RANDOMIZED PROPANE SEEDING EXPERIMENT: WASATCH PLATEAU, UTAH

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Abstract A randomized experiment to test propane cloud seeding effectiveness was conducted on the Utah's Wasatch Plateau during the 2003/04 winter. Propane dispensers were operated at a previously used high altitude site well up the windward slope. The primary target precipitation gauge was 4.3 km downwind, on top the plateau, where earlier plume tracking demonstrated routine targeting with seeding site winds from the southwest quadrant. Gauges were maintained upwind and downwind of the primary target, along the expected plume trajectory, but no more than 6.5 km downwind of the propane dispensers because of targeting uncertainties. A well-correlated crosswind control gauge provided the covariate used in all statistical testing. The experiment was completely automated with 2 hr experimental periods declared when a specified icing rate was exceeded at the seeding site. Each period contained a pair of experimental units, one seeded and one placebo, with treatment by random decision. Three different statistical tests were applied. Statistically significant seeding-caused precipitation increases were strongly suggested by the exploratory experiment for the entire population of 98 experimental units, for a partition of 69 units with wind directions expected to result in successful targeting, and for the same wind directions but excluding highest natural snowfalls. Intriguing but inconclusive suggestions of possible positive seeding effects resulted when supercooled liquid water (icing) was detected, with warmer temperatures and for lighter wind speeds. Hypothetical estimates suggest about an 8% precipitation increase had all experimental hours been seeded during the 3.5 month project period.

1. INTRODUCTION AND PREVIOUS INVESTIGATIONS

The Utah Division of Water Resources, with primary support from the Bureau of Reclamation (hereafter Reclamation), U. S. Department of the Interior, conducted an experimental cloud seeding program using propane (C_3H_8) on the Wasatch Plateau of central Utah. The goal was to demonstrate that seeding winter mountain-induced (orographic) clouds by expansion of liquid propane could result in additional snowfall on the mountainous terrain, enhancing the seasonal snowpack. Spring and early summer melting of mountain snowpacks is the major source for runoff and stream flow in most areas of the western U. S., utilized by agriculture, municipalities, industry, and aquatic environments.

The randomized experiment was conducted from mid-December 2003 through March 2004. The purpose was to statistically test propane seeding effectiveness applied to storm passages over a time period approaching a winter season. Testing whether propane seeding could produce meaningful net snowfall increases from a population of several storms was a significant advance in the development of this potentially important seeding technology. A successful randomized propane seeding experiment for winter mountain clouds had never been conducted. Only one had previously been attempted and it was terminated early in part because of targeting problems as discussed by Reynolds (1996). He concluded that, "Again, it would seem imperative that detailed transport and dispersion studies be performed prior to the onset of any long-term snowfall enhancement program ---." Many transport and dispersion investigations had been conducted prior to the Utah randomized program as discussed herein. They documented routinely successful targeting with seeding site winds from the southwest quadrant.

Propane seeding has the important advantage in being able create ice crystals within mildly supercooled liquid water (SLW) cloud, at temperatures slightly below 0°C. Large concentrations can be achieved below -2°C (Hicks and Vali 1973). Because of its large temperature dependence, silver iodide (AgI) seeding is impractical for SLW cloud temperatures warmer than about -6°C for in-cloud releases resulting in forced condensation freezing (Finnegan and Pitter 1988; Chai et al. 1993). Temperatures must be lower than about -8°C for far more typical below-cloud releases of AgI. Propane seeding has the potential to be an important adjunct to AgI seeding within the "warm temperature window" from -2°C to -6 or -8°C. There is an abundance of winter orographic SLW cloud in that temperature window in the Intermountain West (e.g., Sassen and Zhao 1993) and the Sierra Nevada (e.g., Reynolds 1996) which is untreatable with AgI.

Previous laboratory and field investigations have demonstrated that expansion of liquefied propane in or near SLW cloud or fog produces vast quantities of embryonic ice crystals by homogeneous nucleation. A reviewer kindly pointed out that the propane method was likely initially tested in supercooled mountain clouds as reported by Serpolay (1957) in a French publication. English references to later propane work include Vardiman et al. 1971; Hicks and Vali 1973; Kumai 1982; Super and Holroyd 1997 and Holroyd and Super 1998. Somewhat similar work was reported by Fukuta (1996), using expansion of liquid carbon dioxide rather than propane, released from moving surface vehicles. He noted that latent heat release enhanced mixing of the seeding plumes, resulting in widespread SLW fog clearing. It is well known that supercooled cloud droplets cannot continue to exist at temperatures less than about -40°C, but freeze into ice crystals. Expansion of liquid propane is a convenient means of locally chilling the air well below that temperature and, thereby, producing vast numbers of tiny ice crystals. Hicks and Vali (1973) reported that about 10^{12} ice crystals were produced per gram of propane at all temperatures below -2°C, based on both laboratory and field work. Laboratory results by Kumai (1982) showed about an order of magnitude lower output. The seeding-produced ice crystals will grow within SLW cloud, or within a limited vertical distance below liquid cloud base where ice saturation exists. Snowfall can result when growth times are sufficient, as the seeded crystals are transported by forced airflow up the windward slope and top of a mountain barrier. The same forced airflow produces the orographic SLW cloud which is the "raw material" needed for winter mountain-induced cloud seeding to work.

Reynolds (1989, 1991, 1994) developed a radio-controlled propane dispensing system for California because of the high frequency of mildly SLW clouds over the Sierra Nevada. Super et al. (1995) described Utah tests of the same propane dispenser system which showed that it was inexpensive and very reliable, primarily because of its simplicity. A propane dispenser needs only a propane supply, readily available from commercial sources, an insulated exhaust tube to release liquid propane, a particular type of nozzle at the end, and a remotely controlled on/off value in the tube. Inclusion of a temperature sensor immediately beyond the nozzle, and a flowmeter in the exhaust tube, provide monitoring that propane is indeed being dispensed and at the desired rate. Other compressed gases, like liquid carbon dioxide, can be used in a similar manner (Fukuta 1996). In contrast, radio-controlled AgI generators are much more complex, susceptible to clogging, and seldom are equipped to monitor actual AgI-in-solution flow but only flame temperature. Therefore, one cannot be certain from afar that AgI is actually being released.

There is a great deal of propane (C_3H_8) and butane (C_4H_{10}), another hydrocarbon, being released by human activities at a scale far larger than for propane seeding.[1] Propane does not present an environmental hazard because of its rapid oxidative degradation. Although it is a greenhouse gas, its lifetime in the atmosphere, 28 days, is too short to function in this manner. In contrast, CFCs have atmospheric lifetimes in the range of 60 – 500 yrs. For comparison, methane (CH_4) has stronger bonds which results in slower oxidizing allowing a buildup sufficient to contribute to the greenhouse process. There is no known influence of propane on the ozonosphere. Ethyl mercaptan, a sulfur compound added to propane in minute quantities to make it detectable by smell, poses no hazard.

Super et al. (1995) reported on the first totally automated propane seeding system for winter orographic cloud tested from early January to mid-March 1994. Observations of SLW presence at the central propane dispenser were used to automatically turn it, and two crosswind dispensers, on and off as SLW was available or not. An icing sensor was used to detect SLW. Storm phases with available SLW are usually short-lived, seldom more than a few hours duration. This automated seeding system continues to be used operationally in Utah by the Emery Water Conservancy District. A nearly identical system has been in use by the Eden Valley Irrigation District in Wyoming since the winter of 2000/01.

A limited number of prior case study field experiments (Reynolds 1996; Super and Holroyd 1997; Sec. 2 of this paper), have demonstrated obvious propane seeding effects producing many small ice crystals and resulting light snowfall rates. Holroyd and Super (1998) used a different approach, comparing all attempted pulsed seeding experiments from two winters, 1994/95 and 1995/96, on the Wasatch Plateau to natural data sets, in an attempt to statistically test for differences. This was not a randomized experiment so results should be used with caution. The attempt was made because so many of the pulsed experiments had potential seeding effects masked by the large natural variability in ice particle concentrations (IPCs) and snowfall rates. Their results suggested that propane seeding with one nozzle the first winter typically produced about 10 small ice crystals per liter, in the 100 to 800 μm size range, at the TAR site 4.1 km straight-line distance from the HAS seeding site. Two nozzles were used the second winter, resulting in about 20 small ice crystals per liter, with the difference statistically significant. Precipitation rate increases with two nozzles were about 0.17 mm h^{-1} according to 2D-C particle imaging probe observations of the small

[1] Personal communication with Dr. Bert E. Holmes, U. of North Carolina at Asheville, 20 Feb. 2005.

crystals using the software of Holroyd (1987). The software, calibrated in Colorado Mountains, is known to underestimate actual precipitation rates by about a factor of two in Utah so an estimated rate increase of about 0.34 mm h^{-1} should be more realistic. No changes could be detected with the mechanical Belfort precipitation gauges but such increases would be near their resolution limit.

These prior experiments have demonstrated that the physical hypothesis for propane seeding is reasonably well understood. However, case studies produce obvious seeding effects only during the infrequent periods with negligible natural snowfall in the presence of SLW cloud. Even light natural snowfall, which varies rapidly over time, masks the seeding effects. Moreover, it is not reasonable to extrapolate from the results of a few case study experiments to expected seasonal precipitation increases. Only a randomized experiment can reliably provide this important information. Conducting such an experiment was the logical next step in testing the effectiveness of propane seeding.

The 2003/04 randomized experiment was limited in duration and target area size by available funding. It was not designed to answer all remaining questions, in particular concerning the magnitude of seeding effects more than about 6.5 km downwind of the seeding site. The gauge farthest downwind was established only 2 km east of the plateau top's west edge because of targeting uncertainties further downwind with a single seeding site and varying wind directions. However, the experiment was intended to test whether routine seeding could produce meaningful additional snowfall over the upper portion of the upwind (west-facing) slope and western portion of the plateau top. The exploratory experiment succeeded in demonstrating such increases to a reasonable level of statistical certainty, thereby providing justification for further development of this important emerging seeding technology.

2. TARGETING CONSIDERATIONS

2.1 Need for High-elevation Propane Seeding Locations

Liquid propane expansion can produce meaningful ice crystal concentrations at temperatures as warm as -0.5˚C, but production rates are limited until the cloud temperature is -2˚C or less (Hicks and Vali 1973). In effect, seeding by propane expansion is seeding with ice crystals because they form in vast numbers immediately downwind of the dispenser nozzles. Water vapor in the air is cooled by the expanding propane to force condensation of water vapor into very high concentrations of tiny cloud droplets which immediately freeze. Freezing of existing cloud droplets also occurs, but at much lower concentrations. Propane dispensers must be located well up windward mountain slopes to be in SLW cloud, or just below SLW cloud base where ice saturation exists. Else, the tiny seeding crystals will quickly sublimate back into water vapor. High elevation releases have a major advantage in largely eliminating the targeting problem common with winter orographic cloud seeding projects as discussed below.

It has been recognized for many years that achieving adequate transport and dispersion of the commonly-used AgI seeding agent is the major problem in seeding winter orographic clouds (Rangno 1986; Reynolds 1988; Reynolds et al. 1989; Super 1990; Warburton et al. 1995). Perhaps Smith and Heffernan (1967) stated it best when they said that, "--- persons who release silver iodide from the ground would be wise to find out where it goes." This seemingly obvious advice has seldom been followed. Failure to document that clouds are actually being seeded continues to seriously hamper the development of this promising technology.

Numerous plume tracing studies over different mountain barriers have shown targeting to be routine with high elevation releases (Super 1974; Holroyd et al. 1988; Super and Heimbach 1988; Holroyd et al. 1995). Further evidence is presented in this paper. Moreover, high elevation propane seeding can initiate growth of ice crystals near cloud base, even when SLW temperatures are only slightly supercooled. This approach not only provides a much larger "temperature window" of seeding effectiveness, but maximizes crystal growth times. Ground-released AgI plumes would need to be transported to higher, much colder cloud levels to create ice crystals, providing a much smaller "temperature window" and usually briefer growth times, assuming such plumes are transported up windward mountain slopes. There are conditions where gravity waves may loft valley-released AgI plumes to sufficiently high and cold altitudes well upwind of mountain barriers (Heimbach et al. 1997; 1998). But gravity waves are transient in space and time, and are difficult to predict. It has yet to be demonstrated that they provide a means of *routine* vertical transport for AgI releases in intermountain valleys or foothills. Gravity waves can provide an important source of et al., 1994; Reinking et al., 2000), but the best seeding strategy is likely with generators well up the windward slope of the upwind barrier. However, Reynolds (1996) showed that propane releases too near a crestline may often be transported downward by mountain lee waves, with SLW cloud over valleys between parallel barriers (Bruintjes et al., 1994; Reinking et al., 2000), but the best seeding strategy is likely with generators well up the windward slope of the upwind barrier. However, Reynolds (1996) showed that propane releases too near a crestline may often be transported downward by mountain lee waves, with resulting sublimation of seeding crystals.

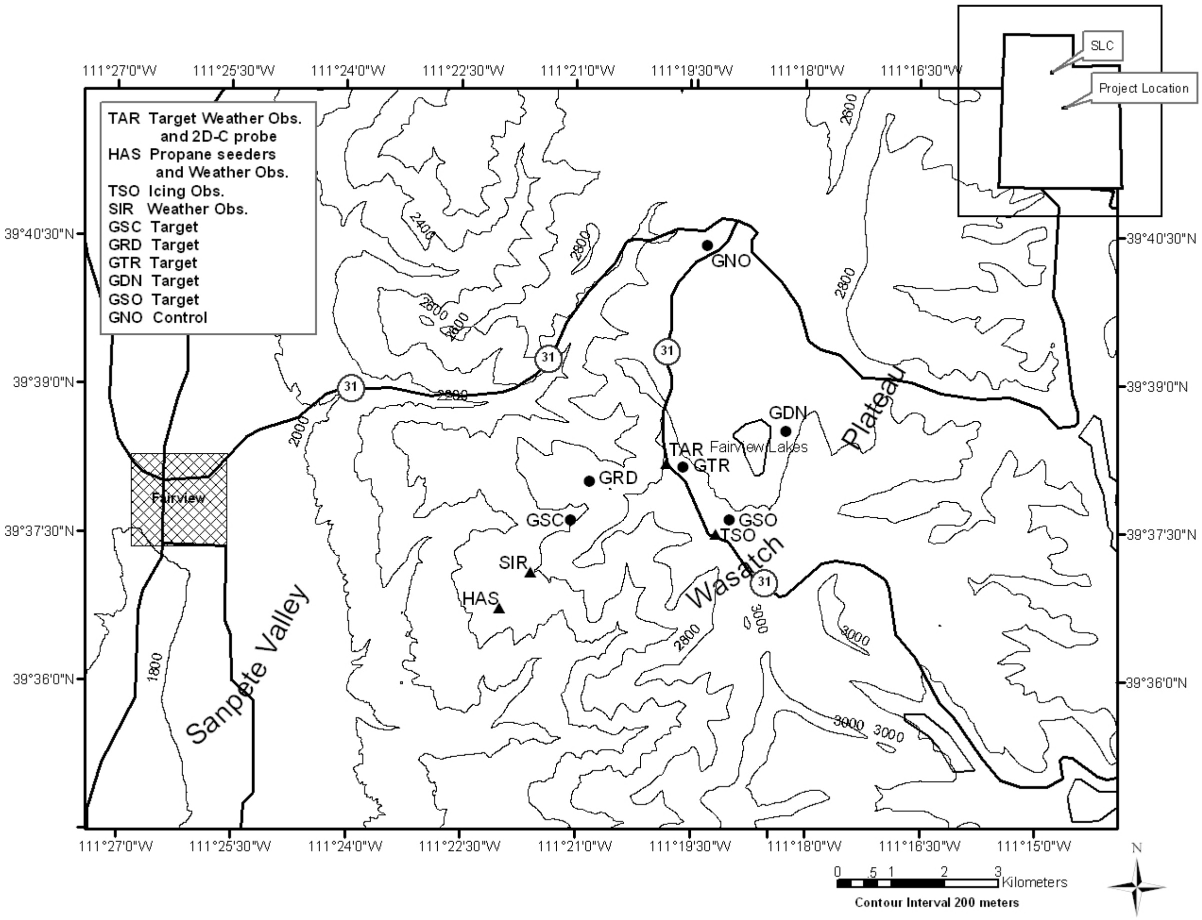

Fig. 1. Map of the experimental area for the Utah 2003-2004 propane seeding experiment. The contour interval is 200 m.

2.2 Examination of Earlier Wasatch Plateau Targeting Observations

Important observations were collected on the Wasatch Plateau during the 1990s as part of the National Oceanic and Atmospheric Administration (NOAA) Atmospheric Modification Program, in cooperation with the Utah Division of Water Resources and Reclamation. A considerable body of publications and papers resulted from these investigations as summarized and cited by Super (1999). Some of these earlier observations were recently analyzed in a manner suitable to address important targeting issues for the randomized experiment. While detailed analyses and results are presented in the project Final Report by Super and Heimbach (2005), the more important findings are discussed herein. The Super and Heimbach (2005) reference is frequently used in this paper and will hereafter be referred to as SH05.

On many occasions during mid-January to mid-March 1994 tracer gas was released from the HAS seeding site also used for the randomized experiment. The gas was sampled with a fast-response detector in an instrumented van driven along Highway 31 for the 7 km north-south distance that the road follows the plateau top's west edge (see Fig. 1), hereafter called the "upwind highway." Location information was recorded using a global positioning system (GPS) receiver. North and south plume edges relative to the position of a future instrumented target known as TAR, were related to HAS wind directions. The TAR, sited immediately west of the upwind highway, was first used during the 1994/95 winter experiments discussed later. Gas plumes were detected at the TAR location during about 90% of all cases when HAS winds were from 170 to 270 deg true. Plumes were transported slightly south of the TAR in the other 10% of cases. Documentation of routine targeting is important physical evidence in support of the 2003/04 randomized seeding experiment.

Many pulsed seeding experiments with AgI or propane were conducted during the winters of 1994/95 and 1995/96 as discussed by Super and Holroyd (1997) and Holroyd and Super (1998). Seeding agent releases were from the HAS with detection at the TAR. Silver iodide "tags" were released for a few minutes at the beginning and end of each propane release to define the propane plume passage. An acoustical ice nucleus counter was used to detect AgI at the TAR. Plume transit times were based on the clock time between start of AgI release and the ice nuclei detection peak at the TAR. These transit times were related to HAS and TAR wind speeds. The resulting equation provided the means to estimate propane seeding plume arrival and departure times past target gauges for the randomized experiment, an obviously important tool. A detailed discussion of plume transit time estimation is given in Sec. 7.1.

All targeting cases rated "good" and "fair" during the 1994/95 and 1995/96 experiments had HAS wind directions between 170 to 270 deg, further verifying routine targeting with HAS winds in the southwest quadrant observed during mid-January to mid-March 1994. This finding removes much of the uncertainty concerning targeting which has been inherent in most experiments and operational projects. Targeting can be considered highly probable for the 170 to 270 deg HAS wind direction range, and should be considered unlikely outside that range.

3. PRECIPITATION MEASUREMENT CONSIDERATIONS

Obtaining accurate snow water equivalent (SWE) measurements of snowfall is far more difficult than generally realized. Details of appropriate precipitation gauge characteristics including wind shields, and the need for having gauges in sheltered clearing in conifer (evergreen) forest, are discussed in detail by SH05. They also describe the difficulties of finding suitable gauge clearings in a high altitude area where much of the terrain is either wide open to the wind or has aspen forest which provides little wind protection. Four of the six high-resolution digitized gauges used were operated in well-protected conifer clearings. The primary target (GTR) and control gauge (GNO) locations (see Fig. 1), used during prior winter programs, were known to be good gauge sites. Two newly chosen clearings (GSC and GSO) also proved to be very satisfactory. The most downwind clearing (GDN) was a reasonable site but somewhat less protected and about 0.6 km further north than desired to be under the estimated most typical plume centerline. Sufficiently dense conifer forest does not exist further south. One gauge was located in a clearing in a saddle atop a ridgeline. While some conifer tree cover existed, it proved too limited and the site was shown to be too windy for suitable snowfall observations. That gauge, GRD, had the lowest correlation with the control gauge and received about 30% less SWE than predicted for its elevation by regression between elevation and the SWE observed by 4 nearby gauges. Measurements from that site were not used beyond some initial statistical analyses which demonstrated some of the problems with gauge undercatch related to excessive winds.

4. RANDOMIZED EXPERIMENTAL DESIGN

4.1 Design Overview

Scientists and statisticians generally agree that demonstration of winter cloud seeding effectiveness requires randomization so that precipitation from nonseeded experimental units (hereafter EUs) is monitored in the same manner as from seeded EUs. All attempts must be made to eliminate human bias in analyses of any randomized experiment. Statistical evaluation of non-randomized seeding projects presents serious difficulties and uncertainties as discussed by Dennis (1980), Gabriel (2000), Super and Heimbach (2003) and several other authors.

The HAS seeding site, well up the windward (west-facing) slope of the north-south oriented Wasatch Plateau, was used for 40 min propane releases and paired nonseeded 40 min placebo periods, the latter to provide a basis of comparison. Figure 1 is a map which shows the general terrain, instrumented sites and other features. The instrumented TAR site on the west edge of the plateau top, along with its companion precipitation gauge GTR, are considered the primary target area. As has been discussed, considerable previous plume tracking demonstrated that HAS-released plumes routinely passed the TAR vicinity when HAS winds were from the southwest quadrant. Pairs of EUs, one seeded and one not treated by random decision, were declared whenever an icing rate sensor at the HAS seeding site detected the presence of SLW above a threshold. It is well documented that SLW availability is the necessary "raw material" for winter cloud seeding in mountains to be effective. Randomized seeding and all observations were totally automated providing 24/7 operations to maximize the population of EUs.

Primary measurements for statistical evaluation of seeding effectiveness were from high resolution precipitation gauges equipped with Alter windshields and located in natural conifer forest clearings to minimize wind-caused undercatch of snowfall. The snow melted in an antifreeze solution within each gauge and resulting weight changes were measured by a sensitive load cell. A data logger within the gauge housing recorded the average weight for each minute. Each gauge was individually calibrated and its coefficients were incorporated into the data logger program. Four gauges were located along the expected seeding plume trajectory, within the limitation of available suitable gauge sites. These are shown on Fig. 1 as GSC, GRD, GTR and GDN. Gauge GSO was located only 1.0 km south of the primary target gauge and was also treated as a target. The other crosswind gauge, GNO, was 4.2 km north of the primary target gauge. It provided a suitable control or covariate for the other gauges.

Wind speed and direction observations at the HAS seeding site and TAR primary target were used to estimate the most likely periods of seeding plume passage by each target gauge, and by the TAR, the latter equipped with a 2D-C ice particle monitoring probe. Periods of estimated plume passage were used in calculation of the SWE amount which fell during each EU at each gauge. Those gauge observations were the primary information used in statistical analyses. The seeding effect (or placebo) periods were also used for averaging measurements of IPC, winds, air temperatures, SLW presence and other parameters of interest at the TAR. The 40 min periods of propane release (or placebo) were used for averaging observations immediately upwind of the HAS. These supporting observations were used to partition gauge observations as part of the statistical analyses.

4.2 Experimental Design of 2003/04 Utah Program

With the limited time and funding available, it was decided that seeding had to conducted on a 24/7 basis. This approach offered the only realistic hope of obtaining a sufficiently large EU population so that statistical testing might reveal a seeding effect at an acceptable level of significance. EUs were kept brief, with propane (or placebo) releases during the first 40 min of each declared hour. The last 20 min of each hour were used as a buffer period, to minimize seeding contamination of any following nonseeded EU. Longer periods would have been required to deal with plume passage timing uncertainties had the downwind target dimension been significantly longer.

Earlier winter orographic randomized experiments have used much longer EUs, often the 24 h day. But more recent microwave radiometer observations of SLW and high resolution gauge measurements of snow precipitation have demonstrated considerable short-term variability in winter orographic clouds, indicating EUs much shorter than a day are more appropriate and better represented by supporting observations used for partitioning. As shown in Table 1 of Sec. 7.3a, correlation coefficients were relatively high at 0.88 or 0.89 between the control and three of the target gauges for all available 40 min EUs. Correlations calculated for *daily* totals for the same gauges had values between 0.89 and 0.98 (see SH05). The large increase in sample size with briefer EUs more than compensates for the reduced target-control correlations.

The main temporal changes of concern were SLW presence and natural snowfall, shown to change dramatically by numerous studies including Huggins (1995) and Holroyd and Super (1998). EUs were obtained in pairs for each 2 h continuous experimental period with a random decision made whether the first or last EU of each pair would be seeded. The other unit in the pair was the untreated placebo used as a basis of comparison with the seeded EUs. This pairing, or blocking, allows a particular type of statistical testing common in some technical fields, but only recently suggested for weather modification experiments (Gabriel 2000). This approach is discussed in detail in Sec. 6.2.

To be reasonably confident that seeded ice crystals would usually be transported past a target, the HAS seeding site and plateau top target (TAR and nearby precipitation gauge GTR) successfully used in prior experiments were again activated. The horizontal distance between the HAS and TAR is 4.1 km although the actual seeding plume trajectory was likely somewhat greater, being largely controlled by local terrain. The vertical separation between the HAS and TAR is about 300 m. The seeding plume would be expected to disperse 300 to 600 m higher than the TAR according to considerable past airborne plume tracking and modeling studies (e.g., Heimbach et al. 1998). Plume dispersion may be caused by a combination of routine mechanical turbulence related to airflow interactions with rugged mountainous terrain, sometimes present weak embedded convection, and the buoyancy caused by the heat of phase change during seeded ice crystal growth as discussed by Fukuta (1996). Direct fallout of *individual* seeded ice particles from the plume top to surface gauges is considered unlikely with the possible exception of the most downwind target gauge, GDN. However, seeded ice particles could be carried a significant vertical distance above the terrain downwind of the HAS and still fall into target gauges if a significant growth mechanism was present. The most likely means of transporting higher level seeded crystals onto surface gauges are: (1) by aggregation of many seeded crystals into snowflakes with much larger fall velocities than individual crystals, (2) by natural snowflakes falling through the seeded crystal plume, colliding with and sweeping out (scavenging) many of the much smaller seeded crystals and carrying them to the ground (also aggregation), and (3) by accretional growth (riming) of snowflakes containing seeded crystals in the SLW rich environment which often exists in the cloudy air forced up the windward slopes of the plateau. These aggregation and accretion growth processes could explain the apparent seeding effects found in snowcourses only 4 km downwind of a high altitude AgI generator used during the Bridger Range Experiment in Montana, reported by Super and Heimbach (1983), and from a later operational/research program using the same AgI seeding site discussed by Heimbach and Super (1988).

Operations on a 24/7 basis are quite expensive if field technicians are required around the clock. This was avoided by using a Goodrich icing rate sensor at the HAS to determine the existence of SLW. Whenever the rate of icing exceeded a threshold, the next two-hour block was "declared" an EU pair by a programmed data logger no matter what subsequently happened to cloud and weather conditions. Of course, SLW presence just prior to the beginning of the two-hour experimental block provides no guarantee that it will continue to be present throughout the period. However, the probability of continued SLW availability, especially during the first EU of the pair, is much enhanced over any other available approach of declaring an experimental period. Supercooled liquid water must be available at the HAS, or not far above it in the case of ice saturation at the HAS altitude, in order for seeding potential to exist. Otherwise, the embryonic seeding crystals will soon sublimate back into water vapor.

Once seedable conditions were measured by the icing rate sensor, and the start of a two-hour experimental period was declared, the same programmed data logger made a random decision to seed either the first or second EU of the pair. The data logger controlled the three propane dispensers near the HAS, releasing propane for exactly 40 min. All dispensers had two nozzles separated across the wind by 3 m. As with previous Utah and Sierra Nevada testing, the propane output per nozzle was approximately 3.5 gal h^{-1}, equivalent to 1.9 gm s^{-1}. According to previously cited laboratory and field investigations, the expected ice crystal production per nozzle would be about 10^{12} seeded crystals per second. The center dispenser was about 6 m northeast (downwind) of the HAS tower and the other two dispensers were about 30 m northwest and southeast (generally crosswind) of the center disperser. This configuration should have reduced aggregation of embryonic seeded ice crystals near the dispensers, resulting in higher concentrations downwind as the seeding plume approached target gauges.

5. FACILITIES

5.1 Overview

Figure 1 provides a map of the experimental area and shows the various precipitation gauges and other instrumented stations. The horizontal locations were used with large-scale maps to estimate elevations to the nearest 10 feet above mean sea level, believed more accurate than the GPS elevation readings. This section briefly describes the instrumentation at these sites. More details are given in SH05.

5.2 Precipitation Gauges

Section 3 briefly discussed siting considerations and the reader is referred to SH05 for details. Primary measurements for statistical evaluation were from high resolution precipitation gauges manufactured by ETI Instrument System, Inc. More gauge information was provided in Sec. 4. Time resolution was about 1 min and data logger times were quite stable. The highly sensitive gauges proved to be very reliable, resulting in no missing data for any EU period at any gauge. Data from gauge data loggers were downloaded into a Palm Pilot device during approximately weekly visits. A running mean of five was fitted to all 1 min gauge samples, centered on the middle minute, before calculations of SWE accumulations. Examination of resulting smooth time history plots suggests that gauge resolution was between 0.002 and 0.003 inch. While scientific papers usually report precipitation in metric units, the common U.S. usage of inches of precipitation will largely be followed in this paper as they are more meaningful to water users in the West.

5.3 HAS Seeding Site

5.3.a Overall Facilities.

As previously discussed, the HAS seeding site included three nearby propane dispensers on an axis across the prevailing wind. All dispenser valve controllers, propane flowmeters and temperature sensors mounted about 10 cm downwind of each propane nozzle were hard-wired into a data logger at the central dispenser.

A tower was installed about 6 m southwest (upwind) of the center dispenser. Sensors on the 6 m tower included a heated anemometer and wind vane just above the tower top, an air temperature sensor, Goodrich (previously Rosemount) Model 0872F1 icing sensor and, after 17 February 2004, a Rosemount Model 0871CB1 tower-type icing sensor. The same data logger at the central dispenser recorded all the tower sensor observations at 1 min intervals. This data logger also controlled the three propane dispensers. Two-way communication with the HAS was by radio link to Mount Pleasant, UT, in the Sanpete Valley to the west, and beyond there by Internet.

5.3.b HAS Icing Sensor Problems

A Goodrich icing rate sensor, similar to the freezing rain sensors used in the national network of Automated Surface Observing System (ASOS) weather stations, was used to declare beginnings of 2 hr experimental periods containing a pair of 40 min EUs plus their 20 min buffers. A diagram of this sensor is shown in Fig. 2 with the 1 inch high by 1/4 inch diameter sensing rod extending vertically from a cone-shaped structure, both of these were automatically heated once rime ice buildup on the rod reduced its frequency by a preset amount. The unheated heat sink consisted of aluminum cooling vanes which collected rime. While the heat sink was unnecessary during the winter randomized experiment, no other configuration was available. The much smaller Rosemount tower-type sensors cause less local airflow distortion and are simpler to mount but do not output frequency with rime buildup. Only heater cycle relay "trips" are recorded, typically output only once or twice per hour, an unsatisfactory time resolution for the randomized experiment.

The HAS data logger calculated a running mean of three 1 min frequency observations from the Goodrich sensor, centered on the middle minute. The running mean had to decrease by at least 34 Hz over exactly a 10 min period in order for an experimental period to be declared. The 10 min period provided a reasonable time sample and minimized the impact of any frequency noise spike. After the first of the EU pair was declared, the icing sensor was monitored but not used to test conditions for start of another EU pair until two full hours had passed. A following pair would be declared as soon as the 34 Hz decrease criterion was again satisfied, equivalent to about 0.005 inch thickness of ice buildup according to wind tunnel tests conducted by the manufacturer[2]. If this criterion was reached during the last ten minutes of the experimental pair, than a new pair would be initiated immediately following the original pair. The same source noted that approximately 0.01 inch ice buildup thickness on the sensing rod is equivalent to about 40 mg mass and results in a 67 Hz decrease in frequency. The ASOS algorithm uses an accretion of 0.005 inch as part of their freezing drizzle reporting threshold, the same value used to declare EUs for this experiment. Some significant problems were experienced with this icing rate sensor during the field season as documented in detail by SH05. The most serious problems are briefly discussed here.

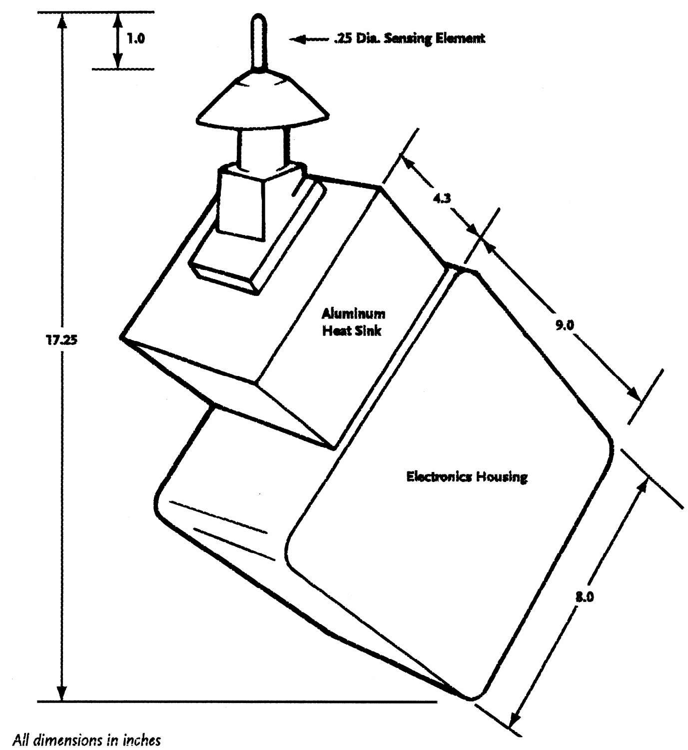

Fig. 2. Scale drawing of the Goodrich Model 872F1 icing rate sensor.

The Goodrich was received without mounting instructions. Technicians initially mounted the electronics box horizontally, but that misoriented the sensing rod 45 deg off vertical (see Fig. 2), while pointing it toward the south. The first storm started with typical southwest flow and the frequency-time history was as expected (see plot in SH05), producing a valid EU pair. But HAS winds then shifted north of west after which an additional 10 pairs of EUs were triggered. Most or all of them are believed invalid because SLW cloud droplets were approaching the improperly oriented sensing rod from a rear quarter, likely resulting in an uneven pattern of rime ice buildup. This was evidenced by a quite noisy frequency record. Similar noisy data were observed later in the season, during infrequent northwest flow

[2] Darren Jackson, Goodrich Aerodynamicist/Systems Engineer, personal communication, 18 Sep. 2003.

periods, even after the sensor was properly oriented. In the spirit of following the randomized design, all EUs were kept in the data pool whether their declaration was suspect or not, the latter applying to the large majority of cases. However, the declaration threshold was increased to 70 Hz immediately after the first storm and remained there until 05 February 2004 after confidence had increased in the icing sensor. By then it was obvious that periods with noisy data were mostly related to northwest flow, and the threshold was returned to 34 Hz. Since the program was randomized, these threshold changes should not have caused any problem other than possibly missing some potential EUs while the threshold was 70 Hz. Apparently the instrument affects the local airflow in such a manner that proper operation requires it to be pointed into the wind. The Goodrich sensor data appeared reasonable for southwest flow cases with few exceptions.

On 17 February 2004 the tower-type Rosemount icing sensor was removed from the SIR location, by then obviously a poor sampling site, and was mounted near the HAS Goodrich unit to provide intercomparisons. Later storm passages resulted in several EUs with the Goodrich sensor output appearing normal, and frequent trips by the Rosemount instrument.

But both sensors eventually quit observing SLW during the major storm passage of 28-29 February 2004. The Goodrich sensor triggered several EU pairs during a 12 hr period after which the frequency data became noisy and soon became constant so no further icing was observed. Many trips were observed from the nearby Rosemount sensor during the first 7 hr of the same 12 hr period, but then no further icing was indicated. Photographs taken the following morning revealed 2 to 3 inches of rime ice buildup on the icing sensor housings and other structures. Both icing sensors had vertical "fingers" of rime ice immediately upwind of, but apparently not attached to, the sensing rods. These "fingers" blocked further icing on the rods, effectively rendering the sensors useless. This same phenomenon was repeatedly observed during Colorado field testing of Rosemount icing sensors (Super et al. 1986). It is obvious that long periods with strong icing can overcome the deicing capabilities of both types of icing sensors. Future users may wish to provide supplemental heating to the sensor housings, and increase the heating applied to the sensing rod and its underlying structure.

5.4 TAR Observatory

The principal target gauge was GTR located 4.3 km northeast of the HAS. Weather parameters and 2D-C probe particle images were monitored on a platform located 0.3 km west-northwest of gauge GTR, at the TAR located immediately west of Highway 31. Data collection from the TAR is now discussed.

Most instrumentation at the TAR was located above the safety rails of a platform located just west of the equipment and personnel trailer. The instruments were between 7 to 7.5 m above ground level. The 2D-C particle imaging probe, with a large vane to keep it pointed into the wind, was mounted over the west (upwind) corner of the platform. Its strobe rate was slaved to the anemometer wind speed to provide symmetrical ice particle images.

The 2D-C imaging probe has been widely used in cloud microphysical studies. It has an 800 μm image width and 25 μm resolution. There is no length limitation along the wind as the probe continues to strobe until a particle is past the vertical laser beam, no longer shadowing the instrument's optical array. Software for calculation of IPC, precipitation rate and estimation of crystal types (habits) is discussed by Holroyd (1987). Particles with a calculated center-of-mass outside the image width are rejected by the software. As a consequence, very few larger particles are sampled by the probe. Another model, the 2D-P probe, is often used to study larger precipitation sized particles, but such a probe was not available for the Utah project. The 2D-C probe is well suited for examination of smaller seeded ice crystals.

Other instruments at the TAR included a Hydro-Tech heated anemometer and wind vane, a Rosemount tower-type icing sensor, air temperature and relative humidity sensors, and an atmospheric pressure sensor.

5.4.a The TAR data acquisition system

Because the experiment was run 24/7 and funding allowed only occasional visits to the TAR, the data acquisition system (DAS) needed to be completely automated. Details of the system and data collection are provided by SH05. The DAS, satellite communications relay, and maintenance items were housed in a small trailer established specifically for this purpose. Electrical power was supplied by a propane-fueled 30 KW generator. Several large propane tanks fueled the generator and provided heat for the equipment trailer. Cell phone communication was possible at the TAR, a major advantage during maintenance visits.

Meteorological parameters were generally sampled at 1 Hz, then averaged, or accumulated for icing sensor trips, over one minute. An exception was the 2D-C probe which had its strobing rate was controlled by the DAS using wind speed measured by heated anemometer. To ensure correct time, even after a system crash and subsequent reboot, GPS time was input to the DAS from a Garmin GPS35-PC.

Internet access was provided by U.S. Satellite Corporation. A satellite dish was set up near the electrical generator with electronics placed in the instrumentation trailer. This system worked with minimal problems, allowing for real-time monitoring and transfer of large data files from afar.

There were several problems which caused the loss of data at the TAR site as discussed in detail by SH05. The primary cause of data loss was stoppages of the electrical generator which powered the TAR. The main problem was caused by drifting snow blocking the air intake. The same generator had been used in its "weather proof" housing at the TAR during two previous winter projects without this problem. It was necessary to mount the generator in a stock trailer, a major mid-winter effort which caused a several day data loss. Other causes of data loss included failure of various computer and network components, and iced or dirty 2D-C probe tip mirrors.

5.5 SIR and TSO Icing Stations

Two observing stations, SIR and TSO, are shown on Fig. 1. They are only mentioned here as their measurements had minimal impact on experimentation for reasons discussed by SH05. They were used with only one of the statistical testing partitions of Sec. 7, where icing anywhere was considered. Both had considerable missing data.

6. STATISTICAL TECHNIQUES

Four statistical tests were applied to the experiment's EUs. The null hypothesis tested was that propane seeding did not produce a change in precipitation. The tests are briefly described below with more details provided in Sec. 7 of SH05. The four tests are regression analysis, pairs analysis of seeded minus nonseeded (S-NS) residuals, the Wilcoxon, and ratio analysis. The last three of these were described in an *a priori* sense in early October, 2003, before any data collection (Heimbach and Super 2003) to preclude any concerns that analysis techniques were "mined" to find the most optimistic test(s). The regression test is a simple screening which was added after the 2003/2004 field program. It is discussed first.

The experiment was designed to reduce the variability among EUs which can be far larger than the treatment signal. One means was through pairing back-to-back EUs assuming some homogeneity within the pairs. Another approach was to establish a control gauge site with sufficient crosswind separation to preclude contamination. The importance of using control gauges as covariates to protect against a "bad draw" cannot be overemphasized as shown by Mielke et al. (1981), Super and Heimbach (1983) and others. Covariates are necessary to reduce natural variability sufficiently to be able to conduct a randomized seeding experiment in a reasonable time period.

Although a test might indicate a seeding signal, confidence had to be established that the apparent change was not due to random selection. This was quantified by the probability value (P-value) which the tests derive. It is the probability of rejecting a true null hypothesis, termed a Type I error. In the tests below, P-values derived from the samples were be compared to the somewhat arbitrarily specified α-level, generally accepted as 0.05 by the meteorological community. If the $P \leq \alpha$, the sample was deemed significantly different from the population. It was assumed that seeding cannot decrease precipitation (Super 1986) so P-values were 1-tailed unless otherwise indicated.

6.1 Regression Analysis

If a seeding effect existed, its signal would be evident in the linear least-squares relation between the target (T) and control (C) sites where an estimate of the target SWE was found using; $\hat{T} = a + bC$. A positive seeding effect would produce a higher Y intercept, a, and/or larger slope, b, for seeded than for nonseeded samples. The differences in y-intercepts were not found to be significant in preliminary screening, therefore, only the slopes were used to judge the significance of the regression.

Tests for homogeneity of slopes were done using an ANOVA (analysis of variance) and the Student's t-test. These are described in greater detail by SH05, Appendix A. The F_s sample statistic is the ratio of the MS (mean squared) explained by the difference of slopes to the MS of unexplained variation.

$$F_s = \frac{MS_{\text{variation among regression}}}{MS_{\text{unexplained by regression}}}. \qquad (1)$$

To find the P-value, F_s was compared to tabulated values of $F_{\alpha\,(1,s+ns-4)}$, where lower case s and ns are the sizes of the seeded and nonseeded samples, respectively. Because the ANOVA cannot distinguish the sign of treatment effect, this test was 2-tailed.

The sample statistic used to derive a P-value in Students t-test is,

$$t_s = \frac{b_s - b_{ns}}{\text{Standard Error of b}}, \qquad (2)$$

where b_S and b_{NS} are the S and NS slopes. The t_s statistic was converted to a 1-tailed P-value by comparing it to tabulated critical values of $t_{\alpha(s+ns-4).}$

6.2 Pairs Analysis of S-NS Residuals

The pairs test exploits the paired (or "blocked") experimental design and makes no assumptions about the distribution of the members. The control SWEs were used as covariates to derive S and NS residuals from the median or least absolute deviation fits forced through the origin to minimize the effect of data which had either the T or C, but not both equal zero SWE:

$$T' = T - b_{lad}C, \qquad (3)$$

where b_{lad} is the slope of the median regression fit. The median regression fit reduced the distortion caused by outliers. Only the nonseeded EUs were used for this regression.

For a specific gauge, pairs meeting a given partition have the difference, R_i, between the S & NS residuals defined as,

$$R_i = T'_{Si} - T'_{NSi}, \qquad (4)$$

where i is the index for the pair and includes pairs 1 through P. From these a mean residual difference, $\overline{R}$, is found. $\overline{R}$ can be interpreted as the mean absolute change in precipitation due to seeding. The distribution of $\overline{R}$ cannot be stated with any reliability. Therefore, statistical inferences require some form of nonparametric testing. Rerandomization is an accepted technique which has been widely applied (Gabriel 2000). It is also called permutation procedure, and if applied to a subset of all possible permutations it is termed a Monte Carlo test. As pointed out by Dennis (1980), this approach has the advantage that resulting probability values are unaffected by any assumptions about the underlying statistical distributions. Moreover, he notes that the probability values, "---- automatically take account of any lack of statistical independence in the experimental units."

In the rerandomization process used for this analysis, each of the P pairs included in the analysis had one of its two EUs randomly "seeded" without regard to how the EU was actually treated. The second of the pair was assigned the opposite treatment and R_1 was found as described above. This random treatment was repeated for each pair from which a mean, $\overline{R}_1$, was found. The subscript 1 refers to the first rerandomized mean S-NS residual. A total of j = 1...1000 rerandomizations were done for each analysis.

If the null hypothesis was correct and no treatment effect existed, the actual $\overline{R}$ would most likely lie somewhere in the middle of the rerandomized $\overline{R}_j$ distribution. A positive treatment effect would have $\overline{R}$ in the high end of the $\overline{R}_j$ distribution. The 1-tailed probability level, P, would be the fraction of the $\overline{R}_j$ distribution at or above $\overline{R}$. The smaller the value of P, the more significant the treatment effect.

6.3 Nonparametric Inference Technique

The Wilcoxon, a nonparametric test, was selected because it is well-known in the weather modification community, easy to understand and has withstood the test of time. Because it is a nonparametric test, nothing needs to be known about the distribution of T and T'. In this test EUs are not associated with pairing. The Wilcoxon was applied herein using control gauge SWEs as covariates to derive residuals T' as defined by Eq. 3. The residuals of both the seeded and nonseeded units were placed in ascending order regardless of S/NS status. The sum of the linear ranks of either S or NS but not both was found. This sum was compared to that of the null distribution of the rank sum which is normal with an expected value and variance, and, therefore, can have a P-value inferred. This form of analysis was done by Super and Heimbach (1983) for the Bridger Range exploratory experiment and follows earlier suggestions by Mielke et al. (1981). The reader is referred to Dennis (1980) for further details, and to Mielke (1967) for handling tied ranks. This test has the advantage of including EUs which may have been paired with an unusable EU rejected as invalid in preliminary screening or by partitioning and, therefore, excluded in the pairs analysis.

6.4 Ratio Statistics

There is a class of analyses called ratio statistics which allows inferences to be made using EUs which are disassociated from their respective pairs. They are analyzed as two samples, one S and the other NS. For an in-depth discussion of ratio statistics applied to weather modification experiments, see Gabriel (1999 and 2002), and for a generic discussion pertinent to this experiment see SH05.

There are several ratios which could be tested including the mean single ratio (MSR), the median double ratio (MedDR) and the mean double ratio (MDR). The focus was on the MDR because it is well-known, removes the influence of natural variation through the use of control gauges, and gives an estimate of treatment effect.

$$\mathrm{MDR} = \frac{\text{Mean Target Single Ratio}}{\text{Mean Control Single Ratio}} = \frac{\sum T_S / \sum T_{NS}}{\sum C_S / \sum C_{NS}}. \qquad (5)$$

Gabriel (1999) parameterized the expected distribution of the MDR given no treatment effect to infer P-values. However, he suggested that an excess of N=100 EUs is required. Because only 98 EUs resulted from this experiment, the null distribution was inferred by rerandomization. This was done similarly to the pairs rerandomization except the EUs were individually "seeded" or "nonseeded" instead of by pairs. Each of the rerandomized experiments had the same number of S and NS samples (indicated by lower case s and ns below) as the actual experiment. The P-values were estimated by comparing the actual MDR to the rerandomized distribution of MDR_j, j=1 … 1000. If, for example, 60 out of 1000 rerandomized MDRs are ≥ the sample MDR, then the P-value is 0.06 for a 1-tailed consideration.

Whereas a significance test can imply there is a seeding effect, confidence intervals can quantify the possible range of effect which seeding may cause. Because N<100 EUs were available, rerandomization was also required for the derivation of confidence limits (Gabriel 1999). The same set of 1000 rerandomized MDRs used to derive the P-values were applied to estimation of confidence limits. The resulting null distribution was centered on the actual or sample MDR by the following transformation,

$$\mathrm{MDR}'_j = \mathrm{MDR}_j + \mathrm{MDR}. \qquad (6)$$

For the (1-α) = 0.95 confidence interval, the bounds were set to exclude the highest and lowest (0.05*1000/2) members of the MDR'_j distribution for a 2-tailed test, and the lowest (0.05*1000) members for a 1-tailed inference. For example, a test of significance using α=0.05 might estimate from the MDR that treatment provided an additional 10% SWE. The 2-tailed confidence interval derived from the same data might show that the seeding effect was between +3% and +20% which indicates a positive effect was very likely at the 5% significance level within the indicated 3% to 20% range. If the confidence interval includes 0%, than the null hypothesis (no seeding effect) is accepted at the specified α-level. If 0% is outside the confidence interval, than the null hypothesis is rejected (a seeding effect exists).

In the spirit of the above example, the confidence interval for the 1-tailed application could be stated to be greater than +2%, with the upper boundary being unknown, as compared to the hypothetical 2-tailed +3% to +20% above. It is possible that the lower confidence boundary can be negative even with 1-tailed applications, and this occurred under some partitions. This merely means that there was enough uncertainty or variance in the MDR'_j distribution that the range of the confidence interval was expanded to include a null treatment effect or less.

6.5 Comments on Statistical Techniques

The pairs analysis was designed to reduce the large natural variance of SWE through the assumption of within-pair homogeneity. The use of blocking must be done with caution because precipitation data tends to not be homogeneous on a long time scale. That was the case for this experiment. The lack of within-pairs homogeneity can be quantified by comparing the variance or mean square within pairs to that for the pooled samples. For GNO, the control site which presumably experienced no seeding effect, the former was 0.00097 inch^2 and the latter was 0.00079 inch^2 which are nearly equal. That result implies the within-pair variance was approximately equal to the pooled variance and the time scale of precipitation events could be on the order of an hour or less. Nevertheless, when the control was applied to find target residuals, the pairs test was powerful enough to detect a seeding signal with comparable and sometimes lower P-values than the other tests.

The Wilcoxon is a linear rank-sum test implying that the ranks to the first power are summed. Because of this, the Wilcoxon test reduces the distortion caused by outliers (Dennis 1980, Mielke et al. 1982). The sensitivity to outlying precipitation amounts can be changed by summing ranks taken to a power other than 1, i.e., >1 to emphasize larger amounts and <1 to emphasize smaller amounts (Mielke 1967, 1974). Nonparametric tests, such as the Wilcoxon, are less powerful than parametric tests because they don't take advantage of what can be known through parameterization (Dennis 1980), making this test conservative. That is, the Wilcoxon is likely to result in slightly higher (less significant) P-values than the other tests used in this paper.

The ratio test reported herein was limited to MDRs. The technique also produced confidence intervals which have the advantage of suggesting a range over which a seeding effect can occur. Ratio statistics are estimates of the proportional effects (Gabriel 2002) or relative increase/decrease caused by treatment. For example, a MDR of 1.20 implies that the treated sample is 1.20 - 1.0 = 0.20 = 20% larger than the untreated sample. This is different from the S-NS residuals of the pairs analysis which gives an estimate of the absolute increase.

Attempting to determine which of the four tests is "best" for this experiment requires the balancing of tradeoffs. Some positive aspects include simplicity (regression); being well-known, robustness and having withstood the test of time (Wilcoxon); benefits of blocking and analysis of absolute increases of SWE (pairs); and analysis of proportional increases and estimation of confidence intervals (rerandomized MDRs). Disadvantages include less sensitivity (regression and to a lesser extent, the Wilcoxon test), and a reduced number of usable EUs (pairs test). For this experiment, the authors favor the rerandomized MDR test. The higher sensitivity and inclusion of confidence intervals gives this test advantages. The Wilcoxon test has second preference, mainly because of its robustness and legacy. The presumed within pairs homogeneity did not occur, however, this test was quite sensitive when applied to residuals.

The significance of a test, or magnitude of the P-value, is related to the number of EUs: the greater the number, the smaller P is likely to be. P varies approximately with $1/\sqrt{N}$ (Sokal and Rohlf 1969). The 3.5 month experimental period during the winter of 2003/2004 was much dryer than normal, limiting the number of EUs to 98 from which there were 47 pairs. These numbers were further reduced when applying partitioning. Many of the test results presented in the next section have encouraging seeding signals as quantified by mean S - NS residuals and MDRs; however, several P-values do not meet the commonly-accepted $\alpha=0.05$ criterion. It is possible that a greater sample size could provide more confident P-values, but that speculation cannot be tested with the available data set.

One must exercise caution in interpreting the P-values and confidence intervals derived by these tests. This is an exploratory experiment, meaning that it was designed to search for possible effects with *post hoc* analyses. As such, statistical inferences or suggestions cannot be considered conclusive. This is in contrast to a confirmatory experiment which tightly establishes the hypotheses, protocols and tests prior to the start of the experiment in an *a priori* fashion. Achieving "scientific proof" in the sense that term is used by scientists and statisticians requires a later confirmatory experiment which would have the hypotheses and testing methods firmly laid down in advance of its conduct.

Because a sufficient number of tests will sooner or later indicate significance where there is none, the results of an exploratory experiment should only be called "suggestive." This is related to the *multiplicity* problem. For example, if significance is defined by an α-level of 0.05, then one out of 20 tests of samples from a population that has no seeding effect can be expected to have a P-value $\leq \alpha$, that is, rejecting a true null hypothesis known as a Type I statistical error.

Mielke et al. (1982) addressed the multiplicity problem in a reanalysis of Climax I and II. They cited two major causes of multiplicity: specifications of partitions, and choices of statistical techniques. Gabriel (2002) expressed concern about the potential for multiplicity caused by applications of multiple tests to the same data and suggested compensating for this by multiplying P-values by the number of tests applied. This is not appropriate for the latter three tests of this section because three different parameters are being tested; S-NS residuals, ranking and MDRs. An alternate approach would be to apply the stringent criterion that significance is assured if low P-values result from all three tests. If this is the case, then a positive seeding signal is strongly suggested. The discussion of the following section takes something of a middle ground, with two out of three low P-values often considered to be strongly suggestive.

7. RESULTS OF STATISTICAL ANALYSES

7.1 Finalizing EU Selection and Calculating Plume Transit Times

The randomized program produced a total of 102 valid EUs, that is, 51 pairs each with one seeded and 1 nonseeded unit. Four EUs were removed from further consideration because observed wind speeds at the TAR and/or HAS were too low to realistically estimate the period of seeding plume passage by any location. They were obvious outliers. The starting threshold of the heated and very sturdy Hydro-Tech anemometers is 4 to 5 mph according to wind tunnel tests by the manufacturer. The starting threshold is less (but unstated) for turbulent airflow, and the instruments operate down to about 2.5 or 3 mph, once started. Accordingly, an EU was rejected if the number of 1-min mean samples with a minimum wind speed criterion of 3.0 mph (1.3 m s^{-1}) did not exceed 10 out of the 40 available. This left 98 EUs of which 94 were paired and the remaining 4 were one member of a pair with the other member rejected by the wind criterion.

Time and duration of 40 min plume passages over any target site was not directly known. A relationship was used based on 45 pulsed seeding experiments with HAS releases of AgI monitored at the TAR (Holroyd and Super 1998). Transit times were all within the range10 to 30 min except for one at 8 min, and outliers at 39 and 54 min. The median was 17 min so a straightforward approach to estimating the passage of seeded ice crystal plumes by the TAR and nearby gauge GTR would be to add 17 min to the propane release times. However, Holroyd and Super (1998) also provided a relationship between transit times and the HAS and TAR wind speeds. The equation for t, the transit time in minutes, was expressed by:

$$t = \frac{(t_{HAS} + t_{TAR})}{2} + 2, \qquad (7)$$

with each t calculated from the relationship t =70/V and V being the wind speed at each site expressed in m s^{-1}. Details of processing cases with missing TAR observations are discussed in SH05. No HAS data were missing. While not ideal, the wind speed approach with the above equation explained 68% of the variance in the earlier directly observed transit times. Equation (7) offered the best estimation in the absence of any direct detection method.

The transit times needed to be adjusted for target gauge distances less than or greater than the HAS to TAR distance of 4.1 km. This was done by simply multiplying t by the ratio of each gauge's distance from the HAS divided by the HAS to TAR distance. The same transit time estimated for the TAR and nearby gauge GTR was used for the other two gauges on the plateau top's west edge (GNO and GSO). That is because the winds on top the north-south oriented plateau were very predominately westerly during storm phases with snowfall and/or SLW present. Consequently, the two gauges north and south of the TAR should have experienced passage of natural storm elements at almost the same times as the TAR and nearby GTR.

7.2 Regression Analysis Applied to Entire EU Sample Population

Regression analysis was discussed in Sec. 6.1. The homogeneity of slopes was tested for each target-control sample. The target sites were gauges GSC, GRD, GTR, GSO, and GDN, each tested individually, which were regressed on the control site, GNO, using the linear least-squares technique. Two regressions were done for each target-control pair; one for the seeded and one for the nonseeded samples.

Mean double ratios were calculated for each target gauge compared with the control. All except GRD had values greater than 1.2, suggesting an approximate 20% seeding effect. One-tailed P-values by the t-test ranged from 0.02 to 0.23. This simple test applied to the entire sample population strongly suggested a positive seeding effect at GTR, the anticipated primary target gauge. The test provided a somewhat suggestive P-value of 0.10 for GSC, between the HAS and GTR. The remaining P-values were higher, so their results are considered inconclusive.

It should be recognized that inconclusive evidence is quite different from concluding that no seeding effect existed. If any seeding effects existed at the other gauges, they simply could not be detected to a generally acceptable level of certainty with the simple regression approach applied to the entire sample population.

7.3 Results of Pairs, Wilcoxon and Ratio Tests

7.3.a Testing of Entire Data Set without Partitioning

Statistical testing results from the entire unpartitioned data set of 98 EUs are summarized in Table 1. The control gauge was GNO f or this table and all following statistical test summaries. The gauge order in each of the following tables is by increasing distance from the HAS. P-values of 0.10 or less are shown in **bold**. In the spirit of exploratory analysis P-values of 0.05 or less will be considered "strongly suggestive" of a seeding effect, while values from 0.06 to 0.10 will be regarded as "somewhat suggestive."

The first entry in Table 1 is for target gauge GSC. Interpretation of its testing results are as follows: The second column has the mean S-NS residual in the pairs analysis equal to 0.006, suggesting that on average, seeded units received 0.006 inch more precipitation per 40 min period than the nonseeded units based on residuals calculated using GNO as a covariant. The third column indicates a P-level of 0.04 was obtained for this S-NS residual using rerandomization. Column 4 lists the target-control linear correlation coefficient for the 98 pooled S and NS units. The Wilcoxon nonparametric test in the fifth column gives the rank-sum P-value of 0.05, also strongly suggesting statistical significance by meeting the often used 0.05 α -level to denote "significance." Column 6 lists GSC's MDR as 1.22, indicative of a 22% SWE increase due to treatment. The MDR was derived from the 50 seeded and 48 nonseeded units, not the 47 pairs. Using rerandomization to derive the statistical inference of this MDR gave a P-level of 0.06, somewhat suggestive. The confidence interval in column 8 indicates a 1-tailed 95% confidence that the actual MDR lies somewhere between +2% and infinity, assuming that seeding can only increase, not decrease, precipitation. No upper boundary can be specified with that assumption.

Table 1. Summary for 98 available EUs with no partitioning**:** 47 pairs, 50 seeded and 48 nonseeded EUs.

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

Results for GRD are inconclusive and its correlation with the control gauge is well below the other correlations. As discussed in Sec. 3, that gauge site proved to be too windy for reliable measurements.

The primary intended target gauge, GTR, and the GSO site 1 km due south of GTR, both had significant P-values by the pairs and MDR ratio tests. Their Wilcoxon P-values were 0.10, somewhat suggestive of a seeding effect. Gauges GSC, GTR and GSO are within 3 km or less of one another and will be referred to as the "core gauges." Taken together, the evidence is strong for a seeding effect at the core gauges with MDRs near 1.22 implying a 22% SWE increase for seeded EUs over nonseeded EUs. The 95% confidence intervals for the core gauges indicate *minimum* increases of 2, 4 and 6%, respectively. The pairs residuals are all 0.006 inch per 40 min, equivalent to 0.009 inch h^{-1} mean snowfall increases. While only light snowfall, it is near the median value for all hours at GTR, found to be just above 0.010 inch h^{-1} by SH05.

Although the downwind GDN gauge MDR was 1.21, P-values were 0.27, 0.12 and 0.09. The latter two values might be considered somewhat suggestive of a seeding effect but, overall, the results must be considered inconclusive for GDN. Failure to detect a significant seeding effect at GDN may be related in part to its having the second lowest correlation, with only the windy GRD ridge location having a lower value. A relatively low association with the control gauge results in the statistical testing being less sensitive, all else being equal.

7.3.b Reasons for Partitioning

It has long been recognized that partitioning (also called stratification) is an important part of exploratory analysis of randomized programs. One of the best known and most controversial examples of partitioning was use of the 500 mb temperature, presumed to approximate cloud top temperature, in the Climax Experiments in Colorado (Grant and Mielke 1967; Mielke et al. 1981). There are good physical reasons to suspect that seeding should be more effective during particular meteorological conditions. The Climax 500 mb temperature partition was based on the expectation that colder cloud tops would provide more natural nucleation of ice crystals leading to naturally efficient snowfalls consuming most or all of any SLW cloud. Another example is that seeding plumes obviously must be transported over expected mountain target areas for seeding to be effective. Partitioning can be used to remove EUs having winds unlikely to affect the target area, resulting in a subpopulation of units which were likely successfully targeted. Testing such a subpopulation would be expected to "sharpen" the statistical analysis, resulting in lower P-values when testing the null hypothesis.

It was stated in Utah's Division of Water

Resources proposal to Reclamation that, "Exploratory partitioning of the EUs will be based on the observations mentioned, including natural precipitation rate from control gauges, wind speed and direction, HAS and TAR temperatures, and icing rates." All partitions were attempted as discussed below except for the TAR temperature. HAS and TAR air temperatures were very highly correlated and several EUs had missing TAR data so only the HAS temperature was used for partitioning.

7.3.c Partitioning by HAS Wind Direction

Analyses of past observations (Sec. 2.2) demonstrated that the TAR was consistently targeted when the HAS mean wind direction was in the 170 to 270 deg range, basically the southwest quadrant. Mean and median wind directions were very similar during propane or placebo release periods. Median directions were used for partitioning as they should be more representative, less affected by outlier samples. The wind direction range for the available sample population of 98 EUs was 169 through 325 deg. A total of 69 EUs had directions in the 169 through 270 deg range which will be the only wind direction partition used. The next highest value was 278 deg providing a natural break in the distribution.

The test results in Table 1 above were run for all 98 EUs with no partitioning. The 69 EUs meeting the HAS direction criterion will be considered next, with results summarized in Table 2. The control gauge was GNO for this partition and all other partitions attempted.

Table 2. HAS wind direction partition from 169 to 270 deg inclusive: 32 pairs, 35 seeded and 34 nonseeded

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

With the exception of GRD, the P-values for the gauges of Table 2 are similar to those of Table 1. Five of the 12 P-values in Table 2 (ignoring GRD) are a little lower, 6 are a little higher and 1 is a tie. This is in spite of all the correlations being a little lower, probably due to the removal of several near zero pairs associated with northwest winds.

Because GRD correlations were consistently well below the other values, believed due to inadequate protection from wind effects, and because all dual partitions showed inconclusive results for GRD as in Tables 1 and 2, often at variance with the other 4 gauges, GRD results will not be discussed further. Measurements from that gauge location were too "noisy" for detection of any seeding effect with the available data set.

All the mean S-NS residuals are greater for the direction partition than for all EUs *as would be expected if the seeding signal was concentrated within that partition*. Moreover, the partitioned MDRs are the same for GSC but somewhat larger for the other target gauges excluding GRD. Overall the MDRs suggest about 25% more snowfall from the seeded EUs. The lower boundaries of the 95% confidence intervals are higher for 3 of the gauges, ranging from 5% to 7% minimum treatment effect for GTR and GSO, both just downwind of the Plateau's west edge, and GDN a little more than 2 km downwind of the edge. Given the low P-values, one can be 95% certain that seeding caused at least a 5% increase in SWE at those gauges.

There would be reason to doubt the statistical results if the seeding signal was not found to be concentrated within the wind direction range known to provide routine targeting. In this case the statistical suggestions are in accord with the empirical evidence from past plume tracing studies. That agreement markedly enhances the credibility of the statistical indications.

7.3.d Partitioning by Exclusion of Larger Natural Snowfalls.

A dual partition was attempted which removed the larger natural snowfall periods with the expectation that a seeding signal would be more detectable during lower natural snowfall rates. All EUs were excluded which had a control gauge GNO accumulation exceeding 0.05 inch for the 40 min period. That criterion removed 20% of the EU population which met the wind direction criterion of

270 deg or less, and had the highest observed natural SWE amounts. In other words, the 0.05 inch SWE value is the 80th percentile for GNO of the ordered 69 EUs with wind direction no greater than 270 deg. The remaining sample population is still of reasonable size with 55 EUs of which 48 were paired. Some of the excluded EUs might be considered outliers.

As seen in Table 3, the partition with 0.05 inch SWE limit at GNO provided P-values of 0.01 and 0.02 at the GSO location for the rerandomized MDR and pairs tests, respectively. The Wilcoxon provided a respectable 0.05 value for that gauge. GSO's confidence interval is high suggesting that if there is a true seeding effect for this partition, one can be 95% sure that it lies at or above a 21% increase. But results are less encouraging for the two nearby gauges with an unremarkable pairs P-value of 0.19 at GTR but 0.10 and 0.04 for the other tests. The GSC gauge has somewhat suggestive P-values of 0.07 and 0.10 for the pairs and MDR tests. Gauge GDN, which often had mediocre results in other tests, has P-values between 0.02 and 0.10 by all three tests, suggesting a downwind seeding signal when natural snowfall is limited to moderate rates or less. The MDR tests are especially encouraging with values of 0.01, 0.02, 0.04 and 0.10 for the four gauges, and associated confidence intervals indicating a 95% certainty of a *minimum* increase of 9% for GTR and between 16 to 21% minimum increases for the other gauges.

Table 3. HAS direction partition <= 270 deg combined with GNO SWE <= 0.05 inch per 40 min: 24 pairs, 30 seeded and 25 nonseeded.

Target Gauge	Sample S-NS Residual (inch)	S-NS 1-tailed P-value	Pooled Target – GNO Correlation	Wilcoxon 1-tailed P-value	Sample MDR	Re-randomized 1-tailed P-value	1-tailed 95% Confidence Interval
GSC	0.006	**0.07**	0.52	0.19	1.30	**0.10**	1.16 ~ ∞
GTR	0.003	0.19	0.67	**0.10**	1.32	**0.04**	1.09 ~ ∞
GSO	0.007	**0.02**	0.58	**0.05**	1.45	**0.01**	1.21 ~ ∞
GDN	0.003	**0.10**	0.60	**0.09**	1.51	**0.02**	1.20 ~ ∞

The mean S-NS residuals all suggest a moderate seeding effect for this partition with values between 0.003 and 0.007 inch per 40 min. The MDRs are quite large, 1.30 to 1.51. GDN and GSO MDRs are the largest, being 1.51 and 1.45, respectively.

The removal of the larger SWEs for this partition substantially lowered the correlation coefficients as might be expected. This shows that there is disproportionately more scatter when reducing the overall range by rejection of the largest natural SWE units. This lower correlation, all else being the same, would cause the P-values to increase and the confidence intervals to expand. Therefore, the occurrence of low correlations along with several significant P-values suggested a stronger seeding signal was imposed on the EUs of this partition. The reasonably large number of EUs, 24 pairs, s=30 and ns=25, improves the confidence of the suggested positive seeding effects for this partition.

Overall, this partition provides some of the strongest evidence of a positive seeding effect, especially when the low correlations with the control gauge are considered. Assuming that the stronger earlier suggestions for a positive seeding effective are correct, it should not be surprising that the seeding signal is most apparent when the larger natural snowfalls are removed.

7.3.e Partitioning by SLW

The remaining test results were not as convincing as those discussed above. All following partition testing is discussed in detail by SH05, including presentations of tables similar to those just discussed. The following discussions are limited to how the partitions were configured plus summaries of results.

Since the wind direction criterion already reduced sample size to 69 EUs, adding another partition in the dual partitioning attempts further reduced sample sizes. This made detection of any real seeding effect even more challenging, that is, less likely. But in the spirit of exploratory analysis a number of dual partitions were attempted, with full realization that this approach reduced the chances of detection of actual seeding signals with inconclusive results likely. It is again emphasized that inconclusive results should not be taken as any indication that seeding failed any more than they provide any indication that it succeeded.

The glaciogenic seeding hypothesis requires the presence of icing, actually SLW cloud, for seeding to be effective. Therefore, it makes physical sense to involve quantification of icing in the partitioning. Unfortunately, the icing sensors used were not optimum. Problems with the HAS Goodrich sensor were discussed in Sec. 5.3.b. The Rosemount 0872B tower-type icing sensors at the TAR, and two other locations for limited periods, did not provide continuous icing rate information. The only output was of heater cycles ("trips") automatically triggered after sufficient rime ice buildup on the sensing rod. Since typical trip rates were 1 or 2 per hour, the time resolution of these data are limited and matching SLW presence with 40 min EUs was problematic. The usual 40 min EU averaging periods were extended by 10 min for detection of Rosemount trips in an attempt to minimize exclusion of EUs with some icing but not quite enough for the sensor to trip.

Icing sensors are only point measurements not far above the ground. Furthermore, tower-type Rosemount sensors can frequently fail to detect periods with low icing and/or brief icing episodes as demonstrated by comparisons with similar aircraft icing sensors (Model 871FA) having an analog output as well as heater cycle trips (Super et al. 1986, Solak et al. 1988). Operation of a microwave radiometer at the HAS or TAR would have provided much improved SLW information, but was not affordable.

With full knowledge of instrumentation limitations, an attempt was made to partition EUs with icing sensor observations. Three separate icing partitions were attempted. The first was based only on icing detection at any station ("icing anywhere") including the SIR and TSO sites which both had limited data. This partition provided 71 EUs and 27 pairs. A dual partition also used icing anywhere but with HAS wind directions no greater than 270 deg. It provided 60 EUs and 24 pairs. Finally, a similar dual partition used the same HAS wind directions but with only TAR icing considered which resulted in 36 EUs and 13 pairs, a quite limited sample population.

The MDR ratio testing provided somewhat suggestive results for all 4 target gauges for each of the three partitions, with P-values between 0.06 and 0.10 except for one 0.11 value. Corresponding MDRs were between 1.19 and 1.41, all indicating large seeding increases if real. But only two gauges had similar fairly low P-values from the pairs and Wilcoxon tests for each partition. Still, fairly low P-values resulted at some of the gauges in spite of the limited sample populations. For the TAR icing combined with the wind partition, GSC's P-value ranged only from 0.06 to 0.08 while GDN had values of 0.04, 0.07 and 0.14. Single somewhat suggestive P-values resulted at the other two target gauges. Therefore, the results for partitioning by icing detection can be considered interesting and intriguing. But they are not conclusive.

It is considered probable that the apparent seeding signal from the randomized experiment was related to SLW availability, as required by the glaciogenic seeding hypothesis. However, this could not be conclusively demonstrated. It is speculated that the main problem, besides limited sample size, was instrumentation limitations. It is not believed that partitioning by SLW presence was adequately tested with the available data set.

7.3.f Partitioning by HAS Temperature

Propane releases can produce ice embryos at temperatures warmer than the effective range of AgI, giving homogeneous nucleation to within a few tenths of 0ºC, although seeded crystal production is limited until temperatures are less than -2ºC (Hicks and Vali 1973). Warmer temperatures might be expected to be associated with less frequent natural snowfall. For this reason, the temperature partition focused on warmer HAS temperatures. To ensure objectivity and reduce the risk of multiplicity, this partition used the 50th percentile of the ordered temperatures as the bottom limit, providing a range from -7.5 to -0.9ºC. Because there were four -7.5 values, 50 EUs ended in this partition instead of 98/2=49. The HAS temperature partition was tested by itself, and as a dual partition with HAS wind direction no greater than 270 deg.

Results from the temperature partitioning were similar for the single partition, with 50 EUs (22 pairs), and the dual partition with 45 EUs (19 pairs). This is not too surprising since the latter partition contained most of the EUs and pairs of the former. Two and sometimes all 3 P-values for gauges GSC, GTR and GDN were in the somewhat suggestive category for both partitions, that is, values were usually between 0.06 and 0.10. Results for GSO were less impressive but even its P-values ranged between 0.09 to 0.19. MDRs ranged between 1.21 and 1.32 for all gauges within both partitions. Pairs residuals were typically 0.009 inch per 40 min with the exception of GDN values near 0.003 inch per 40 min. While none of these results can be considered conclusive they at least suggest that consideration should be given to temperature partitioning in the future. As with the icing tests, the warmer temperature testing provided at least hints of a relationship with seeding effectiveness. However, a larger sample population would be needed to rigorously test these partitions.

The lower HAS temperature partition, -12.0 to -7.6ºC, provided little indication of a seeding effect, either as a sole partition or as a dual partition in combination with the HAS wind direction. But at least there were no indications of decreased snowfall from seeding the colder cases, presumed to be naturally more efficient in conversion of SLW to snowfall.

7.3.g Wind Speed Partition

A dual partition was done using average HAS wind speed combined with the HAS direction criterion. The speed data were divided into two size categories as defined by the 50th percentile, giving the two partitions as 1.8 to 5.3 m s^{-1} and 5.4 to 10.9 m s^{-1}. These cut offs were defined using all 98 EUs out of which there were two with speeds of 5.3 m s^{-1}. There was no clear natural break point in these data.

Slower wind speeds would provide longer ice crystal growth times but also slower SLW production so the final outcome at individual gauges is not obvious. The lighter wind partition produced rather mixed results. Low P-values resulted for at least one test for each gauge but several P-values were large. As an extreme example, GSC had a very low P-value of 0.01 with the pairs test, based on only 15 pairs, but values of 0.47 and 0.23 for the other two tests. Conversely, GSO had very low (< 0.001 and 0.02) to rather low (0.07) P-values by all tests. Yet P-values at nearby GTR ranged were 0.07, 0.09 and 0.14, not nearly as promising. Two of the GDN values were low at 0.01 and 0.04 but the remaining one was 0.26. Overall, this was the most inconsistent set of results of any partition. One complication is that only 15 pairs (30 EUs) were available for the pairs test but 39 EUs were used with the other two tests. In view of the somewhat mixed results, this partition has some suggestions of seeding success but they should be considered as quite tentative, possibly resulting from multiplicity and/or being limited by sample size.

Only GSC, nearest the propane dispensers, had any indication of seeding effects for the higher speeds partition, with all three P-values equal to 0.11 and an MDR of 1.22. That result is unexpected due to the limited ice crystal growth times available. That fact, taken together with the lack of low P-values for the other three gauges, indicates that the most reasonable conclusion is that this partition provided no evidence of seeding effectiveness.

7.3.h Summary of Partitioning Results

The above discussion has presented three tables for the most convincing results, and summary discussions for all other single and dual partitions. The following discussion summarizes the key findings.

It should be recognized that attempting to reach statistical significance in a single winter is challenging. Utah's proposals to Reclamation recognized that reality and noted that a relatively dry winter, as occurred during 2003/04, would likely make statistical testing difficult. Specifically, the second proposal to extend the field season from 10 to 13 weeks cautioned that, "If Utah has yet another in a series of dry winters, there is no guarantee that the EU population will be sufficient for desired statistical testing. That is especially true for partitioned subpopulations needed to define how various atmospheric conditions are affected by seeding."

First of all, it is important to recognize that testing of the entire available population of 98 EUs, summarized in Table 1, yielded P-values between 0.03 and 0.10 for core target gauges GSC, GTR and GSO even when including the Wilcoxon. When only the pairs and MDR tests were considered, the P-value ranged from 0.03 to 0.06. *These values provide strong suggestions of effective seeding at those gauges for the entire available population*. Associated MDRs suggest that seeded EUs had about 22% more snowfall than predicted by the nonseeded EUs' relationship with the control gauge GNO. Average S-NS residuals are 0.006 inch for each gauge, suggesting that much additional SWE fell on average per 40 min EU, equivalent to an hourly rate near 0.01 inch h^{-1}. That may seem a limited amount until it is realized that median natural rates for all significant snowfall days were just above 0.01 inch h^{-1} for the sensitive GTR gauge used in this study (see SH05). The large majority of hours with snowfall in the Intermountain West have similar light rates, and significant accumulations result because so many hours are involved. Obviously, 100 hours with a rate of 0.01 inch h^{-1} results in one inch of SWE. For reference, the long term average April 1st snowpack at the Mammoth-Cottonwood SNOTEL located near GNO is 19.9 inch, so a 1.0 inch increases represents a 5% seasonal increase from 100 hrs of seeding. At least 150 hours with SLW available at the HAS can be expected during a normal winter, and that estimate is likely low given the tendency of the tower-type Rosemount sensors to underestimate during light and/or brief icing episodes. The reader is referred to SH05 for more detailed discussion of possible seeding increases in seasonal snowfall.

The locations of all gauges are shown on Fig. 1. The three core gauges with strongly suggested seeding effects without any partitioning form a triangle with sides ranging from 1.3 to 3.0 km. Their straight line distances from the HAS seeding location range from 2.1 km for GSC to 4.3 and 4.6 km for GTR and GSO, respectively. The latter two gauges are just downwind of the west or windward edge of the plateau top. The downwind gauge GDN had, at best, weak support for any seeding effect when the *entire* population was tested.

The most important single partition resulting from this study is restriction of HAS median wind directions to 169 through 270 deg true inclusive. Considerable physical evidence from earlier investigations indicated that seeding site winds from the southwest quadrant routinely targeted the TAR and nearby GTR gauge. Use of this partition rejects all EUs with a northerly wind component at HAS which should transport seeding plumes south of the TAR. Moreover, the large majority of EUs with winds from the northwest quadrant are believed to be falsely declared, for reasons discussed in Sec. 5.3.b. Northwest flow EUs had quite limited precipitation in all but one of the 29 cases (SH05), although some TAR icing was detected during a number of them.

Results for the HAS wind direction partition are shown in Table 2. P-values for the pairs and MDR tests for the three core gauges were between 0.02 and 0.05 with the single exception of 0.09 at the GSC for one test. There is some suggestion of a possible seeding effect downwind at GDN but the pairs test was inconclusive. The core gauge residuals increased from the nonpartitioned results to 0.008 to 0.010 inch and MDRs suggested 22 to 26% increases. The results of the wind direction partition are also strongly suggestive of effective seeding in spite of the marked reduction in sample size, from 98 to 69 total EUs, and 47 to 32 pairs. That fact, together with the increased residuals, indicated the suggested seeding effect was associated just with HAS winds from the southwest quadrant, that is, the wind directions which would result in routine targeting. While that is exactly what would be expected on a physical basis, the importance of this *statistical result* should not be taken lightly. If the apparent seeding effect was not heavily concentrated in this wind direction partition, the credibility of the statistical findings should be seriously questioned.

One of the dual partitions was quite encouraging, that of excluding the 20% of EUs with GNO control gauge amounts greater than 0.05 inch SWE while limiting HAS wind directions to 270 deg or less. With the exceptions of one mediocre P-value of 0.19 at GSC and one of the same value at GTR, all other P-values at the 4 target gauges ranged between 0.01 and 0.10. Given the somewhat limited sample size and low correlation coefficients, a fairly strong statistical suggestion is provided that seeding effects were especially detectable when the larger natural precipitation rate periods were excluded. That is a physically reasonable result.

Somewhat encouraging suggestions resulted from other single and dual partitions, the latter always limited to HAS winds no greater than 270 deg. There were suggestions that effective seeding may be associated with the presence of SLW as detected by icing sensors, with warmer than median HAS temperatures and with less than median HAS wind speeds. However, none of these results can be considered more than somewhat suggestive, and are certainly not claimed to be conclusive. It is suggested that further attention should be given to these partitions in future experimentation.

7.3.i Application of Median Double Ratios

The MDR can be unduly influenced by outlier target-control pairs. Typically, there is a small portion of high SWE values compared to far more small values. This causes the median value of SWE to be smaller than the mean value, which discounts the influence of the outliers. Because of this, the median double ratio (MedDR), derived by substituting median values into Eq. 5, gives more weight to the smaller EUs. Super and Heimbach (1983) discuss the application of the MedDR to the exploratory Bridger Range winter orographic seeding experiment, done at the suggestion of an anonymous reviewer.

MedDRs were derived for target-control pairs meeting the HAS median direction partition which assured successful targeting, that is, 169 - 270 deg inclusive. These and the respective MDRs are listed in Table 4. The MedDRs are consistently larger than the MDRs for all target sites. The higher values suggested that the seeding effect was clustered in the smaller EUs. This reinforces the encouraging results of the <=270 deg and GNO <= 0.05 inch partition of Sec. 7.3.d. It would be possible for the large EUs to have a seeding signal whose absolute magnitude was the same as for the smaller EUs, but it would be difficult to detect this signal because the fractional increase would be much smaller. The large outliers, which likely had proportionally lower increases, smoothed the seeding signal as estimated by the MDR.

Table 4. Mean Double Ratios and Median Double Ratios for the HAS median direction partition of <= 270: 35 seeded and 34 nonseeded EUs.

Target	MDR	MedDR
GSC	1.22	1.29
GTR	1.24	1.38
GSO	1.26	1.50
GDN	1.27	1.46

It is not known which of the double ratios is more appropriate. The larger MedDRs suggest an intriguing high seeding effect. However, the authors have based estimates of seasonal treatment increases, discussed in detail in Sec. 9.4, on the more conservative MDR.

8. PHYSICAL CASE STUDY EXPERIMENT

Physical case study experiments attempt to document the physical chain of events from seeding to snowfall to the extent practical as discussed by Super (1990). Several reported physical case study experiments with winter orographic cloud have presented obvious effects of AgI seeding at aircraft sampling altitudes. A marked increase in the IPC of smaller ice crystals is the most commonly observed effect. In some limited cases, increased mountain surface snowfall rates have been documented. Experiments which showed short-term increases in surface snowfall from AgI seeding were presented by Super and Boe (1988), Deshler et al. (1990), Holroyd et al. (1995), and Reynolds (1996). Super and Holroyd (1997) demonstrated increased surface snowfall from both AgI and propane seeding.

Review of the cited experiments revealed that they all had very light *natural* snowfall rates if any, with low IPCs of 5-10 per liter or less. Documented seeded snowfall has usually been in the range of 0.1 to 1.0 mm h^{-1} (0.004 to 0.04 inch h^{-1}). These rates are typical of lighter natural plateau-top snowfall where median hourly rates are just above 0.010 inch h^{-1} (Super, 1994; SH05). As a consequence, highly variable natural snowfall can easily mask any existing seeded snowfall. It is difficult to conduct clear-cut physical case studies because at least light natural snowfall usually exists in the presence of SLW cloud (Holroyd and Super 1998).

The case study of 21 December 2003 is discussed in detail by SH05. It will be summarized here because it lends physical support to the randomized experiment. The period to be discussed was a seeded EU between two adjoining nonseeded EUs. Both the nonseeded EUs had considerably more natural snowfall, heavy during the first and moderate during the second with control gauge GNO 40 min accumulations of 0.144 and 0.047 inch, respectively. The control gauge received more snowfall than the targets during both nonseeded EUs but not during the 40 min seeded period when it measured only 0.009 inch. The mean IPCs (sampled by the TAR 2D-C) for the first and second nonseeded EUs were 35 and 17 L^{-1}, respectively, while that for the seeded period was 77 L^{-1}. The marked increase in IPC during the seeded EU, with much reduced precipitation rate at all gauges and especially the control, indicated that seeded EU might be a candidate for a detailed case study.

The TAR had moderate icing rates throughout the entire 3 EU period. Even the heavy snow during the initial EU did not noticeably reduce the SLW supply. Other icing observations showed that SLW was present along the seeding plume trajectory from the HAS to the TAR during the seeded EU. There was consistency of wind velocity and air temperature over the 3 EU duration. The wind was southwesterly at the HAS and almost due west at the TAR, both typical of successful targeting episodes. Wind speeds were also typical, near 5.0 m s^{-1} at the HAS and near 6.5 m s^{-1} at the TAR. Air temperatures averaged -2.4 and -3.8°C at the HAS and TAR, respectively, too warm for silver iodide nucleation but seedable with propane.

Snow water equivalent amounts during the 40 min seeded EU were 0.009 inch at the GNO control. Listed by increasing distance from the HAS, 40 min accumulations were 0.021 at GSC, 0.034 at GTR and 0.040 inch at GDN. Simply subtracting the control amount from those observed at the along-the-wind target gauges results in hourly rates of 0.018 (GSC), 0.038 (GTR) and 0.047 inch h^{-1} (GDN) which might largely be due to seeding. However, examination of all TAR 2D-C ice particle images for the seeded EU revealed some larger natural particles during the first and final few minutes. By chance, the seeded plume passed the TAR during a period with very little natural snowfall, except at each end, so the seeded ice crystals were obvious. Such an apparent seeding signature did not exist in any of the other 2003/04 seeded EUs because natural IPCs were high enough and with sufficient variability to mask any light snowfall seeding effect.

A 30 min period was selected near the middle of the 40 min seeded EU which appeared to be almost free of larger natural snow particles according to the TAR 2D-C ice crystal image data. Data from the four high resolution gauges were examined for that exact period at GTR and GNO, and for somewhat earlier and later periods for GSC and GDN, to coincide with estimated plume passage times. The GNO control observed less than 0.002 inch during the 30 min period, within the "noise" of the gauge resolution, so snowfall was nil at that crosswind location. The 30 min SWE amounts at GSC, GTR and GDN corresponded to respective hourly rates of 0.026, 0.032 and 0.058 inch h^{-1}. These are similar to the rates estimated in the preceding paragraph. But the estimates based on the 30 min sample should be more accurate because natural snowfall was very limited.

Conditions for seeded crystal growth were far from optimum. Wind speeds provided an estimated growth period of only 15 min to reach the TAR and GTR and perhaps 8-10 min to reach GSC, closer to the seeding dispensers. More importantly, ice particle diffusional growth rates are known to be limited at the slightly supercooled cloud temperatures as demonstrated by Redder and Fukuta (1989) and several other studies they cited. As discussed in detail by SH05, their time dependent empirical equations, together with the fall speeds given by Redder and Fukuta (1991), were used to estimate seeding crystal sizes and precipitation rates for purely diffusional growth. Calculations suggest that seeded crystals would have maximum dimensions of about 300-400 µm (microns) after 15 min growth, with precipitation rate only 0.004 inch h^{-1}.

The calculations are admittedly only estimates based on "typical" crystal growth. In fact, precipitation growth is a stochastic process and the relatively small percentage of "fortunate" crystals which experience particularly favorable growth conditions contribute much of the snowfall. Super and Holroyd (1997) presented results from a HAS propane seeding experiment conducted under conditions very similar to this case study. They also used the equations of Redder and Fukuta (1989) to calculate expected seeded crystals sizes near 380 µm at the TAR, in close agreement with 2D-C laser probe observations presented in their Fig. 9. Size spectrum analysis showed that 95% of all seeded crystals were at sizes less than twice the calculated size, suggesting that about 760 µm is the upper size limit to be expected for seeded crystals during the 21 December 2003 experiment. The larger seeded crystals, while only a fraction of the total population, would be expected to significantly increase snowfall by virtue of larger masses and fall speeds. This effect will be seen in Table 5 to follow. Still, differences between estimated and observed precipitation rates suggest that aggregation and/or accretion (riming) aided growth of some seeded crystals. Dennis (1980) notes that riming appears to begin for plate crystals when the a-axis reaches about 300 µm so some riming growth could be expected in this seeded EU. Figure 3 below will show apparent riming of larger presumably seeded crystals.

An obvious propane seeding increase of 0.01 inch h^{-1} was shown by Super and Holroyd (1997). They noted that, "Many seeded images appear to be small plates with a transparent (to the laser) center, suggesting a thin inner structure. Many other seeded images appear to be short columns or thick needles. Capped columns were also frequently observed on edge with the columns quite short." Their findings are cited because of their considerable similarity to seeded crystal images observed for the current case study, with both experiments conducted under similar conditions. Thin plates would be expected to predominate at cloud temperatures between the -2 to -4°C range observed during this case.

While additional 2D-C ice particle images are presented by SH05, only one figure will be presented here. Particles are displayed in about 800 µm wide "strips" corresponding to the instrument's field of view, as particles streamed past, each momentarily shadowing some, and sometimes the entire, laser beam during the particle's passage. Images were sampled at a resolution of 25 µm. Fig. 3 displays 30 sec "snapshots" at the times of peak IPC for each of the 3 adjoining EUs. Corresponding IPCs were 67, 148 and 28 L^{-1} with the highest value for the seeded EU, shown in the middle panel. Larger natural crystals, shown in the upper panel for the heavy snowfall of the first EU, and lowest panel for moderate snowfall during the final EU, were lacking during the seeded middle panel where crystal sizes are relatively small and uniform, but in much higher concentrations. Several of the larger presumably seeded crystals appear to have undergone riming. The middle panel is typical of the entire 30 min middle portion of the seeded EU discussed above. Both nonseeded 30 sec snapshots also have some small but less uniform crystals. It is readily apparent that the obvious seeding signature of the center panel would have been masked had even light natural snowfall been occurring.

Table 5 shows size distributions of seeded IPC and 2D-C software-estimated precipitation rates from 100 µm, the smallest particles considered given the 25 µm resolution of the laser probe, to 1000 µm as larger crystals were rare. The 30 min seeded time period was chosen to minimize contributions from any natural crystals

Table 5. Summary of TAR 2D-C ice crystal concentration and estimated precipitation rate by size ranges from the seeded period 1216 to 1246 MST on 21 December 2003.

Size Range (µm)	100-200	200-300	300-400	400-500	500-600	600-700	700-800	800-900	900-1000	Totals
Crystals per Liter	11.1	23.8	17.1	9.8	6.5	6.0	5.8	0.7	0.04	80.1
Precip Rate (mm h^{-1})	0.002	0.016	0.031	0.041	0.053	0.080	0.107	0.022	0.003	0.355
Accumulated Precip Rate (mm h^{-1})	0.002	0.018	0.049	0.090	0.143	0.223	0.330	0.352	0.355	

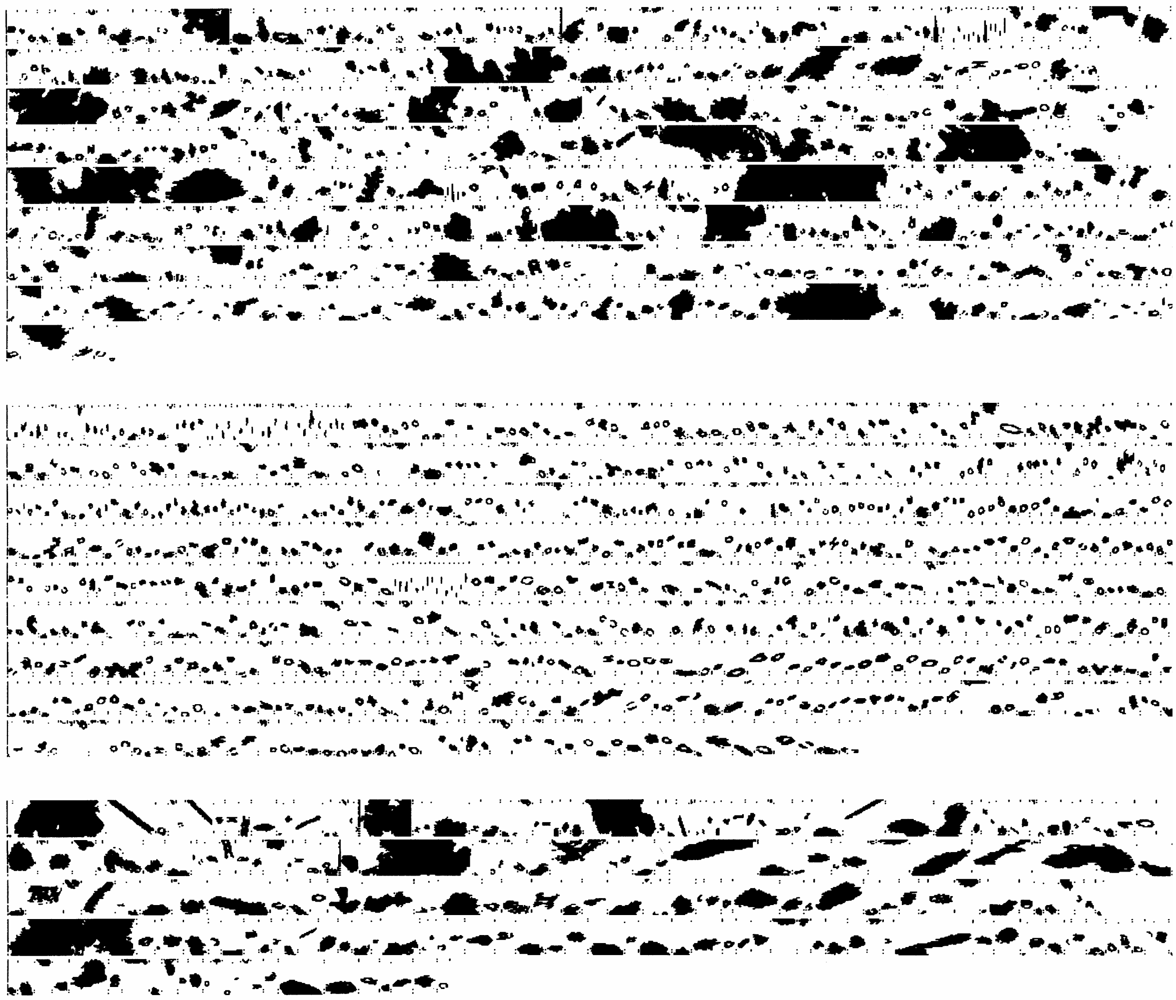

Fig. 3. Thirty second "snapshots" of 2D-C images during peak IPC times for the 3 adjoining EUs used in the case study of 21 December 2003. The width of the strips is about 800 μm, the field of the 2D-C probe. Measurements along the wind are unlimited. The specific 1 min periods start at 1146, 1224 and 1337 MST. The upper and lower panels show typical 2D images of natural snowfall while the central panel shows seeded ice crystals. Mean ice particle concentrations for the 3 periods from top to bottom are 67, 148 and 28 L^{-1}.

Table 5 shows a predominance of small crystals, with 35 L^{-1} (44%) less than 300 μm and 52 L^{-1} (65%) less than 400 μm. Consequently, the median size was less than 350 μm. This is in excellent agreement with the previous estimate of 300-400 μm based on the equations of Redder and Fukuta (1989) for diffusional growth. It will be recalled that some seeded crystals can be expected to reach a size about twice that of these typical crystals according to the size spectrum analysis of Super and Holroyd (1997) for very similar conditions.

The 2D-C estimated rate in Table 5 is 0.355 mm h^{-1}, equivalent to 0.014 inch h^{-1}. A number of past comparisons have shown the 2D-C estimated rates, applying the Holroyd (1987) software calibrated in Colorado to Utah winter clouds, are typically about half gauge observed rates. The software has never been calibrated against Utah ice crystal observations, a tedious process. Therefore, the 2D-C underestimate is typical compared with the nearby GTR observed 0.032 inch h^{-1}. Larger particles have significantly greater mass and fall speeds so having the maximum precipitation rates concentrated in the 600-700 and 700-800 μm ranges is not surprising. Precipitation rates for particles larger than 800 μm were very low because their concentrations were trivial. Almost 90% of the estimated snowfall was from crystals between 300 to 800 μm.

As previously noted, precipitation growth is a stochastic process and a small fraction of "fortunate" crystals develop greater masses and contribute much of the snowfall as shown in the above table. However, the typical seeded crystals in the 300 to 600 µm range produced about 35% of the total precipitation and all crystals smaller than 600 µm accounted for 40%. Even if it were conservatively assumed that all particles greater than 600 µm were natural snowfall, Table 5 indicates an estimated 2D-C rate of 0.143 mm h^{-1} at the TAR. Doubling that value for known software underestimation and converting yields 0.011 inch h^{-1}. Similar values are obtained by calculating 40% of the GSC, GTR and GDN gauge rates for their respective 30 min periods, resulting in 0.010, 0.013 and 0.019 inch h^{-1} with increasing distance downwind of the propane dispensers. These are still reasonable rates for seeded snowfall, especially when the limited growth rates and times are considered for especially GSC and also GTR. They compare favorably with past case studies using AgI, dry ice and propane. This case study, and similar previous studies, together provide strong physical support for seeding-increased snowfall at the target gauges in agreement with several of the statistical tests discussed in Sec. 7.

9. ADDITIONAL RELATED ANALYSES

9.1 Ice Particle Concentration Comparisons for Seeded and Nonseeded EUs

Evidence previously presented indicated the TAR was routinely targeted for HAS wind directions between about 170 to 270 deg. Due to electrical power outages and other system problems only 21 seeded and 22 nonseeded EUs had available 2D-C particle imaging probe measurements *and* HAS wind directions no greater than 270 deg. Ice particle concentrations were compared for these two sample populations which may not be totally representative of all 69 EUs meeting the direction criterion.

The 2D-C probe has limitations for observing larger ice crystals and snowflakes because of its limited 800 µm field of view. However, it is suitable for smaller individual crystals of the sizes created by seeding. Seeded crystals which form aggregates and fall out before reaching the TAR and those scavenged by larger natural crystals will not be sampled. Crystals larger than 800 µm are accepted by the processing software only if their calculated center of mass is within the field of view (Holroyd 1987).

A simple comparison of seeded and nonseeded IPCs is given in Table 6 which provides IPC values at the 25%-tile, 50%-tile, 75%-tile, 90%-tile points of the seeded and nonseeded samples. Values are listed both for all crystal sizes and for "small" crystals between 100 to 600 µm in size. The latter are more likely to be individual seeded crystals.

Table 6 indicates higher IPCs for seeded EUs than for nonseeded samples, respectively. The same differences expressed as percentages of the nonseeded values range from 27 to 38%, or approximately a 1/3 increase possibly caused by seeding. Results are similar for the smaller crystals with differences between 5 to 19 L^{-1}, or 26 to 40% increases. The similarity of the seeded difference numbers for "all" and "small" crystal distributions indicates that much of the presumed seeding-caused increase in IPC was due to the small sizes.

Most of the differences between the seeded and nonseeded population are in the approximate range of 10 to 20 crystals L^{-1}. These differences are very similar to those found by Holroyd and Super (1998) using one or two nozzle propane dispensers with the same propane output per nozzle. Six nozzles were used for the randomized experiment, again with the same output rates, releasing from 3 dispensers located across the wind to reduce aggregation losses.

Holroyd and Super (1998) compared propane seeding IPCs in the 100 to 800 (not 600 as used here) µm range against a large natural data set and found median increases near 15 L^{-1}, significant at the 5% level for a 1-tailed test. That value should be used with caution, not being based on randomized samples. It is somewhat surprising that Table 6 does not suggest larger differences since six nozzles were used instead of one or two. But the 3 dispensers were separated across the wind to reduce aggregation, implying some initial spread of the overall plumes. SH05 speculated on some possible reasons. For example, higher IPCs downwind of the HAS, expected with more nozzles, may have led to greater aggregation and snowfall between the HAS and TAR than during earlier observations. Whatever the cause, IPCs from the available and somewhat limited sample of 43 EUs suggest seeding increases were usually in the 10 to 20 L^{-1} range at the TAR, similar to earlier data sets.

All natural IPCs, averaged over the 40 min EU periods, were between 10 to 90 L^{-1} whatever the SWE observed by nearby gauge GTR. This is in good agreement with the much larger data set of Holroyd and Super (1998) which showed that all but a small portion of natural IPCs were between 10 to 200 L^{-1} when precipitation was 0.01 inch h^{-1} or more. These findings demonstrate that natural IPCs are seldom low enough to prevent masking of seeding effects. A further important implication is that natural snowfall of detectable (and meaningful) rates requires a minimum IPC of at least 10 L^{-1} at the TAR 4.1 km downwind of the HAS, and a minimum of 20 L^{-1} is

Table 6. Distribution of mean IPCs for 21 seeded and 22 nonseeded EUs with available 2D-C observations *and* HAS median wind directions between 169 to 270 deg. Noted percentiles are given for all ice crystal sizes and for small crystals from 100 to 600 µm. Differences per liter between seeded and nonseeded are shown next to their corresponding percentages of the nonseeded concentrations.

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

probably a more realistic threshold. Seeding attempts which cannot achieve higher IPCs are unlikely to produce useful snowfall, especially since seeded crystals tend to have more limited growth times and, therefore, smaller masses than natural crystals.

9.2 Comparison of 2003/04 Experimental Period Precipitation to Long-term Average

A SNOTEL station with snow pillow and precipitation gauge, named Mammoth-Cottonwood (hereafter MC) is operated only 0.74 km north of gauge GNO, at the same altitude. The 24 winter period with pillow data prior to 2003/04 was used to calculate monthly means for December through March, and the 2003/04 monthly totals. The March 2004 total was estimated at 0.9 inch from gauge data because of significant snowmelt. Only one other winter had obvious March melt but it was much less. The result of this comparison was that the 2003/04 four month total was only 69% of the mean from the previous 24 winters. Obviously, the randomized experiment was conducted during an unusually dry period, and more seedable periods would be expected during a typical winter.

9.3 Supercooled Liquid Water Availability and Implications for Seeding Potential

The number of hours with SLW available has an obvious bearing on seeding potential. The presence of SLW was sampled with icing sensors during the 2003/04 project, primarily on the plateau top's west edge at TAR, elevation 2845 m, and at the HAS located 4.1 km southwest from the TAR and about 300 m lower in elevation. Prior observations have been made both on top the plateau and at the HAS which provide a broader context for SLW availability during more typical winters. Plateau top observations will be discussed first.

All available Rosemount icing sensor data were examined from the 2003/04 experimental period of almost four months. However, a significant portion of that period did not have TAR observations because of electrical generator outages, computer systems problems and other causes. TAR data were examined for the 60 days with significant snowfall discussed later in this section, which were most likely to have periods with SLW as well. Only 75% of the total 60 day sample had TAR data so it will be assumed that about 25% of the potential SLW episodes were not recorded.

A total of 107 hr had one or more Rosemount heater cycle "trips" at the TAR. Adjusting that data for the missing 25% suggests that about 143 hours would have had SLW detected from complete TAR observations for the unusually dry four month period. Additional hours likely had some SLW but too little to result in heater trips.

Super (1994) reported on plateau top microwave radiometer observations from a two-month field period. A total of 176 hr had vertically-integrated amounts of at least 0.06 mm, likely to have seeding potential. Extrapolating to a 4 month winter period, about 350 hr with significant SLW would be expected over the plateau top's west edge. Huggins (1995) pointed out that these measurements likely represent an overestimate of seedable periods because of the general trend for SLW to diminish from west to east across the plateau top during traverses with a mobile microwave radiometer. He also noted that traverses were limited in number and more observations were desirable to verify the apparent trend. The observations showed that, as would be expected, additional SLW was produced by the ridge east of gauge GDN. Consequently, seeding potential may exist across at least the western half of the plateau top.

The best available information concerning the frequency of SLW cloud bases at or below the 2550 m HAS seeding site is from a previously unpublished data set. A Rosemount icing sensor was continuously operated about 7 m above ground level at the HAS from 01 December 1994 through 11 March 1995, almost 3.5 months. Recent examination of those observations showed that 120 hr had at least one icing trip. The MC snow pillow observations indicate that period had about 85% of average snowfall. Assuming some correlation between snowfall, storm frequency and SLW presence, and extrapolating to a four month normal winter suggests that about 140 to 150 hours with SLW cloud could be expected at the HAS. That is essentially the same as estimated for the TAR during the even drier winter of 2003/04. This finding suggests that the liquid cloud base often extends down to the HAS elevation during SLW episodes monitored on the plateau top, obviously an encouraging finding for propane seeding potential.

A tower-mounted Rosemount icing sensor was operated at the 2755 m central propane dispenser of an operational seeding program (Super et al. 1995) from 01 December 1994 through 31 March 1995, the same period as the HAS sampling discussed above plus an additional 20 days. Data from that icing sensor, located about 200 m higher than the HAS and 31 km south-southwest of it, were recently analyzed. The operational project sensor detected SLW during 173 hours for the 4 month period, verifying expectations from the HAS data, and perhaps having more hours with SLW because of increased elevation.

It should be recognized that the experimental area used in 2003/04 was *not* chosen for optimal seeding effectiveness but because of ready access to the plateau top provided by Highway 31. Availability of that all weather road was a major reason for the considerable past experimentation in the area. The randomized experimentation could not have been conducted without practical access. The point to remember is that the HAS to TAR vicinity seeding results are not directly applicable to all central Utah terrain much less to other mountain areas. All else being equal, lower elevation mountains will have a lower frequency of seeding success with propane dispensers and higher elevation terrain will have a higher frequency. Terrain providing longer periods of uplift where seeded crystals can grow in a SLW rich environment will be superior to terrain providing shorter growth times. Perhaps the optimum situation is seeding on the upwind side of the first of two parallel barriers with the distance between them too limited for sublimation of the growing seeded ice crystals in subsiding air, like the Bridger Range Experiment (Super and Heimbach 1983). Crystals would grow while being transported up the first barrier, might even sublimate somewhat between the barriers, but be very suitable for rapid growth when reaching the SLW zone over the upwind side of the second barrier.

9.4 Estimation of Possible Seasonal SWE Increases from Propane Seeding

Extrapolation of seeding results from a 3.5 month seeding experiment during a dry winter to "typical" or normal winters of longer duration is a precarious endeavor, fraught with uncertainties. This is particularly the case when expanding beyond the existing precipitation gauge locations to speculation of possible areas of effect, needed to estimate water volumes potentially produced by seeding. Scientists wiser than the authors would probably avoid making such estimates because these estimates move beyond the science of what has been observed and statistically tested into the realm of speculation. Yet it is understood that water users and managers are most interested in seasonal impacts, and volumes of water which might be produced by operational seeding.

With these caveats, the authors have provided some estimates using the 2003/04 and prior data sets and physical reasoning. But the reader should understand that these are, in fact, only estimates which should be used with caution. The only known way to provide firm evidence of seasonal and spatial seeding effectiveness is to conduct a larger scale "pilot project" over perhaps a minimum of three winters and on a confirmatory basis.

Previous discussion in Sec. 7 has demonstrated statistically significant increases in SWE associated with propane seeding. Typical seeded snowfall rates appear to be about 0.01 h^{-1} from a number of physical experiments reviewed in Sec. 8 which discusses the case study of 21 December 2003. That particular case study suggested somewhat higher rates were achieved, perhaps in the 0.02 to 0.04 inch h^{-1} range. The statistical analyses of Sec. 7 suggested a mean value near 0.01 inch h^{-1}. The latter value will be used in a possibly conservative approach to estimating seasonal seeding effects. The 4 month mean total SWE accumulation for gauges GSC, GTR and GSO was about 16 inches. If seeding were to increase this value by, for example, 10%, 160 hours of seeding-produced snowfall would be required assuming a mean rate of 0.01 h^{-1}.

It has been noted that the best available data set from the HAS indicated about 140 to 150 hours with SLW cloud available could be expected during a normal four month winter. It is fair to assume that over 160 hours is a reasonable estimate given the known underestimation resulting from tower-type Rosemount icing sensors. Therefore, achieving approximately a 10% seeding increase in the vicinity of the three noted gauges appears to be a reasonable expectation. As another example, snow pillow observations just north of GNO, discussed in Sec. 9.2, show that the long term average December through March SWE was 16.7 inch at 2680 m elevation. If seeding produced a mean precipitation rate of 0.01 h^{-1} for 150 hours, the increase would represent a 9% seasonal gain over the long term snow pillow average.

As previously discussed it is unlikely that gauges GSC and GTR were targeted during EUs with a northerly HAS wind component. The pairs residual analysis for the 32 pairs with wind directions of 270 deg or less suggested average 40-min increases of about 0.010 for those gauges, equivalent to 0.015 inch per hour. Applying that rate to the 69 EUs without a northerly component at the HAS, and assuming they had been operationally seeded for the full 69 hr results in an increase of 1.04 inch for the 3.5 month experimental period. Summing all daily precipitation totals for that period yielded 11.0 for GSC and 15.9 inch for GTR. Reducing the total gauge catch for that period by the suggested amount caused by seeding during the 35 seeded EUs, each of 40 min duration, yields adjusted "seasonal" totals of 10.65 and 15.55 inch for the respective gauges. Dividing the 1.04 inch estimated increase by those totals results in 3.5 month "seasonal" increases of 9.8% and 6.7% for a mean of 8%.

Another estimate of seasonal SWE increases due to seeding can be made using the mean double ratios (MDR) for the HAS wind direction partition to target gauges GSC and GTR. Details of these calculations are provided by SH05. Resulting estimated 3.5 month increases were 6.7% and 8.5% for gauges GSC and GTR, respectively, also providing a "seasonal" mean increase near 8%.

9.5 <u>Speculation Concerning Possible Water Volume Increases from Propane Seeding</u>

The water user is much more interested in the volume of water produced by seeding than in percentage seasonal increases at a couple of gauges over a limited downwind distance. An estimate of water volume production has been attempted, but the reader is fully warned that this discussion moves into the area of speculation. Results should be treated with caution with the realization that they may represent a significant departure from reality. Only further longer-term randomized experimentation with additional seeding sites and a much larger precipitation gauge network could provide trustworthy water volume estimates. However, funding for such a program seems unlikely in the foreseeable future. Accordingly, a "ballpark" estimate will be attempted but no one should regard it as more than that.

It is challenging to extrapolate these results from two gauges, located 2.1 and 4.3 km horizontal distance from the HAS seeding site, to an estimate of total water equivalent production in terms of volume, such as acre-feet. The only reliable gauge downwind of GTR was GDN located 6.3 km horizontal distance from the seeding site. Two of the three P-values for the wind direction partition were somewhat suggestive of a seeding effect at this gauge, with a MDR of 1.27. Using a 27% increase with the MDR approach discussed by SH05 yielded an estimated seeding increase of 0.70 inch for the 69 EUs within the direction partition, equivalent to a seasonal increase of 6.6%. The seeding plume may sometimes have been transported south of GDN by the typical west winds over the plateau top but there is no way to be sure. It would certainly be desirable to have evidence of seeding effectiveness further downwind but use of any gauge locations would have been hampered by the targeting problem with seeding only from the HAS over a range of wind directions. Further complicating factors to estimation of seeding-caused precipitation volume include lack of knowledge about plume width and how the seeding effect might vary with crosswind distance perpendicular to the seeding plume.

Reasonable plume width estimates can be made from the early 1994 tracer gas studies cited in Sec. 2.2 and discussed in detail by SH05. Typical widths were 2.0 km by the TAR, about 4.5 km downstream of the HAS judging from topographic maps, which translates into a 25 deg plume width. This result is similar to observations from earlier studies over other mountains (Super 1974; Holroyd et al. 1988; Super and Heimbach 1988). A width of 25 deg will be assumed over the target gauges GSC, GTR, GDN and further downwind. There is admittedly no data to test seeding effectiveness downwind of GDN. Huggins (1995) documented a west to east decrease in SLW availability across the plateau top. Yet he showed an increase in SLW over the ridge east of GDN, and previous precipitation gauge observations have shown similar values across the plateau top to about 6 km east of the western edge. It will be assumed that a uniform seeding increase of 1 inch existed within the downwind range beginning midway from the HAS to GSC and ending 6 km downwind of TAR or 10 km from the HAS. This results in an area or "seeded footprint" of about 22 km^2. The resulting volume with an average depth of 2.54 cm is 5.6 X 10^5 m^3, equivalent to about 450 acre-ft of water. Using a cost of $56 per acre-ft for the median incremental cost of agricultural water, supplied by a Utah Division of Water Resources economist, the water would be worth about $25,000. But these calculations are based on a 3.5 month period during a dry winter. Let it be assumed that an 8% seeding increase is achievable over the entire winter ending on 01 April. The Mammoth-Cottonwood snow pillow has a long term average of 20.5 inch SWE on that date. Using that value and a 8% increase with the same assumed "seeded footprint" results in about 740 acre-ft with a value near $41,500. Values would be significantly higher for municipal and industrial water use.

The above admittedly crude estimate, if actually achievable, suggests that the value of water production per propane dispensing location would probably more than pay for all equipment and operational costs during the initial winter season, assuming it had near normal snowfall. Once propane dispensers and associated instrumentation and communication equipment were paid for, annual operating costs should be a fraction of the resulting seeding water production value. In other words, the benefit-cost ratio of propane seeding appears likely to be favorable. But it is again cautioned that the above estimates are only that and firmer estimates would require a more comprehensive and longer-term demonstration period.

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 Overview

Previous laboratory and field investigations have shown that expansion of liquid propane is an effective means of seeding SLW clouds and fog. Propane seeding has a major advantage over the commonly used AgI seeding agent. Propane expansion can create significant IPCs within SLW cloud too warm for effective AgI seeding, usually from about -2 to -8°C. Silver iodide can be effective at -6°C if released directly within SLW cloud but that is not the common release method. Because a large fraction of winter orographic SLW cloud in the West exists at temperature warmer than -8°C, propane seeding has the potential to significantly increase seeded snowfall production over use of AgI alone.

Randomized seeding experiments, backed by physical observations and reasoning, are the "gold standard" for testing the overall effectiveness of a particular seeding methodology applied to many storms. Trustworthy assessments of net seasonal increases caused by seeding are not possible from extrapolation of the results of a limited number of case studies. Accordingly, the next step required in the development of the promising propane seeding approach was to conduct a randomized experiment. The 2003/04 Utah randomized experiment was actually the second such experiment, the first attempt having been made on the Sierra Nevada of California described by Reynolds (1996). The Utah effort overcame the targeting problems encountered in California by seeding on the windward slope of the Wasatch Plateau, over 4 km upwind of the top. This approach provided sufficient growth times for the seeded crystals before they passed over target precipitation gauges. Moreover, the same Utah seeding location and primary target area had been used for considerable past experimentation which documented both routine targeting, and the frequent presence of SLW cloud, at and downwind of the high elevation seeding location.

The essential features of the Utah randomized experiment were:

- Conducted using a seeding site already demonstrated to provide routine targeting.
- Fully automated operation with seeding or placebo treatment triggered by SLW detection.
- Experimental Units (EUs) blocked into pairs with one EU randomly seeded.
- Target precipitation gauges operated along the expected seeding plume trajectory.
- Control gauge operated crosswind to monitor natural precipitation variations.
- Supporting wind and other observations for partitioning EUs into similar subpopulations.
- Application of three sophisticated statistical testing procedures, all using the control gauge as a covariate to substantially reduce the variance caused by natural snowfall fluctuations.
- Two of the tests used rerandomization to estimate statistical significance of results. One of the tests derived confidence intervals to estimate likely ranges of treatment effects.

A total of 102 EUs from 51 blocked pairs resulted from the 3.5 month field program from mid-December 2003 through March 2004. This was an unusually dry period with the SWE being only 69% of the long-term average. Four EUs were discarded because winds were too light to accurately estimate times of seeding plume passage by individual target gauges, located from about 2 to 6.5 km downwind of the seeding location. This left 98 available EUs and 47 pairs for statistical testing. Wind speeds observed at the seeding site and primary instrumented target were used to estimate periods of seeding plume passage over each target gauge. This previously developed approach was based on many plume releases with timed arrivals at the target.

10.2 Statistical Conclusions

Results of statistical testing of the available EU sample population were considered significant and "strongly suggestive" if the probability of indicated seeding-caused differences between seeded and nonseeded EUs not being by chance were at least 95 out of 100 (α-level = 0.05). Results were considered "somewhat suggestive" if the same probability was from 90 to 95 out of 100 (α-level = 0.06 to 0.10).

Results to follow discuss the four gauges consisting of (1) GSC midway between the seeding location and (2) GTR, the primary intended target gauge on the west edge of the plateau top, (3) GSO located 1 km due south of GTR also on the plateau top, and (4) GDN, the only gauge downwind of GTR, about 6.5 km plume travel distance from the seeding site. Because results vary among the statistical tests, each having different strengths and weaknesses, the predominant findings of two or more tests will be noted below. The results of statistical testing of the Utah randomized experiment can be briefly summarized as follows:

- Tests of the entire sample of 98 EUs without any partitioning were strongly suggestive of a real seeding effect of increased snowfall at gauges GSC, GTR and GSO.

- Results for the 98 EUs were inconclusive at the downwind gauge GDN meaning no valid conclusion can be made whether seeding was effective there or not.

- Results for the 69 EUs partitioned by southwest quadrant seeding site winds, known to transport seeding plumes by the primary target, were also strongly suggestive of snowfall increases at the GTR and GSO gauges on the plateau top. Results were somewhat suggestive at the GSC gauge closest to the propane dispensers, and also at the downwind gauge GDN furthest from the seeding location.

- Comparisons of the wind direction-partitioned 69 EUs with all available 98 EUs revealed that basically all the seeding signal was contained within the 69 EUs where targeting was highly likely. The same partition excluded northwest flow EUs likely to transport seeding plumes south of the target gauges.

- A dual partition used the same wind direction partition combined with exclusion of the larger 20% of natural SWE amounts observed at control gauge GNO. Overall results were encouraging, suggesting that real seeding effects were particularly detectable when natural snowfalls were no more than moderate.

- Results were presented for several other single and dual partitions, the latter always including the southwest quadrant winds at the seeding site. These results were mixed, ranging from strongly suggestive to somewhat suggestive to inconclusive depending upon the particular partition, gauge and statistical test. A number of partitions provided interesting suggestions but none of the results were as convincing as the wind direction partition or entire population testing.

- There were suggestions that seeding may have been more effective when SLW cloud (icing) was detected, when seeding plume temperatures were warmer and when wind speeds were lighter. But all of these interesting but mostly inconclusive suggestions would require a larger sample size than available for rigorous testing.

10.3 Estimated Precipitation Increases

The percentage increases in snowfall for the seeded EUs compared to the nonseeded were estimated by mean double ratios. Those for the wind direction partition, considered to have the most trustworthy results, suggested that the seeded EUs had about 25% more snowfall than their nonseeded counterparts. Calculation of median double ratios suggested even higher increases, but it is unknown which is more accurate.

It was hypothetically estimated that if all hours containing the 69 EUs of the wind direction partition had been operationally seeded, the overall "seasonal" precipitation increase would have been 8% for the 3.5 month experimental period. This result was provided both by considering the mean residuals from the pairs testing and from the mean double ratio testing.

A comprehensive case study was presented which showed obvious evidence of seeding-produced snowfall during a rare period with negligible natural snowfall. Results were very similar to previously published studies, with high concentrations of small, uniform thin plate ice crystals providing the most obvious evidence of seeding. Associated precipitation increases were conservatively estimated to be in the 0.01 to 0.02 inch h^{-1} range typical of natural light snowfalls, and similar to earlier case study results. Residuals from the statistical pairs testing provided an average seeded EU increase of 0.014 inch h^{-1} within the same range.

Examination of the frequency of SLW cloud availability from past observations suggests that it is reasonable to expect at least 150 seedable hours over a normal winter. If seeding were to produce an increased snowfall rate of 0.01 inch h^{-1}, that would result in meaningful snowfall increases over a winter season, on the order of 10%, for the upper windward slope and west portion of the Wasatch Plateau top. The downwind extent of seeding increases over the plateau top and perhaps on its lee slope is unknown because such observations were beyond the scope of the 2003/04 randomized experiment.

10.4 Recommendations for Further Development of Propane Seeding

The statistical results from the 2003/04 Utah randomized experiment, together with supporting physical observations during that period and from considerable past investigation at the same location, present a strong case for propane seeding effectiveness in increasing mountain snowfall. To date, applied research into propane seeding has been limited by available resources as federal funding for weather modification research has generally declined over the past several years. Those who would be critical of limited progress should bear that reality in mind. The randomized propane seeding experiment was not been designed to answer all remaining questions, and a number remain. In particular, the downwind extent of seeding effects received little attention. But there is certainly sufficient evidence to justify further development of this promising emerging technology, especially with propane's ability to seed significantly warmer SLW cloud than possible with AgI. That fact alone is a powerful argument for continued development of propane seeding for winter orographic clouds in the western United States and elsewhere.

It is strongly recommended that a follow-on confirmatory randomized experiment be conducted on the Wasatch Plateau or similar mountain barrier over at least three winters. The experiment would require a minimum of three high elevation propane seeding sites separated by about 3 km crosswind distance. A significantly larger precipitation gauge network would be required extending across the plateau top and on the upper portions of the lee side. Crosswind control gauges would be maintained both south and north (crosswind) of the target gauges. Because of the difficulties of finding naturally protected clearings in conifer forest some gauges might require elaborate double-fence wind shields. A numerical model should be verified and used which has the capability of handling local transport and dispersion over the rugged terrain, and with sophisticated microphysics. The experiment should be provided with comprehensive physical observations to include a microwave radiometer to monitor the SLW cloud zone, and to provide much improved microphysical measurements, both in target and crosswind control locations.

These specific recommendations for a propane seeding experiment follow the general recommendations of the current American Meteorological Society Policy Statement on Weather Modification (AMS 1998) which stated, "Whereas a statistical evaluation is required to establish that a significant change resulted from a given seeding activity, it must be accompanied by a physical evaluation to confirm that the statistically observed change was due to the seeding." Until that approach is followed, with results published in the peer reviewed scientific literature, there will continue to be controversy and uncertainty concerning winter orographic cloud seeding effectiveness with either AgI or propane. With ever developing demands on limited water resources in the western states, and evidence of declining mountain snowpacks since about 1950 (Mote et al. 2005), policy makers should be able to make decisions based on physical reality as revealed through sound scientific inquiry. Such information remains limited in the field of winter orographic cloud seeding. In the meantime, water users interested in using cloud seeding to increase the winter mountain snowpack will continue to make choices with the best available information. The 2003/04 Utah randomized experiment has provided important new evidence that propane seeding is an option which should not be ignored, especially where mildly SLW cloud predominates.

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