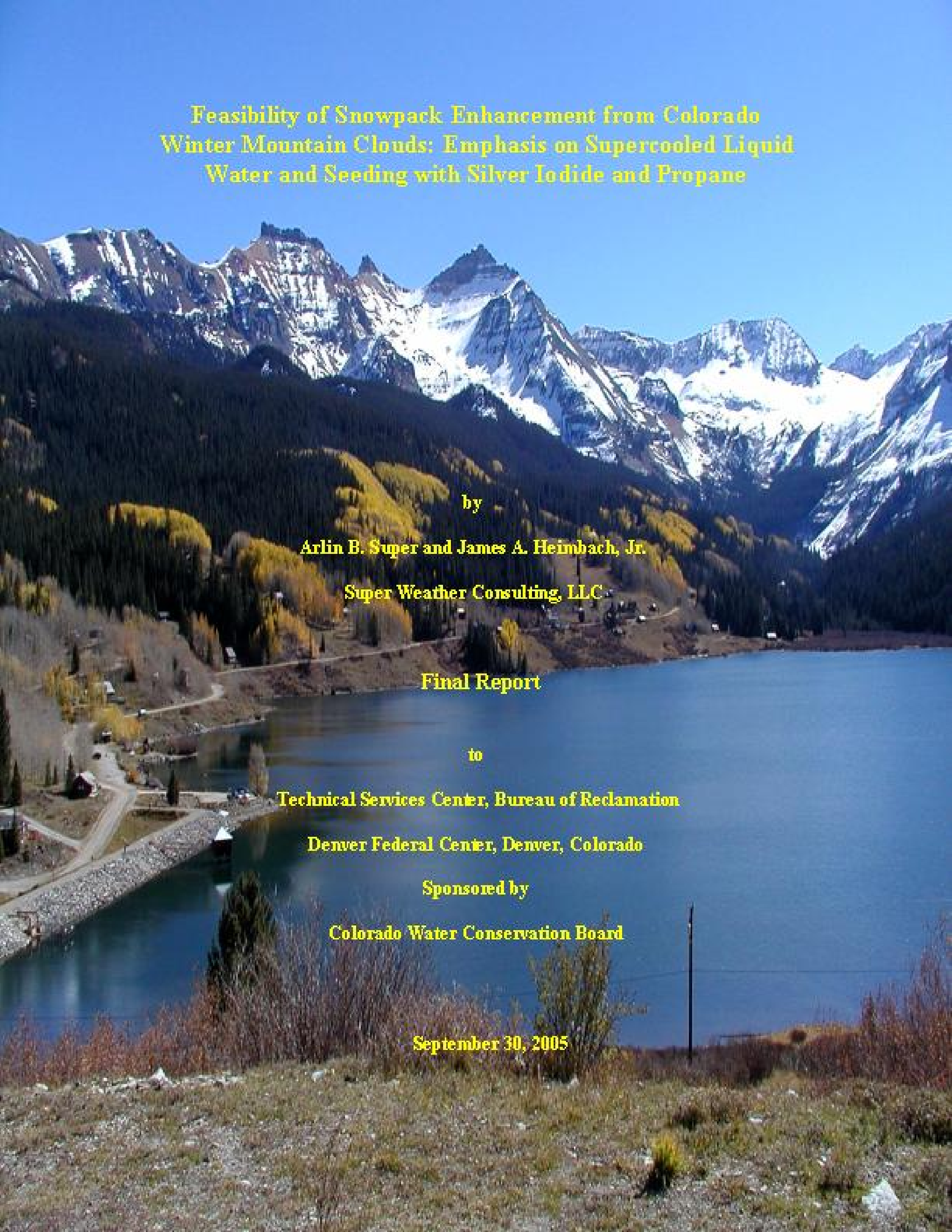

Feasibility of Snowpack Enhancement from Colorado Winter Mountain Clouds: Emphasis on Supercooled Liquid Water and Seeding with Silver Iodide and Propane

by

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Photograph on cover page courtesy of Joe Busto of the Colorado Water Conservation Board, Flood Protection and Weather Modification Permitting Program. The view is of Trout Lake near the Telluride, CO, Ski area.

Executive Summary

The feasibility of using artificial ice nucleation, commonly called "cloud seeding," is considered as a means of increasing seasonal snowfalls from Colorado mountain-induced (orographic) clouds. The report relies primarily on review of numerous scientific articles published in the open, peer-reviewed technical literature, with some use of relevant internal project reports. Where possible, emphasis is given to articles based on investigations of Colorado and Utah orographic clouds, believed to be similar since the states adjoin with Utah mountains generally upwind of Colorado mountains. Considerable winter orographic cloud research has been conducted in both states.

Three main topics are considered. These are, first, the availability, abundance and locations of supercooled liquid water (SLW) cloud which must exist for cloud seeding to enhance snowfall. Second, the complex subject of how and where to release seeding agents in order to effectively seed SLW cloud is discussed at length. Consideration of this topic relies heavily on observational tracking studies of plumes of seeding agents and/or resulting seeded ice crystals, and of tracer gas plumes. The stability of the lower atmosphere, especially at lower elevations within mountain valleys, is given special attention because most winter orographic cloud seeding projects have used valley-based silver iodide (AgI) generators. The stability of the lower atmosphere is critical to whether or not such AgI is transported over intended mountain target areas thousands of feet higher than the valleys. Finally, the suitability of the emerging technology of propane seeding for Colorado clouds is addressed. Propane seeding has the advantage of producing large quantities of seeded ice crystals in clouds only slightly colder than 0°C but not cold enough for AgI to be an effective ice nucleant. Such clouds, in the approximate temperature range of -1 to -8°C, will sometimes be referred to as "mildly supercooled." They are common over windward mountain slopes in the western United States.

The effectiveness of AgI is dependant on temperature. Depending on the particular chemical makeup of the AgI seeding agent, and whether it is released within or below SLW cloud, AgI can become effective from about -6 to -8°C, with efficiency increasing as the temperature lowers. After this "threshold temperature" is reached, at which a small but detectable fraction of a large population of AgI ice nuclei create ice crystals, further cooling of the SLW cloud will result in orders of magnitude more effective AgI ice nuclei until -12°C or even colder. Obviously, SLW cloud temperature is an important factor in AgI seeding effectiveness. Propane releases, on the other hand, can produce abundant ice crystals as warm as -1°C with little temperature dependence below -2°C. A disadvantage of propane seeding is that it must be released within SLW cloud or just beneath in ice saturation conditions. Consequently, high altitude remote-controlled dispensers are required for propane seeding.

Supercooled liquid water cloud observations suggest that excess amounts are available frequently enough to readily support the modest snowfall increases usually associated with successful seeding, that is, approximately 10% on a seasonal basis. In other words, availability of SLW cloud in excess of that naturally converted to snowfall does not appear to be a limitation for successful winter orographic cloud seeding. The primary SLW cloud zone is over the windward slopes and crests of mountains within about 3000 ft of the terrain. This is the obvious zone to target with seeding agents and/or seeded crystals. Fortuitously, it is also the zone in which ground-released seeding plumes are concentrated.

Aircraft seeding is not recommended for the majority of Colorado's mountains for a number of reasons including high expense, difficulties in filling the volume of SLW cloud with seeding agent or resulting seeded crystals, and operational problems in an icing environment with the associated question of safety.

Use of valley or foothill AgI generators is the least expensive and most widely used seeding method. However, there are serious concerns about how frequently this approach actually produces sufficiently high seeded crystal concentrations to result in meaningful snowfall rates. Some storm phases are unstable and appear capable of providing the necessary vertical transport over mountain barriers. However, valley-based inversions appear to be common during many Colorado winter storms which will trap and pool the AgI below the SLW cloud zone. Therefore, valley seeding will not provide routine seeding but only unpredictable intermittent seeding when SLW is available. Moreover, operational seeding projects which use valley generators commonly have overly large crosswind distances between generators, resulting in large unseeded gaps between seeding plumes when vertical transport is sufficient. Generator outputs may also be too low to result in sufficiently high concentrations of seeded crystals. This is of a particular problem of special concern with relatively warm SLW cloud because of the large temperature dependence of AgI effectiveness.

Silver-in-snow concentrations have not exceeded natural background levels in a number of operational project target areas which used valley seeding. Failure to increase silver concentrations can be interpreted to mean failure to target with enough silver iodide for effective seeding. It is acknowledged that relatively few operational projects using AgI have been sampled for silver-in-snow levels wherever AgI generators were located. For that matter, relatively few operational projects have provided any physical evidence of successful seeding.

It is well documented that high altitude releases of either AgI or propane, from sites more than midway from the valley floor to the mountain crest, result in routine transport of AgI and/or seeded crystals over mountain barriers. This is the much preferred method for seeding the primary SLW zone over the windward slopes and crestlines. The ability of high altitude seeding sites to *routinely* seed orographic cloud cannot be overemphasized. Plume widths are typically 20-25 degrees wide with plume tops about 2000 ft above crestline elevations. Depending upon local terrain, high altitude seeding sites should have a crosswind spacing of about 2-3 miles to achieve plume overlap before the crestline is reached, assuming such seeding sites are located on minor ridges extending a few miles upwind of primary crestlines. High altitude seeding is admittedly a more expensive and logistically difficult approach than siting and using manual generators only where roads exist in mountain valleys. However, high altitude releases can be counted on to actually seed the clouds whenever SLW is present. Silver-in-snow concentrations from a number of experiments and projects which used high elevation AgI releases have been well above natural background levels. This finding does not prove that seeding actually increased the snowfall because scavenging by natural snowflakes can bring AgI particles to the surface. However, increased silver-in-snow levels do document that AgI plumes were transported over the intended target area, a necessary step for seeding to have any chance of snowfall enhancement.

Supercooled liquid water temperatures have been observed at a number of mountain-top locations in Colorado and Utah. The observations indicate AgI seeding can be effective some portion of the time but that SLW temperatures are too warm for AgI seeding during other periods. However, it would be more appropriate to consider SLW temperatures some distance downslope, where seeded crystals should be produced to provide sufficient crystal growth times before the lee subsidence region is reached where cloud droplets rapidly evaporate. But windward slope observations have not been common. Consequently, it should be recognized that use of mountain-top temperatures may overestimate the frequency of AgI seeding potential.

The frequency of sufficiently cold SLW cloud for effective AgI seeding largely depends on two factors. First is the mountain elevation, with higher mountains expected to have colder clouds, and second is the geographic location, with more southerly mountains expected to have warmer clouds. In all observational sets available for this report, a relatively high fraction of the observations were too warm for conventional AgI seeding. However, operating AgI generators directly within cloud permits the forced condensation freezing mechanism to function, resulting in very high seeded crystal concentrations immediately downwind of the generator if the temperature is -6°C or colder. Silver iodide released below cloud will need to reach SLW temperature colder than about -8°C to produce target zone seeded crystal concentrations in excess of about 20 per liter, considered the minimum value to produce more than trace snowfall rates. Such concentrations can be achieved with propane dispensers if the temperature is -2°C or colder. Consequently, propane seeding can be effective over a wider range of SLW cloud temperatures.

The choice of AgI or propane, or perhaps both, should be based on a number of factors. Both have advantages and disadvantages as discussed in this report and a number of cited articles. There is no "one size fits all" seeding approach that is best for all mountain ranges and geographical locations. The numerous investigations cited in this report provide important guidance for designing specific area seeding projects. But in the end, each specific area should be evaluated by persons with the appropriate technical and practical expertise, and experience in winter orographic cloud seeding. Approaches which may seem reasonable when discussed in a comfortable office may prove totally impractical in particular mountainous terrain during winter.

Also, seeding project designers should be careful to avoid the temptation to apply dated, almost "traditional," seeding approaches to new areas because they were once believed to be effective elsewhere. Remnants of approaches used during the 1960s Climax Experiments are still evident in some operational seeding projects in spite of later serious challenges to Climax statistical results, and to the large but unsuccessful Colorado River Augmentation Pilot Project (1970-75) which was based in large part on Climax results. A considerable body of more recent knowledge exists, because of much improved instrumentation and computer modeling. There is no valid excuse for ignoring that knowledge, especially regarding valley seeding plume transport limitation and SLW cloud locations, variability and often mildly supercooled temperatures.

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1. Introduction

This technical report is an investigation into the feasibility of using artificial ice nucleation, commonly called cloud seeding, in winter clouds over the mountains of Colorado for the purpose of enhancing the seasonal snowpack. Snowpack enhancement results in increased spring and summer streamflows, important for many water resources purposes including irrigation, power generation, recreational, municipal and industrial uses, and improving the environment. Many cloud seeding projects since the 1950s to the present have claimed seasonal snowpack increases which are generally in the 5-15% range. However, these claims are not universally accepted, especially by the scientific community. That is in large part because of the complexities of demonstrating a relatively small snowpack increase when the seasonal snowpack is known to naturally vary by many times the claimed increase. Most of the claims are based on statistical analyses, often using the historical target-control regression method well known to have serious potential flaws (e.g. Dennis 1980). The most recent weather modification policy statement of the American Meteorological Society (AMS 1998) states that, "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* (emphasis added) to confirm that the statistically observed change was due to the seeding." Surprisingly few winter cloud seeding experiments or operations have met that test over the years, in part because of the lack of long-term commitments to research funding. Federal research support has been very limited during the past several years, so progress has been slow. Although there have been some notable successes with winter orographic cloud seeding experiments, the field remains controversial.

The extent of the controversy can be demonstrated by two recent reports. First, the National Research Council published a report in October 2003 (NRC 2003), the conclusions of which was given considerable coverage by the national media. The report concluded that, "--- there is still no convincing scientific proof of the efficacy of intentional weather modification efforts. In some instances there are strong indications of induced changes, but this evidence has not been subject to tests of significance and reproducibility." However, it is also noted that, "There are strong suggestions of positive seeding effects in winter orographic glaciogenic systems (i.e., cloud systems occurring over mountainous terrain." But suggestions fall short of proof in the sense that term is used by scientists and statisticians.

Second, a review panel of the Weather Modification Association (WMA), with significant input from the membership, replied to many of the NRC findings in Boe et al. (2004). The WMA article correctly pointed out that, "--- the NRC panel members collectively had very limited experience or knowledge in weather modification operations, especially in recent years." The two authors of this report consider the NRC panel members to be especially lacking in expertise in recent winter orographic cloud seeding research as well as operations. Boe et al. (ibid.) provided a lengthy rebuttal to many of the NRC findings. This report will not comment further on the NRC and WMA findings, and only cite the respective reports as evidence that weather modification in general, and winter orographic cloud seeding in particular, are still controversial with a wide range of existing viewpoints.

The goal of this report is to address three general topics related to assessment of winter orographic (mountain-induced) cloud seeding feasibility in Colorado. Two topics are fundamental. First is the examination of supercooled liquid water (SLW) cloud over mountains. Unless excess SLW is relatively abundant there can be no realistic hope of seeding potential for snowfall augmentation. It will be shown that SLW availability and amounts do not present a serious limitation to cloud seeding potential in Colorado.

The second fundamental topic considers the practicalities of seeding SLW cloud over mountains. The most common method of valley releases of silver iodide (AgI) is examined, as well as high elevation ground releases of both AgI and propane, and aircraft seeding. The aircraft approach is ruled out for a number of reasons to be discussed.

The final topic concerns expansion of liquid propane to chill cloudy air below -40°C. This produces vast numbers of embryonic ice crystals by homogeneous nucleation. This is a method of high elevation ground seeding with an agent and mechanism different than AgI seeding. It is given emphasis in this report because the method is not widely known, but recent results from a randomized propane seeding experiment in Utah are very encouraging. Propane seeding may provide an adjunct or alternative to AgI seeding in Colorado.

This report is primarily based on published articles in the peer-reviewed scientific literature. However, some references are given to internal project reports where the work has special relevance but was never published in the open literature. Most articles are based on observations from either Colorado or Utah orographic clouds. Such clouds are believed similar in the adjoining states with mountains at similar latitudes. Considerable field research related to winter orographic seeding has been conducted in each state.

At the risk of oversimplification, there appear to be three general schools of opinion among people with at least a casual interest in winter orographic cloud seeding. Many people, including a large number of meteorologists, hold the view that this type of cloud seeding has not yet been demonstrated as successful in increasing seasonal snowfall, and that more basic research is needed before application will have a sound scientific basis. However, it should be recognized that relatively few meteorologists can presently be considered to be experts in this field. Because of very limited federal research funding for over decade now, researchers and graduate students have needed to move on to other fields. Several scientists who were experts in winter orographic cloud seeding have retired. The views of National Weather Service forecasters or their managers are often quoted by the local media, yet such meteorologists are unlikely to have even a passing knowledge of weather modification. This lack of knowledge can sometimes be the cause of misinformation cited by local and national media.

Another "camp" of people, including many water users and commercial cloud seeders, holds the view that this type of cloud seeding has been sufficiently well established for widespread application. Some have held this view for several decades as evidenced by the long duration of a few operational projects. The main evidence supporting this optimistic view seems to be based on claims by commercial operators, and the large body of internal project reports they have amassed over decades, almost all suggesting positive results from seeding. But such reports are often subject to potential unconscious bias (and possibly deliberate in some cases) because future company earnings will likely be affected. Moreover, many internal reports have shortcomings in application of statistics, with widespread use of the historical target-control regression method, long known to have serious potential flaws, but one of few options in the absence of randomization. One common but incorrect view is that seeding must work if so many reports have shown positive results, even if relatively few have undergone in-depth peer review. And, as evidenced by several published articles which seriously challenged earlier experimental suggestions once held up as "proof," even peer review does not guarantee solid results. Those who maintain that the large number of internally reported "success stories" must mean that winter orographic seeding is on a solid footing would do well to ponder why experimental randomized programs have seldom been able to verify similar results.

The final "camp" consists of those who are not necessarily convinced that seeding is effective but regard that view as a reasonable possibility. This camp simply sees application as a sensible bet when uncertainties and large potential gains are weighted against the relatively low cost of application. They are comfortable applying current technology while welcoming any future research which may provide improvements in application.

Some randomized experiments, considered to provide the "gold standard" for credible results when supported by sufficient physical evidence (AMS 1998), have published results indicating that seeding works during particular atmospheric conditions. The most well known randomized experiments are likely the two conducted near Climax, Colorado, during the 1960s. But the results from Climax and some other randomized experiments have been seriously challenged in the scientific literature. It may be surprising to some, but in fact only a limited number of randomized winter orographic experiments have been conducted in the western United States since about 1970. The two best funded long-term experiments were the Colorado River Augmentation Pilot Project (1970/71 through 1974/75 winters) and the Sierra Cooperative Pilot Project (1977/78 through 1986/87 winters). While much was learned from these experiments, neither was able to demonstrate that seeding had increased the seasonal snowfall over a target area. Only a few randomized experiments have provided both strong statistical suggestions of seeding success, and sufficient physical documentation like routine targeting of the seeding agent, to still be considered credible. And none of these has been followed up with a confirmatory experiment, necessary to provide "proof" in the sense this term is used by scientists and statisticians. The reason for the lack of follow-up experimentation has usually been lack of sustained funding. It is well known that the fields of weather modification in general, and winter orographic cloud seeding in particular, have long suffered from lack of a long-term research funding commitment by federal agencies (NRC 2003).

Metric units will be used for several variables in this report, especially when dealing with cloud physics and temperatures. However, English units will be used for a number of others (e.g., distances, elevations, wind speeds, precipitation rates) in order to make the discussion more meaningful to the majority of readers who are likely to have a water resource or engineering background. Sometimes both metric and English units will be given with one or the other in parentheses. This report in its present state is not intended for the peer-reviewed scientific literature which would require almost exclusive use of metric units.

A major intent of this report is to provide readers who have only a general interest in these topics with a practical approach to assimilating the large amount of previously published information and resulting conclusions. Those with a limited knowledge of winter orographic cloud seeding and its history are unlikely to be aware of the considerable research which has been accomplished over many years at several locations. They are also unlikely to be aware of important complexities and uncertainties in this field.

The report is organized in the following manner. Following the executive summary and table of contents is this section, 1, which is the introduction. Sections 2, 3 and 4 briefly summarize overviews of the most important findings regarding SLW cloud characteristics, delivery of AgI to SLW clouds, and propane seeding, respectively. The casual reader may find the executive summary and the first four sections sufficient for his needs.

Sections 5, 6 and 7 provide more detailed discussion in support of the stated findings for the respective topics of Secs. 2, 3 and 4. Numerous references are given to individual published investigations supporting the results for each topic. It is important that stated technical findings be based on the considerable body of past research. Otherwise, they may be simply opinions of unknown credibility. As would be expected, Secs. 5, 6 and 7 contain some redundancy to information already covered in less detail in Secs. 2, 3 and 4. Section 8 is a list of all references cited within this report including those in Appendices A, B and C.

Several selected articles are briefly summarized in Appendices A and B for those readers with a still deeper interest in the details of SLW availability and AgI seeding considerations. No analogous appendix exists for propane seeding because that topic is well covered in recent and readily available publications cited in Sec. 7. Appendix C is included to discuss recent analyses of stability and wind observations collected over the Wasatch Plateau of central Utah during early 1991 and early 1994 major field programs. The results of those analyses are briefly summarized in Sec. 3, dealing with valley-released AgI seeding.

2. Summary of Findings Regarding SLW Cloud

The major features of winter SLW cloud over Colorado and nearby Utah mountains are summarized as follows:

1) Supercooled liquid water cloud frequently exists over windward slopes and crestlines of mountains. It is estimated that SLW is present during approximately one out of five winter hours for the Park Range and Grand Mesa of Colorado, and the Wasatch Plateau of Utah. The Park Range value was 24% and it is a primary barrier, not shadowed from approaching westerly flow storms by nearby upwind ranges. Both the Grand Mesa and Wasatch Plateau had values of 17% for *significant* (>= 0.05 mm) vertically-integrated SLW, and each has a nearby upwind barrier, although significantly lower for the Grand Mesa. None of the datasets were of long duration and certainly cannot be considered as "climatologies." Thus, the estimate of 1/5 of all hours having meaningful SLW present at mountain top altitudes should be regarded as a first approximation. It may be that frequencies are lower for the secondary, shadowed ranges of central Colorado. Hindman (1986) suggested that, when SLW cloud alone, snowfall alone or both existed at several mountain top locations, SLW was more frequent over primary than secondary ranges. The SLW frequencies for hours with cloud and/or snowfall present were given but not the frequencies for all hours.

The overall results of the Colorado and Utah studies suggest that approximately 300 to 600 seedable hours can be expected during a typical 5 month winter with the lower value estimated for secondary ranges. As with snowfall rates, SLW amounts are highly skewed with many hours having limited values and relatively few hours having abundant values. Even if seeding produced average snowfall rates of only 0.01 inch h^{-1} when SLW was present, beneficial snowpack increases would certainly result. Evidence exists that seasonal excess SLW flux is equivalent to a large fraction of the natural seasonal snowfall over all mountain ranges studied. The "bottom line" finding is that excess SLW availability is sufficient for presumed successful seeding to provide seasonal snowfall increases of at least 10%.

2) Highest frequencies and amounts of SLW cloud are routinely found in a zone just above the windward slopes and crests of mountain barriers. The SLW condensate is produced by forced uplift of moist air over the barriers. This sometimes triggers embedded convection which produces additional SLW. This primary zone of SLW cloud is often concentrated in a shallow layer, usually within about 3000 ft of the terrain (Rauber and Grant 1986, Sassen and Zhao 1993), although the layer may be thicker, especially when embedded convection is present (Super 1995). Fortunately, at least the lower portion of the primary SLW zone can be treated with ground

releases of seeding agent, as discussed in Sec. 2. This is the zone which should routinely be targeted by seeding agents.

3) The primary SLW zone rapidly evaporates downwind of the crest because of warming produced by subsidence, and by depletion from conversion to snowfall. However, secondary ridges and peaks often produce local "pockets" of additional SLW downstream. There is evidence that SLW production is common wherever moist airflow is forced up and over local terrain. While topography varies considerably, typical in-cloud growth rates for crystals formed over the windward slope should be about 15 to 30 minutes before passage through the lee subsidence zone where cloud droplets rapidly evaporate. That is sufficient time for seeded crystals to grow to precipitable sizes. But as a general rule, the sooner that seeded crystals can be introduced into SLW cloud, the greater the snowfall production. All seeding is a "race" between time needed for crystal formation, vertical and horizontal dispersion of the seeded crystal plume, and snowflake growth plus fallout *before* SLW disappears to the lee of mountain barriers. Larger ice crystals sublimate relatively slowly in the lee subsidence zone compared to the rapid evaporation of tiny cloud droplets. But non precipitating seeded crystals will eventually sublimate downwind of mountain barriers unless exposed to a secondary upslope region with additional SLW cloud.

4) Examination of mountain top temperature observations revealed that SLW cloud is mildly supercooled in a large portion of all storm passages. That is, the SLW is too warm for effective seeding with AgI which requires temperatures colder than about -6 to -8°C depending upon where the AgI is released, and on the type of formulation and combustion. This was noted by Boe and Super (1986) and Holroyd et al. (1988), both using Grand Mesa observations. Similar concerns about the limited temperature window for AgI seeding were given by Sassen and Zhao (1993), using observations over the Tushar Mountains of southern Utah. While a significant fraction of storm phases would be seedable with AgI, many others could be treated only by an alternate seeding method like expansion of liquid propane. The percentage of periods seedable with AgI is likely overestimated by mountain top observations because seeded crystals need to be formed a sufficient distance upwind (downslope) of crestlines to allow for growth and fallout.

5) Because saturation water vapor content increases with temperature, clouds only slightly colder than 0°C can be expected to contain the highest SLW amounts. Observations have shown that the highest SLW amounts are usually in cloud only a few degrees colder than 0°C while SLW amounts are generally limited by temperatures -10°C and quite limited by -15°C. This trend has been noted by Boe and Super (1986), Super (1994), Solak et al. (2005) and others, and at least partially explains why SLW maximums are at the lowest and warmest elevations over mountains. This has important implications in selecting the most appropriate seeding technology. The altitudes of maximum SLW are sometimes too warm for AgI to be effective. Consequently, it is strongly recommended that alternative seeding methods be considered in addition to the traditional use of AgI.

6) The best ground seeding situation occurs where two parallel ridges exist perhaps 10-15 km apart. Seeding on the windward slope of the upwind ridge can not only enhance snowfall on its windward and lee slopes, but can also provide relatively large seeded crystals which will rapidly grow in the next SLW zone over the downwind ridge. The Bridger Range Experiment in southwest Montana is a good example of this situation (Super and Heimbach 1983).

7) It has been documented that SLW cloud varies rather rapidly with time over any given point. While some storm episodes may provide semi-continuous SLW presence for as long as a day or more, such events are rare. More typically, SLW presence may alternate a number of

times during a storm passage as natural precipitation processes cycle between inefficient and efficient phases. Depending upon how a seedable episode with SLW present is defined (and no standard definition exists), typical seedable periods last from a few to several hours. Given that spatial variations occur simultaneous with temporal variations, it is not practical to predict just when seedable periods will began and how long they will last. Existing models are not adequate for that task. The most practical means of making seeding decisions is to measure SLW presence and begin seeding as soon as it is detected. Seeding could cease an hour or two after SLW is no longer detectable, with the delay necessary to deal with short-term variations. There is little point in attempting to forecast seedable periods when they can be measured with available instrumentation. There is simply no practical way to forecast short-term variations in winter orographic cloud SLW, and those who attempt to do so with models or other approaches are ignoring the numerous observations by vertically-pointed microwave radiometers which clearly show rapid fluctuations in time. Attempting to make and react to forecasts of SLW presence is simply an unnecessary exercise in futility when real-time continuous observations are now practical. The costs of seeding materials, both AgI and propane, are a small part of total seeding operations. Seeding throughout any period which has potential for production of SLW is worthwhile to avoid squandering seedable opportunities.

8) A relatively thin layer of SLW often exists along cloud bases of shallow clouds. It can extend well upwind of mountain barriers in come cases (Rauber and Grant 1986). Seeding this layer could provide important additional ice crystal/snowflake growth times when such seeding is practical. It is not a zone practical to seed with aircraft unless quite expensive vertical drop flares are used. Achieving adequate horizontal dispersion of the seeding agent and crystals by this means would be prohibitively expensive. The most practical means of seeding the cloud base layer, when it exists, would be with high altitude releases where the presence of upwind terrain permits such releases.

9) Gravity waves have been found to sometimes produce high SLW amounts downwind of mountain barriers (Bruintjes et al. 1994; Heimbach et al. 1997). Reinking et al. (2000) discuss how storms passing parallel ridges, which are common worldwide, will generate embedded gravity waves which may form significant SLW zones and precipitating cloud. But gravity waves require a stable atmosphere, and are transient, subject to rapid buildup and decline, as atmospheric conditions change. Reinking et al. (ibid.) suggest that further work is needed to determine, "--- whether a seeding methodology can be designed to tap the wave-cloud water source." Gravity waves may aid in the vertical transport of seeding material, but this approach may be too unpredictable to apply operationally (Heimbach et al. ibid.).

A recent feasibility study suggests that the State of Wyoming seeding program, scheduled to start during the 2005/06 winter, will attempt to seed gravity wave-induced SLW over and downwind of the Wind River Range with an aircraft. It is not obvious how seeded crystals formed far above the range and/or downwind of it will increase the mountain snowpack.

It is suggested that the State of Colorado continue to monitor investigations of gravity wave SLW zones. However, until a proven seeding technology is shown to target such transient zones, it is strongly recommended that emphasis be given to seeding the frequently existing SLW zone just above the windward slopes and crests of mountains.

10) A relatively thin layer of SLW often exists along cloud tops (Rauber and Grant 1986). While sometimes important for natural snowfall production, seeding this layer would require aircraft releases which have a number of limitations discussed below. The thin cloud top SLW layer is not considered to have serious seeding potential.

3. Summary of Findings Regarding Seeding Methods

1) Aircraft seeding of Colorado orographic clouds is considered impractical for most if not all mountain barriers for several reasons. These include the high expense of 24/7 operations, especially when considering the need to fill most of the SLW volume with seeding material. Previous observations have shown that the along-the-barrier length which can be effectively seeding with a single aircraft is limited to perhaps 20-25 miles (Deshler et al. 1990). Lines of seeding material or resulting ice crystals have slow rates of horizontal and vertical dispersion upwind of mountain barriers. Consequently, it is difficult to fill most of the SLW cloud volume with seeding crystals without an excessive number of high performance aircraft. Safety issues related to flying near mountains in known icing conditions, especially during hours of darkness, and conflicts with airspace availability near high traffic air routes also create problems for aircraft seeding. However, there may be a limited number of mountain barriers where aircraft seeding might be worth considering in more detail. Such mountains would need to be relatively isolated so aircraft could safely descend below the freezing level when airframe icing becomes excessive, or where aircraft could remain well upwind in regions with only limited exposure to icing. Moreover, the value of water augmentation would need to be unusually high to justify this expensive option.

2) The large majority of operational seeding projects in the mountains of the western United States have used valley or, sometimes, foothill ground-based AgI generators which can readily be accessed and manually turned on and off. This is certainly the least expensive seeding approach. However, it has serious problems with routinely achieving transport and dispersion of sufficient concentrations of effective ice nuclei into SLW cloud regions. A number of investigations have shown high frequencies of ground-based inversions which trap the AgI near the valley surface and/or barrier jets which carry seeding material parallel to the barrier rather than over it.

A number of aircraft and mountain top observations of AgI from valley seeding have indicated AgI concentrations too low for effective seeding. Moreover, silver-in-snow analysis of target area snowfalls have generally shown that silver concentrations were not increased over natural background levels, implying mistargeting and/or insufficient AgI for effective seeding. These results would, of course, be expected when the AgI is trapped within a stable atmosphere near the valley floor. Even when AgI was detected at SLW cloud levels, concentrations of effective ice nuclei were low (e.g., Super 1995). This unsatisfactory result was likely partially due to wide crosswind spacing between AgI generators and low generator outputs as well as frequent trapping within a stable lower atmosphere. A recent examination of earlier data from the Wasatch Plateau and upwind Sanpete Valley in central Utah found that hours with significant Plateau-top SLW infrequently had surface winds which were suitably organized to mechanically force valley-based seeding material up the Plateau's windward slope. As discussed in Appendix C, less than 30% of such hours had valley winds with a significant upslope component.

An examination of radiosonde (weather balloon) data taken from just upwind of the Plateau, also discussed in Appendix C, suggests that low-level stability there may not be as serious a problem for valley seeding as found by other cited investigations. This may be because the Valley lies between two nearby parallel ranges, with the San Pitch Mountains to the west, a configuration which could enhance mechanical mixing. During stable conditions, the existence of parallel barriers is conducive to establishment of transient gravity waves which can transport a pool of low-level AgI to high altitudes as suggested by Heimbach and Hall (1994), Heimbach et al. (1997) and Reinking et al. (2000). Gravity waves can also cause subsidence and sublimation of crystals formed too close to a barrier crest, especially if a broad valley exists upwind of the next barrier (Reynolds 1996).

3) Several investigations have demonstrated the best sites for ground-based release of either AgI or liquid propane are at high altitudes, at least midway up the windward slopes from the valley floor to crestline elevations. Propane dispensers must be located high enough to be within or just below liquid cloud base, and at temperatures at least slightly below 0°C. While AgI generators are usually run below cloud, it is best to operate them *within* liquid cloud at -6°C or colder so the forced condensation freezing mechanism can function. This mechanism results from high water vapor concentrations immediately downwind of generators, a byproduct of the combustion of propane and acetone (Finnegan and Pitter 1988, Chai et al. 1993). The mechanism provides large concentrations of seeded crystals just downwind of the generators, maximizing both output and crystal growth times. Operating AgI generators below cloud base can also be effective but only if the seeding agent is vertically transported to altitudes where temperatures are colder than about -8°C.

4. Seeding by Expansion of Liquid Propane

1) It has long been recognized that AgI seeding is ineffective for mildly supercooled cloud, that is, warmer than about -6 to -8°C. The "threshold temperature" at which a tiny fraction of a large population of AgI particles can produce ice crystals has long been stated as near -6°C, well below the 0°C freezing point of bulk water. Some recent papers suggest that newer formulations of AgI have threshold temperatures of -5°C or even -4°C. Unfortunately, the Colorado State University (CSU) cloud chamber facility, used for many years as the standard for testing AgI effectiveness as functions of SLW cloud temperature and other variables, is no longer operational. Consequently, such claims are difficult to verify. The authors are unaware of any published observations which show significant AgI nucleation at such warm temperatures in natural (not laboratory) cloud.

2) A far more important point is that some authors have presented threshold temperatures in a manner which erroneously suggests that AgI seeding can be effective at temperatures $\geq$ -6°C. That is not the case except for the important exception of forced condensation freezing discussed above. But that mechanism requires that AgI be released directly into SLW cloud, requiring use of high altitude remote-controlled generators. Few operational seeding projects operate AgI generators high enough to be in cloud at temperatures of -6°C or colder. Therefore, the following discussion is generally applicable.

3) It is well known that AgI effectiveness is highly temperature dependent, with the percent of the total AgI particle population able to nucleate ice crystals increasing by orders of magnitude from about -6 to -12°C. For example, DeMott et al. (1995) used the CSU cloud chamber facility to show that a particular commercial AgI generator with unusually good warmer temperature yield (effectiveness) had an increase in ice crystal production over its -6°C output which was 33 times higher at -8°C and 314 times higher at -12°C. The same comparison for the type of AgI generator used in the Bridger Range Experiment (Super and Heimbach 1983) showed the increase from the -6°C effectiveness was 770 times higher at -8°C and about 7000 times higher at -12°C. The Bridger Range Experiment strongly suggested significant snowfall increases for ridgeline temperatures of -9°C and colder. But the half of all experimental periods with ridge temperatures warmer than -9.5°C showed no significant seeding effect. And it is likely that much of the success of the Bridger Range Experiment was due to frequent AgI release directly into cloud,

immediately forming ice crystals when temperatures were below -6°C as suggested by Finnegan and Pitter (1988). It is probably not coincidence that seeding site temperatures of -6°C correspond to a ridgeline temperature near -9°C for in-cloud lapse rates.

With the exception of in-cloud releases, the authors are unaware of solid field evidence showing AgI cloud seeding to be effective with SLW cloud temperatures warmer than about -8 or -9°C. This should not be surprising once calculations take into account typical generator outputs, along-the-wind spacing and horizontal and vertical transport and dispersion of AgI plumes from generators to the target area. It has been shown that seeded crystal concentrations need to exceed about 20 L^{-1} over the target to result in more than trace snowfall rates as far back as the classic paper by Ludlam (1955) and as recently as Super and Heimbach (2005a).

4) There is an obvious large "temperature window" from 0°C to at least -6°C (for forced condensation freezing) and, more commonly, about -8°C, that cannot be effectively seeded with conventional formulations of AgI and typical generator networks. Yet mildly supercooled cloud, warmer than -6 or -8°C, frequently exists in the primary SLW zone near the windward slope and crestlines of mountains throughout the West. Of course, the frequency of mildly SLW cloud varies with geographic location and altitude. The frequency of warm temperatures was found to be so high over the northern Sierra Nevada of California that a new winter orographic seeding method was developed (Reynolds 1989, 1996). The new approach adapted propane dispensers, previously used for SLW fog suppression over airports, for use in high mountain terrain by configuring them to be remotely controlled by radio. Expansion of liquid propane causes homogeneous nucleation[1] by local chilling of the air below -40°C (equal to -40°F). Reynolds (1996) noted that the temperature of SLW in the Sierras, determined from mountain top icing meters, was warmer than -4°C about 80% of the time. Since ground-released AgI seeding plumes are usually concentrated within about 2000 ft (600 m) of the terrain, AgI plume tops would not be cold enough (-8°C) for effective seeding about 80% of the time. Even this value is an overestimate because seeded crystals need to be formed some distance upwind of the mountain top, as will be discussed. Propane has been shown to be an effective seeding agent at temperatures slightly below 0°C, and has little temperature dependence at temperatures colder than -2°C according to the laboratory and field investigations of Hicks and Vali (1973).

The ability of propane seeding to create meaningful snowfall when SLW cloud is too warm for AgI effectiveness is well-demonstrated by Fig. 1, taken from Super and Holroyd (1997). An extended period with SLW available but very limited natural snowfall, until the end of the experiment, was first seeded with propane and later with AgI, both released from the same high altitude site. The large increase in seeded crystals is obvious during the propane seeding, but AgI seeding was ineffective. The mountain top sampling location temperature was near -4°C during the entire period.

5) A small-scale randomized propane seeding experiment was conducted in central Utah during the 2003/04 winter described in detail by Super and Heimbach (2005a, 2005b). Propane was released from the same high altitude location used in Fig. 1, known to routinely pass over the Wasatch Plateau by the same mountain-top observatory used in constructing that figure. Many prior plume tracking experiments verified the routine transport and dispersion during seeding site

[1] Homogeneous nucleation occurs when water droplets freeze without the presence of foreign material. This will occur spontaneously at temperatures below about -40°C. Expansion of liquid propane produces temperatures well below -40°C in a small volume just downstream of the spray nozzle. Heterogeneous nucleation of ice requires a foreign surface or substrate for water molecules to collect. Silver iodide is especially effective because it has a crystalline structure nearly identical to that of ice.

winds between south and west. A line of precipitation gauges was operated along the expected plume trajectory, and one crosswind gauge provided the covariate of natural snowfall. The exploratory statistical analyses presented by Super and Heimbach provided strong suggestions of seasonal seeding increases near 10%. These and other studies have provided convincing evidence that propane seeding can produce useful additional snowfall for mildly supercooled cloud temperatures where AgI is not effective, as well as for colder temperatures where both AgI and propane are effective. Propane seeding requires the use of high altitude dispensers operated at or above the SLW cloud base. Such dispensers are economical to build and operate, and are highly reliable. They can be used in a completely automated mode, using a device to sense SLW presence to determine when to seed. A small operational program in Utah, described by Super et al. (1995), has continued to use this approach for over a decade. The randomized experiment of 2003/04 was also completely automated. Both the operational program and the experiment were able to seed on a 24/7 basis whenever SLW cloud was present. This approach provides a major advantage over use of forecasts and calling out personnel to operate manual generators.

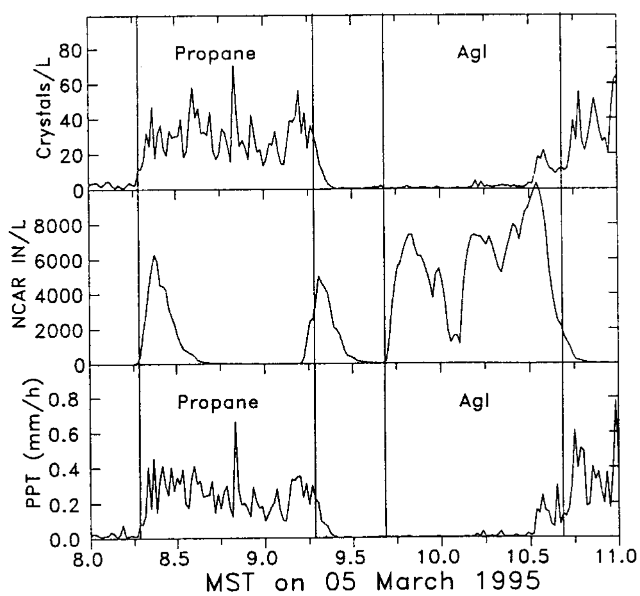

Fig. 1. Temporal distribution of ice crystal concentration (top) and precipitation intensity (bottom), both calculated from the mountain-top observatory 2D-C probe, and acoustical counter measurements of AgI, effective at -20°C (middle panel). Two 3-min "tags" of AgI were released at the beginning and end of the hour of propane release which appear much longer because of the response characteristics of the acoustical counter. The estimated hour of maximum plume presence is shown by vertical lines for propane seeding (left) and AgI seeding (right). The increase in snowfall rate after 10.5 hrs (10:30 a.m.) MST was associated with a natural shower.

6) Cloud base altitude is an important consideration when siting propane dispensers which must be in-cloud or just below cloud base (at ice saturation) to be effective. Rauber and Grant (1986) stated that cloud base over the windward slope of northern Colorado's Park Range was typically about 650 to 1000 ft below the 10,370 ft crest line (all elevations above mean sea level), which would place typical bases near 9400 to 9700 ft. Rauber and Grant (ibid.) also noted that occasionally cloud base would lower to as much as 1600 ft below crest line or rise 150 ft above it. This range would place cloud bases from as low as 8800 to as high as 10,500 ft.

Hindman et al. (1994) cited a typical cloud base value for the windward slope of the Park Range as 9200 ft. Since detailed statistics on Park Range cloud base altitudes have apparently not been published, the lead author spoke with the two scientists believed to be most experienced with Park Range surface observations at the Storm Peak Laboratory (SPL). One estimated that cloud bases were usually in the range 9100 to 9700 ft (Ed "Ward" Hindman, personal communication, July 1999). The other, who currently directs the SPL, believes that cloud base descends as low as 8300 to 8500 ft infrequently, but often enough to be considered (Randy Borys, personal communication, July 1999). However, he estimated that "typical" cloud bases were between 9000 and 9500 ft. He also noted that cloud base is above crest line only 10 percent of the time when snow is falling at the SPL. Borys also stated that cloud bases were rarely warmer than 0°C from December 1 through April 1. In that case, propane seeding would almost always produce ice crystals as long as the dispenser was in-cloud or not far below cloud base.

Based on the information presented, it appears reasonable to assume most seedable winter orographic cloud bases over the Park Range will be in the range 8500 to 10,500 ft. In order to locate propane dispensers to usually be within SLW cloud, or at least at ice saturation, they should be sited no lower than about 9000 ft which would provide about 1400 ft of vertical lift before passing the mountain crest. Cloud base information for other Colorado mountain ranges is not as readily available as at the Park Range where considerable research has been conducted over decades. But this information just stated can be used as a guide for other locations. Local ski area personnel could be contacted for cloud base information at their particular locations, but accomplishing that is beyond the scope of this study.

As a matter of interest concerning ice saturation, the levels of ice and water saturation are identical at 0°C. For the altitudes and pressures relevant to this study, it has been calculated that the ice saturation level would be about 240 ft below the water saturation level (liquid cloud base) at -5°C, and about 460 ft below it at -10°C. Consequently, propane dispensers will often be ineffective if sited more than a few hundred feet below liquid cloud base. Since visual cloud base may be related to both liquid droplets and falling ice crystals and snowflakes, it will sometimes be significantly lower than liquid cloud base.

5. Characteristics of Supercooled Liquid Water Cloud

This section reviews published information concerning the availability and variability of SLW cloud over mountain barriers, elaborating on the information of Sec. 2. While the primary area of interest is Colorado, the available data set was significantly enhanced by inclusion of Utah measurements. Numerous observations have been made in both states. Utah orographic clouds are believed similar to those in Colorado as the mountains are at similar latitudes in the adjoining states. Cloud observations from further-removed states like Arizona and California are unlikely to be very representative of Colorado conditions, and are generally ignored herein.

In order for winter orographic cloud seeding to succeed, SLW cloud droplets must exist in excess of those naturally converted to snowfall. Tiny cloud droplets can, and often do, exist at temperatures below 0°C, the freezing point of bulk water. While natural ice crystals typically form in abundance when SLW cloud temperatures are lower than about -15 to -20°C, cloud seeding can initiate the precipitation process at warmer temperatures, even slightly below 0°C for some types of seeding. It will be shown that primary SLW zones in orographic clouds in Colorado and Utah usually have temperatures warmer than -15°C, and often warmer than -10°C. Thus, cloud seeding presents an opportunity to enhance snowfall from warmer SLW clouds when nature may be partially or totally inefficient in ice crystal and snowfall production. Seeding when nature is producing abundant ice crystal concentrations may not be effective, but there is no convincing evidence that it decreases snowfall with the possible exception of some deliberate attempts to overseed in order to redistribute snowfall patterns (e.g., Hobbs 1975b). Detailed discussion of how the formation of seeded ice crystals within SLW cloud can enhance mountain snowfall is given in several sources (e.g., Dennis 1980), and will not be repeated here. A facts brochure entitled "Weather Modification in the United States" presents the basics of cloud seeding. It is available from the Weather Modification Association and can be downloaded from: www.weathermodification.org/facts.htm

To design an optimum winter orographic seeding project, the following information is desired. How frequently does SLW exist, where and in what amounts? Knowledge of the frequency and amount of excess SLW, not naturally converted to snowfall, is important for estimation of the maximum potential snowfall production by seeding. In other words, does SLW exist often enough and in sufficient amounts that seeding has a reasonable chance of producing meaningful additional snowfall? It is obviously important to know the spatial distribution of SLW, and its vertical temperature distribution, when considering what seeding approaches to apply. Will ground-based releases be routinely transported into the SLW cloud or is aircraft seeding required? Is the SLW zone cold enough for AgI seeding to be effective or should an alternative agent like propane be considered? Similarly, if airborne seeding is required, should seeding be done with acetone generators, pyrotechnic flares or dry ice pellets?

The common operational practices of simply assuming SLW will often be present, and will be effectively seeded by deploying a conveniently-accessed ground generator network can no longer be justified in light of current knowledge. Such simplistic approaches do minimize costs. However, there is little physical evidence, or credible statistical evidence, to support typical claims of about 10% increases in precipitation through the indiscriminate application of valley-based ground generators.

The availability of SLW cloud in excess of that converted by natural processes to snowfall has long been assumed for cloud seeding projects. The classic paper by Ludlam (1955) described extensive low clouds over the mountains of central Sweden, no more than several hundred meters thick, which were composed of SLW cloud droplets without snowfall production. But most orographic clouds in the Intermountain West have higher, colder tops and are composed of varying concentrations of both droplets and ice crystals. In Colorado mountain clouds, typical natural ice crystal concentrations are in the 10 to 100 per liter range while tiny cloud droplets often range from 100,000 to 300,000 per liter (100 to 300 cm^{-3}). Conversion from SLW to snow requires that vast numbers of droplets combine to make a single snowflake. Introduction of relatively few ice crystals into a SLW cloud can initiate snowfall by one or more of three processes: vapor deposition on the crystals because of the greater saturation vapor pressure over liquid than over ice at the same temperature; liquid deposition on the larger crystals (often called "riming" or "accretion") as they fall through and collide with numerous droplets which freeze on the crystals; and aggregation (chaining together) of many crystals into a larger snowflake. More details can be found in Dennis (1980) and other sources.

The large majority of operational and experimental seeding projects have been conducted without routine evidence of SLW availability. That is, it was assumed but not documented that SLW was often present, in large part because of instrumentation limitations. Prior to about 1980, SLW orographic cloud was manually sampled on an intermittent basis at a few western mountain observatories. Some aircraft sampling was done, usually at altitudes more than 3000 ft above mountain barriers for reasons of safety. The presence of SLW was inferred from observations of riming (freezing of SLW droplets) on snowflakes. It was certainly known from such measurements that SLW existed some of the time in winter orographic clouds. But the frequency, durations, amounts and horizontal and vertical positions of SLW were not well documented. As a consequence, seeding projects implicitly assumed frequent SLW presence during presumably "seedable conditions." Such conditions were often assumed to exist based on some indication or forecast of cloud top temperature. Cloud tops colder than about -20 to -25°C were believed to indicate naturally efficient storms while storm periods with warmer cloud tops were thought to be seedable. This opinion was based in part on the statistical suggestions of the Climax Experiments, conducted near Leadville, Colorado, during the 1960s. These results were widely accepted for several years but more recently have been seriously challenged in the scientific literature. Most commercial seeding operators still attempt to forecast seedable conditions, some still using an estimate of cloud top temperature, without documenting that SLW actually exists. This may be an adequate operational approach if SLW cloud is often present, and often targeted by sufficiently high concentrations of seeded crystals. But it is unlikely to be an optimum seeding approach.

Even large earlier experimental programs like the Colorado River Basin Pilot Project (CRBPP), conducted in the San Juan Mountains of southwest Colorado during the five winters 1970/71 through 1974/75, did not routinely monitor SLW cloud presence. Given the fact that SLW is necessary for seeding to be effective, failure to monitor it now seems shortsighted, but suitable instrumentation was not generally available until about 1980. The then limited knowledge concerning winter orographic SLW distributions and variability can be evidenced by the book on weather modification by Dennis (1980) which provides little in the way of observational results. Nor does a major planning document for the CRBPP contain much insight into SLW availability (Grant et al. 1969). The Bridger Range Experiment (Super and Heimbach 1983), conducted in the early 1970s, did not monitor SLW, nor did a number of concurrent experiments. These comments are not meant as criticism but simply illustrate previous limitations in knowledge and instrumentation.

An important exception which monitored SLW cloud was the then cutting edge experimental work conducted over the Cascade Mountains of Washington from 1969 to 1974 (Hobbs 1975a, Hobbs and Radke 1975, Hobbs 1975b). Attempts were made to heavily seed the orographic clouds with AgI and dry ice in order to both increase and redistribute snowfall, producing more on the drier downwind mountain slopes. The average distribution of SLW cloud, based on 22 aircraft flights, was given as Fig. 3 of Hobbs (1975a). The figure shows that,

- the maximum SLW was at lowest sampling altitudes over the windward slopes,
- SLW was found at highest altitudes over the crestline, and
- SLW decreased rapidly with increasing altitude.

This 1975 general portrayal of the SLW distribution over mountains has since been observed over several other mountain ranges, and extended to mountain surface altitudes by improved instrumentation.

Much of the earlier knowledge of SLW was based on interpretation of rawinsonde relative humidity and temperature data, shown to have serious instrument-caused flaws by Hill (1978). Rawinsondes have the additional shortcoming of usually ascending upwind of the primary SLW zone now known to exist near the windward slopes and crests of mountains. Aircraft observations of icing were also commonly used (e.g., Hill 1982a), but such measurements were typically made well above the barrier-induced SLW zone because of Federal Aviation Agency (FAA) flight restrictions.

Henderson and Solak (1983) presented routine California mountain-top measurements of SLW from a Model 871B Rosemount icing rate sensor designed for aircraft use. (A review of article titles in the first 15 volumes of the Journal of Weather Modification suggested this was the first article to provide winter orographic SLW observations.) More recent surface icing rate observations have usually used a similar Rosemount icing rate sensor, Model 872B, designed specifically for use on towers. These icing rate sensors, combined with wind and temperature observations, provided an important new approach for assessing low-level SLW over mountain barriers, which have been used at several locations.

Henderson and Solak (ibid.) stated that, "The measurements strongly support the conclusion that SLW is occurring throughout larger portions of stormy periods, particularly in pre-frontal portions, than past airborne observations over the SCPP (Sierra Cooperative Pilot Project) project have indicated. In many cases, the SLW simply occurs over the mountainous area below the altitudes considered safe for aircraft operations." According to Solak et al. (1988), such surface measurements, combined with microwave radiometer measurements of SLW, "--- influenced a shift in the focus of SCPP research from primarily postfrontal convection to the more stratiform and widespread cloud types." Their article also compared the aircraft type and tower type Rosemount icing sensors, collocated on a mountaintop, and found the latter underestimated SLW because only deicing heater cycles are output for recording. That finding was also reported by Super et al. (1986) who noted that about 100 hours of limited but additional icing were indicated by an aspirated aircraft type Rosemount sensor located next to a tower type sensor during a several month period atop the Grand Mesa. However, as discussed in Appendix A, under the review of the Solak et al. (2005) article, it is possible that many events by their aircraft sensor may have been false.

Similar findings of near-terrain SLW have since been verified over other mountain ranges including in Colorado and Utah. For example, similar observations over the Tushar Mountains of southern Utah were presented by Solak et al. (1988). They made the important point that, "Comparisons of low-altitude SLW flux values and precipitation rates suggest that increased precipitation <u>alone</u> does not necessarily signal diminished augmentation potential." Other investigations have questioned the concept that moderate or even heavy snowfall totally eliminates seeding potential (e.g., Super and Heimbach 2005a).

The development of the microwave radiometer (Hogg et al. 1983), capable of remotely sensing both water vapor and liquid water along a selected path, can be credited with rapid increases in SLW documentation. Moreover, use of special waivers from the FAA, which allowed sampling over carefully selected relatively flat mountains (Bangtail Ridge target of the Bridger Range Experiment in Montana; Grand Mesa of Colorado; Wasatch Plateau of Utah; Mogollon Rim of Arizona), has permitted aircraft sampling to within 1000 ft of the highest terrain. Such low level sampling has been found by experience to typically be about 2000 ft above the average barrier top of such semi-rugged terrain. Even occasional minor peaks force aircraft observations well above the 1000 ft special waiver minimum above highest terrain. Lowest practical aircraft sampling over more rugged mountains would be even higher, perhaps 3000 ft or more over the average crestline elevations. Nevertheless, use of microwave radiometers, aircraft measurements nearer the mountains and routine surface measurements with icing rate sensors, together have lead to a much improved portrayal of the spatial and temporal distributions of SLW cloud over mountains.

The locations of surface icing sensors and microwave radiometers have important implications for interpretation of resulting data. It is now recognized that subsiding air normally exists immediately to the lee of barrier crests, and descent may even begin just upwind of the crest, with the result that the air mass warms, causing the tiny SLW cloud droplets to rapidly evaporate downwind of crestlines. The downwind disappearance of orographically-produced SLW is often accelerated by natural conversion to snowfall. Accordingly, the best observing locations for both surface icing sensors and microwave radiometers are on top of mountain crestlines rather than some distance upwind. That is because SLW measured upwind of barriers may be partially or totally converted to natural snowfall before the moist ascending airflow passes over crestlines. Therefore, observations over upwind slopes may result in overestimates of cloud seeding potential. The same is true of crestline observations but to a lesser extent.

The situation over generally flat-topped barriers is more complex. For example, mobile microwave radiometer observations of SLW were made over the Wasatch Plateau (Huggins 1995). Subsiding air motions were implied immediately downwind of the Plateau top's upwind edge. But downward motions over such terrain may not be as abrupt as over more typical narrow crestlines, which could provide more time for natural conversion of SLW to snowfall. Huggins (ibid.) showed a decrease of SLW across the Wasatch Plateau top, thought to be due to a combination of conversion to snowfall and descending airflow. But the number of cross-barrier observations was limited, and additional locally-produced SLW was apparent over a minor ridgeline midway across the Plateau top. Weak embedded convection may also enhance SLW. These remarks are made to caution the reader that estimating seeding potential from SLW observations, wherever made, is a complex and imperfect undertaking. Yet since SLW is the necessary "raw material" for cloud seeding to work, improved knowledge of its spatial and temporal variations is important for improving cloud seeding practices. Several published articles and project reports have been reviewed and briefly summarized in Appendix A to present current understanding of SLW availability over Colorado. Observations have been used from Colorado where available, and also from Utah, to expand the knowledge base. As previously noted, Utah measurements are believed to be reasonably representative of Colorado mountains.

6. Transport and Dispersion of Ground Seeding with Emphasis on Valley Releases

As discussed in Sec. 5, wintertime SLW cloud is primarily found in the lowest few thousand feet above the windward slopes and crests of mountain barriers. It was also noted that a thin layer of SLW frequently exists at cloud top and sometimes near cloud base as well. Evidence for the primary SLW zone was provided from a number of sources. The cloud top and cloud base zones are based primarily on the work of Rauber and Grant (1986), briefly reviewed in Appendix A. A conceptual portrayal of the three SLW zones is given in Fig. 13 of their paper. More recent work has shown that gravity waves sometimes produce abundant SLW zones over or downwind of mountain barriers. These transient zones may contain more SLW than found near windward mountain slopes, but often can only be seeded by aircraft, as also true for the thin layers found at cloud tops. Targeting of seeded snowfall from gravity wave-produced SLW would be difficult unless a mountain barrier existed an appropriate downwind distance from the wave-produced SLW zone. The facts that the presence of such SLW zones are transient, and that they shift their positions with time, further complicates any attempt to seed them in a manner that produces additional snowfall on a desired mountain target area. Perhaps future research will show such SLW zones to be seedable under some circumstances, but such evidence does not currently exist. Consequently, seeding of gravity wave SLW zones will not be considered further.

While thin cloud top SLW layers may contribute to natural ice crystal formation, they are not considered an important moisture source for seeding. In addition to the problems cited, seeding cloud top SLW would require aircraft releases. That requirement makes routine seeding impractical over the rugged and extensive Colorado mountains. As discussed in detail by Super (1999a), now available as Appendix A of Medina (2000), aircraft seeding has several drawbacks. Briefly, such seeding is quite expensive, especially if operations are to be undertaken on a 24/7 basis needed to maximize seeding effectiveness. Flying in winter orographic cloud can be dangerous if moderate or heavy icing exists, that is, when SLW is abundant at flight levels. Pilots are especially reluctant to fly near mountains at night, even with twin-engine aircraft equipped for flight into known icing conditions. Experience with expensive twin jet-prop engine research aircraft has demonstrated they cannot remain in moderate much less severe icing for very long. Operational seeding aircraft are usually less capable of remaining in an icing environment. Should loss of an engine or a forced landing be required, darkness is an obvious additional danger, especially over rugged terrain.

Besides the high expense and safety issues of airborne seeding, there are serious problems attempting to fill a significant portion of the SLW cloud with seeding material or seeded ice crystals. These have been discussed in detail by Hill (1980) and Deshler et al. (1990) among others. Deshler et al. (ibid.) used aircraft and ground-based microphysical observations over California's Sierra Nevada to conclude that, "Achieving fairly continuous coverage along the direction of seed line advection requires seed lines to be no longer than 37 km (23 mi), yet treatable cloud may extend for hundreds of kilometers along the barrier." Based on their finding it would require many aircraft to effectively seed Colorado's major ranges during large-scale storm passages. Another major problem for aircraft seeding in several areas is conflicts over available airspace, especially if seeding is desired near major air traffic routes where preference will be given to commercial or military flights. There are locations where aircraft seeding may be practical, such as some of California's coastal ranges, where aircraft can descend below the freezing level to shed rime ice buildup. But, for all the reasons given, aircraft seeding is not considered practical for Colorado mountains. Consequently, it will not be considered further in this report.

The large majority of winter orographic cloud seeding programs have used ground-based AgI generators. These are most frequently located in mountain valleys and are typically manually controlled. Sometimes generators are sited on somewhat higher foothills and/or canyon mouth locations. Remote-controlled AgI generators are used less commonly, because of increased cost and operational complexity, although some California and Nevada projects have used them exclusively. It will be shown that, in general, higher elevation seeding releases are more likely to be successful in providing seeding agent to orographic SLW cloud. In fact, if generators are located higher than about midway from a valley floor to a crestline, AgI transport into the primary SLW zone has been shown to be routine within the appropriate range of upslope wind directions.

Further discussion of ground-based seeding will be separated into two categories. The first and most common will be called "valley" releases, considered to include any releases up to and including foothill and canyon entrance locations. Such releases typically use manually operated AgI generators with ready access to the seeding sites, usually by road. The second category will be referred to as "high-altitude" releases meaning any seeding higher than midway from the valley floor to typical crestline elevations. Such sites are significantly more difficult to access, requiring travel by skies, snowshoes, snowmobile or helicopter. Remote-controlled AgI generators or propane dispensers are used at high altitude seeding sites. Only limited attention will be given to releases in the elevation interval between canyon entrances and midway up the windward slope. Plume tracking information from such locations is limited and results have been mixed. Use of such "lower slope" locations would usually require remote-controlled AgI generators. Review of the evidence shows that the frequency of targeting success is significantly greater from higher elevations. Therefore, there seems little point in siting expensive remote-controlled AgI generators on lower slopes.

Much of the following discussion has been paraphrased or taken verbatim from Super (1999a), in which he presented the results of a feasibility study for seeding Colorado's northern mountain ranges. The same is true for portions of Appendix B, as little new information as been published since the 1999 study was completed.

6a. Seeding from Valley Locations

A considerable body of evidence, including some presented in Appendix B, indicates valley-released AgI plumes are often trapped by stable air, especially when valley-based inversions are present. Sometimes such AgI plumes are transported parallel to mountain barriers rather than over them (e.g., Parish 1982). A number of scientists have recognized for several years that attempting to seed winter orographic clouds from valley locations is fraught with difficulties. When one considers that the SLW zones over mountains are typically thousands of feet above valley AgI generators, and that the atmosphere is often stable for some distance above valley floors, the potential problem is obvious. Furthermore, part or the entire SLW zone may be too warm for AgI to produce adequate seeded ice crystal concentrations. Therefore, even when AgI is vertically transported to the SLW zone, seeding may still be ineffective.

Smith and Heffernan (1967) expressed the problem well when they stated, " --- persons who release silver iodide from the ground would be wise to find out where it goes." Yet this seemingly obvious advice has seldom been followed, in part because tracking plumes over rugged terrain can be difficult and expensive.

As a body of evidence built up, the review articles by Rangno (1986) and Reynolds (1988) recognized that achieving adequate transport and dispersion was possibly the most difficult problem facing winter orographic cloud seeding. The difficulties of targeting SLW regions in winter orographic clouds were more recently noted in the review article by Bruintjes (1999). But the special difficulties with valley AgI releases were recognized well before these publications.

Some of the earliest airborne AgI plume tracking was done over the Park Range of northern Colorado as reported by Langer et al. (1967) during testing of a new acoustical ice nucleus counter. A limited data set resulted which the authors stated was collected, "--- under conditions approximating those conducive to cloud seeding." It was found that much of the AgI released from the 8,200 ft top of Emerald Mountain was trapped in the Yampa Valley between the release point and the intended Park Range target area to the east. None of the tests showed reasonable AgI concentrations more than a few thousand feet above the ground. A much larger set of observations from five winters was used by Rhea et al. (1969) to demonstrate that valley-based trapping inversions typically occurred at least half way up the Park Range during snowfall. Such inversions would be expected to severely limit the vertical dispersion of valley-released AgI.

Similar findings were reported by Super et al. (1970) who presented the results of seven months of observations of atmospheric stability during snowfall over the Bridger Range of Montana, based on surface temperature measurements along the windward slope. Their stability data also indicated that AgI generators needed to be at least midway up the windward slope to be above the frequent stable layer extending above the valley floor. As might be expected with a stable atmosphere, valley floor and foothill winds were typically calm or very light during mountain snowfall. Like the Park Range, the Bridger Range has a broad upwind valley for prevailing winds.

Consequently, initial attempts to use foothill generators were abandoned, and the randomized Bridger Range Experiment (Super and Heimbach 1983) deployed manual AgI generators about 2/3 of the way up the windward slope. These were maintained by field technicians who lived in small shelters while frequently checking the generators. They also optically tracked pilot balloons when visibility permitted. This was an expensive seeding approach compared to use of foothill generators, as all major supplies and equipment were lifted in by helicopter. It had been intended to use remote-controlled AgI generators at these sites, but they proved unreliable. Winter access was limited to arduous climbs to the seeding sites. But the result was that clouds were routinely seeded as shown by Super (1974), Super and Heimbach (1983), Heimbach and Super (1988) and Super and Heimbach (1988). Even to the present day, few other experiments or operational projects have provided such strong evidence that orographic clouds were routinely seeded. The general lack of such documentation is considered a major weakness in several past and ongoing winter seeding programs, leaving open the very real possibility that clouds were, and are, often inadequately seeded or not seeded at all. Physical evidence always trumps suggestions from statistical analyses, especially when the latter may be subject to bias.

Marwitz (1980) presented results based on 3 months of aircraft sampling and other observations made over the San Juan Mountains of southwest Colorado. That investigation was during the final 1974/75 winter of the five winter Colorado River Basin Pilot Project (CRBPP), described in detail by Elliott et al. (1978). They noted that seeding was done with 20 manually-operated AgI generators and 13 remote-controlled units, "--- placed in valleys and on hills 10-30 km (6-19 miles) south and west of the target area." The study reported by Marwitz (ibid.) was prompted by results of aircraft and other sampling made the prior winter by the University of Washington Cloud Physics Group under the leadership of Professor Peter Hobbs. Marwitz (ibid.) cited their 1975 internal report, no longer available to the authors of this report, as follows, "Hobbs et al. also studied the transport of ice nuclei from the ground-based seeding generators. They found that the ice nuclei did not reach cloud level under stable conditions, and entered the cloud too close to the target area under marginally unstable conditions to increase snowfall over Wolf Creek Pass. These unexpected and important results led to our additional field investigation." Clearly the University of Washington study raised grave concerns about ground-based seeding of the San Juan Mountains, even during marginally unstable conditions.

The investigation reported by Marwitz (1980) used aircraft sampling, rawinsondes released at 3 hr intervals, and finer scale data from 12 storm passages. He concluded that, "The typical storm was seen to evolve through four stages: stable, neutral, unstable and dissipation. During the stable stage, much of the flow below mountain top level is blocked and diverted toward the west. During the neutral stage, the storm is deep - typically extending throughout much of the troposphere. During the unstable stage, a zone of horizontal convergence appears to form near the surface at the base of the mountain on the upwind side of the mountain and a convective cloud line is often present over this convergence zone. Subsidence at mountain top height causes dissipation."

A companion paper to Marwitz (ibid.), by Copper and Marwitz (1980), indicated that seeding potential might exist over the San Juans during some storm phases. They suggested that the unstable storm stage was most suitable for seeding as it had the highest liquid water contents and regions with relatively low natural ice concentrations. These regions were associated with convection. But AgI was detected during only 3 of 10 sampled storm periods indicating the ground-based seeding approach used by the CRBPP was not very effective. And detection does not necessarily mean that a sufficient concentration of AgI ice nuclei were present. Valley generators were primarily used for the CRBPP but some higher remote-controlled generators were also used (Elliott et al. ibid.). Cooper and Marwitz (ibid.) did not suggest any specifics as to how a better seeding generator network might be designed.

Rangno and Hobbs (1980), in their criticism of published CRBPP results by Elliott et al. (1978), noted that, "Three separate airborne sampling programs in Colorado, two of which occurred in support of CRBPP and the other in support of the Park Range Project in northwest Colorado, all found negligible vertical dispersion under stable conditions." They were referring to the same two aircraft sampling programs just mentioned, and results from the report by Rhea et al. (1969).

Rangno and Hobbs (1993), in one of their several criticisms of the Climax, Colorado, experiments, upon which the CRBPP design was largely based, presented convincing evidence that valley-released AgI was often transported away from rather than toward the Climax target area.

Super (1994) summarized the results of monitoring valley-released AgI during 12 storm days on the Wasatch Plateau of central Utah. He questioned the operational program's effectiveness because of the relatively warm SLW temperatures and resulting low concentrations of *effective* AgI ice nuclei found in the SLW clouds. Another concern with the long-term Utah operational seeding program, also contributing to low concentrations of effective AgI ice nuclei, was the typical 16 km (10 mile) spacing between generators. Technical personnel of the operational seeding company stated that about 4-5 km (2.5 to 3.1 mile) spacing would be required in order to achieve AgI plume overlap (Griffith et al. 1992; Griffith 1996). The expected consequence of the significantly larger 16 km spacing would be wide unseeded gaps between instantaneous AgI plumes passing over the mountain barriers which must reduce seeding effectiveness.

Six cases studies of valley-based AgI seeding over the Wasatch Plateau were described by Super (1995). These were the only 1991 field season sampling periods when AgI released from eight valley generators was detected at aircraft sampling altitudes over the Plateau. The spacing of these generators was closer than usual, about 5-10 km (3.1 to 6.2 mile) in support of the research program (Griffith et al. 1992). Silver iodide concentrations, observed at -20°C in the acoustical ice nucleus counter cloud chambers, were about an order of magnitude less at lowest aircraft sampling levels about 2000 ft above the Plateau top than observed atop the Plateau by an instrumented van. The AgI was seldom transported up to 3300 ft above the plateau top. Aircraft cloud physics aircraft sensors failed to indicate any ice particle concentration (IPC) increases during three of the six experiments, when sampling level temperatures were warmer than -9°C. Evidence existed that seeding caused IPC increases during at least two of the three colder cloud experiments. However, any associated increases in snowfall were minor, even during an experiment with heavy aircraft icing in cloud cold enough for plentiful nucleation by AgI. The observational evidence from the 1991 field season indicated the valley-based operational seeding was usually ineffective.

Heimbach and Hall (1994) applied the three-dimensional, time dependent numerical model of Clark and associates of the National Center for Atmospheric Research to a case study over the Wasatch Plateau. Model results were in good agreement with a comprehensive set of surface and aircraft observations. Both showed considerable pooling of valley-released AgI with limited transport over the Plateau. The model indicated that higher elevation generator sites would have been superior to the valley releases.

Another modeling case study over the Wasatch Plateau, reported by Heimbach et al. (1997), suggested that gravity waves could transport valley-released AgI through a surface-based inversion under some conditions. While the plateau top was reached by abundant AgI, measured concentrations at aircraft sampling altitudes were very limited, indicating the seeding material was confined to a layer no more than 2000 ft thick while being transported over the Plateau.

Further model evidence of the gravity wave mechanism sometimes transporting valley-released AgI to plateau top elevations was presented by Heimbach et al. (1998). Their investigation stratified rawinsonde observations into five stability classes, although several soundings did not fit the criteria for those classes. Not unexpectedly, the most unstable sounding class produced the best targeting. It also had the coldest temperatures, resulting in more effective AgI ice nuclei. That class had 26% of the 46 soundings which meet the criteria but only 17 % of the total of 72 soundings. However, as discussed in Appendix C, a number of soundings were not made during actual storm conditions. Only weak vertical transport was indicated for another stability class and virtually none for the other three classes. Cases studies with comprehensive observations were found which represented the various classes, and generally good agreement existed between these measurements and model results.

6b. Silver-in-snow Concentrations

One approach for testing whether AgI seeding material was transported over a target area is to monitor the concentration of silver-in-snow to determine whether it exceeds natural background levels (Warburton and Young, 1968). Enhanced silver concentrations from AgI seeding have been found for some programs including Super and Heimbach (1983), Heimbach and Super (1988), Chai et al. (1993), Warburton et al. (1995a), Warburton et al. (1995b) and McGurty (1999). These programs all used high altitude AgI generators.

Reynolds et al. (1989) reported upon ground-based seeding experiments with AgI generator sites ranging from the foothills to sites on the west slope of the Sierra Nevada of California. A network of 24 generators consisted of 3 long-term operational networks of remote-controlled generators and 1 specially-installed network of manually-operated generators. All generators were operated in a coordinated fashion during a 2-mo period. A numerical targeting model was used to compute nucleation and fallout locations for each generator on a given day. It appeared to provide reasonable estimates of AgI plume transport and dispersion when compared with aircraft observations. Silver iodide plumes released from foothill generators frequently had trajectories parallel to the mountain barrier rather than over it. Targeting was more successful downwind of higher elevation generators, above 6600 ft.

Extensive snow chemistry analysis revealed targeting effectiveness at 14 sampling sites within the intended target, from north to west to south of Lake Tahoe, for the combined generator network. Finding increased silver-in-snow does not prove that AgI seeding produced snowfall because natural snowfall will scavenge AgI and bring it to the surface. However, failure to find silver greater than natural background levels indicates the AgI plume did not pass over the sampling location in adequate concentrations during the sampled snowfall period. Therefore, lack of enhanced silver is interpreted to mean seeding was ineffective.

A large number (1,681) of individual target snow samples were collected from the 14 sampling sites for chemical analysis of silver concentration. Less than 15 percent of the samples indicated any silver greater than background. In summarizing the silver-in-snow sampling program, Reynolds et al. (ibid.) concluded that, "These are disturbing results, even if one considers only scavenging, in that the AgI must not have passed over large regions of the target during precipitation events. Much of the AgI may be transported westward or northwestward at low levels, effectively not passing over the barrier." These results are indeed disturbing, especially since most of the generators were used for three long-term operational seeding projects, and some were located at relatively high elevations, above 6600 ft. The results raise serious concerns about generator siting, inadequate crosswind coverage by adjoining generator plumes and the reliability of remote-controlled AgI generators.

Similar poor targeting results were reported by Warburton et al. (1995b) for two large target areas in the Sierra Nevada. They showed that on average no more than 20 percent of the precipitation falling during seeding operations had "seeding silver" over several winters in the Truckee-Tahoe region. Silver concentrations were above threshold in 42 percent of the westerly wind seeded events in the Lake Almanor region, but only 8 percent with southerly flow, again showing lack of proper targeting in about 80 percent of all cases. In fact, the results suggested that intended upwind *control* areas were often seeded during southerly flow, again showing the importance of documenting seeding plume trajectories rather than assuming where they will be transported.

Other studies which found little indication of enhanced silver-in-snow, in these cases from Utah valley seeding, include Long (1984) and Super and Huggins (1992a). A companion article to the latter study, Super and Huggins (1992b), found limited support for effective valley-based AgI seeding using aircraft observations. A recent large operational seeding project in Colorado had seasonal snowpack samples tested for enhancement of silver (Super et al. 2003). There was little indication that the observed silver concentrations were high enough for effective seeding.

The following was stated by Holroyd et al. (1988) who reviewed two project reports, Hill (1982b) and Long (1984), which are no longer readily available: "Hill (1982b) presented results obtained during an evaluation of the Utah State operational seeding program. Ground and airborne measurements were made in the vicinity of the Tushar Mountains to determine if the AgI seeding material was being effectively transported from upwind valley generators to clouds over the mountains. A high incidence of inversions was noted, in which the AgI was frequently trapped. Significant IN (ice nuclei) concentrations were rarely transported to sufficient height and in adequate concentrations to achieve significant seeding effects. It was concluded from physical evidence that the ground-based generator network was ineffective. This finding was reinforced by model studies described in Long (1984) that used a Tushar Mountain dataset. Application of the GUIDE model, with local upwind soundings as input, resulted in the conclusion that 'only 36% of the soundings considered showed seeding material was delivered to the clouds.' In the majority of cases, intended transport was apparently not achieved, due to easterly downslope flow, trapping inversions, or air flow parallel to the mountains."

The above cited evidence strongly suggests that use of valley or even foothill generators generally does not provide a reliable seeding method, at least for the several projects cited. It is recognized that this view is at variance with many internal historical target-control statistical analyses of operational projects and even some peer-reviewed analyses of experimental research projects, later questioned in the open literature. Reasons for regarding such statistical results with caution, especially if they are not supported by physical evidence and reasoning, are discussed by Dennis (1980) and Super and Heimbach (2003).

Not all long-term operational projects have failed to show routine enhancements in silver-in-snow concentrations. McGurty (1999) reported on observations from the Southern California Edison Big Creek program in the San Joaquin River drainage. Both ground-based and aircraft AgI releases were routinely made, with inert trace chemicals also released from January to April 1994. Cesium was used with the ground generators, located from 1,800 to almost 10,000 ft in elevation, and indium was used with the aircraft generators. The snowpack was profiled at 2 cm (0.8 inch) intervals at 11 different locations resulting in over 600 individual snow samples. On average, 73%

of all samples from 7 different primary target stations contained silver above background levels, considered to be 6 parts per trillion by mass (ppt). Percentages of samples with above background silver concentrations ranged from 39 to 100%, but only 2 stations had less than 73%. Average silver levels per sampling site ranged from 14 to 118 ppt with an overall average value of 61 ppt and median of 29 ppt. As expected, concentrations were lower at the 4 secondary target stations, ranging from 10 to 14 ppt. These primary targets values are all well above the natural background and are impressive results.

Two primary target stations, both near 10,000 ft, were used to examine the two different inert tracers released for ground-based and aircraft seeding, respectively. One is exposed to southwesterly flows and the chemical tracer analyses showed it was primarily targeted by ground releases. It had the second highest silver level averaging 118 ppt. The other site was sheltered by ridges from the predominant southwesterly flow and showed no evidence of ground-based seeding. All the silver there was from aircraft seeding with an average silver concentration of 22 ppt.

It should not be concluded that valley or foothill AgI seeding always fails, even though published physical and chemical evidence supporting such seeding is weak. Several articles cited in this report discussed frequent stable layers which would trap valley-released AgI. But such layers were not always present. The discussion of near-valley winds in Appendix C suggests that a cross-barrier component with adequate speed to support mechanical forcing up the Wasatch Plateau's windward slope was sometimes present, but during less than 30% of the hours with significant SLW over the Plateau. General lack of detection of adequate concentrations of ice nuclei above the Plateau, effective at SLW cloud temperatures, may not have been primarily caused by trapping inversions as suggested for a number of other mountain ranges. As discussed in Appendix C, the proximity of two parallel ranges may have enhanced gravity waves which sometimes helped AgI transport and dispersion over the Plateau. The main factors causing the limited IN concentrations observed may have been a combination of the wide spacing between generators, relatively low AgI consumption rates of 8 g h^{-1} (20-30 g h^{-1} are common), and use of an AgI solution which provided limited effective IN at mildly supercooled cloud temperatures.

Since such low-level manual seeding has considerable economic advantages, it is recommended that further testing be done with especially foothill and canyon-mouth AgI generators, but with the following improvements. Generators should be spaced no more than 2.5 miles apart, AgI outputs should be increased to about 30 g h^{-1}, and an improved AgI solution should be used that is as effective and fast-acting as possible while still being practical for field use. Finally, the generator IN effectiveness per gram of AgI should be as high as possible. Unfortunately, the Colorado State University Cloud Simulation Laboratory is no longer available for testing particular generator configurations and AgI solutions. Consequently, reference to their most recent reports would have to provide guidance in these areas.

6c. Seeding from High Elevation Locations

A large body of observations exists which demonstrates that seeding plumes released from high elevation sites are *routinely* transported over downwind mountain crestlines when the wind direction in that layer has a component perpendicular to the crestlines. That is, transport and dispersion are routine when the airflow is forced up and over the windward slope of the barrier. Mountain surface and aircraft observations have included sampling the AgI itself with acoustical counters, seeded ice crystals produced by AgI or propane, and fast-response tracer gas detection, usually with SF_6. Published articles which support this assertion, briefly reviewed in Appendix B, include Super (1974), Holroyd et al. (1988), Super and Heimbach (1988), Holroyd et al. (1995), Super and Heimbach (2005a), and references in the next paragraph.

Many high altitude, ground-based seeding experiments were conducted during the multi-winter research program on the Wasatch Plateau of central Utah summarized by Super (1999b). Either AgI or liquid propane was released well up the windward slope about 1000 ft vertical distance below the plateau top. Sometimes a tracer gas was simultaneously released to permit detailed plume definition using a fast-response detector. Results from these experiments have been reported by Super and Holroyd (1994), Super (1995), Super and Holroyd (1997) and Holroyd and Super (1998) and Super and Heimbach (2005b). Holroyd et al. (1995) discussed an additional experiment where both AgI and tracer gas were released from another high altitude site 1850 ft below the plateau top.

There is no point in belaboring this issue. Quite simply, every published observational study the authors are aware of which tracked plumes from high elevations releases, more than 1/2 to 2/3 of the way up windward slopes, demonstrated routine plume transport over the mountain barrier. Of course, the wind in the layer between the high elevation seeding site and the ridgeline must have a significant cross-barrier component for such transport to occur. When that is the case, high elevation releases will result in the seeding agent reaching SLW cloud to a height of about 2000 ft above the crestline. Whether the SLW cloud is cold enough for effective AgI seeding and whether growth and fallout times are adequate for meaningful snowfall are separate issues.

7. Propane Seeding Potential in Colorado

This section is brief because thorough discussions of propane seeding in general, and the results of the Utah randomized seeding experiment, are contained in the peer-reviewed article by Super and Heimbach (2005a), and in more detail in the final report by Super and Heimbach (2005b). The development of radio-controlled propane dispensers for use on California's Sierra Nevada has been discussed by Reynolds (1996) and a number of his articles cited therein including Reynolds (1989). Since all this information is readily available, it will not be repeated here except that the summarized conclusions of Super and Heimbach (2005a) on the Utah winter of 2003/2004 *randomized* experiment have been extracted and are paraphrased below. There were a total of 98 experimental units (EUs) produced by this experiment. Each EU had a 40 min release of propane which was separated from adjacent releases by 20 min buffers. The Utah results are expected to be transferable to Colorado because of similarities in SLW cloud characteristics presented in this report.

- Tests of the entire sample of 98 EUs without any partitioning were strongly suggestive of a real seeding effect of increased snowfall at a target gauge on the windward slope and the two target gauges on the west edge of the Wasatch Plateau.

- Results for the 98 EUs were inconclusive at the most downwind gauge just 1.2 miles east of the plateau top's west edge, meaning no valid conclusion can be made whether seeding was effective there or not. Frequent mistargeting of that gauge was possible.

- Results for the 69 EUs partitioned by southwest quadrant seeding site winds, known to transport seeding plumes from the high altitude release point over the primary target, were also strongly suggestive of snowfall increases at the target gauges on west edge of the plateau top. Results were somewhat suggestive at the windward gauge closest to the propane dispensers, and also at the downwind gauge 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 which were expected 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 precipitation amounts observed at the crosswind control gauge. 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, statistical test, and number of experimental units available. 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. Funding was not available for an experiment longer than a single winter, or for one with a larger target area including the more downwind portions of the plateau.

The main reason for using propane seeding is to treat mildly supercooled cloud, too warm for effective AgI seeding. The frequency of such cloud over Colorado's mountains is discussed in Secs 2 and 5 and Appendix A, and the topic is briefly covered below. However, there are other good reasons for consideration of propane seeding as an adjunct or replacement for ground-based AgI seeding. Propane dispensers are relatively simple devices, significantly less complex than remote-controlled AgI generators which must use corrosive solutions. This makes them more amenable for fully automatic deployment. Consequently, propane dispensers are significantly more reliable and less expensive.

Few remote-controlled AgI generators have been capable of monitoring the relatively low flow rates of AgI in solution as this is an expensive option. A number of cases have been documented where the remote generator was believed to be producing AgI smoke but where no AgI was detected. Silver iodide generators capable of monitoring solution flow rates have recently been fielded in the Snowy Mountains of Australia and are planned for a State of Wyoming program to begin during the 2005/06 winter. The authors consider it essential that any remote-controlled AgI generator provide positive evidence of both solution flow rate and flame temperature to insure that seeding is actually occurring. Personal communications with people familiar with these newer generators have suggested their purchase price is at least a factor of two higher than propane dispensers, and probably the factor is much higher for the Snowy Mountain generators. The reliability of these newer and more expensive generators has yet to be demonstrated. The authors' considerable experience with propane dispensers indicates that they are highly reliable, and both propane flow rate and temperature downstream of the expansion nozzle can easily be monitored.

Cloud temperatures in the SLW zone over windward slopes and crestlines have largely been based on mountain-top measurements. For example, Boe and Super (1986) noted that the greatest production of SLW was associated with Grand Mesa top temperatures in the -4 to -10°C range. The observations were collected at 10,800 ft in west-central Colorado. Their results are in good agreement with the findings of Hindman (1986) for the San Juan Mountains of southern Colorado (11,750 ft observations) and Monarch Pass (11,800 ft) in central Colorado. Hindman (ibid.) indicated somewhat colder temperatures, usually in the range -5 to -13°C, for frequent and abundant SLW at 10,400 ft in the Park Range of northern Colorado.

Microwave radiometer observations of SLW above a 8850 ft site atop the Wasatch Plateau of central Utah were reported for a 1.5 month period in early 1991 (Super 1994). The 194 h with vertically-integrated amounts of 0.05 mm or greater, considered to have significant snowfall potential, were examined for this report. Only 10% of those hours had plateau top temperatures below -6°C, but much of the plateau is at higher elevations where temperatures would be colder. Had measurements been made at an altitude of 10,800 ft, as on the Grand Mesa almost due east of the Plateau, about 10% of the SLW hours would be expected to be colder than -10°C for typical in-cloud lapse rates. This comparison suggests the Utah mountain top observations are similar to those of Colorado for approximately the same elevations.

As previously discussed, a number of plume tracing studies have shown that ground-released AgI plumes are mostly confined to the lowest 2000 ft above the terrain. Consequently, plume top temperatures would be expected to be about 4°C colder than mountain top observations, using a moist adiabatic lapse rate appropriate for the mountain top temperatures and pressures involved. When plume top temperatures are colder than about -8°C, AgI would provide adequate concentrations of seeded crystals. The mountain top temperature ranges cited in the two above paragraphs, adjusted 4°C colder, might be considered to suggest that AgI seeding could be effective much of the time when SLW was present.

However, it should be recalled that mountain airflow usually rapidly descends downwind of the crestlines, resulting in rapid evaporation of tiny cloud droplets and slower sublimation of larger ice crystals. Therefore, creating seeded crystals over crestlines often will not result in effective seeding. In order to have sufficient time for seeded crystals to grow large enough to settle to the mountain surface, or be swept out by larger natural snowflakes, seeded crystals need to be in a favorable growth environment for at least 10 min. A 20-30 min growth period would be much preferred. That requirement means that seeded crystals need to be created between 10-30 min travel time upwind of the intended target area. The actual target area will vary with the type of terrain. If the crestline is abrupt with a steep lee slope, most crystal growth needs to occur upwind of the crestline. For relatively flat-topped terrain like the Grand Mesa and Wasatch Plateau, growth may continue, but likely at a reduced rate, in the airflow over such barriers where local higher terrain may produce additional SLW. Probably the best seeding situation is when parallel barriers exist, without too wide a valley between, so that many of the seeded crystals formed over the windward slope and crest of the windward barrier will still exist upon reaching the SLW-rich zone over the windward slope of the downwind barrier. Parallel barriers are common but valleys between them may be wide providing too much time in subsiding and warming air for seeded crystals to survive to the second barrier. Most mountains are rugged and complex, and airflow patterns change with wind direction and other variables. As a result, potential target area situations should be individually evaluated concerning seeding generator or dispenser placement.

One general rule is clear. Seeding crystals should be formed as far upwind of an individual mountain crest as practical to maximize growth and fallout times. Therefore, the SLW cloud temperatures of greatest interest are not over mountain tops but over windward slopes, and as far upwind as effective seeding agent can be introduced into SLW cloud. That requirement means placing the generators on high ridges between windward slope canyons, but still well upwind of the crestline. Consequently, the frequency of AgI being effective will likely be less than suggested by the cloud top temperatures previously discussed, even when adjusted to colder seeding plume top altitudes.

Some have argued that valley seeding with AgI is the preferred method because more time is available for the AgI to disperse to sufficiently high and cloud regions of the SLW cloud zone. But unless transient gravity wave results in considerable vertical transport, the valley released plumes can be expected to be confined to less than 2000 ft above the windward slopes. Even aircraft observations over the downwind ridge of the two parallel barriers forming the Bridger Range did not show additional vertical dispersion (Super and Heimbach 1988). That is, AgI was still confined to the lowest 2000 ft over the barriers regardless of the upwind fetch. The authors are unaware of any observational evidence which suggests greater vertical plume dispersion over windward slopes than found over crestlines. That being the expected case, the AgI will often need to be transported far up the mountain slope to have any chance of reaching sufficiently cold temperatures to nucleate ice. Therefore, there should not be any advantage for early introduction of AgI by valley releases as the AgI will still not activate until transported to sufficiently high and cold altitudes over the windward slopes, if indeed sufficiently cold temperatures are reached.

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Appendix A: Brief Summaries of Selected Published Articles and Reports Dealing with SLW Cloud Characteristics.

The summaries are presented in order of publication date to provide historical context.

Ludlam, F. H., 1955: Artificial snowfall from mountain clouds. *Tellus*, **7**, 277-290.

Without providing observational support, the classic and farsighted article by Ludlam (1955) stated that, "During the winter in Scandinavia extensive low clouds often occur which are only several hundred meters thick and which give no precipitation. The clouds are composed of supercooled droplets, but the temperature is not low enough for an abundant natural formation of ice crystals, which could lead to the development of snow." His Fig. 1 provided a conceptual portrayal of these clouds which is very similar to current understanding. The cloud base is below the crestline and extends upwind for a considerable distance. The SLW cloud top has its maximum elevation directly over the crestline, and SLW quickly evaporates downwind of the crest. Calculations were given which suggested the optimum concentration of seeded ice crystals would be about 20 per liter, but it was shown that the concentration could be several times higher without seriously reducing the efficiency of the seeding operation. The thin orographic clouds described by Ludlam (ibid.) are admittedly a "simple case" over minor mountains compared to the rugged and complex Colorado Rockies.

Boe, B. A. and A. B. Super, 1986: Wintertime characteristics of supercooled liquid water over the Grand Mesa of western Colorado. *J. Weather Modification*, **18**, 102-107.

Microwave radiometer observations of vertically-integrated SLW were made over the Grand Mesa of west-central Colorado during November and December 1983 and January through March 1985. The Grand Mesa is a high, generally flat-topped barrier averaging about 3200 m msl (10,500 ft) in elevation. It is located 125 miles southwest of the Park Range. The radiometer location was just south of and 400 ft below the mesa top. Almost all SLW episodes in the 5-month data set had 700 mb wind directions from the southwest quadrant with typical speeds near 10 m s^{-1} (22 mph). The local topography of the east-west oriented Grand Mesa often caused the near-surface winds to turn to southerly which blew directly upslope. Virtually no SLW was observed when mesa top temperatures were below -14°C, and greatest SLW production was associated with mesa top temperatures in the -4 to -10°C range, in good agreement with the findings of Hindman (1986) for the Park Range.

Another similar finding was that 29% of all 3351 hours with valid data from 5 months of sampling had some SLW present over the mesa. However, many of these hours had vertically-integrated amounts less than 0.05 mm. Such low amounts can be safely ignored as only trace precipitation could result from seeding them as shown by Super (1999a). He estimated that about 17% of all hours with radiometer observations had values of 0.05 mm or greater; that is, significant SLW amounts, over the five month dataset. This is still a relatively high frequency when one considers the many fair weather days included in the large sample.

Aircraft observations of LWC over the Grand Mesa, also presented by Boe and Super (1986), showed greatest amounts on the lowest passes made 1000 ft above the highest terrain (about 2000 ft over the average mesa top terrain), and near the mesa's upwind edge. Subsidence dramatically reduced the aircraft-sampled LWC within about 4 miles of the southern edge. It was estimated that seeded crystals formed over the windward slope would typically have about 30 min growth time while crossing the mesa.

Exclusion of mesa-top precipitation rates exceeding 0.15 mm h^{-1} (0.006 inch h^{-1}) resulted in the removal of many hours with no SLW during conditions otherwise favoring its formation; that is, southwest flow of moist air at relatively warm supercooled temperatures. It might be expected that moderate to heavy snowfall rates would convert all available SLW to snow. However, that precipitation rate exclusion criterion also removed over 50% of the high-SLW data, demonstrating that much SLW was often present during periods of significant natural snowfall. This finding is contrary to suggestions from the Park Range, but in agreement with recent observations from the Wasatch Plateau of Utah (Super and Heimbach 2005a). Even heavy natural snowfall does not always remove all available SLW, especially when its production rate is high because of relatively strong winds forcing moist air up and over mountain barriers. This result is at variance with the concept that storms producing moderate to heavy snowfall rates are not seedable.

Boe and Super (1986) defined a "SLW episode" as the continuous presence of radiometer-observed SLW for longer than 2 h. If SLW was again detected within 2 h of the first 2 h block, the episode was considered to be continuing. A total of 115 episodes resulted from the 5-mo dataset, with 50% of them less than 3 h in duration. Only 12% were longer than 12 h. However, the 50% of episodes less than 3 h long contained only 14% of the total hours of SLW while episodes longer than 5 h comprised 80% of the total hours.

A distribution was given of 1 h average SLW amounts observed by the radiometer (their Fig. 5). The distribution was highly skewed, with 57% of all SLW hours having 0.10 mm or less, and the median value 0.08 mm. When converted to SLW flux by considering the wind speed, those many hours with 0.10 mm or less contributed only 16% of the total flux for the five months. The relatively infrequent hours with high SLW amounts contributed significant fractions of the total flux. This skewed distribution might be anticipated, and has since been found over other mountain barriers. It has long been known that snowfall rates, which require SLW presence, are also highly skewed. Many hours have very light snowfall rates and relatively few hours have heavy rates.

Rauber, R. M., L. O. Grant, D. Feng and J. B. Snider, 1986: The characteristics and distribution of cloud water over the mountains of northern Colorado during wintertime storms. Part I: Temporal variations. *J. Climate Applied Meteorology*, **25**, 468-488.

A scanning dual channel microwave radiometer was operated at 15 deg tilt above the horizon, scanned through 360 deg of azimuth about every 15 min. The unit was in a "hole" near Steamboat Springs, at an elevation of 2050 m (6726 ft), with a minor ridge to the west and major ridge, the Park Range, to the east (see their Fig. 2). Time histories of SLW content were shown by azimuth. Greatest SLW amounts were consistently over the windward (west-facing) slopes of the Park Range. This finding indicates that forced uplift of moist air over the barrier, sometimes associated with the release of weak embedded convection, produced the zone with greatest SLW amounts. Thus, the most seedable zone would be expected to be over the windward slopes of the main mountain barrier. A secondary maximum was often observed over the minor ridge west of the radiometer. Unfortunately, the radiometer location required that its beam scan some distance above the windward slopes to avoid viewing the rugged terrain. A better location would have been at the SPL, elevation 10,370 ft, and due east of the radiometer on the west edge of the barrier crest. Surface observations of SLW were often made at SPL which were in general agreement with radiometer observations.

A total of ten wintertime storms were studied. Liquid water was found to occur in all stages of most storms *but temporal variations in cloud water were significant* (emphasis added). Analyses of individual storms indicated that SLW amounts were often inversely associated with precipitation rates at the radiometer location, and that SLW tended to decrease as cloud top temperature decreased. However, it was emphasized that while these relationships applied to individual storms, simple correlations between SLW and either of the other parameters were substantially weakened when several storms were grouped together. This result was believed to be caused by seasonal changes in various parameters such as condensate supply rate and natural ice nuclei availability.

Another way of stating their result is that, for the entire population of ten storms, relationships between SLW and either precipitation or cloud top temperature were weak. Similar results were found at other locations discussed elsewhere in this report. It would be a mistake to assume that moderate-to-heavy snowfall rates and/or high, cold cloud tops necessarily mean seeding potential is lacking.

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

Eight instrumented aircraft sampling flights were made over the Park Range area during the 1979/80 and 1980/81 winters, all in stable or neutral cloud, or cloud with no more than weak embedded convection. No clouds were sampled with strong convection. It is important to note that flight restrictions prevented aircraft sampling below 13,800 ft, which prevented observations in the important lowest 3000 ft or more above the Park Range. Some studies discussed elsewhere in this report were able to sample within 1000 ft of the highest terrain by operating under special waivers from the FAA. Thus, while the upper cloud regions were monitored, the important SLW zone formed near the windward barrier slopes of the Park Range was not well observed by aircraft. Microwave radiometer measurements were made as discussed in Rauber et al. (1986), but they provided no ranging information. That is, only the path-integrated SLW amounts were observed with no direct indication of where the SLW was along the path or view of the antenna. However, combining radiometer and aircraft observations allowed for inferences about likely SLW zones.

Overall analyses of all observations revealed three SLW zones: a thin layer near cloud top; near cloud base; and especially in regions of strong orographic forcing. The last zone was above the windward slopes of the mountain barrier. The shallow cloud top SLW layer can be important for formation of natural ice crystals, which can lead to precipitation formation, but likely does not offer a suitable SLW zone for cloud seeding. That is, the cloud top layer can only be seeded by aircraft, is often underlain by thick zones with limited SLW if any (see the conceptual model in their Fig. 13), and targeting seeded snowfall on the mountain barrier would be difficult.

In all aircraft cloud sampling SLW contents were found to vary significantly over short distances. Cloud droplet concentrations were low, usually between 50-200 cm^{-3} and seldom more than 300 cm^{-3}. It was noted that inversions are frequently present over broad regions during winter in the northern Colorado Rockies. These inversions limit mixing from the surface to cloud levels, which may inhibit cloud condensation nuclei supplies to the clouds, partially explaining the low droplet concentrations. These inversions would also be expected to limit the vertical transport of AgI ice nuclei from generators operated in valleys.

Based on both aircraft and radiometer sampling, SLW was most consistently found in shallow clouds with tops warmer than -22°C and low snowfall rates. The greatest SLW was found directly upwind of and over the barrier crest. The SLW was found to decrease rapidly downwind of the crest in descending air.

Visual mean cloud bases were usually between 200 to 300 m (656 to 984 ft) below ridge top. Occasionally bases were as low as 500 m (1641 ft) below or about 50 m (164 ft) above ridge top. Cloud base temperatures were usually in the range from -5 and -10 deg C.

Hindman, E. E., 1986: Characteristics of supercooled liquid water in clouds at mountaintop sites in the Colorado Rockies. *J. Climate Applied Meteorology*, **25**, 1271-1279.

A network of observing sites at six cooperating ski areas was established to monitor SLW at high elevation surface locations, essentially clear of trees, along a north-south transect across the Colorado Rockies. These locations were frequently in-cloud. Professional ski patrol personnel made manual observations each morning and afternoon of the ski season when either (1) liquid water cloud (fog) was present without snowfall, (2) snowfall was present without the site being in cloud or (3) both cloud and snowfall were observed near the mountain top. Wooden dowels were exposed for periods from 30 to 60 minutes and the thickness of any rime ice which formed on them was measured. Wind speed, temperature, snowfall, and crystal riming observations were also made.

It was found that the most frequent presence of SLW was at Wolf Creek Pass in the San Juan Mountains of southern Colorado, with 95% of all observations recording SLW. Seventy-five percent of those observations had mountain-top cloud and snowfall, 20% had only cloud and 5% had only snowfall. The next highest SLW frequency was 90% at SPL on the Park Range of northern Colorado. Both these barriers are well removed from the next upwind mountain ranges. The third highest value was 82% for Monarch Pass in a gap between the San Juans and central Colorado mountains. Monarch Pass has no upwind barriers for a long distance to the west but could be influenced by blocking from upwind mountains for southwest and northwest flows. The three remaining locations were in central Colorado and all had mountain barriers not far upwind; that is, there were secondary barriers while the other 3 locations are primary barriers. The secondary barriers produced values of 57, 45 and 20% of observations with SLW present, suggesting that the presence of upwind barriers reduced the frequency of their available SLW. The reduction could be caused by sinking and warming air downwind of the primary barriers, or by a reduction of atmospheric water, or some combination of the two effects. However, one should be cautious about these suggestions, based on only six locations, each with its own local exposure and characteristics. It is known from other investigations that local topography plays a major role in SLW production. While one might expect the secondary barriers of the central Colorado Rockies to have less frequent SLW episodes, as Hindman's data suggest, more comprehensive and longer term observations would be required to consider the matter firmly settled. In any event, SLW was frequently found when either cloud, snow or both were present, with 5 of the 6 sites reporting SLW frequencies between 45 to 95%.

Liquid water content (LWC) was calculated for each observation which had a duration not exceeding one hour, with snowfall and cloud present at the beginning and end of the sampling period, and with the average wind speed 7 m s^{-1} (16 mph) or greater. Comparison with an independent instrument revealed that the dowel observations underestimated SLW for lighter wind speeds. This procedure eliminated many of the observations with riming, so the following results are not typical of all periods as they ignore lighter wind speeds.

To provide a comparison between vertically-integrated SLW depths measured in millimeters by a microwave radiometer, and LWC expressed in g m^{-3} by aircraft sensors or estimated by dowels or Rosemount icing rate sensors, a depth of 0.1 mm is equivalent to a LWC of 0.10 g m^{-3} uniformly distributed along a 1 km (3281 ft) path above the radiometer.

Average values ranged between 0.14 and 0.23 g m^{-3} for the three primary mountain barriers. The LWC was plotted against surface temperature for these three locations (Hindman's Fig. 8). Considerable scatter existed in the LWC data with the measurement uncertainty estimated as +/- 50%. Inverse relationships were suggested by the author, with warmer temperatures tending to have greater LWC as might be expected. However, only one of the three plots (Monarch Pass) had a relationship significant at the 5% level and it was based on only ten data pairs. That relationship explained 45% of the variance. The largest data set by far was from the SPL on the Park Range. It had 47 pairs of observations, but the relationship was significant only at the 15% level and explained just 5% of the variance. The available data set does not make a very convincing case for greater LWC at warmer temperature as suggested in the article.

Individual plotted points on Fig. 8 of the Hindman article were used by the authors of this report to tabulate surface temperatures listed below for SPL in northern Colorado, Monarch Pass in central Colorado and Wolf Creek Pass in southern Colorado. Monarch Pass observations were available from a single winter while data from two winters existed for the other two sites. Colorado State University personnel were available for a couple of months at SPL which resulted in the much larger population of 47 observations relative to the limited number of 10 and 11 at the other sites. None of the LWC values occurred with temperatures warmer than -5°C or colder than -18°C.

Table A1. Comparison of mountain-top temperatures with SLW present at three Colorado locations. Observations from Hindman (1986).

Observing Site	Elevation feet - msl	Total # of Obs.	-5 to -10°C	<-10 to -15°C	<15°C to – 18°C
Storm Peak Laboratory	10,390	47	49%	45%	6%
Monarch Pass	11,600	10	60%	10%	30%
Wolf Creek Pass	11,750	11	91%	9%	0%

Over 90% of the LWC observations were in the -5 to -10°C temperature range at the southern Colorado site, Wolf Creek Pass, and none were colder than 15°C. This decreased to 60% at Monarch Pass, located at a similar elevation, with 10% in the next coldest 5°C interval and 30% in the 3°C interval colder than 15°C. However, these results should be used with caution because of the small sample sizes. The largest dataset from the SPL, obtained at the lowest elevation near 10,400 feet elevation on the Park Range of northern Colorado, can be considered most reliable. It indicates that about half of all cases with LWC were in the -5 to -10°C range, almost half in the <-10 to -15°C range, with occasional observations at slightly colder temperatures.

Plume tracing results discussed elsewhere in this report indicate that most AgI (or tracers) released from high elevation windward slope sites are confined to about 1500-2000 ft above the terrain where the air temperature would be about 3 to 4°C cooler with in-cloud lapse rates. Table A1 above indicates that AgI plume tops could be expected to be -8°C or colder over the Colorado mountain barriers. That is sufficiently cold for AgI to produce abundant concentrations of ice nuclei and, hence, seeded crystals in SLW cloud. However, as discussed in Sec. 7, seeded crystals need to be created some distance upwind of the crestline to provide time (distance) for growth and fallout. The SLW cloud temperature will be warmer at lower elevations over the windward slope where seeded crystals need to be created. Consequently, the data of Hindman (ibid.) suggest that AgI seeding would often be practical over Colorado mountains, but that SLW cloud be too warm for AgI seeding during warmer episodes. And it is worth recalling that the data are biased since instrumentation limitations prevented calculation of LWC values when wind speeds were less than 7 m s^{-1} (16 mph).

The Hindman (ibid.) article also describes a special 2-month observing program conducted by Colorado State University personnel during December 1981 and January 1982 at the SPL. Observations were made during 83% of all hours. Supercooled liquid water was present 24% of the time with observations suggesting, for a first approximation, that SLW exists atop that primary barrier about 1/4 of all hours.

Mountaintop icing rates and snowfall rates were compared. It was concluded that the icing rates were, on average, ten times greater than precipitation rates indicating that a considerable amount of SLW was flowing over the Colorado Rockies "unused;" that is, not naturally converted to snowfall. This strongly suggests considerable cloud seeding potential exists in that region.

Depending upon the site, more crystals were rimed than not in 30 to over 70% of samples. As a generality for all locations, roughly half the snowfall periods had more than half the falling ice crystals rimed, indicating they collided with SLW cloud droplets, proving its existence somewhere along the snowflake trajectories.

Using hourly observations from SPL, the most frequent duration of SLW episodes was from 4 to 8 h, with 80% between 3 and 20 h, and a total range from 3 to 48 h. However, examination of continuous microwave radiometer observations from the Grand Mesa of western Colorado, discussed by Boe and Super (1986), revealed more short-term variability than evident from the pairs of manual observations taken 30 to 60 min apart.

Super, A. B., E. W. Holroyd, B. A. Boe and J. T. McPartland, 1986: Colorado River Augmentation Demonstration Program Technical Report: January 1983 - March 1985. Bureau of Reclamation Technical Report, May, 1986, 42 pp.

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Solak, M. E., R. B. Allan and T. J. Henderson, 1988: Ground-based supercooled liquid water measurements in winter orographic clouds, *J. Weather Modification*, **20**, 9-18.

Comparisons between Rosemount aircraft type and tower type icing rate sensors were made on an exposed ridge of the Tushar Mountains of southern Utah as reported by Solak et al. (1988). It was stated that the tower type sensor underestimated the hours with SLW available because it only outputs heater deicing cycles while the aircraft unit continuously outputs a frequency change which is a function of ice buildup on the probe. Periods with light icing rates or alternate icing-sublimation-icing were apparent with the aircraft unit but often did not "trip" the tower unit's heater cycle.

Similar underestimates by tower type Rosemounts were reported by Super et al. (1986). However, they also noted a serious problem with the aircraft unit related to the relatively light wind speeds encountered on towers compared to aircraft flight. Visual observations atop the Grand Mesa showed that water from the melted ice was often not fully shed from the aircraft unit sensing rod during the brief but hot heating cycles. Rather, the water refroze and had to be melted again whether the rod was pointed toward the zenith or downward. With the unit pointed upright the water puddled around the bottom of the sensing rod. With the unit pointed downward a drop adhered to the lowest tip of the rod. Sometimes a sheath of ice would lean to windward, effectively blocking most droplets from freezing on the rod. In general, the aircraft unit reported an unknown amount of additional SLW than it would have if all the melted water was fully shed as during aircraft flight at high speeds. A special aspirator (leaf blower), switched on only during heating cycles, was successful in blowing off all melted water from the aircraft unit. But that is not a practical alternative unless electrical power is abundant. The puddling and refreezing of melt water was never a problem with the tower type unit in its normal position with the rod pointed toward the zenith. However, the problem with the aircraft unit likely explains some of the difference between the two types of sensors reported by Solak et al. (ibid.).

Nevertheless, tower type units do underestimate SLW by some unknown amount. Grand Mesa comparisons over several months (exact period no longer known) had the aspirated aircraft unit detecting limited icing over about 100 additional hours than observed by the tower unit (Super et al. ibid.). These likely tended to be hours with limited icing rates.

Solak et al. (ibid.) showed the temperature distribution of many 5 minute samples on the Tushar Mountains with icing indicated by the aircraft unit's analog (frequency) output. The main maximum, with by far the most data points, was between -2 and -3°C. A secondary maximum existed between -7 and -8°C. The icing observations were made at 9770 ft about 2 miles west (generally upwind) of the main crestline which averaged about 11,150 ft. Crestline temperatures with typical in-cloud lapse rates would be about 2.7°C colder than the observing site so most windward slope icing data were collected when crestline temperatures were warmer than -6°C. Consequently, many of the SLW periods over the Tushar Mountains were too warm for effective seeding with conventional types and output rates of AgI. This result is in agreement with the remote sensing observations over the same mountain range reported by Sassen and Zhao (1993).

Solak et al. (ibid.) concluded with the important point that, "Comparisons of low-altitude SLW flux values and precipitation rates suggest that increased precipitation <u>alone</u> does not necessarily signal diminished augmentation potential. This suggestion must be further investigated, taking into account other factors to more objectively determine seedability." Section 10f of the recent technical report by Super and Heimbach (2005b) provides further support for this notion from the Wasatch Plateau of central Utah. They found that for all hours with at least trace (0.005 inch) precipitation, the 21% of hours with SLW detected by a tower type Rosemount icing sensor had substantially higher snowfall rates than the 79% of hours with no SLW detected. This counter-intuitive finding was explained by the markedly stronger wind speeds during SLW hours, which would produce more liquid condensate as moist air was forced up the mountain barrier. In spite of a substantial portion of that condensate being converted into snowfall, excess SLW often coexisted with significant snowfall rates on the windward edge of the plateau top.

Uttal, T., R. M. Rauber and L. O. Grant, 1988: Distributions of liquid, vapor, and ice in an orographic cloud from field observations, *J. Atmospheric Sciences*, **45**, 1110-1122.

A case study was presented based on aircraft observations over the Park Range. These are some of the same measurements discussed by Rauber and Grant (1986), which sampled no lower than about 3300 ft above the highest terrain. Evidence was presented of SLW production well above the Park Range, and the small mountain immediately upwind (west) of it. The SLW decreased with increasing altitude. Apparently precipitation did not convert all the SLW to ice at aircraft sampling altitudes. However, the vertical distribution of crystal habits suggested a significant downdraft existed just downwind of the Park Range which could be expected to soon evaporate SLW. While orographic production of SLW existed well above barrier elevations in this case, aircraft seeding would likely be required to seed that high. Of course, based on other studies, it is likely that even greater amounts of SLW existed at lower elevations over the windward slopes and crestlines, but such observations were not presented in this study.

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

Vertically-integrated SLW amounts from microwave radiometers were combined with wind observations to estimate SLW fluxes for four different mountain barriers. These were the Grand Mesa of west-central Colorado, the Wasatch Plateau of central Utah, the Tushar Mountains of southern Utah and the Mogollon Rim of central Arizona. The last barrier is lower in elevation, and significantly further south, so its observations would not be expected to be as representative of Colorado mountains as those from the other mountains. Precipitation measurements were also made over each mountain area.

Observational periods were only two months in duration at two of the locations and five months long at the other two. Consequently, results and comparisons should be considered preliminary and far from being a climatology. However, there were some interesting similarities in the datasets. For example, one to a few major storms at each site produced most of the seasonal SLW flux. Half or more of all storms at each site produced, in total, only small amounts of flux. Apparently significant relationships existed between SLW flux and precipitation at each location, with the larger flux-producing storms also having greater precipitation amounts.

None of the four datasets supported the hypothesis that large precipitation-producing storms are highly efficient in converting all available SLW to snowfall. The analyses suggested that large SLW flux-producing storms may be efficient in snowfall production during some phases and inefficient during other phases. This conceptual picture was supported by a case study of a moderate-sized Utah storm.

Again realizing that each field program was of limited duration, the Grand Mesa storm frequency was markedly higher, averaging 13 per month, than the other locations. Comparable averages for storm passages per month were 8 for the Wasatch Plateau, 5.5 over the Mogollon Rim and 5.4 for the Tushar Mountains. The two more northern barriers had the higher storm frequencies.

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

This dataset included SLW amounts from a microwave radiometer, heights of SLW layers from a polarization lidar, and associated temperature, moisture and wind profiles from rawinsondes. The observations were obtained during 19 winter storms in the Tushar Mountains of Utah from mid-January through mid-March 1985 and February to mid-March 1987. The Utah site is at about the same latitude as the northern edge of the San Juan Mountains, and the data should be reasonably representative of southern Colorado mountains. The authors demonstrated the dominance of barrier-level, mildly supercooled (0 to -10°C) orographic clouds. Scanning radiometer measurements showed a close association between local topography and SLW distributions. The latter showed localized concentrations where the airflow was forced to ascend steep slopes which were perpendicular to the wind direction. Thus, local SLW concentrations could be expected to vary with wind direction in rugged terrain.

The authors noted that a substantial fraction of the SLW cloud layers were likely too warm for effective seeding with AgI. The SLW cloud thickness was estimated to be generally between 500 and 800 m (1641 and 2625 ft) with some approaching 1 km (3281 ft). They concluded that AgI seeding appeared to have only a limited "window" for success, involving the upper portions of the relative warm (> -7°C liquid cloud bases) in southern Utah as colder clouds had limited SLW amounts.

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

Observations of vertically-integrated SLW were made with a microwave radiometer between 28 January and 14 March 1991 on the west (windward) edge of the Wasatch Plateau top in central Utah. Twenty days (midnight to midnight) were selected for analysis of SLW and precipitation. These days had almost complete data available as well as significant SLW and/or snowfall. The sampling period was almost 480 h (20 X 24). Both SLW and snowfall were very limited on the remaining days of the 46 day period. The 46 day total sampling period is equivalent to about 1100 h.

A total of 333 h had observed SLW of 0.01 mm or more, or about 30% of all hours during the 1.5 mo period. These values were correlated with a number of variables. Local wind speed explained the most variance (27%) with stronger winds associated with greater SLW amounts as might be expected from forced uplift. The wetter half (164 h), with values of 0.07 mm or more, were given special emphasis as lower values contributed a small fraction (about 10%) of the total SLW flux. Only 2% of these wetter hours, most likely to have cloud seeding potential, had plateau-top temperatures colder than -7°C.

Ignoring values less than 0.05 mm which could only result in trace snowfall (Boe and Super 1986), it was found for this report that 194 of the 333 h had 0.05 mm or greater SLW. That result suggests that about 18% (194/1100) of all hours, including fair weather periods, had meaningful SLW atop the Plateau. That is almost the same value as the 17% found over a 5 mo period above the Grand Mesa (Boe and Super 1986).

Aircraft observations revealed that AgI was usually found only at the lowest aircraft sampling altitudes, about 2000 ft above the average plateau-top elevation, and sometimes not that high. This result is in agreement with other plume tracing results from the intermountain West. Simultaneous surface sampling along the west edge of the plateau top consistently revealed much higher AgI concentrations at the same -20°C cloud chamber temperature than at aircraft altitudes. This does not account for the marked temperature dependence of AgI particles as effective ice nuclei, but further verifies that ground-released AgI was concentrated near the terrain surface.

With typical in-cloud lapse rates the temperature 2000 ft above the Plateau would be expected to be about 4°C colder than on top the Plateau. Therefore, the wetter hours seldom had a seedable layer top colder than -11°C. Since temperatures need to be colder than about -8°C to nucleate significant seeded crystal concentrations (> 20 L^{-1}) with typical AgI solutions and generator release rates, this finding implies that many of the wetter hours were too warm for effective AgI seeding. These results are in good agreement with those of Sassen and Zhao (1993) who used Tushar Mountain observations about 95 miles south of the Wasatch Plateau. The Plateau is at about the same latitude as most central Colorado mountains and somewhat north of the Grand Mesa. A similar preponderance of mildly supercooled cloud was found on the Grand Mesa as discussed by Boe and Super (1986).

Hindman, E. W., M. A. Campbell and R. D. Borys, 1994: A ten-winter record of cloud-droplet physical and chemical properties at a mountaintop site in Colorado. *J. Applied Meteorology*, **33**, 797-807.

The main purpose of this paper was to examine possible effects of anthropogenic (man-caused) pollution releases far upstream on cloud droplet characteristics over the northern Colorado Rockies. Thus, it was not intended to provide information on amounts and frequency of SLW cloud. However, some results were relevant to the present study. Liquid water content amounts were typically about 0.07 g m^{-3} but the most frequent values were between 0.02 and 0.04 g m^{-3}. Approximately 65% of observations had "continental" cloud characteristics with higher concentrations of smaller droplets. Warmer "maritime" clouds with fewer but larger droplets, and higher LWCs, were observed about 9% of the time and the remaining 26% of samples had mixtures of continental and maritime characteristics. The SPL was enveloped in cloud about 1/4 of all wintertime hours by clouds which formed when stably stratified moist air from the Pacific Ocean was forced over the Park Range. About 80% of the clouds contained both SLW droplets and snow crystals while the remaining 20% contained only droplets. The average duration of a cloud event was about 4 h but occasionally events persisted for 2 to 3 days.

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

A mobile microwave radiometer was used to make many repeated transects over and along the west edge of the Wasatch Plateau of central Utah during the mid-January to mid-March 1991 experimental program. Sampling was accomplished during 12 different storm days. While many passes were made up the windward slope, and along Highway 31 which follows the west (windward) edge of the plateau top, only 14 traverses were made across the plateau top on Highway 64. Simultaneous observations were made with a similar but stationary radiometer on the west edge of the plateau top. Significant variability in vertically-integrated SLW amounts was shown over 30 to 60 min time periods in some cases while relatively steady-state conditions over periods of several hours were sometimes documented.

West-to-east liquid water depths consistently increased to a maximum about 1.5 miles west of the plateau top's west edge. That is, the maximum was over the windward slope. Decreased SLW existed for a couple of miles east of the stationary radiometer, in an expected subsidence zone over lower terrain. Conversion of SLW to snowfall was also a likely partial cause of the reduced SLW amounts. However, a secondary SLW maximum existed about 3 miles east of the west edge, coinciding with a local north-south ridge near the middle of the plateau top. Local terrain-induced SLW has been reported at other locations (e.g., Sassen et al. 1990). The author notes that, "The relatively infrequent number of observations across the plateau top warrants further observations to verify the general decrease in cloud liquid."

It was noted that, "--- on average the orographic liquid cloud edge was upwind of the most westward position of data collection, implying that vertical lift typically began upwind of the initial rise in terrain on the west side of the plateau." But the liquid cloud edge varied considerably from sampling period to sampling period, and within sampling periods.

Median cloud bases along the canyon highway traveled by the mobile radiometer were slightly below the local 8860 ft height of the Plateau where the stationery radiometer was parked. Temperatures there averaged near -5°C. (A larger 1991 dataset was presented by Super [1994] who showed that wetter SLW periods were warmer than dryer periods.) Simulated profiles of cloud thickness were presented which showed thickness of about 650 to 2600 ft above the windward slope at temperatures in the -5 to -11°C range. These results were in good agreement with the Sassen and Zhao (1993) findings in the Tushar Mountains of southern Utah. One case study showed a maximum SLW layer thickness of about 3300 ft near the plateau top's upwind edge. These findings are in agreement with considerable aircraft sampling which also showed that SLW was concentrated in the lowest 3300 ft or less over the Plateau's west edge.

Solak, M. E., D. P. Yorty and D. A. Griffith, 2005: Observations of rime icing in the Wasatch Mountains of Utah. *J. Weather Modification*, **37**, 28-34.

Supercooled liquid water was observed atop a 11,000 ft peak located about 1.25 miles west of the Wasatch Range summit, 7 miles east of the mouth of Little Cottonwood Canyon, and about 22 miles southeast of downtown Salt Lake City. A tower-type Rosemount ice detector (Model 872B) produced a record of deice cycles ("trips") each time the rime ice buildup decreased switched on a heater to melt the rime ice from the sensing rod. These switch closures or trips are the only icing indication from the tower-type unit which has no frequency output. Measurements were made from 24 November 2003 through April 2, 2004, just over 4 months duration. A total of 619 deice cycles were recorded.

The distribution of "all deice cycles" was plotted on their Fig. 3. There is some confusion as to exactly what was plotted since "all" should mean 619 trips. However, this author estimated the number of deice cycles for each bar in the graph and reached a total of 477. That is approximately the same as his estimate of 488 for their Fig. 5 labeled "icing frequency" on the ordinate and "riming periods" in the legend. The only number in the article similar to the estimated graph totals is the estimated total duration of 491.5 h in Table 1 which is a quartile analysis of all "riming periods," somewhat arbitrarily defined as all blocks of time with less than 3 h between sensor deice cycles. The average icing cycles per hour for the four quartiles ranged from only about one (lower 3 quartiles) to about two for the upper quartile. Allowing up to 3 h between trips, and still considering the entire period to have had SLW present, very likely overstated the number of hours with SLW actually present. It is unfortunate that the authors did not simply present the total number of hours which had one or more trips within them. That approach would have allowed direct comparisons with earlier published results using the same model icing sensor at other locations.

Their temperature distribution plot in Fig. 3, whatever is actually plotted on the ordinate (deice cycles, hours of "riming periods," or something else), indicates that about 8% of icing "events" had local temperatures between 0 and -6°C, about 64% between -6 and -12°C and the remaining 28% at colder temperatures. Given that ground-released silver iodide (AgI) typically disperses to about 2000 ft above the terrain, where in-cloud temperatures can be expected to be about 3.6°C colder than surface temperatures, the observations imply that the large majority of cases could be effectively seeded with AgI. However, that presumes that sufficient concentrations of effective

AgI ice nuclei are transported into the SLW layer near and above barrier crestlines. Considerable documentation has been cited in this report which indicates frequent past failures to meet that goal with valley-released AgI.

The summary of Solak et al. (ibid.) makes a point that their observations show colder temperatures during riming periods than anticipated from Super (1999b) who is quoted as stating, "Plateau top (2750 m) temperatures were colder than -4°C during less than 25 percent of the (observation) hours." The "2750 m" and "observation" within the parentheses were added by Solak et al. (ibid.) and both are incorrect. Super (1999b) is a summary article which makes clear that the original article was Super (1994). The 1994 article discusses how vertically-integrated microwave radiometer observations were made atop the Wasatch Plateau from a 2700 m (not 2750 m) location during mid-January to mid-March of 1991. While misquoting the radiometer elevation by 50 m is a minor error, discussion of "observation" hours contained a major error. The "observation" hours referred to by Solak et al. (ibid.) were actually a subset of about half of *all* hours with detectable SLW which had values of 0.07 mm or more. These wetter half of all hours had a markedly warmer temperature distribution than the dryer half as shown by Fig. 2 of Super (1994). The tendency for greater SLW to be associated with warmer temperatures is well known and can be seen in Table 1 of Solak et al. (ibid.) which lists average temperatures of -5.5 and -9.1°C for the 1st and 2nd quartiles, respectively, based on riming. That results in an average temperature of -7.3°C for the warmer, wetter half of their observations. The surface temperatures of Super (1994) were made about 2130 ft lower than in the Solak study. That fact alone should result in about 4.2°C colder in-cloud temperatures at the higher Wasatch Range sampling location. Thus, if the Wasatch Plateau average surface temperature for the wetter half of SLW hours, -2.2°C as cited in Super (1994), is adjusted by 4.2°C for the site elevation difference, an average of -6.4°C results. That is in close agreement with the -7.3°C average of the Wasatch Range measurements made about 100 km further north. The agreement may be somewhat fortuitous given that point surface observations were made by Solak et al. (ibid.) and vertically-integrated radiometer measurements were used by Super (1994). The comments made in the Solak et al. (ibid.) summary near the beginning of this paragraph were based on an "apples and oranges" comparison, taken out of context, and are invalid.

In summary, this reviewed article, while sometimes casual in its presentation, does document that SLW temperatures near the 11,000 ft level of the Wasatch Range are often cold enough for AgI to be an effective seeding agent if delivered in adequate concentrations. There is some question about the number of hours with SLW available, because of the arbitrary definition used to calculate the durations of "riming periods." However, it appears from the data that at least a few hundred hours with some SLW present could be expected during a typical winter.

It should be noted that the tower-type 872B Rosemount sensor used in this study can 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) as previously discussed. If such hours with limited icing had been documented, it might well be that approximately 400-500 h with SLW existed over the 4 month sampling period. Of course, the hours with icing over the windward slopes, where maximum SLW amounts are often found (e.g., Huggins 1995), do not provide a direct estimate of the number of hours which are seedable. A possibly large fraction of all icing hours may have all available SLW naturally converted to snowfall further downwind. Still, the high number of hours with possible seeding potential is encouraging.

Hindman, E. E., R. D. Borys, D. H. Lowenthal and N. Phillip, 2005: Long-term, wintertime aerosol, cloud and precipitation measurements in the Northern Colorado Rocky Mountains, USA. *Atmospheric Research*, **75**, in press.

This soon-to-be published article is an update of the findings presented by Hindman et al. (1994). Its stated purpose is, "to summarize the 21-year SPL aerosol, cloud and snow measurements, report trends and explain their significance." As with the previous article, references to SLW (actually liquid water content, LWC) were secondary.

The long-term trend in LWC was best fit by a parabola, with higher values in the earlier and later winters of record and lower values during the middle years. Overall, the average LWC was 0.061 g m^{-3} with a standard deviation of 0.029 g m^{-3}. Droplet concentrations showed a general decrease over time, from about 340 to 120 cm^{-3}, with an associated general increase in mean droplet diameter from 7.2 to 9.5 µm. The mean droplet diameter had an overall average value of 8.0 µm with a standard deviation of 1.6 µm.

The authors conclude that, "The significant decrease in cloud droplet concentrations and increase in mean droplet diameters in the long-term, winter-time SPL record are consistent with decreasing condensation nucleus concentrations, and most likely cloud-condensation nucleus concentrations. The trend in droplet concentrations may reflect decreased upwind USA aerosol particle emissions." An earlier report of an apparent effect of increasing aerosol concentrations resulting in decreased precipitation rates could not be confirmed with the most recent and larger dataset. Some recent articles have suggested that man-made pollution releases have been decreasing snowfall over some mountain ranges. However, the SPL long-term observations do not support that hypothesis for the Park Range of northern Colorado.

Appendix B: Brief Summaries of Selected Articles and Reports Dealing with the Transport and Dispersion of Ground-released Seeding Agents and Tracers.

These summaries are presented in order of publication date to provide historical context.

Rhea, J. O., P. Willis and L. G. Davis, 1969: Park Range Atmospheric Water Resources Program. Final Report to the Bureau of Reclamation by the EG&G Corporation, Contract No. 14-06-D-5640, 30 Sept. 1969, 385 pp.

The authors reported the results of a 5 year program of statistical and physical cloud seeding investigations on the Park Range of northern Colorado. Many tests were conducted to track the transport and dispersion of ground-based and aircraft releases of both AgI and tracer material. The important point was made that valley-based inversions were present during at least half of all hours with snowfall. The inversions totally trapped any seeding material released within them which greatly limited the effectiveness of the valley-based seeding generators. The trapping inversions were found to typically occur up to a height of at least half of the mean terrain height of the main barrier, but with wide variability. Trapping inversions often existed up to between 8,000 and 9,000 ft. For reference the Yampa Valley to the west has elevations near 6,800 ft and the Park Range crestline exceeds 10,000 ft. Consequently, it would be prudent to site ground-based generators on the windward slope about 2/3 of the way up from the valley floor to the crestline.

Super, A. B., 1974: Silver iodide plume characteristics over the Bridger Mountain Range, Montana, *J. Applied Meteorology*, **13**, 62-70.

Plume widths downwind of the Temperature Ridge high elevation seeding site on the windward slope of the Bridger Range of Montana were measured using 13 pairs of passes over the north-south oriented Main Ridge. The seeding site was 425 m (1400 ft) below the crestline. Sky cover was broken or overcast during all flights, with cloud bases above aircraft sampling levels to permit sampling from very near the Main Ridge to above plume tops. That layer was slightly stable in all cases but inversions were not present. The known response time of 23 sec for the aircraft-type acoustical ice nucleus counter to AgI injection was used to locate the entry position into each plume. The long hold-up time in the counter's cloud chamber made it impractical to locate plume exit locations. Temperature Ridge plumes traveled about 3 miles before crossing the Main Ridge. The median plume width was 27 deg above the crestline. The lead author operated the acoustical counter on all sampling flights and can attest to the strong mechanical turbulence routinely found over the Main Ridge as westerly winds forced airflow over the north-south oriented barrier. The intended target area was the parallel Bangtail Ridge located about 7.5 miles east of the Main Ridge.

Hill, G. E., 1980: Dispersion of airborne-released silver iodide in winter orographic storms. *J. Applied Meteorology*, **12**, 978-985.

A serious shortcoming of aircraft seeding is the limited dispersion rate of the seeding material and any resulting ice crystals. Hill (1980) used aircraft observations to investigate this problem in Utah. He stated that, "It is concluded that both the vertical and horizontal diffusion of silver iodide released from airborne generators in the northern Wasatch Mountains during nonconvective winter orographic storms are much lower than that desired for effective seeding." Hill (ibid) recommended that (1) AgI seeding be carried out several hours travel time upwind from the desired target, (2) dry ice be dropped from, preferably, a jet aircraft to permit rapid traverses to maximize the cloud volume filled with seeded crystals and (3) that, "an entirely new delivery system/seeding agent be designed for seeding winter orographic clouds." The authors of this report consider recommendation (1) to be impractical because of targeting uncertainties associated with complex air trajectories over mountainous terrain, and the difficulty of predicting SLW availability hours in advance. Recommendation (2) is also considered impractical because of the very high costs of using jet aircraft and the limited dry ice payload which can be carried. Moreover, dry ice seeding requires that the pellets be dropped into SLW cloud. Such cloud often exists only a limited distance upwind of a mountain barrier which could present targeting difficulties. Fortunately, the technology to follow recommendation (3) has been developed over the past decade, using remote-controlled or automated liquid propane dispensers as discussed in Sec. 7.

NOTE: The authors no longer have access to the two following final reports and could not find the results published in either the Journal of Applied Meteorology or the Journal of Weather Modification. The quoted paragraph following the Hill (1982b) and Long (1984) references was taken verbatim from Holroyd et al. (1988) cited in this summary. The material is relevant to ground-based seeding with valley generators.

Hill, G. E., 1982b: Evaluation of the Utah operational weather modification program. Final Report from Utah State Univ., Logan, UT, under NOAA contract NOAA/NA-81-RAC-00023, 291 pp.

- and -

Long, A. B., 1984: Physical investigations of winter orographic clouds in Utah. Final Report from the Desert Research Institute, Reno, NV, under NOAA coop. agreement NA82RAH00001, 286 pp.

"Hill (1982b) presented results obtained during an evaluation of the Utah State operational seeding program. Ground and airborne measurements were made in the vicinity of the Tushar Mountains to determine if the AgI seeding material was being effectively transported from upwind valley generators to clouds over the mountains. A high incidence of inversions was noted, in which the AgI was frequently trapped. Significant IN (ice nuclei) concentrations were rarely transported to sufficient height and in adequate concentrations to achieve significant seeding effects. It was concluded from physical evidence that the ground-based generator network was ineffective. This finding was reinforced by model studies described in Long (1984) which used a Tushar Mountain dataset. Application of the GUIDE model (Elliott et al. 1983), with local upwind soundings as input, resulted in the conclusion that 'only 36% of the soundings considered showed seeding material was delivered to the clouds.' In the majority of cases, intended transport was apparently not achieved, due to easterly downslope flow, trapping inversions, or air flow parallel to the mountains."

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

In-cloud sampling was done over the Bangtail Ridge target area of the earlier Bridger Range Experiment (see Super and Heimbach 1983). The Temperature Ridge seeding site was again used with the same type of AgI generator. A well-instrumented cloud physics aircraft was operated under special waiver to as low as 1000 ft above the highest terrain. Six successful instrument flight rules (IFR) missions were flown during January 1985 by making north-south passes over the Bangtail target located 7.5 miles east of the Main Bridger Ridge during westerly winds. Plume width estimates were made using an acoustical ice nucleus counter in the same manner as discussed in Super (1974). The median reported plume width about 1000 ft above the highest terrain was 3.1 miles for 14 pairs of passes. Using the typical 10.6 mile downwind distance from the seeding generator to the flight track, the corresponding angular median plume width was 17 deg. Three of the six missions were flown when SLW cloud was present over the target. During each of those three missions, seeded ice crystals were obvious as monitored with a 2D-C particle imaging probe. The resulting median plume width of seeded crystals was 4.1 miles for 20 individual plume passes between 1000 and 2000 ft above the highest terrain. That value corresponds to a median width of 22 deg, based on actual seeded crystals with concentrations well above natural background levels.

Holroyd, E. W., J. T. McPartland and A. B. Super, 1988: Observations of silver iodide plumes over the Grand Mesa of Colorado. *J. Applied Meteorology*, **27**, 1125-1144.

Lateral and vertical plume positions of ground-released AgI plumes from eight separate generator sites on the Grand Mesa of western Colorado were tracked by aircraft. Ground seeding experiments were sampled during 14 missions on 12 different days under several wind, cloudiness and stability conditions. Plume widths were determined with an acoustical ice nucleus counter and often by 2D-C observations of seeding ice crystals. The median plume width was found to be 15 deg with almost all plumes within a factor of two of that value, that is, between 7.5 and 30 deg. Optimum cross-wind spacing should allow the merger of 15 deg plumes by the time they reach the crest. There were suggestions that ground generators should not be placed much lower than about 2300 ft below the crest or the seeding materials might not be transported over the Grand Mesa, but the best lower elevation limit for routine targeting had yet to be determined. Typical plume rise exceeded 1640 ft above crest elevations.

Deshler, T., D. W. Reynolds and A. W. Huggins, 1990: Physical response of winter orographic clouds over the Sierra Nevada to airborne seeding using dry ice and silver iodide. *J. Applied Meteorology*, **29**, 288-330.

Based on aircraft and ground-based microphysical observations upwind from and over the Sierra Nevada of California, Deshler et al. (1990) concluded that, "Achieving fairly continuous coverage (by aircraft) along the direction of seed line advection requires seed lines to be no longer than 37 km (23 mi), yet treatable cloud may extend for hundreds of kilometers along the barrier." A reasonably high performance twin engine aircraft (Aero Commander) was used for the Sierra Nevada seeding. Less expensive single engine aircraft are usually not used in icing conditions near mountains for safety reasons. Since the presence of SLW cloud is transient and cannot be well predicted, several twin engine aircraft and crews would need to be available on an almost continuous basis to effectively seed most of the Colorado Rockies. The logistic problems and costs of such an operation would be considerable. Moreover, experience gained during a Utah experimental program indicated that even a high performance research aircraft could not safely continue to operate during the wetter SLW periods because of moderate to severe icing, or during more windy phases because of severe turbulence (Super 1999b). Hours of exposure may cause serious ice buildup on those portions of a seeding plane airframe not equipped with deicing mechanisms, even if SLW amounts are limited. Aircraft seeding may be practical in situations where seeding may be done well upwind from the target barrier in a region where safe flight is possible down to within 1000 to 1650 ft of mountain crest altitudes.

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

Aircraft observations were presented from two flights conducted under IFR (storm) conditions when SF6 was released from the mouth of a major canyon during the mid-January to mid-March 1991 field program on the Wasatch Plateau. A total of ten passes were made through the tracer gas plume along the west flight track which was over the west edge of the plateau top. The mean distance from the canyon mouth release site to the flight track where SF6 was detected was about 5.3 miles. The median plume width was 22 deg. Four plume traverses were made above the east side of the plateau top at a mean distance of 11.7 miles downwind of the SF6 release site. The median plume width for these passes was also 22 deg. The authors noted that in order for the AgI plumes released from the valley to be continuous over the plateau top's west edge, located 6.2 miles downwind of the generators, the required spacing between generators would be 2.7 miles. That value is much less than the typical spacing of approximately 10 miles used in the Utah operational seeding program according to the authors. The suggested 2.7 mile spacing is equivalent to a 25 deg plume width 6.2 miles downwind.

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

Five aircraft missions tracked AgI and SF6 tracer gas releases from valley and canyon mouths sites used in the Utah operational seeding program for the Wasatch Plateau. All flights took place in visual flight rules (VFR) conditions to permit very low level sampling over both mountainous terrain and within valleys. Missions were flown under atmospheric conditions typical of prefrontal winter storm phases with snowfall occurring at higher elevations during some flights. Four of the five missions found the real and simulated (tracer gas) seeding material was transported along the mountain barrier rather than over it, or the material was trapped by low level stability and was drifting about near the valley floor.

The AgI and SF6 were tracked over the Wasatch Plateau during part of one mission when the lower atmosphere likely had neutral stability. However, estimated effective ice nuclei concentrations were very limited at SLW temperatures typical of the prefrontal storm phase.

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

The application of the sophisticated three-dimensional, time dependent numerical mesoscale model by T. Clark and associates of the National Center of Atmospheric Research (NCAR) (hereafter "Clark model") was demonstrated using one case study from early 1991 with good observations of SF6 tracer gas and ice nuclei. The model results were in reasonable agreement with observations of plume positioning. Several points were illustrated by the model including: (1) Seeding material can be confined to a depth of several hundred meters over the terrain; (2) The horizontal and vertical positions of the release point are critical. In this study the best release points were on the windward slopes of the barrier to take advantage of terrain-forced vertical motions; (3) pooling of seeding material can occur in the valley areas, and its transport can be guided by the lower terrain character; and (4) patterns of SLW predicted by the model indicate that the depletion of SLW downwind of the crest could be due to subsidence warming.

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

A case study was analyzed for plume characteristics including seeding responses for a single AgI plume, co-released with SF6 tracer gas, well up the windward slope from the Aspen Hills site of the early 1994 field program. The angular plume width over the west edge of the plateau top was about 15 deg with a brief wider period caused by a shift in wind direction. The AgI seeding produced strong microphysical evidence of enhanced ice particle concentrations on the plateau top and at aircraft levels. Plumes were readily transported over the Plateau in spite of limited winds, and vertical dispersion was likely aided by weak embedded convection. Plume widths were limited suggesting that that high altitude seeding generators should be spaced no more than 3 miles crosswind.

The Clark model correctly predicted plume transport from the release point over the target area, but at a slower rate than indicated by field measurements. The heights to which the model-simulated plumes were transported were in reasonable agreement with aircraft observations, but the simulated lateral spread was excessive at the surface. Overall, the model simulation produced a reasonable first-approximation of reality.

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

Six early 1991 seeding experiments were conducted during which AgI, released from a network of eight valley generators, was observed by aircraft during storm conditions. These cases were not representative of valley seeding in general as AgI was not transported to plateau top and aircraft altitudes during any other sampling periods. Little AgI was found as high as 3300 ft above the Plateau and the aircraft sometimes over-flew plumes while sampling at about 2000 ft above the plateau top. The median combined plume width was 25 km, well less than the 40 km north-south extent of the AgI generator network, and the maximum width observed was 36 km. These results suggest that either the aircraft typically over-flew some of the individual plumes or that some plumes were not transported over the Plateau. Generators were located closer together for these experiments than the 10 mile spacing typical of the operational program. No discernable seeded zone IPC (ice particle concentration) was found when cloud temperatures were warmer than -9°C. Valley seeding very likely increased the IPC during the two coldest experiments and may have increased it during an additional experiment. However, IPC increases were limited to about 10 L^{-1} with one exception of 27 L^{-1} for the coldest temperature sampled -19°C. Increases less than about 20 L^{-1} are likely to produce only trace snowfall rates (Super and Heimbach 2005a), and observations from the five available precipitation gauges suggested any snowfall rate enhancement was limited. One of the two colder cases had abundant supercooled liquid water and the mission was terminated early because of aircraft icing. The minor snowfall amounts measured during that mission raise special concern because all microwave radiometer and aircraft sensor observations indicated quite seedable conditions.

Griffith, D. A., 1996: Potential application of results from the NOAA atmospheric modification program to the conduct of a Utah winter orographic cloud seeding program. *Preprints for 13th Conf. on Planned and Inadvertent Weather Modification*, Atlanta, GA, American Meteorological Society, 118-120.

The following three paragraphs in quotes were taken verbatim from the preprint paper. Some comments follow the cited quoted material.

"Transport of valley-released silver iodide/SF6 over Utah mountain barriers over Utah mountain barriers has been documented. Since the supercooled liquid water is predominately located at low level on the windward slopes of mountain barriers and the generators are located in valleys upwind of these barriers, the silver iodide nuclei are encountering the preferred supercooled liquid water formation zones. This is also an important result related to the second part of the Utah conceptual model (Background). In some cases valley-released silver iodide/SF6 is not transported over the mountain barrier. These cases generally occur when there are low level atmospheric inversions. An interesting observation on some cases indicated nuclei 'pool' under these conditions which are sometimes subsequently scoured from the valley and transported over the barrier with the passage of a synoptic feature. This may suggest that valley generators should be operated under trapping inversions ahead of the passage of synoptic features. NAWC seeding criteria have typically precluded operations under these conditions.

Location of manually operated ground generators at the mouths of canyons on the windward slopes of target barriers may offer a preferred location for transport of silver iodide nuclei over the barrier when transport from valley locations is ineffective.

The plume spread from ground-based releases of silver iodide and SF6 (15 to 25 deg) suggest that generators should be located at a spacing of 4 to 5 km apart upwind of the barrier in order to achieve plume overlap. The spacing currently used on the Utah operational program is on the order of 16 km."

The authors of this report are not aware of any documented cases in which the above suggested transport mechanism of a synoptic feature transported pooled AgI from a valley over a mountain barrier. Acoustical ice nuclei counters were routinely operated on top the Plateau during the early 1991 and early 1994 field projects, both at mountain observatories and in vans driven along Highway 31. Any sudden increase in AgI concentration during passage of a synoptic feature should have been obvious. If such events occurred, the lead author does not recall them, and does not recall reading about them in the published literature from the Wasatch Plateau of which he is well aware, having been the project scientific director. Therefore, while he cannot rule out the possibility suggested by Griffith, caution should be exercised in accepting the reality of the proposed transport mechanism.

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

The transport of AgI from three valley sites was examined for an experiment which had unexpected transport of the seeding material and tracer gas released from a canyon mouth, during stable conditions. The AgI and SF6 were readily detected on the plateau top's west edge but not at aircraft sampling levels which were no lower than about 2000 ft above the typical plateau top terrain. This is another example of plumes being confined to a rather shallow layer over the mountainous terrain.

Modeling with the Clark Model suggested that the valley-released AgI had an initial vertical impetus by the gravity wave mechanism which provided transport above the surface-based inversion. That was followed by orographic forcing in a more organized westerly flow. The model confirmed the confinement of the plume to a shallow layer and subsequent lifting, again due to a gravity wave, but further eastward over the west edge of the plateau top. The north-south oriented San Pitch Mountains lie west of, and parallel to, the Wasatch Plateau, and is responsible for initiation of gravity waves over the valley between the two mountain barriers. It seems doubtful that gravity waves would generally exist to provide a similar vertical transport mechanism in the absence of a barrier upwind of the target barrier. It was suggested that seeding from the high altitude sites on the windward side of the San Pitch Mountains would provide the best means of utilizing the intermittent gravity wave phenomena.

Although both AgI and SF6 were observed on the plateau top during this experiment, estimated concentrations of AgI ice nuclei, effective at the mildly supercooled cloud temperatures within the seeding zone, suggested any snowfall increases would have been trivial.

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

Rawinsonde observations from the early 1991 and early 1994 Utah/NOAA research projects were stratified into five classes based on temperature profiles. Ignoring 7 soundings with either early termination or questionable data, a total of 65 valid soundings were available. A subset of 46 of these (71%) fit the criteria for the five classes, with the remaining 19 simply classified as "other." Five soundings representing the 46 classed soundings were used to initialize the Clark mesoscale model to simulate AgI transport from three operational generator sites in the valley upwind of the Wasatch Plateau. Not unexpectedly, the most unstable sounding class produced the best targeting. This class was the coldest of the five, thereby producing more effective AgI ice nuclei. In general, the modeled results were in agreement with selected cases studies of field observations. Wind characteristics were also shown to be important for successful targeting.

Several factors were highlighted by the modeling applied in this investigation, most of which were confirmed by field observations. These included: (1) A frequent tendency for a low-level northward drift of valley-released AgI parallel to, rather than over, the Wasatch Plateau; (2) Sometimes a westward or northwestward drift of AgI occurred in the valley in spite of organized westerly flow aloft; (3) Strong upward motion was possible under some stability and wind speed conditions because of gravity wave transport; (4) Mechanical forcing was important for transport over the barrier; (5) Targeting was poor for the stable classes D and E which comprised 26% of all 65 soundings and 37% of the 46 soundings fitting the criteria; (6) Class A, dry neutral or unstable, which comprised 18% of all 65 valid soundings (26% of the 46 classed soundings), appeared to be most effective because of successful targeting and relatively cold cloud temperatures in the seeded zone; (7) Even when properly targeted, AgI effectiveness can be handicapped by warm cloud temperatures over the Plateau.

Super, A. B. and J. A. Heimbach, Jr., 2005b: Final Report on Utah cloud seeding experimentation using propane during the 2003/04 winter. Utah Division of Water Resources technical report to the Bureau of Reclamation, April, 2005.

Sec. 4b of the cited report presents an analyses of SF_6 gas plumes released from the

HAS (high altitude site) used for AgI seeding during the mid-January to mid.-March 1994 field program. A van-mounted fast-response SF6 detector and GPS positioning were used to measure near-instantaneous plume widths along the north-south "upwind highway" (Highway 31). The upwind highway was about 1000 ft above the HAS seeding site where the plumes were routinely detected. Observations were made during 35 separate passes made during 5 different storm periods. The average plume centerline was very near the instrumented TAR (target) established later, during the fall of 1994. The median plume width was 1.2 miles. The TAR was 2.5 miles straight line horizontal distance from the HAS, but it is estimated that the actual plume trajectories were slightly longer, controlled by terrain features. The distances traveled by the plumes were estimated as 2.7 miles as they crossed the upwind highway. While the initial plume trajectories were toward the northeast, the plume transport was almost due east while crossing the upwind highway; that is, essentially perpendicular to the highway and west edge of the Plateau. Using the median width of 1.2 miles and transport distance of 2.5 miles yields a typical plume width of 25 deg in the mechanically turbulent airflow forced up the windward slope of the Wasatch Plateau. Less initial dispersion might be expected from valley-released plumes over much smoother terrain.

APPENDIX C: Application of Utah Weather Modification Research Results to Colorado Feasibility Study.

Introduction

This appendix focuses on transport and diffusion of valley-released seeding agents. Although valley releases have the advantages of being logistically easier and cheaper to operate than high elevation sites and aircraft seeding, their efficacy is controversial as discussed in the main text of this report. Colorado data appropriate for the analyses to be presented, which include soundings, surface measurements and supercooled liquid water (SLW) collected specifically for this purpose, are not available to the authors of this report. However, they were involved in a series of winter cloud seeding experiments conducted over the Wasatch Plateau of Utah during the 1990s and the winter of 2003/04. Those data are still available. The results of these experiments are appropriate for estimating the seeding potential of Colorado targets because Utah is up the prevailing wind, at approximately the same latitude, and many of the terrain features are similar. The Wasatch Plateau experiments examined targeting from valley, foothill, canyon-mouth and high altitude seeding sites; the occurrence of SLW; and a recently-developed propane seeding technique. Periods of major effort were conducted in the early winters of 1991 and 1994 (Super 1999b). Both of these were supported by NOAA's Atmospheric Modification Program in cooperation with the Utah Division of Water Resources. A randomized propane seeding experiment was conducted during the winter of 2003/04 which was supported by the U.S. Bureau of Reclamation, also in cooperation with the Utah Division of Water Resources (Super and Heimbach 2005a).

There are two data sets applied in this appendix: (1) atmospheric soundings (aka RAOB, rawinsondes, radiosondes) released during two field research programs from mid-January to mid-March of both 1991 and 1994, and (2) surface data corresponding to periods during the 1991 program which had hourly-averaged, vertically-integrated liquid water depths of 0.05 mm or more as observed by a plateau-top microwave radiometer. The text below describes these data starting with the justification for using the Utah soundings for this feasibility study.

Colorado has two National Weather Service release sites where radiosondes are released on a 12 hr schedule at 0000 and 1200 GMT (1700 and 0500 MST). These are:

Grand Junction, KGJT (72476), west central CO, Lat.//Lon. = 39.12//-108.54,
Elev. = 4859 ft.

Denver, KDNR (72469), central CO, Lat.//Lon. =39.75//-105.87, Elev. = 5331 ft.

KGJT is northeast of the north end of the Uncompardre Plateau and west-northwest of the higher elevation Grand Mesa. Soundings from KGJT are not representative of valleys between barriers which might be considered as candidates for seeding. Comparisons between KGJT winds and those observed by an acoustic sounder and tower sensors above the Grand Mesa showed only coarse agreement (Holroyd et al. 1988). KDNR is on the Great Plains, just east of the Rocky Mountains, and frequently samples dryer subsiding air masses downwind of the large mountainous area where a seeding infrastructure could be beneficial. With the releases being on a rigid 12 hr schedule, these soundings do not focus on storm periods.

The Wasatch Plateau soundings were released from the Mt. Pleasant Airport:

Mt. Pleasant Airport, 43U, central UT, Lat.//Lon. = 39.53//-111.48, Elev. = 5853 ft.

Mt Pleasant's latitude is approximately the same as KGJT's and KDNR's, and is located on the east side of the Sanpete Valley west of the approximately south-north Wasatch Plateau, the target of the research. The San Pitch Mountains, orientated parallel to the Plateau, are west of the valley with the crest at Mt. Pleasant's latitude about 9000 ft. The crest of the Wasatch Plateau at this latitude is about 9300 ft. At this latitude, the valley is approximately 15 miles wide. This type of terrain is more compatible with several cloud seeding target candidates in Colorado. Since the soundings were in support of winter weather modification research, they were mainly during storm periods without a firm release schedule.

A total of 96 soundings were taken at the Mt. Pleasant Airport, 63 in 1991 and 33 in 1994. The operational criteria for taking soundings differed. For 1991, radiosondes were "...released at 3 hour intervals during periods of interest." [C1], whereas in 1994, they were launched "... in support of aircraft missions..."[C2]. The 1994 criterion made a release more likely to be in storm conditions since the aircraft's mission was to sample these conditions. Some releases were for training and testing, and, especially during 1991, for forecasting purposes.

To determine which of these soundings represented storm conditions, notes and archived data from sounding periods were examined. These included notes by field staff taken in an instrumented surface vehicle and aircraft, data from surface weather stations on the Plateau, and references to relevant technical reports. The Plateau-top data came from the Department of Transportation (DOT) snowplow storage facility in 1991 and the Radar Radiometer Site (RRS) in 1994. The reader is referred to Super and Holroyd (1994 and 1997) for maps which depict locations. A microwave radiometer was operated at these mountain observatories as well as a Rosemount icing rate meter. The presence of SLW is a strong indication of storm conditions. Some non-storm periods were obvious, e.g., training, aircraft flight tests during visual conditions, and soundings released for forecasting purposes. There was some uncertainty with others, especially since original field logs no longer exist. To err on the conservative side, if there was any question, the sounding was excluded from the list of storm releases. Out of 96 soundings, there were 73 soundings which were definitely in storm conditions, 47 from 1991 and 26 from 1994, and 23 soundings which were not clearly in storm soundings, although some may have been. The 73 storm soundings were used in the analyses reported below.

During 1991, a microwave radiometer recorded vertically-integrated liquid water depths at the DOT site at an elevation of 8850 ft (2697 m) above mean sea level (msl). All elevations are given above msl and heights are noted as above ground level (agl). Hourly mean depths of liquid water ≥ 0.05 mm, considered to have potential for significant snowfall augmentation, were detected during 194 hours or 17% of the hours over the mid-January to mid-March project. Hourly means of weather parameters, excepting medians for wind directions, were derived for these periods using 10-min records from a data logger at the DOT and 10-min automatic weather station data at the Mt. Pleasant Airport site. The wind instrumentation for the weather station was on a tower at 21 ft agl. In 1991, there was also a Doppler acoustic wind sounder at the Mt. Pleasant Airport located next to the sounding release site and weather station. Hourly horizontal Doppler winds were derived for 591 ft (180 m) agl for this study, or 6444 ft (1964 m) elevation. This level corresponds to the elevation of the Birch Creek Canyon mouth where AgI and SF_6

[C1] Utah Dept. of Natural Resources, Division of Water Resources, 1991: *1991 Field Operations Plan, Utah/NOAA Cooperative Atmospheric Modification Research Program.* 27 pp.
[C2] Utah Dept. of Natural Resources, Division of Water Resources, 1994: *1994 Operations Plan, Utah/NOAA Atmospheric Modification Program*. 28 pp.

tracer gas were released in 1994. Excepting a distant crosswind generator located well to the north at 6726 ft (2050 m) in 1991, all release points of the concurrent operational program had lower elevations, ranging from 5693 to 6021 ft (1735 to 1835 m) in 1991 along the valley floor. In an attempt to improve targeting, operational generators were moved to higher valley levels nearer the Plateau in 1994, from 6076 to 6152 ft (1852 to 1875 m).

Each data set has its merits. The rawinsondes provide vertical profiles of temperature, humidity, and winds. However, these data are instantaneous and the horizontal positioning is not consistent. Also, these data are limited in number. The 1991 data set produced by the radiometer, Mt. Pleasant Airport valley weather station, DOT data logger, and Doppler acoustic sounder is larger and represents stationary hourly averages. In the discussion below, the rawinsondes will be used primarily for stability estimates, whereas the other data set will be applied to the analysis of temperatures and winds.

Temperatures During Periods of Significant SLW

Seeding strategy is partly dependant on the temperature profile. Three temperatures highlighted in this report are -1^{o}C at which propane becomes an effective seeding agent, -6^{o}C at which AgI becomes effective by the forced-condensation freezing process when released within cloud, and about -8^{o}C where AgI produces substantial concentrations of seeded ice crystals when released below cloud. Mt. Pleasant and DOT surface temperatures were used to produce Fig. C1, a plot of temperature percentiles during hours when significant SLW existed above the DOT. The valley surface temperatures were quite warm with less than 8% having temperatures of -1^{o}C or colder. During some storm periods the upper portions of the Plateau are shrouded in orographic cloud but skies remain clear over the Sanpete Valley floor.

Seventy-one percent of the Plateau-top (DOT) temperatures were in the -1^{o}C or colder range. The numbers were significantly lower for the AgI in-cloud release threshold of -6^{o}C or less: 0 and 9%. But valley AgI generators are seldom within cloud so the -8^{o}C threshold would be appropriate for typical below-cloud releases. Plateau-top temperatures were that cold or colder only a few percent of the time. However, the early 1991 SLW observations were made at 8850 ft elevation and much of the Wasatch Plateau is at higher elevations, with the Plateau generally rising further southward. The early 1994 microwave radiometer observations from RRS, not available for this report, were made only 4 miles south of the DOT at an elevation of 9780 ft. With normal in-cloud temperature lapse rates, RRS surface temperatures would be expected to be about 2^{o}C below those at DOT at any given time. And some portions of the Plateau have elevations over 1000 ft higher than the RRS so their temperatures would be yet another 2^{o}C or more colder than DOT observations. For a higher location which was 4^{o}C colder than the DOT, Fig. C1 suggests that perhaps about 25% of significant SLW hours would have surface temperatures of -8^{o}C or colder, assuming the DOT observations are representative of clouds over higher terrain. There is no doubt that AgI seeding would be more effective if the seeding agent was transported over the higher and colder Plateau-top elevations found south of the DOT and RRS, or on the Wasatch Range well north of the Plateau as shown by the icing rate observations of Solak et al. (2005) atop an 11,000 ft peak. As discussed in Appendix A, their measurements included all hours with riming even if icing rates were quite low. They are not compatible with this discussion, which is limited to hours with enough SLW to produce more than trace precipitation rates.

Although SLW cloud cold enough for effective AgI seeding will exist more frequently over higher terrain, a key question is whether valley-released AgI will often be transported that high in sufficiently high concentrations to produce meaningful snowfall rates. That question is addressed in detail elsewhere in this report. But the data plotted in Fig. C1 suggest that propane seeding within or just below cloud will often be a better choice than relying solely on AgI for snowfall augmentation.

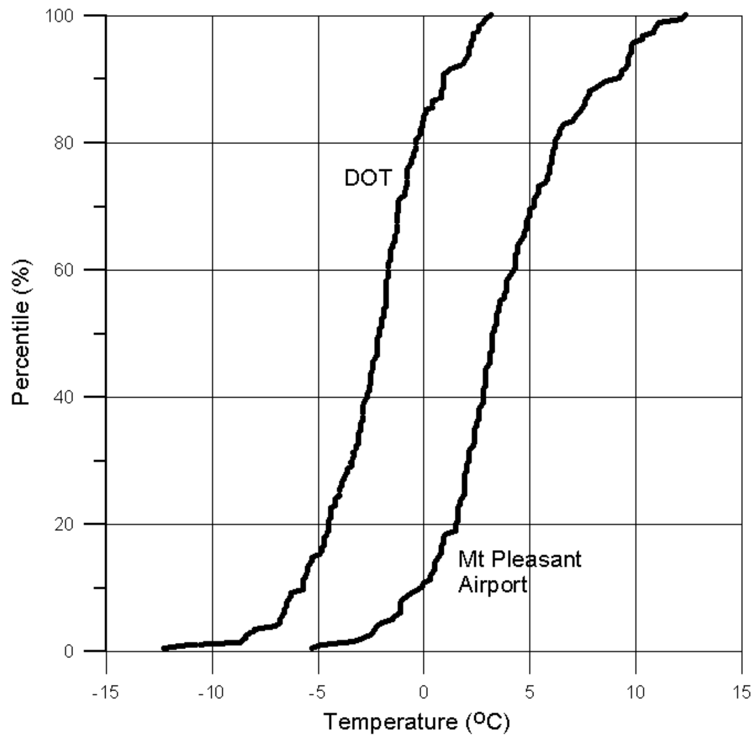

Fig. C1. Percentiles of Mt. Pleasant and DOT temperatures for hours which had vertically-integrated SLW ≥ 0.05 mm during the period mid-January to mid-March 1991.

High SLW fluxes[C3] tended to occur during warmer periods principally for thermodynamic reasons; the amount of moisture an air mass can hold increases with temperature. For the same reason, colder temperatures would be expected to have lower fluxes of SLW. This was shown empirically by Super (1994) using the same Utah 1991 data set. It is enigmatic that the periods with high SLW, and therefore better seeding potential, are frequently too warm for the traditional surface-released AgI to work, whereas the periods with temperatures cold enough for AgI to be active are less likely to have significant SLW.

Low-Level Lapse Rates

Ambient lapse rates[C4] for the storm soundings were found for the layer between the surface and first elevated level,

$$\text{Ambient lapse rate} \equiv \gamma = -\frac{\partial T}{\partial z} \approx -(T_1 - T_{sfc})/(z_1 - z_{sfc}).$$

[C3] ***Flux*** is the rate of flow of some quantity. In this case it is the rate of flow of SLW through a vertical plane across the Plateau.

[C4] As used herein, ***lapse rate*** is the change of temperature with height, usually expressed as degrees Celsius per kilometer. If the temperature decreases with height, the lapse rate is positive. Inversions, which have temperature increase with height, have negative lapse rates. ***Ambient*** infers that the measurements are in the free air.

The lapse rates were stratified into four classes defined by:

1. Absolutely unstable, $\gamma > 9.76^{o}C\ km^{-1}$, the dry adiabatic lapse rate[C5],
2. Conditionally unstable, pseudo-adiabatic lapse rate[C6] $\leq \gamma \leq 9.76^{o}C\ km^{-1}$,
3. Absolutely stable, isothermal $\leq \gamma \leq$ pseudo-adiabatic lapse rate, and
4. Absolutely stable with inversion, $\gamma <$ isothermal (0).

The pseudo-adiabatic lapse rates used for comparison were interpolated from a table in the Smithsonian Meteorological Tables (1968, p. 323), which gives the pseudo-adiabat as a function of temperature and pressure. This was done for both the surface and first level data points. An average of the two was used for criteria 2 and 3 above.

Table C1 summarizes the storms' stability types. For example, 8 out of 73 storm soundings, or 11%, had an absolutely unstable surface layer. To check for any bias imposed by variable depth of the layer sampled nearest the valley floor, the table lists the stability class distribution for soundings whose thickness of the first layer ≤ 1063 ft (324 m) agl, a natural break point near the median, ≤ the 75 percentile which was 1506 ft (459 m), and ≤ 90 percentile, at 1929 ft (588m) above the rawinsonde release point.

Table C1. Stability classes of storm soundings' lowest reported layer. The columns headed by "Elev. ≤" give the number of storm soundings with elevations at or below the listed percentiles. The respective elevations are 6196, 7359, and 7782 ft msl. Values are given by number and percentage.

Class	All Storm Soundings	Elev. ≤ Median, 1063 ft agl	Elev. ≤ 75 percentile, 1506 ft agl	Elev. ≤ 90 Percentile, 1929 ft agl
1	8 / 10.9%	5 / 13.5%	6 /11.1%	7 / 10.8%
2	43 / 58.9	16 / 43.2	28 / 51.9	37 / 56.9
3	14 / 19.2	9 / 24.3	13 / 24.1	14 / 21.5
4	8 / 10.9	7 / 18.9	7 / 13.0	7 / 10.8
Total	73/100	37/100	54/100	65/100

There is a reasonable consistency of the stability class distributions throughout the height percentiles. This suggests that the criteria for defining significant levels in the rawinsonde data were properly applied, and that in general, the stability of the surface layer is not a function of its depth, although some exceptions are discussed below. There is a preponderance of conditionally unstable storm soundings. This gives a γ between the dry adiabatic lapse rate and the pseudo-adiabat, not surprising for storm conditions. The portion of conditionally unstable soundings is smaller for storms with a surface layer depth ≤ the median, but increases as the depth of the surface layer increases. The stable classes comprised 30% of all the storm soundings, but for those soundings with level 1 being ≤ 1506 ft agl, the proportion with stable lapse rates is higher. Conversely, stability class 2 has fewer soundings when only shallower surface layers are included. These values suggest that surface-based stable conditions tend to be in shallower layers than conditionally unstable layers. This may be a result of relatively more vertical mixing being possible in conditionally unstable conditions. The absolutely unstable percentages are consistent

[C5] ***Dry adiabatic lapse rate*** is the rate of temperature decrease with height of a dry air parcel lifted without exchange of heat (adiabatic) with its environment.
[C6] ***Pseudo-adiabatic lapse*** rate is the rate of cooling with height of a saturated parcel. This cooling rate is less that that of the dry adiabatic lapse rate because of the release of latent heat. This is nearly the same as the saturated adiabatic lapse except the removal of condensate is not accounted for in the latter.

throughout the four columns of layer thickness. By definition absolutely unstable implies a facilitated vertical mixing, reducing the likelihood of a thin surface sounding layer. Only 11% of all storm soundings had a surface-based inversion. This portion is larger for shallower surface layers.

Research in other winter programs reviewed in this report found a higher proportion of inversions during snowfall periods than in the Wasatch Plateau area. In five years of observations in the Park Range, Rhea et al. (1969) found frequent valley-based trapping inversions which extended at least half way up barrier. Grant and Rauber (1988) used radar observations to classify winter clouds in the Park Range and Tennessee Pass of Colorado, and at Beaver, Utah, on the upwind base of the Tushar Mountains. At Beaver, the clouds had a stable signature 69% of the time, 58% for shallow clouds and 11% for deep clouds. The Park Range and Tennessee Pass areas likewise had a high proportion of stable clouds, 88 and 70%. Comparing the 73 Mt. Pleasant sounding stability results to those of Grant and Rauber (ibid.) could be misleading because the former summarizes surface-based lapse rates, whereas the latter examined clouds above the surface. Their number of deep stable periods at Beaver was much less than their shallow stable, 11% vs. 58%, making a better match to table C1. Similar differences, though to a lesser degree, were found for the Park Range and Tennessee Pass soundings.

Peterson et al. (1991) demonstrated that decoupled flow would sometimes be responsible for stagnant low-level air upwind of the Park Range and similar mountain barriers. They stated that, "During winter orographic storms, the surface layer upwind of the barrier can flow up and over the barrier, it can be blocked and stagnant, it can flow parallel to the mountain barrier, or it can even flow back upstream 180 degrees with respect to ridge-top winds. When the low-level air is not flowing over the barrier with the synoptic-scale winds, the low-level flow can be considered decoupled from the free atmosphere." All of these possibilities were also observed at various times in the Sanpete Valley just upwind of the Wasatch Plateau. Decoupled flow with stagnant flow near valley floors would be expected to pool and trap valley-released AgI as was sometimes observed in the Sanpete Valley.

Peterson et al. (ibid.) used a network of 24 weather stations in the Yampa Valley, which extends several tens of miles west of the Park Range, to analyze 708 hr with both snowfall and wind data during a 2 month period. Decoupled flow was nonexistent or limited to the upper valley during 29% of those hours, extended into the middle valley during 32.5% of the hours and was observed well westward all the way to the lower valley during the remaining 38.5% of the 708 hr. The implications for limiting transport and dispersion of valley-released AgI are obvious, and these results are in general agreement with the earlier findings of Rhea et al. (1969).

Marwitz (1980) has shown that conditions for transport and diffusion cannot be considered as steady state in an analysis of case studies from the San Juan Mountains. He identified four stages of storm development.

1. Stable: "--- much of flow below mountain top is blocked and directed toward the west."
2. Neutral: "--- the storm is deep; it typically extends throughout much of troposphere."
3. Unstable: "--- a zone of horizontal convergence appears to form near the surface at the base of the mountain on the upwind side and a convective line is often present over this convergence zone."
4. Dissipation: "Subsidence at mountain top height causes dissipation."

His analysis suggests that storm periods can have at least some portions with improved chances of transport from lower levels to passage over a mountain barrier. He found that in some rare storms, a baroclinic zone extended throughout the troposphere and there was no blocked flow.

Super et al. (1970) used a network of thermographs located on the upwind slope of the Bridger Mountains of Montana during two winter field seasons from 1968 to 1969. They found that the valley-based layer was absolutely stable 87% of the periods with snowfall, decreasing to 20% near the ridge crest. Although the use of surface thermographs to estimate stabilities is not the same as using soundings which sample temperatures above the surface, their results suggest that the valley-based Mt. Pleasant storms were more unstable than found in southwestern Montana. The Plateau storms were also more unstable than the Park Range storms, or those reported by Long (1984) for the Tushar Mountains of southern Utah as discussed in Sec. 6b.

Another possible reason for fewer stable storms over the Wasatch Plateau is that the Sanpete Valley is narrow compared to the valleys of the other cited projects. For example, at the latitude of Mt. Pleasant, the Sanpete Valley is only 15 miles wide, whereas the Park Range and Bridger Range have far wider upwind valleys. The closer proximity of an upwind terrain feature could promote mechanical mixing in narrow valleys. This would include gravity waves[C7], as discussed by Bruintjes et al. (1994), and Heimbach et al. (1997). Moreover, the San Pitch Mountains end about 20 miles south of the Mt. Pleasant Airport while the Wasatch Plateau extends much further south. Airflow through this major gap would tend to enhance up-valley flow which may have influenced the rawinsonde observations.

Heimbach et al. (1998) used the mesoscale model by Clark and associates (Clark 1977; Clark et al. 1996) to simulate the transport and diffusion of Sanpete Valley AgI releases for five classes of soundings. The Clark model is four-dimensioned, nonhydrostatic and anelastic. For this application it used three nested domains with 1 km horizontal resolution in the innermost domain. All the soundings which met seedability criteria were examined and classed according to the criteria in Table C2 below. Seedability was defined as having a westerly component at 700 mb (near Plateau top) and an indication of icing by a Rosemount icing meter or radiometer located on top of the Plateau. These criteria give a somewhat different pool of sounding types than the storm soundings listed Table C1 because the latter were partitioned using only low-level stability classes. There are fewer soundings in included in the partitioning of Table C2 than for Table C1 in part because different storm selection criteria were applied, but more so because some storms could not be classed as A through E.

The model was initialized by composite soundings which were representative of each class. Only Class A, the most unstable, showed a clear transport of valley AgI over the Plateau. This corresponded to stability 1, absolutely unstable, implying that 11% of the storm soundings are clearly conducive to successful targeting of valley-released seeding material. The Class B simulation suggested the possibility of some transport over the Plateau, but weakly.

The remaining three of Heimbach et al. (ibid.) sounding classes indicated no successful targeting and showed pooling of the plumes in the valley. This feature was verified by surface plume tracing. This picture is complicated somewhat by the potential of gravity wave formation in stable conditions which may have been enhanced by the spacing of the San Pitch and Wasatch Plateau ridges. Heimbach et al. (1997) reported on modeling a valley release in stable conditions.

[C7] ***Gravity waves*** are vertical undulations in the atmosphere which are driven by buoyancy. Vertical stability is required for their formation. In mountainous areas, gravity waves are induced by vertical perturbations caused by flow perpendicular to mountain barriers.

The initializing sounding had a surface-based inversion with a pseudo-adiabatic lapse rate above 700 mb corresponding to Class E above. This simulation had a gravity wave established by the San Pitch Mountains to the west with a wavelength on the order of the valley width, 12 to 15 miles. In the model this produced sufficient vertical transport during stable conditions to allow movement over the Plateau. This was in spite of there being an easterly component at the valley surface. Surface and airborne tracing indicated there was successful transport over the Plateau but only in a shallow layer. Gravity waves should not be considered a panacea for targeting. They require stable conditions with an organized cross-barrier wind component, are difficult to predict, and are transient.

Table C2. Sounding types defined by Heimbach et al. (1998). The third column is the relevant stability class applied in this report.

Sounding Class Defined by Heimbach et al. (1998)	no. / %	Stability Class from Table __
A Γ_d from surface to greater than the Plateau top.	12 / 16.7%	1
B Γ_d from surface changing to Γ_s below Plateau top.	9 / 12.5	1 and 2
C Γ_s from surface to > 600 mb.	8 / 11.1	2
D Elevated stable layer between 750 mb and Plateau top.	5 / 6.9	3 and 4
E Surface-based stable layer ($\gamma < \Gamma_s$).	12 / 16.7	3 and 4
Not A through E	19 / 26.4	
Other (Early termination and questionable data.)	7 / 9.7	
	72 / 100.0	

Low-level Winds

The transport of valley-released seeding agent over a barrier is controlled by the character of the wind. A significant speed is required to provide mechanical mixing and impetus to move air over the barrier, and the direction must have a cross-barrier component. Surface winds sampled by the Mt. Pleasant weather station at 21 feet atop a tower, and winds at 591 ft above the surface taken by a Doppler acoustic sounder, both during the 1991 field program, are summarized in Fig. C2. These are for hours with vertically-integrated liquid water ≥ 0.05, considered to be significant, during the early 1991 field program described above. There were 194 hr meeting this criterion, all of which had weather station data, and of these,178 hr had Doppler acoustic data.

The speeds increased with height as would be expected in a sheared environment typical of surface layers. The surface measurements (actually 21 ft agl) showed 45% of the hours with light winds, somewhat arbitrarily-defined as ≤ 4.5 mph (2 m s^{-1}) including calm. At 591 ft agl, 17% in were in this range. One percent and 4.5% of the surface and 591ft agl respective speeds were ≥ 22 mph (10 m $s^{-1)}$, documenting that few of the hours with significant SLW were associated with more than moderate wind speeds at valley levels.

It would be useful to have an estimate of the hours with significant SLW during which a valley-released seeding plume would be transported over the Plateau. Although there is insufficient plume tracing data to make direct measurements, inferences can be made using surface directions and speeds. One would expect insufficient transport under light wind conditions and wind directions which do not have an up-slope component. In this report, a light wind speed is defined as 4.5 miles per hour or less including calm. Pooling may occur at higher speeds, but the use of this definition should give a conservative estimate.

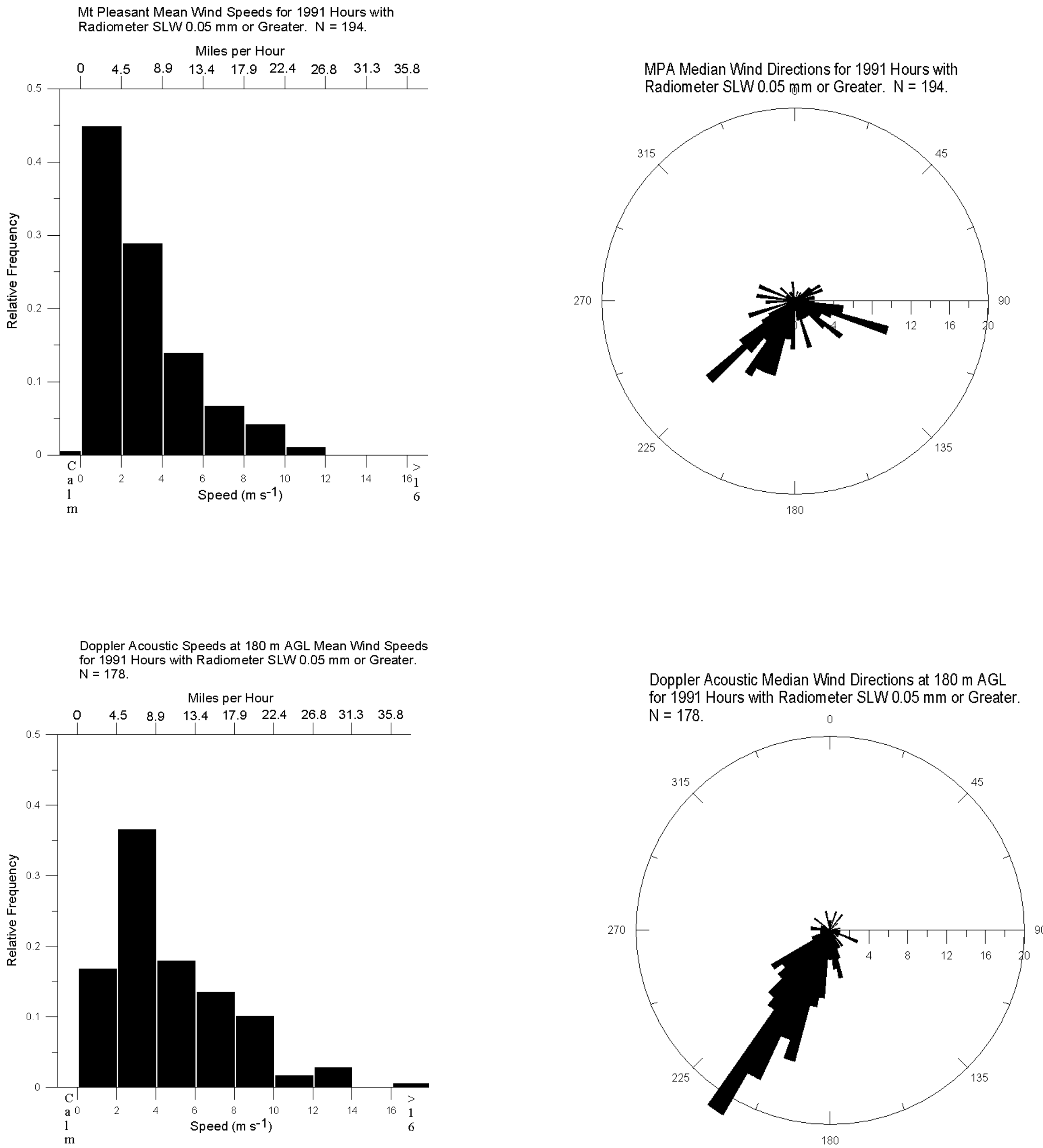

Fig. C2. Wind speeds and directions for Utah Wasatch Plateau investigations in the Sanpete Valley at Mount Pleasant. Plots are for hours in the early 1991 field program which had vertically-integrated radiometer measurements of SLW ≥ 0.05 mm. The top two panels are for the surface and the bottom two are for Doppler acoustic wind samples at 591 ft (180 m) agl.

Mt. Pleasant is at the north end of where the Sanpete Valley has a south-southwest to north-northeast orientation. North of Mt. Pleasant the valley has a south-to-north orientation. Surface winds are influenced by the valley relief and this is borne out by the direction of the Mt. Pleasant Airport runway which is oriented 200 - 020^{o} magnetic. Converting this to true direction using 14^{o}E declination gives the runway orientation as 214 - 234^{o} true. This may not follow the exact climatological prevailing wind because runway headings are reported to the closest 10^{o}, and land use and ownership add constraints. However, the southern portion of the west flight track used in the early 1991 and 1994 experiments was carefully selected to sample above the west (upwind) edge of the Wasatch Plateau top. The flight track was oriented 193 - 013^o magnetic, or 207 - 227^o true. One of the authors was the aircraft scientist and visually verified that this track exactly followed the ridge. This range was selected to define whether or not the wind direction had an upslope component. Again, this is a conservative approach because winds near the cutoff points would have a limited upslope component.

The hours of Mt. Pleasant Airport weather station data which had significant vertically-integrated SLW at the DOT site were partitioned using mean wind speeds greater than 4.5 mph, and median wind directions between 207 and 027^o true inclusive. That is, winds with directions from 207 through 027, inclusive, were assumed to have a chance of mechanically forcing the seeding plume up the barrier provided the speeds were greater than 4.5 mph. Out of the 194 hr with significant SLW, 58 hr, or 30%, met both these criteria. In other words, it is estimated that 30% of the hours which had significant SLW at the DOT site had a chance of transporting seeding material released from the valley floor over the Wasatch Plateau.

This is admittedly a coarse estimate, and it only considers mechanical or forced transport over the barrier. Super (1995) documents the only six case studies of valley plumes which were detected over the Plateau by aircraft and instrumented van during the early 1991 observational program. Five of the 6 had embedded convection and the sixth, the coldest case, was associated with a short wave passage. In five cases, vertical transport was aided by buoyancy and likely by turbulence, allowing ascent to elevated winds which typically have a more organized westerly component. The sixth did not have embedded convection, and was slightly stable near the surface. The short wave likely forced vertical mixing for this case. The six cases had low concentrations of AgI at the surface on the Plateau top, and very low or non-existent at aircraft sampling levels, at least 1000 ft above the highest terrain.

Remarks

Estimating the targeting potential of ground-based plumes released in the Sanpete Valley is difficult. Two aspects of targeting valley-based seeding material are discussed; (1) dynamic contributions to transport controlled by stability, and (2) mechanical forcing which is controlled by the character of the wind. Each can dominate the transport of plumes, but the reality is that both are involved to some degree and are linked, e.g., a valley inversion is associated with light and variable winds, both inhibiting cross-barrier transport.

Modeling and observations indicate that unstable and, to a lesser degree, conditionally unstable conditions will increase the chance of successful targeting. Sixty-nine percent of the 1991 and 1994 soundings during storm conditions were of these stabilities whereas 31% were stable with and without a surface-based inversion. This is a small proportion when compared to other mountain observing sites as discussed above, leaving one to wonder if limiting the analysis to storm soundings placed a bias favoring the less stable periods. Field operations were scheduled when storm passages were believed likely from forecasts and other information. This practice likely favored sampling of the larger, more obvious storms and missed some of the more localized orographic storms. Observations are not available to test this suspicion.

Supercooled liquid water is necessary for successful cloud seeding operations. Approximately 0.05 mm of vertically integrated SLW is needed to produce above trace snowfall rates. During the early 1991 experiment there were 194 such hours, and of these, 30% had winds which could reasonably provide the mechanical forcing to successful targeting. This is a small portion which can be culled further by considering the temperature of the SLW cloud being targeted. Higher

SLW values typically occur during warmer temperatures. This is a thermodynamic fact which unfortunately makes seeding with AgI unproductive during many periods of otherwise high seeding potential.

Valley seeding has economic and logistic advantages, and this examination of valley seeding has shown some encouraging results; however, the conditions for success are diverse and nowcasting which periods can be successfully treated may not be practical on an operational basis. Those considering new valley-based seeding projects are advised to start small, take appropriate weather measurements and, most important, conduct transport and diffusion studies verifying adequate targeting before committing to a large-scale operation. This appendix, and a significant body of published research summarized by Super (1999a), suggests that low concentrations of effective seeding material or none were detected over the Plateau during most periods of valley seeding. Overly wide spacing and low generator outputs likely contributed to this result. It would be more productive to place generators on the windward foothills and canyon mouths, but far better to locate them well up the windward slope of the main ridge. This last option is logistically expensive, but worth considering to achieve reliable targeting and release into colder temperatures.