temperature near -20 °C.

The NCAR counter mean ice nucleus concentration (INC) observations for the 100 h were multiplied by 3.0 to bring them in line with the Colorado State University (CSU) calibration of this device based on the isothermal cloud chamber results, also at –20 °C. A correction was applied to the cloud chamber values to compensate for dilution airflow (DeMott et al. 1995). For the uncorrected values usually provided by CSU generator calibrations, the two NCAR counters tested were found to indicate about two-thirds of the INC observed in the Isothermal Cloud Chamber, and the two NCAR counters tested at CSU consistently agreed. A third NCAR counter, not tested at CSU, had also been used during the Plateau experiments. Periodic side-by-side comparisons showed consistent results among all three units in the field.

An adjusted INC exceeding 10 L^{-1} at -20 °C can be considered clear evidence of AgI presence because the natural background observed during many hours without seeding was rarely that great, usually being in the 0 to 5 L^{-1} (adjusted) range. Ninety percent of the 100 sampled hours meeting the stated criteria showed evidence of AgI, with the adjusted INC exceeding 10 L^{-1}. Half the hours exceeded 500 L^{-1}, effective at -20 °C, and 10 percent of the hours exceeded 2,000 L^{-1}. Therefore, the AgI was usually transported from the valley up to the canyon head, a vertical distance of over 900 m. This is remarkable when is it realized that valley-based inversions are common during winter storms. However, most hours with SLW amounts of 0.05 mm or greater had weak embedded convection present, which likely assisted vertical AgI transport.

As discussed by Super (1994, section 8.3) these 100 sampled hours may be atypical of most hours with SLW present because of the high frequency of embedded convection and associated large SLW amounts. Many additional hours were sampled, which have not been reported in the literature, during which very large AgI concentrations were confined to a shallow layer over the Sanpete Valley. A large fraction of these hours also had SLW present above the Plateau, although average amounts were less than the 100 h sample just discussed. During several experimental periods, the only AgI that could be found with an instrumented vehicle carrying an NCAR counter were within about 100 m elevation of the valley floor. During these experiments, when only background INC was found along the Plateau top, the vehicle was driven down a major canyon toward the town of Fairview in the valley. The INC effective at -20 °C would abruptly shift from background levels of 1-3 L^{-1} within the canyon to many thousands per liter as the vehicle passed below the canyon mouth just above Fairview. The NCAR counter would become saturated with ice crystals so absolute INC cannot be quantified beyond stating that they were at least thousands per liter. Clearly, as the eight valley generators were operated hour after hour, they produced vast quantities of AgI aerosol, trapped in a shallow layer above them. Valley winds during these events were no more than a light northward drift.

In spite of observations of trapped AgI during a number of experiments, it appears that the valley-released AgI was often transported to Plateau top altitudes when SLW was reasonably abundant as represented by the 100 h data set discussed above. However, it is necessary to consider the adjusted NCAR counter INC values in the context of typical Plateau top temperatures which are much warmer than the -20 °C cloud chamber operating temperature. For example, the median Plateau top temperature during all 100 h was a mild -2.6 °C, while the median for the 50 wettest hours, with SLW exceeding 0.16 mm, was an even warmer -1.5 °C. The latest calibration of the NAWC generator shows that the effective INC at -6 °C, the warmest temperature sampled in the CSU Isothermal Cloud Chamber, is only 1/4 of 1 percent of that at -20 °C. Hence, even an adjusted NCAR counter INC of 2,000 L^{-1} yields an estimated effective INC of 5 L^{-1}, considered too low for significant snowfall production (Super 1994, section 8.2). Furthermore, only 9 of the 100 h were colder than -6 °C at the Plateau top altitude of 2700 m.

A more recent data set by Holroyd and Super (1998) showed that the Plateau top temperature was colder than -7 °C during only 20 percent of AgI seeding experiments conducted during the 1994-95 and 1995-96 winters. Temperatures were even warmer during many other experiments when liquid propane seeding was attempted. These large data sets leave no doubt that SLW near the Plateau top is typically only slightly supercooled during storm episodes.

The CSU generator calibration showed that at -8°C the effective INC was 8 percent of that at -20 °C, while the effective INC increased to 33 percent at -10 °C. If the AgI concentrations measured on the Plateau existed at higher altitudes corresponding to these temperatures, the median effective INC would be 40 and 165 L^{-1}, respectively. Such concentrations would be considered sufficient for effective seeding. However, for typical in-cloud lapse rates, the stated temperatures would be about 800 and 1,100 m above the Plateau for the median Plateau top temperature of -2.6 °C.

Aircraft observations were made during six experimental days when valley-released AgI was transported to the lowest permissible aircraft sampling altitude, about 600 m about the average Plateau top terrain as reported by Super (1995a). Four of these experiments were conducted on some of the same days that provided the 100 h Plateau top data set just discussed. The aircraft missions showed that AgI concentrations 600 m above the Plateau were typically more than an order of magnitude less than those measured on top of the Plateau, both at the fixed canyon head site and by an instrumented vehicle driven along the Plateau top's west edge. Some of the lowest aircraft passes failed to detect any AgI during these experiments. On some other experimental days the aircraft failed to detect any AgI even though many passes were made while abundant AgI concentrations (at -20 °C) were being monitored on the Plateau. The considerable body of aircraft observations from many experimental days has shown that AgI is rarely transported as high as 1,000 m above the Plateau, and then only in weak concentrations.

Another important factor to be considered is the rate at which AgI activates ice particles. The discussion above presents the most optimistic case in which calculations of effective AgI concentrations assume total nucleation by the aerosol. However, CSU Isothermal Cloud Chamber AgI generator calibrations are done over extended periods, often tens of minutes, to allow aerosol the time necessary to nucleate. NCAR counters are operated at very high cloud droplet concentrations to enhance nucleation during their limited cloud chamber residence time. But Rocky Mountain orographic clouds have limited droplet concentrations (Rauber and Grant 1986).

DeMott et al. (1995) show that the AgI aerosol produced by the NAWC generator and the AgI-NH_4I-acetone-water solution operates by contact nucleation, a slow process. They calculated that, for a constant temperature, only about 7 percent of the potential yield would be realized during a 20 minute transit of this AgI aerosol through a natural cloud of 100 droplets cm^{-3}. Simple calculations of transport times within SLW cloud over the Plateau show that AgI will be exposed to liquid cloud on the order of 20 minutes. Therefore, prior calculations of INC effectiveness, based on NCAR counter measurements and the latest CSU generator calibration, are probably overestimated by more than an order of magnitude. The sooner ice particles are formed within SLW cloud, the greater their probability of growing to snowflake sizes and settling to the surface before being transported beyond the mountain barrier.

These INC observations indicate a limited window of opportunity for effective AgI seeding

"REVIEWED"

since measurements have shown little evidence of significant ice particle enhancement in cloud warmer than -9 °C. This finding is in agreement with the Tushar Mountains observations presented by Sassen and Zhao (1993). Both data sets demonstrate the difficulty of effective ground-based AgI seeding with mildly supercooled orographic clouds typical of Utah's mountains. Seedable opportunities are limited to the colder "tail" of the distribution of SLW temperatures.

Further evidence on this point was provided by the Bridger Range Experiment conducted in the colder climate of southwestern Montana. Statistical analysis of that experiment by Super and Heimbach (1983), later supported by aircraft microphysical observations (Super and Heimbach 1988), strongly suggested that AgI seeding from high altitude sites was effective only when ridge top (equivalent to Plateau top) temperatures were colder than -9 °C. About half the Bridger Range experimental periods were that cold. But if one assumes similar vertical transport of AgI over the Bridger Range and the Plateau, as aircraft observations have indicated, a much smaller fraction of Utah storm periods would be seedable with AgI. This comparison further indicates that effective ground-based AgI seeding in Utah is limited to a fraction of the time that SLW is available. Moreover, at least a portion of the apparent success of the Bridger Range seeding may have been due to the frequent in-cloud operation of the AgI generators, with instantaneous ice particle production caused by the supersaturated conditions very near the generators (Finnegan and Pitter 1988). It is known the AgI generators produce abundant quantities of water while consuming propane fuel and the acetone in which the AgI is mixed. This can lead to local condensation-freezing as soon as the AgI aerosol is exposed to the quite supersaturated and supercooled cloud. This rapid ice nucleation mechanism will not occur with valley-released AgI.

3.4 Seeding-Induced Snowfall Calculations

Laboratory observations have indicated that the NCAR counters used in the Plateau studies were in reasonable agreement with CSU Isothermal Cloud Chamber results. Plateau-top and aircraft observations of ice particle concentrations have been shown to be in reasonable agreement with NCAR counter estimates of effective ice nucleus concentrations using CSU generator calibrations to extrapolate to temperatures warmer than the -20 °C NCAR counter cloud chamber temperature. Therefore, it is reasonable to use CSU generator calibration data to calculate upper limit snowfall increases possible with the Utah operational seeding.

It will be assumed in the following calculations that seeding-induced ice crystals do not participate in any secondary "ice multiplication" process. That is, any single AgI aerosol particle will have the potential to produce only one ice crystal. There is ample justification for this assumption. The conditions necessary for significant ice particle multiplication to occur are reasonably well understood (Mossop 1985). Such conditions are not characteristic of Rocky Mountain orographic clouds, especially at the colder temperatures where AgI can be effective.

The latest CSU calibration of the NAWC generator, for the AgI solution used in Utah's operational seeding, can be used to show that it is highly unlikely that the Utah operational seeding program produced the snowfall increases suggested by previously cited statistical analyses. The normal April 1st snow water equivalent found at snow courses in or near the Plateau's experimental area is about 50 cm. The most recent statistical analysis by the seeding operator (Griffith et al. 1997) suggests that about a 15 percent seasonal increase was achieved, equivalent to 7.5 cm for a normal winter. Using the typical AgI generator spacing of 16 km (Griffith 1996) and approximate Plateau top width of 10 km provides an estimated area per generator of 1.6×10^{12} cm^2. The water volume provided by a 7.5 cm increase would be 1.2×10^{13} cm^3, equivalent to 1.2×10^{13} g of water mass.

We will make the highly optimistic assumption that *all the AgI aerosol reached SLW cloud at a relatively cold temperature of -8 °C.* This is contrary to the large NOAA/Utah AMP data set which indicates that only limited AgI reaches cloud temperatures that cold. The CSU calibration indicates the generator output at –8°C is 1.4×10^{14} crystals g^{-1} for natural draft conditions. We will make the additional highly optimistic assumption that *all the available aerosol nucleated ice crystals at that temperature*. Then the resulting seasonal output of ice crystals can be calculated as 2.8×10^{17}, since generator output is 8 g h^{-1} (Griffith et al. 1992), and the generators are operated for about 250 h per 5 month winter (Super and Huggins 1992a, table 2). These crude and quite optimistic calculations yield an average mass per ice crystal of 0.04 mg per crystal. But as discussed by Super and Huggins (1992a) and Super (1994), observations from a number of locations show that the mass of a typical natural ice crystal is less than half that value. Furthermore, seeding-caused ice crystals are likely to be smaller because of less in-cloud residence time.

These calculated results would require that *all AgI reached a significantly colder temperature than supported by the multitude of field observations.* In reality, AgI was sometimes trapped in the upwind valley and did not reach SLW cloud. When it was transported over the Plateau, the bulk of the AgI was typically in a thin layer where temperatures were too warm for significant ice crystal formation. Often, this layer contained negligible SLW because natural snowfall processes consumed it. In-cloud residence times provided a further limitation to AgI nucleation ability. Finally, natural snowfall could be expected to sweep out some AgI aerosol. For all these reasons, the above calculations of the typical ice crystal mass which AgI would need to produce to achieve a 15 percent seasonal snowpack increase are excessively low. During the fraction of the time when storm conditions made it possible for seeding to create ice crystals, they would have to grow to unrealistically large sizes (masses) to produce the claimed 15 percent increase. *Therefore, such reported increases could not be the result of the Utah operational seeding program according to current physical understanding.*

Additional information on transport and dispersion is provided in the following two sections. It will be shown that release from high altitude locations, well up the windward slopes of the barrier, results in much more consistent transport over the Plateau. However, plume widths may be reduced as compared to valley releases. The vertical dispersion of the high altitude releases is not believed to be markedly different from valley releases. Both plume types were often found at, and limited to, the lowest aircraft sampling levels and below. Both plume types were sometimes too shallow for detection at even the lowest permissible aircraft sampling altitudes.

4. RESULTS OF PHYSICAL CLOUD SEEDING EXPERIMENTS

4.1 Background Information

There is no doubt that AgI released into sufficiently cold SLW cloud will produce multitudes of embryonic ice particles. The same result is achieved when liquid propane is expanded into even slightly supercooled liquid cloud. The challenge is to create seeding-induced ice particles at such locations that their subsequent trajectories will be within SLW cloud for a sufficient time (distance) to permit growth to precipitation sizes. The expectation is that some of the precipitation-sized ice particles will fall to the mountain surface as snow before sublimating in the lee subsidence zone. Ideally, the tiny seeding-caused crystals should be formed very soon after SLW condensate is produced as air is forced up a mountain barrier, is carried upward by embedded convection, is transported upward by gravity waves, or ascends by some combination thereof. Releasing AgI even at cloud base will not result in immediate nucleation unless the temperature is colder than -6 °C.

Numerous attempts were made to document the effectiveness of AgI and propane seeding in creating ice particles and snowfall during the Plateau experiments. Most emphasis was placed on such documentation during the limited programs of the 1994-95 and 1995-96 winters, as summarized by Super and Holroyd (1997) and Holroyd and Super (1998).

With two exceptions previously noted (March 2 and March 6, 1991) and discussed by Super (1995a), all AgI and propane seeding experiments which demonstrated IPC enhancements used high altitude release sites well up the windward slope of the Plateau. Unless specifically mentioned otherwise, it can be assumed that high altitude seeding sites were used in the cases to be discussed.

4.2 Case Study Analyses

The first article in this series to document seeding-caused ice particles was by Super and Holroyd (1994). A several-fold enhancement in IPC was shown at aircraft levels for the

"REVIEWED"

experiment of February 17, 1991. The co-located AgI and SF_6 were both detected with aircraft instruments. Measurement of SF_6 with a fast-response detector allowed for precise delineation of the seeded zones. Seeding-caused IPC was near 70 L^{-1} at cloud temperatures of -13.0 to -15.5 °C over the Plateau top's west edge.

Holroyd et al. (1995) presented a detailed analysis, with numerical modeling support, of the February 21, 1994, experiment. It was shown that high concentrations of ice particles were associated with measured and predicted plume locations sampled on the Plateau top with an instrumented 4-wheel drive vehicle, and above the Plateau with the NOAA aircraft. Ice particle concentrations and precipitation rates were enhanced by a factor of about 10 along the Plateau top's west edge highway, and by about a factor of 40 according to aircraft sampling above the west edge. Most growth was upwind of these sampling tracks, that is, above the windward slope where SLW was concentrated. Aggregation of high concentrations of ice particles appeared to be the primary snowfall mechanism. Plateau top observations suggested that only limited precipitation reached the surface, perhaps 0.5 mm accumulation over a few hours at some gages. But no gages were sited near the windward edge where most seeding-induced snow likely fell.

Super (1995b) presented detailed analyses that demonstrated an obvious increase in IPC and snowfall associated with the propane seeding experiment of March 5, 1995. Less obvious but still fairly convincing evidence of IPC and snowfall enhancement was presented from an experiment on March 11, 1995. Light natural snowfall "contaminated" the impacts of propane seeding during the latter experiment.

Super (1996) showed another obvious case of IPC and snowfall enhancement caused by AgI seeding during relatively cold Plateau top temperatures (-10.7 °C). This seeding, on December 15, 1994, produced about 1 mm additional snowfall on the Plateau top's west edge during the hour of seeding. The successful March 5, 1995, propane experiment at a Plateau top temperature of -4.5 °C was again reviewed, and it was shown that AgI seeding soon after the propane seeding was ineffective under similar conditions.

Significant documentation of seeding-caused IPC and snowfall resulted from the 1994-95 and 1995-96 winter field programs. This could be expected since these limited, economical experiments were designed for that purpose. Moreover, it was practical to conduct many such experiments with only limited ground equipment and two to three field technicians. The basic design was to release seeding material, AgI or propane, in a brief "pulse" of one-half hour or one hour duration. The release point (HAS on figure 1) was on a high, exposed ridge only 4.2 km horizontal distance and 315 m below the instrumented "target" site (TAR on figure 1) located at the head of a major canyon. Prevailing southwest winds funneled the seeded cloud up the canyon and past the target. Ice particle characteristics and snowfall rates could be examined before, during, and after plume passage of the target.

Some experiments provided obvious IPC enhancement, and sometimes snowfall augmentation, when examined on a case study basis. However, seeding effects were not obvious in most of the experiments. Some of the failures to clearly demonstrate IPC increases were caused by cloud temperatures too warm for seeding agent effectiveness, especially when AgI was used. Other failures were due to short-term natural variability of snowfall rates that often masked the signal produced by any seeding-caused ice particles. It is likely that many of the seeding experiments created tiny crystals that were swept out by larger natural snowflakes and, therefore, were undetectable by the experimental design. Furthermore, abundant natural snow may have consumed all available SLW, thereby starving the embryonic seeding-induced crystals. This series of experiments showed the difficulties of clearly demonstrating ice particle and snowfall production in the presence of even light natural snow. Orographic clouds are not steady-state, and natural snowfall rates often vary considerably over a few tens of minutes or less.

4.3 Statistical Analysis of Pulsed Seeding Experiments

When natural snowfall was none to very light and seeding potential existed, obvious effects of seeding could be demonstrated (Super and Holroyd 1997). But such conditions occur during a minority of the time that orographic cloud is present. However, statistical analysis provided an overview of all similar experiments conducted during the 1994-95 and 1995-96 winters (Holroyd and Super 1998). There were indications of AgI effectiveness in creating small ice particles when target (Plateau top) temperatures were colder than about -6 °C. However, the number of such cases was limited because less than 20 percent of all seeding experiments had target temperatures colder than -7 °C. Stronger evidence existed of propane-caused small ice particles, and even the difference between using one propane nozzle (1994-95 winter) and two nozzles (1995-96 winter) was evident. Snowfall increases caused by the seeding-caused crystals were limited, as might be expected from the limited distance (4.2 km) and travel time (median 17 min) between seeding release and the target. This distance was purposely limited to maximize successful targeting as the seeded cloud was funneled up a major canyon.

Perhaps the most important finding of these "pulse seeding" experiments was that propane seeding was effective in producing ice particles even with slightly supercooled cloud at the dispenser site (-0.4 to -3.4 °C). About 10 ice particles L^{-1} was typical at the target with one propane nozzle releasing about 3 gal h^{-1}, and 20 L^{-1} with two nozzles releasing twice that rate. As argued by Super (1994), a seeded IPC over a target in excess of 10 L^{-1} has the potential to produce meaningful snowfall. Holroyd and Super (1998) confirm that view as their figure 3 shows only a small fraction of the many hours with significant natural snowfall at the target had IPC less than 10 L^{-1}. The target IPC during natural snowfall was usually between 20 to 200 L^{-1}. Some operational programs have attempted to enhance snowfall with estimated IPC near 1 L^{-1}. Such an approach would have a negligible chance of success in Utah and probably elsewhere.

Cases with target temperatures colder than -4 °C were usually seeded with AgI, but no evidence of AgI ice particle production was evident with target temperatures warmer than about -6 °C. As noted, periods with SLW cloud infrequently have Plateau top temperatures colder than -6 °C, which seriously limits the window of opportunity for ground-based AgI seeding unless significant vertical dispersion occurs. These experiments did not sample above the target (Plateau top) elevation, but earlier work demonstrated vertical dispersion of AgI was limited.

5. NUMERICAL MODELING RESULTS

5.1 Background Information

Numerical modeling provided significant insight into the physical processes involved during winter orographic storms over the Plateau. The model used in these investigations was the sophisticated, three-dimensional, time dependent numerical model developed by Terry Clark and associates at NCAR.

Modeling results should be treated with caution until it is demonstrated that they are in reasonable agreement with observations. However, observations are limited in time and space and are impractical to make in some very important locations over mountains. Therefore, model results can fill in where observations do not exist, provided model results and observations are in good agreement where both exist.

The Clark model was applied to the Mogollon Rim of Arizona, as discussed by Bruintjes et al. (1995). They showed the model was quite successful in reproducing the dispersions of SF_6 tracer gas observed during 1987 experiments (Super et al. 1989). The importance of gravity wave dynamics in the transport and dispersion of seeding material was demonstrated by their work.

5.2 Model Applications to the Wasatch Plateau

Heimbach and Hall (1994) discuss the Clark model and its application to the Plateau. They compared model results with a well-observed case from the early 1991 field season which involved seeding with valley AgI generators. Reasonable agreement was found with AgI plume positioning. Considerable pooling of AgI occurred within the valley, but a shallow layer was eventually transported over the Plateau. The importance of gravity waves in seeding agent vertical transport was demonstrated in agreement with the results of Bruintjes et al. (1995). Gravity waves were also found to be influential in the production of liquid water and its subsequent downwind depletion in zones of subsidence. The horizontal and vertical position of the seeding release point was critical in determining whether the model-simulated seeding agent was transported over the Plateau for particular conditions.

Modeling results also suggested that seeding from the San Pitch Mountains, the next barrier west (upwind) of the Plateau, might provide broader plumes, earlier ice nucleation, and opportunity for greater vertical transport. These factors might increase seeding effectiveness if embryonic seeding-induced crystals that formed over the San Pitch Mountains were transported into the SLW condensate zone over the Plateau's west slope, where further growth and fallout could occur. A similar approach was apparently successful during the Bridger Range Experiment (Super and Heimbach 1983), although the valley between the barriers was narrower. The approach of seeding on the windward slopes of one barrier to affect another farther downwind should receive further consideration in view of limited growth times found over the Plateau (e.g., Huggins 1995).

Reasonable model agreement with observations was found in the case of a high altitude ground release of AgI reported by Holroyd et al. (1995). This experiment produced marked IPC enhancement on and above the Plateau top and apparently limited accumulations of snowfall. The heights to which model-simulated AgI plumes reached were in good agreement with aircraft measurements. The model's smoothed terrain failed to simulate some of the small-scale but important effects of major canyons which funnel the airflow. The model produced weak and shallow clouds that were driven orographically with little buoyant contribution. Gravity waves were shown to be important for transport over the Plateau and produced a secondary maximum of simulated AgI over the eastern portions of the Plateau.

Heimbach and Hall (1996) and Heimbach et al. (1997) modeled a well-observed case study during which AgI was released from three valley generators and tracer gas was released in a major canyon mouth. In spite of a surface inversion, the AgI was transported up and over the Plateau in a shallow layer, below minimum aircraft sampling levels. The model results suggest the initial vertical impetus for vertical transport was by the gravity wave mechanism. This was followed by orographic forcing in a more organized westerly flow. The model simulation predicted the observed confinement of the AgI to a shallow layer.

5.3 Modeling of Generalized Weather Classes

Valley AgI seeding was modeled for five generalized weather classes by Heimbach et al. (1998). A total of 46 rawinsonde observations from the early 1991 and early 1994 field programs were grouped into five classes according to temperature profiles. (Nineteen additional soundings did not fit within the five class criteria.) In general, the modeled results were in agreement with well observed case studies selected to represent each sounding class. Some of the important results from the modeling include:

a. A tendency frequently existed for a low-level northward drift of the valley-released AgI, parallel to rather than over the Plateau.

b. Poor targeting resulted from valley releases during the two most stable classes. Thirty-seven percent of the classified soundings were in these two classes.

c. The best targeting was with the most unstable class, which also had the coldest temperatures, thereby resulting in greater AgI effectiveness in ice particle production. Twenty-six percent of the classified soundings were in this class.

d. Warm temperatures over the Plateau frequently resulted in negligible AgI effectiveness even when transport over the barrier occurred.

e. Strong upward motion existed over the valley under some stability and wind conditions because of gravity wave transport. This mechanism can significantly aid the transport of valley-released AgI, but its presence, magnitude, and location vary markedly with time.

f. Mechanical forcing is important for AgI transport over the Plateau.

g. In some conditions, there can be a westward and north-westward drift of valley-released tracer in spite of organized westerly flow aloft.

5.4 Summary of Model Results

In summary, the Clark model results were in good agreement with field observations. Valley-released AgI was often trapped by surface-based inversions and usually drifted northward, parallel to the Plateau, rather than over it. Sometimes the drift was westward or north westward, contrary to flow aloft. Very large AgI concentrations were modeled (and observed) along the valley floor on several occasions after generators had been operated for several hours.

A gravity wave mechanism sometimes aided the vertical AgI transport even in the presence of inversions. The positioning of the gravity waves relative to the terrain and AgI generator locations was critical in determining whether vertical AgI transport occurred. Since gravity wave positioning varies with time, and AgI generators are at fixed locations, it can be argued that generators should be located at various distances west of the Plateau across the broad upwind valley. Heimbach and Hall (1994) modeled this latter approach.

During more unstable conditions, the valley-released AgI was consistently transported over the Plateau. The AgI plumes were consistently shallow over the Plateau top, often below lowest aircraft sampling levels about 600 m above average Plateau top elevations. Prevailing cloud temperatures within the shallow plumes were frequently too warm for effective ice nucleation by the AgI.

It has been demonstrated by model-simulations and observations that valley-released AgI is transported over the Plateau during only a minority of hours with storm conditions. When transport does occur, the AgI plumes are often too warm for much ice nucleation. These two factors are in agreement with previous documentation from the Tushar Mountains of southern Utah (e.g., Sassen and Zhao 1993). These findings suggest that valley AgI releases should be augmented or replaced with other treatment technologies (e.g., high-altitude AgI releases and propane seeding) in order to increase the efficiency of the Utah operational cloud seeding program.

6. MISCELLANEOUS ASSOCIATED WORK

A number of topics were explored during the Plateau program that do not fit under the above section headings. Consequently, these are included here.

6.1 Effect of Type II Statistical Errors on Experimental Duration

Heimbach and Super (1992, 1996) explored the important problem of encountering type II statistical errors in past randomized weather modification experiments. A type II error occurs when an experiment fails to detect an actual response to seeding, usually because the experimental unit population is too limited. Many experiments did not estimate the duration (population size) needed to achieve an acceptably low probability of encountering a type II error, say 10 percent. If an experiment failed to indicate a seeding effect upon completion (usually determined by the sponsor's patience and available resources), a type II error may have caused the "failure". The only valid conclusion from such an experiment is that it failed to demonstrate anything about seeding effectiveness. Unfortunately, the incorrect interpretation is often given, that is, that the seeding approach did not produce the desired effect.

When attempts were made to estimate the experimental duration needed to demonstrate real seeding effects, it was usually assumed that each treated unit would respond in the same manner. A considerable body of physical evidence shows this assumption to be improbable. The effectiveness of seeding can be expected to vary widely depending upon cloud and airflow conditions. Heimbach and Super (1992, 1996) investigated the more likely possibility that different experimental units (storms or days) have different responses to treatment. They demonstrated that this more realistic response leads to much longer experimental durations than if every treated unit responded uniformly. This important finding raises the question of whether many past seeding experiments interpreted as failures were simply too brief to demonstrate real seeding responses. Of course, if their physical design was flawed, they should have failed whatever their duration. But the point is that little can be gleaned about the seeding effectiveness of many past statistical experiments because of the uncertainty of whether they had type II errors. While Heimbach and Super (1996) made recommendations for possible improvements in future statistical experiments, their main recommendation was that such experiments be postponed until a much improved physical understanding emerges. An improved physical understanding was the main goal of the NOAA/Utah AMP work.

6.2 Runoff Increases Associated with Snowfall Enhancement

Super and McPartland (1993) reported on an investigation of likely runoff increases from an *assumed seasonal snowpack increase of 10 percent*. Cloud seeding programs are usually evaluated in term of seasonal percentage increases of snow water equivalent, but water users are interested in streamflow enhancement. Historical snow water equivalent and streamflow measurements were used from high elevation watersheds in the Upper Colorado River Basin. Drainages were selected for which streamflow measurements were not significantly affected by upstream diversions and were not regulated by upstream reservoirs. A simple linear regression analysis predicted seasonal streamflow increases between 6 and 21 percent. Ten percent or more additional runoff was estimated for most drainages for the assumed 10 percent snow water equivalent increase, an encouraging result. Reasons for differing responses were discussed which included variations in geology, vegetation, drainage slope, and aspect.

6.3 New Instruments and Observational Approaches

A number of new instruments and observational approaches were developed and deployed during the NOAA/Utah AMP. For example, the mobile microwave radiometer (Huggins 1992, 1995, 1996; Wetzel et al. 1996) provided a useful new way to map SLW over a mountain barrier. This approach is particularly important when it is recognized that safety concerns often prevent instrumented aircraft from flying low enough to monitor the orographic cloud SLW field in the region where most snow particles grow. It is also far less expensive to operate a radiometer than an aircraft. If it turns out that SLW detection is needed to initiate seeding, the radiometer is a more cost effective way to monitor SLW.

Truck-mounted NCAR counters and SF_6 detectors were used in tracking plumes up and over the Plateau. One truck carrying plume detection equipment also had a vane-mounted 2D-C laser probe on a mast above it. The vane kept the probe pointed into the resultant wind as the truck was driven along the Plateau top, while an anemometer controlled the 2D-C strobe rate. Tower-mounted 2D-C probes, also pointed into the wind by vanes, provided similar ice particle observations at fixed locations (Super and Holroyd 1997). Use of vane-mounted 2D-C probes provided a new and more accurate means of observing ice crystals caused by seeding. As it became available in the early 1990s, Global Positioning System (GPS) equipment was used to record truck and aircraft positions.

Super (1993) reported on testing of an automated, self-antifreeze-recharging, recording precipitation gage in a winter mountain environment. This gage, manufactured by Electronic Techniques, Inc. (ETI), was shown to be as accurate as the conventional Belfort Universal gage which requires manual service and chart reduction.

Two methods of estimating AgI ice nucleus concentrations effective at cloud temperatures sampled by aircraft were discussed by Super and Holroyd (1994). One method used tracer gas concentration measurements while the other was based on NCAR counter observations. Both methods were compared with the preferred, but often unavailable, approach of directly observing resulting ice particle concentrations with a laser probe. The methods were found to provide reasonable first approximations for the AgI aerosol and cloud conditions sampled by the study.

The tracking of AgI and SF_6 tracer gas with instruments on aircraft and ground vehicles was important in many of the reported studies. The sometimes maligned NCAR acoustical ice nucleus counter was shown to closely approximate AgI observations made by the "standard" CSU Cloud Simulation Laboratory (DeMott et al. 1995). Of course, the counter must be in good condition and must be maintained by someone knowledgeable in its proper operation. Several past applications used faulty NCAR counters or insufficiently trained counter operators. The three NCAR counters used during the Plateau experiments were often compared with one another and consistently found to be in good agreement.

Considerable effort was expended in calibrating and comparing fast response SF_6 detectors during the field programs. Known concentrations of the gas were injected into the detectors at frequent intervals. Like NCAR counters, these instruments also require significant maintenance and knowledgeable operators.

The CSU laboratory studies by DeMott et al. (1995) provided a new calibration of the NAWC AgI generator. It demonstrated that improvements had been made since the last calibration because warmer temperature ice particle yields were significantly enhanced. In addition to the generator calibration with the standard AgI-NH_4I-acetone-water solution used Utah operational seeding, one was done with a solution also containing sodium iodide and paradichlorobenzene. This latter solution was expected to produce ice nuclei that operated by the condensation-freezing mechanism. Laboratory tests showed that ice crystal production rates were much faster with the latter solution. The results imply that an order of magnitude increase in ice crystal formation could be obtained simply by switching seeding solutions. It is strongly recommended that such a change be made in the operational program.

Considerable development, testing, and improvement of liquid propane dispensers was accomplished during the Plateau program. These dispensers were used during many of the seeding experiments. Propane dispenser development was based on important earlier work by Reynolds (1991) in California. A totally automated propane seeding system was constructed (Super et al. 1995). An icing rate meter detected SLW at the main propane dispenser site, and that dispenser and two satellite dispensers were turned on and off as appropriate by programmed data loggers. All propane dispensers were on high elevation exposed ridges well upwind of the main barrier. This automated system remains in operation in the mountains east of Ephraim, Utah, and a similar dispenser was recently deployed to the Wind River Range of Wyoming (Roger Hansen, personal communication).

Cripps and Abbott (1997) developed a prototype icing rate meter for possible use with propane dispensers. Ideally, each dispenser would be activated by its own icing rate meter whenever SLW was detected at the dispenser. It was hoped that more economical units could be developed, using direct current electrical power from solar panels. While initial tests were promising, additional field tests and possible modifications would be required before the device could be considered operational.

7. SUMMARY AND RECOMMENDATIONS

7.1 Overview

Results of the final several years of the NOAA/Utah AMP program, conducted on central Utah's Wasatch Plateau from early 1990 through early 1996, are summarized in this paper. Considerable earlier work accomplished on the Tushar Mountains of southern Utah has been presented elsewhere.

The main goals of the NOAA/Utah AMP have been to investigate the effectiveness of the Utah winter operational (applied) cloud seeding program and to recommend ways to improve that program's effectiveness. Findings and recommendations have been reported to the NOAA AMP and to the Utah Division of Water Resources. The latter agency partially sponsored the operational program in cooperation with local water user groups. Operational program sponsors obviously have decision making authority concerning implementation of changes suggested in this paper and elsewhere.

Findings and recommendations have been provided in various levels of detail. An extended overview is given in this paper. The reader is referred to the original 29 articles and conference papers for complete discussions of the various investigations. Finally, for anyone interested in greater detail, various contractor reports and field operation plans exist which are not listed herein.

7.2 Key Physical Questions

The NOAA/Utah AMP did not pursue statistical evaluations of the operational seeding program because of the many difficulties and uncertainties involved with such analyses as referred to in section 1. Rather, the NOAA/Utah AMP used physical observations and reasoning, including sophisticated numerical modeling, to investigate the key processes involved in winter orographic cloud seeding aimed at snowfall augmentation. As noted in section 1.2, the key physical questions involved in evaluation of such seeding can be briefly stated as follows:

1. When, where, and in what quantities does SLW exist within orographic clouds in excess of that naturally converted to mountain snowfall?
2. When, where, and in what quantities does the seeding agent affect the SLW cloud, converting portions of it to embryonic ice particles? In Utah, the operational seeding agent has been AgI produced by valley generators using the acetone-silver iodide-ammonium iodide solution.
3. When, where, and in what quantities do the seeding-induced ice crystals grow to snowflake sizes and fall to the mountain surfaces?

Most of the investigations reported during the NOAA/Utah AMP addressed one of more of the above questions.

7.3 Key Physical Findings

Brief answers to the above questions, based largely on the work reported herein, are now stated.

a. A considerable body of evidence from the Plateau investigations and some other work shows that significant SLW cloud exists over western mountains in excess of that naturally converted to snowfall. This "excess" SLW flux represents a large fraction of seasonal snowfall amounts. While the existence of excess SLW water cloud has been assumed for decades, and is necessary for operational seeding to have any potential, adequate documentation has been provided only during the past several years. Field deployment of microwave radiometers has been especially important in this documentation.

b. Orographic cloud SLW varies rapidly in time and space. Some of the greatest SLW amounts have been found during storms with strong synoptic support which are naturally very efficient snow producers during some phases but inefficient during others. Conversely, weaker localized storms typically produce lesser SLW amounts but these persist over many hours per winter. Both storm types are important in total seasonal SLW flux production.

c. Orographic cloud SLW is usually found over the windward slopes and crests and rapidly diminishes further downwind, even as cloudy air moves across the relatively flat Plateau top, about 10 km wide. The SLW is depleted by a combination of snowfall production and subsidence.

d. The SLW cloud is confined to a shallow layer above the Plateau. Most SLW condensate exists in the lower 500 m above the terrain and SLW amounts are usually negligible by 1,000 m above the terrain. Forced orographic uplift, weak embedded convection, and gravity waves all combine to produce the liquid condensate.

e. The SLW cloud found near the mountainous terrain is typically mildly supercooled over Utah's mountains. Frequently, the SLW cloud is too warm for significant ice nucleation with AgI, except perhaps in its upper portions. Often natural ice nucleation processes become efficient as cloud temperatures become cold enough for effective AgI nucleation. Consequently, the window of opportunity for effective AgI seeding is limited to a fraction of the periods with excess SLW. To restate this important point, *most SLW periods cannot be effectively seeded with the present type of operationally applied AgI, especially when it is released from the ground with resulting limited vertical dispersion.*

f. The frequency of successful transport of AgI plumes over the Plateau is directly related to generator elevation relative to the mountain barrier. Plumes released from high altitude sites within 300 to 500 m of the Plateau top were routinely transported over the barrier when winds had a cross-barrier component, necessary for significant SLW production. Similar results have been demonstrated at several other mountainous locations, including Montana, Colorado, and Arizona. High altitude release sites on the Plateau were usually just below or just above cloud base.

g. While experimental cases are limited, a definite impression developed over the course of the experiments that canyon mouth releases have a significantly greater probability of over-Plateau transport than valley releases.

h. Plumes released from the valley floor are less likely to be transported over mountain barriers than plumes released from higher elevation sites. A number of experimental periods showed that AgI was trapped near the valley floor for several hours. However, storm periods with relatively abundant SLW over the Plateau and embedded convection present usually also had valley AgI transport to the Plateau top. Nevertheless, effective ice nucleus concentrations from valley-released AgI were usually quite small at prevailing cloud temperatures.

i. On some occasions, the gravity wave mechanism transported valley-released AgI over the Plateau in spite of valley-based inversions. The timing and frequency of gravity waves, and the specific surface locations affected by them, are all uncertain, but this mechanism is sometimes important in vertical transport of the AgI aerosol.

j. High altitude AgI generators have at least three advantages over valley-released generators. First and very important is their ability to routinely target the intended cloud zones.

k. Second, concentrations of AgI released by high altitude generators are usually much higher as are resulting ice particle concentrations. This was repeatedly shown by observations along the Plateau top and above the Plateau. The results of model simulations were in agreement with these surface and aircraft observations. The main reasons for the higher concentrations are less horizontal dispersion (vertical dispersions were similar) and greater probability of transport over the Plateau. Of course, this result likely means significantly less crosswind spacing between high altitude generators compared with the typical 16 km or so spacing between Utah valley generators. But closer spacing of valley generators, perhaps about 4 to 5 km apart, has been recognized as desirable for plume overlap by the operational seeding firm (Griffith 1996).

l. The third advantage of high altitude generators is that they are usually located within cloud or just below cloud base. The AgI generators produce a large water by-product from combustion of propane and acetone. The resulting high supersaturation very near the generators allows for instantaneous activation by the condensation-freezing mechanism (Finnegan and Pitter 1988, DeMott et al. 1995). Thus, under favorable conditions, embryonic ice crystals may be formed immediately downwind of the generators, providing important additional time for growth to snowflake sizes. The condensation-freezing mechanism is unlikely to occur with valley-releases of AgI. If ice crystals are occasionally formed because valley fog is present, they cannot be expected to survive transport to orographic cloud altitudes.

m. A fourth possible advantage of high altitude AgI releases is reduced potential for photo-deactivation of ice nucleating ability. This may not be a significant factor since limited sunlight penetrates the usual cloud deck over valley generators during storms. Moreover, earlier concerns about photo-deactivation (Dennis 1980) may be unwarranted, at least for the type of AgI aerosol operationally used in Utah (Super et al. 1975).

n. Disadvantages of high altitude AgI generators include the practical difficulties of installing and maintaining them at remote locations, and limited horizontal plume dispersion. While aerosol from high altitude generators will routinely be transported over the mountain barrier, cross-wind spacing of such generators should not exceed perhaps 5 km if most of the SLW condensate zone is to be affected. However, it may be more important to routinely seed a portion of the SLW cloud with adequate INC than to sometimes seed more of it with weak AgI concentrations. Vertical dispersion from the high altitude generators appeared similar to that from the valley-based generators, but this impression may be partially based on the much greater INC found during aircraft sampling within high altitude released plumes. Valley-released plumes generally had weak INC at aircraft altitudes.

o. A seeding solution was tested in the CSU laboratory which produces an AgICl-0.125NaCl aerosol rather than the AgI aerosol used in the Utah operational program. The laboratory results showed that the former solution can nucleate ice crystals by the condensation-freezing mechanism rather than the contact-freezing nucleation mechanism resulting from the operational seeding (in the absence of supersaturation at the generators). *This fast-acting aerosol was shown to increase the number of effective ice nuclei by over an order of magnitude in the limited time available for transport through orographic SLW cloud.* It is strongly recommended that the operational seeding program use this improved solution. This is one of a number of actions which could increase effective ice nucleus concentrations over Utah's mountain barriers.

p. Numerous physical seeding experiments demonstrated that sufficiently great AgI concentrations exposed to sufficiently cold SLW cloud will produce abundant ice particles. Ice particle concentrations were similar to those expected, based on earlier laboratory results, tending to verify laboratory findings in actual orographic cloud. When obvious seeding-caused snowfall occurred, rates were light as is typical of natural snowfalls. The heaviest hourly accumulation observed during the seeding experiments was 1 mm liquid equivalent.

q. Propane releases at rates of 3-7 gal h^{-1} were clearly demonstrated as capable of producing 10 to 20 ice crystals per liter at the Plateau top target site even during slightly supercooled conditions. This approach offers a practical adjunct or alternative to AgI seeding during the mildly supercooled episodes typical of Utah winter orographic storms. Moreover, propane seeding was totally automated, using an icing rate meter to detect SLW cloud and a data logger to "decide" to release the liquid propane only during seedable conditions.

7.4 Summary of Findings and Recommendations

In summary, SLW, the necessary raw material needed for glaciogenic cloud seeding to be effective is frequently present in Utah's orographic clouds. Amounts of SLW are adequate to provide the potential for artificial nucleation by cloud seeding to enhance the mountain snowfall at higher elevations. However, numerous physically-based investigations reported herein indicate that the current operational seeding program likely converts very little of the available SLW to additional snowfall.

The main problem with the Utah operational seeding program is that observed effective AgI ice nucleus concentrations are too low for significant snowfall enhancement from the mildly supercooled clouds. Much of the time, the entire SLW layer is too warm for effective seeding with AgI, which begins to nucleate ice crystals near -6 °C, but which is ineffective in the concentrations observed until the SLW cloud is colder than about -9 °C. Under such circumstances, a different seeding agent is needed, such as liquid propane. When colder SLW cloud does exist, the window of opportunity is quite narrow before natural processes produce sufficient ice particles for effective snowfall.

A number of steps aimed at increasing the operational program's effectiveness can be taken. Admittedly, most of them would increase the program's cost. However, in terms of snow enhancement, these improvements may make economic sense. It is beyond the scope of this work to provide such economic evaluations.

If the Utah operational program continues to rely on AgI seeding, the following possible steps should be seriously considered for improving program effectiveness.

a. Convert to a seeding solution capable of producing an AgI aerosol which nucleates by the condensation-freezing mechanism rather than continuing to rely on slow-acting contact-freezing with the current solution.

b. Significantly increase the density of seeding generators and the ice nucleus output per generator. These steps will increase both effective ice nucleus concentrations and volume coverage within SLW clouds.

c. As a minimum, place AgI generators in canyon mouth rather than at valley floor locations. A superior approach would be to use high altitude generators located at least half way up the windward slope of mountain barriers.

d. Use high altitude generators on barriers immediately upwind of the intended target barriers, such as the San Pitch Mountains in the case of the Wasatch Plateau. This approach would provide important additional time for seeding-caused ice particles to grow and fall to the surface.

e. Seriously consider whether aircraft seeding can provide AgI aerosol to sufficiently cold SLW regions during relatively warm storm periods. The author recognizes that aircraft seeding with AgI generators will often be impractical when the SLW is contained in a shallow, mildly supercooled layer just above the mountain barrier. That is, aircraft with attached AgI generators will not be able to safely operate at sufficiently low altitudes during many storm episodes. Dropping of AgI flares is an alternative which is likely cost prohibitive when duration and volume of coverage are considered. While this author doubts that effective aircraft seeding would be practical and affordable, the question has not received serious consideration during the NOAA/Utah AMP. However, in light of the typical location and limited supercooling of liquid condensate over the Wasatch Plateau, aircraft seeding may deserve closer examination.

f. Whether or not AgI seeding is continued, it is recommended that automated liquid propane seeding be expanded from the three dispenser operation already in use east of Ephraim, Utah. This approach would profit from the use of direct current icing meters which could be operated in the field with solar panels and storage batteries. Available commercial models employ an alternating current heater requiring field use of an inverter. However, according to personal communication with one of their representatives, circuit changes could be made by the manufacturer. This approach should be affordable and has the several advantages previously discussed. Unlike automated AgI generators, automated propane dispensers are simple, reliable, and economical devices which can be programmed to release propane only when SLW exists at the dispensers.

g. Whatever the seeding approach, numerical modeling studies should be used to determine optimum seeding locations and source strengths of both AgI generators and liquid propane dispensers. The Clark model has been shown to produce reasonable simulations of the spatial distributions of SLW cloud and of tracer gas and small particle transport. The model is set up on a workstation and simulations can be produced at limited cost. The model should be run with various seeding configurations and under the range of storm conditions found in Utah. An abundance of sounding observations already exists for model initiation. Such modeling investigations should lead to improved AgI generator and propane dispenser placement. Reasonable estimates can be made of the AgI ice nucleus production and propane ice crystal production needed to affect the range of SLW cloud temperatures typically found over Utah's mountains.

REFERENCES:

Bruintjes, R. T., T. L. Clark, and W.D. Hall, 1995: The dispersion of tracer plumes in mountainous regions in central Arizona: Comparisons between observations and modeling results. J. Applied Meteorology, 34, 971-988.

Cripps, D., and B. Abbott, 1997: The use of capacitance to detect icing. J. Weather Modification, 29, 84-87.

DeMott, P. J., A. B. Super, G. Langer, D. C. Rogers, and J. T. McPartland, 1995: Comparative characterizations of the ice nucleus ability of AgI aerosols by three methods. J. Weather Modification, 27, 1-16.

Dennis, A. S., 1980: "Weather Modification by Cloud Seeding." Academic Press, New York, NY, 267 pp.

Finnegan, W. G., and R. L. Pitter, 1988: Rapid ice nucleation by acetone-silver iodide generator aerosols. J. Weather Modification, 20, 51-53.

Gabriel, K. R., 1981: On the roles of physicists and statisticians in weather modification experimentation. Bulletin of the American Meteorological Society, 62, 62-69.

Golden, J. H., 1995: The NOAA Atmospheric Modification Program - A 1995 update. J. Weather Modification, 27, 99-109.

Griffith, D. A., 1996: Potential application of results from the NOAA Atmospheric Modification Program to the conduct of a Utah winter orographic cloud seeding program. Preprints 13th Conference on Planned and Inadvertent Weather Modification, American Meteorological Society, Jan. 28 - Feb. 2, Atlanta, GA, 118-120.

Griffith, D. A., J. R. Thompson, and D. A. Risch, 1991: A winter cloud seeding program in Utah. J. Weather Modification, 23, 27-34.

Griffith, D. A., J. R. Thompson, D. A. Risch, and M. E. Solak, 1997: An update on a winter cloud seeding program in Utah. J. Weather Modification, 29, 95-99.

Griffith, D. A., G. W. Wilkerson, W. J. Hauze, and D. A. Risch, 1992: Observations of ground released sulfur hexafluoride tracer gas plumes in two Utah Winter storms. J. Weather Modification, 24, 49-65.

Heimbach, J. A., Jr., and W. D. Hall, 1994: Applications of the Clark model to winter storms over the Wasatch Plateau. J. Weather Modification, 26, 1-11.

Heimbach, J. A., and W. D. Hall, 1996: Observations and modeling of valley-released silver iodide seeding over the Wasatch Plateau. Preprints 13th Conference on Planned and Inadvertent Weather Modification, American Meteorological Society, Jan. 28 - Feb. 2, Atlanta, GA, 31-37.

Heimbach, J. A., Jr., and A. B. Super, 1992: The number of experimental units required to achieve a statistical significance with different seeding responses in a winter orographic experiment. Preprints Symposium on Planned and Inadvertent Weather Modification, American Meteorological Society, Jan. 5-10, Atlanta, GA, 132-135.

Heimbach, J. A., and A. B. Super, 1996: Simulating the influence of type II error on the outcome of past statistical experiments. J. Applied Meteorology, 35, 1551-1567.

Heimbach, J. A., W. D. Hall, and A. B. Super, 1997: Modeling and observations of valley-released silver iodide during a stable winter storm over the Wasatch Plateau of Utah. J. Weather Modification, 29, 33-41.

Heimbach, J. A., A. B. Super, and W. D. Hall, 1998: Modeling AgI targeting effectiveness for five generalized weather classes in Utah. J. Weather Modification, 30, 35-50.

Holroyd, E. W., and A. B. Super, 1998: Experiments with pulsed seeding by AgI and liquid propane in slightly supercooled winter orographic clouds over Utah's Wasatch Plateau. J. Weather Modification, 30, 51-76.

Holroyd, E. W., J. A. Heimbach, and A. B. Super, 1995: Observations and model simulation of AgI seeding within a winter storm over Utah's Wasatch Plateau. J. Weather Modification, 27, 36-56.

Huggins, A. W., 1992: Mapping Supercooled Liquid Water with a Mobile Radiometer. Preprints Symposium on Planned and Inadvertent Weather Modification, American Meteorological Society, Jan. 5-10, Atlanta, GA, 102-107.

Huggins, A. W., 1995: Mobile microwave radiometer observations: Spatial characteristics of supercooled cloud water and cloud seeding implications. J. Applied Meteorology, 34, 432-446.

Huggins, A. W., *1996: Use of radiometry in* orographic cloud studies and the evaluation of ground-based cloud seeding plumes. Preprints 13th Conference on Planned and Inadvertent Weather Modification, American Meteorological Society, Jan. 28 - Feb. 2, Atlanta, GA, 142-149.

Huggins, A. W., and K. Sassen, 1990: A high altitude ground-based cloud seeding experiment conducted in southern Utah, J. Weather Modification, 22, 18-29.

Mossop, S. C., 1985: The origin and concentration of ice crystals in clouds. Bulletin American Meteorological Society, 66, 264-273.

Rauber, R. M., and L. O. Grant, 1986: The characteristics and distribution of cloud water over the mountains of northern Colorado during wintertime storms. Part II: Spatial distribution and microphysical characteristics. J. Climate and *Applied Meteorology, 25, 489-504.*

Reinking, R. F, 1992: The NOAA Federal/State cooperative program in atmospheric modification research: A new era in science responsive to regional and national water resources issues. Preprints Symposium on Planned and Inadvertent Weather Modification, American Meteorological Society, Atlanta, GA, Jan. 5-10, 136-144.

Reynolds, D. W., 1991: Design of a ground based snowpack enhancement program using liquid propane. J. Weather Modification, 23, 49-53.

Sassen, K., and H. Zhao, 1993: Supercooled liquid water clouds in Utah winter mountain storms: Cloud-seeding implications of a remote-sensing dataset. J. Applied Meteorology, 32, 1548-1558.

Super, A. B., 1990: Winter orographic cloud seeding status in the intermountain West. J. Weather Modification, 22, 106-116.

Super, A. B., 1993: Precipitation gauge testing on the Wasatch Plateau, Utah during early 1993. Bureau of Reclamation Research Report R-93-17, Denver, CO, 10 pp.

Super, A. B., 1994: Implications of early 1991 observations of supercooled liquid water, precipitation and silver iodide on Utah's Wasatch Plateau. J. Weather Modification, 26, 19-32.

Super, A. B., 1995a: Case studies of microphysical responses to valley-released operational AgI seeding of the Wasatch Plateau, Utah. J. Weather Modification, 27, 57-83.

Super, A. B., 1995b: Observations of microphysical effects of liquid propane seeding on Utah's Wasatch Plateau during early 1995. Appendix E of Bureau Reclamation Research Report R-95-12, Denver, CO, 109-133.

Super, A. B., 1996: Two case studies showing physical effects of both AgI and liquid propane seeding on Utah's Wasatch Plateau. 13th Conference on Planned and Inadvertent Weather Modification, American Meteorological Society, Jan. 28 - Feb. 2, Atlanta, GA, 156-163.

Super, A. B., and B. A. Boe, 1988: Microphysical effects of wintertime cloud seeding with silver iodide over the *Rocky Mountains. Part III:* Observations over the Grand Mesa, Colorado. J. Applied Meteorology, 27, 1166-1182.

Super, A. B., and J. A. Heimbach, 1983: Evaluation of the Bridger Range winter cloud seeding experiment using control gages. J. Climate and Applied Meteorology, 22, 1989-2011.

Super, A. B., and J. A. Heimbach, 1988: Microphysical effects of wintertime cloud seeding with silver iodide over the Rocky Mountains. Part II: Observations over the Bridger Range, Montana. J. Applied Meteorology, 27, 1152-1165.

Super, A. B., and A. W. Huggins, 1992a: Investigations of the targeting of ground-released silver iodide in Utah - Part I: Ground observations of silver-in-snow and ice nuclei. J. Weather Modification, 24, 19-33.

Super, A. B., and A. W. Huggins, 1992b: Investigations of the targeting of ground-released silver iodide in Utah - Part II: Aircraft observations. J. Weather Modification, 24, 35-48.

Super, A. B., and A. W. Huggins, 1993: Relationships between storm total supercooled liquid water flux and precipitation on four mountain barriers. J. Weather Modification, 25, 82-92.

Super, A. B., and J. T. McPartland, 1993: Preliminary estimates of increased runoff from additional high elevation snowfall in the Upper Colorado River Basin. J. Weather Modification, 25, 74-81.

Super, A. B., and E. W. Holroyd, 1994: Estimation of effective AgI ice nuclei by two methods compared with measured ice particle concentrations in seeded orographic cloud. J. Weather Modification, 26, 33-40.

Super, A. B., and E. W. Holroyd, 1997: Some physical evidence of AgI and liquid propane seeding effects on Utah's Wasatch Plateau. J. Weather Modification, 29, 8-32.

Super, A. B., J. T. McPartland, and J. A. Heimbach, 1975: Field observations of the persistence of AgI-NH$_4$I in acetone ice nuclei in daylight. J. Applied Meteorology, 14, 1572-1577.

Super, A. B., E. W. Holroyd and J. T. McPartland, 1989: Final Report to the Arizona Dept. of Water Resources, Bureau of Reclamation Research Report R-89-02, Denver, CO, 173 pp.

Super, A. B., E. Faatz, A. J. Hilton, V. C. Ogden, and R. D. Hansen, 1995: A status report on liquid propane dispenser testing in Utah with emphasis on a fully-automated seeding system. J. Weather Modification, 27, 84-93.

Thompson, J. R., and D. A. Griffith, 1981: Seven years of weather modification in central and southern Utah, J. Weather Modification, 13, 141-149.

Wetzel, M. A., R. D. Borys, and A. W. Huggins, 1996: Combined Satellite Remote Sensing and Ground-Based Measurements for Evaluation of Cloud Seeding Opportunities and Effects. Workshop on Theoretical and Practical Aspects of Regional Precipitation Enhancement Programme for the Middle East and Mediterranean, Bari, Italy. 12 pp.

ACKNOWLEDGMENTS

Many individuals contributed to the NOAA/Utah AMP during the 1990s. These include Joe Boatman, Joe Golden, Roger Reinking, Dennis Wellman, Stan Wilkison, and several pilots of NOAA; Clark Ogden, Barry Saunders, and several seasonal field technicians of the Utah Division of Water Resources; Glenn Cascino, Ed Holroyd, Roger Hansen, Arlen Hilton, and Jack McPartland of the Bureau of Reclamation; Jim Heimbach of the University of North Carolina at Asheville; Arlen Huggins and Melanie Wetzel of the Desert Research Institute, University of Nevada; Terry Clark and Bill Hall of the National Center for Atmospheric Research; Gerhard Langer, who maintained the NCAR acoustical ice nucleus counters; Paul DeMott of Colorado State University; Ken Sassen of the University of Utah; and Don Griffith, Bill Hauze, and George Wilkerson of North American Weather Consultants.

The reviewers of this article are acknowledged for their many worthwhile suggestions, which resulted in a significantly improved final version. Their considerable efforts are appreciated.

This research was sponsored primarily by NOAA's Atmospheric Modification Program, with additional support from NOAA's Environmental Research Laboratories and the Bureau of Reclamation.