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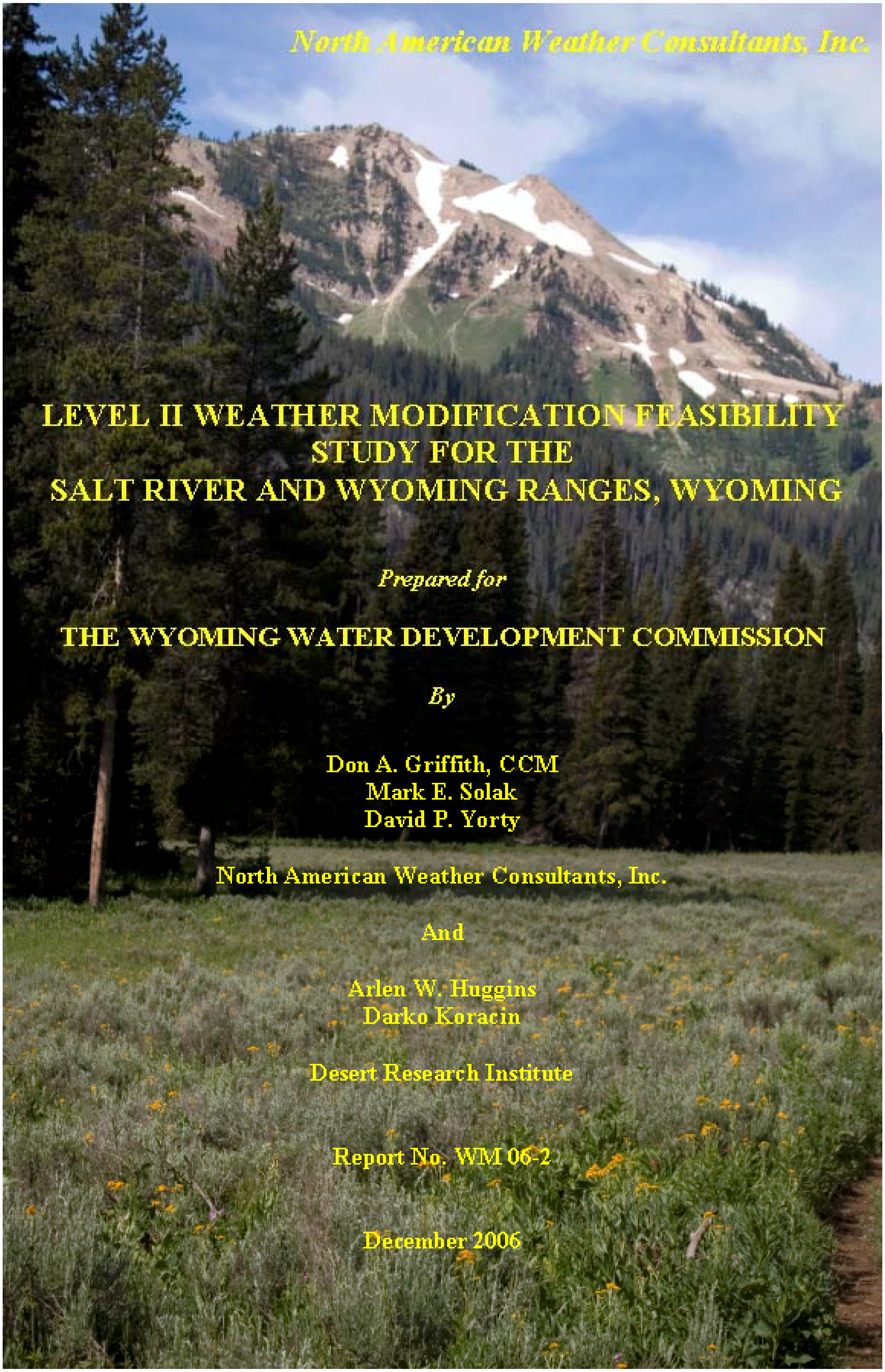
Funding for WRDS and the creation of this electronic document was provided by the Wyoming Water Development Commission (http://wwdc.state.wy.us)



North American Weather Consultants, Inc.

LEVEL II WEATHER MODIFICATION FEASIBILITY STUDY FOR THE SALT RIVER AND WYOMING RANGES, WYOMING

Prepared for

THE WYOMING WATER DEVELOPMENT COMMISSION

By

Don A. Griffith, CCM
Mark E. Solak
David P. Yorty

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Report No. WM 06-2

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1.0 INTRODUCTION

North American Weather Consultants, Inc. (NAWC) received a pre-qualification notification for Request for Proposals No. 0183-M in January, 2005. NAWC responded with the requested forms. NAWC then received a formal Request for Proposals (RFP) in early March, 2005. This RFP was issued by the Wyoming Water Development Commission (WWDC) for a Weather Modification Level II Study (RFP # 0183-M). NAWC responded to this RFP with a formal proposal (NAWC # 04-169), which was due April 1, 2005. The purpose of the work, as stated in the RFP, was to: "Perform a Level II Weather Modification Feasibility Study of the Salt River and Wyoming Ranges (including the Tunp Range) located in Lincoln and Sublette Counties."

The general project description of the scope of work to be performed contained in the Pre-Qualification for Request for Proposals is as follows: "The Consultant will be requested to assess the feasibility of conducting cloud seeding programs in the Salt River and Wyoming Ranges for winter snowpack augmentation. The Consultant shall analyze the climatology of the region, including storm frequencies and characteristics, barriers, seeding potential, etc. Project designs are to be developed, including methods and materials, equipment, siting issues, operational criteria, and the evaluation of project results through monitoring and statistical methods. Cost estimates are to be produced along with the identification of the potential benefits to be realized, yielding a preliminary cost/benefit analysis."

The RFP provides a history of events, which led to the release of this RFP. This history is as follows: "The 2004 Wyoming State Legislature funded a state sponsored weather modification feasibility study for the Medicine Bow/Sierra Madre and Wind River Ranges. The study evaluated the feasibility of conducting cloud seeding programs in each of the two project areas for winter snowpack augmentation. The study identified methods, equipment, siting issues, permitting, operational criteria, monitoring regimes, evaluation methodology, potential water resource benefits, costs, and a cost/benefit analysis. Recommendations from this study are being used as the framework for the design and operation of a 5-year pilot program in each of the two target areas."

"Area V of the Wyoming Association of Conservation Districts, representing six conservation Districts in five counties (Teton, Lincoln, Uinta, Sublette, and Sweetwater), has since requested that the Water Development Commission conduct a state sponsored Level II Weather Modification Study of the Salt River and Wyoming Ranges (including Tunp Range) located in west central Wyoming. Runoff from winter snowpack in these areas impact flows in the Bear, Green and Snake/Salt River Basins. Since extensive weather modification programs exist in each of the nearby neighboring states (Idaho and Utah), close evaluation of these other programs will be necessary during the course of this feasibility study."

NAWC reached an agreement with the Desert Research Institute (DRI) for their Division of Atmospheric Sciences to assist NAWC in possibly working on this project as a subcontractor. NAWC and DRI representatives were invited to participate in a best and final presentation regarding their proposal. This presentation was conducted at the Wyoming Water Development Commission offices located in Cheyenne, Wyoming on May 5, 2005. This presentation was made before a selection committee that was composed of Wyoming Water Development Commission personnel plus a number of representatives of other resource management agencies (e.g., National Weather Service, U.S. Forest Service). NAWC was informed that it had been selected to perform this work and the Water Development Commission and Select Water Committees had approved this study on June 2, 2005. A contract was approved and NAWC notified to begin work on June 30, 2005. NAWC subcontracted with the Desert Research Institute of the University of Nevada system for plume dispersion modeling trials as part of the feasibility study.

The following sections of this report describe the work that NAWC/DRI conducted in completing the various tasks that were documented in the initial RFP and subsequent contract language. We will use the abbreviation SRWR to refer to this Salt River Wyoming Range feasibility/preliminary design study.

2.0 GENERAL DESRCIPTION OF THE POTENTIAL TARGET AREAS

The Salt River and Wyoming Ranges (including the Tunp Range) located in Lincoln and Sublette Counties are considered to be the primary target area in this preliminary feasibility/design study. These mountain ranges lie in western and southwestern Wyoming. Figure 2.1 provides the locations of these mountain ranges. In this figure, approximately the 8,000 foot (2.4 km) contour is highlighted for reference purposes. Figure 2.2 provides an overview of the potential target areas and the surrounding terrain. The Salt River and Wyoming Ranges are oriented in approximately a north to south direction, which is an important factor in regards to the type of winter storm conditions that produce significant precipitation over these barriers. This topic will be discussed in a later section. The two major barriers (Salt River and Wyoming Ranges) are nearly parallel to each other with a mountain valley separating the two barriers, through which the Greys River flows in a northerly direction.

The Wyoming Range lying along the eastern side of Lincoln County and the western side of Sublette County and extends southward approximately 50 miles (80 km), from the northern border of Lincoln County. South of this point the Wyoming Range abuts other smaller, lower elevation mountainous areas (e.g., the Absaroka and Commissary Ridges). The highest point in the Wyoming Range is Wyoming Peak with an elevation of 11,378 feet (3.5 km). Some of the other significant peaks include: Hoback Peak (10,864', 3.3 km), Mount McDougal (10,780', 3.3 km), and Bradley Mountain (9,292', 2.8 km).

The Salt River Range begins in north central Lincoln County and runs southward some 50 miles (80 km) through the approximate center of the county. This mountain range is also abutted by another lower elevation mountain range on its southern extent known as the Tunp Range. The highest point in the Salt River Range is Mount Wagner (10,709', 3.3 km). Some of the other significant peaks include: Stewart Mountain (10,080', 3.1 km), and Commissary Ridge North (9,985', 3.0 km).

Figure 2.3 provides a vertical profile of the terrain between Grover and Daniel, Wyoming. This figure clearly shows the two potential target barriers with the Greys River Valley separating the two barriers. The locations of Grover and Daniel are provided in Figure 2.1.

Rivers and streams that originate in these mountain ranges include the Greys and Salt Rivers (with numerous smaller tributaries) that drain northward and join the Snake River at Palisades Reservoir. Streams that drain eastward from the Wyoming Range include: Cottonwood Creek, Piney Creek, La Barge Creek, Fontenelle Creek, and Hams Fork, all tributaries of the Green River. One significant stream, the Smiths Fork, drains to the southwest from the southern end of the Salt River Range and is a tributary of the Bear River.

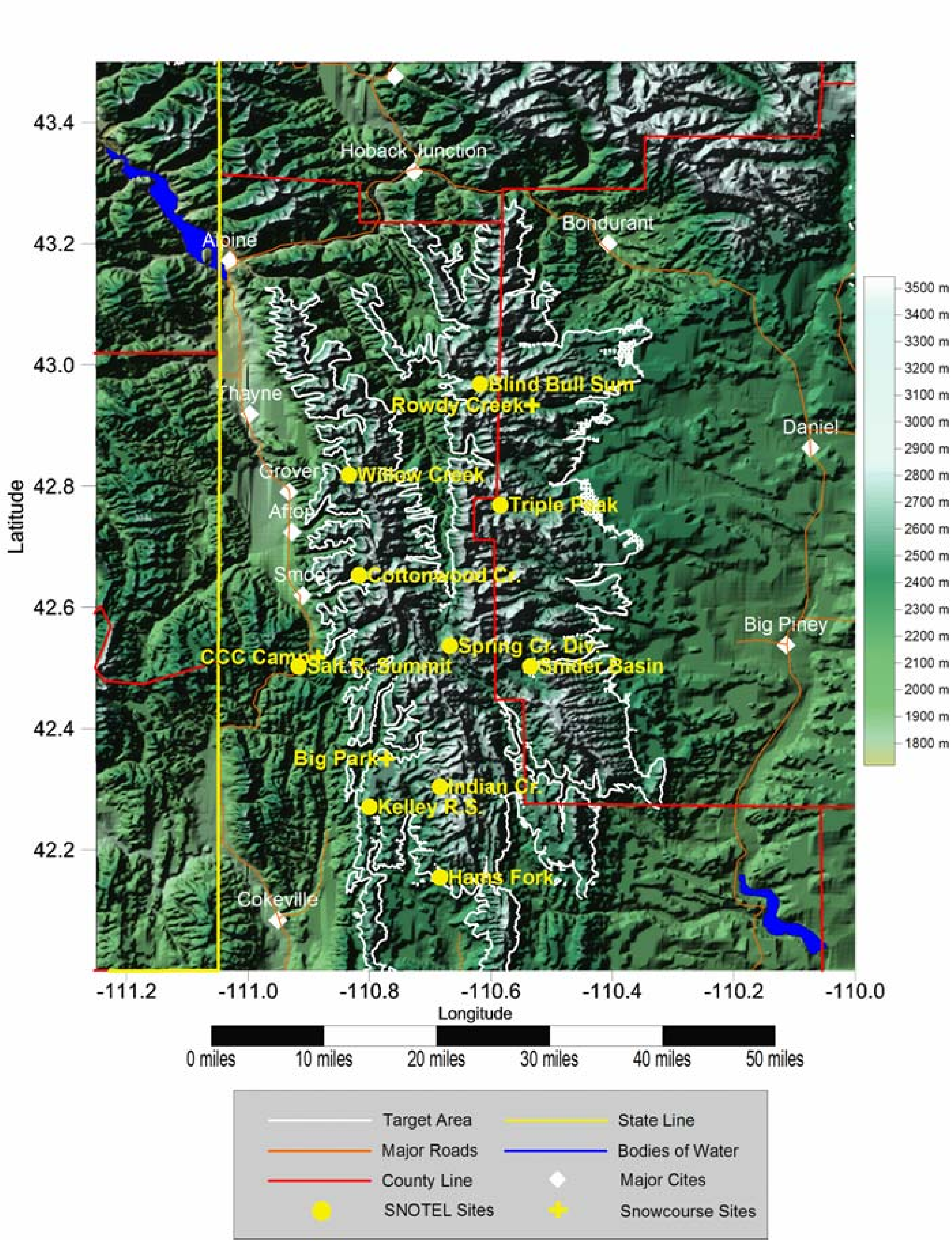

Figure 2.1 Potential Target Areas as Defined by 8,000' Contour, Salt River and Wyoming Ranges

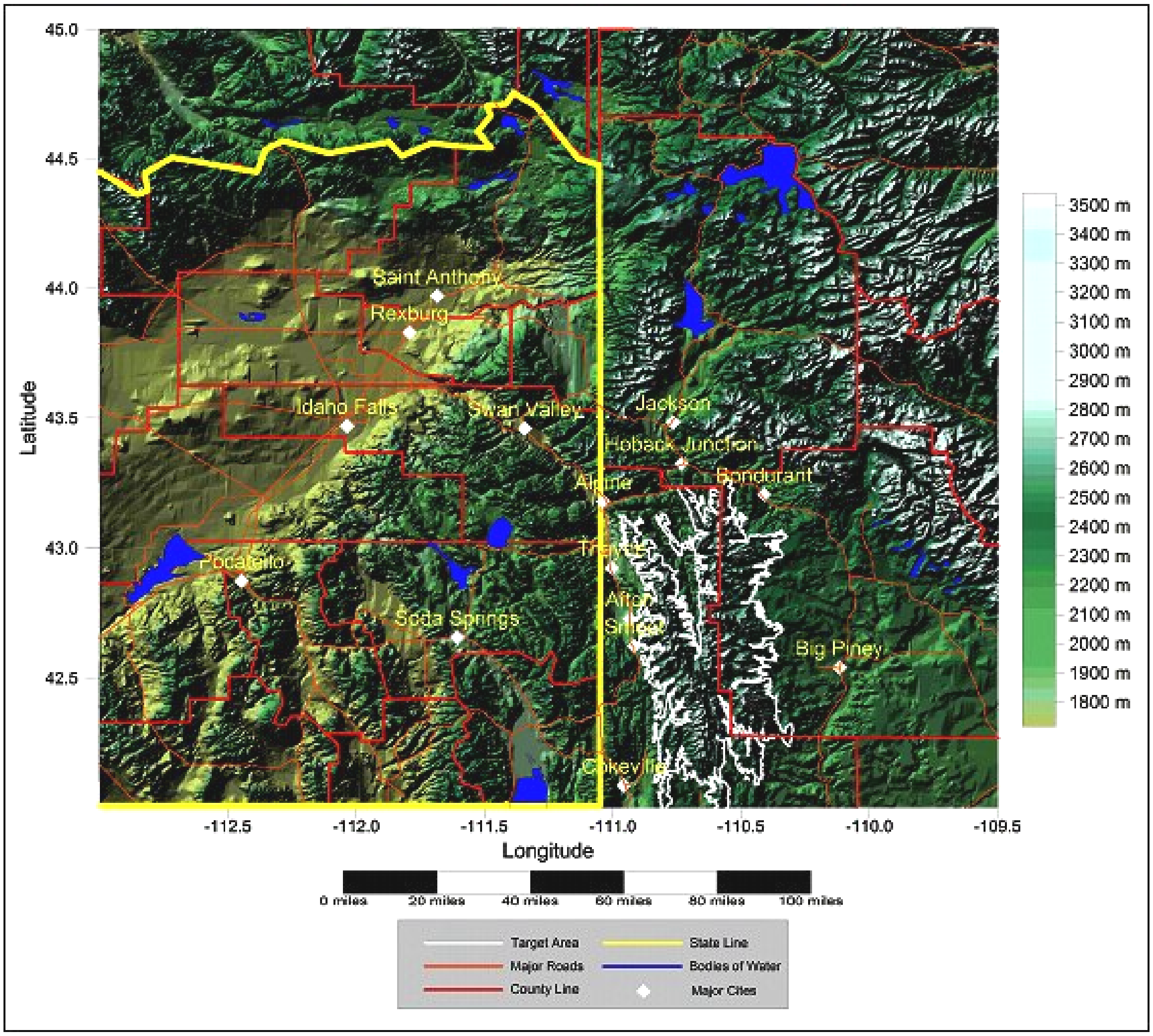

Figure 2.2 Potential Target Area and Surrounding Areas

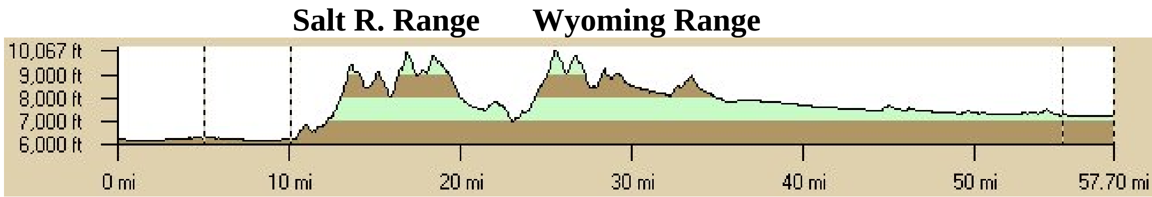

Figure 2.3 Topographic Profile from Grover to Daniel, Wyoming

Two major reservoirs are located downstream of these rivers and streams that originate in Lincoln and Sublette Counties: Palisades Reservoir, located in extreme eastern Idaho with a portion in western Wyoming; and Fontenelle Reservoir, located in eastern Lincoln County. Palisades is a reservoir that was developed by the Bureau of Reclamation in 1957 and designed as an irrigation storage, power generation, and flood control impoundment. The maximum capacity of Palisades reservoir is 1,417,810 acre feet. The State of Wyoming owns 33,000 AF of joint use space in Palisades. All Palisades Reservoir spaceholder contracts provide for the use of a proportionate share of the water accruing to the reservoir water rights, the ability to keep unused stored water for use in subsequent years. Additionally, Wyoming has the option of making exchanges to allow the use of their Palisades Reservoir space to retain water in Jackson Lake or to increase winter flows in the Snake River for cutthroat trout. This space also insures Wyoming's ability to fulfill Snake River Compact obligations. Fontenelle is a Bureau of Reclamation reservoir constructed in 1964. It has a maximum capacity of 345,397 acre feet and was developed as a multi-purpose project with permitted uses that include irrigation, domestic, industrial, municipal, stock, fisheries, recreation and hydropower. The power generation facilities at these two reservoirs could be important when considering the potential dollar benefits from a cloud seeding program, as discussed in a later section. There is also a smaller reservoir, Viva Naughton on the Hams Fork, operated by Rocky Mountain Power. This reservoir has also been the subject of a recently completed WWDC Level II study, which examined the feasibility of enlarging this Green River Basin storage facility.

3.0 SCOPING AND PROJECT MEETINGS

NAWC's contract with the WWDC calls for public meetings to be conducted during the course of the work. Scoping meetings were scheduled to be conducted near the beginning of the contractual work to familiarize the WWDC, technical advisors, and the public with the scope of the project, and to obtain input from affected parties. These meetings were held near the project area. The first scoping meeting was conducted in Afton, Wyoming on July 19, 2005 in the Lincoln County School Administration Building at 3 p.m. The second meeting was held at the Marbleton, Wyoming Fire Hall at 10 a.m. on July 20, 2005. The attendees of these two meetings are listed in Appendix B. Among other issues, two of substance were raised during the conduct of these scoping meetings: 1) what impact would the cloud seeding program have on snow removal costs? and 2) would suspensions in seeding activities be called when avalanche warnings were issued that impacted the proposed target areas? These questions are addressed in later sections of this report.

Additional meetings (two near the project area and one meeting with the Weather Modification Technical Advisory Team) were conducted, to present the methodology and findings of the feasibility study. The first of the project area meetings was held on September 5, 2006 at 7:00 PM at the Lincoln County School Administration Building in Afton, Wyoming. The second project area presentation of study findings was held on September 6, 2006 at 2:00 PM as part of the Wyoming Association of Conservation Districts – Area V meeting in Lyman, Wyoming. The presentation to the Weather Modification Technical Advisory Team (TAT) occurred at the National Center for Atmospheric Research in Boulder, Colorado on September 7, 2006, as part of the Wyoming Weather Modification TAT meeting. The results of this feasibility/design study were presented at these meetings.

4.0 REVIEW AND SUMMARY OF PREVIOUS RESEARCH

When considering the feasibility of a proposed activity, in this case the seeding of winter storms to augment snowpack and resultant runoff, it is good practice to review earlier similar efforts. This can take the form of individual project reviews, but can also benefit greatly from consideration of the statements or policies of professional societies or associations concerned with such issues. In this section, we do both, beginning with the generalized indications at the organizational level, and then summarize project-specific indications from particularly relevant efforts within the realms of field operations and research. The various indications are then summarized according to what we consider to be the key relevant questions involved in a credible assessment of winter snowpack augmentation feasibility for Wyoming.

4.1 Relevant Winter Weather Modification Research Programs

This section contains summaries of findings from some of the weather modification research programs that we deem relevant to the design of the SRWR project.

4.1.1 Utah Research Programs

The Utah State government, specifically the Division of Water Resources, has been highly supportive of weather modification research in the State of Utah. Over a period of more than two decades, the state has sponsored or co-sponsored such activities, including cooperative efforts with the U.S. Bureau of Reclamation (USBR) and the National Oceanic and Atmospheric Administration (NOAA).

4.1.1.1 Utah State University

Some early investigations in Utah are reported in Hill (1980). Via analyses of supercooled water concentrations, precipitation records, aircraft icing reports and upper air soundings, it was found that winter orographic clouds over windward slopes of mountains in northern Utah, with cloud-top temperatures between 0^0 C and -22^0 C, are primarily composed of supercooled liquid water (SLW) and therefore offer high modification potential. The SLW concentrations were found to be correlated with updraft velocity. The potential precipitation yield is dependent on the SLW flux over the barriers. Hill concluded that high seedability was associated with 1) postfrontal conditions, when a) the cross-barrier flow is strong, b) high level subsidence is occurring, c) moisture remains high at mountaintop levels; and 2) weak low-level moisture systems with strong airflow and perhaps subsidence aloft. Hill also speculated that, in the absence of convection, seeding opportunity is limited, especially in well-developed cyclonic systems.

4.1.1.2 NOAA/Utah Atmospheric Modification Program (AMP)

Utah was one of two original states selected by NOAA for the conduct of research superimposed on an on-going operational program (North Dakota was the other state). Research in Utah began in 1981 (Golden, 1995). A variety of remote sensing and in situ observations have been acquired in this research program in Utah in/over a variety of mountain ranges (Wasatch Plateau, Wasatch Range and Tushar Range). Some key results from the Utah Atmospheric Modification Program (AMP) are summarized in the following. Much of the work done in the 1990's is summarized in Super (1999).

- Supercooled Liquid Water

Microwave radiometer, aircraft cloud physics and ridge-top ice detector observations have indicated that supercooled liquid water commonly occurs in Utah winter storms. The amounts of liquid water are oftentimes not large but liquid water is frequently present for significant periods during the passage of winter storms. The supercooled liquid water is concentrated along the windward slopes of the Utah mountain barriers and frequently occurs at relatively low levels in the storms (i.e., near or below the crest height). Some of the liquid water occurs at relatively warm (e.g.,>-5^{0}C) temperatures. (Super and Huggins, 1993; Huggins, 1995).

- Trajectories of Ground Releases of Silver Iodide Seeding Material

In the Utah research conducted in the 1990's, increasing attention was focused upon observing the trajectories and estimated concentrations of ground releases of silver iodide seeding material. Primary observations included ground based and aircraft based National Center for Atmospheric Research (NCAR) acoustic counters and sulfur hexafluoride (SF_6) real-time analyzers.

A ground based NCAR counter (Langer, 1973) located at the 2.2 km elevation in Big Cottonwood Canyon in the Wasatch Front Mountains during the 1989-90 winter season, detected silver iodide nuclei released from two silver iodide generators located further down the canyon. One or both generators were activated during 13 separate storm events. Silver iodide nuclei were detected in significant concentrations on each of the 13 events (Super and Huggins, 1992).

SF_6 and/or silver iodide releases from valley locations upwind of the Wasatch Plateau were detected by aircraft and/or ground based analyzers over or along the ridgeline of the Wasatch Plateau in a number of different cases (Griffith, **et al**., 1992; Super, 1995). Other cases did not indicate the transport of seeding material released from valley generators over the Wasatch Plateau. The latter cases normally corresponded with the presence of low-level stable layers or temperature inversions and light surface winds. Some cases apparently demonstrated a "pooling" of silver iodide nuclei under inversion conditions followed by the transport of these nuclei over the barrier with the passage of some weather feature. The spread of seeding plumes, as evidenced by SF_6 analyzer and NCAR counter measurements, is suggested as occurring in a sector on the order of 15^0 to 25^0 (Griffith, et al**,** 1992; Super, 1995).

Calculations of the spacing of valley generators to obtain overlap of plumes over the Wasatch Plateau suggest spacing on the order of 4 to 5 km. Tests of remotely controlled silver iodide generators located part way up the windward side of the Wasatch Plateau indicated more reliable transport of silver iodide material over the Wasatch Plateau than that obtained from valley based generators.

Utah research reported by Heimbach et al (1998) and summarized in Super (1999) indicated that, when surface-based temperature inversions existed, valley released seeding material was sometimes transported up and over the intended mountain target area, likely by the action of gravity waves induced by an upwind mountain range. Such gravity wave effects can be migratory.

The Utah research efforts indicate that in that a large proportion of the investigations aircraft cannot (for safety reasons) reliably fly low enough relative to the underlying rugged terrain to sample the SLW pool and the ground-released seeding plumes. An extremely important finding is that the two (both the SLW and seeding material) are commonly <u>commingled</u> relatively (and enticingly) close to the mountainous terrain, but it is difficult to obtain in-situ measurements of the admixture.

- Propane Seeding

The results of additional experimentation on the Wasatch Plateau during the winter of 2003-04, randomized seeding trials testing the effectiveness of mid-mountain releases of unburnt propane, are reported in Super and Heimbach (2005). Using a seeding site already demonstrated in earlier research to provide routine targeting of target gages a short distance (2.0 – 6.5 km) downwind of the seeding site, 98 short duration experimental units (EU's) and 47 randomized pairs were obtained and subjected to testing. Some of their results include:

- Statistical tests of the 98 EU's without partitioning were strongly suggestive of a seeding effect; increased snowfall at the three target gages. Results for a gage farther downwind were inconclusive.

- A partition focused on southwest flow cases was also strongly suggestive of seeding increases.

- There were suggestions that seeding may have been more effective when SLW cloud was detected, when seeding plume temperatures were warmer, when wind speeds were lighter, and when natural snowfall was lighter. The evidence for these relationships was inconclusive, requiring a larger EU sample size for rigorous testing.

- Inconclusive indications of up to 25% more snowfall for seeded EU's in one wind direction partition were reported.

- Statistical pair testing provided an average seeded EU increase of 0.014 in h^{-1}.

- The authors speculated that, via extrapolation of these suggestive, small area seeding coverage indications to a much larger area, snowfall increases of the order of 10% might result. Note: This would require installation and operation of a very large number of propane seeding sites, given the small horizontal dispersion possible, since the dispensers must be located quite close to the barrier summit in this particular location. This is an important point, since narrow barriers are typical of Utah's mountain ranges and the Salt River and Wyoming Ranges.

- Ground Generator Effectiveness

Tests were conducted on Montana State "Skyfire" and NAWC manually operated silver iodide generators. These tests were conducted at the Colorado State University Cloud Simulation Laboratory (Demott et al**,** 1995). These tests indicated an improvement in the performance of the NAWC generator over earlier tests conducted at the same facility in 1978 and 1981. This improvement was most noticeable at the warmer temperature ranges of -6^0 to -8^0 C. The improvement in efficiency was apparently related to some minor modifications made to the burn chamber and nozzle on the NAWC generator.

- Mesoscale Modeling

An application of the Clark Mesoscale model (Clark, 1977) has been made to the Utah Atmospheric Modification Program (AMP) Wasatch Plateau studies (Heimbach et al**,** 1997; Holroyd, et al**,** 1995). The model appears to provide reasonable simulations of plume transport with some under prediction of plume concentrations in two different cases.

- Observations of Enhanced Ice Crystal Production

Some of the Utah AMP research cases sampled with cloud physics aircraft have indicated enhanced ice crystal production within the silver iodide plumes (Holroyd, et al**,** 1995; Super, 1995). Linkages of these increased ice crystals to fallout to the ground have not been adequately documented due in part to the inability to fly the aircraft near ground level in storm conditions over the Wasatch Plateau. There are limited indications of increases in precipitation measured at ground level in some of these cases.

- Application of Utah AMP Results to the Utah Operational Seeding Programs

The results from the focused research programs support the Utah operational seeding conceptual model. This is an important verification of what was assumed to be true of Utah storms based upon observations made in other geographical areas. Some refinements were made to the operations programs based on these findings.

Transport of valley released silver iodide/SF_6 over Utah mountain barriers has been documented. Since the supercooled liquid water is predominately located at low levels on the upwind 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. In some cases, valley released silver iodide/SF_6 is not transported over the mountain barrier. These cases generally occur when there are low-level atmospheric inversions. An interesting observation from some cases was the indications that nuclei "pool" under these conditions, and are sometimes subsequently scoured from the valley and transported over the barrier with the passage of a synoptic-scale weather feature. This might 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 SF_6 (15^0 to 25^0) 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.

Remotely controlled generators may be effective during periods when valley based generators are not effective. The addition of such generators in high yield, high water value locations could offer an improvement to the current Utah operational program. Such operations are substantially more expensive than valley based networks, thus the restriction of such remote generators to high yield/high water value target locations. NAWC has installed manually operated silver iodide generators at higher elevation areas where local residents can be located to operate the units.

The improvement in efficiency of the NAWC manual silver iodide generator, as documented in the CSU tests, is an important result. The supercooled liquid water detected in Utah winter storms is frequently in the 0^0 to -10^0C range. It is in the -6^0 to -10^0C range that the recent CSU tests indicated improved efficiency over earlier tests.

Information from the Utah AMP suggested higher concentrations of seeding material and faster acting nuclei are desirable. A change has been made from a 2% to a 3% (by weight) mixture of silver iodide in acetone, along with sodium iodide and para-dichlorobenzene, so the seeding plumes now consist of silver chloro-iodide. The change to a solution using sodium iodide and para-dichlorobenzene will produce nuclei that react much faster (a condensation/freezing mechanism) than the previous formula that used a silver iodide and ammonium iodide solution, which produced nuclei that reacted slowly through a contact nucleation mechanism (Finnegan and Pitter, 1988). The density of seeding generators has been increased, further increasing the seeding material concentrations.

4.1.2 Climax I and II

Researchers at Colorado State University conducted two wintertime orographic cloud seeding experiments during the 1960's: Climax I (1960-1965) and Climax II (1965-70). The research included randomized seeding experiments and parallel physical studies of cloud and seeding processes. Climax I indicated a positive precipitation difference of about 6% and in Climax II the difference was about 18%, with a high probability that the differences were not due to chance. Evidence was found for greater increases from seeded systems when warmer orographic cloud-top temperatures prevailed (indexed by the 500 mb temperature being $\geq -20^{0}$C), with no difference indicated when temperatures were colder. The analysis results were reported in Mielke et al (1971) and a reanalysis by the same author (Mielke et al, 1981). Re-analyses of Climax I & II by Rangno and Hobbs (1987, 1993) yielded lower, but still positive, indications of seed effect. The Climax results regarding cloud-top temperature influence on seeding effects, along with similar indications from other projects, led to the recognition of a cloud-top "temperature window" for seeding effectiveness (Grant and Elliott, 1974).

4.1.3 Colorado River Basin Pilot Project (CRBPP)

A five-year randomized cloud seeding experiment was conducted by the U.S. Bureau of Reclamation offices located in Denver, Colorado (USBR) during the early 1970's in the San Juan Mountains of southwestern Colorado, to determine whether the experimental procedures applied in the earlier Climax work would be effective in an operational mode. Seeding was accomplished using ground-based AgI generators. A formal statistical analysis based on 24hr blocks of precipitation data from 71 experimental treated days and 76 experimental control days found no significant difference between precipitation, gage-by-gage, on seeded and unseeded days. However, an *a posteriori* analyses based on shorter (6hr) data intervals indicated that strongly positive seeding effects may have been achieved during periods of relatively warm-topped cloud occurrences, as expected from the Climax experiment. The results of the *a posteriori* analyses suggested that a flawlessly conducted program of selective seeding could increase overall winter precipitation by ~10-12%. The results of the 24hr block analysis may have been negatively affected by seeding material targeting difficulties during the more stable storm phases.

Microphysical studies within the CRBPP showed that supercooled liquid water was generally found in three regions. One was located slightly upwind of the mountain barrier, one was located ~15-20 km upwind of the mountain barrier, and a third associated with an initial rise in the topography ~60-70 km upwind of the barrier. Their studies showed little or no SLW development during stable storm phases, but frequent SLW development in the neutral-unstable phases.

4.1.4 Colorado Orographic Seeding Experiment (COSE)

Researchers from Colorado State University conducted investigations in the Park Range of northwestern Colorado during the winter of 1981-82, in a project named the Colorado Orographic Seeding Experiment. The 1981-82 field campaign was a much expanded version of a field effort that was conducted during the winter of 1979-80. Airborne measurements were conducted during the 1979-80 season. The emphasis of COSE was to determine the natural physical structure of the cloud systems that affect the region toward establishment of a sound weather modification hypothesis. For that reason, no seeding was done prior to or during any of the study period storm systems. Key findings from the experiments are summarized in Rauber et al (1986) and Rauber and Grant (1986). In 1981-82, the full suite of observations involved a scanning dual-channel microwave radiometer and supporting measurements including vertically pointing short wavelength radar, mountaintop liquid water measurements, low and high altitude measurements of ice crystal rime characteristics, rawinsonde data, and precipitation intensity measurements. Storm systems subjected to intensive case studies included prefrontal and frontal storms, postfrontal storms and orographic storms, with a particular emphasis on development of conceptual models of the structure and evolution of liquid water fields in a variety of storm situations.

Cloud top, cloud base and zones of strong orographic lift were identified as regions in stratiform systems where SLW production can occur, i.e., when the condensate supply rate exceeds the diffusional growth rate of the ice crystals present in the volume. In the aforementioned Rauber articles, SLW was found to occur in all stages of most of the storms studied, but temporal variations in the magnitude of the SLW were significant. SLW was most consistently present in relatively shallow cloud systems with warm (>-22^{0}C) cloud top temperatures and low precipitation rates. From a COSE case study reported by Sassen (1984), a deep, cold-topped storm system was found to rather consistently show the presence of SLW, leading that article's author's statement: "This raises, then, the question of the seedability of this type of storm from the standpoint of weather modification practices. On the basis of cloud-top temperature criteria, this storm would not have been a candidate for seeding… Nonetheless, in view of the documented presence of supercooled liquid water, it may be worthwhile to reexamine the criteria applied to this type of deep cloud system." Note: Similarly, analysis by NAWC of mountain-top ice detector measurements in Utah during the winter of 2003-04 (Solak et al**,** 2005) found several deep, cold storms exhibiting SLW production considered adequate for seedability.

4.1.5 Grand Mesa, Colorado

The following is excerpted from a USBR report entitled *The Feasibility of Operational Cloud Seeding in the North Platte River Basin Headwaters to Increase Mountain Snowfall* (2000). The excerpt is from Appendix A of the report, prepared by Arlin B. Super.

"Holroyd et al (1988) discussed the results of several airborne plume tracking experiments with high altitude ground-based AgI seeding generators on the Grand Mesa of western Colorado. Sampling was done under a variety of cloud, wind and stability conditions. Ground releases were made from different sites, ranging from 650 to 2,300 feet below the 10,500 ft mesa top. Instantaneous plume widths were almost always within a factor of two of the 15-degree median angle. The instantaneous plumes meandered through a wider angle with a median of 38 degrees. With a single exception, plumes were confined to within 2,600 ft of the Mesa top, and the median vertical extent was about 1,800 ft. These results were in close agreement with earlier observations from the Bridger Range of Montana. Both mountain barriers rise about 5,000 ft above upwind valleys.

Super and Boe (1988) presented various airborne observations for two of the cases discussed by Holroyd et al (1988). They showed that the ice crystal concentrations and estimated snowfall rates were markedly increased about 2000 ft above the mesa top approximately 3.7 mi downwind from the high altitude AgI generator."

These findings provide useful information regarding seeding plume horizontal spread and vertical rise for comparison with the spatial distribution of SLW noted elsewhere in this section.

4.1.6 NCAR / Wyoming

As part of the recent (March 2005) weather modification feasibility study conducted for the Wind River Range and Medicine Bow/Sierra Madre Ranges in Wyoming, investigators from NCAR conducted a number of modeling trials. The results and implications for seeding project design appear in the report prepared by Weather Modification Inc., for the Wyoming Water Development Commission. A few key points, relevant to the current feasibility work include the following:

- SLW associated with orographic lifting was strongly linked to the upwind side of the mountain barriers and the amount of SLW available for seeding is tied to the strength of the cross-barrier wind component.
- Tracer/seeding material released on the upwind side of the mountain barriers was shown as spreading horizontally and being lofted over the barriers, with a vertical depth of less than 500 m above the sloping terrain.
- Gravity waves and associated SLW regions were evident, forming in lines in the lee of the mountains orthogonal to the wind direction.
- Ground-based generators should be used to target the SLW associated with orographic lifting, with the understanding that the vertical depth of the seeded plumes, in the absence of convection, would be limited to about 500 m above the terrain.
- Aircraft could be used to seed the SLW above 500 m AGL, assuming the ability to fly safely relative to the underlying terrain. Aircraft could also be used to seed the SLW associated with gravity waves.

4.1.7 Bridger Range Experiment

A randomized exploratory seeding experiment was carried out in the Bridger Range of southwestern Montana during the winters of 1969-72. The seed mode was ground-based AgI generators located at mid-mountain or higher locations to avoid seeding material trapping by lower stable layers. Airborne plume sampling and silver-in-snow analysis provided evidence of successful targeting of the seeding material. A *post hoc* statistical analysis using control gage data indicated ~15% more seasonal target area precipitation than predicted. Snowpack data analysis indicated positive effects of the same seasonal magnitude. The experiment is summarized in Super and Heimbach (1983).

4.1.8 Nevada/Desert Research Institute Projects

Cloud seeding has been conducted in the Lake Tahoe area in the Sierra Nevada since the 1960's. The Desert Research Institute (DRI) has conducted both operational and research programs in this area. The purposes of the research programs have varied. One of the significant developments pioneered by DRI has been in snow chemistry. One of the accomplishments in recent snowpack augmentation research is the establishment of the direct link between the seeding activity and the water reaching the ground in the form of snow. The mm/hr increases in precipitation caused by silver iodide seeding have been documented several times in the reviewed scientific literature between 1988 and 1999. The link has been established by physical and chemical techniques. The snow precipitated at particular targeted sites is connected directly to the seeding material and to concurrently released chemical tracers in that snow. The advantage of this snowpack sampling work is that the scientists are dealing with solid-state precipitation that can be sampled during and after storm events and stored in the frozen state until analyzed. The methodologies used to establish this direct linkage have been described by Warburton et al. (1985, 1995a,b, and 1996), Chai et al. (1993), Super and Holroyd (1997), and McGurty (1999). DRI has also used remote measurements (e.g., microwave radiometers) to study the "seedability" of winter storms. Other recent work at DRI has included the development of sophisticated atmospheric models to study the evolution of features of interest (e.g., supercooled liquid water) and the predicted transport and diffusion of ground released silver iodide seeding material.

4.1.9 University of Wyoming (Elk Mountain)

The University of Wyoming, Department of Atmospheric Sciences was involved in cloud seeding research in the 1960's and 1970's. A majority of this research was conducted in "cap" clouds that often occur over Elk Mountain located in south-central Wyoming. Observations were made of ice crystal and ice nuclei concentrations (Auer, et al, 1969), the presence of surface released silver iodide plumes, cloud droplet concentrations and cloud condensation nuclei (Black, 1980), ice crystal development using cloud physic aircraft (Cooper and Vali, 1981), precipitation efficiencies based upon aircraft measurements (Dirks, 1973), and condensation-freezing ice nucleation (Kelly, 1978). Whether the results obtained from this interesting research conducted in "cap" clouds are representative of larger scale winter cloud systems in Wyoming is open to question. Certainly some of the information would likely be the same in either situation. For example, the finding that ground released silver iodide plumes seldom rise to heights greater than 1500 feet (450 m) above the surface and the dispersion angle of such plumes being on the order of 10^{0} is similar to other studies conducted in Colorado and Utah.

4.2 Organizational Statements or Policies

The principal societies or associations concerned with weather modification capabilities in all or part include the following:

- The Weather Modification Association (WMA)
- The American Meteorological Society (AMS)
- The World Meteorological Organization (WMO)
- The American Society of Civil Engineers (ASCE)

Each group maintains and publishes a policy or capability statement regarding weather modification in its primary categories. Excerpted from their overall statements, the statements of each organization pertaining to winter precipitation augmentation are presented here.

Weather Modification Association (2005)

"Winter Precipitation Augmentation

The capability to increase precipitation from wintertime orographic cloud systems has now been demonstrated successfully in numerous "links in the chain" research experiments. The evolution, growth and fallout of seeding-induced (and enhanced) ice particles have been documented in several mountainous regions of the western U. S. Enhanced precipitation rates in seeded cloud regions have been measured in the range of hundredths to >1 mm per hour. Although conducted over smaller temporal and spatial scales, research results tend to be consistent with evaluations of randomized experiments and a substantial and growing number of operational programs where 5% - 15% increases in seasonal precipitation have been consistently reported. Similar results have been found in both continental and coastal regions, with the potential for enhanced precipitation in coastal regions appearing to be greater in convective cloud regimes. The consistent range of indicated effects in many regions suggests fairly widespread transferability of the estimated results.

Technological advances have aided winter precipitation augmentation programs. Fast-acting silver iodide ice nuclei, with higher activity at warmer temperatures, have increased the capability to augment precipitation in shallow orographic cloud systems. Numerical modeling has improved the understanding of atmospheric transport processes and allowed simulation of the meteorological and microphysical processes involved in *cloud seeding. Improvements in computer and communications systems have resulted in a steady improvement in remotely controlled cloud (ice) nuclei generators (CNG's), which permit improved placement of CNG's in remote mountainous locations.*

Wintertime snowfall augmentation programs can use a combination of aircraft and ground-based dispersing systems. Although silver iodide compounds are still the most commonly used glaciogenic (causing the formation of ice) seeding agents, dry ice is used in some warmer (but still supercooled) cloud situations. Liquid propane also shows some promise as a seeding agent when dispensers can be positioned above the freezing level on the upwind slopes of mountains at locations adequately far upwind to allow growth and fallout of precipitation within the intended target areas. Dry ice and liquid propane expand the window of opportunity for seeding over that of silver iodide, since they can produce ice particles at temperatures as warm as -0.5^o C. For effective precipitation augmentation, seeding methods and guidelines need to be adapted to regional meteorological and topographical situations.

Although traditional statistical methods continue to be used to evaluate both randomized and non-randomized wintertime precipitation augmentation programs, the results of similar programs are also being pooled objectively in order to obtain more robust estimates of seeding efficacy. Objective evaluations of non-randomized operational programs continue to be a difficult challenge. Some new methods of evaluation using the trace chemical and physical properties of segmented snow profiles show considerable promise as possible means of quantifying precipitation augmentation over basin-sized target areas."

American Meteorological Society (1998)

"Precipitation Increase

There is statistical evidence that precipitation from supercooled orographic clouds (clouds that develop over mountains) has been seasonally increased by about 10%. The physical cause-and-effect relationships, however, have not been fully documented. Nevertheless, the potential for such increases is supported by field measurements and numerical model simulations."

World Meteorological Organization (2004)

"Precipitation (Rain and Snow) Enhancement

This section deals with those precipitation enhancement techniques that have a scientific basis and that have been the subjects of research. Other non-scientific and unproven techniques that are presented from time to time should be treated with the required suspicion and caution.

Orographic mixed-phase cloud systems

In our present state of knowledge, it is considered that the glaciogenic seeding of clouds formed by air flowing over mountains offers the best prospects for increasing precipitation in an economically-viable manner. These types of clouds attracted great interest in their modification because of their potential in terms of water management, i.e. the possibility of storing water in reservoirs or in the snowpack at higher elevations. There is statistical evidence that, under certain conditions, precipitation from supercooled orographic clouds can be increased with existing techniques. Statistical analyses of surface precipitation records from some long-term projects indicate that seasonal increases have been realized.

Physical studies using new observational tools and supported by numerical modeling indicate that supercooled liquid water exists in amounts sufficient to produce the observed precipitation increases and could be tapped if proper seeding technologies were applied. The processes culminating in increased precipitation have also been directly observed during seeding experiments conducted over limited spatial and temporal domains. While such observations further support the results of statistical analyses, they have, to date, been of limited scope. The cause and effect relationships have not been fully documented, and thus the economic impact of the increases cannot be assessed.

This does not imply that the problem of precipitation enhancement in such situations is solved. Much work remains to be done to strengthen the results and produce stronger statistical and physical evidence that the increases occurred over the target area and over a prolonged period of time, as well as to search for the existence of any extra-area effects. Existing methods should be improved in the identification of seeding opportunities and the times and situations in which it is not advisable to seed, thus optimizing the technique and quantifying the result.

Also, it should be recognized that the successful conduct of an experiment or operation is a difficult task that requires scientists and operational personnel. It is difficult and expensive to fly aircraft safely in supercooled regions of clouds. It is also difficult to target the seeding agent from ground generators or from broad-scale seeding by aircraft upwind of an orographic cloud system."

American Society of Civil Engineers (2003)

A more general statement, the ASCE's policy (Policy Statement #275, 2003) is based largely on evidence in winter precipitation augmentation operations and research.

"Policy

The American Society of Civil Engineers (ASCE) supports and encourages the protection and prudent development of atmospheric water (also known as "weather *modification" or "cloud seeding") for beneficial uses. Sustained support for atmospheric water data collection, research and operational programs, and the careful evaluations of such efforts including the assessments of extra-area and long-term environmental effects, is essential for prudent development. ASCE recommends that the results and findings of all atmospheric water-management programs and projects be freely disseminated to the professional community, appropriate water managers and to the public.*

Issue

Atmospheric water management capabilities are still developing and represent an evolving technology. Longer-term commitments to atmospheric water resource management research and operational programs are necessary to realize the full potential of this technology.

Rationale

Water resources worldwide are being stressed by the increasing demands placed upon it by competing demands generated by population growth and environmental concerns. As a result, nations have become sensitive to year-to-year variations in natural precipitation. The careful and well-designed management of atmospheric water offers the potential to significantly augment naturally-occurring water resources, while minimizing capital expenditures or construction of new facilities. New tools, such as radar and satellite tracking capabilities and other imaging devices, atmospheric tracer techniques and advanced numerical cloud modeling offer means through which many critical questions might now be answered. Continued development of atmospheric water-management technology is essential. ASCE has developed materials providing guidance in the use of atmospheric water-management technology with weather modification organizations for dissemination to local communities and governments as well as state, regional and international interests."

From the preceding organizational statements, the following key points regarding the current status of winter orographic seeding for snowpack augmentation emerge:

- Of the primary categories of cloud seeding for precipitation increase; seeding of winter orographic storm systems seems to offer the best prospects for increasing precipitation in an economically viable manner.
- Strong (albeit largely non-randomized) statistical evidence exists for (winter) seasonal increases of the order of 5% to 15%.
- A growing body of evidence from focused physical studies is confirming some key steps in the weather modification process, in support of the statistical evidence.
- Additional research is recommended/encouraged. It is recognized that (needed) additional applied research can shed much valuable light on the physical processes involved, leading to improved opportunity recognition and intervention, resulting in more optimum augmentation operations, especially

given technological advancements in observational systems and computer modeling.
- Accurately quantifying the effects of cloud seeding programs remains a challenge.

Other Organizations

A few additional organizations, although not having published formal policy statements on weather modification, do encourage additional weather modification research and operations. They include, for example, the North American Interstate Weather Modification Council, a non-profit organization of regulatory agencies, research institutions and sponsoring organizations involved in cloud seeding technology, and the Western States Water Council, an organization including representatives from eighteen western states, including Wyoming.

4.3 Relevant Operational Projects

A substantial number of winter operational cloud seeding projects have been conducted in regions of the western U.S. that have relevance to the proposed Salt River and Wyoming Range project. These are largely purely operational projects, i.e., the seeding is done on a non-randomized basis. Nonetheless, mathematical evaluations (estimations of seeding effects) have been performed for essentially all of them. Further, some have included research components during at least some of their duration.

4.3.1 Utah Power and Light

A winter snowpack augmentation seeding project was conducted by NAWC for Utah Power & Light (UP&L), focused on portions of the Bear Lake watershed, including the Thomas Fork and Smiths Fork region of Wyoming. The project used ground-based solution-burning AgI generators and was conducted during the periods of 1955-1970, 1980-1982, plus 1989 and 1990. A target/control mathematical evaluation of snowpack during the 18 winter seasons through 1982 (Griffith, et al, 1983) indicated a positive difference of 11 percent, reported as statistically significant at the .055 level using the one-tailed Student's t test. That analysis also presented a convincing double-mass plot of target and control seasonal snowpack data encompassing the pre-project (statistical base period) years and the subsequent seeded and embedded not-seeded years. The double mass plotting technique is a tool frequently used in engineering circles as a means of detecting changes that may occur between two variables. That plot is shown in Figure 4.1. A distinct and sustained upward break is seen in 1955, the season marking the start of seeding operations. The line breaks downward during the non-seeded years in the 1970's, then upward again corresponding with the resumption of seeding operations for the winter of 1979-1980. The latter upward (seeded) slope returns to that of the earlier seeded period. The combined statistical and double-mass plot indications are quite compelling.

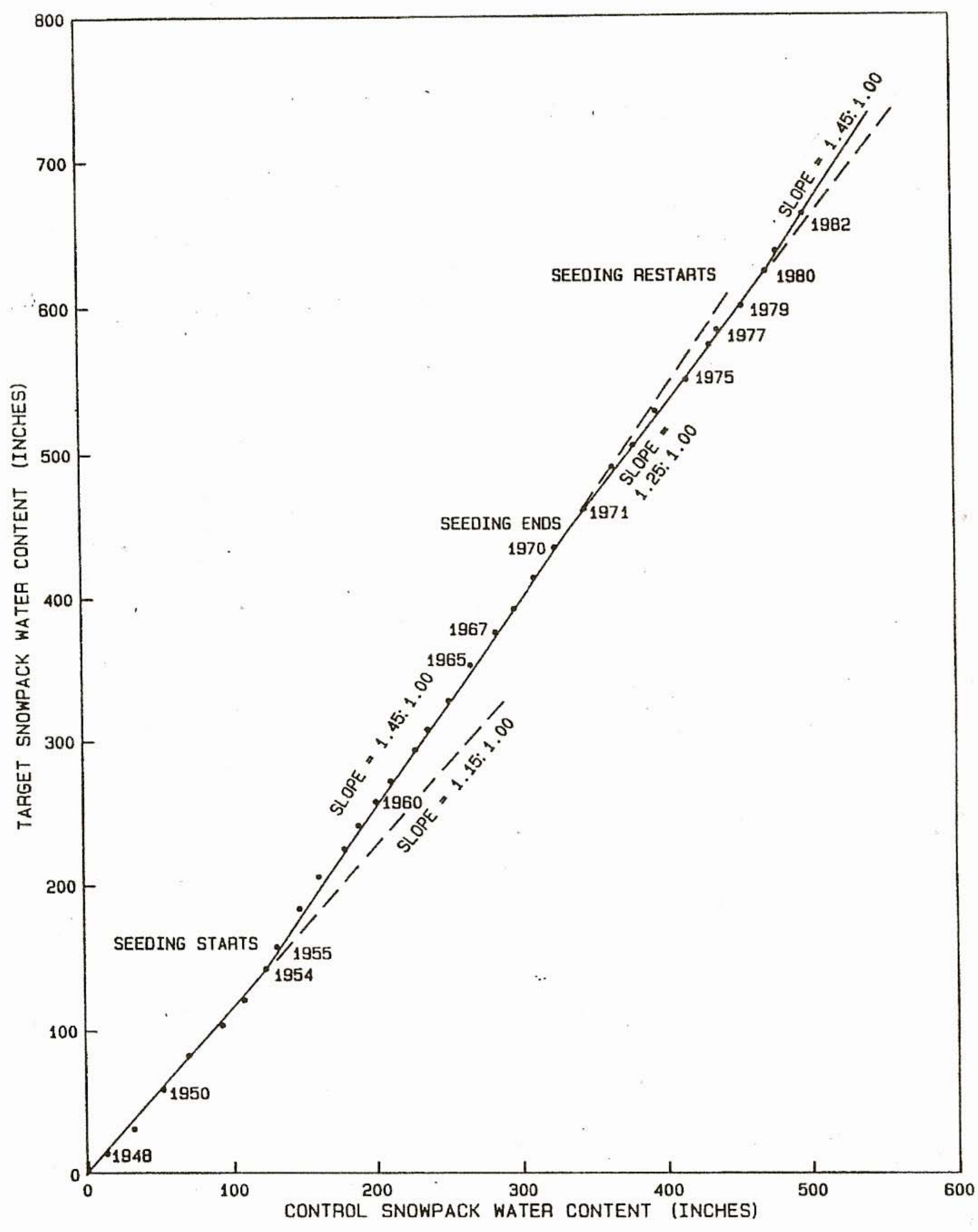

Figure 4.1 Double Mass Plot for UP&L Program

4.3.2 Utah Projects

NAWC has been the cloud seeding contractor for a number of Utah winter snowpack augmentation projects covering much of the mountainous terrain in the state since the mid-1970's. Figure 4.2 provides the locations of the target areas in Utah for the 2004-2005 winter season. These projects employ ground-based AgI solution-burning generators in valley and foothill locations. Numerous mathematical evaluations have been conducted of those projects, some now spanning more than 25 years. The results of the mathematical (non-randomized) estimations of seeding effects averaged over multiple season range from 9% to 21% increases, with a gradient of apparent effects increasing from south to north for the project areas located west and on the upwind slopes of the primary north-south oriented Wasatch Range. One of these operational projects was the host of research efforts described in section 4.2.1.2 of this report. For the longest-standing project, positive seasonal results (increases) have been indicated in statistical evaluations of precipitation for 26 of the 27 seeded seasons to date. A plot of the ranked ratios of observed/statistically estimated snowpack for the seeded seasons and the historic base period (non-seeded sample) is shown in Figure 4.3. The dark bars are seeded seasons, and the open bars are the historical base period years. East of the Wasatch Range, similar mathematical evaluation method results indicate positive effects from 1% to 6%.

Effectiveness estimations for each of the Utah operational projects are shown below. All estimations are based on NAWC's standardized non-randomized target/control regression method, analyzing precipitation and snowpack data.

- Northern Utah (Cache and eastern Box Elder Counties)

  Precipitation: 18% average seasonal increase; 15 of 16 seasons positive.
  Snowpack: 11% average seasonal increase; 13 of 16 seasons positive.

- Northern Utah (northwestern Box Elder County)

  Precipitation: no sites available for analysis.
  Snowpack: 19% average seasonal increase; 12 of 13 seasons positive.

- Eastern Tooele County

  Precipitation: 21% average seasonal increase; 20 of 21 seasons positive.
  Snowpack: 17% average seasonal increase; 16 of 21 seasons positive.

- Western Uinta Mountains (Weber and Provo Rivers)

  Precipitation: 1% average seasonal increase; 5 of 11 seasons positive.
  Snowpack: 4% average seasonal increase; 7 of 11 seasons positive.

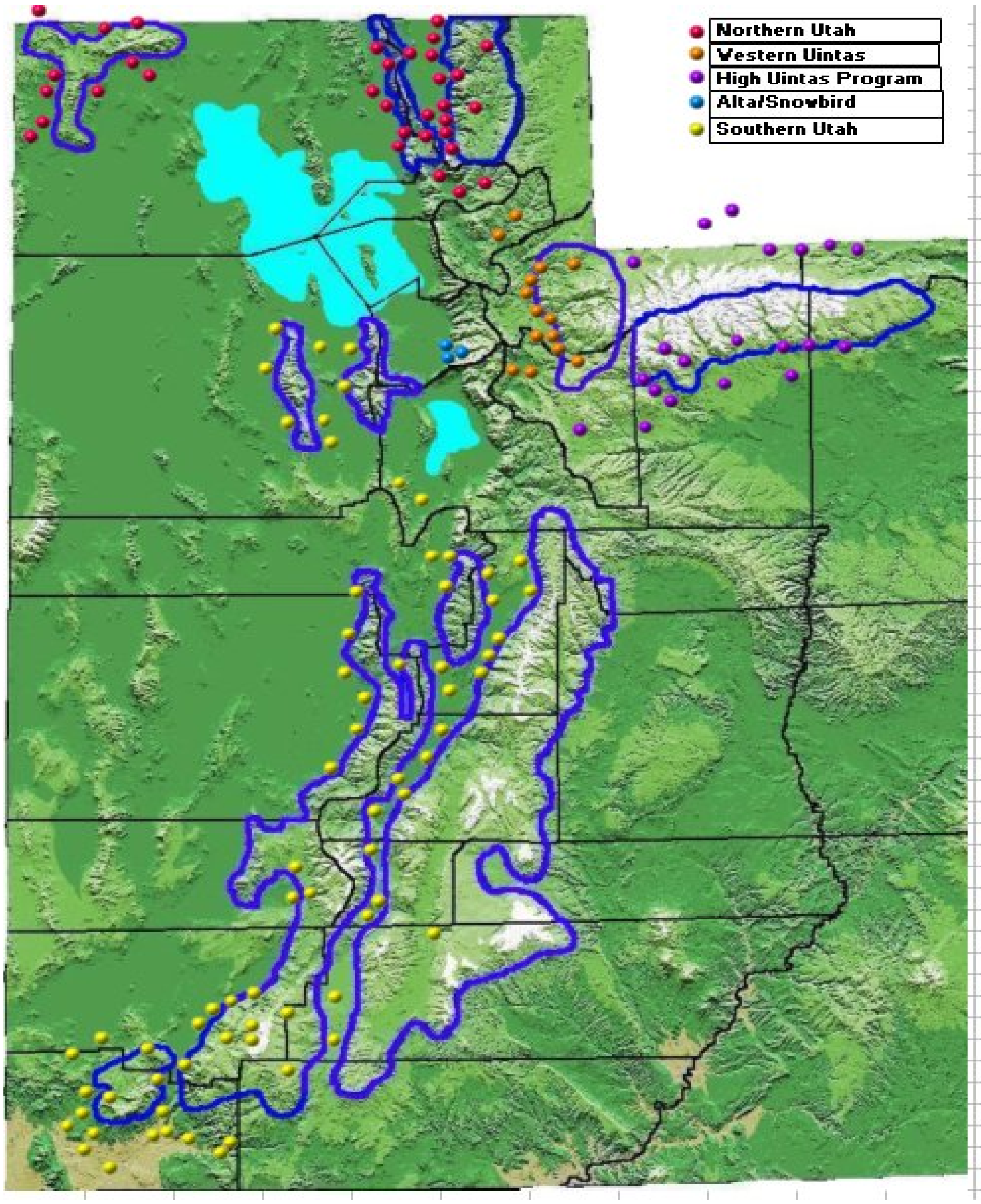

Figure 4.2 Locations of Cloud Seeding Target Areas and Ground Generator Sites within Utah, 2004-2005 Winter Season

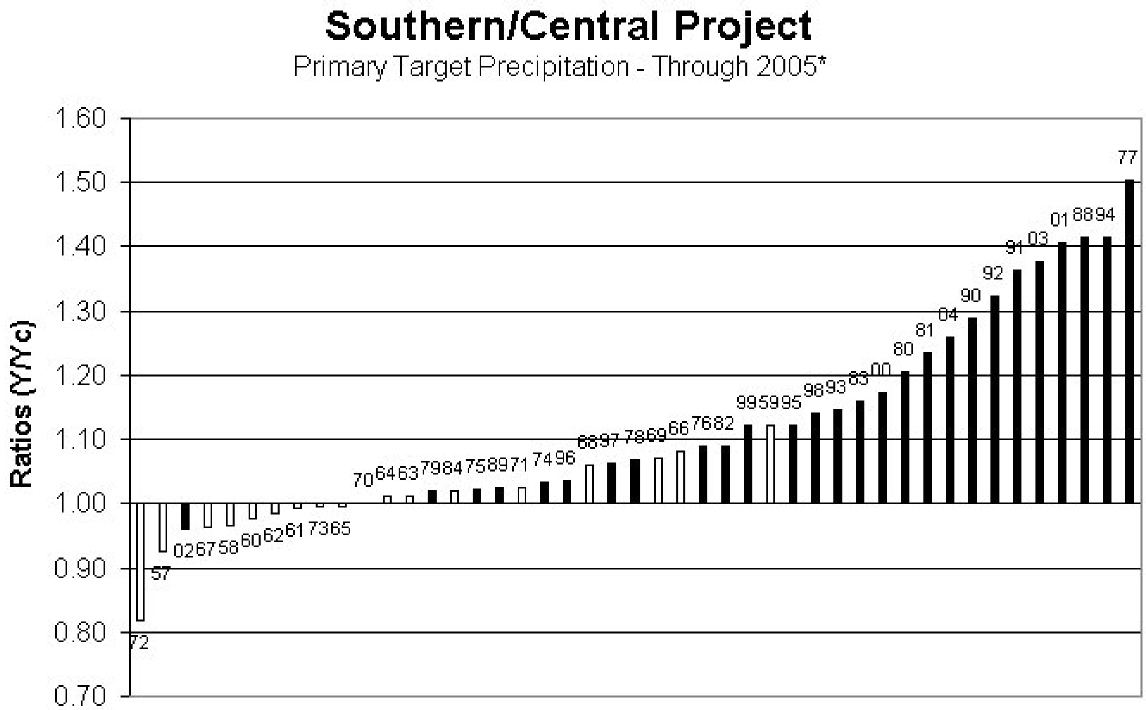

Figure 4.3 Southern Utah Seeded Year Target/Control Ratios through 2005

- <u>High Uinta Mountains</u> (southern slope)

  Precipitation: 4% average seasonal increase; 3 of 3 seasons positive.
  Snowpack: 6% average seasonal increase; 2 of 3 seasons positive.

- <u>Central and Southern Mountains</u>

  Precipitation: 16% average seasonal increase; 26 of 27 seasons positive.
  Snowpack: 4% average seasonal increase; 17 of 27 seasons positive (note, NAWC's annual project report for the 2003-2004 winter season indicated that a change (reduction) in indicated results was due to our decision to use NRCS adjusted snow water contents in this evaluation. The precipitation evaluations are considered more representative for this target area).

4.3.3 Nevada/Desert Research Institute Projects

The State of Nevada, through the Desert Research Institute (DRI) has conducted cloud seeding since the 1960's, beginning in the Tahoe area and expanding to other areas in more recent decades. These projects are an outgrowth of DRI weather modification research programs funded through the U.S. Bureau of Reclamation and the National

Oceanic and Atmospheric Administration (NOAA). Most relevant to the projects in Wyoming are the projects for the Ruby and Tuscarora Mountains in northeastern Nevada the Toiyabe Mountains in the central portion of the state. The projects employ automated ground-based AgI solution-burning generators and have been in operations since the 1980's. DRI's estimates of seasonal seeding effectiveness have indicated increases ranging from 4% to 10%.

4.3.4 Boise River

NAWC has operated an operational cloud seeding project for the Boise River drainage in southwestern Idaho for several years beginning with the winter of 1992-93. The seed mode involves ground-based AgI solution burning generators in valley and mountain locations. Mathematical, target/control, estimations of seeding effectiveness over eight winter seasons are of average seasonal increases of the order of 5% to 8% (Griffith, et al, 2005).

4.3.5 Idaho Power

The Payette River drainage in western Idaho has undergone cloud seeding since 2003, a project conducted by Idaho Power. Automated ground-based AgI solution-burning generators and aircraft are employed to conduct the seeding. The project has included some interesting research components, including trace chemistry analyses. Estimates of seasonal (three seasons) seeding effectiveness indicate an average of about 7% to 9% increases.

4.3.6 Eden Valley

The WMI Weather Modification Study (WMI, 2005) contains a description of a long-term project conducted by the Eden Valley Irrigation District headquartered in Farson, Wyoming. The following is a description of this project contained in the referenced report:

"*The Eden Valley Irrigation District is the only entity presently actively seeding clouds on an annual basis. Each winter, from 15 November through 30 April, the EVID uses three ground-based cloud seeding ice nuclei generators to seed clouds upwind of the southern Wind River Mountains. These generators are placed at 10 mile intervals along U.S. Highway 191 north of Farson. These generators which burn a silver iodide solution are complimented by two additional high-altitude propane ice crystal generators. While the generators along Highway 191 are operated manually by EVID staff, the propane generators are remote controlled and operated by the Provo, Utah office of the Bureau of Reclamation.*

The EVID program was designed by the University of Wyoming's Department of Atmospheric Sciences, and for a time, also operated by the Department. However, the program is presently operated independently by the EVID, and the Wyoming State Engineer's office issues the operations permit to the irrigation district itself.

Operations have been conducted annually since 1975. The irrigation district believes it realizes an 11% to 13% increase in snowfall (water equivalent) as a result of the seeding operations."

4.4 Summary of Findings from Relevant Research and Operational Winter Cloud Seeding Programs

Key Indications

From a review of the relevant research and the large and quite consistently positive overall results of (albeit largely non-randomized) statistical estimations, the following key points emerge:

- It appears that the potential exists for winter snowpack augmentation in the mountainous west. The potential effects range from about 5% to about 15%.
- It is clear that statistically significant evaluations of seeding effects are exceedingly difficult to achieve, due to the relative magnitude of natural precipitation variability compared with the magnitude of anticipated cloud seeding effects. Carefully controlled, randomized experiments are considered necessary by some for attaining such results.
- The basic prerequisite ingredient for cloud seeding potential is the presence of supercooled liquid water (SLW), which has been observed to develop at low altitudes over the windward slopes of mountain ranges. The SLW develops during a sufficiently large proportion of the time during winter storms to constitute a credible target for cloud seeding efforts. This critical characteristic has been identified not only in the projects cited in this report, but also in numerous projects and investigations in a wide variety of locations around the world.
- A key challenge is to identify the most effective methods necessary to "tap" the SLW reservoir, such that the affected precipitation will fall to the surface within the intended area of effect.
- Critical factors regarding effective seeding methods and materials include atmospheric stability, the temperature thresholds of various seeding materials, times/distances available for growth of the seeding-induced ice particles, etc.
- AgI solution formulations incorporating sodium iodide and para-dichlorobenzene, acting more quickly via the condensation-freezing nucleation method, are available for operational use.
- Each potential cloud seeding method has benefits and limitations. A number of project-specific considerations must be factored into selection of the most appropriate seeding method(s). More than one seeding method may well be appropriate for a given project area.
- A practical approach to seeding method selection is appropriate, weighing the potential benefits each may achieve against the costs and the logistical considerations associated with each prospective method. In other words, is a given seeding method worth the effort? What is each seeding method's relative

(incremental) contribution (value) versus its cost? This is a basic benefit/cost issue of the type common to every day decision-making in business, etc.

Siting of ground-based AgI generators should take into account the trapping effects of surface-based temperature inversions. The character and frequency of such inversions in the region **during seedable storm occurrences** should be determined via analysis of regional observations. **Occurrences of trapping temperature inversions during non-seedable storm periods or non-stormy periods are generally irrelevant and must not be included in such climatologies.** Modeling (using only validated model results) can be helpful in such considerations, but analysis of real data is much preferred, especially if a suitable period of record is available. The typical (range of) height of the top of the inverted layers can be used to establish a critical elevation for ground-based generators if the inversion frequency of occurrence during seedable storm occurrences is deemed significant. In any case, the critical elevation should be kept in mind during the site selection process. The frequency of occurrence issue can be used to assess the apparent seasonal benefit/cost of using lower elevation generators, given their seeding coverage advantages. The seeding formulation issue should also be addressed, with close attention to activation temperature threshold and the speed of activation of the nuclei produced.

Siting of high elevation generators (AgI or propane) should take into account the attendant constraints pertaining to their cost effectiveness. These are primarily distance-to-target issues, i.e., considerations of adequate time for the seeding-induced ice particles to grow and fall out into the intended area of effect. In the case of propane, the generators must be at sufficiently high elevations to consistently position them in-cloud to have any effect. In the case of AgI, their location in-cloud adds the potential benefit of forced condensation-freezing. The assessment issues include the precipitation rates possible, the degree of plume spread and, thus, the crosswind spacing required to produce overlapping plumes sufficiently far upwind to produce a cost effective benefit. High elevation sites typically are located strategically in areas with difficult access, necessitating the significant additional cost of high capacity, full automation, communications equipment and on-site solar power (panel) system. Obtaining site permission/leases can also be problematic. Storm-to-storm equipment reliability can be difficult to ascertain with automated systems due to less frequent on-site human involvement. The costs of repair and replenishment visits add to the benefit/cost consideration.

Use of aircraft for operational seeding, albeit costly, does offer some benefits over ground-based releases. Those include better targeting of the low altitude SLW layer above 500-1000 m AGL when safety considerations allow, seeding of SLW layers when low elevation stable layers or temperature inversions would likely trap ground-based releases from lower or even upper elevations, and seeding when the nucleation temperature threshold is significantly above a mountain barrier summit height.

This section has summarized some key prior data, results of operational projects and research programs relevant to Wyoming. The remainder of this overall report addresses the major feasibility issues in a more site-specific manner, focused on the Salt River and Wyoming Ranges in west central Wyoming.

5.0 CLIMATOLOGY OF PROJECT AREAS

There are certain aspects of the climatology of the area that are important to the exploration of the feasibility/preliminary design aspects of this study. Several relevant sections from the Wyoming Climate Atlas (Curtis and Grimes, 2004) are provided verbatim in Section 5.1. This general information provides a backdrop to more specific climate information regarding the potential project areas contained in section 5.2.

5.1 Climate of Wyoming

5.1.1 Topographical Features

"*Wyoming's outstanding features are its majestic mountains and high plains. Its mean elevation is about 6,700 feet above sea level and even when the mountains are excluded, the average elevation over the southern part of the State is well over 6,000 feet, while much of the northern portion is some 2,500 feet lower. The lowest point, 3,125 feet, is near the northeast corner where the Belle Fourche River crosses the State line into South Dakota. The highest point is Gannett Peak at 13,785 feet, which is part of the Wind River Range in the west-central portion. Since the mountain ranges lie in a general north-south direction, they are perpendicular to the prevailing westerlies, therefore, the mountain ranges provide effective barriers which force the air currents moving in from the Pacific Ocean to rise and drop much of their moisture along the western slopes. The State is considered semiarid east of the mountains. There are several mountain ranges, but the mountains themselves cover less area than the high plains. The topography and variations in elevation make it difficult to divide the State into homogeneous, climatological areas.*

The Continental Divide splits the State from near the northwest corner to the center of the southern border. This leaves most of the drainage areas to the east. The runoff drains into three great river systems: the Columbia, the Colorado, and the Missouri. The Snake with its tributaries in the northwest flows into the Columbia; the Green River drains most of the Southwest portion and joins the Colorado: the Yellowstone, Wind River, Bighorn, Tongue, and Powder drainage areas cover most of the north portion and flow northward into the Missouri; the Belle Fourche, Cheyenne, and Niobrara covering the east-central portion, flow eastward: while the Platte drains the southeast and flows eastward into Nebraska. There is a relatively small area along the southwest border that is drained by the Bear which flows into the Great Salt Lake. In the south-central portion west of Rawlins, there is an area called the Great Divide Basin. Part of this area is often referred to as the Red Desert. There is no drainage from this Basin and precipitation, which averages only 7 to 10 inches annually, follows creekbeds to ponds or small lakes where it either evaporates or percolates into the ground.

Snow accumulates to considerable depths in the high mountains and many of the streams fed by the melting snow furnish ample quantities of water for irrigation of thousands of acres of land. The snowmelt also furnishes the water to generate electric power, and for domestic use.

Rapid runoff from heavy rain during thunderstorms causes flash flooding on the headwater streams, and when the time of these storms coincides with the melting of the snowpack, the flooding is intensified. When overflow occurs in the vicinity of urban communities situated near the streams considerable damage results."

5.1.2 <u>Temperature</u>

"Because of its elevation, Wyoming has a relatively cool climate. Above the 6,000 feet level the temperature rarely exceeds 100°F. The warmest parts of the State are the lower portions of portions of the Bighorn Basin, the lower elevations of the central and northeast portions, and along the east border. The highest recorded temperature was 114°F on July 12, 1900, at Basin in the Bighorn Basin. The average maximum temperature at Basin in July is 92°F. For most of the State, mean maximum temperatures in July range between 85 and 95° F. With increasing elevation, average values drop rapidly. A few places in the mountains at about the 9,000 foot level have average maximums in July close to 70°F. Summer nights are almost invariably cool, even though daytime readings may be quite high at times. For most places away from the mountains, the mean minimum temperature in July ranges from 50 to 60 °F. Of course, the mountains and high valleys are much cooler with average lows in the middle of the summer in the 30s and 40s with occasional drops below freezing.

In the wintertime it is characteristic to have rapid and frequent changes between mild and cold spells. Usually there are less than 10 cold waves during a winter, and frequently less than half that number for most of the State. The majority of cold waves move southward on the east side of the Divide. Sometimes only the northeast part of the State is affected by the cold air as it slides eastward over the plains. Many of the cold waves are not accompanied by enough snow to cause severe conditions. In January, the coldest month generally, mean minimum temperatures range mostly from 5 to 10°F. In the western valleys mean values go down to about 5°below zero. The record low for the State is -66°F observed February 9, 1933, at Yellowstone Park. During warm spells in the winter, nighttime temperatures frequently remain above freezing. Chinooks, warm downslope winds, are common along the eastern slopes.

Numerous valleys provide ideal pockets for the collection of cold air drainage at night. Protecting mountain ranges prevent the wind from stirring the air, and the colder heavier air settles into the valleys often sending readings well below zero. It is common to have temperatures in the valleys considerably lower than on the nearby mountain side. Big Piney in the Green River Basin is such a *location. Mean January temperatures in the Bighorn Basin show the variation between readings in the lower part of the valley and those higher up. At Worland and Basin in the lower portion of the Bighorn Basin, not far from the 4,000 foot level, the mean minimum temperature for January is zero, while Cody, close to 5,000 feet on the west side of the valley has a mean January minimum of 11°F. January, the coldest month, has occasional mild periods when maximum readings will reach the 50s; however, winters are usually long and cold."*

5.1.3 Precipitation

"Like other states in the west, precipitation varies a great deal from one location to another. The period of maximum precipitation occurs in the spring and early summer for most of the State. Precipitation is greater over the mountain ranges and usually at the higher elevations, although elevation alone is not the predominant influence. For example, over most of the southwest portion, where the elevation ranges from 6,500 to 8,500 feet, annual precipitation varies from 7 to 10 inches. At lower elevations over the northeast portion and along the eastern border, where elevations are mostly in the range from 4,000 to 5,500 feet, annual averages are from 12 to 16 inches. The relatively dry southwest portion is a high plateau nearly surrounded by mountain ranges.

The Bighorn Basin provides a striking example of the effect of mountain ranges in blocking the flow of moisture laden air from the east as well as from the west. The lower portion of the Basin has an annual precipitation of 5 to 8 inches, and it is the driest part of the State. The station showing the least amount is Deaver at 4,105 feet with an annual mean of about 5.50 inches. In the southern part of the Basin, Worland at 4,061 feet has an annual mean of 7 to 8 inches as compared with Thermopolis at 4,313 feet and 11 to 12 inches. There is another good example in the southeastern part of the State where Laramie at 7,236 feet has an annual mean of 10 inches, while 30 miles to the west, Centennial at 8,074 feet receives about 16 inches. Only a few locations receive as much as 40 inches a year, based on gage records.

During the summer, showers are quite frequent but often amount to only a few hundredths of an inch. Occasionally there will be some very heavy rain associated with thunderstorms covering a few square miles. There are usually several local storms each year with from 1 to 2 inches of rain in a 24-hour period. On rare occasions, 24-hour amounts range from 3 to 5 inches. The greatest 24-hour total recorded for any place in Wyoming is 5.50 inches at Dull Center, near Newcastle, on May 31, 1927."

5.1.4 Snow and Blizzards

"Snow falls frequently from November through May and at lower elevations is light to moderate. About five times a year on the average, stations at

the lower elevations will have snowfall exceeding 5 inches. Falls of 10 to 15 inches or more for a single storm occur but are infrequent outside of the mountains. Wind will frequently accompany or follow a snowstorm and pile the snow into drifts several feet deep. The snow sometimes drifts so much that it is difficult to obtain an accurate measurement of snowfall. An unusually heavy snow occurred at Sheridan on the 3rd and 4th of April 1955. During this period the snowfall amounted to 39.0 inches, had a water equivalent of 4.30 inches and blizzard conditions lasted more than 43 hours. High winds and low temperatures with snow cause blizzard or near blizzard conditions. These conditions sometimes last a day or two, but it is uncommon for a severe blizzard to last over three days.

Total annual snowfall varies considerably. At the lower elevations in the east, the range is from 60 to 70 inches. Over the drier southwest portion, amounts vary from 45 to 55 inches. Snow is very light in the Bighorn Basin with annual averages from 15 to 20 inches over the lower portion and 30 to 40 inches on the sides of the Basin where elevations range from 5,000 to 6,000 feet. The mountains receive a great deal more and in the higher ranges annual amounts are well over 200 inches. At Bechler River Ranger Station in the southwest corner of Yellowstone Park, the snowfall averages 262 inches for a 20-year period.

The weather pattern most favorable for precipitation is one with a low-pressure center a little to the south of the State. This will normally provide a condition where relatively cool air at the surface is overrun by warmer moist air. Studies of wind flow patterns indicate that Wyoming is covered most of the time by air from the Pacific. A smaller percentage of time the State is covered by cold air masses that move down from Canada."

5.2 Relevant Climatological Features of the Salt River and Wyoming Ranges

The Request For Proposals (RFP) requested that climatologies be developed with the goal of assessing the seeding potential of the project area after consideration of the information gathered in Task #2, and via evaluation of storm frequencies and characteristics, temperatures, precipitation characteristics, prevailing winds, surface observations, barriers, etc. A variety of data were available from which these climatologies could be developed, including surface observations, upper air observations, satellite observations and radar observations.

The meteorological parameters of greatest interest in this feasibility/preliminary design work are: precipitation, surface and upper-level wind direction and velocity, temperatures at the surface and aloft, and the structure of the lower to mid-levels of the atmosphere. Information on these parameters during winter storm periods that impact the proposed target areas are of primary interest. Two factors drive these considerations: 1) the likely presence of seedable conditions, and 2) the potential ability to target these seedable regions. Considerations involving the first factor (seedability) may be focused on the temperatures within the storms. To be seedable, a portion of the cloud system needs to be colder than freezing. Also, the height of certain temperature levels such as the 23^0 F (-5^0 C) are important for one of the primary seeding materials (silver iodide), since this is the temperature at which silver iodide begins to be active as an ice or freezing nuclei (a topic to be discussed further in section 6.0). Another consideration may be the speed and direction of the lower level winds. If winds are blowing up and over the mountain barrier and the cloud top temperatures are not too cold, then supercooled liquid water droplets will likely be present in the storm clouds. It is the presence of these supercooled water droplets that determine whether there is any seeding potential within the clouds (more on the theory of cloud seeding is contained in section 6.1). A photograph illustrating the extreme build up of ice that was formed from supercooled water droplets impacting structures on the top of Mt. Washington in New Hampshire is provided in Figure 5.1. Targeting considerations are related to the likely transport and diffusion of seeding materials, which becomes a function of seeding mode (ground based, aerial), the lower level wind speed and direction, and lower level atmospheric stability. These targeting issues are also discussed in a later section (section 6.5).

Information on these parameters of interest is provided in the following sections. This feasibility/preliminary design study was defined as a wintertime activity. We have therefore provided information for the October through April time frame.

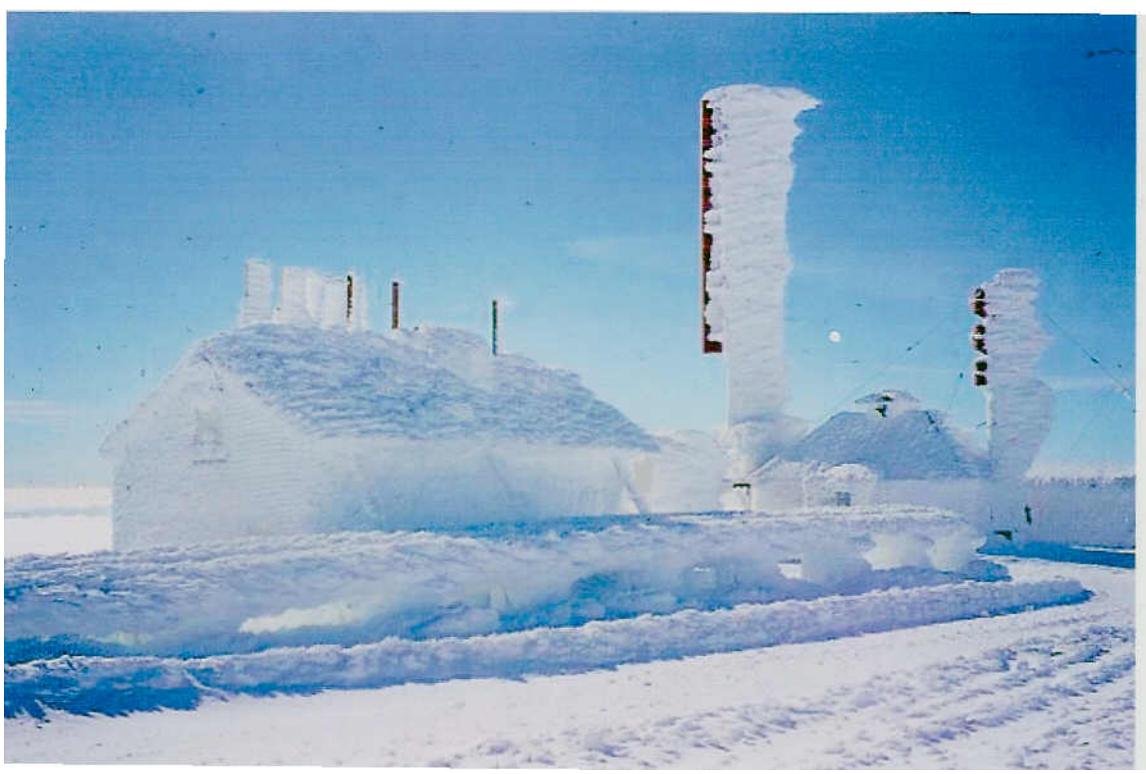

Figure 5.1 Riming on Mt. Washington, NH

5.2.1 Precipitation

Data on the natural precipitation of the project areas provides useful information concerned with the different types of storms that impact these areas. Such data also provide a baseline for estimation of the magnitude of precipitation increases that may be possible through cloud seeding. For example, if a potential target site receives an average 30 inches (76 cm) of precipitation during the winter months and our analyses indicates that a 12% increase in precipitation is possible from cloud seeding, then the estimated increase in an average winter season at this site would be 3.6 inches (9.1 cm) of additional precipitation. This estimate may then be used to provide estimates of increases in streamflow. Observations of precipitation in the higher elevation areas that will be considered as potential target areas have been made primarily by the Natural Resources Conservation Service (formerly the Soil Conservation Service). These observations are of two basic types: 1) measurements of snow water content and 2) measurements of rainfall and melted snowfall. Manual observations of the water content of snowfall throughout the mountainous areas of the west began in 1906 through the pioneering work of manual snow water measurement techniques by Dr. Church in the Reno, Nevada area (Church, 1918). These measurements were mandated by congress to “measure snowpack in the mountains of the West and forecast the water supply.” Sampling locations were established throughout the mountain ranges of the west. Typically a high elevation snow course was visited approximately once per month during the winter months and ten measurements of the snowpack were taken with a hollow tube that converted the weight of the snow into a water content measurement in inches. The ten observations were then averaged to give an estimate of the snow water content in inches. Some of these snow course sites were also equipped with stand pipe storage gages. These storage gages were charged with an anti-freeze solution, which melted the snow as it fell into the gage. A pressure transducer provided the resultant precipitation amount in inches of water. The crews making the snowcourse measurements would also record the standpipe storage gage precipitation amounts at those sites equipped with such devices. A major improvement to this measurement technique was implemented by the Soil Conservation Service in the early to mid-1980’s. This new technique was called SNOTEL (for SNOwpack TELemetry). SNOTEL utilizes a unique data transmission system that relies upon meteor burst technology. VHF radio signals are reflected at a steep angle off the ever present band of ionized meteorites existing from about 50 to 75 miles (80-120 km) above the earth. With the advent of the SNOTEL system, data are available with time resolution as short as hourly. The data typically consist of snow water content, precipitation and temperature. Snow water content is measured by a snow pillow which is a flat metal device approximately 8 feet (2.4m) in diameter. Precipitation is measured with the same standpipe storage gages described previously.

Figure 5.2 contains a photo of an NRCS SNOTEL site taken in the fall, to allow the reader a better understanding of the two types of observation systems. The vertical

Figure 5.2 SNOTEL Site in the Fall

tube is the standpipe storage gage, which is approximately 12" (30.5cm) in diameter. The gages are approximately 20' (6.1m) in height so that their sampling orifices remain above the snowpack surface. In the fall, the storage gage is charged with antifreeze, which melts the snow that falls to the bottom of the gage. A pressure transducer records the weight of the solution. The weight of the antifreeze is subtracted from the total weight, giving the weight of the water, which is then converted into inches. There are at least two types of problems associated with high elevation observations of the water equivalent of snowfall. There are potential problems associated with each type of observation. The two areas of concern are clogging at the top of the standpipe storage gage, and blow-by of snowflakes past the top of the standpipe gage. Either situation would result in an underestimate of the actual precipitation that fell during such periods. Heavy, wet snow may accumulate around the top of the standpipe storage gage, either reducing or stopping snow from falling into the standpipe and resulting in an underestimate of precipitation. Snow that falls with moderate to strong winds may blow past the top of the gage, which can also result in an underestimate of precipitation. NRCS sites are normally located in small clearings in forested areas to help reduce the impacts of wind problems. Sites that are near or above timberline are more likely to be impacted by wind since sheltered sites may be difficult to find in these areas. The snow pillow pictured in the foreground in Figure 5.2 is filled with antifreeze. This system senses the weight of the snowpack, providing time-resolved records of the snowpack water content. Snow pillows can also have difficulty in providing accurate measurements of snow water content, because of wind either adding or removing snow from the measurement site when snow conditions are favorable for drifting. Consequently, either measurement should be considered an estimate of the actual amount of precipitation that falls.

Figure 5.3 provides the locations of NRCS sites located within or near the potential target areas for cloud seeding. Table 5-1 provides specifics for each of these sites. Fortunately, there are several SNOTEL sites within these areas. Figure 5.3 also provides the locations of three manual snow course sites that are still active; Big Park, CCC Camp and Rowdy Creek.

Average monthly values of snow water content and precipitation have been calculated for the 1971-2000 period. Tables 5-2 and 5-3 contain this information for the October through April period.

The data contained in Table 5-2 were used to develop graphical plots of the average monthly and seasonal amounts of precipitation for the proposed target areas. Figures 5.4 through 5.10 provide the monthly plots. Figure 5.11 provides contours of the mean precipitation values for the November through March period, which is proposed as the core operational period as discussed in section 6.10. Figure 5.12 graphically portrays the mean April 1 snow water content accumulation amounts for the proposed target areas. Figure 5.13 provides a plot of the monthly data from Kelley R.S. This figure demonstrates that there is a peak in the average precipitation in the area during the month of December, then a gradual decline from this peak during the months of January through April. October has the lowest average monthly precipitation of the October through April period. This information will be considered later in the proposed design of the program in regards to the recommended period of cloud seeding. One other feature, which can be calculated from the data provided in Table 5-2, is the percentage of the average annual precipitation that occurs at these potential target stations during the October – April period. These percentages are provided in Table 5-4.

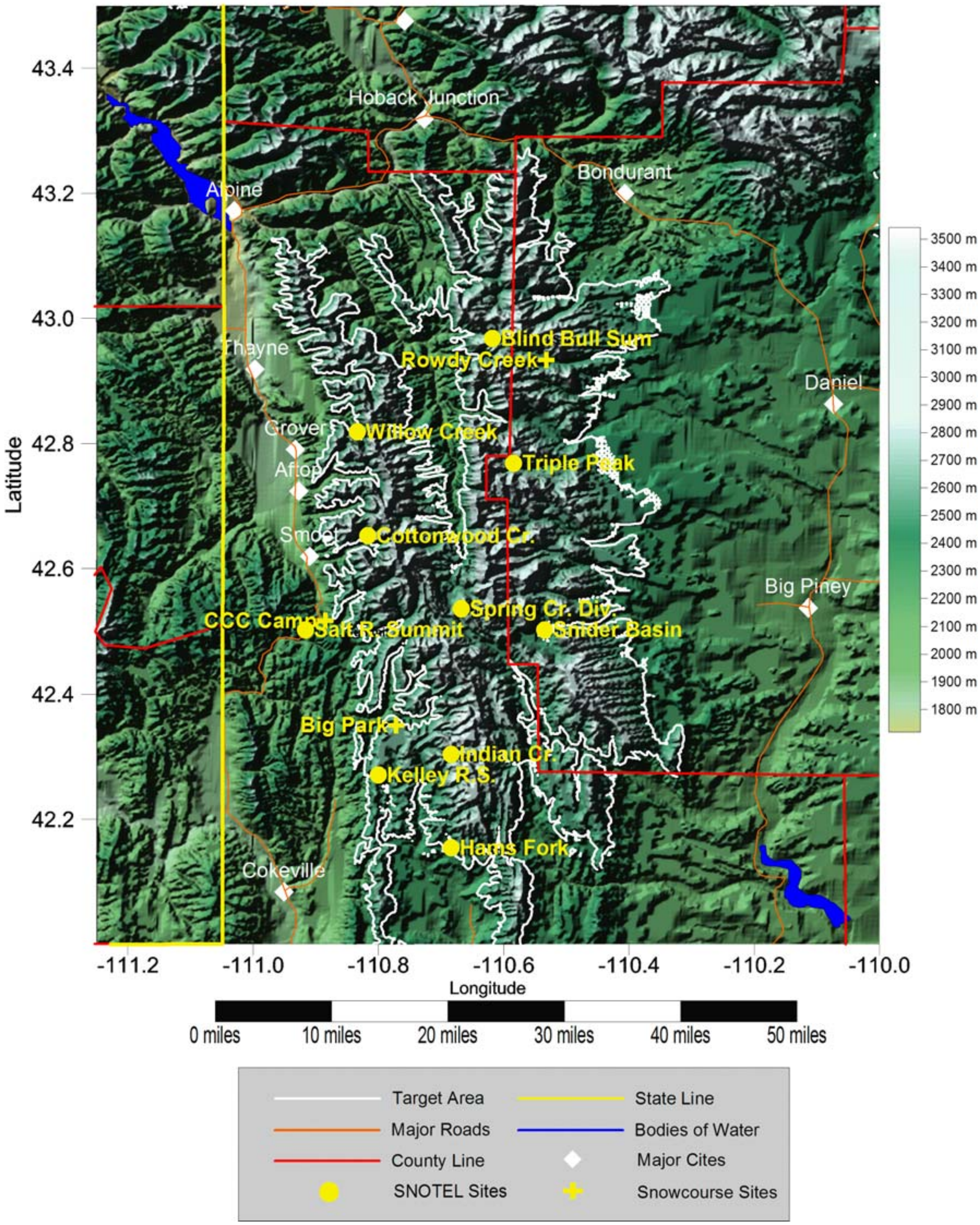

Figure 5.3 Target Area SNOTEL Sites

Table 5-1 SNOTEL Sites Within or Near the Proposed Target Areas

Site	Lat (N)	Long (W)	Elevation	Start Date
Blind Bull Sum	42^0 58'	110^0 37'	8650'	Oct. 1981
Cottonwood Cr.	42^0 39'	110^0 49'	7670'	Oct. 1981
Hams Fork	42^0 09'	110^0 41'	7840'	Oct. 1981
Indian Cr.	42^0 18'	110^0 41'	9425'	Oct. 1981
Kelley R.S.	42^0 16'	110^0 48'	8180'	Oct. 1981
Salt R. Summit	42^0 30'	110^0 55'	7760'	Oct. 1982
Snider Basin	42^0 30'	110^0 32'	8060'	Oct. 1981
Spring Cr. Div.	42^0 32'	110^0 40'	9000'	Oct. 1981
Triple Peak	42^0 46'	110^0 35'	8500'	Oct. 1986
Willow Creek	42^0 49'	110^0 50'	8380'	Oct. 1981

Table 5-2 Average Monthly Precipitation at Target Area SNOTEL Sites (Inches), 1971-2000

Site	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Oct-Apr	Oct-Sep
Blind Bull Summit	2.31	4.12	4.66	4.32	3.64	3.42	2.74	25.21	34.38
Cottonwood Cr.	3.15	4.83	5.55	5.15	4.34	4.73	4.19	31.94	42.91
Hams Fork	1.47	2.07	2.26	2.58	2.01	1.96	2.40	14.75	21.78
Indian Creek	2.68	4.28	5.20	4.65	4.29	4.62	3.74	29.46	38.23
Kelley R.S.	2.24	3.46	4.40	3.78	3.32	3.37	3.02	23.59	31.43
Salt R. Summit	2.02	2.96	3.98	3.67	3.18	3.19	2.61	21.61	29.65
Snider Basin	1.68	2.81	3.46	3.13	2.65	2.57	2.23	18.53	24.88
Spring Cr. Divide	2.67	4.67	5.70	5.28	4.17	4.27	3.44	30.20	39.42
Triple Peak	2.34	4.20	4.67	4.98	4.54	4.33	3.59	28.65	38.50
Willow Creek	3.85	5.51	6.18	6.27	5.22	5.52	5.12	37.67	51.81

Table 5-3 Average Monthly Snow Water Equivalent Accumulations at Target Area SNOTEL Sites (Inches), 1971-2000

Site	Nov. 1	Dec. 1	Jan. 1	Feb. 1	Mar. 1	Apr. 1
Blind Bull Summit	1.8	7.1	13.2	18.4	23.1	28.3
Cottonwood Cr.	1.0	4.7	9.7	14.2	18.5	24.2
Hams Fork	0.5	2.5	5.5	8.4	11.0	12.0
Indian Creek	1.6	6.7	12.5	17.6	22.3	28.2
Kelley R.S.	1.0	4.2	7.6	10.7	14.0	17.1
Salt R. Summit	0.4	2.6	5.4	9.2	12.2	14.6
Snider Basin	0.8	3.6	6.9	9.8	12.4	14.7
Spring Cr. Divide	1.6	6.8	12.5	17.4	22.2	26.9
Triple Peak	1.3	6.3	11.9	16.6	20.9	25.2
Willow Creek	1.9	7.7	14.3	20.2	25.4	30.6

Table 5-4 Percentage of Average Annual Precipitation that Falls During the October – April Period

Site	Oct – Apr Precip.	Entire Water Year Precip.	% Oct – Apr vs. Water Year
Blind Bull Summit	25.21	34.38	73%
Cottonwood Cr.	31.94	42.91	74%
Hams Fork	14.75	21.78	68%
Indian Creek	29.46	38.23	77%
Kelley R.S.	23.59	31.43	75%
Salt R. Summit	21.61	29.65	73%
Snider Basin	18.53	24.88	74%
Spring Cr. Divide	30.20	39.42	77%
Triple Peak	28.65	38.50	74%
Willow Creek	37.67	51.81	73%

Data from Table 5-4 indicate that approximately 75% of the water year precipitation occurs during the seven-month period of October through April.

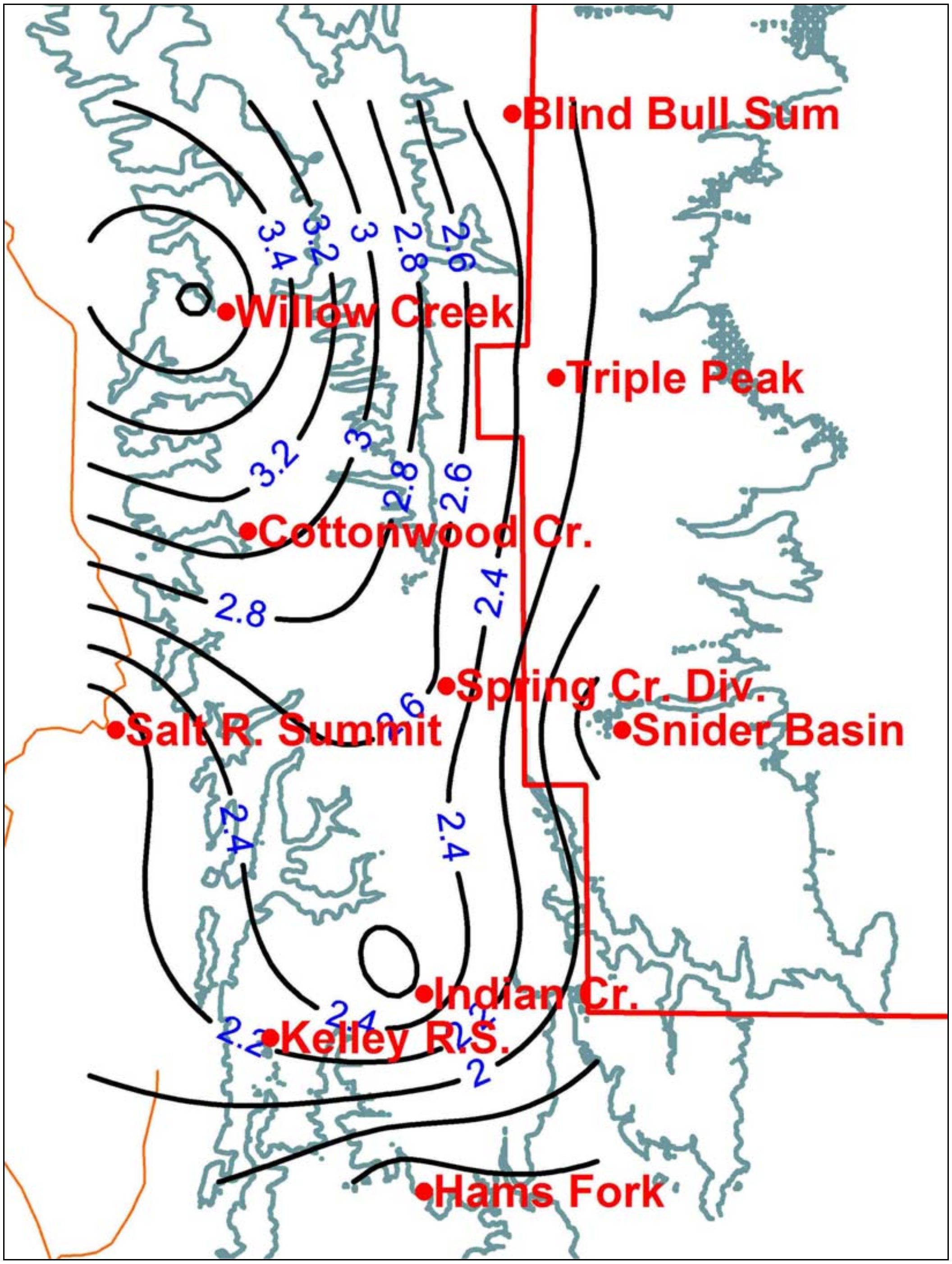

Figure 5.4 Mean October Precipitation

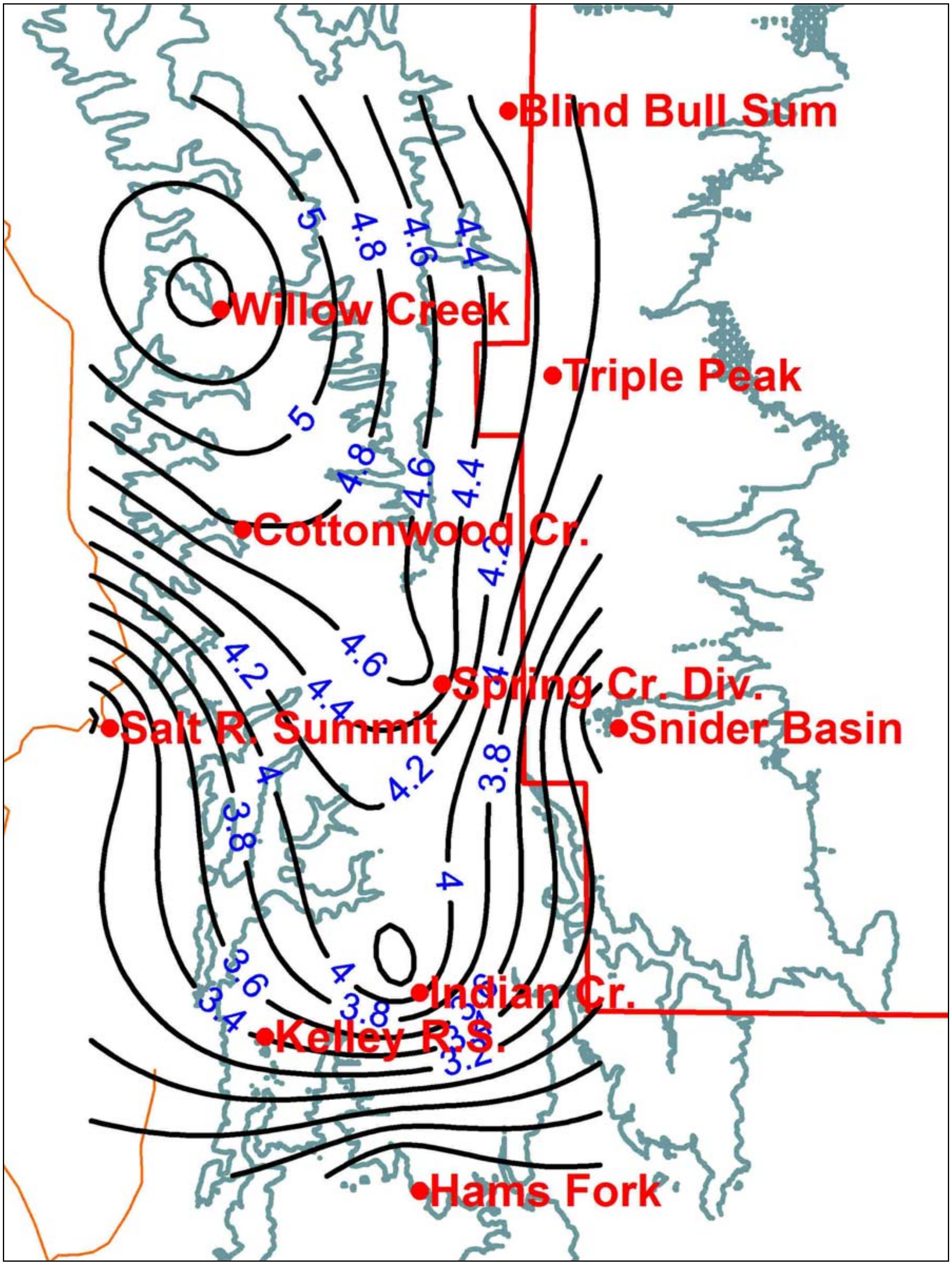

Figure 5.5 Mean November Precipitation

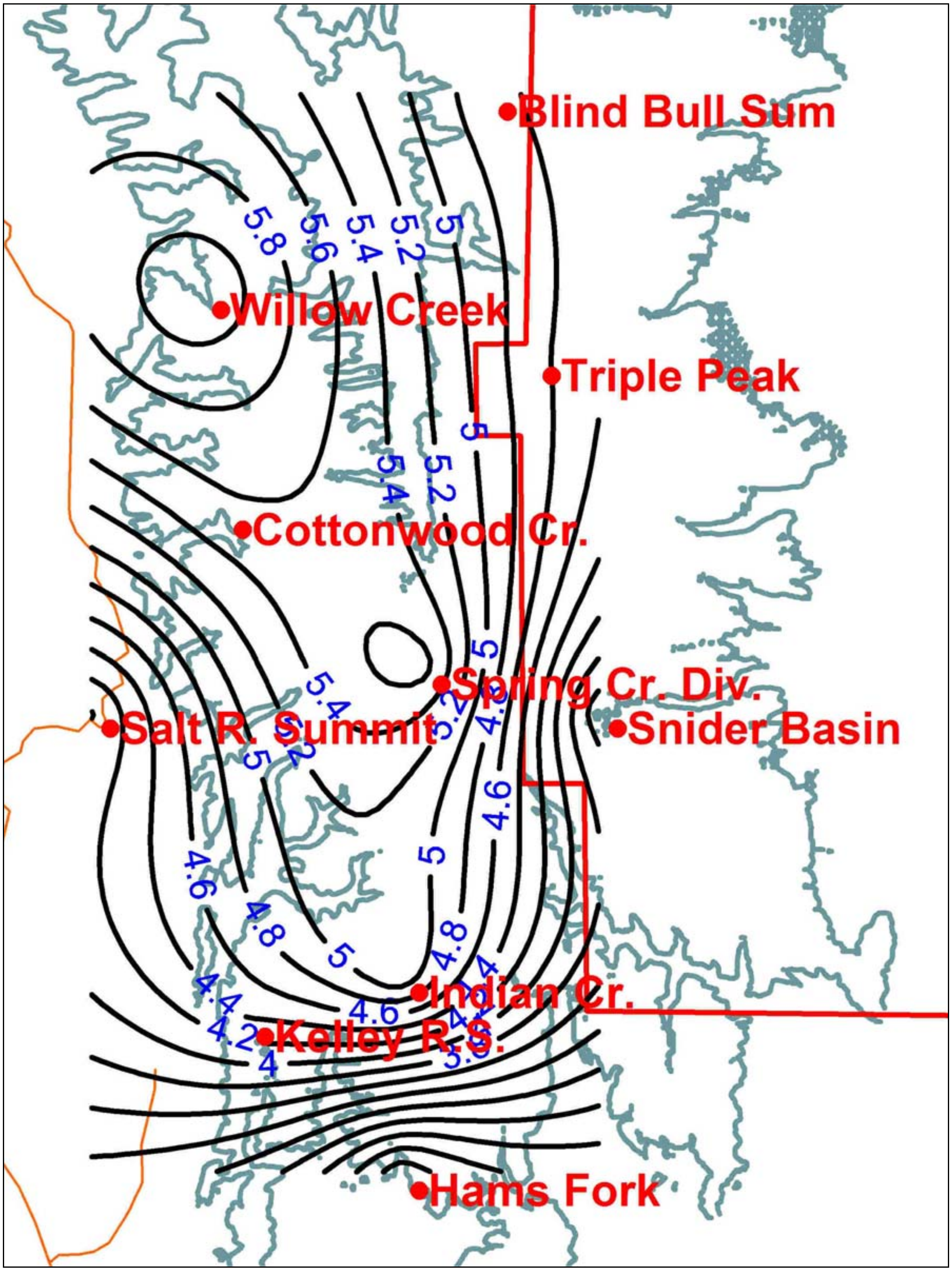

Figure 5.6 Mean December Precipitation

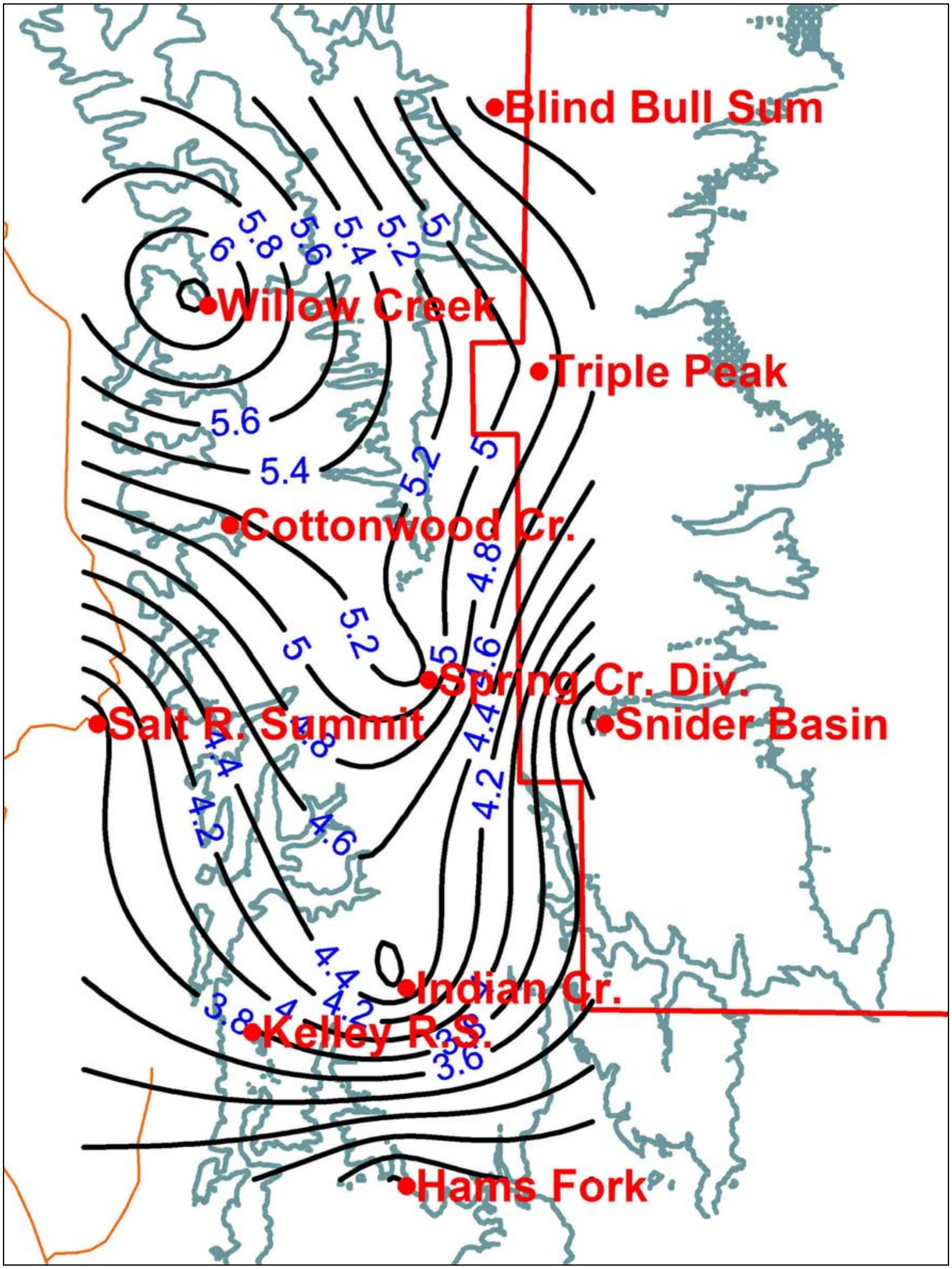

Figure 5.7 Mean January Precipitation

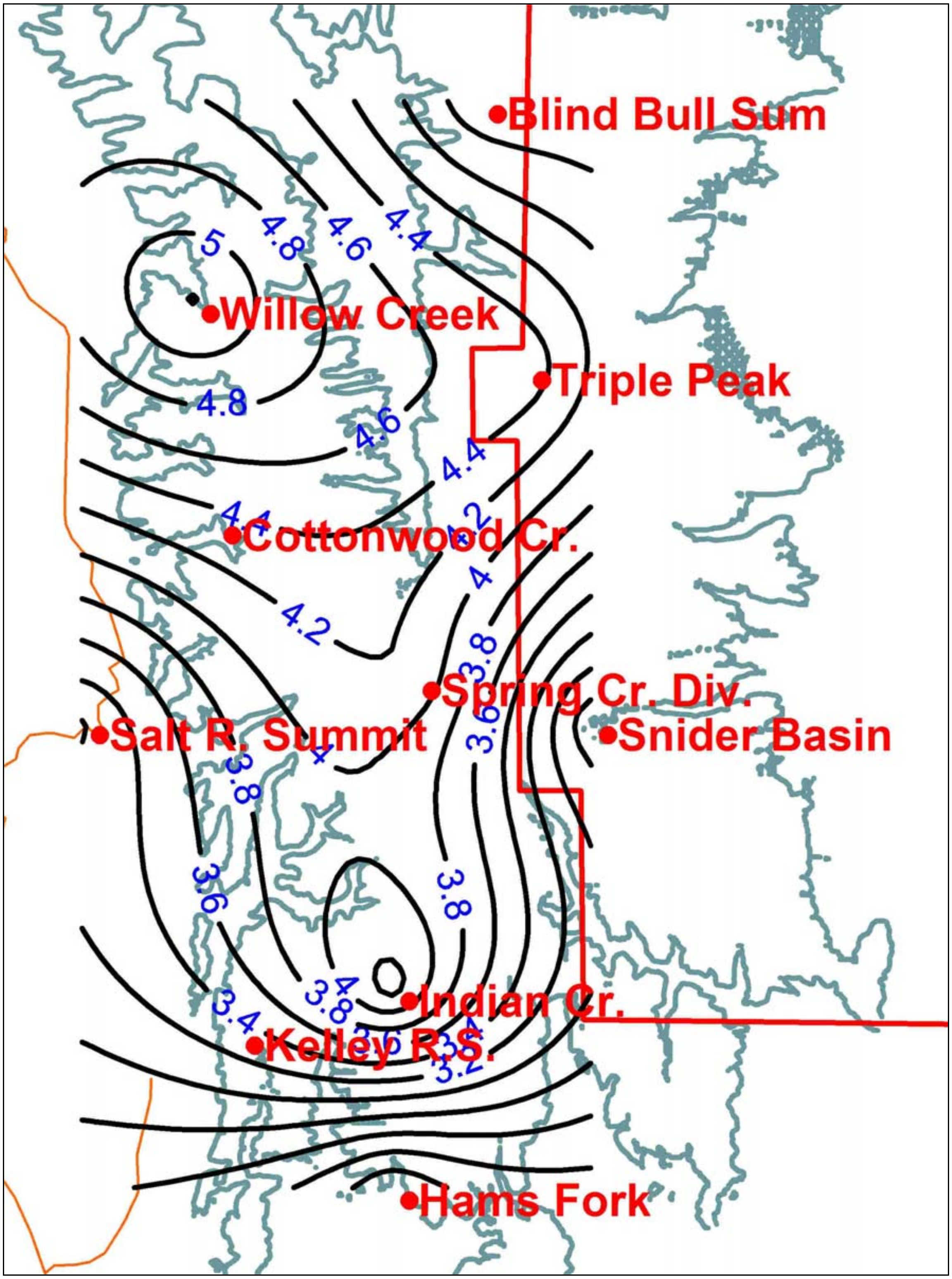

Figure 5.8 Mean February Precipitation

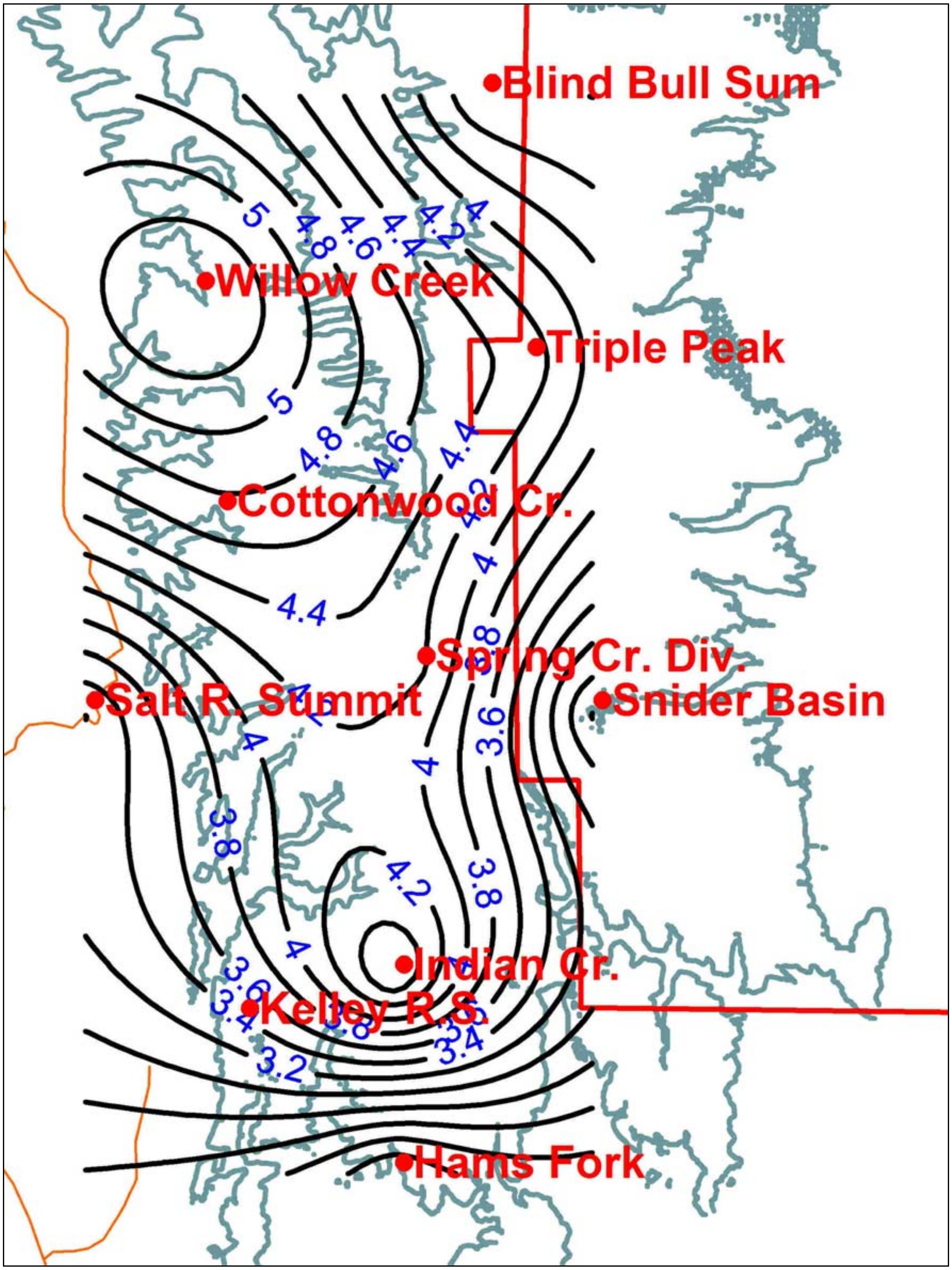

Figure 5.9 Mean March Precipitation

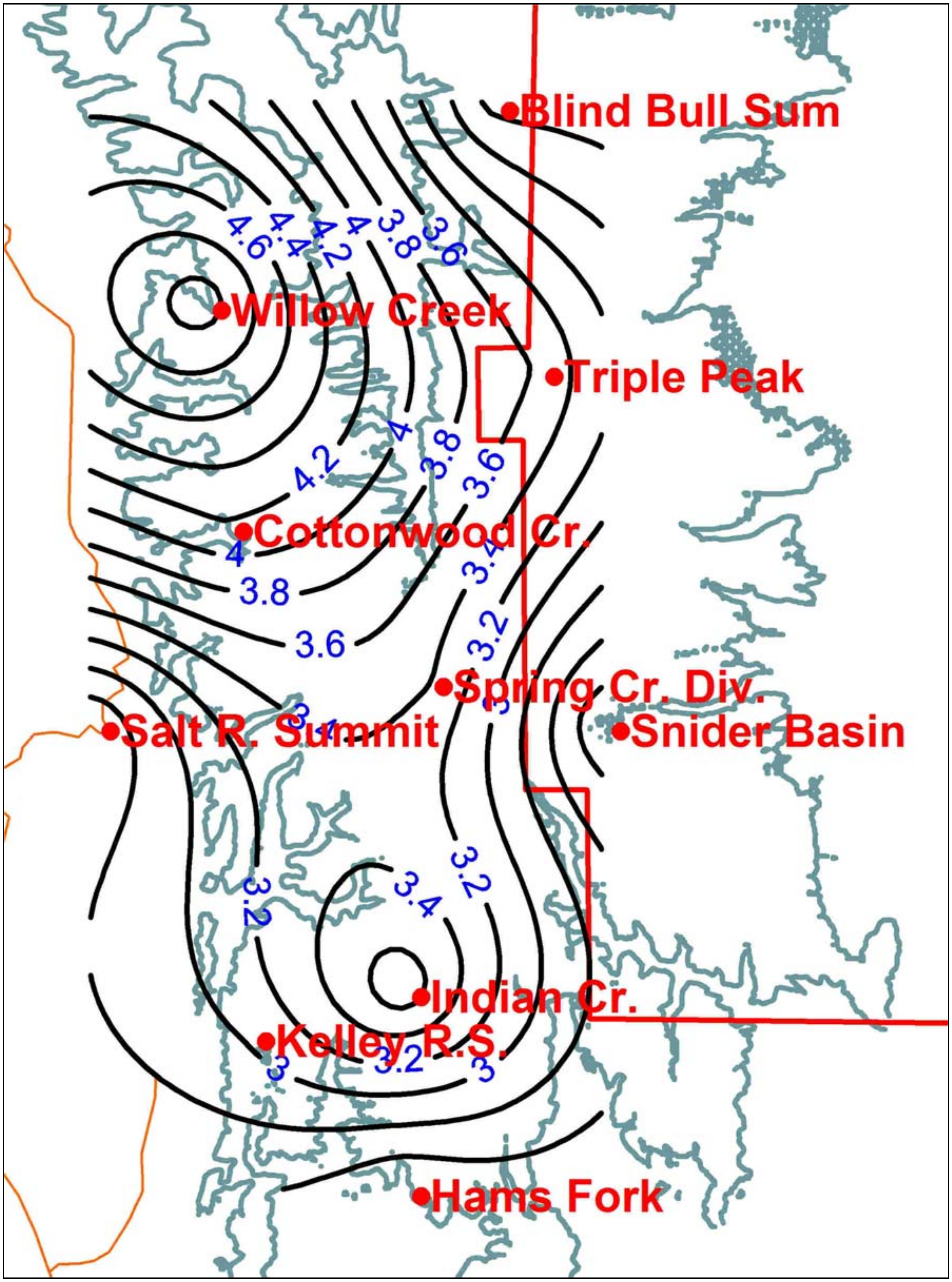

Figure 5.10 Mean April Precipitation

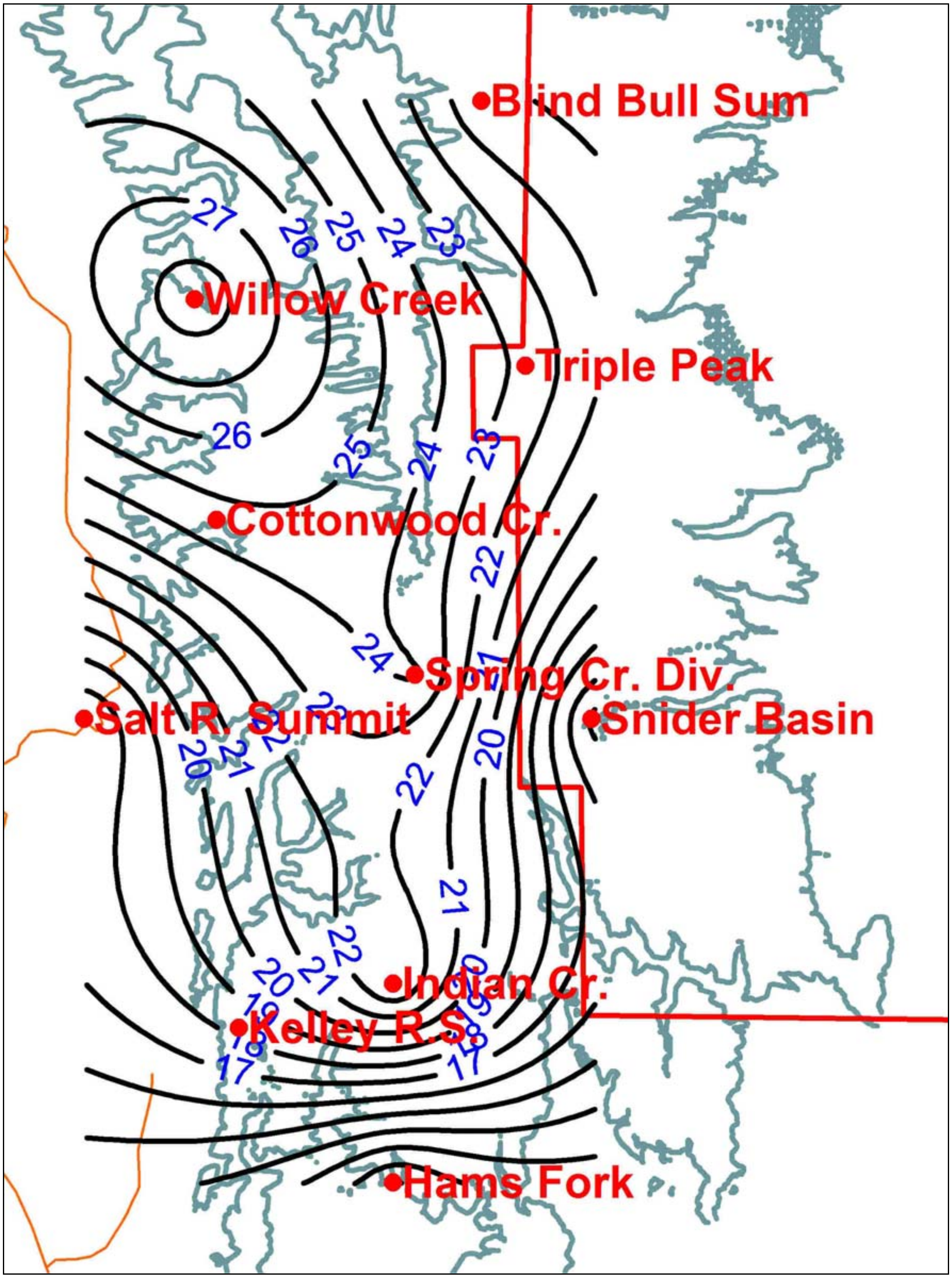

Figure 5.11 Mean November through March Precipitation

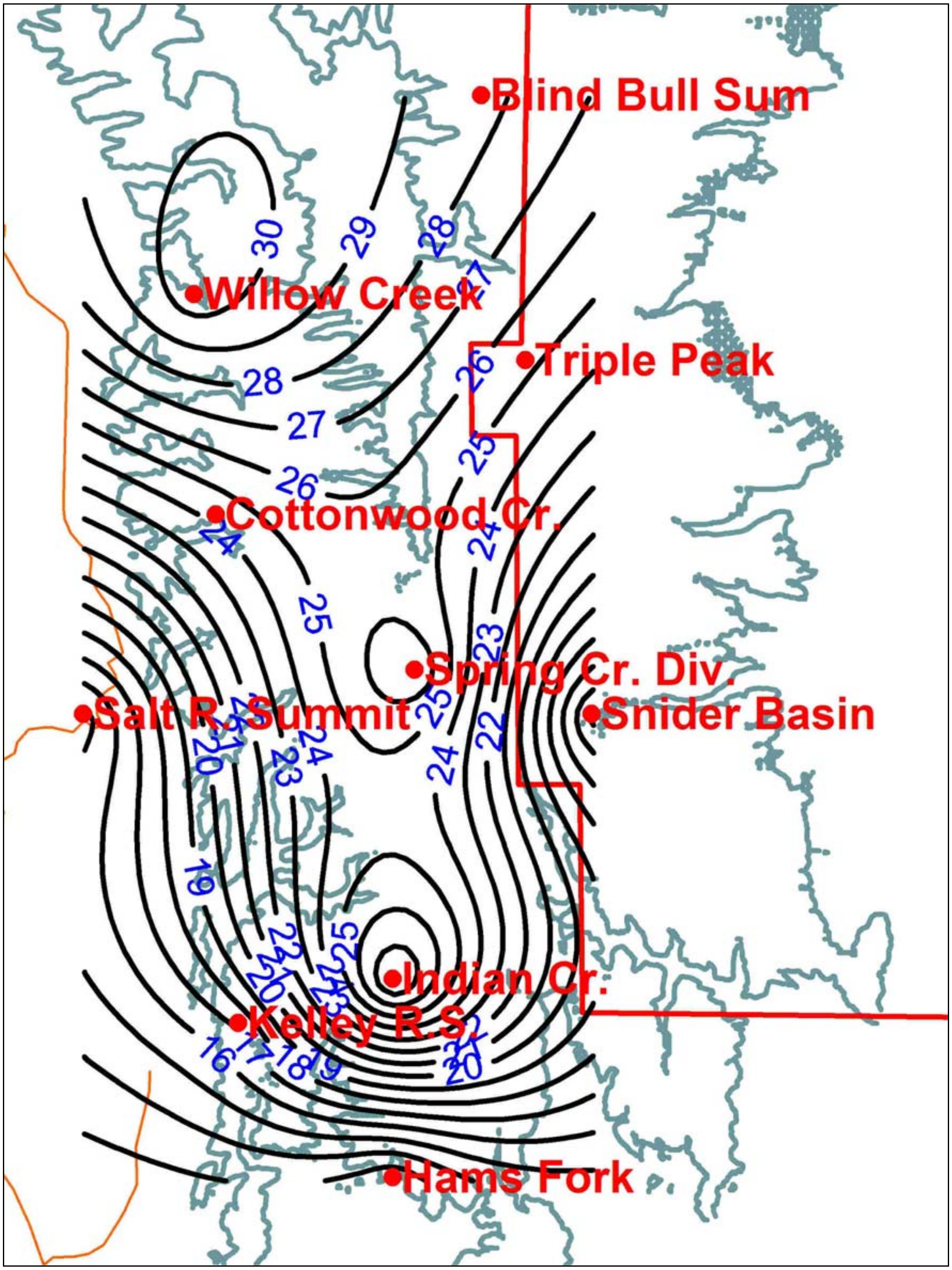

Figure 5.12 Mean April 1st Snow Water Content

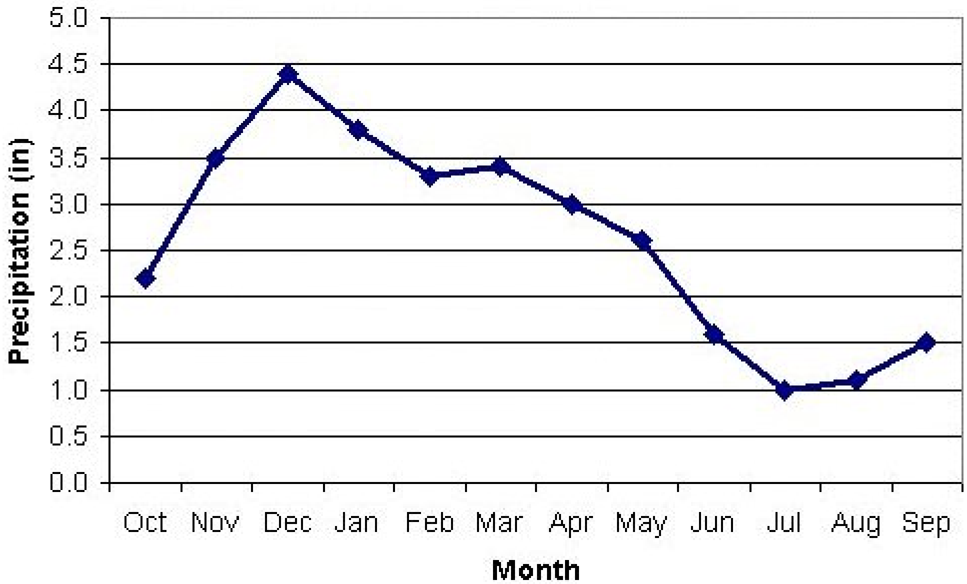

Figure 5.13 Kelley RS Average Monthly Precipitation

Figure 5.14 provides the snow water content accumulation for Spring Creek Divide for the 2004-05 winter season and the average snow water contents for this site. This site, located at the 9,000 foot (2.7km) level, typically experiences increases in snow water content through approximately the third week of April based upon the average plot provided in this figure. Snowmelt typically begins near this time and continues through about June 1st.

5.2.2 Temperature

The temperatures observed in the proposed target areas during the winter are a function of a number of factors including elevation, time of year, cloud cover, and the origin and type of air masses present over these areas at a given time. Normally, temperatures in the free atmosphere decrease ~ 2.7^0 F (1.5^0 C) per 1,000 foot rise in altitude. Figures 5.15 and 5.16 provide average maximum and minimum temperatures for the highest (Indian Creek, 9,425 feet, 2.9 km) and lowest (Cottonwood Creek, 7,670 feet, 2.3 km) elevation SNOTEL sites located within the proposed target areas. These average values are of general interest but the temperatures of special importance are those associated with the winter storm periods that impact the proposed target areas. This type of information will be provided in the following section.

5.2.3 Specialized Climatological Information

The information provided in the previous sections is primarily general information or monthly or seasonal types of information. Data most useful in developing a preliminary design for the SRWR project are those representative of winter storms in the area. NAWC obtained precipitation and snow water content data from the NRCS

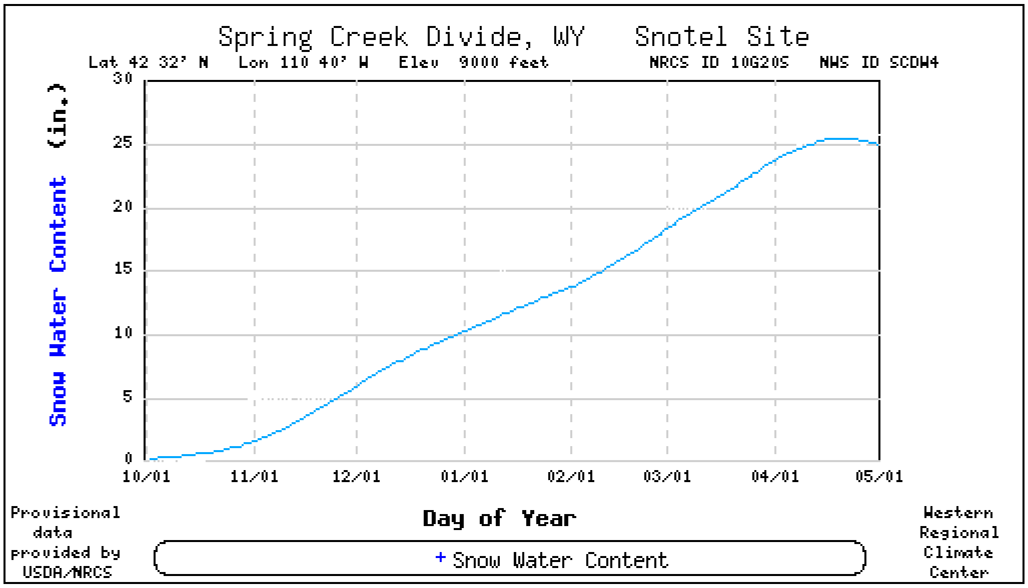

Figure 5.14 Spring Creek Divide Average Snow Water Content Accumulation

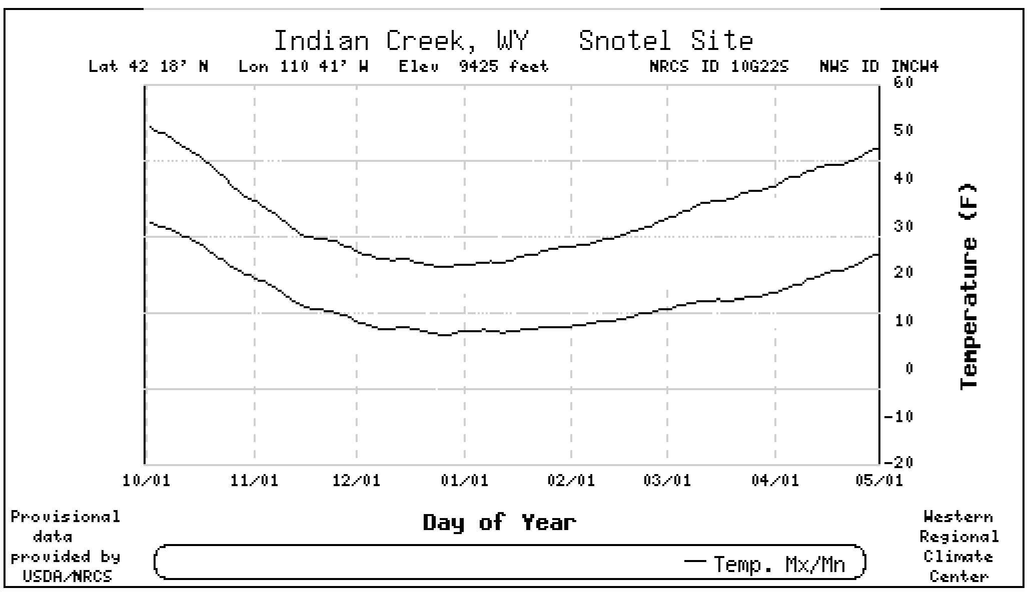

Figure 5.15 Indian Creek Average Maximum and Minimum Temperatures

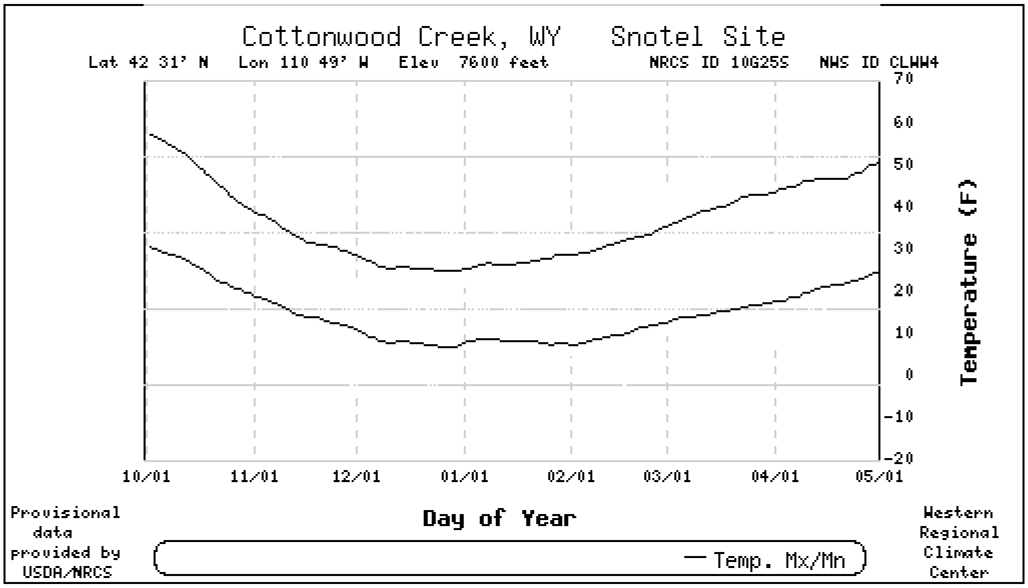

Figure 5.16 Cottonwood Creek Average Maximum and Minimum Temperatures

offices in Portland, Oregon for the 2001-2005 period in order to define discrete storm periods that impacted the SRWR project areas. Data from four representative SNOTEL sites (Blind Bull, Hams Fork, Indian Creek, and Spring Creek) were examined to identify storm periods. These data were available beginning in the 2001-2002 season. A more detailed analysis was then conducted, using snow water accumulations for these SNOTEL sites. The data were partitioned into 6-hour periods when snow accumulation was clearly occurring in the target area. Precipitation data for each site were recorded to the nearest 0.1". A diurnal cycle in the recorded data made identification of these periods less than straightforward at times, although comparison between the sites allowed for good confidence in identifying 6-hour periods when real snow accumulation was occurring. The amount of increase in snow water content during these 6-hour periods was recorded for each of the sites.

The next step involved obtaining rough atmospheric sounding profiles from available NCEP (National Centers for Environmental Prediction) reanalysis data. A point was available in southeastern Idaho located approximately 25 miles south of Pocatello. A site somewhat closer to the potential target areas would have been desirable but these data were only available on a grid of 2.5 ^{0} in latitude. Note: NAWC has recommended that balloon soundings be released during an initial winter of meteorological observations aimed at fine-tuning of the proposed operational cloud seeding project design. For the analyses shown in this current study, these atmospheric profiles were available every six hours (00Z, 06Z, 12Z, 18Z) and were matched as closely as possible to the middle of the 6-hour snow accumulation periods. As it turned out, the sounding times are one hour after the middle point of each 6-hour period (in other words, a 12Z sounding profile represented the 6-hour period from 8-14Z, centered on 11Z). These sounding profiles allowed the collection of 700-mb, 500-mb, and surface temperature data, height of the $–5^0$ C isotherm, winds at 850 and 700 mb, and an estimate of atmospheric stability. Note that the 850-mb level is technically below the surface, but winds at this level could be used to approximate surface winds. Because the temperature data in the reanalysis sounding profiles is sparse (approximately every 100 mb) and near-surface inversions were not detected, surface temperature and wind observations from Afton (when available) were used to help categorize the stability for each time period.

5.2.3.1 Precipitation

A plot of the mean 6-hour precipitation amounts (as described in the above) by month was prepared (Figure 5.17). This figure, which is similar to Figure 5.13, indicates that the two months with the average highest precipitation amounts are December followed by March. Figure 5.18 provides the average number of events per winter season (October through April) in four different ranges of 6-hour snow water amount. This figure suggests that the 6-hour range of 0.10 – 0.19 inches is the most common, with an average of ~ 24 such periods per winter season. Likewise, there are on average 11 six hour periods with <0.10 inch amounts, ~12 with amounts between 0.20 – 0.29 inches, ~ 3 in the range of 0.30 – 0.39 inches and only ~ 1.5 with amounts >0.40 inches. Note that six hour mean snow water content amounts for the four SNOTEL sites are given in hundredths of an inch, for greater precision, even though the original data are in tenths. This snow water information, combined with other information on the potential seedability of these events, will be used in a later section to estimate the amount (duration) of seeding that could be conducted.

5.2.3.2 700-mb Winds

NAWC has utilized the 700 mb level (approximately 10,000 feet MSL) as an index for a couple of important meteorological features regarding seeding targeting. First, the 700 mb wind is considered a good steering level approximation of the direction which storm elements will move along. NAWC has also used this level as guidance in the selection of ground -based generator sites. The 700 mb wind directions and speeds for the 6-hourly, four-season sample described above were used to generate wind roses that graphically display the average information by month and for the entire winter season (October – April). The wind roses provide the frequency of wind direction and speeds by 22.5^0 wind sectors. Recall that wind directions in meteorology are reported according to the direction from which the wind is blowing. For example, a wind direction of 270^0 means the wind is blowing directly out of the west towards the east. Figures 5.19 through 5.25 provide the monthly wind roses and Figure 5.26 provides the seasonal (October – April) wind rose. These figures show some variation from month to month, with the April storm periods having by far the most variable wind conditions. The storm period wind directions in this four-season sample favored a southwesterly direction in October, west-northwesterly in November, westerly in December, west-southwesterly in January and February, westerly in March, and west-southwesterly in April. The plot (Figure 5.26) for the entire winter season (October through April) indicates the predominant storm-period wind direction is from the west. This information is used in a later section in discussions concerning the potential siting of ground generators.

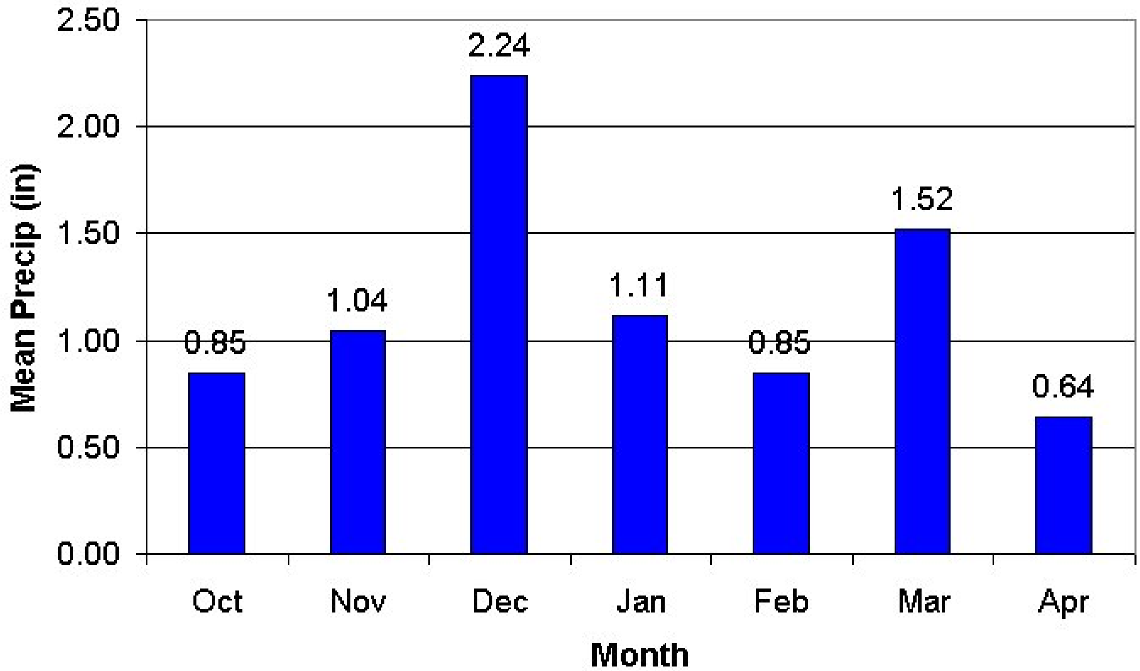

Figure 5.17 Mean 6-hr SWE amounts by Month

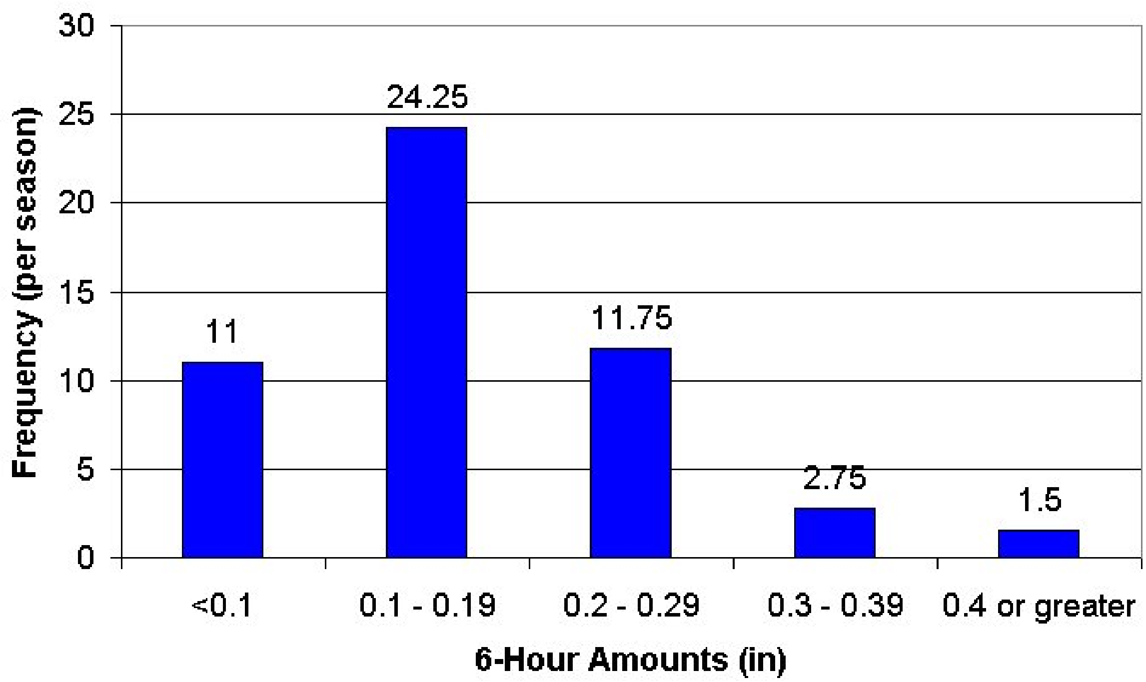

Figure 5.18 Frequency of 6-hr SWE amounts

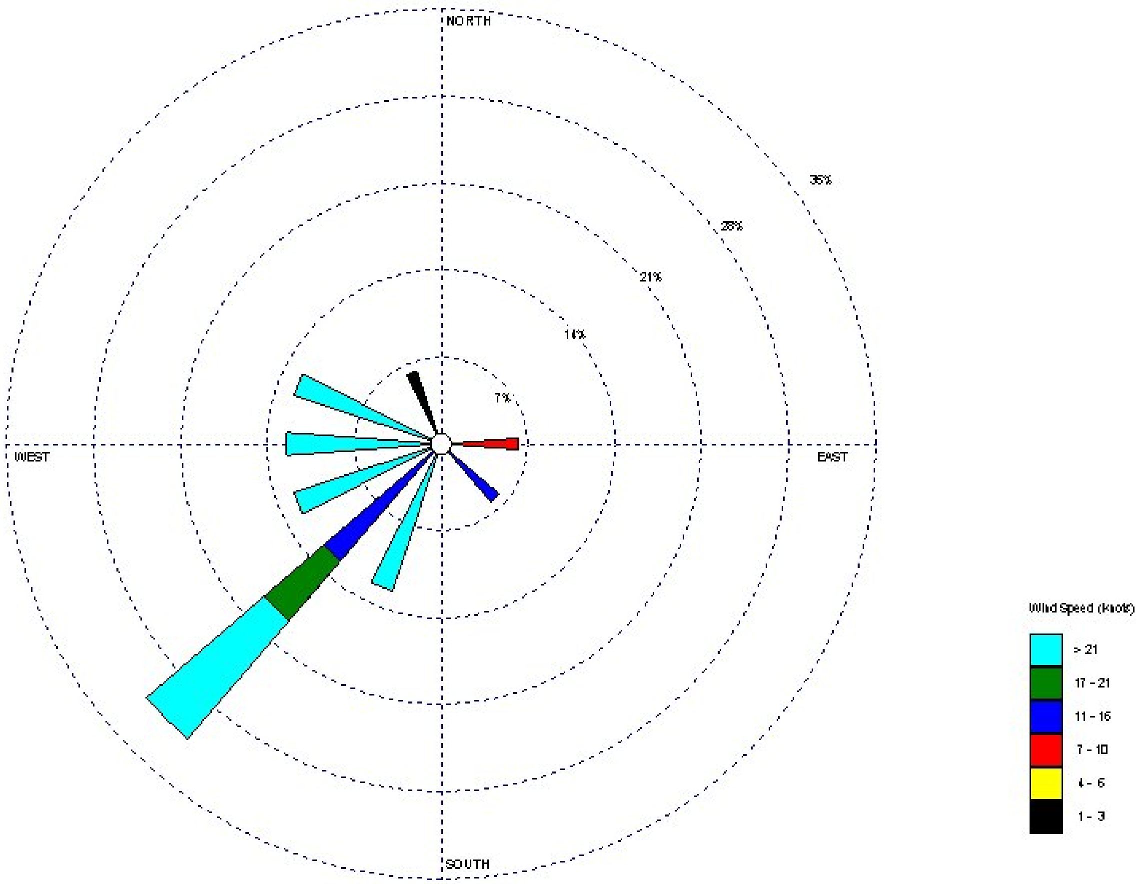

Figure 5.19 October 700-mb Wind Rose

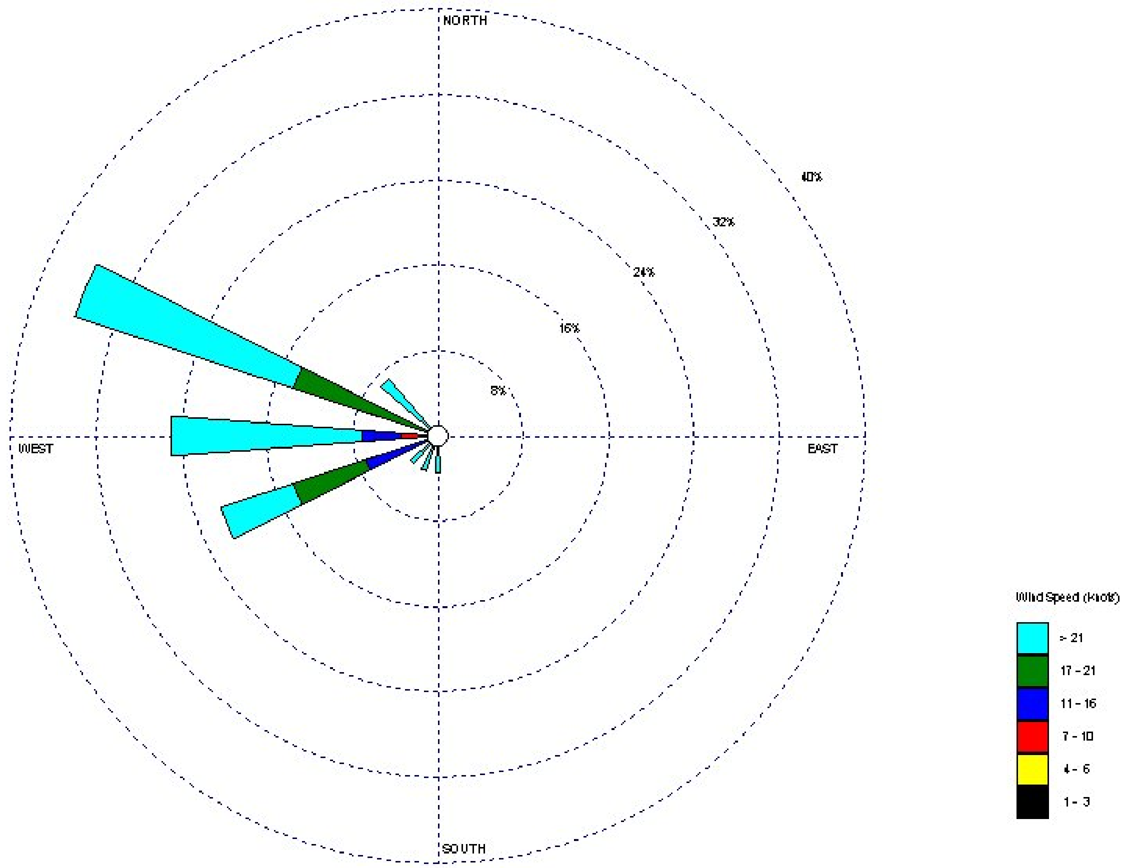

Figure 5.20 November 700-mb Wind Rose

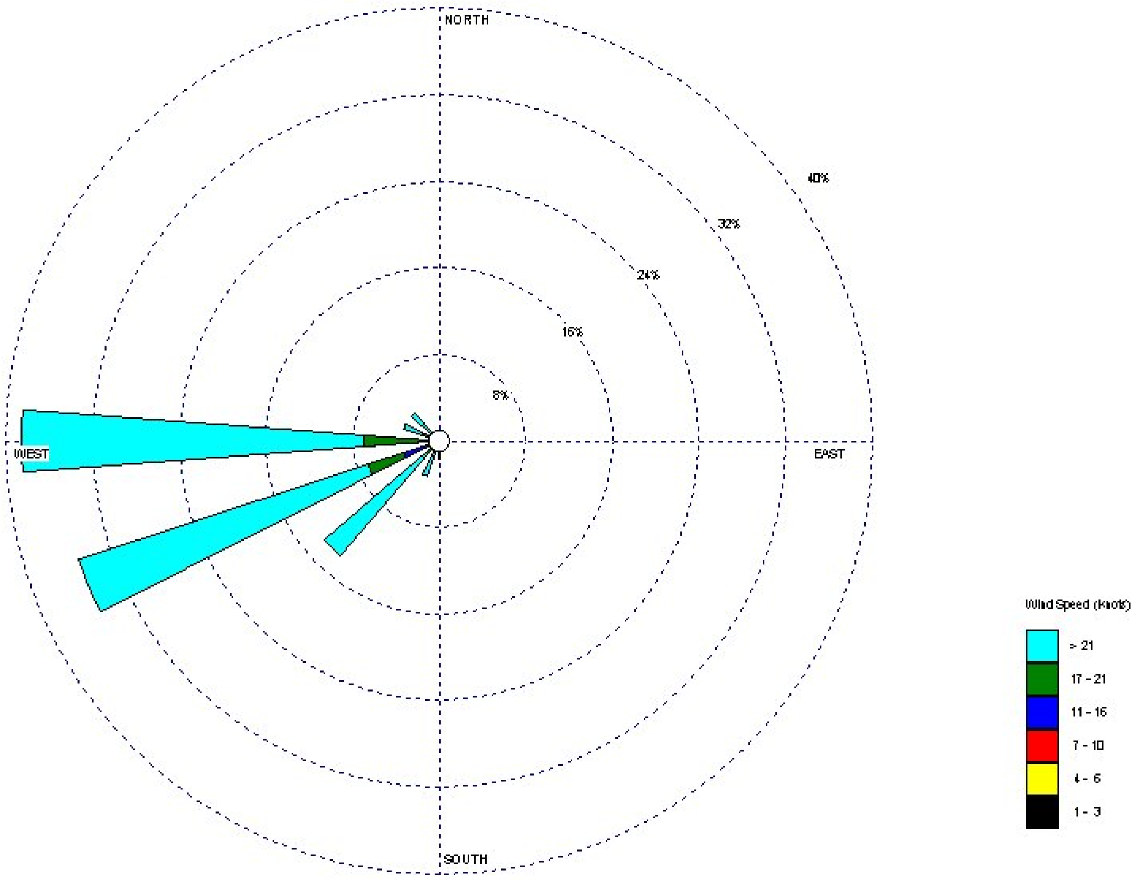

Figure 5.21   December 700-mb Wind Rose

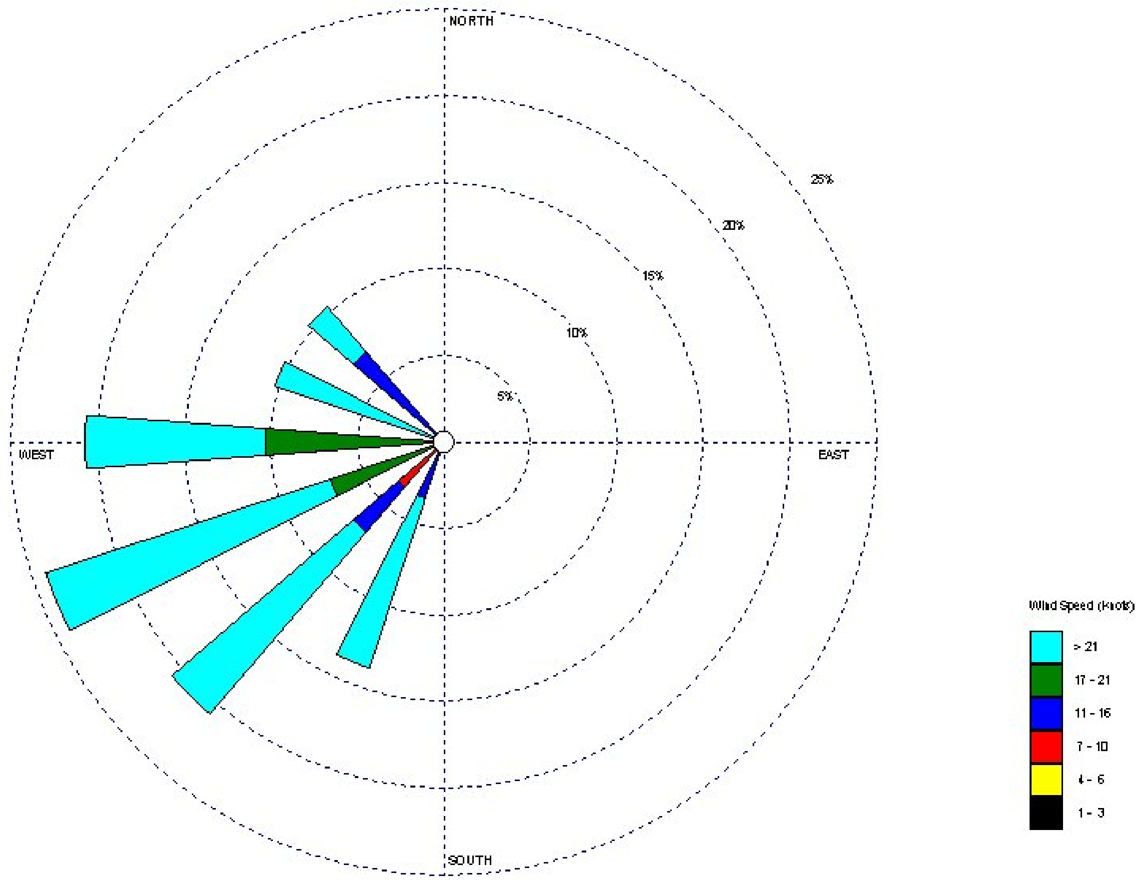

Figure 5.22 January 700-mb Wind Rose

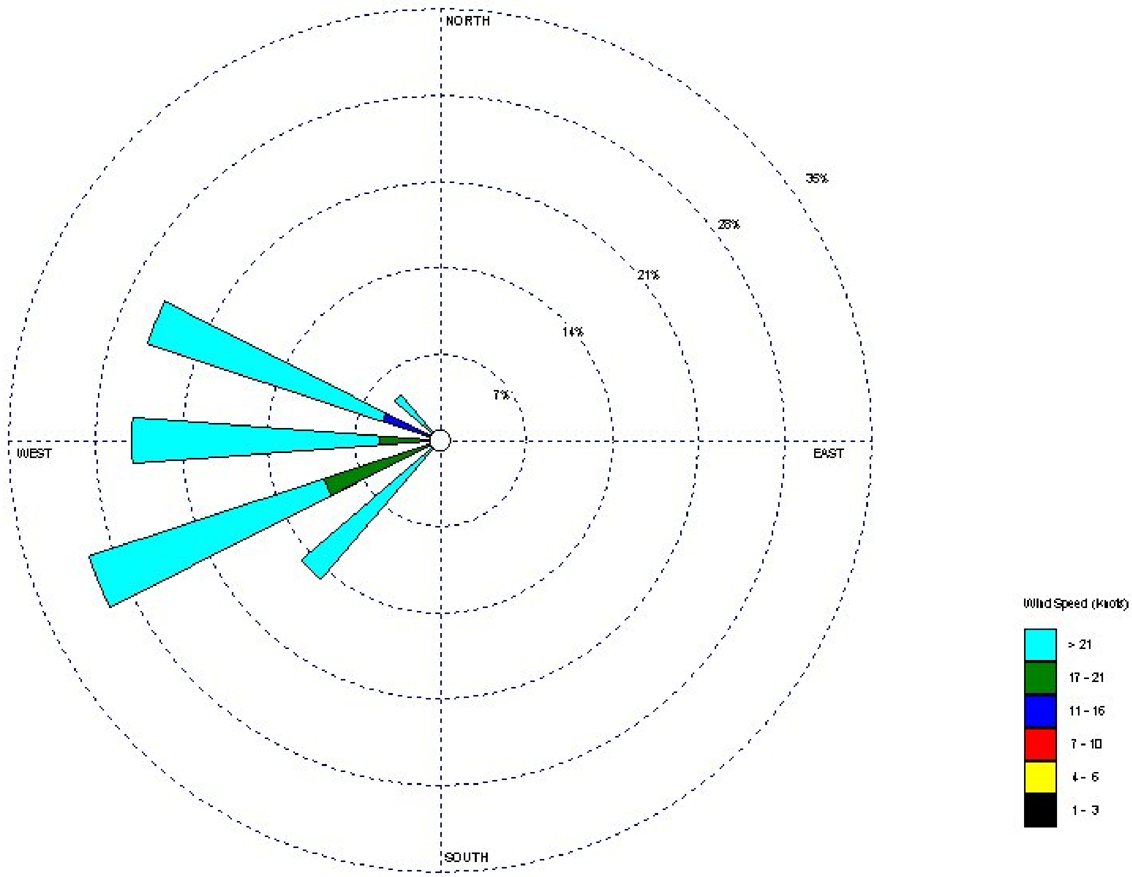

Figure 5.23   February 700-mb Wind Rose

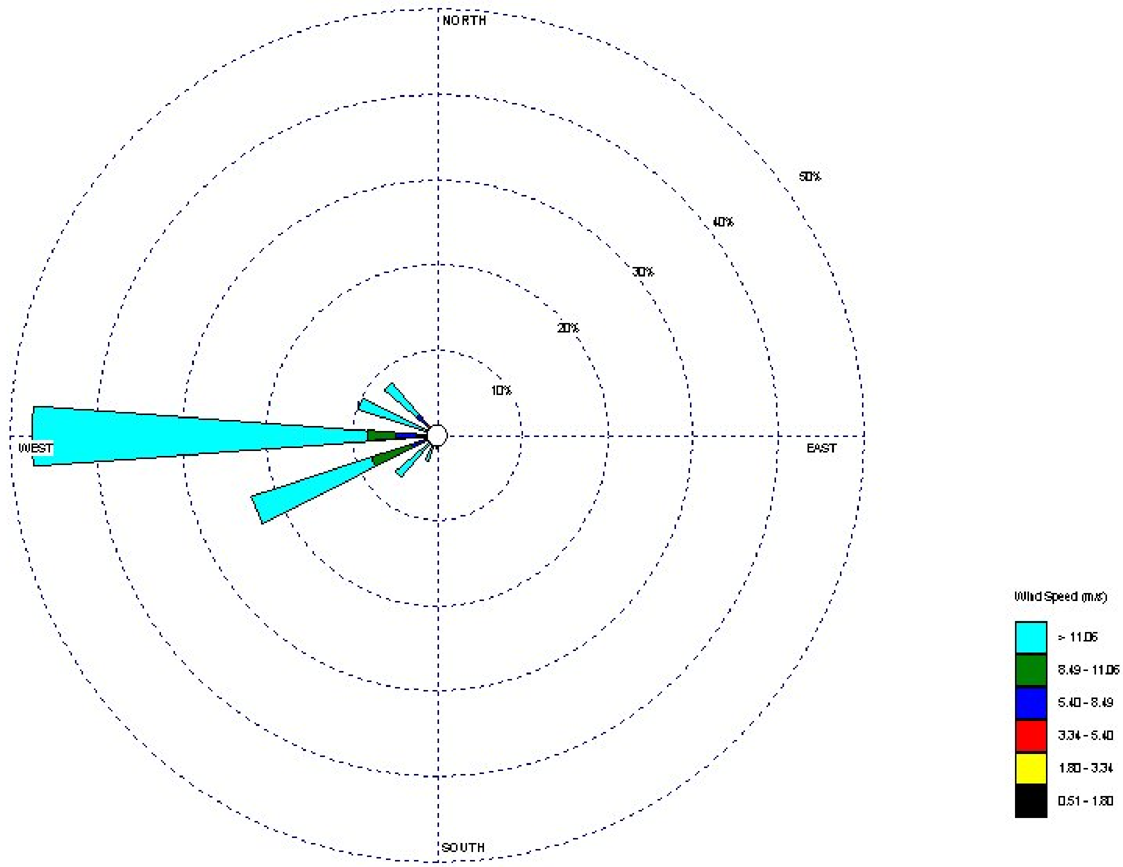

Figure 5.24 March 700-mbWind Rose

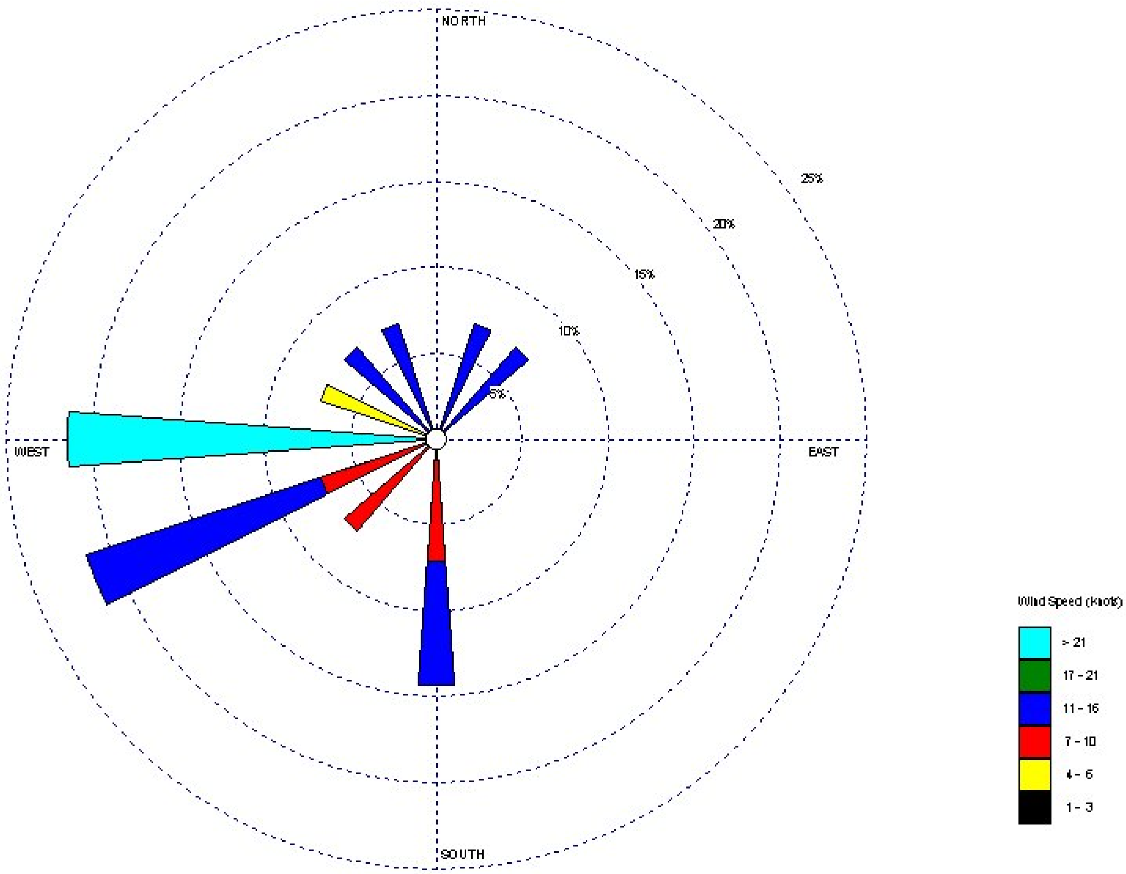

Figure 5.25 April 700-mb Wind Rose

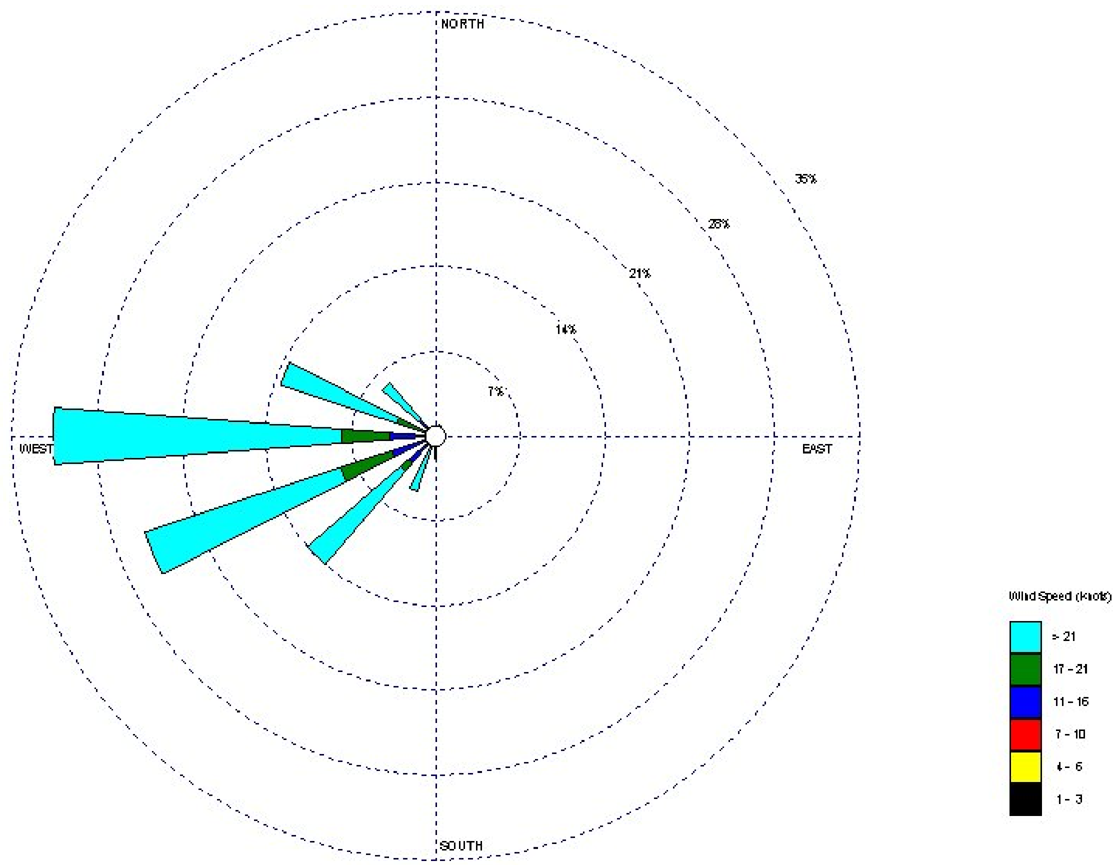

Figure 5.26 October – April 700-mb Wind Rose

5.2.3.3 <u>700-mb Temperatures</u>

A plot of the average 700-mb temperatures during storm periods by month was prepared (Figure 5.27). Temperatures at this level are used in helping decide whether a specific storm period is considered seedable using ground-based generators. The concept is that the 700-mb level is typically near the height of the target mountain barriers. Seeding materials released from ground generators have been shown to rise up to approximately 1000-2000 feet (300-600 m) above the mountain crest heights. Silver iodide becomes an active ice nucleant at temperatures of about -4 to -5^0 C or colder. These factors indicate that the 700-mb temperature should be approximately -5^0 C or colder in order for seeding to be effective. The seeding material must have the opportunity to form ice crystals upwind of the barrier, which can then grow into snowflakes and fall onto the barrier. Figure 5.27 indicates that 700-mb temperatures did average –5^0 C or colder for storm periods examined in the SRWR target area, with the month of October being on the marginal (warm) side. Figure 5.28 provides a plot of the mean height of the -5^0 C isotherm by snowfall intensity (based on 6-hour snow water

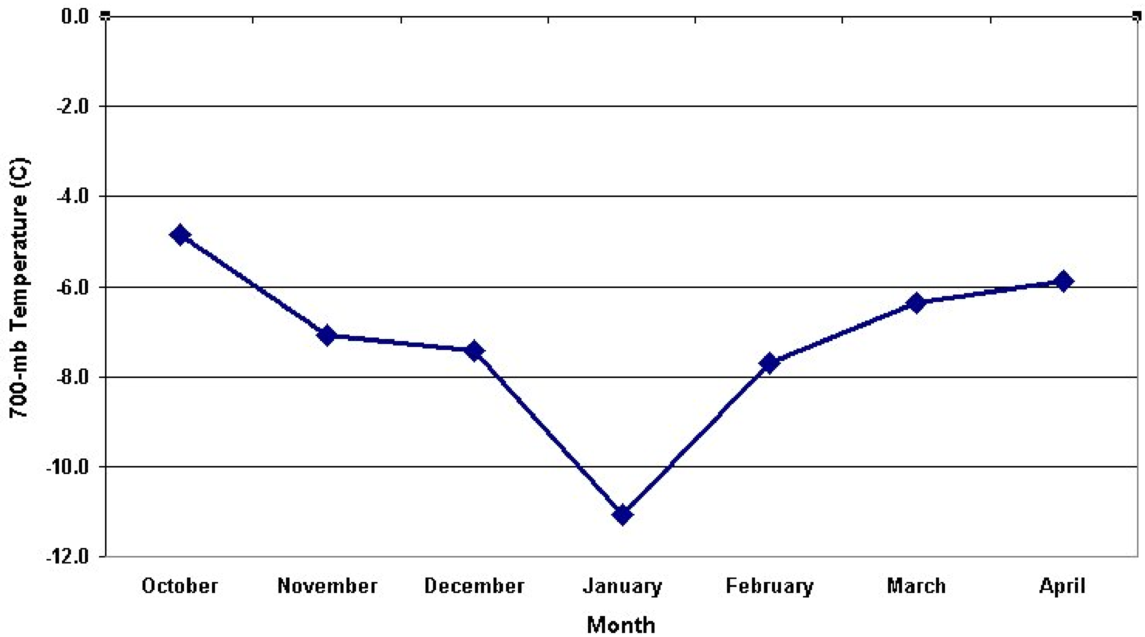

Figure 5.27 Mean 700-mb Temperature by Month

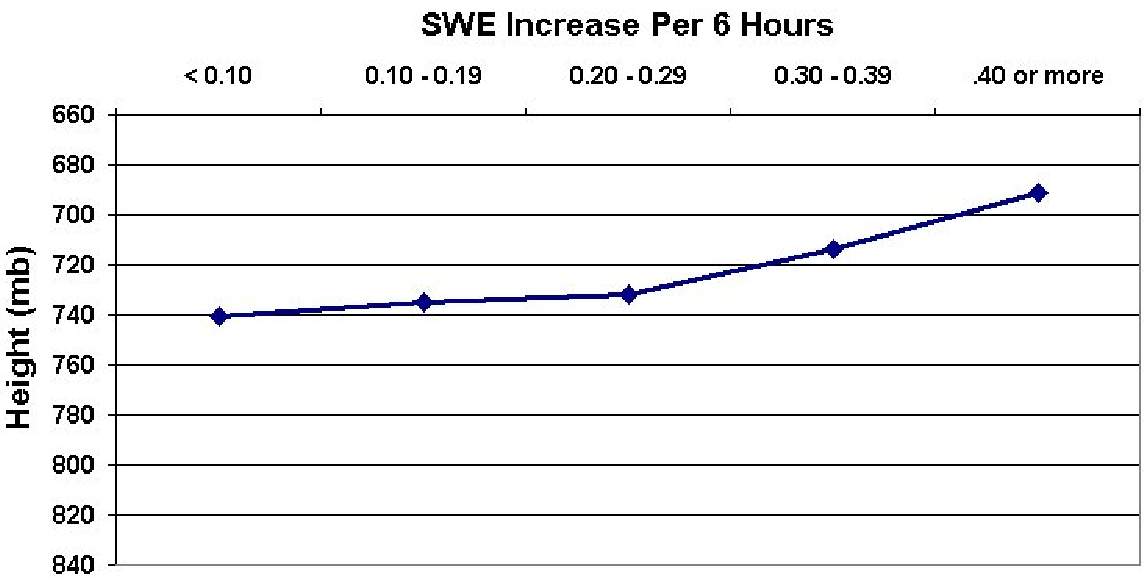

Figure 5.28 Mean Height of -5^0 C Isotherm by Six Hour Snow Water Content Amounts

amounts for the four SNOTEL sites described in section 5.2.3). This figure demonstrates that, on average, the -5^0 C isotherm is higher during periods of greater snowfall intensity. The storms with mean 6-hour amounts of > 0.30" are not very frequent, however, as shown earlier in Figure 5.18. Figure 5.29, which shows mean height of the -5^0C isotherm by month, does indicate that the -5^0 C level is normally at or below the mean crest height of the Salt River and Wyoming Ranges, approximately 9,500 feet MSL (2.9 km). This suggests that most of these 6-hour storm periods would be within the proper temperature range for cloud seeding. Figure 5.29 suggests that the month of October is on the marginal side of meeting these temperature criteria.

We also compared the mean 700-mb temperatures to the snowfall intensity (based on the average 6-hour snow water accumulation for the four SNOTEL sites described in section 5.2.3). Figure 5.30 is a plot of the mean 700-mb temperature vs. six-hour snowfall intensity. This figure indicates that greater snowfall intensity is generally associated with warmer 700 mb temperatures, consistent with the higher –5^0 C levels shown in Figure 5.29. This makes sense meteorologically since warmer air masses can hold more water, which can be converted into more snowfall, under the right conditions, than possible with colder storms.

5.2.3.4 <u>Low-Level Stability</u>

Another meteorological feature of special interest when considering ground-based cloud seeding is the frequency of occurrence of low-level temperature inversions in the atmosphere that may restrict the vertical transport of seeding materials released from the ground into effective cloud regions. Temperatures in the atmosphere typically decrease with height. An inversion is said to exist if there is a layer in the atmosphere in which the temperatures increases instead of decreases with height. Such inversions are responsible for the trapping of pollutants and formation of smog in places like the Los Angeles Basin.

An analysis was performed to examine whether this phenomenon would potentially present a problem in seeding from ground generators in the SRWR project. For this analysis, atmospheric stability (between the surface and 700 mb) was determined for precipitating periods based on both the NCEP reanalysis - derived sounding and on the surface temperature report at the Afton, Wyoming automated station (AFTY). The stability was classified into four categories - “Neutral”, “Slightly Stable”, “Moderately Stable”, or “Very Stable”. “Neutral” means that the atmosphere was apparently well mixed between the surface and 700 mb. Transport of seeding material should be excellent under these conditions, with appropriate wind direction. “Slightly Stable” means that there was a small amount of stability, such that heating of the surface of approximately 4 degrees F (2 degrees C) or less would mix out the atmosphere to the 700-mb level. These are cases where seeding from ground generators would probably still be attempted, as the stability may be overcome by winds and other forcing mechanisms, allowing some mixing to occur. Mixing and vertical transport of the seeding material under these conditions would vary considerably from case to case. “Moderately Stable” or “Very Stable” were used for cases where heating of more than about 4 degrees F would be needed at the surface to mix out the atmosphere to 700 mb. These are cases where

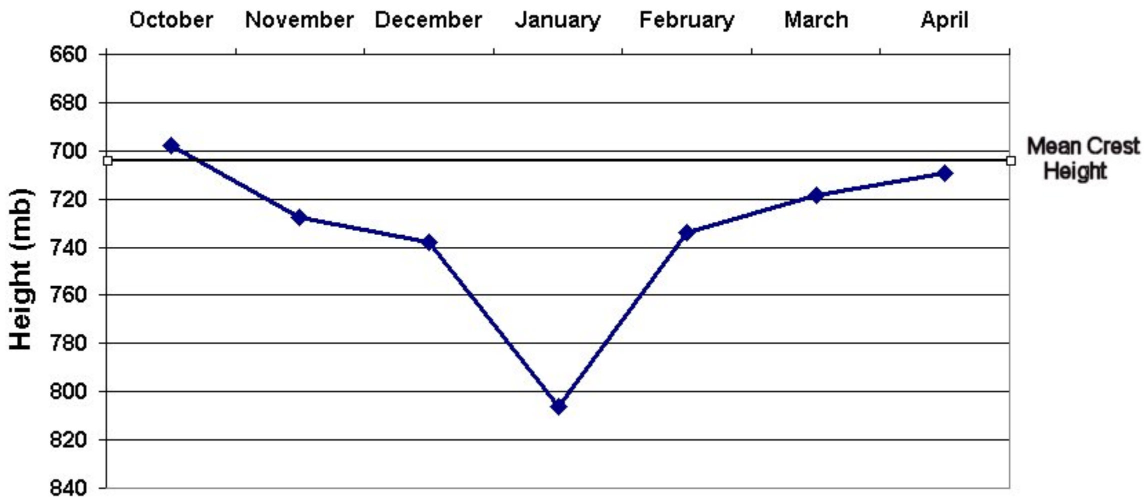

Figure 5.29 Mean Height of –5^0 C Isotherm by Month
(mean barrier crest height is 705 mb, shown by horizonal line)

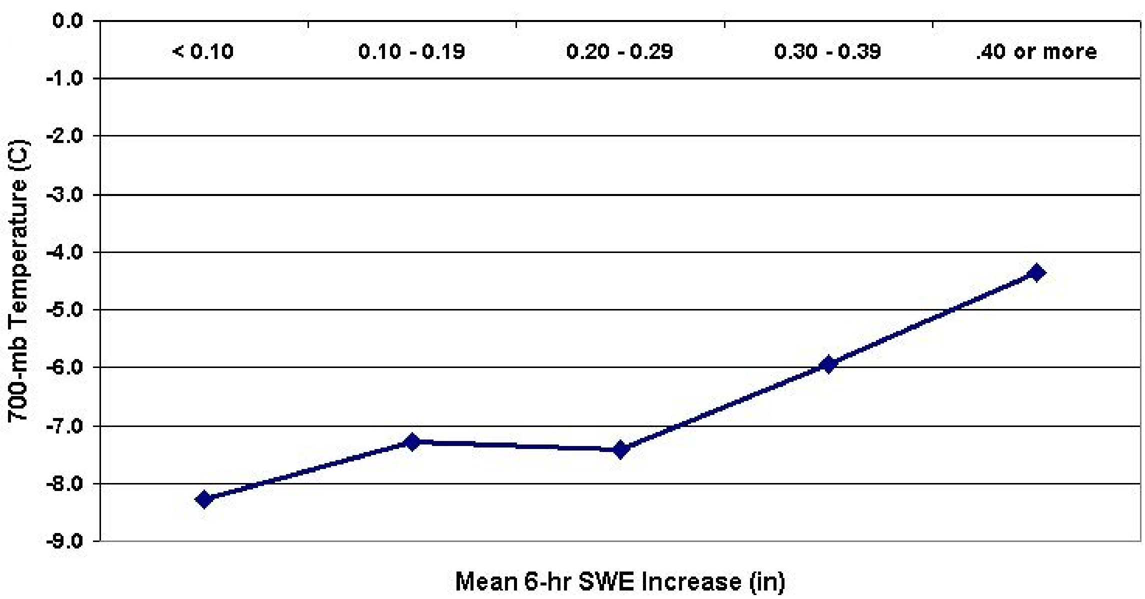

Figure 5.30 Mean 700-mb Temperature by SWE 6-hr Accumulation

ground-based seeding would probably not be attempted due to stability considerations. Figure 5.31 provides a plot of the frequency of “neutral” stability below 700 mb by month, expressed as the percentage of the time during stormy periods. This figure indicates that the most favorable category of stability (neutral) averages around 60-80 % of the time during the months of October, November, February, March and April but declines to ~35 % of the cases during the months of December and January. If the cases of neutral or slightly stable stability categories are combined, the percentages range from ~ 70 – 90%. This implies that low-level inversions may not be a major factor in the utilization of ground-based generators in the SRWR project area. However, Bridger-Teton National Forest staff have noted that temperature inversions are observed at times during the winter months. Actual observations during future storm periods would be highly desirable to verify this conclusion. For example, rawinsonde (weather balloon) observations could be conducted perhaps at 6-hour intervals during storm periods for one winter season to provide this verification. These observations should be conducted from a central location in Star Valley. This possibility will be discussed in a later section concerned with project recommendations.

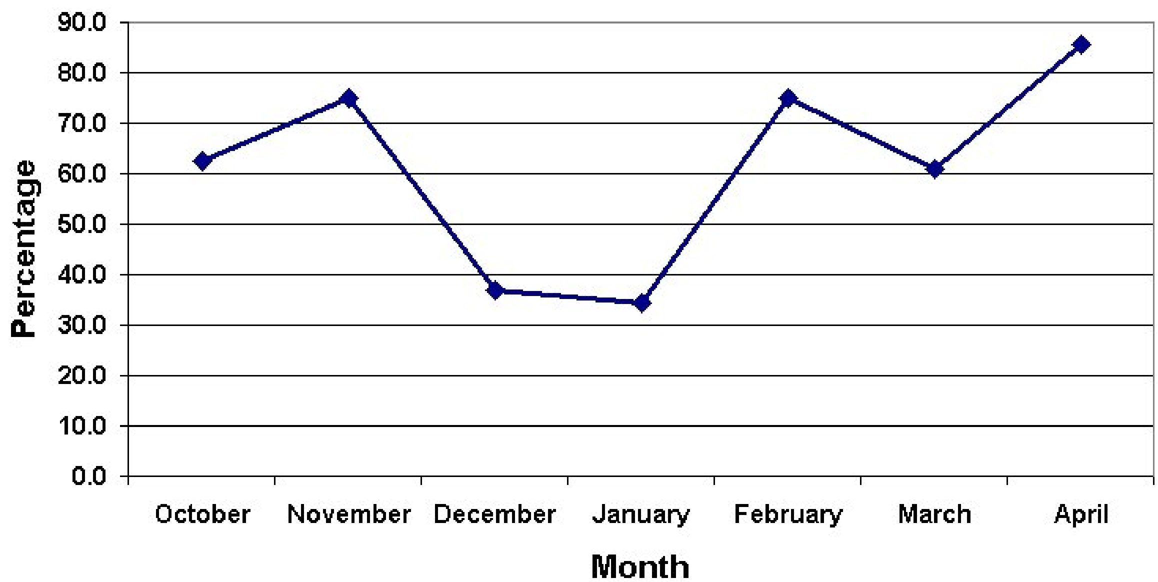

Figure 5.31 Frequency of “Neutral” Stability by Month

6.0 DEVELOPMENT OF PRELIMINARY DESIGN

The development of a preliminary project design assumes that the application of cloud seeding to the proposed target areas appears feasible. There are two primary considerations in determining whether a project appears feasible: 1) is there a scientific basis supporting the conduct of the proposed project? and 2) if the project appears scientifically feasible, is it economically feasible?

Is the Proposed Project Scientifically Feasible?

NAWC believes that a project can be designed for the SRWR potential target areas that is scientifically feasible based upon the transferability of the techniques and results obtained in the conduct of previous research programs as described in section 4.0. In addition to these research programs, there are a large number of operational projects that have been conducted in the Intermountain West that provide additional support to the concept that a viable cloud seeding technology exists that can be applied in wintertime orographic (mountainous) programs. The Weather Modification Association's response (WMA, 2004) to a National Research Council report entitled "Critical Issues in Weather Modification Research" contains the following summary:

"There is a broad body of evidence in the literature and in company reports describing the results from various operational projects involving winter orographic clouds. Some projects in California have been in existence since the 1950's and 1960's. The Kings River project in southern California has been operational for 48 years and has produced an average 5.5% additional runoff per year (Henderson, 1986, 2003). An operational project run for the past 25 years or so in Utah has published results for 13 and 19 years of operations that indicate 11-15% increases in seasonal precipitation (Griffith, et al, 1991; Griffith, et al, 1997). Add to these results the San Joaquin River project showing at a minimum 8% increase in target area seasonal precipitation using trace chemistry studies of snowpack (McGurty, 1999), the Climax indications of 10 % increases, and the Tasmanian results of 10% increases when storm *cloud top temperatures are in the range of -10 ^{0} C to -12 ^{0} C and the evidence becomes very convincing that cloud seeding conducted under proper conditions increases precipitation in winter orographic situations. These findings and statements are in accord with the American Meteorological Society policy statement on weather modification regarding capabilities of winter orographic cloud seeding (AMS, 1998)."*

As a consequence, we propose that the design of the SRWR project be based upon the assumption that winter cloud seeding programs, when properly conducted, are effective. The resulting design will not attempt to "prove" that cloud seeding "works". This work is therefore focused on the development of a **state-of-the-art operational cloud seeding project.** This approach assumes the fact that there is an existing technology that has been developed over the past 50 plus years that can be applied in orographic winter settings to produce beneficial increases in precipitation of the order of 10%. This is not to say that all facets of cloud seeding, nor natural cloud processes for that matter, are completely understood; they are not. Additional research is needed to advance our understanding in both areas. This project is **not** envisioned to be of the type that would be research oriented with the primary goal being to advance understanding in this manner. Rather, this project would be oriented towards the production of additional water at a reasonable cost, as requested by the stakeholders of the region. **In a sense, we therefore propose to develop a core project whose goal would be the production of additional water at a reasonable cost via cloud seeding.** Such a core project could serve as a platform for the addition of ancillary measurements by the State or other interested parties including universities or federal agencies if additional funding sources are available and the WWDC wishes to sponsor such research activities. The National Oceanic and Atmospheric Administration (NOAA) utilized this "piggy-back" research concept in the 1990's under their Atmospheric Modification Program (AMP) (Reinking, 1992). Research components were added to ongoing operational programs in several states, including Nevada, North Dakota and Utah.

Is the Proposed Project Economically Feasible?

Determination of whether the program appears to be economically feasible can be accomplished by compiling estimates of the expected increases (if any) due to cloud seeding and then determining the potential value of such increases. Oftentimes sponsors of winter programs are interested in estimates of additional streamflow that may result from implementation of the cloud seeding programs. Once such estimates are obtained (through relating increases in precipitation to increases in runoff), approximate values of the additional streamflow may be established based upon the perceived value of the water to different end uses (e.g., irrigated agriculture, municipal water supplies, hydroelectric generation). Calculations of the cost of conducting the program can then be considered versus estimated costs in order to derive a preliminary benefit to cost estimate. These topics will be discussed later in this section and also in sections 12, 13 and 14.

6.1 General Description of the Theory of Cloud Seeding for Precipitation Augmentation

A basic summary of the concept of how cloud seeding is thought to work in wintertime mountainous (orographic) settings is worthwhile at this juncture in order to set the stage for the development of designs for the proposed project areas. A number of observational and theoretical studies have suggested that there is a cold "temperature window" of opportunity for cloud seeding. Some information contained in a report from the Weather Modification Association (Orville, et al, 2004) is paraphrased in some of the following discussions.

Numerous observations in the atmosphere and in the laboratory have indicated that cloud water droplets can remain unfrozen at temperatures well below freezing. These droplets are in a "supercooled" state. Thus the phrase supercooled liquid water (SLW) has been coined to refer to the presence of such water droplets in a cloud. In fact, pure water droplets in a laboratory setting have been observed to remain unfrozen to a temperature of -38.2^{0} F (-39^{0} C). Droplets at -40^{0} F (-40^{0} C) freeze spontaneously through a process known as homogeneous nucleation. In order for water droplets to freeze at temperatures between 30.2^{0} F (-1^{0} C) and -38.2^{0} F (-39^{0} C) they must come in contact with foreign particles to cause them to freeze. These particles are called freezing nuclei. The process is known as heterogeneous nucleation. Such nuclei occur in nature and are primarily composed of tiny soil particles. Numerous observations around the world have indicated that the numbers of naturally occurring freezing nuclei that can cause heterogeneous nucleation to occur are temperature dependent. These nuclei become increasingly active with decreasing temperatures. Once a supercooled water droplet is frozen, creating an ice crystal, it will grow through vapor deposition (and possibly aggregation) from the water droplets surrounding it and, given the right conditions, form a snowflake large enough to fall from the cloud and reach the ground. Supercooled water droplets are the targets of opportunity in order to increase precipitation through seeding.

Studies of both orographic and convective clouds have suggested that clouds colder than ~ -13^{0} F (-25^{0} C) have sufficiently large concentrations of natural ice crystals such that seeding can either have no effect or even reduce precipitation (Grant and Elliott, 1974; Grant, 1986; Gagin and Neumann, 1981; Gagin et al., 1985). It is possible that seeding such cold clouds could reduce precipitation by creating so many ice crystals that they compete for the fixed supply of water vapor and result in numerous, slowly settling ice crystals which sublimate before reaching the ground. There are also indications that there is a warm temperature limit to seeding effectiveness (Gagin and Neumann, 1981; Grant and Elliott, 1974; Cooper and Lawson, 1984). This is believed to be due to a) the low efficiency of ice crystal production by silver iodide at temperatures greater than 24.8^{0} F (-4^{0} C) and b) the slow rates of ice crystal vapor deposition growth at comparatively warm temperatures. Thus, there appears to be a "temperature window" of about 23^{0} F (-5^{0} C) to -13^{0} F (-25^{0} C) where clouds respond favorably to silver iodide seeding (i.e., exhibit seedability). Dry ice (frozen carbon dioxide) seeding via aircraft extends this temperature window to temperatures just below 32^{0} F (0^{0} C), but the slow rates of ice crystal vapor deposition growth are a factor at this warm end of the temperature spectrum.

Orographic clouds in the mountainous western states are associated with passing storm systems. Wind flow over a mountain barrier causes the orographic lift to produce the cloud. Other types of clouds associated with frontal boundaries, convergence bands, and convective instability are also present during these storm systems, thus the orographic cloud scenario is often complicated by the dynamics of the storm system (changing winds, temperatures, and moisture). In situ and remote observations of SLW in orographic clouds (e.g., Reynolds, 1988) have indicated significant periods of the occurrence of SLW with passing winter storms. These studies have indicated that the preferred location for the formation of zones of SLW is over the windward slopes of the mountain barriers at relatively low elevations (typically only reaching to approximately or slightly above the height of the mountain barrier). Figure 6.1 provides a stylized

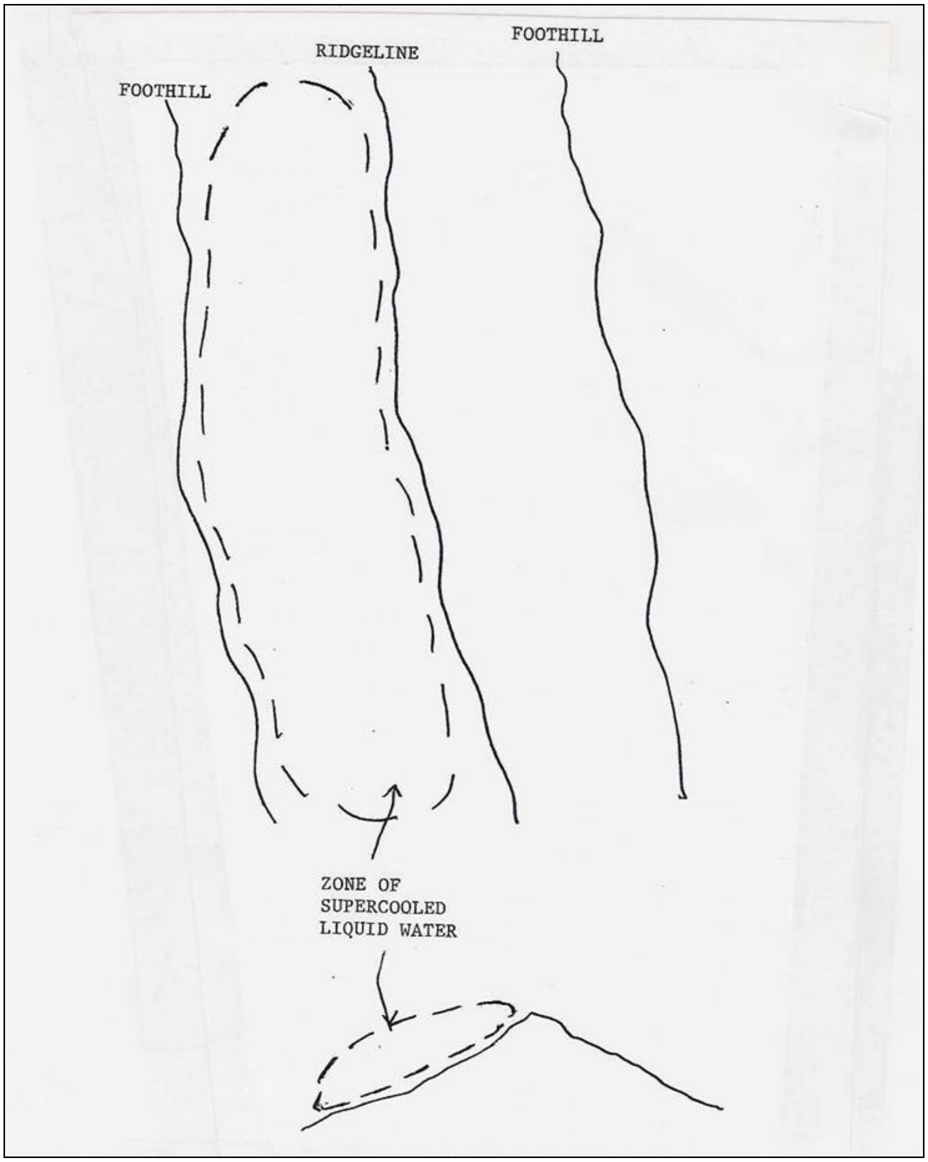

Figure 6.1 Depiction of SLW Zone

depiction of this SLW zone associated with a mountain barrier that has been derived by NAWC based on the results from a number of winter research programs that have used microwave radiometers and aircraft to document the presence of the SLW. Super, 1990, reporting on measurements of SLW observed in winter research programs in the western U.S. states, "There is remarkable similarity among research results from the various mountain ranges. In general, SLW is available during at least portions of many storms. It is usually concentrated in the lower layers and especially in shallow clouds with warm tops". Another series of quotes from Super, 1990 are as follows: "The tendency for greatest SLW content near the windward slopes of a barrier is clearly shown from a composite of 22 aircraft missions over the Cascade Mountains (Hobbs, 1975), and also based upon data from 57 vibrating wire sondes released over the Wasatch Mountains of Utah. Holroyd and Super (1984) examined data from many aircraft passes over the flattopped Grand Mesa of Colorado and showed that SLW was concentrated over the windward slope and barrier top, with higher water contents nearer the surface." Research conducted in the Sierra Nevada Mountains of California as summarized by Reynolds (1988) indicate that shallow orographic clouds are considered the best candidates for winter snowpack augmentation, similar to the findings found in the above references.

The basic consideration in the development of the design of a winter orographic cloud seeding project is to develop a seeding methodology that will tap this reservoir of SLW to convert water into snowflakes that otherwise would be lost through evaporation over the downwind side of the barrier. In other words, we wish to improve the efficiency of the natural storm system in terms of producing precipitation that reaches the ground. Figure 6.2 provides a computer simulation of SLW over the Wind River Mountain barrier as found in the WMI Executive Summary (WMI, 2005). This simulation depicts this same zone of SLW at low-levels on the upwind side of the barrier much like that depicted in Figure 6.1. It is believed that the upslope zone of SLW depicted in this figure is important to the production of a positive seeding effect within the intended target area. Based upon some limited modeling of storms in the proposed target area conducted by the Desert Research Institute (Appendix C) it was concluded "aircraft seeding to specifically target liquid regions in gravity waves does not appear to be a viable option for enhancing precipitation over the Salt River and Wyoming Ranges." If SLW clouds upwind and over mountain barriers are routinely seeded to produce appropriate concentrations of seeding ice crystals, exceeding 10 to 20 per liter of cloudy air, snowfall increases can be anticipated in the presence or absence of natural snowfall. It has been repeatedly demonstrated with physical observations that sufficiently high concentrations of seeding agent, effective at prevailing SLW cloud temperatures, will produce snowfall when natural snowfall rates are negligible. Seeded snowfall rates are usually light, on the order of .04"/hr (1 mm/hr) or less of water equivalent, consistent with median natural snowfall rates in the intermountain West (Super and Holroyd, 1997).

6.2 Preliminary Design Components

There are a number of factors to be considered in the development of a design for a cloud seeding program. The American Society of Civil Engineers published a Standard entitled "Standard Practice for the Design and Operation of Precipitation Enhancement Projects" in 2004 (ASCE, 2004). This Standard lists the following as factors that should be considered:

1) Definition of project scope
2) Seeding agent selection
3) Targeting and delivery methods
4) Meteorological data collection and instrumentation
5) Selection and siting of equipment
6) Legal issues
7) Environmental concerns.

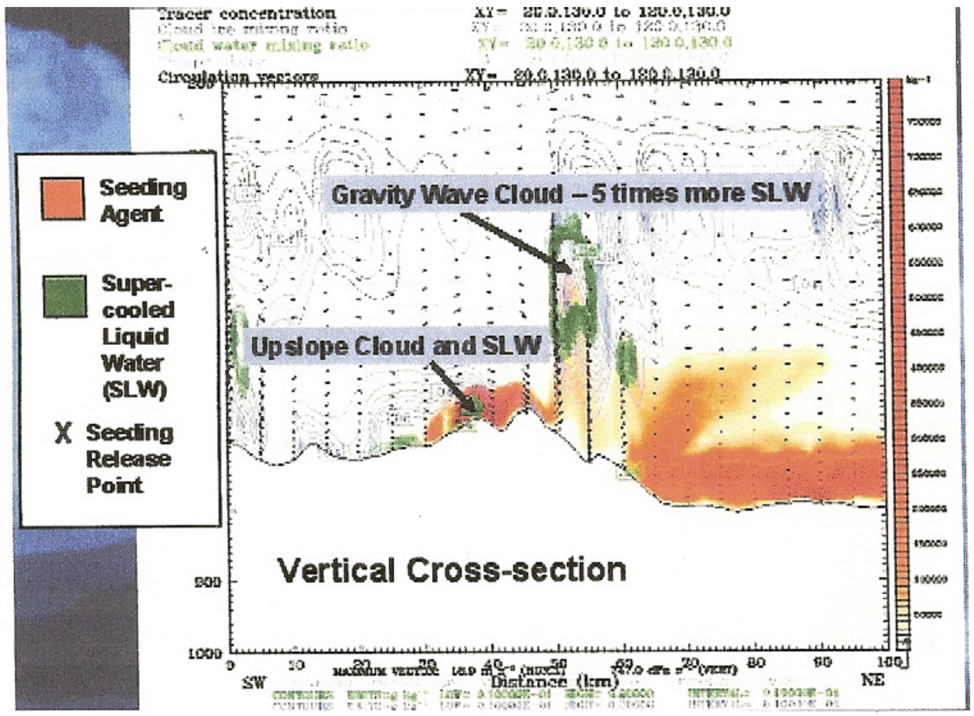

Figure 6.2 Reproduction of Figure 6 from WMI (2005) Executive Summary. A west to east (left to right) vertical cross section through the Wind River Mountains is depicted in this output from the Weather Research and Forecasting (WRF) model, for a storm observed on 7 February 2004.

The study scope includes estimates of seeding effects, which were added as item 8 in the list shown above. The Desert Research Institute of Reno, Nevada was subcontracted to conduct some sophisticated atmospheric modeling work. This work is added as a ninth item.

Items 1-5, 8 and 9 will be discussed in this section. Items 6 and 7 are discussed in Section 8.0.

With this brief explanation as background, the previous seven topics will be addressed in the following sections.

6.3 Project Scope

Definition of the scope of the project needs to include a statement of the goal or goals of the proposed program and definition of the project areas. This is an important step. Is a basic operational program desired? Is an operational program with the addition of a number of research type components desired? The answer to the first two questions may be defined by a third question; what is the desired level of proof to establish that the cloud seeding program is working? Are the sponsors of the program willing to employ randomization (a statistical design approach) of the treatment to quantify the effects of seeding? What is considered to be a favorable benefit/cost ratio for the program to proceed? One approach that could be considered is the development of a basic core program that can reasonably be expected to produce some level of increase with optional additions to the program that are prioritized to accomplish the goals of the program. The priority of these additions would be evaluated according to an assessment of the additional cost versus the increase in benefit (i.e. produce more water on the ground; better demonstrate the effectiveness of the seeding, etc.) Other considerations can help refine the generic goals mentioned in the above.

NAWC worked with the WWDC to define the goal(s) of the program and to establish the boundaries of the proposed target areas. **The stated goal of the program is to increase winter snowpack in the target areas to provide additional spring and summer streamflow and recharge underground aquifers at a favorable benefit/cost ratio (e.g. 4-5/1 or greater) without the creation of any significant negative environmental impacts.**

The mountain ranges that comprise the proposed target areas were identified in the RFP as the Salt River Range, Wyoming Range (including Tunp Range) in Lincoln and Sublette Counties, but a more specific definition of the target area(s) was not provided. NAWC normally defines target area boundaries in terms of elevation. After due consideration, it is proposed that the target area be defined as those elevations in the Salt River Range and Wyoming Range (including the Tunp Range) above 8,000 feet MSL (2.4 km) located within Lincoln and Sublette Counties. This area encompasses approximately 3,590 square miles. Figure 6.3 provides a graphical depiction of this area.

6.4 Seeding Agent Selection

The ASCE/EWRI Standard Practice for the Design and Operation of Precipitation Enhancement Projects (ASCE 2004) contains a summary of the different types of cloud seeding agents. This summary is as follows.

> *"The materials placed within the targeted clouds are known as seeding agents. While glaciogenic agents intended to increase ice formation are the most common, others having hygroscopic properties are being used with increasing frequency. The full effects of this latter class of seeding agents are only beginning to be explored.*

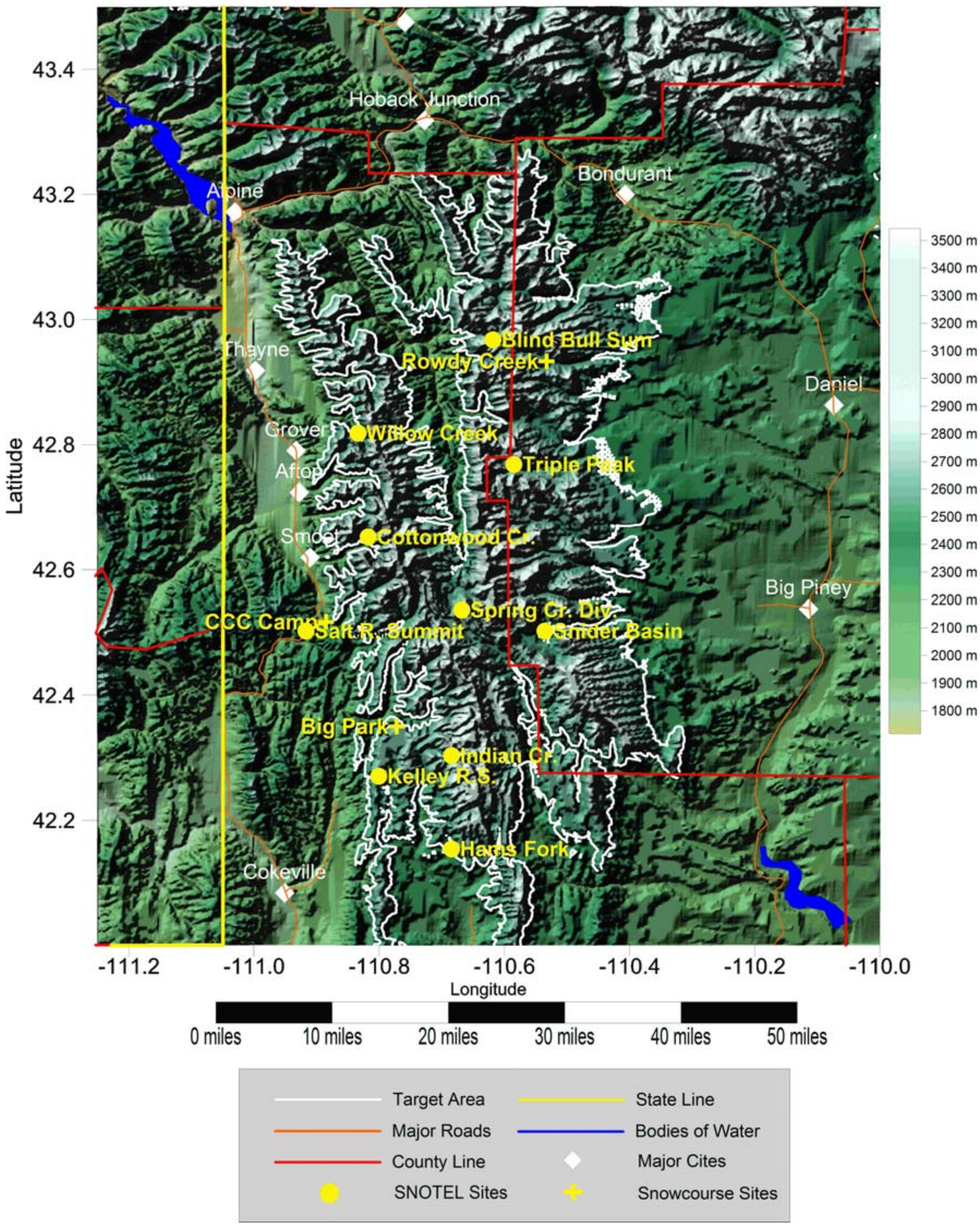

Figure 6.3 Potential Target Areas with SNOTEL and Snowcourse Sites

Precipitation enhancement involves intervening in the microphysical and/or dynamic development of convective cells and stratiform clouds to improve the efficiency of the precipitation processes. The most widely employed method consists of introducing glaciogenic agents, materials which have the capacity to generate additional cloud ice. When added to the natural ice (if any) within the supercooled cloud region, the collective cloud ice population may alter the cloud sufficiently to result in additional rain or snow.

In nature there are many substances which are capable of acting as glaciogenic agents. Not all these substances, however, form ice crystals with the same facility, since their efficiency in this respect is a function of their composition. For example, each substance has a crystallization temperature threshold, which is the temperature at which it begins to cause the formation of ice crystals. In general, it may be said that a substance's ability to act as an ice nucleating agent is higher to the extent that its threshold value approaches the range from 0 to –4^{o}C. The discovery of silver iodide (Agl) as an extremely efficient ice nucleating agent, with a threshold near -5°C, made by Vonnegut (1947), was therefore a major contribution to weather modification activities.

In addition to this widely-used method, there is another which uses a quite different approach (Dennis and Koscielski 1972; Mather et al. 1997). This approach, called hygroscopic seeding, aims to speed the development of large cloud droplets and rain drops through coalescence in the warmer (lower altitude) portions of the cloud. Such accelerated rain development may result in added rain at the ground. Numerical modeling of hygroscopic seeding also indicates that ice processes are enhanced in the seeded clouds."

Silver Iodide

"Silver iodide, in combination with various other chemicals, most often salts, has been used as a glaciogenic agent for half a century. In spite of its relatively high cost, it remains a favorite, especially in formulations which result in ice nuclei (IN) with hygroscopic tendencies.

Silver iodide has utility as an ice nucleant because it has the three properties required for field application. These are: (1) it is a nucleant, regardless of mechanism, (2) it is relatively insoluble at $<10^{-9}$ g per gram of water, so that the particles can nucleate ice before they dissolve, and (3) it is stable enough at high temperatures to permit vaporization and re-condensation to form large numbers of functional nuclei per gram of AgI burned (see Finnegan 1998). Thus, the ice crystallization temperature threshold for AgI is about -5°C, significantly warmer than the threshold for most naturally-occurring IN, which commonly have thresholds closer to -15°C. The chemical formulations of AgI seeding agents may be modified further, so that the resulting IN function at even warmer temperatures (DeMott 1991, Garvey 1975).

In many cases, AgI is released by a generator that vaporizes an acetone-silver iodide solution containing 1-2% AgI and produces aerosols with particles of 0.1 to 0.01 µm diameter. AgI is insoluble in acetone; commonly used solubilizing agents include ammonium iodide (NH_4I), and any of the alkali iodides. Additional oxidizers and additives commonly include ammonium perchlorate (NH_4ClO_4), sodium perchlorate ($NaClO_4$), and paradichlorobenzene ($C_6H_4Cl_2$). The relative amounts of such additives and oxidizers modulate the yield, nucleation mechanism, and ice crystal production rates.

Some of the substances used in AgI mixtures are oxidants, and may oxidize (rust) and corrode the metal parts of some IN-generating equipment. Solutions may be obtained pre-mixed, or can be mixed in the field. Care must be taken too that the AgI is thoroughly dissolved, because if it is not, the un-dissolved reagent can block flow in the generator, resulting in generator failures. Once produced, some AgI aerosols may lose some of their glaciogenic capacity with time. Exposure to sunlight, and UV light in particular, may accelerate the deactivation process for some aerosols, while others have shown limited degradation with exposure to sunlight (Super et al. 1975).

As may be imagined from the foregoing, it is of great importance to arrive at a formula for the preparation of silver iodide complexes which provides maximum efficiency, producing the greatest possible number of active IN per unit mass of AgI. Numerous studies have been carried out at Colorado State University using isothermal cloud chambers to analyze the efficiency of different AgI mixtures, and many different formulae have been proposed (e.g. DeMott et al. 1995, Finnegan et al. 1994, Pham Van Dihn 1973, Rilling et al. 1984). Ice nucleus generators may be ground-based, or carried on aircraft, usually at or near the wing tips.

The generation of AgI aerosols can also be accomplished by burning specialized pyrotechnics. In many cases, a mixture containing silver iodate ($AgIO_3$) to diminish the tendency of AgI to break down into its component silver and iodine molecules (Ag and I_2) has been used. Powdered aluminum and magnesium, and some kind of organic agglutinant are also often added to the mixture (Dennis 1980). In recent years, advances in nucleation physics have resulted in a number of more effective pyrotechnic formulations which produce nuclei that, in addition to having ice nucleation thresholds near -4°C, are also somewhat hygroscopic. The resulting nuclei are not only effective as IN, but they also attract water molecules. This results in particles that in high relative humidities (near saturation) quickly form droplets of their own, which then freeze shortly after becoming supercooled. This condensation-freezing nucleation process generally functions faster than that achieved using simple AgI. Laboratory testing has shown that AgI by itself functions primarily by the contact nucleation process, which is more dependent upon cloud droplet concentration, and consequently, a much slower process (DeMott 1991). Speed in nucleation is *very desirable in applications such as hail suppression where quick glaciation of modestly-supercooled cloud turrets is required."*

Dry Ice

"The direct creation of cloud ice particles by dispensing dry ice (CO_2) pellets into the cloud is another glaciogenic seeding technique which modifies the natural ice formation process by rapidly transforming nearby vapor and cloud droplets into ice (Schaefer 1946, Holroyd et al. 1978, Vonnegut 1981).

Compared with silver iodide complexes, this system has an advantage in that it makes use of a natural substance (frozen carbon dioxide, CO_2, which sublimes at -78°C at 1,000 hPa). However, effective delivery of the CO_2 requires the use of aircraft. The CO_2 is also difficult to store, as sublimation (and therefore loss) is continuous. It is uncommon for dry ice to be the only seeding agent used in a project; it is sometimes used in conjunction with AgI seeding."

Other Ice Nucleants

"Certain proteins derived from a naturally-occurring bacterium, pseudomonas syringae, fall within the description of nucleating proteins, because of their ability to induce the formation of ice crystals in seeding applications. Many other organic substances have this property; among these metaldehyde and 1.5-dihydroxynaphthalene, which have contact freezing temperatures of -3°C and -6°C respectively. Their efficiency in generating ice crystals is very similar to that of dry ice (Kahan et al. 1995)."

Hygroscopic Agents

"Numerous precipitation enhancement projects have been using AgI complexes as their primary nucleating agent since the 1950s. Nevertheless, the injection of hygroscopic agents which may alter the initial cloud droplet spectra or create raindrop embryos immediately may be an efficient method for treating warm-based continental cumulus clouds, in which the vertical distance from cloud base to the freezing level can be as much as several kilometers. Ludlam (1958) and Appleman (1958) described the concepts involved in hygroscopic seeding with salt particles by dropping large numbers of salt particles into cumulus clouds. Salt seeding was used experimentally in the North Dakota Pilot Project, a combination hail suppression and rainfall enhancement project, in 1972. In this experiment and others conducted in South Dakota, finely ground salt particles were released near the bases of moderate sized cumulus clouds to create raindrop embryos around the salt particles. Experiments carried out in South Africa in the early 1990s underlined the potential importance of seeding with hygroscopic agents. Mather strongly recommends the use of hygroscopic agents to combine hail suppression with precipitation enhancement activities (Mather 1991; Mather and Terblanche, 1994).

Hygroscopic agents deliquesce (that is, become liquid by absorbing moisture from the air) at relative humidities significantly less than 100%. Mather (1991) has made use of flares containing primarily potassium perchlorate , which when burned produces potassium chloride (KCl) particles of about 1 µm diameter. These flares were burned near the base of cumulus clouds in an attempt to alter the cloud droplet spectra. The hygroscopic flares weigh about one kilogram. Although there are many naturally-occurring hygroscopic substances, KCl particles have an advantage of only requiring a relative humidity on the order of 70-80% to deliquesce, and readily act efficiently as CCN.

Project planners should bear in mind that the hygroscopic flare method is relatively new and is not yet used as widely as the AgI complexes, but has shown considerable promise (Cooper et al. 1997, Mather et al. 1996, 1997). A project in southern France is experimenting with hail suppression based on the new hygroscopic flare technique at the time of writing; other experiments are being conducted in Mexico for rain enhancement (Bruintjes et al. 1999)."

In addition to the possible seeding agents mentioned in the above ASCE reference, there is one other category of possible seeding agents that needs consideration for application in winter cloud seeding programs; this category is liquefied compressed gases. One example of such an agent is liquid propane. The following description is reproduced from Manual #81 prepared by the American Society of Civil Engineers (ASCE, 2006).

"Liquid propane is a freezing agent much like dry ice. It produces almost the same number of crystals per gram as does CO_2 (Kumai 1982). It cannot be dispensed from aircraft because it is a flammable substance. However, it can be dispensed from the ground if released at elevations which are frequently within supercooled clouds. The United States Air Force has used liquid propane dispensed from ground-based sites to clear supercooled fog at military airports for over thirty years."

Propane seeding was tested as a cloud seeding agent on a winter research program conducted in California for winter snowpack enhancement through the development of a remotely operated ground-based dispenser (Reynolds 1991, 1992). Liquid propane seeding experiments were also conducted on the Utah/NOAA Atmospheric Modification Project (Super, 1999). A recent randomized research experiment was conducted on the central Wasatch Plateau of Utah testing this agents' possible utility in winter cloud seeding programs (Super and Heimbach, 2005). This paper does indicate seeding increases due to a randomized treatment of storm periods with liquid propane but the area of coverage appeared to be quite small, being on the order of 3-4 km x 3-4 km from a single release point.

NAWC's discussion and recommendations concerning seeding agents to be used on the SRWR project are provided in Section 6.6.

6.5 Targeting and Delivery Methods

The ASCE/EWRI Standard Practice for the Design and Operation of Precipitation Enhancement Projects (ASCE 2004) contains a summary on targeting and delivery methods (seeding mode) associated with cloud seeding projects. The introductory portion of this summary is as follows:

> "*The most critical portion of any cloud seeding program is the proper delivery of cloud seeding material to the appropriate portion of the cloud. Concentrations of the cloud seeding agent must be adequate to modify a sufficient volume of cloud to significantly affect the precipitation process in the desired manner. To date this has been, and continues to be the most critical element in the development and implementation of precipitation enhancement technology.*
>
> *A number of alternatives exist concerning cloud seeding delivery systems. A basic division exists between these alternatives consisting of ground based or aerial generating systems. Most systems currently in use are designed to dispense silver iodide nuclei, particles of dry ice, or hygroscopic particles. The choice of the delivery system (or systems) should be made on the basis of the project design, which should establish the best system for the specific requirements and the topographic configuration of a given project.*"

The following section contains specifics on possible seeding modes and targeting issues as related to the SRWR feasibility/preliminary design study.

6.6 Seeding Modes

The specification of the seeding mode(s) and seeding agent(s) for the SRWR feasibility study presents a challenge. In reality there is no one right answer. A number of factors need to be considered to arrive at a reasonable recommendation including effectiveness of the seeding material, cost of the seeding material and delivery mode, reliability of the seeding mode, ability to fly aircraft in the appropriate regions or the ability to locate ground dispensing equipment at the preferred locations, ability to disperse the seeding material in the appropriate concentrations somewhat uniformly and continually into the supercooled cloud regions, areas likely to be affected by seeding, and lack of any negative environmental consequences associated with the recommended seeding agents. From this description of factors there is an obvious overlap between seeding modes and the ability to effectively target the seeding material.

6.6.1 Ground Based Silver Iodide Seeding

Silver Iodide ground based seeding systems are the oldest and most widely used type of seeding mode for winter storms in the western United States. The most common seeding generator burns a solution of acetone in which a certain percentage (usually 2-3%) of silver iodide has been dissolved. Manually operated generators can be located at accessible sites upwind of the intended target areas and operated by these residents as specified by the project meteorologist. Figure 6.4 provides a photograph of a typical manually-operated unit. Such locations are often in valley or foothill locations. Remotely controlled silver iodide generators are frequently used at higher elevation unmanned locations. Figure 6.5 provides a photograph of a remotely controlled solution-burning generator. Ground-based generators normally disperse from 0.4 – 1.6 ounces (10- 40 grams) of silver iodide per generator per hour of operation. Normal consumption rates with these solution-burning generators are on the order of 0.1 – 0.2 gallons (0.4- 0.8 l) per hour of operation. The effectiveness of this type of generator has been established through the conduct of tests at the Colorado State University Cloud Simulation Laboratory. Figure 6.6 provides the results of tests performed on one of NAWC's manually operated generators. This figure indicates that approximately 8×10^{14} ice crystals can be produced from a single gram of silver iodide at a temperature of $+14^0$ F (-10^0 C). This figure also demonstrates that silver iodide becomes increasingly effective with decreasing temperatures. Measurements of naturally occurring ice nuclei (typically soil particles) demonstrate this same tendency.

Another method of dispensing silver iodide from ground-based sites is via flares impregnated with seeding material. This approach is used primarily in regions where discrete cloud structures with significant seeding potential can be seeded beneficially via high seeding material dosage rates during their passage over an area. Such seeding sites are commonly remotely operated via computerized control systems. An example is shown in Figure 6.7.

Figure 6.4   Manually Operated, Ground Based Silver Iodide Generator

Figure 6.5   Remotely Controlled, Ground Based Silver Iodide Generator

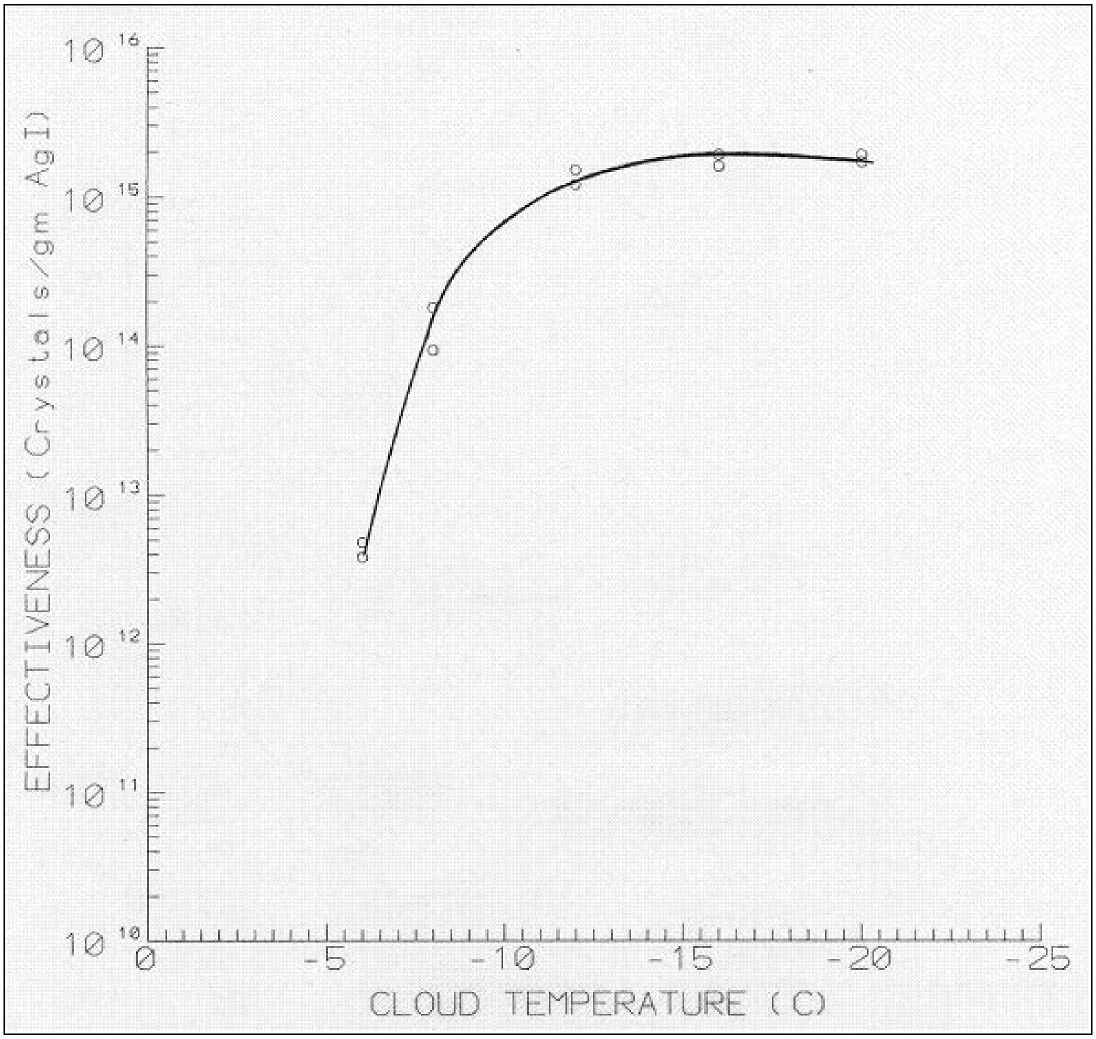

Figure 6.6 Colorado State University (CSU) Cloud Chamber Tests of NAWC's Manually Operated Silver Iodide Generator (tests conducted in 1994)

Figure 6.7 Example of a Seeding Flare Site. The masts are approximately 10' tall.

6.6.2 <u>Airborne Silver Iodide Seeding</u>

Seeding with silver iodide using aircraft is the second most common mode of seeding in existing operational winter cloud seeding projects in the United States. In fact, ground generators and aircraft seeding using silver iodide as the seeding agent is a frequently utilized combination seeding mode. Aircraft seeding to dispense silver iodide is normally accomplished by one of two methods. Flares (similar to highway flares) that have been impregnated with silver iodide can be carried in racks mounted on the trailing edges of the wings. Flares of this type burn in place, i.e., they remain in the wing-mounted racks as they are ignited and burn. Each flare may contain on the order of 1.4 – 7.0 ounces (40 to 200g) of seeding material. The burn duration of these flares is ~ 1 – 5 minutes so the average rate of release is ~ 0.4 – 4.0 ounces (10 – 100 g) of seeding material per minute. Some of these flares have been tested at the Colorado State University Cloud Simulation Laboratory to determine their efficiency. Table 6-1 provides data from a test performed on a flare manufactured by Ice Crystal Engineering (ICE), Inc. of Fargo, North Dakota. This flare exhibited activity up to temperatures as warm as 24.8^0 F (-4^0C). This is a very desirable feature that will be discussed in a later section. The flare formulation also acted very quickly in forming ice crystals, apparently through a condensation freezing mechanism (in most applications this is also a desirable characteristic). Figure 6.8 provides a photograph of a typical installation. The other commonly used means of dispensing silver iodide from aircraft is accomplished using acetone/silver iodide generators mounted under each wing tip. These generators hold approximately 8 gallons of a mixture of acetone and silver iodide. This mixture is ignited in the tail cone section of the generator, producing the desired silver iodide particles. Typical consumption rates of the solution are on the order of 2 gallons per hour per generator, which results in a release rate of approximately 4.2 – 6.3 ounces (120-180 grams) of silver iodide per hour. Figure 6.9 provides a photograph of a typical installation. Work performed by Dr. Finnegan of DRI (Finnegan and Pitter, 1988) indicates that the silver iodide particles produced by these generators also act very quickly if the generator is operated in clouds, due to a transient super-saturation condition resulting from the combustion of acetone producing water in an already saturated environment. Normally airborne generators are operated in-cloud on winter projects. Figure 6.10 provides the results of the tests conducted at the Colorado State University Cloud Simulation Laboratory on a generator manufactured by AeroSystems, Inc. of Erie, Colorado. These tests indicate that this generator is very effective.

A third means of dispensing silver iodide from aircraft consists of racks mounted on the bottoms of aircraft fuselages (see Figure 6.11). These racks are then loaded with flares that can be fired vertically downward. The payloads of seeding material in these "ejectable" flares fall away from the aircraft, traveling about 2000 to 6000 feet (610 – 1830m) vertically before being completely consumed. This seeding mode is frequently used in seeding isolated towering cumulus clouds via "on top" cloud penetration seeding on summer programs, but is seldom used on winter programs due to the expense involved in seeding large areas in a nearly continuous fashion.

Table 6-1 Cloud Chamber Test Results for Ice Crystal Engineering Flare

Pyro type	Temp (°C)	LWC (g m^{-3})	Raw Yield (g^{-1} Agl)	Corr. Yield (g^{-1} Agl)	Raw Yield (g^{-1} pyro)	Corr. Yield (g^{-1} pyro)	Yield (per pyro)
ICE	-3.8	1.5	3.72x10^{11}	3.87x10^{11}	4.01x10^{10}	4.18x10^{10}	6.27x10^{12}
	-4.0	1.5	9.42x10^{11}	9.63x10^{11}	1.02x10^{11}	1.04x10^{11}	1.56x10^{13}
	-4.2	1.5	1.66x10^{12}	1.70x10^{12}	1.80x10^{11}	1.84x10^{11}	2.76x10^{13}
	-4.3	1.5	2.15x10^{12}	2.21x10^{12}	2.32x10^{11}	2.39x10^{11}	3.53x10^{13}
	-6.1	1.5	6.01x10^{13}	6.13x10^{13}	6.49x10^{12}	6.62x10^{12}	9.93x10^{14}
	-6.3	1.5	5.44x10^{13}	5.56x10^{13}	5.87x10^{12}	6.00x10^{12}	9.00x10^{14}
	-6.4	1.5	6.22x10^{13}	6.34x10^{13}	6.72x10^{12}	6.85x10^{12}	1.03x10^{15}
	-10.5	1.5	2.81x10^{14}	2.85x10^{14}	3.03x10^{13}	3.07x10^{13}	4.61x10^{15}
	-10.5	1.5	2.34x10^{14}	2.37x10^{14}	2.87x10^{13}	2.91x10^{13}	4.37x10^{15}
	-4.2	0.5	1.41x10^{12}	1.45x10^{12}	1.53x10^{11}	1.57x10^{11}	2.36x10^{13}
	-6.0	0.5	7.42x10^{13}	7.73x10^{13}	8.01x10^{12}	8.34x10^{12}	1.25x10^{15}
	-10.5	0.5	2.38x10^{14}	2.41x10^{14}	2.91x10^{13}	2.96x10^{13}	4.44x10^{15}

Figure 6.8 Aircraft with Seeding Flare Racks

Figure 6.9 Aircraft with Silver Iodide/Acetone Ice Nuclei Generators

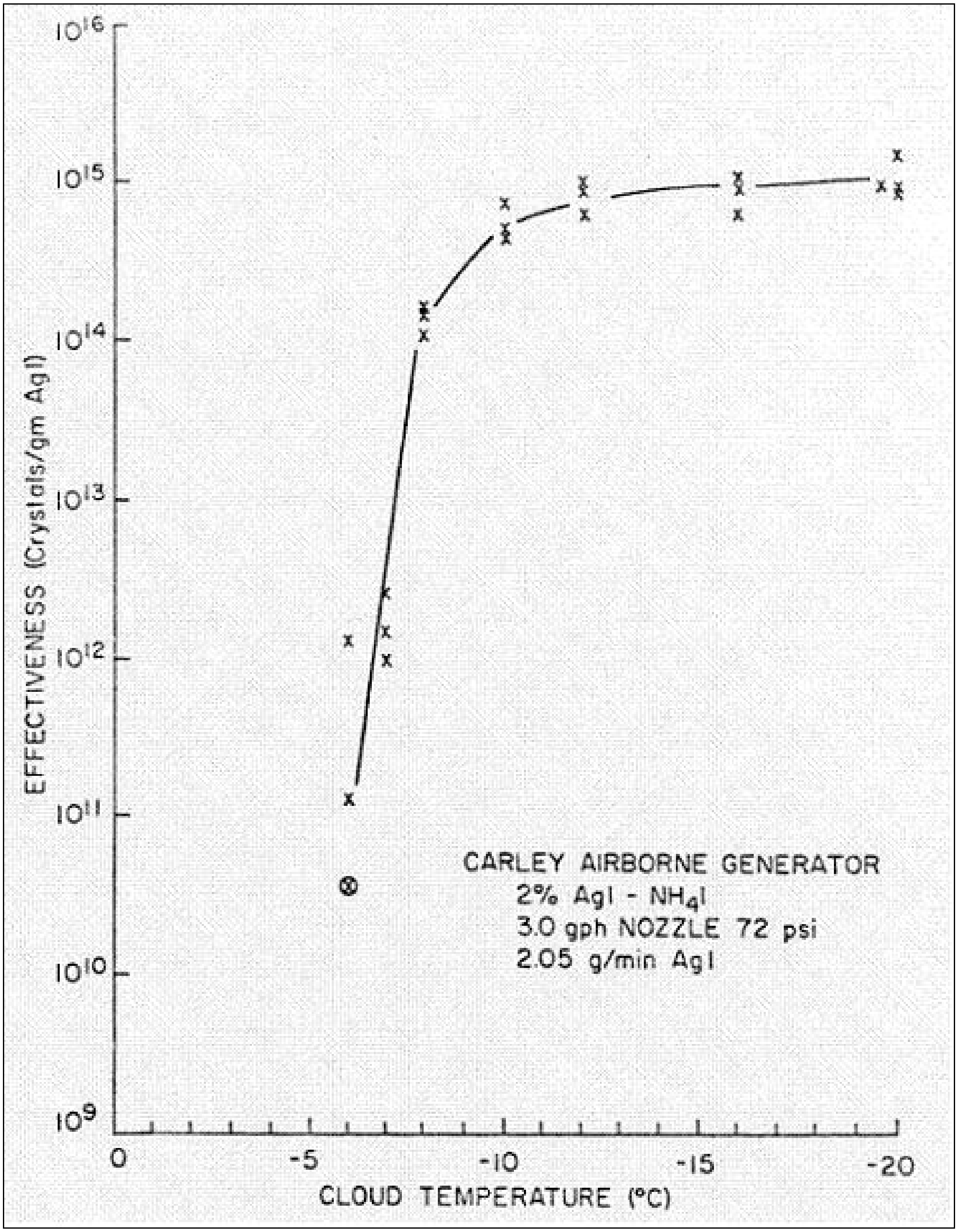

Figure 6.10 CSU Cloud Chamber Tests of AeroSystems Generator

Figure 6.11 Aircraft Belly Mount, Ejectable Silver Iodide Seeding Flares

6.6.3 Airborne Seeding with Dry Ice

A less commonly used mode of seeding winter storms is airborne seeding using dry ice (this particular seeding mode is more commonly used to disperse cold fogs at airports to allow aircraft to land and takeoff by improving runway visibilities). Oftentimes dry ice pellets with diameters of 0.2 – 0.4" (0.6 – 1cm) and lengths of 0.4 - 1" (1 – 2.5cm) in length are carried onboard aircraft in hopper/dispensing systems and are dropped through the floor of baggage compartments or extra passenger seat locations on modified cloud seeding aircraft. These pellets will fall about 3300-6600 feet (1-2km) before they completely sublimate. Typical release rates are from one to a few pounds of dry ice per mile of flight path. Dry ice is an effective ice nucleant, producing 2×10^{11} to 8×10^{11} ice crystals per gram of dry ice dispensed. Its effectiveness is relatively independent of temperature in the range of $30^0 – 12^0$ F (-1^0 C to -11^0 C) (Holyroyd, et al, 1978). Figure 6.12 provides a photograph of a dry ice dispenser mounted in a seeding aircraft.

6.6.4 Ground-Based Propane Seeding

Some investigators have suggested that the use of liquid propane as a seeding agent should be considered since it theoretically could produce ice crystals near the freezing level, while silver iodide does not begin to become effective until temperatures of 23 – 25^0 F (-4 or -5^0 C) are reached. Some research (e.g., Super, 1999) has indicated that there are periods near the crests of mountains in the west that experience significant periods of supercooled liquid water at temperatures in the $32^0 – 23^0$ F (0 to -4^0 C) range in which

Figure 6.12 Dry Ice Dispenser in Aircraft

liquid propane seeding may be effective while silver iodide would not be. There has only been one research-oriented program that used liquid propane as the seeding agent that was designed to produce an effect over a sizable target area (Reynolds, 1994). The program was terminated after three winter seasons of seeding with no indication of any positive seeding effects. Recent research conducted in Utah (Super and Heimbach, 2005) did demonstrate positive seeding effects using this technique, but apparently only over a very small area. It is NAWC's position that positive results are needed from a research program conducted over a sizable area before this technique is considered for use on operational winter cloud seeding programs. This position is supported by a statement in ASCE Manual 81, (ASCE, 2006) which was recently updated. This statement is "Future experimentation needs to be conducted to demonstrate that this technique can increase precipitation over a fixed target area for a significant period of time (e.g., a winter season)." NAWC, for the reasons stated herein, does not recommend the use of liquid propane as a seeding agent on the SRWR project.

6.6.5 Seeding Rockets

One other possible seeding mode is that of seeding rockets. The WWDC received a proposal for the operations portion of the Wind River, Sierra Madre/Medicine Bow Range five-year program that proposed using seeding rockets instead of seeding dispensers located on the ground or flown on aircraft. NAWC was asked to consider the feasibility of using seeding rockets on the SRWR project. A Colorado firm proposed the use of small model seeding rockets to the WWDC. Two sizes are apparently available, either 1.15" by 11.5" (2.9- 29.2 cm) or 1.15" by 16.75" (2.9 – 42.5 cm). They have a 2.2 oz. solid rocket motor (model rocket motors may contain up to 4.4 oz of material). They contain ~ 3 ounces (90 grams) of silver iodide seeding material and cost $180 each. They can travel 1,500' to 4,000' (450- 1,220 m) above ground level. The seeding material is dispersed for 15-20 seconds over approximately 2,000' (610 m) during the upper levels of ascent, through apogee, and during the upper levels of descent. Teams would be needed to manually launch these seeding flares in appropriate winter storm conditions upwind and over the Wind River and Sierra Madre Ranges. Since these systems are basically experimental at this time, NAWC does not recommend their consideration as a seeding mode for the SRWR project. Furthermore, members of the Technical Advisory Team expressed serious concerns about recovering debris from the target areas.

6.6.6 General Discussion on the Considerations that Govern the Specification of a Seeding Mode(s)

The goal of a wintertime orographic cloud seeding program is to convert supercooled liquid water droplets (SLW) upwind of and over the mountain barrier(s) into ice crystals in a timely fashion, such that they have time to grow into snowflakes and fall within the intended target area. From the discussions contained in Section 6.5 we believe that the primary area of opportunity is over the upwind slopes of the mountain barrier extending to heights of perhaps 1600 – 3200 feet (500- 1000 m) above the crest of the mountain barrier. Figure 6.1 contains a stylized schematic depiction of this zone of opportunity. It appears that this zone of SLW is frequently present in winter storms, although it does appear that SLW concentration and extent fluctuate with storm conditions. For example, if there are deep clouds upwind and over the barrier there may be enough natural nucleation occurring in the colder portions of these clouds such that the natural precipitation processes are efficient in removing any lower level SLW. Under these conditions precipitation rates may be substantial but there is little if any opportunity for seeding to increase snowfall rates. It appears that shallower cloud systems and those that contain embedded convection[1] are more likely to have significant periods with the lower level SLW profile as depicted in Figure 6.1.

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[1] Embedded convection – convective cells embedded in a stratiform cloud deck that promote upward vertical motion.

There are a number of considerations that impact the ability to fill this zone of opportunity in a timely fashion with seeding materials in sufficiently high concentrations to produce a positive effect of seeding in the target area. Several of these considerations are time related. For example, how long does it take to transport silver iodide nuclei from ground generators into this zone of SLW at cold enough temperatures for the silver iodide to nucleate forming ice crystals? Then how long does it take for these ice crystals to grow into snowflakes that are large enough to fall to the ground? This transport, nucleation, growth, and fallout scenario is directly impacted by the wind speeds that are encountered at different stages in this scenario. Stronger wind speeds will mean that the effects of cloud seeding (if any) will occur at increased distances from the release point. The seeding agent used is also related to these timing issues. If one possible ground based seeding agent threshold is 23^0 F (-5^0 C) and another is 28.4^0 F (-2^0 C), it will take longer for the agent active at 23^0 F (-5^0 C) to reach its nucleation level than the one that begins to nucleate at 28.4^0 F (-2^0 C). Cloud chamber tests also indicate that some seeding agents act very quickly through a condensation freezing mechanism, while others act more slowly though a contact freezing mechanism.

One of the other considerations is how can we fill a majority of this SLW zone in a satisfactory way. In other words, how well do the seeding plumes merge or overlap horizontally to fill this volume? Consideration of this question in combination with the expected lower level wind flows that will be encountered upwind and over the target area will lead to the development of the proposed spacing and location of ground generators. A network of generators will typically be needed to be able to effectively seed under a variety of different wind directions. Not all such generators will be used to seed at the same time, but differing combinations of generators will be used to correctly target the seeding material with changing wind directions. In a similar manner, aircraft seeding tracks need to be flexible to account for these changing conditions.

6.6.7 Advantages and Disadvantages of Ground Based Generators

There are advantages and disadvantages associated with manually operated and remotely controlled ground based seeding devices (typically ground based silver iodide generators). Some research (e.g., Super 1999**)** has suggested that there may be low-level atmospheric temperature inversions[2] during winter storm periods that may trap the silver iodide particles released from valley or foothill based ground generators. NAWC has found that such inversions certainly do occur, but the strength, height and frequency of such inversions vary considerably from one area to another. An earlier NAWC feasibility/design study (North American Weather Consultants, 2002) conducted for the Uintah Basin in northeastern Utah documented that low-level atmospheric inversions were a fairly frequent phenomenon in that region during the wintertime. There were two types of inversions identified: 1) ones that were based at the surface, and 2) ones that were elevated. The height of the tops of the surface based inversions averaged 1,340 feet (0.4 km) above ground level, or at an elevation of 6,290 feet MSL (1.9 km). The tops of the elevated inversions were also relatively low, being on the order of 2,600 feet (792 m)

[2] Departure from the usual decrease in temperature with height to an increase in temperature with height.

above ground level or at an elevation of ~7,570 feet MSL (2.3 km). In order to address the concerns about the possible trapping of silver iodide released from valley locations, NAWC recommended that seeding sites be located above the average top height of the elevated inversions (i.e. at or above ~ 7,600 feet in elevation). This would potentially avoid trapping of the silver iodide seeding material in at least half of the occurrences with elevated inversions, and a large majority of those cases with surface based inversions. This data analysis-based approach was accepted by the clients, and suitable sites were found which could utilize manually operated units (similar to Figure 6.4). These manually operated units are far less expensive than remotely controlled units. In central Utah, a case study that utilized tracer data to document the likely plume transport of seeding material found that seeding material released beneath a low-level inversion from a valley site between two mountain ranges was transported over the second barrier (Heimbach, et al, 1997). The explanation given by the authors was that apparently a gravity wave[3] was responsible for the transport of the seeding material through the inversion.

Research work conducted in Utah, summarized by Super (1999), suggested that transport from valley generators was limited and that concentrations of silver iodide were too low when transport did occur. There are least two problems associated with these conclusions: 1) some flights conducted to determine if valley released seeding materials were being transported over the crest were conducted under Visual Flight Rule (VFR) conditions in order to allow the aircraft to fly at low altitudes over the barrier, and 2) concentrations of seeding material were primarily inferred from counts recorded on a device known as an NCAR counter. In regards to the first point, it is NAWC's position that atmospheric conditions are different during active storm periods than they are in pre-frontal VFR conditions. The presence of lower level inversions (indicated to occur ~37% of the time based upon valley rawinsonde observations) may not be a problem anyway if there is no supercooled liquid water associated with such occurrences. It is unknown whether supercooled water existed in these cases, since no stratifications of the data were presented using these criteria. Interestingly, this paper does indicate successful transport of valley-released silver iodide to the crest line in 90% of seven different relatively wet cases with supercooled liquid water present. The explanation given was that at most times when supercooled liquid water was present in amounts of 0.002 inches (0.05 mm) or more (i.e. the better cases), weak embedded convection was also present, which likely assisted vertical transport of the valley released silver iodide. Regarding the second point, NAWC believes that counts of ice nuclei observed on an NCAR counter at -4^0 F (-20^0 C) provide qualitative, not quantitative, numbers. This position is supported by the fact that the actual counts observed by the NCAR counters are often multiplied by 10 to account for possible accumulation of ice crystals on the sidewalls of the device. Further, the crystal growth times in NCAR counters are only on the order of approximately three minutes. We know from cloud chamber tests conducted at Colorado State University that activation of silver iodide particles may take as long as 15-20 minutes. This is another likely source of undercounting of the silver iodide nuclei that may be present.

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[3] Oscillations over or downwind of mountain barriers resulting in a repeating pattern of upward and downward motions typically organized in waves.

Finally, there have been evaluations of the operational programs being conducted in Utah using lower elevation silver iodide generators that indicate that this type of cloud seeding is effective (Griffith, et al, 1991). There are no doubt winter periods in Utah and in other western mountain ranges when seeding from low level generators will be ineffective. Whether the addition of higher-elevation remotely controlled generators to seed more effectively under these conditions is warranted must be examined in light of the additional costs and logistical complications that arise versus the perceived increment in additional precipitation that may be produced using such systems.

Going back to the timing discussions found in section 6.5, a case can be made that it is better to locate the generators upwind of the mountain barriers (usually at lower elevations) since this may allow seeding material reaching effective levels well upwind of the crest. In this scenario, longer growth times are available for the ice crystals to reach snowflake sizes and fall on the barrier. Placing remotely-controlled generators near the crest lines of these barriers (as has been done on research programs such as the Bridger Range and Utah NOAA programs) may result in only very small snow flakes being formed on the upwind side of the barrier (due to the short times for growth), which may not contribute significantly to the overall water balance on the upwind side of the barriers. Any positive effects are more likely to occur on the downwind side of the barriers. Generation of significant effects in downwind areas, however, will be hampered by descending air motions on the lee side of the barriers, which will likely result in poor growth of the snowflakes due to lack of significant SLW and warming temperatures. In fact, the Bridger Range experiment was designed for seeding over a first barrier to produce effects over a secondary downwind barrier located approximately 8 miles downwind. The experiment was successful in accomplishing this goal, but these results are only transferable to locations that have dual or perhaps multiple barriers located at similar distances downwind from the first barrier. In these situations, downslope descending flow may not develop (or not develop very strongly) since the second barrier provides uplift to the air mass.

To generalize, seeding the relatively narrow mountain barriers typical of the intermountain west with remotely controlled generators located well up the windward side of these barriers will probably only produce appreciable positive effects on the downwind slopes of these barriers. In other words, little or no seeding effect would be expected on the upwind slopes of these barriers. Unfortunately, higher amounts of precipitation normally occur on the upwind slopes of such barriers, so a major opportunity to provide significant amounts of additional water may be limited. To illustrate, a 10% increase on a 25" (63.5 cm) base is 2.5" (6.4 cm), whereas a 10% increase on a 15" (38 cm) base amount would be 1.5" (3.8 cm). In addition, if seeding can be accomplished from generators located further upwind of the barriers, some of these effects would be expected to affect the downwind slopes of the mountain barrier as well. Releases further upwind also allow more time for the seeding plumes to spread horizontally, perhaps even overlap, thus potentially affecting larger areas. Finally, recall that we expect the seeding potential to occur as shown in Figure 6.13; the potential is expected on the upwind side of the barriers. Remotely controlled generators located near the crest would be missing a large majority of the SLW, which would be located further upwind. These features are demonstrated in a schematic fashion in Figure 6.13. Mountain barriers which are wider (along the wind in stormy conditions) than those typically found in the intermountain west offer a better potential for the location of remotely controlled generators at mid-elevation ranges, which still have the potential of impacting more of the SLW zone and also have the advantage of being far enough from the barrier crest to allow snowflakes to grow in favorable growth regions and fall on a portion of the upwind side of the barrier. An excellent example of such a situation is the Sierra Nevada in California where a number of long term programs have effectively employed remotely controlled ground generators (McGurty, 1999; Henderson, 2003). Interestingly, some of these projects also employ lower elevation, manually operated units.

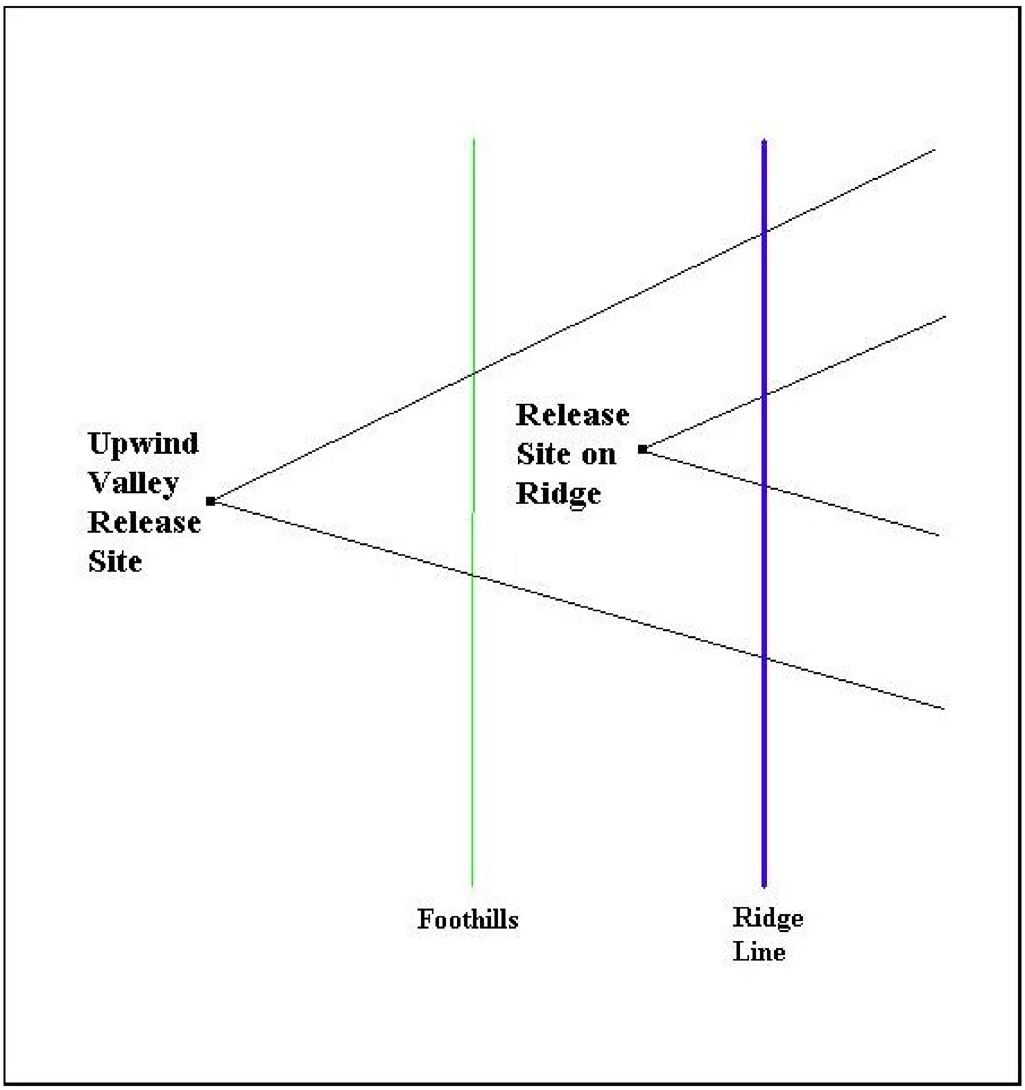

Figure 6.13 Illustration of Seeding Plume Spread (black lines) from an Upwind Valley Site and a Site Near the Ridge Line

Other advantages of ground generator systems (compared to aerial seeding) include lower cost of operation and the ability to operate continuously for extended periods. Ground generators also can be operated to affect mountainous target areas during winter storms under shallow orographic cloud conditions that are impractical or unsafe to seed using aircraft. These conditions can occur for extended durations in winter storms and frequently offer favorable seeding situations.

Disadvantages of ground-based seeding include greater targeting uncertainty, when using ground generators, since assumptions have to be made regarding the combined horizontal and vertical transport of seeding material as well as in nuclei activation, ice crystal growth, and fallout time. The high cloud seeding rates possible with aircraft at effective cloud seeding heights ((i.e., colder than about 24.8^0 F (-4°C)) are probably not possible using a ground generator system. Another possible disadvantage is that special use permits from federal agencies (e.g., U.S. Forest Service) are frequently required in order to site remotely controlled generators on federal lands. Requests for these special use permits on federal lands within Wyoming will trigger the National Environmental Policy Act, mandating that an environmental analysis be completed prior to permit issuance. Also, maintenance of remotely controlled generators in isolated locations often requires costly, regularly scheduled maintenance trips involving over-snow vehicles or helicopters.

Most of the above comments dealing with remotely controlled silver iodide generators would also apply to seeding using releases of liquefied propane, especially since these systems must be in-cloud at temperatures <0^0 C to have any effect. This characteristic forces installations at higher elevations, which results in concerns regarding the nucleation and growth time issues discussed elsewhere in this report. The main advantage of seeding with propane is that it will create ice crystals at warmer temperatures than silver iodide (threshold temperatures of perhaps 30.2^0 F (-1^0 C) instead of 24.8^0 F (-4^0 C). As Super (1999) points out supercooled liquid water may occur rather frequently in the temperature range of 30.2 – 24.8^0 F (-1 to -4^0 C) during portions of winter storms in the West where silver iodide seeding would be ineffective. It should be noted again, however, that the growth rates of ice crystals are relatively slow in this temperature range compared to growth rates at 17.6^0 F (-8^0 C). Figure 6.14 (Rogers, 1976) shows this temperature dependence. The highest growth rates actually occur at a temperature of ~ +5^0 F (-15^0 C). Propane dispensers must be located at locations where the temperatures are below +32^0 F (0^0 C) and releases must be made in cloud. These conditions dictate that the dispensers be located well up the windward side of the relatively narrow mountain barriers typical of those found in the intermountain west, thereby invoking some of the disadvantages of such locations mentioned earlier. Seeding effects are only produced in a small cone (perhaps 12" (30cm) in diameter and 36" (91cm) in length) of supercooled air that results from the venting of the liquid propane. Seeding effects are instantaneous through homogeneous freezing of the supercooled water droplets. There are, however, no downwind effects. By comparison, silver iodide particles can be released in upwind valleys at temperatures above freezing and then proceed to nucleate supercooled liquid droplets several miles downwind. This feature offers the opportunity to potentially treat much larger areas from a single silver iodide generator than from a single propane dispenser.

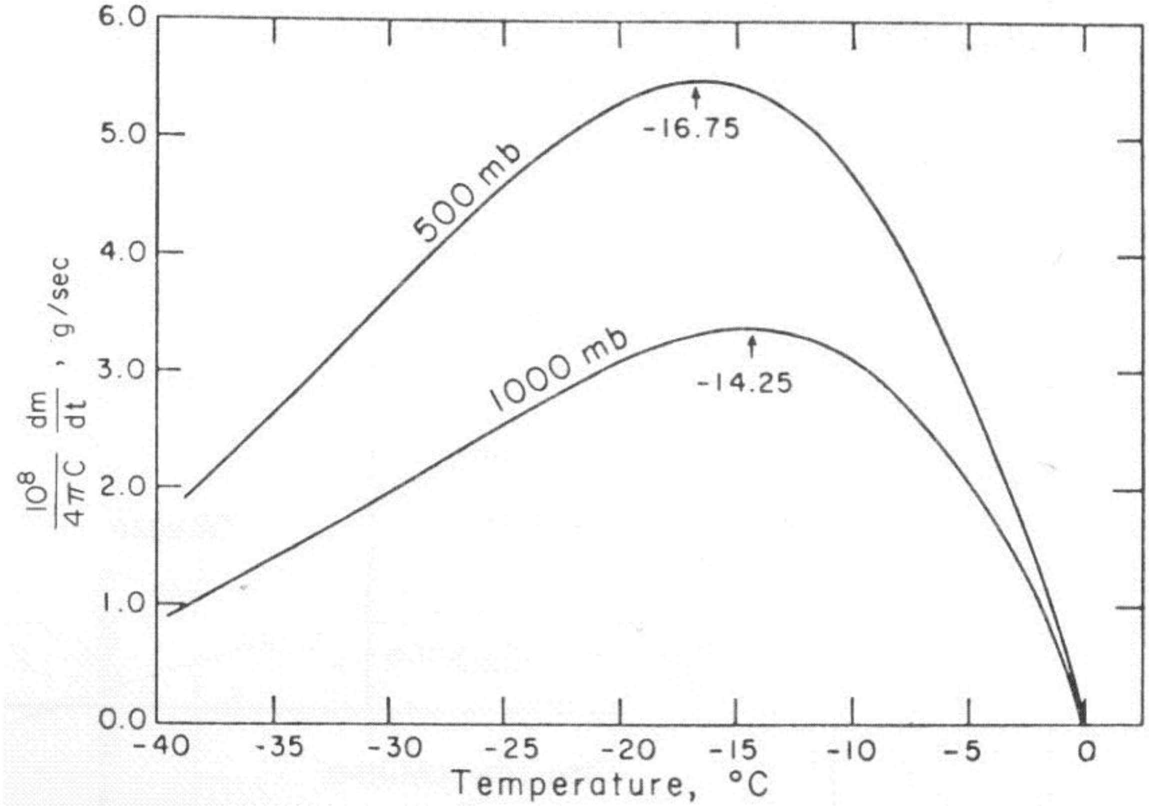

Figure 6.14 Normalized Ice Crystal Growth Rate as a Function of Temperature (Adapted from Rogers, 1976)

6.6.8 <u>Advantages and Disadvantages of Airborne Seeding</u>

Seeding winter clouds with silver iodide from aircraft offers some attractive features. Theoretically, an aircraft may be flown at flight levels at which silver iodide will activate immediately (~ 23^0 F, -5^0 C and colder) without the requirement for the silver iodide to rise from a ground source to these levels. Aircraft may also be flown at locations selected to effectively target the intended target area(s). Aerial systems also offer advantages in terms of the ability to deliver higher seeding rates into given volumes of cloud, and the ability to seed stable atmospheric situations that may not be effectively treated using ground-based systems.

Disadvantages of aerial seeding include higher costs (much greater than ground generator operations). It also is difficult to maintain an effective amount of cloud seeding material feeding into clouds affecting a target area over long periods of time and of perhaps substantial size (i.e., multiple aircraft may be required). In addition, there are potential hazards of flying in icing or extreme turbulence, and there are possible flight restrictions near major airports and within Military Operations Areas (MOAs). The Federal Aviation Administration also restricts minimum altitudes that may be flown in a specific area under Instrument Flight Rule (IFR) conditions (e.g., cloud obscured conditions). The general restriction is that the aircraft may not fly less than 2,000 feet (610 m) above the highest terrain located 5 nautical miles (9.25 km) either side of the proposed flight path. This last item has proven to present a problem in an attempt to use aircraft to seed in some winter projects, e.g., a project conducted by Idaho Power on the Payette River Drainage in Idaho (Riley and Chavez, 2004). The WMI (2005) study also indicates possible problems with aircraft seeding to target low-level SLW over the upwind side of the Wind River barrier, which NAWC considers to be the most prevalent seeding situation as depicted schematically in Figure 6.1.

There are two concerns which are interrelated: 1) can an aircraft be flown at low enough altitudes to effectively target this low-level SLW which seldom extends above the crest of the mountain barrier, and 2) can it be done safely? The answer to the questions will depend upon the topography upwind of the intended target area and the height of the freezing level during storm periods. For example, if there is a second mountain barrier upwind of the target barrier and it is 10 miles (16 km) between the mountain ranges with a narrow valley between, then the aircraft could fly no lower than 2,000 feet (610 m) above the crest height of the barriers, which would mean it would be flying above the top of the seedable SLW layer. In other words seeding would be ineffective. If the spacing between barriers is greater with an intervening valley, then the aircraft may be able to fly along the axis of the valley at low enough altitudes to effectively target the SLW layer over the downwind barrier. The ability to conduct effective targeting in this scenario is confounded by the tendency of the air parcels flowing over mountain barriers to rise over the mountain barrier in stable to neutral stability situations. This could mean that the seeding material could still rise above some or all of the SLW, again resulting in ineffective targeting. This scenario is depicted schematically in Figure 6.15. A further complication arises if the freezing level is within about 2,000' (610 m) above the valley floor. In these conditions, if the aircraft encounters icing (which is likely), it cannot descend to temperatures warmer than freezing to melt off the ice while airborne. High performance aircraft, which can be a costly approach, may be necessary to overcome this potential problem out of concern for the safety of the aircraft crew. Even so, it may be difficult to maneuver the aircraft within the valley in order to make 180 ^{o} turns in order to remain upwind of the target areas. The aircraft will typically be flying under IFR flight rules (in cloud) so the pilot cannot see the underlying terrain to make these maneuvers. The mountain barriers in the intermountain west are typically rather narrow and there often are relatively close upwind barriers (i.e., separated by rather narrow mountain valleys).

Aircraft seeding in winter storms is quite common in the Sierra Nevada of California. Primary factors in this area is that the upwind San Joaquin Valley (west of the Sierra) is quite wide and that the height of the freezing level in winter storms in this area is typically significantly above the valley floor. As a consequence, seeding aircraft can

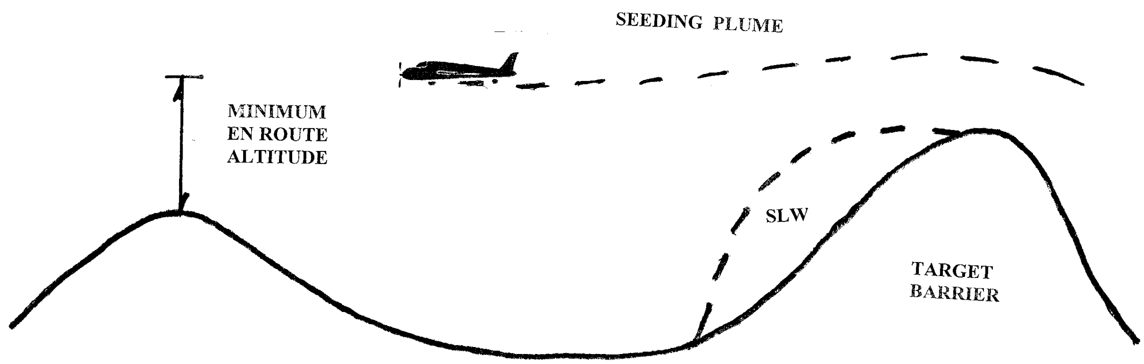

Figure 6.15 Schematic of Aircraft Seeding Upwind of a Mountain Barrier

fly at about the 23^0 F (-5^0 C level), an effective flight level for silver iodide seeding due to the activation threshold of silver iodide being ~ 24.8^0 F (-4^0 C), and readily descend to altitudes warmer than freezing to shed any ice build up periodically. Lower performance aircraft can be safely operated in this environment. The seeding is also likely to be effective since the aircraft may be flown at low enough altitudes that the seeding material will encounter the SLW pool well upwind of the barrier in time for the growth and fallout of augmented precipitation on the upwind side of the barrier. Physical studies of the silver plus tracer content of snow samples taken from one of the long-term target areas in the Sierra Nevada confirm that silver released from aircraft is found in a significant portion of these snow samples (McGurty, 1999).

6.6.9 Seeding with Rockets

The topic of seeding rockets was recently addressed in the second edition of Manual 81(ASCE, 2006) by the American Society of Civil Engineers. The following is a quote from this publication:

> *" Ground-based rockets and artillery shells loaded with silver iodide or some other seeding agent have been used extensively in several of the former Soviet Bloc countries and China on hail suppression projects. The projectiles are launched with directions from radar and targeted for the supercooled tops of the growing cloud elements. While these methods appear to offer the advantages of both ground and airborne delivery systems in some countries, they are costly and unacceptable for use in regions where there are numerous private or commercial aircraft operations."*

As explained in section 6.6.5, a Colorado firm proposed the use of model rockets to carry small quantities of silver iodide to seed winter clouds. NAWC was asked to include a discussion on this possible use of this seeding mode on the SRWR program. The idea of transporting seeding material from the ground to higher and colder regions of seedable winter clouds is an intriguing one. Such a technique might be especially useful in situations with low-level inversions. There are, however, several potential problems with this technique. One concern is that, according to our knowledge, there have been no tests of effectiveness of the seeding agent used in these rockets. Normally, new seeding devices or methods are tested in a cloud simulation laboratory under controlled conditions to determine how many effective ice nuclei are formed per gram of seeding material. This type of information may then be used in calculations of the number of effective nuclei present in a seeded cloud volume. Desired concentrations are typically considered to be ~10/liter. Another concern would be with the spacing and timing of these rocket firings. It was proposed that a seeding rate of four per hour from ~ 12 sites in each of the two Wind River and Medicine Bow/Sierra Madre target areas. Assuming a spacing of these sites that is similar to the initial design for these projects as developed by WMI (WMI, 2005) would mean the release sites would be ~ 30km apart. These flares only burn for ~ 20-30 seconds. The problem with this seeding approach is similar to the problem with aircraft seeding; only small portions of the seedable cloud volume would be treated. Rate of plume speading estimates derived from the Utah/NOAA research program conducted in Utah using tracer gases indicated plumes spread in the horizontal about $15\text{-}20^0$ (Griffith, et al, 1992). This information translates into desired spacing of generators in Utah of ~5 miles (8km). This spacing would be approximately triple to that proposed for the rocket firings. The above discussion deals with spatial distribution questions. There will also be temporal distribution problems as well. If four rocket flares are fired per hour, they would only collectively cover approximately one minute of each hour with seedable conditions. Both of these distribution problems could be overcome, but that would mean that flares would need to be fired from locations much closer together and much more frequently than proposed. This could be done but the expense will be cost prohibitive.

The most significant concern, as was the case with propane seeding, is the lack of any randomized research program results for a sizable target area that would justify consideration of this seeding approach. It certainly was not a recognized technique when the ASCE Precipitation Standards document (ASCE, 2004) was published. For all of the above reasons, NAWC does not recommend seeding with rockets on the SRWR project.

6.6.10 Summary

All of the information contained in sections 6.4, 6.5 and 6.6 was combined with the results obtained from the Desert Research Institute's atmospheric modeling work for this feasibility study (section 6.8), along with specific considerations (e.g., topography, climatology) associated with the proposed target area, to identify the recommended seeding agents and seeding modes which are provided in section 6.9.

6.7 Meteorological Data Collection and Instrumentation

Specialized types of equipment, data collection and instrumentation will be needed to conduct the cloud seeding project(s). The various types of equipment or observations will include seeding devices, means of communication, information and observations used in real-time to make seeding decisions and observations used after the fact in evaluations of the effectiveness of the seeding projects. Possible observational systems that will be considered include: microwave radiometers, icing rate meters, rawinsondes, project dedicated weather radars, cloud physics aircraft, and project specific precipitation gages. **There are three primary uses of or justifications for the addition of meteorological measurements or instrumentation: 1) such additions will assist in better targeting of the seeding material, 2) such additions will provide better real-time recognition of seeding opportunities, and 3) such additions will provide the means to help evaluate the effectiveness of the seeding operations.**

NAWC proposes that a phased data collection approach be adopted in the performance of this program. The goal will be to make critical observations early in the history of the program, which may later be discontinued or replaced with more basic measurement or prediction approaches. For example, one of the primary concerns regarding the conduct of a winter orographic cloud seeding program in a new area is the frequency, magnitude and location of supercooled liquid water upwind and over the barriers in question. We propose that a microwave radiometer (Hogg et al, 1983) and a ground based icing rate meter be operated during the first winter or two of the program (Figures 6.16 and 6.17). The first device is expensive, and the latter inexpensive, to acquire and operate. Data from the two devices can be compared for the first winter or two of operations to see how well the inexpensive device depicts the presence of icing as shown on the more expensive device. Data from the radiometer are integrated samples of the water content of the atmosphere from the surface to the top of the atmosphere, while the data from the icing rate meter are only point observations. NAWC utilized the second type of device at a mountain top location located east of Salt Lake City, Utah to study icing events at that location (Solak et al, 2005), with interesting and useful results.

We also propose that project specific rawinsonde (weather balloon) observations be taken during storm periods during the first winter season of the program. Predicted soundings based upon some of the operational National Weather Service atmospheric models (e.g., NAM, GFS) would be obtained for 6 or 12 hours for the coordinates of the rawinsonde release site. The predicted soundings will then be compared with the actual sounding information to determine if the predicted soundings are providing information that is sufficiently accurate for direction of cloud seeding operations. If so, the project specific soundings could be discontinued in future seasons of operation.

Figure 6.16 Example of a Microwave Radiometer

Figure 6.17 Icing Rate Meter

The need for project communications will be partially dependent upon the type of seeding methodology or methodologies that are adopted. For example, if both higher elevation remotely controlled generators and seeding aircraft were utilized, there would be a need for radio, cell phone or satellite links to the remotely controlled generators. Means of communication between the pilot of the seeding aircraft and the project meteorologist would also be needed (e.g. radio). Both situations may entail some form of licensing by the Federal Communications Commission.

A variety of public information and observations will be useful in the real-time decision making on these projects. Weather observations (surface and upper-air), weather forecasts, weather warnings, prognostic charts, satellite photos (both visible and infrared), NEXRAD radar displays and predicted or observed streamflow will all be utilized. Such information is readily obtained through the internet from a variety of web sites and is therefore available to the project at no cost. Providers of this type of information include, for example, the National Weather Service (NWS) and the Natural Resources Conservation Service (NRCS).

The need for other additional project specific observations has been considered. For example, should additional precipitation gages be installed in the potential target areas? One might think that installing additional precipitation gages in the cloud seeding target areas would provide a better means of evaluating the effects of the cloud seeding. This would be true if the program design called for randomization of the seeding treatment decisions as discussed in Section 11.3. The program design that we are recommending does not call for this randomization technique to be used, since the project goals focus on maximizing the precipitation augmentation potential. As a consequence, we do not recommend that any additional project specific gages be installed. The reason that additional gages would not be useful in detecting effects of cloud seeding is that most of the precipitation episodes will be seeded. Consequently, there will not be any useful non-seeded data within the project target area to compare with the seeded data. There will be some non-seeded data but they will have built-in biases. The non-seeded events will be either very weak events with little or no seeding potential or perhaps very strong ones that are considered to have very limited seeding potential or are not seeded because seeding suspension criteria are exceeded.

Weather radars provide very useful information in terms of real-time decision making on operational cloud seeding programs. Radars that are installed specifically to support cloud seeding programs are more commonly used when cloud seeding aircraft are used on a project. This is especially true in the case of summertime programs where echo developments observed by the project meteorologist on the weather radar can be relayed to the pilot of the seeding aircraft. Such information can be useful in both identifying favorable areas for seeding as well as areas to avoid while flying (safety issues). The National Weather Service (NWS), through a modernization effort in the 1990's, installed a network of very sophisticated 10 cm wavelength weather radars throughout the U.S. These sites are known as NEXRAD (Next Generation Radar) installations. Each installation costs on the order of $1,000,000. Figure 6.18 provides the array of these sites across the U.S. There are approximately 160 NEXRAD sites now in service. Each of the radars provides information on precipitation and wind speed and direction within the precipitation echoes. The radars step scan through 14 different elevation angles in a 5 minute period and a computer program integrates the stepped scans into a volume scan. Several very sophisticated algorithms then produce a large number of specialized displays and products from each volume scan. The maximum range for the detection of precipitation echoes is ~140 miles from each site. The NWS provides all the necessary support for these systems; operation, calibration, spare parts and maintenance. Because the NEXRAD network is important to NWS forecasting and public safety responsibilities, as well as many hydrometeorological applications and aviation safety, these radars enjoy high priority support and a resultant high degree of reliability.

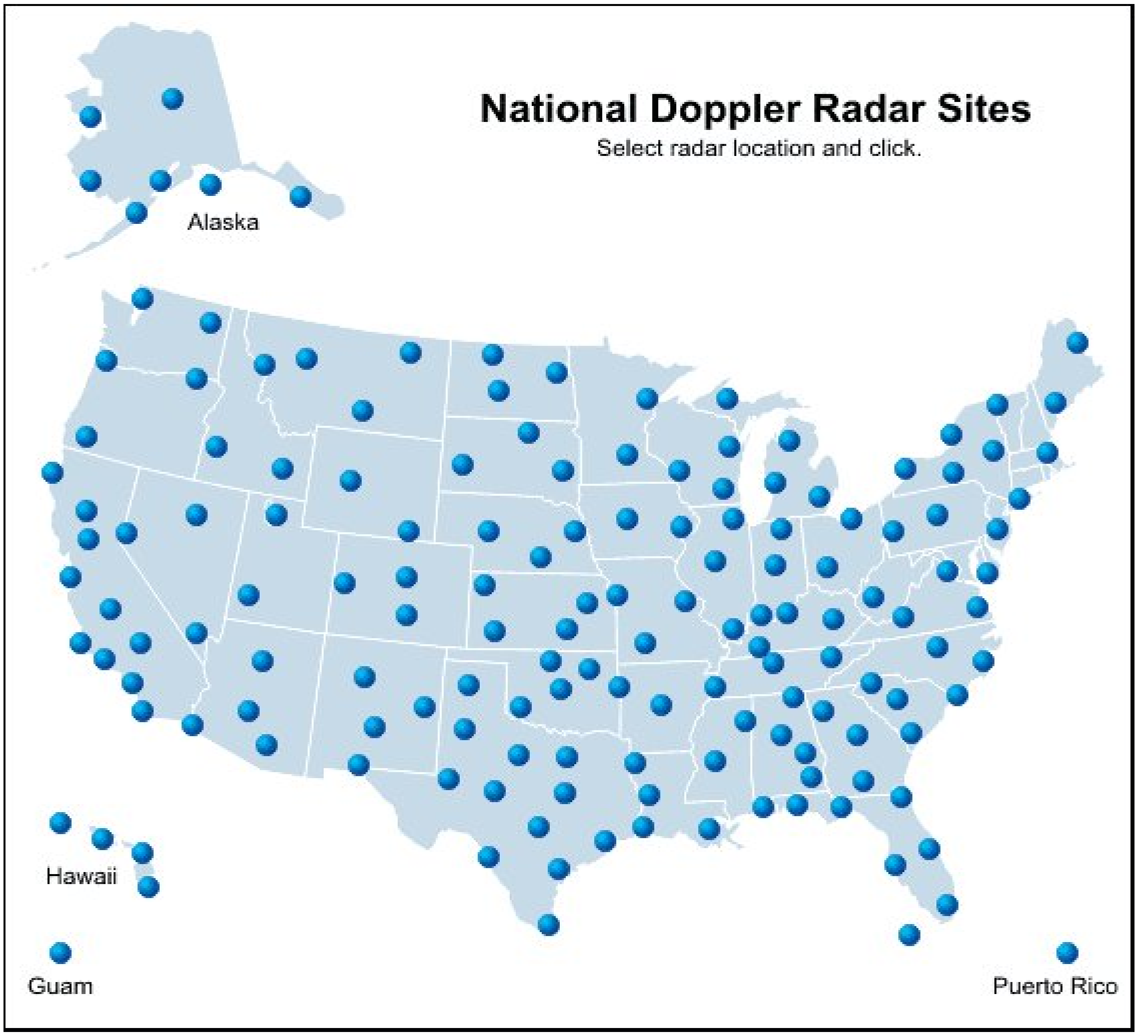

Figure 6.18 National Weather Service NEXRAD Radar Locations

There are two NEXRAD installations of potential usefulness to the conduct of the SRWR project. These sites are Pocatello, Idaho and Riverton, Wyoming. The Pocatello, Idaho site would provide good coverage over the intended target areas since these areas would be within 90 miles (~145 km) of the radar site. The NEXRAD radars provide information out to ~144 miles (230 km), but the usefulness of this information declines beyond ~100 miles due to the curvature of the earth (i.e. The radar beam at a 0.5 ^{0} elevation angle would be viewing potential cloud developments at increasing elevations above the earth's surface with distance. The Riverton, Wyoming site is located ~ 135 miles from the western edge of the Salt River Range. As a consequence, this site would be less useful than the Pocatello site. NAWC's recommends that the NEXRAD site at Pocatello (with some backup from the Riverton site) be used to help direct the SRWR project. NEXRAD data are available in near real time at approximately 5-6 minute intervals through a variety of internet web sites. NAWC has utilized a commercial, subsciption web site extensively over the past three years to provide radar data to conduct wintertime cloud seeding programs. This web site provides a variety of useful products including: echo intensities (precipitation), echo tops, vertical wind speed and direction (the very useful VAD displays mentioned earlier) and composite echo displays that integrate radar returns from all of the 14 different elevation scans.

The additional cost of providing a project-dedicated weather radar is not justified. This recommendation is based not only on a cost consideration but also upon actual experience in which NAWC has successfully used the NEXRAD radar at Vandenberg AFB, California to help direct a winter cloud seeding program for the Santa Barbara County Water Agency. This program utilizes both ground based seeding equipment and a cloud seeding aircraft.

Since NAWC has indicated that a cloud seeding aircraft may be potentially useful in the conduct of the SRWR project, it is concluded that the Pocatello, Idaho NEXRAD weather radar would provide sufficient weather radar support to these airborne operations. Computer programs can be developed to overlay the aircraft track on the most recent weather radar depiction from the Pocatello site. This combined information can be relayed to the aircraft pilot by the project meteorologist to provide seeding guidance and safety advisories. Systems are also commercially available that can provide surface-based radar depictions for use in-flight by the seeding aircraft aircrew.

Typical observations used in post-project assessments of seeding effectiveness include NWS cooperator precipitation measurements, NRCS SNOTEL and snow course measurements and USGS streamflow measurements. Potential means of evaluating these projects will be discussed in section 11.0.

6.8 Atmospheric Modeling (DRI)

The Desert Research Institute at the University of Nevada – Reno has applied sophisticated atmospheric modeling to this feasibility study. The use of mesoscale models to evaluate cloud structure and the associated potential for cloud seeding has become relatively commonplace. Over the past decade several different models have been used for this purpose. Bruintjes et al (1994, 1995) used the Clark Model to predict cloud development and silver iodide plume dispersion over the mountains of northern Arizona. Heimbach et al (1997) used the same model to study airflow patterns and seeding plume dispersion over the Wasatch Plateau of central Utah. Meyers et al (1995) used the CSU RAMS model with explicit microphysics to model the evolution of seeding effects from airborne seeding experiments over the Sierra Nevada. Huggins et al. (1998) employed MM5 and a Lagrangian particle dispersion model (LAP) to compare simulated ground seeding plume locations with concurrent surface observations of snowfall and its trace chemical composition. More recently Huggins et al (2005) used the same modeling scheme to evaluate airflow, cloud and precipitation development, and simulated ground seeding plume dispersion over a cloud seeding target area in the Sierra Nevada.

Models and computer systems are evolving to the point where real time simulations at high spatial resolution are possible. Weather Modification, Inc. (WMI, 2005) revealed some of this new capability demonstrated by the NCAR WRF modeling system in the Wyoming Level II Weather Modification Feasibility Study for the Wind River, Sierra Madre and Medicine Bow mountain ranges. For the purpose of this (SRWR) feasibility study, several other models offer similar capabilities. DRI used the modeling system based on familiarity and that which has been shown to produce reliable simulations over equally complex topography. It has the advantage of being verified in a previous application (Huggins et al, 1998) during an actual ground-based cloud seeding experiment.

This task involves analysis of MM5 wind field and cloud parameters, and dispersion simulations using the DRI Lagrangian random particle dispersion model. The main objective of this task is to provide an assessment of the transport and dispersion of simulated cloud seeding agent releases from potential ground-based cloud seeding generator sites in the vicinity of the proposed target areas. This task is being accomplished by using Mesoscale Model 5 (MM5) atmospheric simulations (Grell et al 1995; Koracin et al. 1999b, 2000, 2004; Koracin and Dorman 2001) as input to the Lagrangian random particle dispersion model developed at DRI and applied to studies of the transport and dispersion of atmospheric pollutants and tracers in complex terrain as well as the transport and dispersion of cloud-seeding agents (Koracin et al, 1998, 1999a, and 2000; Huggins et al, 1998).

The Lagrangian random particle model estimates the dispersion of pollutants (particles) by tracking a large number (on the order of millions) of hypothetical particles in the model domain. The fate of the particles is determined by the simulated atmospheric fields and a modeled direct link between the turbulence transfer and dispersion. In addition, environmental atmospheric parameters at every point of the domain are available from the meteorological model in an Eulerian framework. The Lagrangian random particle dispersion model is capable of simultaneously treating multiple seeding sources (point, line, areal, and volume) without restrictions on position and movement, as well as prescribed time variations of emission rates. In the case of a known source emission rate, the model can predict the magnitude of concentrations in all three dimensions. In the case of an unknown emission rate, the model can still predict fractional (normalized concentrations) in all three dimensions. Meteorological input to the LAP model includes 3D fields of U, V, and W wind components, as well as potential temperature simulated by MM5. A synthesis of the model results is then used to examine the potential transport and dispersion of cloud-seeding agents from the source areas into the target regions. The LAP results, together with MM5 predictions of cloud parameters, can be used to select positions for cloud-seeding generators in the Salt River and Wyoming Ranges. The results will help determine if, when, and how often ground-based seeding could be considered a viable option in a weather modification program for these regions.

For the MM5 and LAP simulations specific to SWSR, two winter storm periods from 2004-05 were selected. The cases were selected using SNOTEL and other meteorological data sets which showed periods with precipitation in the Salt River and Wyoming Ranges, and storm structure (air flow, temperature, etc.) that suggested that some potential for cloud seeding existed. The cases were also chosen to illustrate a variety of meteorological conditions. The feasibility study compiled for the Wind River, Sierra Madre and Medicine Bow regions (WMI, 2005) stressed the occurrence of both low-level orographic cloud water and cloud water that developed in mountain-induced waves as being important for cloud seeding. The WMI study indicated that only aircraft could deliver seeding material to the cloud liquid regions generated by the waves due to their height being generally above the regions where ground seeding plumes were predicted to be transported. However, the examples shown in that (WMI) study also suggested that, even if successfully seeded, the fallout trajectories of the seeded ice particles would terminate downwind of the intended target areas. Such features were analyzed in the current study and assessed relative to their importance in potential cloud seeding operations.

The results of the SWSR-specific simulations conducted by DRI are provided in Appendix C.

6.9 Personnel and Project Headquarters

The personnel needed to conduct this program and the location of the operations headquarters will be a function of the components of the final design. These needs will primarily be dictated by the seeding mode or modes selected for implementation. If the decision was made to conduct only a ground based seeding program, then the operations headquarters could be removed from the proximity of the target areas. In this scenario a qualified project meteorologist would direct seeding operations and handle the logistics associated with the program. A technician living near the target area could be hired to perform installation, filling and maintenance activities associated with the generator networks. The situation would change if aerial seeding were utilized in conjunction with ground based seeding. In this scenario an operations headquarters would typically be located at a suitable airport as close as possible to the target areas. A project meteorologist and a pilot or pilots would operate the field program from this facility. A technician(s) living near the target areas would also be needed if ground generators are used. As discussed in section 6.10.3, one possibility that appears to offer the various services that would make an airport suitable for this type of operation is located in Pocatello, Idaho. Should a combined airborne/ground-based seeding program go forward, a visit to this airport facility would be in order to insure the right type of support services are available.

6.10 Operational Period and Selection and Siting of Equipment

An operational period of November through March is recommended based upon the climatology of the area and the likelihood of generating positive seeding effects during this period. Operations could be continued into the month of April.

NAWC recommends that silver iodide be the seeding agent used in the conduct of the SRWR project. It is also recommended that manually operated, possibly remotely operated ground based generators, and possibly airborne seeding (the use of the latter two seeding modes will be a function of their costs versus projected benefits, as discussed in section 12.0). It is not recommended that a project-dedicated weather radar be used, but it is recommended that one season of rawinsonde observations be taken. The addition of microwave radiometer observations of supercooled liquid water for one season is also recommended (possibly supplemented through the installation of a ground based icing rate meter). It is not recommended that any new precipitation gages be installed in support of the project. The recommendations are discussed in the following sub-sections.

6.10.1 Manually Operated, Ground Based Silver Iodide Generators

It is proposed that a network of ground based, manually operated silver iodide generators be installed for this project. Figure 6.4 (earlier figure) provides a photograph of a generator of this type. These generators would be sited at local residences or ranches at which the residents agree to be trained in their operation. The operator contracts with these residents to run the generators as requested by the project meteorologist. The ideal sites will be those within the foothill areas on the windward sides of the mountain barriers. **Sites in the mouths of canyons have been shown to be especially favorable locations based upon research conducted in Utah (Super, 1999).** The ideal spacing between generators would be approximately 5 miles (8km), again based upon research conducted in Utah (Griffith, 1992). These generators should burn an acetone/silver iodide mixture that results in the generation of fast acting ice nuclei. Research summarized by Finnegan (1999) documents some possibilities (e.g., acetone, silver iodide, sodium iodide and para-dichlorobenzene). Release rates should be in the 0.4- 0.9 ounces (10-25 grams) of silver iodide per hour range. Based upon the discussion in Section 6.4, fast acting nuclei are desirable in order to generate ice crystals as far upwind of the crest of the barriers as possible, in order to allow time for them to grow into snowflakes and fall onto the barrier.

The results of the climatology work in Section 5.2.3.2 suggest that the favored locations would be southwest, west and northwest of the intended target area (refer to Figure 5.26). Table 6-2 provides preliminary information on these sites. Figure 6.19

provides the approximate locations for these manual generator sites. Approximately 16 generators would be used in this network. If the decision is made to proceed with the SRWR program, site surveys will be necessary to locate suitable site locations with local residents willing to contract with the seeding contractor for operation of the generators.

Table 6-2 Manually Operated Ground Generator Approximate Locations

Location	Latitude (N)	Longitude (W)	Approx. Elev. (feet)
1. Alpine	43^0 10.2'	111^0 0.9'	5,670
2. 7ESE of Alpine	43^0 8.6'	110^0 52.5'	6,800
3. 7NNE of Freedom	43^0 3.7'	110^0 59.1'	6,460
4. 2NE of Thayne	42^0 57.0'	110^0 56.4'	6,490
5. 3 N of Grover	42^0 50.5'	110^0 56.2'	6,590
6. Afton	42^0 43.7'	110^0 55.6'	6,260
7. Smoot	42^0 37.3'	110^0 54.5'	6,760
8. 7S of Smoot	42^0 32.3'	110^0 53.6'	7,430
9. 10ENE of Geneva	42^0 26.8'	110^0 51.3'	7,360
10.3NE of Geneva	42^0 22.5'	110^0 59.3'	6,970
11.7E of Geneva	42^0 20.8'	110^0 52.7'	7,360
12. 1NE of Raymond	42^0 17.1'	111^0 1.8'	6,820
13. 2SE of Border	42^0 11.2'	111^0 1.0'	6,340
14. 7NE of Cokeville	42^0 11.8'	110^0 52.9'	6,460
15. Cokeville	42^0 5.0'	110^0 55.6'	6,370
16. 10ENE of Cokeville	42^0 8.0'	110^0 44.2'	7,730

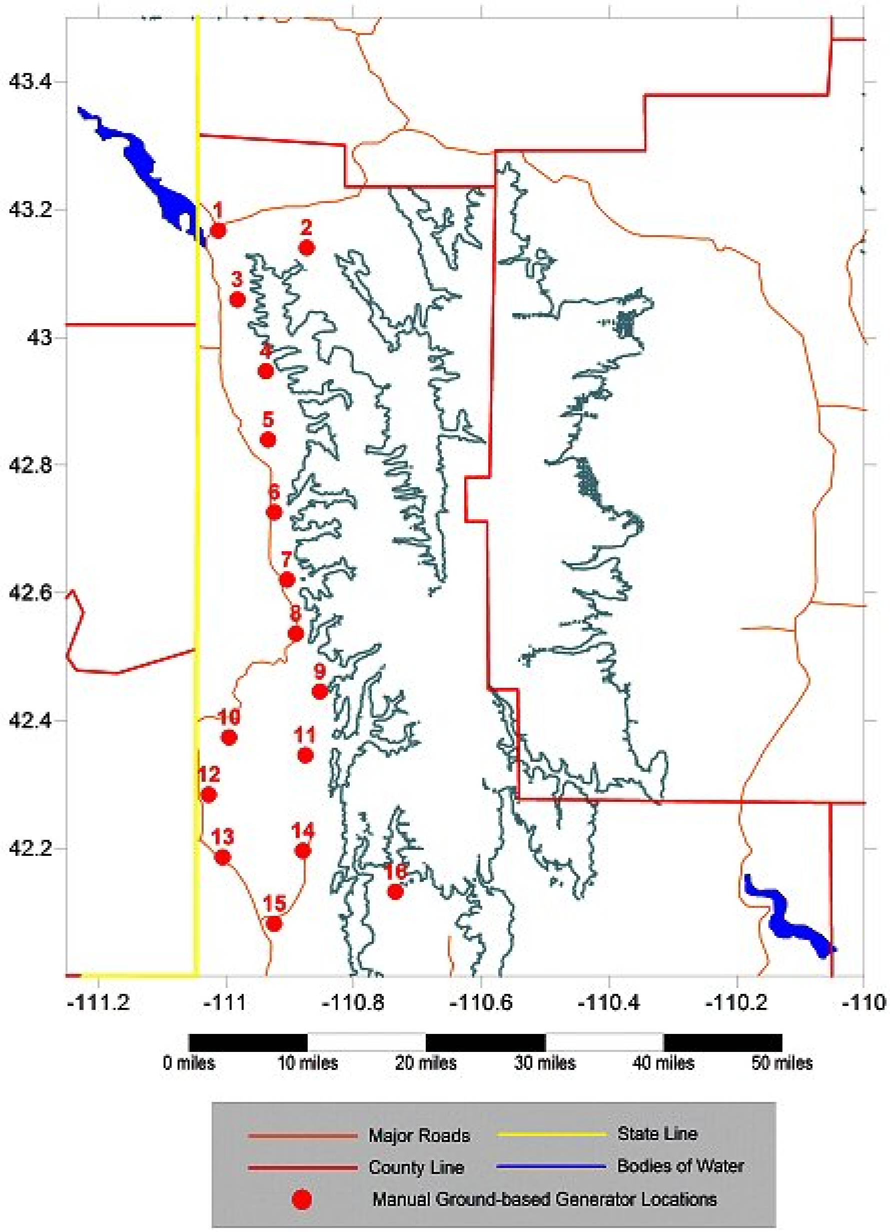

Figure 6.19 Approximate Locations of Manually Operated Ground-Based Generators

The proposed target area is somewhat unusual in that it consists of two mountain barriers separated by a central valley (Greys River Valley) that is inaccessible during the wintertime except by over-snow vehicles or helicopter. Normally, manually operated generators would be installed in the foothills of a central valley area between two mountain barriers, but this is only feasible if the central valley is accessible in wintertime and there are year-round residents in the area. There will be impacts of seeding on the second barrier (Wyoming Range) from seeding operations upwind of the first barrier

(Salt River Range). Remotely controlled silver iodide generators may provide a means to more effectively seed this second barrier using ground-based equipment. A discussion of this possibility is provided in the next section.

6.10.2 Remotely Controlled, Ground Based Silver Iodide Generators

Since the Greys River Valley is basically inaccessible by standard vehicles in wintertime, as discussed in the previous section, there will not be the opportunity to install manually operated ground based generators in this area. Based upon the twin barriers represented by the Salt River and Wyoming Ranges and the fact that the barriers are located close to one another, it is recommended that a network of remotely controlled, ground based silver iodide generators be considered for installation on the upwind side of the Salt River Range. This recommendation is predicated upon there being a favorable benefit/cost ratio that would justify the inclusion of these generators (this topic is discussed in Section 14.0) and the assumption that obtaining special use permits from the Forest Service will not be difficult to obtain. Most of the study area consists of National Forest Service lands managed in accordance with the forest plan and specific travel management restrictions for both summer and winter travel. It is believed that seeding from the upwind side of the Salt River Range will likely produce some effects near the crest and downwind slopes of the Salt River Range, as well as over the Wyoming Range. This latter expectation is based upon the indicated results from the Bridger Range research program conducted in Montana in the 1980's. Table 6- 3 provides preliminary information on the remotely controlled sites. Figure 6.20 provides approximate locations. Approximately five remotely controlled generators are proposed. Locations are proposed in areas at 8,000 to 8,500 feet (2.4 to 2.6 km) in elevation as far west of the crest line of the Salt River Range as possible. Such locations will allow the greatest opportunity for nucleation and growth of ice crystals into snowflakes and fallout beginning near the crest of the Salt River Range and continuing downwind over the remainder of the target area. These generators should use the same fast-acting seeding solution as used in the manually operated generators.

Table 6-3 Remotely Controlled Ground Generator Approximate Locations

Location	Latitude (N)	Longitude (W)	Approx. Elev. (feet)
1. 10ENE of Cokeville	42^0 6.6'	110^0 47.9'	8,760
2. 12E of Geneva	42^0 22.9'	110^0 49.2'	8,210
3. 5SE of Smoot	42^0 35.7'	110^0 52.0'	8,540
4. 5ENE of Grover	42^0 48.9'	110^0 51.5'	8,850
5. 4ENE of Etna	43^0 2.5'	110^0 56.2'	8,810

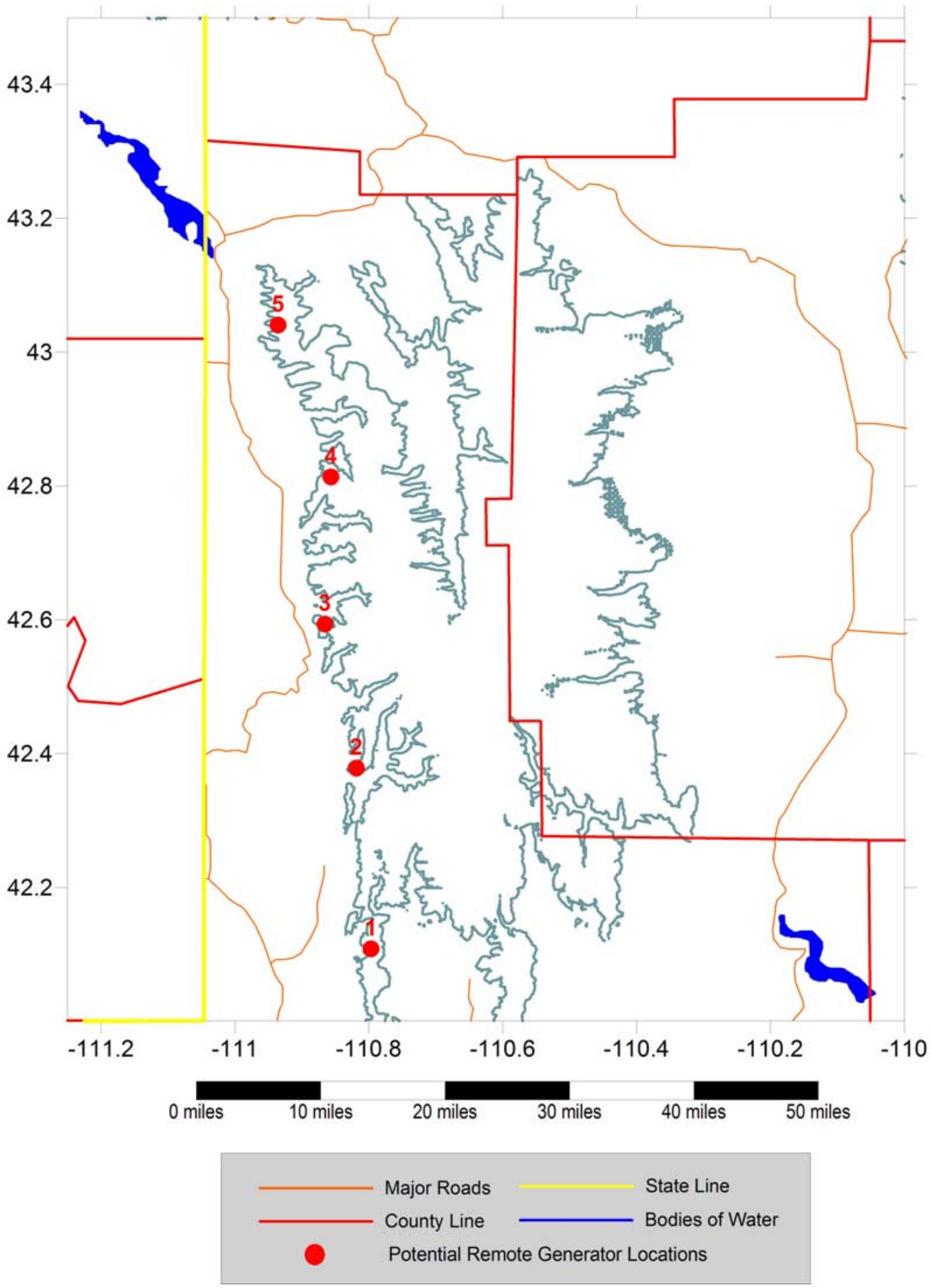

Figure 6.20 Approximate Locations of Remotely Controlled Ground-Based Generators

6.10.3 Airborne Silver Iodide Seeding and Rawinsonde Observations

The terrain upwind (west) of the potential target areas in southeastern Idaho is rather mountainous. There are several mountain ranges such as Dry Ridge, Gannett Hills, Webster and Caribou in this area. These mountains are not particularly high, however, being on the order of 7,000-9,000 feet (2.1 – 2.7 Km) with one isolated peak (Meade Peak) northeast of Montpelier at an elevation near 10,000 feet (3.0 km) feet). Star Valley, which lies between the Salt River Range and these lesser ranges to the west, is rather narrow, being on the order of 5-10 miles (1.5 – 3.0 km). Aircraft operations within this valley below the height of the mountains is not considered practical even if special waivers could be obtained from the FAA to do so. As a consequence, seeding aircraft flights would need to be conducted 2000 feet (610 m) above the terrain five nautical miles (9.3 km) either side of the flight path. The highest terrain elevation in the likely seeding area over southeastern Idaho according to the FAA Salt Lake City Sectional Aeronautical chart is 10,100 feet (3.1 km). This would mean flights could generally be conducted down to altitudes of 12,100 feet (3.7 km) MSL. Lower altitude fixed flight legs may be possible, such as ones that avoid the highest terrain in the area by at least 5 nautical miles. However, these would require FAA approval. Such flights would potentially impact the Salt River Range and, perhaps to a lesser extent, the Wyoming Range. The seeding impacts would involve the rather complex interactions of several factors: 1) timing of the seeding material coming into contact with supercooled water droplets, 2) the speed at which ice nucleation occurs (a function of the type of seeding agent), 3) the growth rate of the ice crystals (a function of the ambient temperature), and 4) wind direction and especially wind velocities from the flight level down to the surface. Flights that would have a higher likelihood of impacting the Wyoming Range would be ones conducted over Star Valley as far eastward as perhaps the crest line of the Salt River Range. The FAA Salt Lake City Sectional Aeronautical chart indicates a maximum terrain elevation in this area of 11,700 feet (3.6 km). This would mean that minimum flight levels would generally be on the order of 13,700 feet (4.2 km) MSL. As in the case of flights over southeastern Idaho, lower elevation flight legs could possibly be developed, requiring FAA approval. NAWC considers the 13,700 foot (4.2 km) flight level to be too high to routinely produce cloud seeding effects in the target area. The following discusses this and other concerns.

There are two concerns associated with the minimum flight altitudes described in the above:

1) The seeding material released at these altitudes may remain over the zones of supercooled liquid water that are depicted in Figure 6.1 and as illustrated in Figure 6.15. If this were to happen routinely, there would be minimal if any increases in precipitation in the intended target areas due to airborne seeding.

2) The second concern is somewhat related to the first, namely the question of what the temperatures will be in the altitude range of 11,000 to 12,000 feet (3.4 – 3.7 km) during winter storms that affect the target areas. If temperatures are below ~ -15^0 C, there will likely be adequate numbers of natural ice nuclei present, in which case the silver iodide seeding material will not have any impact.

We investigated the second concern by examining the upper air storm climatology for the area using rawinsonde data as described in Section 5.2. This climatology suggests that occurrence of these conditions (i.e. 700mb temperatures < -15^0 C) are relatively infrequent.

Perhaps the primary reasons that airborne seeding should be considered for the SRWR project are related to the following two issues:

1) How frequently do low-level atmospheric temperature inversions occur in Star Valley and adjacent river valleys *during active storm periods*? Section 5.2.3.4 contains some information on this topic, but it is based primarily upon reanalysis data from NCEP and is lacking any actual sounding profiles. There are, however, some surface reporting weather stations in the Star Valley that can provide some indirect indications of the presence of low-level inversions. The concern is that low-level inversions could prevent the transport of seeding materials released from the ground into the supercooled liquid droplet regions upwind of the mountain barriers. Aircraft seeding under these conditions may be beneficial, but only if the two concerns noted above are not a factor in these situations.

2) Aircraft seeding may be conducted when the temperatures near crest level are too warm for silver iodide released from the ground to be effective. In other words, the aircraft can be flown at or near the $-5\,^0$C level in these storms, assuming there is liquid water present at these altitudes, thus having the potential for augmenting the natural snow fall in the target areas.

The importance of the first aircraft advantage scenario noted above is difficult to assess without having some actual temperature profile data from one of the valleys (probably Star Valley, since it is accessible). This issue, in part, leads to the recommendation that rawinsonde data be collected for one winter season in this area as described in section 5.2.3.4. A limited analysis of rawinsonde data from Salt Lake City, Utah during the storm periods identified in the four-season data set described in Section 5, was conducted as an attempt at estimating valley inversion and stability characteristics for events when stability may have been a factor. The Salt Lake City rawinsonde data were selected for this analysis because of general proximity, as well as topographic similarities with the study area in Wyoming. After adjustments were made for surface elevation differences, etc., this analysis suggested that stable layers that may restrict vertical transport of seeding material were limited to a <u>very shallow layer</u> near the surface most (about 69%) of the time that precipitation was occurring over the target barriers. The Salt Lake rawinsonde data also suggested that in about 12% of these cases, stability (or inversion layers) likely extended to about 1000 - 3000 feet above the surface, and that stable layers likely extended to above crest height about 9% of the time. Multiple stable layers were implicated in about 8% of the “stable” cases. These results, if transferable to the study area, suggest that locating ground-based seeding equipment in areas elevated slightly above the valley floor will likely eliminate most stability problems. A similar study of stable layer depth conducted using Salt Lake City sounding data, for cases where icing was measured by an icing rate meter at the Snowbird ski resort in the nearby

Wasatch Mountains, indicated somewhat deeper stable layers, with a median depth of about 2,000 feet (610 m) above the valley floor. The discrepancy between these stable layer depth results and those for the Wyoming storm events may relate to storm sector biases (e.g., pre-frontal vs. post-frontal) or to many other factors. The bottom line here is that, while the presence of stable layers (that would restrict transport of cloud seeding material) can be inferred from surface temperature measurements and other factors, the typical depth and structure of these layers tends to be very location-specific and is difficult to estimate without sounding data from the area in question.

The second question or issue (suitability of temperature near or just above crest height) was examined using some of the climatological information developed for storm periods as described in Section 5.2. Analysis of 700-mb temperature data, representative of temperatures just above crest levels, showed temperatures warmer than -5^0 C 20% of the time for all of the events examined, and about 15% of the time for the November – through March period. These are cases where aircraft may be more suitable for seeding than either type (manual or remote) of ground-based seeding equipment. This is because, under these conditions, orographic lifting alone is unlikely to transport seeding material into effective temperature zones in these cases.

The types of aircraft used in the conduct of cloud seeding programs vary depending upon the seeding modes selected, the time of year and safety considerations. For the SRWR project, if aircraft seeding is to be conducted, it is recommended that turbine engine aircraft (e.g., Cheyenne II's) be used. This recommendation is based primarily on aircraft performance as it relates to safety considerations. As discussed in Section 6.8, if the aircraft were to encounter extreme icing conditions, it could not descend to altitudes warmer than freezing to shed the ice due to the high ground elevations. As a consequence, the seeding aircraft requires ample power to operate safely for adequate durations under such (airframe icing) conditions. Turbocharged, piston engine aircraft may not have enough power to operate safely under these conditions. The aircraft should be equipped with a basic data collection package that would record: location, altitude, time of seeding equipment operation, temperature and supercooled liquid water content. Some of this information will be useful in both real-time to make seeding decisions as well as post operations assessments of seeding operations.

Potential bases of operation for the aircraft would include airports at Pocatello, Idaho, Idaho Falls, Idaho and Jackson, Wyoming. The more suitable airports are those that are manned for significant portions of each day (including weekends), have good navigational aids, have an adequate length of runway, have lit runways at night, have aircraft maintenance services available, and have 24-hour fueling services available. Airports with control towers offer an additional attraction for basing aircraft operations at these locations. Another consideration is the location of the airport in relation to the normal flight operational areas, all things being equal, the airport closest to the operational area would be preferred since there will be less ferry time involved. It is recommended that if this program goes forward and seeding aircraft are utilized, that the contractor who is awarded the work has the flexibility to select the airport from which to base operations, in consultation with the funding agency.

6.10.4 Supercooled Liquid Water Observations

As mentioned in section 6.7, NAWC recommends that both a microwave radiometer and a ground-based icing rate meter be installed for one winter season. It is desirable to locate the radiometer at a location at which the temperature during storm periods is below freezing. Such a location removes the confounding effects of water droplets above the radiometer warmer than freezing being included in the observations, since these droplets are not viable targets for cloud seeding using silver iodide as the recommended seeding agent. A limited analysis of surface temperatures at Afton in Star Valley during selected storm periods that occurred during the 2001 - 2005 winter seasons was performed. The results suggest that mean storm-period temperatures at Afton are somewhat above freezing in October and April, and below freezing from November through March, as illustrated in Figure 6.21. A slightly higher elevation site would therefore be desirable.

Past experience has shown that the simplest location at which a surface based icing rate meter can be installed is one at which other weather parameters of interest (temperature, wind direction and speed and precipitation) are already being measured and recorded. A prime example of such locations is ski areas. The Pine Creek Ski Resort, located approximately seven miles east of Cokeville, is a possible site for an ice detector system. The next nearest ski area is located near Jackson. A field survey may be needed to identify a potentially useful location.

6.11 Estimates of Seeding Effects

The RFP requests estimates of the extent of the seeding effects to be realized in the target area based upon the recommended preliminary project design. We assume the use of the term "extent" applies to both a quantitative estimate of the magnitude of the seeding effect as well as the potential geographical distribution of the effect.

Developing quantitative estimates of the effects of seeding offers a challenge, but is a necessary step in order to have any hope of developing reasonable benefit/cost analyses for this project. The use of a range of potential increases in precipitation, probably expressed as percentage increases and the resultant additional quantities of precipitation (e.g. 10-15% increases amounting to an extra 1.0 to 1.5", 2.5- 3.8 cm of precipitation), may offer the best approach. The technique used to develop these quantitative estimates is described in the following section. We feel the best estimates of potential increases from winter snowfall augmentation projects can be derived from previously conducted research projects in similar geographical and climatological settings.

6.11.1 Estimated Increases Based upon the Climax Research Programs

The analysis used results from a well-known, randomized research project conducted in the Climax region of the central Colorado Rocky Mountains in two phases,

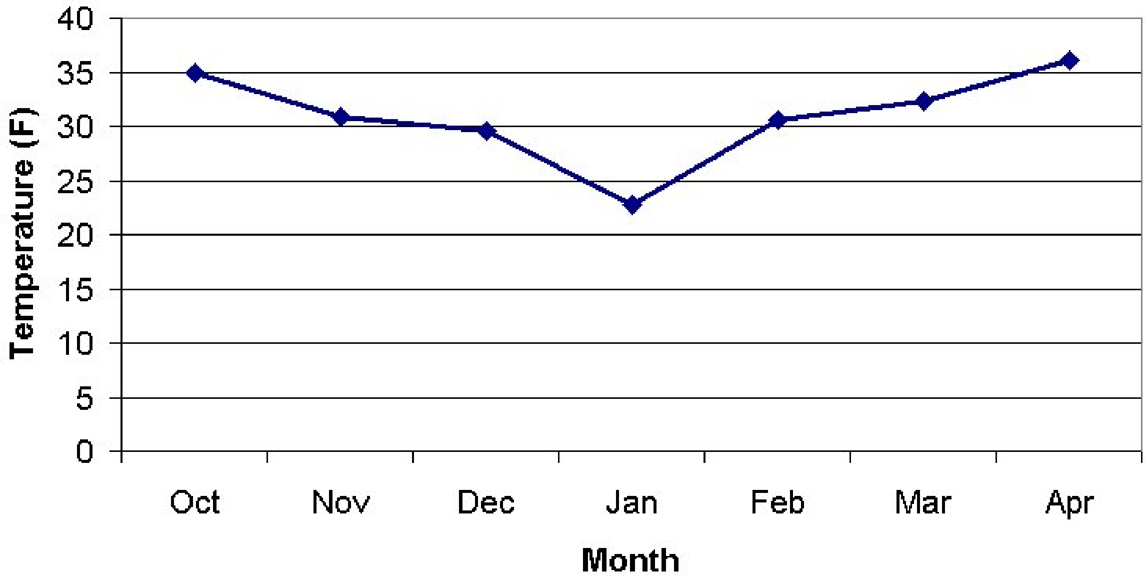

Figure 6.21 Afton Monthly Mean Surface Temperatures during Storm Periods

Climax I (1960-65) and Climax II (1965-70) (Mielke et al, 1981). These experiments utilized ground-based releases of silver iodide in 24 hour treatment periods. The detailed statistical analyses indicated that precipitation was increased by 25%-41% (depending upon whether a single or double ratio analysis was used) when 500mb (approximately 18,000 feet) temperatures were in the –4 to +12.2^0 F (-20 ^{0}C to –11^0 C). These results were statistically significant at the .05 level. Other reports on the two Climax programs indicated positive effects of seeding at 500mb temperature ranges of ~ -5.8 to –14.8^0 F (-21^0 to – 26^0 C). One report (Hess, 1974) indicated approximately 10% increases in that 500mb temperature range. This information was used to derive an estimate of the possible seeding increases in the SRWR project areas as discussed in the following.

Ten seasons (1996-2005) of SNOTEL snow water content data were compiled for four of the sites listed in Table 5-1 (Blind Bull Summit, Hams Fork, Indian Creek, and Spring Creek Divide). An event was tabulated any time one or more of these sites reported 0.2” (.5cm) or greater increase in snow water content for a 24-hour period. National Weather Service rawinsonde (weather balloon) data from Lander, Wyoming were examined to associate 500 millibar (approximately 18,000', 5.5 km) temperatures with these precipitation events. Two rawinsonde observations are available from this site daily (0500 and 1700 MST). The two 500 mb temperatures for each event day were averaged and this average was reported for the event.

Using this data set, a 25% increase (the increase indicated for this temperature range indicated by the Climax double ratio analysis) was applied to the events that had 500mb temperatures ≥ -4^0 F (-20^0 C) and 10% increases for events between –5.8 to –14.8^0 F (-20^0 and –26^0 C). These increases were averaged for the four sites and for the 10-season period. The results are expressed as a percentage of the April 1st snow water contents at each site (Table 6-4). This means that some of the lesser events (ones with only .10" (.25cm) at one of the four sites) would not contribute to differences provided in Table 6-4. This conversely assumes that all events that would naturally produce at least 0.2" (.5cm) at one of the four sites would be seedable. The average increases of the four sites on a seasonal basis vary between 11.7% and 14.4%, with absolute differences between 1.7" and 4.6" (4.3 – 11.7 cm). The ten-season average predicted increase is 13.1%, with an average absolute difference of 2.8" (6.7 cm).

An item that is implied by the results in Table 6-4 needs to be stated, which is that all storms that contribute to the snowpack observed on April 1st would be seeded to obtain the absolute values provided in the table. Figure 6.22 indicates snowpack normally begins to accumulate during the month of October at the Spring Creek Divide SNOTEL site. Therefore, in order to achieve the indicated absolute increases indicated in Table 6-4 would mean that the seeding program would operate from October 1st through March 31st. An operational season of this length may not be justified in terms of cost. As a consequence, calculations similar to those found in Table 6-2 were made for a shorter core operational period of December 1st through March 31st (Table 6-5). The average increase for this period was 11.5%, with an absolute average increase of 2.0" (5.1 cm). It appears this four-month period (December through March) would be the most productive operational period. Similar calculations were then performed for the month of November (Table 6-6). Summations of the individual storm events identified were utilized, rather than published NRCS snow water averages for November, since there is likely some melting of snow during November in some of the seasons. The resulting average snow water increase due to seeding for November was 0.5" (1.3 cm). Figure 6.22 also indicates that the snow water accumulation normally continues at the Spring Creek Divide site through mid to the latter part of April. This may mean that the operational period should extend through part or all of April. Snow melt normally begins in April, so estimates of the increases in snow water content if the program was extended into April would be low if only snow water content observations are considered. Calculations for April were therefore based on precipitation instead of snow water content to avoid this melting bias. The average absolute increase due to seeding was estimated to be 0.4" (1.0 cm). The information from Tables 6-4 through 6-6 can be combined for different periods to determine the best operational period as a function of increased precipitation versus cost. The proposed operational period will be discussed in Section 6.12.

Table 6-4
Results of 10-Year 500-mb Temperature Analysis For October-April Storm Events
BB=Blind Bull Summit, SCD=Spring Creek Divide, IC=Indian Creek, HF=Hams Fork

	BB	SCD	IC	HF	**Mean**
1995-1996	35.3	35.1	33.8	14.7	**29.7**
after seeding	40.7	39.5	38.5	16.6	**33.8**
difference	**5.4**	**4.4**	**4.7**	**1.9**	**4.1**
%	**115.3**	**112.7**	**114.0**	**113.0**	**113.8**

	BB	SCD	IC	HF	**Mean**
1996-1997	41.5	36.8	39.5	15.8	**33.4**
after seeding	47.4	41.7	44.8	17.9	**38.0**
difference	**5.9**	**4.9**	**5.3**	**2.1**	**4.6**
%	**114.2**	**113.4**	**113.5**	**113.2**	**113.6**
1997-1998	24.3	21.8	24.7	10.8	**20.4**
after seeding	27.3	24.4	27.7	11.9	**22.8**
difference	**3.0**	**2.6**	**3.0**	**1.1**	**2.4**
%	**112.3**	**111.9**	**112.1**	**110.1**	**111.8**
1998-1999	29.0	29.6	29.4	13.4	**25.4**
after seeding	33.1	33.7	33.3	15.1	**28.8**
difference	**4.1**	**4.1**	**3.9**	**1.7**	**3.4**
%	**114.3**	**113.7**	**113.3**	**112.3**	**113.5**
1999-2000	24.9	22.5	22.6	11.7	**20.4**
after seeding	28.5	25.6	25.7	13.1	**23.2**
difference	**3.6**	**3.1**	**3.1**	**1.4**	**2.8**
%	**114.6**	**113.7**	**113.7**	**111.9**	**113.7**
2000-2001	15.5	16.9	17.3	7.5	**14.3**
after seeding	17.3	18.9	19.4	8.3	**16.0**
difference	**1.8**	**2.0**	**2.1**	**0.8**	**1.7**
%	**111.4**	**111.9**	**112.0**	**111.0**	**111.7**
2001-2002	21.0	20.4	21.2	10.0	**18.2**
after seeding	24.0	22.9	23.8	11.1	**20.5**
difference	**3.0**	**2.5**	**2.6**	**1.1**	**2.3**
%	**114.2**	**112.2**	**112.5**	**110.9**	**112.7**
2002-2003	23.0	25.9	24.0	11.9	**21.2**
after seeding	26.1	29.0	26.9	13.3	**23.8**
difference	**3.1**	**3.1**	**2.9**	**1.4**	**2.6**
%	**113.5**	**112.0**	**111.9**	**111.4**	**112.3**
2003-2004	20.1	21.2	21.3	6.2	**17.2**
after seeding	22.6	23.7	23.8	6.9	**19.2**
difference	**2.5**	**2.5**	**2.5**	**0.7**	**2.0**
%	**112.3**	**111.6**	**111.6**	**111.3**	**111.8**
2004-2005	19.1	24.2	28.3	12.5	**21.0**
after seeding	21.9	27.8	32.4	14.2	**24.1**
difference	**2.8**	**3.6**	**4.1**	**1.7**	**3.0**
%	**114.6**	**114.8**	**114.6**	**113.3**	**114.4**

	BB	SCD	IC	HF	**Mean**
			10-season average		
April 1 snowpack	25.4	25.4	26.2	11.5	**22.1**
after seeding	28.9	28.7	29.6	12.8	**25.0**
difference (in)	**3.5**	**3.3**	**3.4**	**1.4**	**2.9**
S/NS ratio*	**1.139**	**1.129**	**1.131**	**1.120**	**1.131**

Table 6-5
Results of 10-Year 500-mb Temperature Analysis For December-March Storm Events
BB=Blind Bull Summit, SCD=Spring Creek Divide, IC=Indian Creek, HF=Hams Fork

	BB	SCD	IC	HF	**Mean**
1995-1996	24.1	25.3	24.4	11.5	**21.3**
after seeding	27.1	27.6	27.2	12.7	**23.6**
difference	**3.0**	**2.3**	**2.8**	**1.2**	**2.3**
%	**112.3**	**109.2**	**111.3**	**110.6**	**110.9**
1996-1997	33.6	30.1	32.0	12.2	**27.0**
after seeding	37.9	33.7	35.7	13.5	**30.2**
difference	**4.3**	**3.6**	**3.7**	**1.3**	**3.2**
%	**112.9**	**111.8**	**111.7**	**110.7**	**112.0**
1997-1998	19.9	18.2	20.5	9.5	**17.0**
after seeding	22.3	20.3	22.9	10.5	**19.0**
difference	**2.4**	**2.1**	**2.4**	**1.0**	**2.0**
%	**112.2**	**111.6**	**111.5**	**110.1**	**111.5**
1998-1999	23.0	24.5	24.3	12.1	**21.0**
after seeding	25.9	27.4	27.4	13.6	**23.6**
difference	**2.9**	**2.9**	**3.1**	**1.5**	**2.6**
%	**112.8**	**112.0**	**112.7**	**112.8**	**112.6**
1999-2000	20.3	19.3	20.5	11.0	**17.8**
after seeding	22.8	21.7	23.1	12.3	**19.9**
difference	**2.5**	**2.4**	**2.6**	**1.3**	**2.2**
%	**112.2**	**112.2**	**112.5**	**111.4**	**112.2**
2000-2001	11.0	12.1	12.1	5.7	**10.2**
after seeding	12.1	13.4	13.4	6.2	**11.3**
difference	**1.1**	**1.3**	**1.3**	**0.5**	**1.0**
%	**110.1**	**110.6**	**110.7**	**109.0**	**110.2**
2001-2002	14.6	16.0	15.8	8.4	**13.7**
after seeding	16.2	17.6	17.5	9.3	**15.2**

	BB	SCD	IC	HF	**Mean**
difference	**1.6**	**1.6**	**1.7**	**0.9**	**1.5**
%	**111.2**	**109.9**	**111.0**	**110.2**	**110.6**
2002-2003	19.1	20.9	19.0	9.1	**17.0**
after seeding	21.5	23.2	21.0	9.9	**18.9**
difference	**2.4**	**2.3**	**2.0**	**0.8**	**1.9**
%	**112.4**	**110.9**	**110.3**	**109.3**	**110.9**
2003-2004	13.5	15.1	15.3	3.5	**11.9**
after seeding	15.2	17.0	17.2	3.9	**13.3**
difference	**1.7**	**1.9**	**1.9**	**0.4**	**1.5**
%	**112.8**	**112.3**	**112.3**	**112.3**	**112.4**
2004-2005	14.4	18.5	21.1	10.0	**16.0**
after seeding	16.0	20.6	23.5	11.1	**17.8**
difference	**1.6**	**2.1**	**2.4**	**1.1**	**1.8**
%	**111.2**	**111.4**	**111.4**	**110.8**	**111.3**
			10-season average		
Dec 1 – Mar 31 snow incr	19.4	20.0	20.5	9.3	**17.3**
after seeding	21.7	22.2	22.9	10.3	**19.3**
difference (in)	**2.4**	**2.2**	**2.4**	**1.0**	**2.0**
S/NS ratio*	**1.122**	**1.112**	**1.116**	**1.108**	**1.115**

Table 6-6 Results of 10-Year 500-mb Temperature Analysis For November Storm Events; BB=Blind Bull Summit, SCD=Spring Creek Divide, IC=Indian Creek, HF=Hams Fork

	BB	SCD	IC	HF	**Mean**
1995-1996	8.8	7.3	6.6	2.6	**6.3**
after seeding	10.6	8.7	7.9	3.1	**7.6**
difference	**1.8**	**1.4**	**1.3**	**0.5**	**1.3**
%	**120.1**	**119.5**	**120.0**	**120.4**	**119.9**
1996-1997	5.8	4.4	4.3	2.2	**4.2**
after seeding	7.0	5.3	5.2	2.7	**5.1**
difference	**1.2**	**0.9**	**0.9**	**0.5**	**0.9**
%	**120.4**	**120.9**	**121.5**	**121.6**	**121.0**
1997-1998	2.5	2.3	2.4	1.2	**2.1**
after seeding	2.7	2.5	2.7	1.3	**2.3**
difference	**0.2**	**0.2**	**0.3**	**0.1**	**0.2**
%	**108.6**	**107.8**	**110.4**	**107.9**	**108.8**

	BB	SCD	IC	HF	**Mean**
1998-1999	4.9	3.8	3.5	1.2	**3.4**
after seeding	5.8	5.0	4.1	1.3	**4.0**
difference	**0.9**	**1.2**	**0.6**	**0.1**	**0.7**
%	**118.5**	**118.7**	**115.7**	**115.0**	**117.5**
1999-2000	3.9	2.7	1.7	0.7	**2.3**
after seeding	4.8	3.3	2.1	0.8	**2.8**
difference	**0.9**	**0.6**	**0.4**	**0.1**	**0.5**
%	**123.1**	**122.2**	**121.5**	**120.7**	**122.3**
2000-2001	1.9	2.3	1.8	1.3	**1.8**
after seeding	2.2	2.6	2.1	1.5	**2.1**
difference	**0.3**	**0.3**	**0.3**	**0.2**	**0.3**
%	**114.5**	**114.8**	**115.0**	**115.8**	**114.9**
2001-2002	2.6	2.1	2.5	1.5	**2.2**
after seeding	3.1	2.4	2.9	1.7	**2.6**
difference	**0.5**	**0.3**	**0.4**	**0.2**	**0.4**
%	**120.4**	**116.4**	**117.2**	**116.0**	**117.8**
2002-2003	3.0	3.3	2.4	1.6	**2.6**
after seeding	3.5	3.9	2.8	1.9	**3.0**
difference	**0.5**	**0.6**	**0.4**	**0.3**	**0.5**
%	**117.3**	**117.0**	**118.1**	**120.6**	**117.9**
2003-2004	6.0	5.8	4.8	1.7	**4.6**
after seeding	6.6	6.4	5.3	1.9	**5.0**
difference	**0.6**	**0.6**	**0.5**	**0.1**	**0.5**
%	**110.4**	**109.8**	**109.9**	**107.8**	**109.8**
2004-2005	1.2	1.1	1.3	1.0	**1.1**
after seeding	1.3	1.3	1.5	1.1	**1.3**
difference	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
%	**115.0**	**119.4**	**115.5**	**118.8**	**117.0**
			10-season average		
November precip	4.1	3.5	3.1	1.5	**3.0**
after seeding	4.8	4.1	3.7	1.7	**3.6**
difference (in)	**0.7**	**0.6**	**0.5**	**0.2**	**0.5**
S/NS ratio*	**1.175**	**1.180**	**1.167**	**1.160**	**1.173**

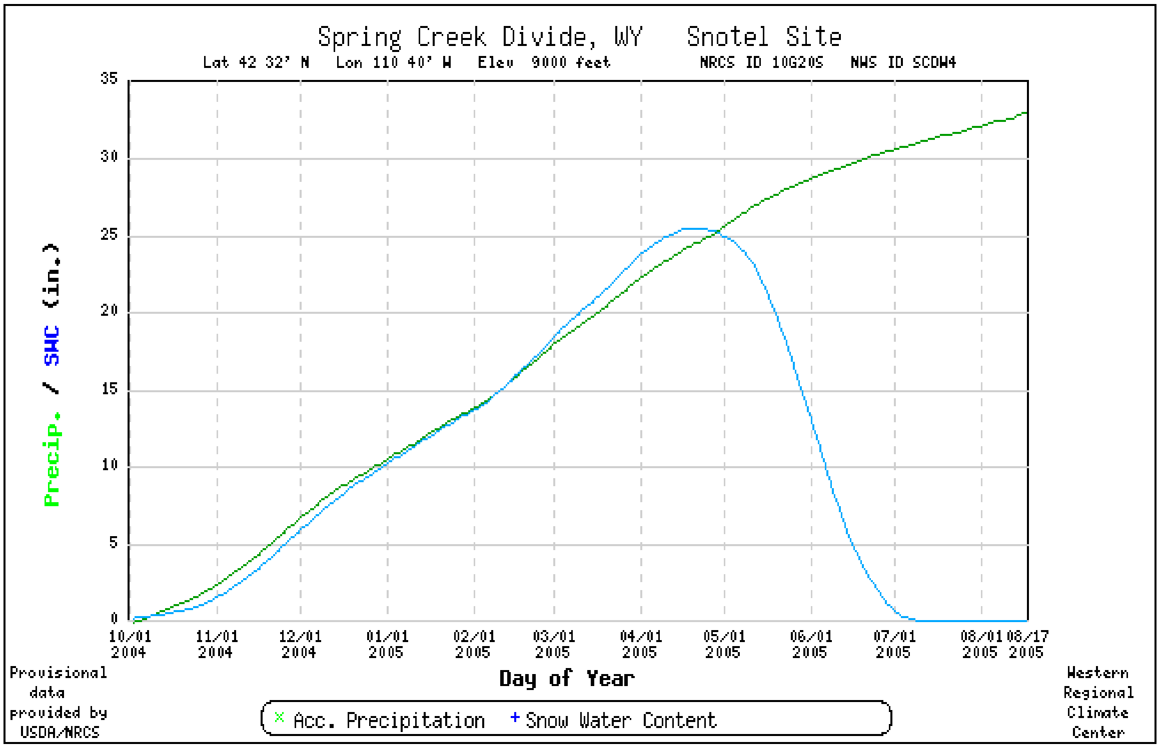

Figure 6.22 Spring Creek Divide Normal Snow Water Content (SWC) and Precipitation Accumulation

6.11.2 Modifications to the Climax Analysis

The 500-mb analysis described in 6.11.1 contains a very important assumption: that the 500-mb temperature level approximates the height of the effective cloud tops. The theory is that ice crystals produced near the tops of stratiform winter clouds may descend through the cloud and “seed” it naturally. It has been established that the natural ice nuclei in the atmosphere become increasingly active as the ambient temperatures decrease. As a consequence, clouds that have cold tops are normally naturally efficient in producing snowfall that reaches the ground. In other words, the Climax results suggest that the clouds in this area are efficient once their top temperatures reach -17^0 F (–27^0 C) or colder. Grant and Elliott (1974), when discussing the Climax research programs use of the 500 mb level to approximate cloud top heights, make the statement “Undoubtedly, this pressure height is not representative of cloud top temperatures over many other mountain barriers”.

It was decided to examine this question of whether the 500 mb height represents the cloud tops in the proposed SRWR project area. **Cloud-top temperatures were used in an alternative analysis to the 500-mb temperature evaluation**, in order to try to address the issue more directly. For each 6-hour time block in the detailed analysis, three sounding profiles were considered in an attempt to estimate the cloud top height/temperature. These include the soundings derived from the NCEP reanalysis data, which have temperature and humidity data every 100 mb, and appropriate upper-air soundings from Riverton, Wyoming and Salt Lake City, Utah. An attempt was made to estimate the cloud-top temperature for the cloud layer at or immediately above crest height of the proposed target areas. Higher cloud layers separated by significant dry layer(s) were not considered, as any precipitation would be expected to evaporate during its descent through the dry layer(s), and therefore not seed the lower layer(s). Once these estimates of cloud top heights and temperatures were completed for the four-season period (2001-2005), the results were plotted versus the associated 500 mb temperature (Figure 6.23). It is obvious from this figure that the 500-mb level is not a good approximation of cloud top temperatures for the SRWR area. It was therefore decided to focus on the use of the cloud top temperature data set to provide alternative estimates of the potential seeding increases in the Salt River and Wyoming Ranges.

Figure 6.24 illustrates the percentage of the 6-hour events that would be "seedable" (cloud top temperatures ≥ -26^0 C, –14.8^0 F) versus those that are colder than -26^0 C, –14.8^0 F. This figure indicates that a little less than 60% of the events would be classified as "seedable" according to these cloud top temperature criteria. Identification of the cloud-top temperature of the appropriate cloud layer allows an estimation of the seeding effect to be applied, based on the amount of natural nucleation expected to occur in the cloud layer. The same percentages as derived from the Colorado 500-mb study were used; that is, a 25% seeding increase (in the snow water accumulation) when cloud tops were –20^0 C, - 4^0 F or warmer, a 10% increase when cloud tops were between –20^0 and –26^{0}C, -4^0 F to –14.8^0 F) and no seeding increase for cloud top temperatures (CTT) below –26^{0}C, –14.8^0 F. **These criteria were applied to the four-season data set for the period of November through March.** The month of October was not included, since we concluded that seeding during that month would be of marginal value. This was based on the fact that the mean monthly snow water content accumulation during October averaged 2.44 inches for the proposed target area stations, less than the other months examined, and also due to the fact that 700 mb temperatures were marginal, as least for ground-based seeding, during October (refer back to Figure 5.27). April was not included since there is the likelihood of substantial snowmelt during the month and we are dealing with snow water contents in this data set. A separate analysis was made for the month of April, using precipitation data, described later in this section. An attempt was made to stratify the analysis to estimate the potential effects from three different seeding modes:

- Lower Elevation, manually operated silver iodide generators
- Higher elevation, remotely operated silver iodide generators
- Aircraft silver iodide seeding

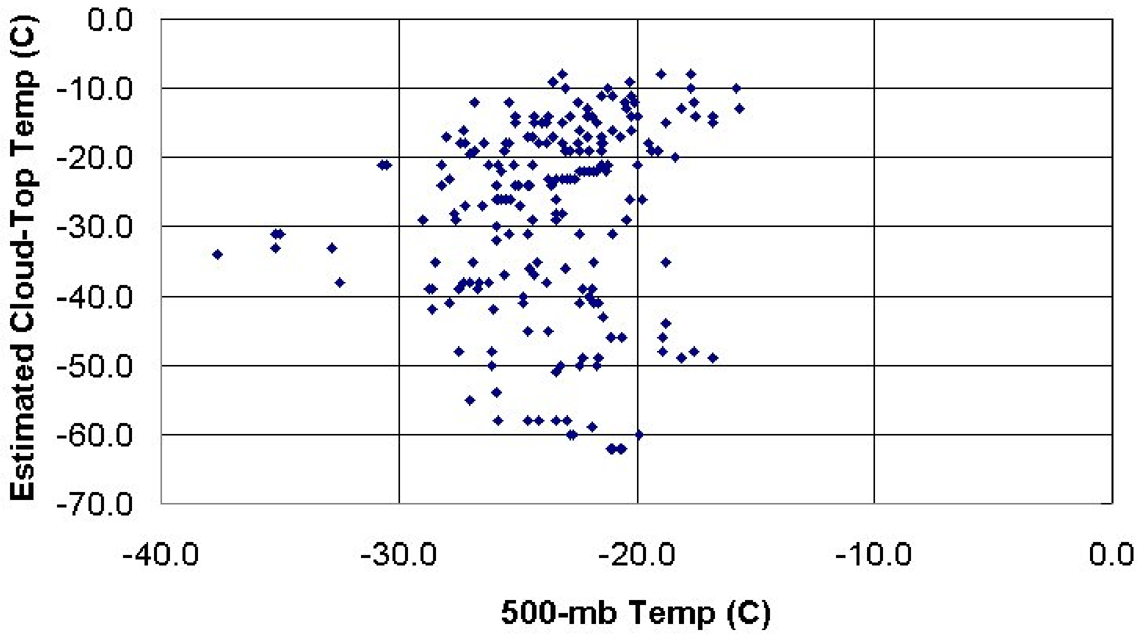

Figure 6.23 Estimated Cloud Top Temperature vs. 500-mb Temperature for Storm Periods

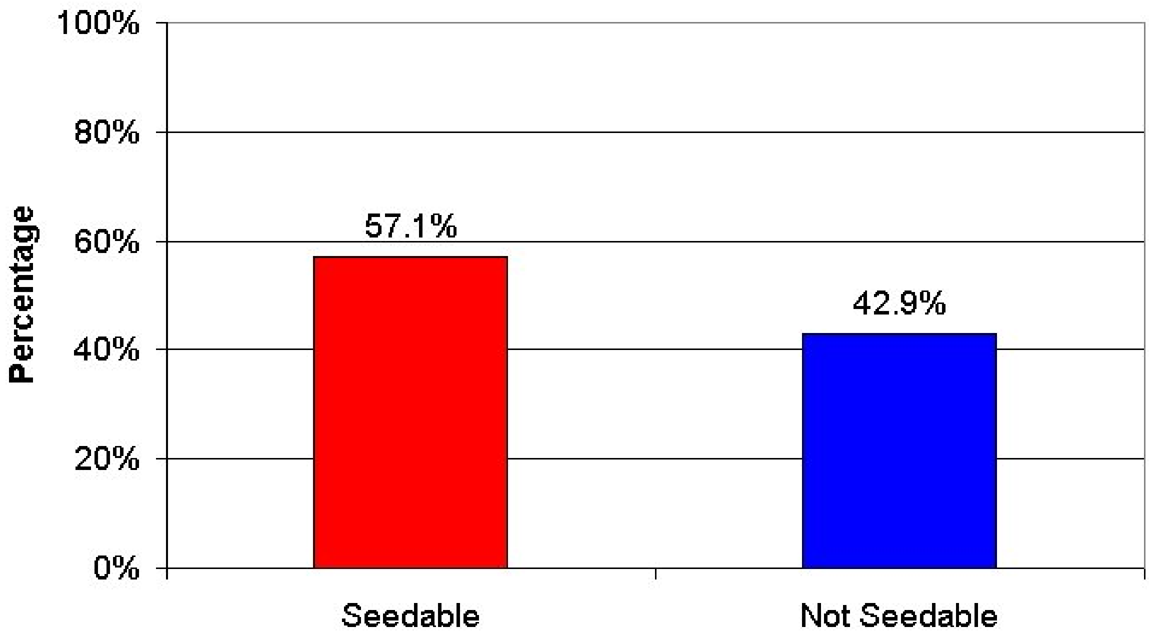

Figure 6.24 Seedability of 6-Hour Periods in Detailed Analysis

The assumptions made to accomplish this stratification were:

<u>For lower elevation manually operated silver iodide generators</u>

1. The low level atmospheric stability (surface to the 700 mb level) was neutral or slightly stable.
   The 700 mb temperature was ≤ -5^0 C, 23^0 F.

<u>For higher elevation remotely operated silver iodide generators</u>

1. The low level atmospheric stability was moderately or very stable
2. The 700 mb temperature was ≤ -5^0 C, 23^0 F.

<u>For Aircraft silver iodide seeding</u>

1. The 700 mb temperature was > -5^0 C, 23^0 F.

For this analysis, stability (between the surface and 700 mb) was determined based on both the NCEP reanalysis derived sounding data utilized in the development of climatological information (section 5.2.3) and on the National Weather Service surface temperature report at the Afton automated station (AFTY), as also discussed in Section 5.2.3.4. The stability was classified into four categories: "Neutral", "Slightly Stable", "Moderately Stable", and "Very Stable". "Neutral" means that the atmosphere was apparently well mixed between the surface and 700 mb. Transport of seeding material from lower elevation, ground based generators should be excellent under these conditions, with appropriate wind direction. "Slightly Stable" means that there was a small amount of stability, such that heating of the surface of approximately 4^0 F (2^0 C) or less would mix out the atmosphere to the 700-mb level. These are cases where seeding from ground generators would probably be successful, as the stability may be overcome by winds and other forcing mechanisms, allowing some mixing to occur. Mixing and transport of the seeding material under these conditions would vary considerably from case to case. "Moderately Stable" or "Very Stable" were used for cases where heating of more than about 4^0 F (2^0 C) would be needed at the surface to mix out the atmosphere to 700 mb. These are cases where lower elevation ground-based seeding would probably not be attempted due to stability concerns.

Because cost (i.e., benefit/cost) considerations are important to program sponsors, especially in operational cloud seeding programs, the analysis considered each seeding mode in order of their relative cost, beginning with the least costly. Accordingly, Figure 6.25 provides a plot of the estimated percentages of the storm events that would be potentially seedable from lower elevation ground generators (~ 67%) based upon the cloud top temperature, stability and 700 mb temperature criteria. In similar fashion, percentages are provided of the <u>additional</u> events that might be seeded from remote ground generators (~17 %) and those using aircraft (~16%). This is not to suggest that the effectiveness of remote generators and aircraft is limited to the percentages shown, rather, only their incremental ability to seed additional opportunities beyond the preceding seeding mode(s). Table 6-7 provides some additional information on the percentages of the cases with cloud top temperatures (CTT) ≥ -26^0 C, -14.8^0 F and those <-26^0 C, -14.8^0 F. These percentages are also provided for the three seeding modes. The

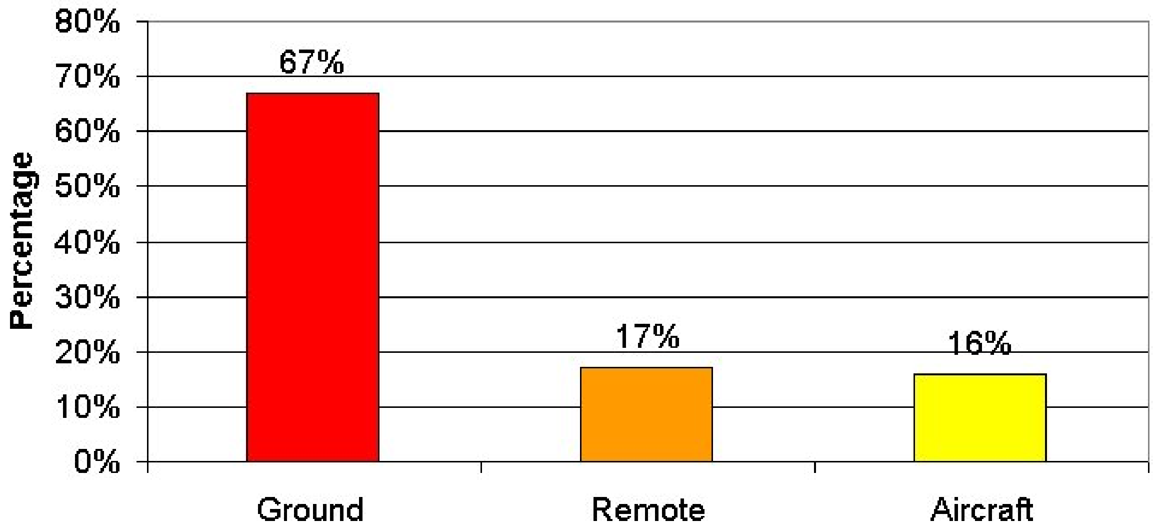

Figure 6.25 Percentage of 6-Hour Periods Considered Seedable by Ground-Based Generators, as well as Additional Percentages Gained by Supplemental Remote Generators and Aircraft

Table 6-7
November-March 6-Hour Periods

	Cloud Top Temp -26 C or warmer	Cloud Top Temp colder than -26 C	Comment
Total	100	75*	57% -26 C or warmer
Ground	67	55*	55% -26 C or warmer
Remote	17	10*	63% -26 C or warmer
Aircraft	16	10*	61% -26 C or warmer

Aircraft only	Type	Occurrences
6-hr Periods:	Single	10
(26 periods total)	2 Consecutive	1
	3 Consecutive	2
	4 Consecutive	2
	5 Consecutive	0

* Not considered seedable, but shown to represent the full data set

table also contains information on how often 6 hour events that would be deemed "seedable" occur back to back, for both aircraft-only operations and for aircraft and remote generator modes (this latter mode could be used to consider only aircraft seeding when low elevation ground seeding is not feasible). If a decision was made to utilize aircraft for the program, this information may be useful in determining whether one seeding aircraft would be adequate or if two might be needed. The data suggests the occurrence of back to back 6-hour seedable periods, when only aircraft seeding may be effective, would occur ~62% of the time. This implies that there may be a number of lost opportunities if only one seeding aircraft was utilized for the program. The concern is one of flight duration and on the ground turnaround times, which may preclude seeding in any subsequent 6-hour periods. Flight durations of perhaps 4 hours are reasonable. The time it takes to descend, land, refuel, replenish seeding supplies and climb back to the desired seeding locations and altitudes is the reason why potential seeding time is lost when events occur back to back. If only aircraft seeding were to be used without any remote generators, then back to back events may occur ~64% of the time. There is also a limitation on how frequently one pilot can fly effectively. Normally, one pilot would not be expected to fly more than two missions in any 24-hour period. Some projects have a second pilot on standby to address this concern.

There are caveats built into these estimates of seeding increases according to the different seeding modes. Some of these caveats are as follows:

- To achieve the increases using manually operated ground based generators assumes that suitable sites can be found at the proper spacing where local residents are willing to operate the equipment, and that these locations will be in the desired areas (i.e. to the southwest, west and northwest of the intended target areas). The other rather unusual nature of the proposed target areas is that they consist of two separate mountain barriers separated by an intervening river valley (Greys River) that is inaccessible in winter. As a consequence, it would need to be assumed that the plumes released upwind of the Salt River Range would affect both the Salt River and Wyoming Ranges. There is some scientific support for this assumption. The Bridger Range research program conducted in Montana (Super and Heimbach, 1983) indicated effects downwind of a first barrier over a second barrier in relatively close proximity. The distances between the crests of the two mountain barriers on the Bridger Range program are similar to those found between the Salt River and Wyoming Ranges (i.e. approximately 8-12 miles).
- To achieve the increases indicated for the remotely operated ground generators, it is assumed that suitable remote locations at the proper spacing can be found for which any needed permits might be obtained.
- To achieve the increases indicated for aircraft seeding assumes (in addition to those mentioned in the above concerning the number of aircraft and pilots) that the aircraft can be safely flown low enough so that the seeding plumes impact the regions of supercooled liquid water occurring during the storm periods. The other assumption, if only using one seeding aircraft, is that the seeding plumes will spread and merge together (in the horizontal) before they reach the supercooled liquid water regions. Deshler et al. (1990) concludes that "Achieving fairly continuous coverage along the direction of seed line advection requires seed lines to be no longer than 37 km (23 miles)."

Obviously, remote generators could be used in conditions suitable for lower elevation, manually operated generators; however, it was decided to start with the less expensive (or most economical), yet effective technology first (manually operated generators). The study indicates that remote ground-based generators would likely contribute additional seeding increases in snow water content. Likewise, aircraft seeding could be used under most conditions (an example of a situation that might not be seedable with aircraft are very shallow clouds), but our focus for any potential aircraft seeding is in situations that probably could not be effectively seeded using ground generators of either type. The potential effectiveness of each seeding mode based on the cloud top temperature criteria discussed in the above was then estimated. Recall that this estimation is based on the specific 6-hour periods selected earlier for detailed analysis. It was decided that these estimates could be applied to the longer-term April 1st snow water content averages for all of the SNOTEL target sites in the proposed target area. This step makes at least two assumptions: 1) that the four seasons selected for detailed analysis are representative of the longer period records, and 2) the estimated increases calculated for the 6 hour periods can be extrapolated to estimate seasonal increases in the April 1st water content.

The results of the November through March analysis are provided in Table 6-8, which contains data for the 12 individual target SNOTEL sites and an average for these 12 sites. Table 6-8 contains some interesting information; for example, lower elevation, manually operated silver iodide generators are predicted to produce an average ~7% increase in April 1st water content, while the use of higher elevation, remotely controlled silver iodide generators would likely add an additional estimated 1.2% increase., and the use of aircraft another ~1.75 % increase, based upon the proposed design. The resulting average increases in April 1st snow water contents are 1.53" (3.9 cm) for lower elevation ground generators, an additional 0.26" (0.7 cm) for remote ground generators, and another 0.38"(1.0 cm) if aircraft are included. The combination of the three seeding modes is predicted to result in an average of 2.17" (5.5 cm) of additional April 1st snow water content. These estimates will be used in later sections in the process of estimating: 1) increases in streamflow from the proposed SRWR target areas, 2) the value of this additional streamflow, and 3) the costs of implementing the various seeding modes and then comparing those costs to the estimated benefits, resulting in a first approximation of potential benefit/cost ratios.

Since snowmelt is a consideration during the month of April, NAWC performed an analysis similar to that above, using precipitation data from the target SNOTEL sites for the month of April. Table 6-9 summarizes the results of this analysis in the same format as used in the November through March analysis. The month of April is indicated to be a good month in terms of seeding potential (an average 16.7% increase), but the 700-mb temperatures are relatively warm. The warmer temperatures in April means that aircraft may be needed in order to realize ~ 6% of this increase potential. The use of only lower elevation ground generators is still predicted to yield approximately a 10% increase. The fact that there are fewer temperature inversions to deal with in April is a benefit to the ground-based seeding potential. The calculated average increase in precipitation from seeding during April is 0.56" (1.4 cm), with 0.21" (0.5 cm, or 38%) of this seeding potential attributed to aircraft seeding. The seeding costs and estimates of seeding potential for the month of April could be added to the November through March estimates, to determine the potential advantages of extending the seeding project and each seeding mode through the month of April.

The estimated average seasonal increases are in general agreement with evaluations that NAWC has performed on several programs within or near the vicinity of the proposed SRWR project. The results from some of these programs are summarized in Table 6-10. All of these programs have utilized only the lower elevation, silver iodide ground-based seeding mode. <u>If the results from these operational programs conducted by NAWC are reasonably accurate, then the indicated estimates from the</u>

Table 6-8
Increases in April 1 SWE based on November-March Increases for Storm Periods Using Cloud-Top Temperature Estimation

Site	April 1 Normal	Total Increase 10.0%	Ground 7.07%	Remote 1.18%	Aircraft 1.75%
Blind Bull Summit	28.3	2.82	2.00	0.33	0.49
Rowdy Creek*	21.6	2.15	1.52	0.25	0.38
Willow Creek	30.6	3.05	2.16	0.36	0.53
Triple Peak	25.2	2.52	1.78	0.30	0.44
Cottonwood Creek	24.2	2.42	1.71	0.29	0.42
Spring Creek Divide	26.9	2.69	1.90	0.32	0.47
CCC Camp*	12.7	1.27	0.90	0.15	0.22
Snider Basin	14.7	1.47	1.04	0.17	0.26
Big Park*	19.4	1.94	1.37	0.23	0.34
Indian Creek	28.2	2.81	1.99	0.33	0.49
Kelley R.S.	17.1	1.71	1.21	0.20	0.30
Hams Fork	12.0	1.20	0.85	0.14	0.21
Average	**21.74**	**2.17**	**1.53**	**0.26**	**0.38**

* Snowcourse only

Table 6-9
Increases in April Precipitation based on April Increases for Storm Periods Using Cloud-Top Temperature Estimation

Site	April Avg Precip	Total Increase 16.67%	Ground 10.08%	Remote 0.39%	Aircraft 6.20%
Blind Bull Summit	2.7	0.45	0.27	0.01	0.17
Willow Creek	5.1	0.85	0.51	0.02	0.32
Triple Peak	3.5	0.58	0.35	0.01	0.22
Cottonwood Creek	4.1	0.68	0.41	0.02	0.25
Spring Creek Divide	3.4	0.56	0.34	0.01	0.21
Snider Basin	2.2	0.37	0.22	0.01	0.14
Indian Creek	3.8	0.62	0.38	0.01	0.24
Kelley R.S.	3.0	0.50	0.30	0.01	0.19
Hams Fork	2.4	0.40	0.24	0.01	0.15
Average	**3.4**	**0.56**	**0.34**	**0.01**	**0.21**

Table 6-10
Results of Programs in the Vicinity of the Proposed Project

Project Area	Water Years of Operation	Estimated Increases in Apr.1 Water Content
Smith and Thomas Forks, ID and WY	1954-1970,1979-1982,1989-1990	11%
Eastern Box Elder & Cache Counties, UT	1989-2005	11.5%
Western Box Elder County, UT	1989-1997, 2000-2001, 2004-2005	14%
South Slopes Uinta Mountains, UT	2003-2005	11%

analyses shown in the current feasibility study for the SRWR area are perhaps a little on the conservative side.

This range of potential seeding increases is supported by a World Meteorological Statement on cloud seeding capabilities. The 1992 Policy Statement of the World Meteorological Organization (WMO) on winter orographic clouds states:

> *"In our present state of knowledge, it is considered that the glaciogenic seeding of clouds or cloud systems either formed, or stimulated in development, by air flowing over mountains offers the best prospects for increasing precipitation in an economically viable manner. These types of clouds attract great interest in modifying them because of their potential in terms of water management, i.e., the possibility of storing water in reservoirs or in the snowpack of higher elevation. Numerous research and operational projects conducted since the beginning of weather modification as a science provide the evidence. Statistical analyses suggest seasonal increases (usually over the winter/spring period) on the order of 10 to 15% in certain project areas."*

Other capability statements from the Weather Modification Association and the American Meteorological Association provide estimates of seeding increases in a similar range (e.g., 10-15%) in winter orographic conditions.

We recommend that the estimated seeding increases for the cloud top temperature analysis (not the 500mb analysis) be used to estimate the potential additional streamflow that might be derived from the conduct of a program (specifically, data contained in Tables 6-8 and 6-9). These estimates are provided in Section 12 of this report.

6.12 Summary of Recommended Design

The proposed design for the Salt River/Wyoming Range (SRWR) program can be summarized as follows:

- The target area will be those areas in Sublette and Lincoln Counties that lie above 8,000 feet (2.4 km) encompassing approximately 3,590 square miles.
- The operational period will be November through March. Seeding operations could be effectively extended into April especially if a seeding aircraft were used on the program although ground based seeding would still be effective as well.
- Silver iodide will be the seeding agent.
- A core program of lower elevation ground based generators is recommended. This core program could be supplemented by higher elevation remotely controlled ground based generators and a seeding aircraft equipped with two acetone/silver iodide generators if the estimated benefits are a multiple of the estimated costs to utilize these additional seeding modes. As a cost saving measure if needed, one of the supplemental seeding modes could be selected in combination with lower elevation ground based generators, considering any advantages of one supplemental seeding mode over the other (e.g., aircraft seeding would not require special use permits from entities like the U.S. Forest Service).
- Seeding suspension criteria will be followed with primary emphasis on percent of normal snowpack values and avalanche concerns.
- One winter season of data collection is proposed prior to the beginning of the full operational SRWR seeding program. Data would be collected via rawinsonde observations, icing rate meter observations and radiometer observations of liquid and vapor.
- The SRWR program would be an operationally oriented one with the following goals: **The stated goal of the program is to increase winter snowpack in the target areas to provide additional spring and summer streamflow and recharge under-ground aquifers at a favorable benefit/cost ratio (e.g. 5/1 or greater), without the creation of any significant negative environmental impacts.**
- Due to the operational nature of the proposed program, the seeding decisions would not be randomized. In addition, there would not be a research component built into the program, although "piggyback" research components could be added to the core operational program should interest and additional funding from other sources be present. For example, the type of research that resulted from write-in funding to the Bureau of Reclamation for the recent Weather Damage Mitigation Program.
- Evaluations of the effectiveness of the cloud seeding program would be based upon historical target and control techniques (target and control sites with corresponding regression equations are provided in this report) and some snow chemistry analyses verifying that silver above background levels is being observed at various sampling points in the target areas.

7.0 ESTABLISHMENT OF OPERATIONAL CRITERIA

Preliminary operational criteria were developed that contain the protocols and procedures necessary to operate the projects within established guidelines as set forth by the American Society of Civil Engineers (ASCE).

Some of the more important considerations include opportunity recognition, communication of seeding decisions, monitoring of meteorological and hydrological conditions for possible suspension of seeding activities, conformance with applicable regulations, and informing interested parties regarding the conduct of seeding activities. Regarding opportunity recognition, operators typically develop a table of conditions (criteria) that must be met to determine that a given storm situation is “seedable”. Table 7-1 provides an example.

7.1 Opportunity Recognition Criteria

For the proposed SRWR project seeding criteria were developed to serve as opportunity recognition tools. Basically, these criteria have been designed to recognize the combination of weather events deemed to be “seedable”. These criteria have been broken down into three different categories based upon the seeding mode to be used (ground based, low-elevation, manually operated generators; high elevation, remotely operated generators; and, aircraft). The criteria are listed in Tables 7-1 through 7-3.

7.2 Communications of Seeding Decisions

The means by which seeding decisions are communicated/implemented will be a function of the type(s) of seeding methodology employed (e.g. for manually operated ground generators; telephone calls). Remotely controlled generators typically utilize cellular or satellite phones for communications. Aircraft seeding typically involves locating a project office at a suitable airport near the project area. One or more project meteorologists man this office. The pilot(s) of the seeding aircraft are also based at this office. Communications regarding aircraft missions are therefore conducted prior to take-off. Communications continue between the meteorologist and pilot via VHF or UHF radios.

Table 7-1
Opportunity Recognition Criteria for
Lower Elevation Manually Operated Ground-Based Generators

1. Cloud top temperatures expected to be $\geq - 26^0$ C.
2. 700 mb level temperatures expected to be $\leq - 5^0$ C.
3. Low level temperature profile from the surface to 700 mb expected to be no more than slightly stable
4. Low-level wind directions expected to be favorable for the transport of the seeding material over the target barrier(s).
5. Cloud bases expected to be at or below target barrier crest height.

Table 7-2
Opportunity Recognition Criteria for
Higher Elevation Remotely Operated Ground-Based Generators

1. Cloud top temperatures expected to be ≥ - 26^0 C.
2. 700 mb level temperatures expected to be ≤ - 5^0 C.
3. Low-level temperature profile from the surface to 700 mb expected to be moderate to very stable.
4. Low-level wind directions expected to be favorable for the transport of the seeding material over the target barrier(s).
5. Cloud bases expected to be at or below target barrier crest height.

Table 7-3
Opportunity Recognition Criteria for
Aircraft Seeding

1. Cloud top temperatures expected to be ≥ - 26^0 C.
2. 700 mb level temperatures expected to be ≥ - 5^0 C.
3. Mid-Level wind directions expected to be favorable for the transport of the seeding material over the target barrier(s).
4. Cloud bases expected to be at or below target barrier crest height.

7.3 Seeding Suspensions

Seeding suspension criteria will be developed for each of the project areas. The primary concern will be suspension of seeding whenever flash flooding may occur during or following stormy periods (typically based upon issuance of such warnings by the local National Weather Service offices), or if unacceptably high streamflows may be produced during the spring snowmelt periods. These latter suspensions are typically based upon a sliding temporal scale of percent of normal values of higher elevation snow water contents. Suspension criteria have been established for several winter programs in areas of the west, which are climatologically similar to the SRWR area.

Certain situations require suspension criteria to minimize either an actual or apparent contribution of seeding to a potentially hazardous situation. The ability to forecast and avoid hazardous conditions is very important in limiting liability associated with weather modification and to maintain a desirable public image.

There are five hazardous situations around which suspension criteria have been developed. These are:

1. Excess snowpack accumulation
2. Rain and/or snowmelt-induced winter flooding
3. Severe weather

4. Avalanches
5. Special conditions such as recent burn areas

7.3.1 Excess Snowpack Accumulation

Snowpack begins to accumulate in the mountainous areas of Wyoming in October and continues through April. The heaviest average accumulations normally occur from January through March. Excessive snowpack becomes a potential hazard because of the potential for excess snowmelt. The Natural Resources Conservation Service (NRCS) maintains a network of high elevation snow measurement sites in the State of Wyoming, known as SNOTEL. SNOTEL observations are routinely updated at least several times per day. The following set of recommended criteria, based upon these SNOTEL site observations, has been developed as a guide for suspension of operations.

a. 200 % of average on January 1st
b. 180 % of average on February 1st
c. 160 % of average on March 1st
d. 150 % of average on April 1st

Table 7- 4 contains the average 1971 – 2000 snow water contents in inches for the ten SNOTEL sites that are located in the proposed target areas. The averages for the ten sites would be used to consider whether the above suspension criteria have been exceeded. For example, if the average snow water content (of the various SNOTEL sites) on February 1st of a particular season is 23.0" (58 cm) and the long-term February 1 average is 14.3", then the suspension point would be 14.3" x 1.80 = 25.7" (65 cm), so the seeding would not be suspended based upon this criteria. Since SNOTEL observations are available on a daily basis, suspensions (and cancellation of suspensions) can be made on a daily basis using linear interpolation of the first of month criteria. The two target area snow course sites were not included in these criteria, since data from these sites are only available on a monthly basis.

Table 7-4 Monthly Target Area SNOTEL Snow Water Content Normals (1971-2000)

Site	Jan 1	Feb 1	Mar 1	Apr 1
Blind Bull Summit	13.2	18.4	23.1	28.3
Cottonwood Cr.	9.7	14.2	18.5	24.2
Hams Fork	5.5	8.4	11.0	12.0
Indian Creek	12.5	17.6	22.3	28.2
Kelley R.S.	7.6	10.7	14.0	17.1
Salt R. Summit	5.4	9.2	12.2	14.6
Snider Basin	6.9	9.8	12.4	14.7
Spring Cr. Divide	12.5	17.4	22.2	26.9
Triple Peak	11.9	16.6	20.9	25.2

Willow Creek	14.3	20.2	25.4	30.6
Average	**10.0**	**14.3**	**18.2**	**22.2**

Streamflow forecasts, reservoir storage levels, soil moisture content and amounts of precipitation in prior seasons are other factors which need to be considered when suspending seeding operations.

7.3.2. Rain-induced Winter Floods

There is the potential for wintertime flooding from excessive rainfall, particularly on top of low elevation snowpack. Every precaution must be taken to ensure accurate forecasting and timely suspension of operations during these potential flooding situations. The objective of suspension under these conditions is to eliminate the real and avoid any perceived impact of weather modification when any increase in precipitation has the potential of creating a flood hazard.

7.3.3 Severe Weather

During periods of hazardous weather phenomena associated with both winter orographic and convective precipitation systems, it is sometimes necessary or advisable for the National Weather Service (NWS) to issue special weather bulletins advising the public of the weather phenomena. Each phenomenon is described in terms of criteria used by the NWS in issuing special weather bulletins. Those of concern in the conduct of winter cloud seeding programs include:

- **Snow Advisory** - This is issued by the NWS when 4-12 inches of snow in 12 hours or 6-18 inches (15 – 46 cm) in 24 hours in mountainous regions above 7,000 feet (2.1 km) are forecast. Lower threshold criteria (in terms of the number of inches of snow) are issued for valleys and mountain valleys below 7,000 feet (2.1 km).

- **Heavy Snow Warning** - This is issued by the NWS when it expects snow accumulations of twelve inches (30 cm) or more per 12-hour period or eighteen inches or more per 24-hour period in mountainous areas above 7,000 feet (2.1 km). Lower criteria are used for valleys and mountain valleys below 7,000 feet (2.1 km).

- **Winter Storm Warning** - This is issued by the NWS when it expects heavy snow warning criteria to be met along with strong winds/wind chill or freezing precipitation.

- **Flash Flood Warning** - This is issued by the NWS when flash flooding is imminent or in progress. In the intermountain west, these warnings are generally issued relative to, but not limited to, fall or spring convective systems.

Seeding operations may be temporarily suspended whenever the NWS issues a weather warning for or adjacent to any target area. Since the objective of the cloud seeding program is to increase winter snowfall in the mountainous areas of the state, operations will typically not be suspended when Heavy Snow or Winter Storm Warnings are issued unless there are special considerations.

Flash Flood Warnings are usually issued when intense convective activity causing heavy rainfall is expected or occurring. Although the probability of this situation occurring during operational seeding periods is low, the potential does exist, particularly during the spring months. The type of storm that may cause problems is one that has the potential of producing 1-2 inches (2.5 – 5 cm) or greater of rainfall in approximately a 24-hour period with high freezing levels (e.g. > 8,000 feet, 2.4 km) MSL). Seeding operations should be suspended for the duration of the warning in these cases.

7.3.4 Avalanches

The Bridger-Teton National Forest has a daily Backcountry Avalanche Hazard and Weather Forecast, which is available via the internet at www.jhavalanche.org. The forecast of interest is issued for the Southwest Trails/Greys River Area. There are five hazard categories used in these forecasts which are as follows:

Low:	Mostly stable snow exists. Avalanches are unlikely except in isolated pockets.
Moderate:	Areas of unstable snow exist. Human triggered avalanches are possible. Larger triggers may be necessary as the snowpack becomes more stable. Use caution.
Considerable:	Dangerous unstable slabs exist on steep terrain on certain aspects. Human triggered avalanches probable. Natural avalanches are possible.
High:	Mostly unstable snow exists on a variety of aspects and slope angles. Natural avalanches are likely. Travel in avalanche terrain is not recommended.
Extreme:	Widespread areas of unstable snow exist and avalanches are certain on some slopes. Backcountry travel should be avoided.

As discussed in section 8.3 of this report, temporary seeding suspensions based upon avalanche warnings would occur when a day is rated in either the Extreme or High category.

7.4 Communications of Seeding Activities

Arrangements may be made to communicate seeding decisions in real-time to the interested parties (e.g., project sponsors) utilizing an internet site to post activities. More often summaries of seeding activities are provided on a weekly, bi-weekly or monthly basis via written reports.

8.0 ENVIRONMENTAL CONSEQUENCES AND LEGAL IMPLICATIONS

There are a number of issues related to the conduct of a cloud seeding program that are concerned with potentially negative impacts from the seeding program on the environment or upon residents in and downwind of the region of the cloud seeding operations. A summary of what is known associated with those items of particular concern is provided in the following.

8.1 Downwind Effects

Perhaps the most frequently asked question regarding the possible establishment of a cloud seeding program in an area that has not been involved in previous cloud seeding programs is "Won't you be robbing Peter to pay Paul if you conduct a cloud seeding program in this area?" In other words, won't areas downwind of the intended target area experience less precipitation during the seeded periods? The perhaps surprising answer to this question is "no." This answer is based upon analysis of precipitation in areas downwind of research and operationally oriented cloud seeding programs. In a review paper on this topic, Long (2001) provides information from a variety of both winter and summer programs. One winter research program that is perhaps most relevant to wintertime programs was one conducted by Colorado State University scientists in the Climax, Colorado area. This area is located in a mountainous area located in the central Colorado Rockies. This randomized seeding program was conducted in two phases that came to be known as Climax I and Climax II. Quoting from Long (2001), "Janssen, Meltsen and Grant (1974) investigated downwind effects of the Climax I and II projects. They noted that their investigation was post hoc and as such was exploratory rather than confirmatory. In order to detect downwind precipitation effects drifting from the Climax target area various time lags ranging from 3 to 187 hours of precipitation data from hourly stations in downwind locales were considered. Significant ratios of seeded to not-seeded precipitation, with low probabilities of being due to chance, were found downwind east and northeast of the Climax area. These ratios were in the range of 1.15 to 1.25 during the 3-12 hour time lag period." This suggests **increases** in precipitation on the order of 15-25% downwind of the intended target area. Long makes a summary statement in his paper as follows: "Downwind precipitation effects have been observed in geographic areas and time frames that are about the same magnitude as primary effects intended for the target area. There is little evidence of a decrease in precipitation outside the target area."

An example of an analysis of potential downwind effects from an operational winter program is found in Solak, et al, (2003). This paper examined the precipitation that fell in areas located in eastern and southeastern Utah and western Colorado located downwind of a long-term winter program that has been conducted most winters since 1974 in the central and southern Wasatch Mountains of Utah. The abstract from this paper is as follows: "Estimations of effects on precipitation downwind of a long-standing operational snowpack augmentation project in Utah are made, using an adaptation of the historical target/control regression technique which has been used to estimate the seasonal effects over more than twenty seasons within the project's target area. Target area analyses of December-March high elevation precipitation data for this project indicate an overall seasonal increase of about 14%. Estimations of downwind effects are made for distance bands downwind as far as 150 miles. The downwind analyses indicate increases of similar magnitude to those for the target, expressed as percentages or ratio values, extending to about 100 miles downwind. Beyond 100 miles the ratio values decay, reaching about 1.0 (e.g., no effect) at about 125 miles. Expressed as average-depth precipitation amounts, the target area precipitation difference is about 1.4 inches of additional water, while the values within downwind distance bands range from 0.4 to 0.25 inches, reaching zero at about 125 miles."

8.2 Toxicity of Seeding Agents

By far the most common seeding agent in use today on winter orographic cloud seeding programs is silver iodide. The potential environmental impacts of silver iodide have been studied extensively. Klein (1978) in a book entitled "Environmental Impacts of Artificial Ice Nucleating Agents" concludes that "The major environmental concerns about nucleating agents (effects on plant growth, game animals, and fish, etc.) appear to represent negligible environmental hazards. The more subtle potential effects of silver-based nucleating agents, such as their possible ability to potentiate the movement or effects of other materials of environmental concern, or to influence the activity of microorganisms in soils and aquatic environments after being bioconcentrated by plants, warrant continued research and monitoring. Effects, if they occur, are not expected to involve unacceptable risks. The long-term use of silver iodide and the confidence which the weather modification profession has in delivery systems and in the efficacy of this material, make it unlikely that other agents, with the exception of dry ice, will be used on a large scale, unless there are improvements in delivery systems and major changes in the economics of silver availability." In the same book a summary of potential impacts on humans is as follows: "The effects on humans of ingestion or topical contact with silver iodide used in cloud seeding can be considered negligible. Decade-long observations of cases (unrelated to cloud seeding) of ingestion of large silver doses revealed no physiological concern. In addition, surveys of seeding generator operators who have had long-term intensive contact with silver iodide reveal that they have not experienced medical difficulties."

A report prepared by Tom Ryan (Ryan, 2005) of the Metropolitan Water District of Southern California contains the following summary on the topic of possible toxicity of silver iodide:

> "*There has been a concern about the toxicity of the most common cloud seeding material, silver iodide (AgI) on the environment. The typical concentration of silver in rainwater or snow from a seeded cloud is less than 0.1 micrograms per liter. The Environmental Protection Agency recommends that the concentration of silver in drinking water not exceed 0.10 milligrams per liter of water. Many regions have much higher concentrations of silver in the soil than are found in seeded clouds. Industry emits 100 times as much silver into the atmosphere in many parts of the country, and silver from seeding is far exceeded*

by individual exposure from tooth fillings. The concentration of iodine in iodized salt used on food is far above the concentration found in rainwater from a seeded storm. No significant environmental effects have been noted around operational projects, many of which have been in operation for 30 to 40 years (WMA, 1996)."

The concentration of silver in rainwater or snow from a seeded cloud using the above information is on the order of 1000 times less than the EPA Standard.

8.3 Avalanche Considerations

Avalanche hazard is a factor worth consideration due to the amount of back country recreational activity in the project area. The Greys River Ranger District, Big Piney, and Kemmerer, within the Bridger-Teton National Forest contains trails for snowmobiling, cross country skiing and snowshoeing, primarily in the elevations ranging from 6,000 feet to 8,000 feet.

Regional avalanche conditions within the Bridger-Teton National Forest during the winter months are monitored by a group of ski area and back country specialists in a cooperative effort organized through the U.S. Forest Service. Conditions are assessed daily and reported to a central location from which daily (morning) advisories are issued. The information is readily available via the internet in the form of a *Backcountry Avalanche Hazard & Weather Forecast* which can be accessed at www.jhavalanche.org. This product is issued for each of three regions within the overall Bridger-Teton National Forest. The project area is located within the Southwest Trails/Greys River Area, which includes the Salt River and Wyoming Ranges.

The organization's daily product consists of a weather summary for the preceding 24-hr period, mountain weather forecasts for the current day and three days, and a General Avalanche Advisory. That advisory includes an avalanche hazard rating within a range of five levels of hazard. During the latter portion of the winter season, when more spring-like conditions can occur, separate hazard ratings are shown for morning and afternoon. The five hazard categories and their published definitions are shown here.

Low:	Mostly stable snow exists. Avalanches are unlikely except in isolated pockets.
Moderate:	Areas of unstable snow exist. Human triggered avalanches are possible. Larger triggers may be necessary as the snowpack becomes more stable. Use caution.
Considerable:	Dangerous unstable slabs exist on steep terrain on certain aspects. Human triggered avalanches probable. Natural avalanches possible.

High:	Mostly unstable snow exists on a variety of aspects and slope angles. Natural avalanches are likely. Travel in avalanche terrain is not recommended.
Extreme:	Widespread areas of unstable snow exist and avalanches are certain on some slopes. Backcountry travel should be avoided.

The organization's web site includes archives of the daily advisories. Daily data from the archive for two recent winter seasons were tabulated, noting the highest hazard category shown for each of 312 total days. The season and average proportion of days within each category are shown in Table 8-1.

Table 8-1 Avalanche Advisories for the 2001-2002 and 2002-2003 Winter Seasons

Hazard Cat.	2001-2002	2002-2003	Total	Percentage
Extreme	0	0	0	0%
High	10	14	24	8%
Considerable	45	58	103	33%
Moderate	67	60	127	40%
Low	28	30	58	19%

<u>Seeding Suspension Considerations</u>

The information contained in the daily advisories appears to be adequately objective and consistently provided to be of use in suspension considerations. From the language in the category definitions, it would seem that days rated as in the Extreme or High categories should trigger a temporary seeding suspension.

8.4 Snow Removal

Some have questioned what the associated costs are related to the removal of snow that is created by winter cloud seeding programs. This topic was addressed in a couple of studies. One such study was performed by the Colorado Department of Natural Resources (Sherretz and Loehr, 1983). The conclusions from this study are as follows:

> "*Simulating the effects of cloud seeding on the costs of snow removal indicates that the costs do increase when recorded snow amounts, in approximately one-third of the storms in selected winters, are augmented by 25 percent. The increases in costs range from 0.8 percent to 12.6 percent in the counties studied. Average increases are 6.1 percent in winters of high and average snowfall, and 4.9 percent in winters of low snowfall. Costs in winters of low snowfall average 81 percent of costs in winters of average snowfall, while costs in winters of high snowfall average 141 percent of costs in winters of average snowfall. These variations of 19 percent and 41 percent indicate that*

costs generally change more with natural variations in seasonal snowfall than with augmentation.

Actual effects of cloud seeding on the costs of removing snow cannot be determined definitively, however, until more accurate records of employee and equipment expenses are available and until atmospheric scientists determine if, and by how much, seeding can increase snowfall. Recommendations for record-keeping include daily accounting of the hours employees spend performing removal tasks, hours machines are used, maintenance costs and fuel consumption."

The Bureau of Reclamation supported contractors that designed and conducted a winter cloud seeding research program in the American River Basin of the northern Sierra Nevada Mountains of California. This program was known as the Sierra Cooperative Pilot Project (SCPP). The SCPP preliminary studies included assessments of the effect of the project upon highway use, safety, and operation and maintenance costs.

A California Department of Transportation (CALTRANS) memorandum report (CALTRANS, 1976) discussed socio-environmental effects that might occur. The study considered:

1) The effect if accumulated snowpack were increased up to 15 percent per annum in normal or below-normal years
2) Manpower and equipment requirements for snow removal per year and per storm under historical conditions
3) The costs for dry, average, and wet years

The report noted that avalanche control has been required only on Route 50 in El Dorado County between Echo Summit and Meyers. No substantive correlation was found between an incremental storm increase and the cost of highway avalanche control.

The study found little direct relationship to increased costs for small incremental changes in storm size because of the amount of equipment and manpower necessary to maintain a traversable roadway under frost conditions or handle the problems of freeze-thaw of snowbanks adjacent to the roadway which cause icy conditions. Also, road closures are more frequently caused by blowing and drifting snow or severe icing conditions rather than the amount of snowfall.

Existing recorded data do not allow an analysis of costs involved in snow removal for small incremental increases in precipitation. However, data are available for maintenance costs related to storm severity.

8.5 Delay of Snowmelt

One concern formerly mentioned in conjunction with cloud seeding programs in the west was whether the increases in snow due to cloud seeding would extend the snow melt period. This concern was voiced by ranchers having grazing rights in some of the targeted areas who questioned if the cloud seeding would delay their moving of livestock into these areas in the springtime. This topic was addressed in an environmental study conducted in the Uinta Mountains of Utah which was funded by the Bureau of Reclamation offices in Denver (Harper, 1981). The conclusion reached in this study was that "An increase of 10% in the average snowpack is estimated to retard the 75% snow-free date 0.7 – 1.5 days." In other words this should not be a significant concern.

8.6 General Statements on the Potential Environmental Impacts of Winter Cloud Seeding

A large number of studies have been conducted in the western United States related to the potential environmental impacts of winter cloud seeding. Most of these studies were funded under the Bureau of Reclamation's "Skywater Program". Four programs of note concerned with wintertime programs were:

- Potential Ecological Impacts of Snowpack Augmentation in the Uinta Mountains, Utah. A 1981 report from Brigham Young University authored by Kimball Harper (Harper, 1981) summarizing the results of a four year study.
- Ecological Impacts of Snowpack Augmentation in the San Juan Mountains, Colorado. A 1976 report edited by Harold Steinhoff (Colorado State University) and Jack Ives (University of Colorado) summarizing the results of a five year study (Steinhoff and Ives, 1976).
- The Medicine Bow Ecology Project. A 1975 report on studies conducted in the Medicine Bow Mountains of southern Wyoming (Knight et al**,** 1975).
- The Sierra Ecology Study. A five-volume report summarizing work on possible impacts on the American River Drainage in California (Smith, et al, 1980) (Berg, et al, 1980).

In general, the findings from these studies were that significant environmental effects due to the possible conduct of cloud seeding programs in these areas were not expected to occur. A couple of examples that support this conclusion are as follows:
A statement made in the final report on the San Juan Mountains program (Steinhoff and Ives, 1976): "The results of the San Juan Ecology Project suggest that there should be no immediate, large-scale impacts on the terrestrial ecosystems of these mountains following an addition of up to 30 percent of the normal snowpack, but with no addition to maximum snowpacks. Further, much of the work reported here suggests that compensating mechanisms within the study's ecosystems are such that any impacts would be buffered, at least for short periods of time, and of lesser magnitude than the changes in snow conditions required to produce them."

The Bureau of Reclamation published an "Environmental Assessment and Finding of No Significant Impact (Harris, 1981) for the Sierra Cooperative Pilot Project. Quoting from the introduction of this report:

"*This document and the project environmental assessment serve as the basis for determination that no further action is necessary to comply with the National Environmental Policy Act of 1969 (Public Law 91-190) for the following reasons:*

1) *The Sierra Cooperative Pilot Project Environmental Assessment examines a research program designed to seed, on a randomized basis, some of the cloud types which occur within winter storms in the Sierra Nevada of California and Nevada. The increase in annual precipitation expected from seeding all eligible storms during an average or less-than-average year would be 10 to 15 percent. The annual precipitation increase expected from randomized seeding of selected cloud types would be 5 to 7.5 percent. The report analyzes the potential effect of these increases upon weather elements, hydrologic and physiographic phenomena, plant and animal communities, the human environment, and land and water resource use in the project area. It also discusses possible impacts of the seeding agents, dry ice and silver iodide. The report concludes the research program will not result in significant or adverse effects upon the environment.*
2) *Consultation with Federal and State agencies has resulted in the determination that this project will not affect endangered or threatened species of plants or wildlife or their habitats in a significant or adverse manner.*
3) *Archeological and historic sites and sites of extraordinary aesthetic value will not be significantly or adversely affected by the project.*
4) *Project activities and resultant increases in precipitation will not affect the human environment, lifestyle, or existing land and water resource use in a significant or adverse manner. The project design includes suspension criteria to prevent operations during periods that would lead to public safety hazards."*

8.7 Legal Implications

There are legal implications associated with the conduct of cloud seeding programs. For example, who owns any additional water produced from cloud seeding activities? Most state regulations claim ownership of these waters remain with the state to be distributed according to the existing water rights in the area. There are permitting and reporting requirements normally associated with the performance of cloud seeding programs. There would be both state and national requirements associated with the SRWR program. These requirements are summarized in Section 9.

Another possible legal consideration is what exposure the program sponsors have regarding legal responsibility for any perceived damages caused by the seeding activities. For example, if seeding was conducted and a flood occurred in or near the program's target area, would the sponsors be liable? Such situations are sometimes referred to as the possible "consequential effects" of cloud seeding. The first line of defense in such circumstances is to have adequate safeguards built into the design of the seeding program to suspend seeding operations in questionable circumstances (as discussed in Section 7.3). A few lawsuits have been filed over the years claiming damages caused by cloud seeding programs. According to ASCE Manual No. 81 (2006): “Defendants have won almost all liability suits.” The primary reason for this outcome is that the burden of proof falls upon the plaintiffs to prove the cloud seeding activities caused or contributed to the damages.

Some weather modification operators also carry a special type of insurance commonly known as “consequential effects of cloud seeding liability insurance.” This insurance protects both the operator and sponsors of insured programs.

9.0 PERMITTING AND REPORTING

There will be some permitting and reporting requirements associated with the conduct of the SRWR cloud seeding program should the decision be made to proceed to an operational phase based upon this preliminary design work.

9.1 State of Wyoming Permit Requirements

The Wyoming Statutes 9-1-905 to 9-1-907 adopted in 1977 deals with legislative declarations concerning weather modification, definition of weather modification and weather modification permit requirements. These regulations are administered by the Wyoming State Engineer's office.

The 9-1-907 statute dealing with weather modification permits is worded as follows:

"(a) It is unlawful for anyone to engage in weather modification activities except by permit prescribed and issued by the state engineer.

(b) A separate permit shall be issued for each experiment or activity. Permits are revocable by the state engineer. Permits are to be issued for one (1) year from October of one year to September of the following year. A fee of twenty-five ($25.00) shall be charged for each permit issued or renewed. Fees received by the state engineer shall be deposited with the state treasurer to be placed into the general fund. A permit by the state engineer shall be issued only to one person who can demonstrate to the state engineer's satisfaction that he has adequate qualifications in the atmospheric sciences. The state engineer shall promulgate rules and regulations necessary to implement this act.

(c) The state engineer shall demand and receive a written report, in such manner as he shall provide, covering each separate experiment or activity for which a permit is issued.

(d) Any person engaging in a weather modification experiment without a permit is guilty of a misdemeanor and upon conviction is subject to a fine not to exceed five thousand dollars ($5,000.00) or by imprisonment for not more than ninety (90) days."

The State Engineer's office has issued 90 permits from April of 1951 through November of 2003. Appendix D provides a listing of these permits.

9.2 U.S. Forest Service and Bureau of Land Management Permits

Permits are normally required to install any type of equipment on U.S. Forest Service or BLM lands. Since we are tentatively recommending that remotely controlled silver iodide generators be considered in the conduct of the SRWR project, special use permits will likely be required. This permitting process would require an environmental analysis under NEPA.

9.3 National Oceanic and Atmospheric Administration Reporting

In 1971, Public Law 92-205 was enacted that required all non-federally sponsored attempts to modify the weather be reported to the Secretary of Commerce of the United States. Public Law 92-205 requires the submittal of Initial, Interim and Final Reports covering weather modification activities for individual target areas. An initial report is required each year seeding is planned and at least 10 days prior to the start of activity. Interim reports are required for those projects active on January 1st of each year and must be filed within 45 days of that date. A final report must be submitted within 45 days after the completion of the weather modification activity (Golden, 1995). The information required in the interim activity and final reports include: 1) number of weather modification days each month, 2) number of modification days for purposes of increasing rain or snow, reduction of hail, fog or other, 3) hours of apparatus operation (airborne or ground), and 4) type and amount of cloud seeding agent used.

It is important to note that Public Law 92-205 is a reporting requirement but establishes no regulatory authority as does, for example, the State of Wyoming permit requirements.

10.0 ACCESS/EASEMENTS

Siting of project specific ground equipment needed to support this program requires consideration of land ownership and the potential need for leases, permits or approvals to site such equipment. There are two primary classes of land ownership: private and public. Private lands are self-explanatory. Public lands in the areas of interest potentially include: U.S. Forest Service lands, U.S. Bureau of Land Management, State of Wyoming lands, and local municipality lands. Typically, long-term land leases can be arranged with private landowners to allow the installation of project equipment. Figure 10.1 provides the boundaries of the Bridger-Teton National Forest Lands in and in the vicinity of the proposed target areas. Comparison of this figure with Figure 6.19 indicates that the potential locations of the five remote, ground-based silver iodide generators would likely be within the National Forest boundaries. In this case, a special use permit would be required. The application for such permits may require that some type of environmental assessment be completed. Siting equipment at already disturbed sites (e.g. old mining claims) may result in fewer obstacles in obtaining the required permits. There are no designated wilderness areas within the proposed target areas, a fact which may also assist the operator in obtaining these permits.

Land ownership should be one of the important considerations in selecting specific project equipment locations. Such selections would typically be done by the cloud seeding contractor shortly after the award of a contract to implement a winter cloud seeding program, and in consultation with the project sponsor(s).

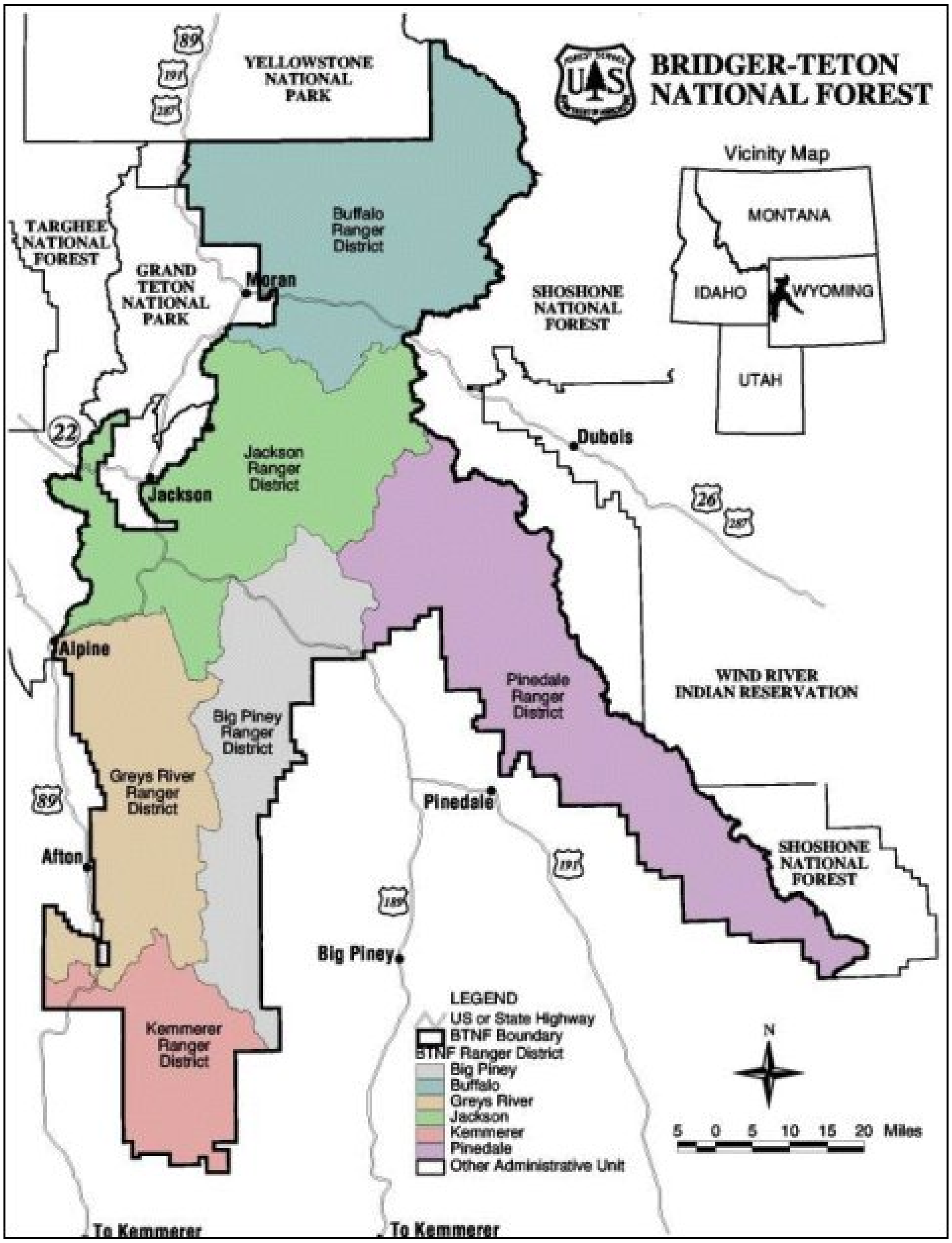

Figure 10.1 Bridger-Teton National Forest District Boundaries (from the Bridger-Teton National Forecast website)

11.0 EVALUATION METHODOLOGY

Specification of an evaluation methodology is a necessary requirement in the development of any comprehensive project design. This step represents one of the more difficult aspects of the development of a design of an operational cloud seeding project. A powerful approach, utilized in the conduct of research projects, is that of "randomly" specifying storm units to be seeded and others to be left unseeded. This is usually done on about a 50/50 seed to no seed basis. Observations and procedures are specified in advance, dictating how the project will be evaluated for detecting effects of seeding (e.g. as in Climax I and II, 24 hour amounts of precipitation at selected measurement locations within the target area). After seeding trials are conducted for several seasons, the average seeded precipitation at these key precipitation stations can be compared with the average not-seeded precipitation. The idea is that a large enough sample size will eliminate much of the natural variability that accompanies precipitation, such that a 10-15% difference can be detected with some degree of confidence. Parametric and non-parametric statistical tests can be applied to these data sets to determine how strong (significant) the indicated differences may be. Most sponsors of operational cloud seeding projects are unwilling to sacrifice a proportion of up to one-half of the potential benefit of the project (via randomization) for the purpose of documenting more precisely what the effects of seeding may have been. This is a question that would need to be addressed by the potential sponsors of the project, to randomize or not?

Assuming at this stage that the decision will be to not randomize the project, a brief discussion on the background associated with evaluation of non-randomized projects is provided in the following.

11.1 Background

The task of determining the effects of cloud seeding has received considerable attention over the years. Evaluating the results of a cloud seeding program for a particular season is rather difficult. The primary reason for the difficulty stems from the large natural variability in the amounts of precipitation that occur in a given area and between one area and another during a given season. Since cloud seeding is normally feasible only when existing clouds are near to (or already are) producing precipitation, it is not usually obvious if, and how much, the precipitation was actually increased by seeding. The ability to detect a seeding effect becomes a function of the magnitude of the seeding increase and the number of seeded events, compared with the natural variability in the precipitation pattern. Larger seeding effects can be detected more easily, and with a smaller number of seeded cases, than are required to detect small increases.

Historically, the most significant seeding results have been observed in wintertime seeding programs in mountainous areas. However, the apparent differences due to seeding are relatively small, being of the order of a 5-20 percent seasonal increase. In part, this relatively small percentage increase accounts for the significant number of cases required to establish these results (often five years or more).

Despite the difficulties involved, some techniques are available for estimation of the effects of operational seeding programs. These techniques are not as rigorous or scientifically desirable as is the randomization technique used in research, where roughly half the sample of suitable storm events is randomly left unseeded. Most clients do not wish to cut the potential benefits of a cloud seeding project by as much as half in order to better document the effects of the cloud seeding project. The less rigorous techniques do, however, offer an indication of the long-term effects of seeding on operational programs.

A commonly employed technique, and the one utilized in this assessment, is the "target" and "control" comparison. This technique is one described by Dr. Arnett Dennis in his book entitled “Weather Modification by Cloud Seeding, 1980”. This technique is based on the selection of a variable that would be affected by seeding (such as liquid precipitation or snowpack). Records of the variable to be tested are acquired for a not-seeded historical period of many years duration (20 years or more if possible). These records are partitioned into those located within the designated "target" area of the project and those in a nearby "control" area. Ideally the control sites should be selected in an area meteorologically similar to the target, but one which would be unaffected by the seeding (or seeding from other adjacent projects). The historical data (e.g., precipitation) in both the target and control areas are taken from past years that have not been subject to cloud seeding activities in either area. These data are evaluated for the same seasonal period of time as planned for the seeding evaluation. The target and control sets of data for the unseeded seasons are used to develop an equation (typically a linear regression) which predicts the amount of target area precipitation, based on precipitation observed in the control area. This regression equation is then applied to the seeded period, to estimate what the target area precipitation would have been without seeding, based on that observed in the control area. This allows a comparison to be made between the predicted target area natural precipitation and that which actually occurred during the seeded period, to look for any differences potentially caused by seeding activity. This target and control technique works well where a good historical correlation can be found between target and control area precipitation. Generally, the closer the target and control areas are geographically, and in terms of elevation, the higher the correlation will be. Control sites that are too close to the target area, however, can be subject to contamination by the seeding activities. This can result in an underestimate of the seeding effect. For precipitation and snowpack assessments, a correlation coefficient (r) of 0.90 or better would be considered excellent. A correlation coefficient of 0.90 would indicate that over 80 percent of the variance (r^2) in the historical data set would be explained by the regression equation used to predict the variable (expected precipitation or snowpack) in the seeded years. An equation indicating perfect correlation would have an r value of 1.0.

For a large-scale winter project sponsored by the Denver Water Board, NAWC documented a historical regression (unseeded) period target/control relationship *a priori* and then applied the predetermined and published target/control evaluation methodology after the seeding took place, to evaluate the results. This operational seeding project was conducted by another cloud seeding contractor, to affect some of the higher elevation drainages of the central Colorado Rockies (Solak, et al, 2003). In this manner, an independent evaluation method was developed.

Experience has shown that it is virtually impossible to provide an accurate assessment of the effectiveness of cloud seeding based on one or two seeded seasons for this type of winter-season program. However, as the data sample size increases, it becomes possible to provide at least a qualitative answer to the question, "How effective was the seeding?" Even if the results are somewhat imprecise, the ability to provide a credible estimate of project effectiveness is critical to the health and longevity of any program, as noted in an earlier section.

11.2 Target/Control Evaluations

11.2.1 <u>Background</u>

It is proposed that a non-randomized target/control evaluation method be developed as one means to evaluate the SRWR program. One issue that could have been discussed in the earlier section on the equipment and observation requirements (section 6.7) was the need or desire to install additional precipitation measurement sites in the intended target areas. The motive would be primarily to use such additional measurements in the evaluation of the effectiveness of the seeding. Although at first this seems like a logical suggestion, albeit one with potential considerable associated expense, it is in fact not worthwhile unless the project is randomized. The reason for this is that if additional sites are installed and a seeding project initiated, there will not be any representative not-seeded data (i.e., no historical data) that can be used in evaluating the effects of seeding at these sites (ASCE, 2004). As a consequence, the utilization of the historical target/control evaluation technique needs to rely upon measurement sites that are still in use but that also have a significant (15 or more years) historical record as well. Since higher elevation areas receive considerable quantities of snowfall during the winter, they are naturally the preferred target areas in which cloud seeding is directed. Historical measurements of precipitation in these areas of the intermountain west have typically been made by the former SCS (currently the NRCS) and in some cases by state water resources agencies. Since approximately 1980, monthly manual snow course measurements of snow water content have been mostly replaced by automated measurements several times per day of snow water content and precipitation, provided by two different sensors (e.g. snow pillows and standpipe storage gages). Both types of data will be used in the development of historical target/control evaluation techniques. Typically evaluations are performed using both types of data such as April 1st snow water contents and November–March or December-March precipitation amounts. Each type of observation has different advantages and disadvantages. It is proposed that both types of data be used in the development of evaluation methodologies for this project.

Potential target and control site locations are shown in Figures 11.1 and 11.2.

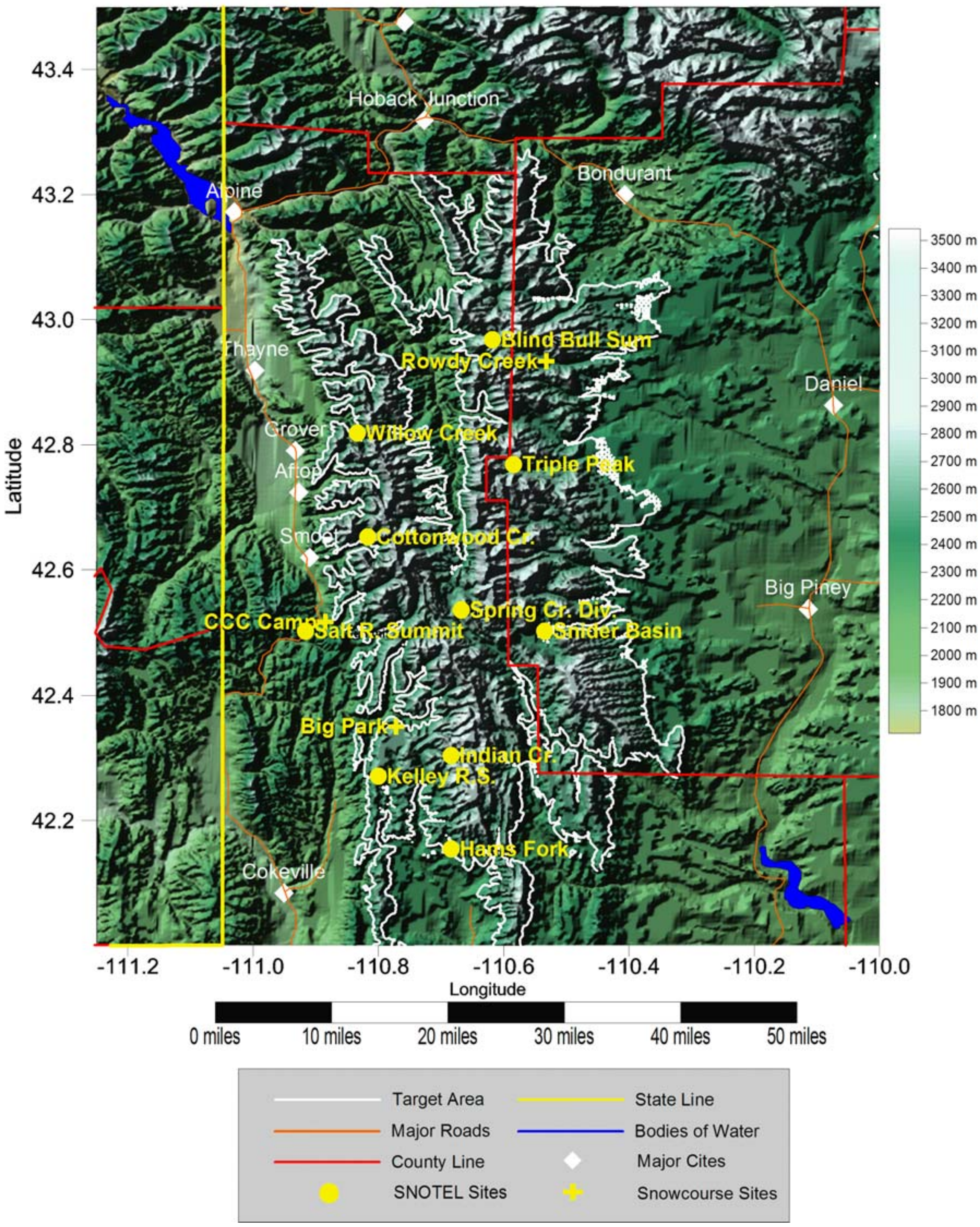

Figure 11.1 Proposed Target Area, showing Available SNOTEL and Snow Course Target Sites for the Salt River/Wyoming Ranges

Figure 11.1 provides the location of the proposed target area historical snow water and precipitation measurement sites. These would constitute the potential target sites. Fortunately, there are a number of sites located within the proposed target area that could be used in this type of evaluation. Figure 11.2 provides the adjacent SNOTEL sites that may be considered as control sites.

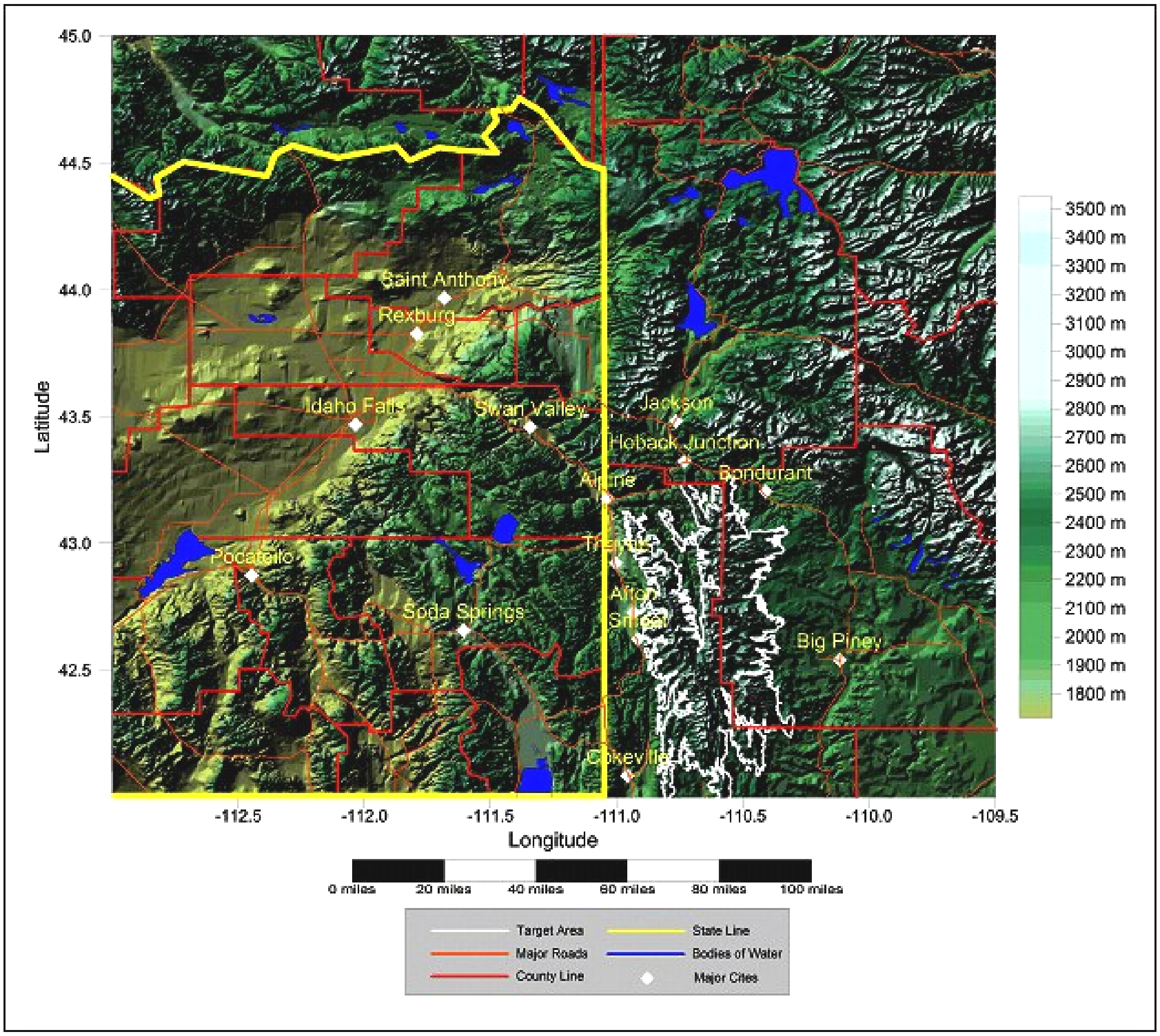

Figure 11.2 Potential SNOTEL Control Sites for the Salt River/Wyoming Ranges Program

Several lessons have been learned over the years in performing these types of target/control evaluations. Some of the concerns/considerations in performing historical target/control evaluations are discussed in the following.

The number of sites operated by agencies such as the NRCS (especially snow course sites) is continually being reduced. Even some cooperative program observer sites, which are managed by the National Weather Service, have either been discontinued or become inactive at several locations. This can necessitate changes in the regression equations developed to evaluate cloud seeding projects.

Another consideration in the selection of control sites is the potential downwind effects of other cloud seeding projects beyond the intended target areas. Some earlier weather modification research program evaluations have indicated that the precipitation can be modified not only within the intended target areas, but also in areas downwind of the intended target areas. Analyses of some of these programs have indicated increases in precipitation in these downwind areas out to distances of 50-100 miles (80-160 km). NAWC recently completed an analysis of the potential downwind effects of cloud seeding, utilizing a long-term program that has been conducted in central and southern Utah (Solak, et al, 2003). Historical regression equations were developed for that study to examine the possible existence of downwind effects. Figure 11.3 (taken from the study) shows ratio values of actual over predicted precipitation for several sites in southeast Utah and southwest Colorado, downwind of the seeding project target area shown in the figure. This figure indicates possible positive downwind effects from this program out to at least some locations near the Utah/Colorado border, a distance of approximately 100 miles (160 km) from the location of the intended target area.

The normal approach in selecting control sites for a new project is to look for sites that will geographically bracket the intended target area. The reason for this approach is that some winter seasons are dominated by a particular upper airflow pattern while other seasons are dominated by other flow patterns. The result of different upper airflow patterns often results in heavier precipitation in one area versus the other. For example, a strong El Nino pattern may favor the production of heavy winter precipitation in the southwestern United States while a strong La Nina pattern may favor below normal precipitation in that region. Having control sites on either side of (geographically bracketing) the target area relative to typical windflow patterns, particularly with regards to latitude, can improve the prediction of target area precipitation under these variable upper air flow pattern situations and result in more consistency in the evaluation results

An additional consideration in the selection of control sites for the development of an historical target/control relationship is one of data quality. A potential control site may be rejected due to poor data quality, which is usually manifested in terms of missing data. Fortunately, missing data (typically on a daily basis) are noted in the historical database so that sites can be dropped from consideration if they have much missing data. A site is normally dropped if it has more than 2 or 3 days of missing data in a month for 4 or 5 months during the historical period we are considering, which could be a 15–30 year period. Data quality may appear to be satisfactory but another consideration is whether the station has been moved during its history. If a significant move (more than a mile or change in elevation of 100-200 feet, 33-66 meters) is indicated in the station records, then a double mass analysis may be performed of the station of interest versus another station in the vicinity with good records and location stability. The double mass plot (an engineering tool) will indicate any changes in relationships between the two stations. If these changes (deflections in the slope of the line connecting the points) are coincident with station moves and they suggest a significant difference in the relationship, the site is dropped from further consideration.

Another factor should be noted. That is concerned with the two types of precipitation observations typically available from mountainous areas in the west: standpipe storage precipitation gages and snow pillows. There are potential problems associated with each type of observation. With the advent of the Natural Resources

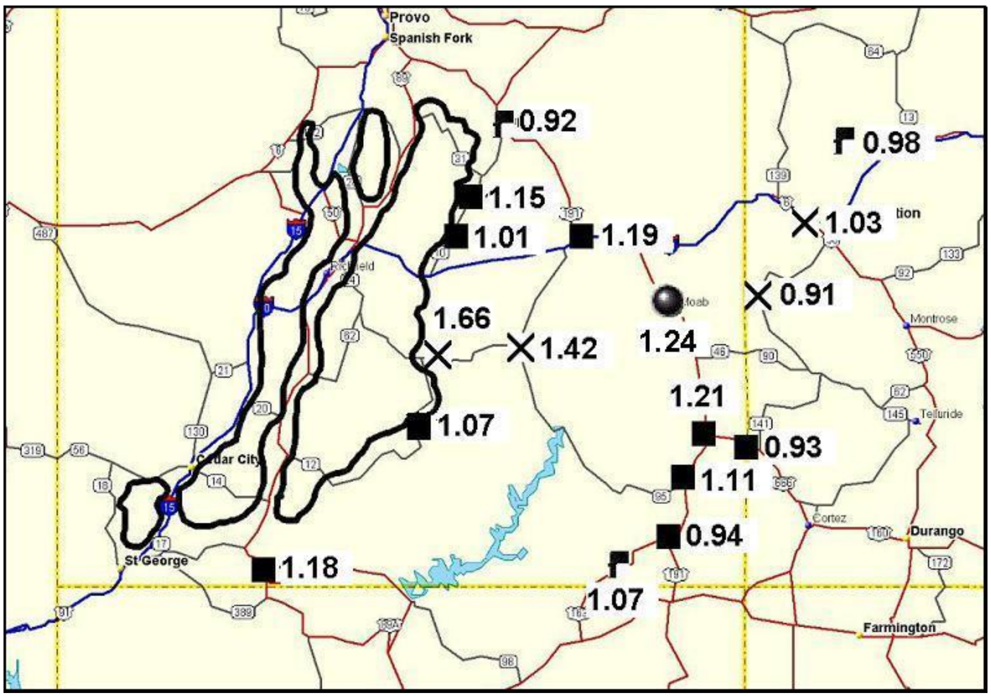

Figure 11.3 Actual/Predicted Downwind Ratios from Utah Study (target area enclosed by solid lines)

Conservation Service's (NRCS) SNOTEL data acquisition system in the late 1970's, access to precipitation and snowpack (water equivalent) data in mountainous locations became routine. Before the system was developed, these data were acquired by actually visiting the site to make measurements, a practice which is still being done at some sites. Figure 11.4 is a photo of an NRCS SNOTEL site taken in the fall, to allow the reader a better understanding of the two types of observation systems. The vertical tube is the standpipe storage gage, which is approximately 12" (30.4 cm) in diameter. The gages are approximately 20' (6.1 m) in height so that their sampling orifices remain above the snowpack surface. There are at least two types of problems associated with high elevation observations of the water equivalent of snowfall, as measured by standpipe precipitation storage gages. The two areas of concern are clogging at the top of the standpipe storage gage, and blow-by of snowflakes past the top of the standpipe gage. Either situation

Figure 11.4   SNOTEL Site in the Fall

would result in an underestimate of the actual precipitation that fell during such periods. In the fall, the storage gage is charged with antifreeze, which melts the snow that falls to the bottom of the gage. A pressure transducer records the weight of the solution. The weight of the antifreeze is subtracted from the total weight, giving the weight of the precipitation water, which is then converted into inches. Heavy, wet snow may accumulate around the top of the standpipe storage gage, affecting its catch, either reducing or stopping snow from falling into the standpipe, resulting in an underestimate of precipitation. Snow that falls with moderate to strong winds may blow past the top of the gage, which can also result in an underestimate of precipitation. NRCS sites are normally located in small clearings in forested areas to help reduce the impacts of wind problems. Sites that are near or above timberline are more likely to be impacted by catch deficiency due to wind since sheltered sites may be difficult to find in these areas. The snow pillow pictured in the foreground in Figure 11.4 is filled with antifreeze. This system weighs the snowpack, providing time-resolved records of the snowpack water content. Snow pillows can also have difficulty in providing accurate measurements of snow water content, because of wind either adding or removing snow from the measurement site when snow conditions are favorable for drifting.

The bottom line is that it is difficult to accurately measure snow water equivalent at unmanned high-elevation sites. Both types of NRCS observations (gage and snow pillow) can best be viewed as approximations of the actual amount of water that falls during a winter season. NRCS SNOTEL sites frequently provide the only type of precipitation observations available from higher elevation areas targeted by winter cloud seeding programs. They are well suited for use in estimations of seeding effects, but interpretation of the indicated seeding effects must keep in mind the limitations of the measurement systems and their data.

One final consideration; air pollution from major cities or from power plants in the west may be impacting mountainous precipitation downwind of these source regions. Givati and Rosenfeld, 2004 documented reductions in ratios of mountainous precipitation to upwind valley precipitation for regions downwind of major cities in Israel and California. They attributed these changes to the effects of air pollution. NAWC recently investigated this potential problem in Utah (Griffith et al, 2005). This study indicated reductions in mountainous precipitation were occurring downwind of the Salt Lake City complex as well out to distances of ~50 nm (111 km). Both studies further pointed out how such changes in precipitation patterns might impact the ability to estimate the effects of cloud seeding.

Even with the above caveats, **NAWC still considers the historical target/control technique to be the best choice in evaluations of non-randomized, operational wintertime cloud seeding projects if the goal of such an evaluation is to establish some quantitative estimate of the increase in precipitation due to seeding**. The development of regression equations using the target/control technique **before any seeding is conducted** offers a means of eliminating any question of bias on the part of those conducting the subsequent evaluations. This is a step that is encouraged by the Weather Modification Association; that is, procedures to be used in evaluations should be specified in advance. This approach was applied to the evaluation work conducted for the Denver Water Board (Solak, 2003). Some statistical tests may be applied to test the significance of any indications of possible seeding effects obtained using the target/control analyses, although in the strict sense the application of such tests is only valid when applied to randomized data sets.

11.2.2 Snow Water Content Target/Control Evaluations

April 1st snow water content data was accumulated for the potential target and control sites as depicted in Figures 11.1 and 11.2. These data consisted of NRCS corrected data for manually observed snow course sites that were converted into SNOTEL sites (typically in the early to mid 1980s) plus any sites that continue as manual snow course sites. The NRCS recognized the potential problem of switching from manual to automated data collection methods. Their solution was to obtain concurrent data at the newly established SNOTEL sites using both (collocated) measurement techniques for an overlap period of approximately 10 years in duration. They then developed correlations between the two types of measurements and applied a site-specific correction factor that converted the previous monthly snowcourse measurements to estimated values as if the SNOTEL measurements had been available at these sites from the outset. The NRCS also attempted to correct the timing problem in these estimates to reflect first of the month values. In other words, if an historical year had a measurement taken on the 25th of January instead of the first of February, the NRCS used adjacent precipitation data to estimate the snow water content on the first of February. NAWC believes these revised data sets provide more cohesive data (e.g., not an apples and oranges situation).

Double mass plots were prepared for the potential target and control sites, comparing sites with one another. All of the target sites seemed to be in good agreement, but one of the potential control sites was not. Figure 11.5 shows a plot of the Oxford Spring site versus Big Park. There is an obvious break in this plot. Other plots with Big Park versus other sites did not indicate a break, so it was concluded that the Oxford Spring data were unusable. Similar plots for other potential control sites led to the elimination of Sheep Mt., ID; Slug Creek Divide, ID; and Giveout, ID.

Data were excluded from historical periods when earlier seeding programs may have impacted either the target or control areas. These earlier programs were conducted by NAWC in the Smith and Thomas Fork areas in southeastern Idaho and western Wyoming (water years 1954-1970, 1979-82, and 1989-1990). Another program was conducted in eastern Idaho (water years 1993-1995), and one in southeastern Idaho (water years 1992-1993). With these considerations and the length of available historical records at the potential target and control sites, a base historical period was selected, consisting of the water years 1971-1978, 1983-1987, 1991, 1994, and 1996-2005 (a total of 25 seasons of data) from which the historical (unseeded) target/control regression equations were developed.

An examination of the potential control sites led to dropping the following sites from consideration: Franklin Basin, ID; Granite Peak, WY; Gros Ventre Summit, WY; and Togwotee Pass, WY. Franklin Basin was eliminated since it is in close proximity to one of NAWC's on-going winter programs being conducted in Eastern Box Elder and Cache Counties, Utah and therefore is potentially contaminated as discussed earlier in this section. The other three sites in Wyoming would be located generally downwind of the SRWR seeding program, should it be conducted. As a consequence, these sites would have the potential of being contaminated by the SRWR seeding.

After making these decisions, there were nine potential control sites and 11 potential target sites. Information regarding these sites is provided in Tables 11-1 and 11-2. In these tables the start dates are given when manually observed snow course sites were converted to SNOTEL sites. Three of the potential target sites are presently manually observed snow course sites (Big Park, CCC Camp, and Rowdy Creek); the other eight are SNOTEL sites. The average elevation of the control sites is 7185 feet (2.2 km) while that of the target sites is 8390 feet (2.6 km). It would have been desirable for the target and control sites to be at more similar average elevations since springtime snowmelt rates and other factors can be very dependent on elevation. The historical regression technique generally compensates for such differences since these factors affect the historical period as well. Where differences are noticed, it is when there is an unusually warm (or perhaps cold) spring, for example. It is recognized that regression equations do not do particularly well in abnormal weather situations, and these are dealt with on a case-by-case basis.

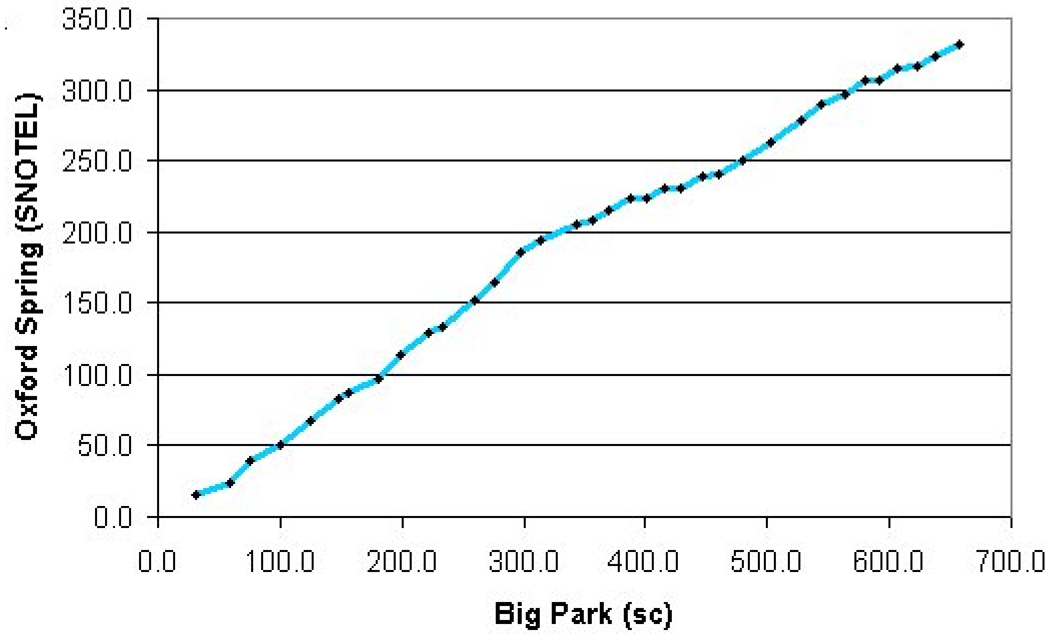

Figure 11.5 Double Mass Plot, Oxford Spring (control) vs. Big Park (target, snow course)

Table 11-1

SNOTEL/Snow Course Target Sites, Snow Water Content

Site Name	Lat (N)	Long (W)	Elevation	Start Date
Big Park	42^0 21'	110^0 46'	8620'	Snow course
Blind Bull Sum	42^0 58'	110^0 37'	8650'	Oct. 1981
CCC Camp	42^0 31'	110^0 53'	7500'	Snow course
Cottonwood Cr.	42^0 39'	110^0 49'	7670'	Oct. 1981
Indian Cr.	42^0 18'	110^0 41'	9425'	Oct. 1981
Kelley R.S.	42^0 16'	110^0 48'	8180'	Oct. 1981
Rowdy Creek	42^0 56'	110^0 32'	8300'	Snow course
Snider Basin	42^0 30'	110^0 32'	8060'	Oct. 1981
Spring Cr. Div.	42^0 32'	110^0 40'	9000'	Oct. 1981

Triple Peak	42^0 46'	110^0 35'	8500'	Oct. 1986
Willow Creek	42^0 49'	110^0 50'	8380'	Oct. 1981

Table 11-2 SNOTEL/Snow Course Control Sites, Snow Water Content

Site Name	Lat (N)	Long (W)	Elevation	Start Date
Base Camp, WY	43^0 56'	110^0 26'	7,030'	Oct. 1981
Emigrant Summit, ID	42^0 22'	111^0 34'	7,390'	Oct. 1981
Grassy Lk., WY	44^0 08'	110^0 50'	7,265'	Oct. 1981
Philips Bench, WY	43^0 31'	110^0 55'	8,200'	Oct. 1981
Pine Cr. Pass, ID	43^0 34'	111^0 13'	6,720'	Oct. 1988
Sedgwick Pk., ID	42^0 32'	111^0 58'	7,850'	Oct. 1988
Snake R. Station, WY	44^0 08'	110^0 40'	6,920'	Oct. 1989
Somsen Rch., ID	42^0 57'	111^0 22'	6,800'	Oct. 1981
Wildhorse Div., ID	42^0 45'	112^0 29'	6,490'	Oct. 1981

A linear regression equation was then developed using the data sets. Table 11-3 contains this information. The resulting equation was $y = 1.04(x) -0.16$, where x is the seasonal average April 1st snow water content for the control sites and y is the predicted average seasonal April 1st target area snow water content. There was a good correlation between the target and control sites, with an r^2 value of 0.89. This statistic means that 89% of the variance between the target and control areas is explained by the regression equation. A perfect prediction would have an r^2 value of 1.0. This result compares favorably with other target/control evaluation equations that have been developed for other winter cloud seeding programs being conducted in the intermountain west.

Different target/control regression equations can be developed in the future for other potential operational periods (e.g., Dec. 1 – Mar. 31) by using the same target and control stations used above and then creating a new data set for the period of interest. In the case of a December – March period, the accumulated snow water content at a given site for a particular October and November period would be subtracted from the corresponding April 1st value.

11.2.3 Precipitation Target/Control Evaluations

An analysis similar to that for the snow water content target/control analysis was conducted for precipitation data available from NRCS for the target and upwind areas.

Table 11-3
Linear Regression Equation Data for April 1st Snow Water Content (inches)

Regression (non-seeded) period:

YEAR	CONTROL (XOBS)	TARGET (YOBS)	YCALC	RATIO	EXCESS
1971	32.71	34.96	34.00	1.03	0.96
1972	30.12	32.17	31.30	1.03	0.88
1973	19.66	18.06	20.37	0.89	-2.30
1974	29.02	29.27	30.15	0.97	-0.88
1975	25.69	25.74	26.67	0.97	-0.93
1976	29.54	29.91	30.69	0.97	-0.79
1977	9.79	9.02	10.06	0.90	-1.04
1978	26.98	32.02	28.01	1.14	4.00
1983	24.14	21.20	25.05	0.85	-3.85
1984	24.33	21.96	25.25	0.87	-3.29
1985	21.10	18.44	21.87	0.84	-3.44
1986	25.87	32.51	26.85	1.21	5.66
1987	12.52	14.18	12.91	1.10	1.27
1991	17.14	16.60	17.74	0.94	-1.14
1994	14.64	15.34	15.13	1.01	0.21
1996	24.68	28.53	25.61	1.11	2.92
1997	31.77	31.73	33.02	0.96	-1.29
1998	20.64	19.80	21.40	0.93	-1.60
1999	23.76	24.36	24.65	0.99	-0.28
2000	19.24	20.19	19.94	1.01	0.26
2001	11.30	13.57	11.64	1.17	1.93
2002	16.97	17.23	17.56	0.98	-0.33
2003	17.27	20.60	17.87	1.15	2.73
2004	18.37	16.98	19.02	0.89	-2.04
2005	16.70	19.66	17.28	1.14	2.39
Mean	21.76	22.56	22.56	1.00	0.00

X Obs = Ave. Control SWC (inches)
Y Obs = Ave. Target SWC (inches)
Y Calc = Predicted Target SWC
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.943687

R Square	0.890545
Adjusted R Square	0.885786
Standard Error	2.402859
Observations	25

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	-0.16481	1.729434	-0.0953	0.924903	-3.74241
X Variable 1	1.044491	0.076354	13.67962	1.55E-12	0.886541

There were seven potentially suitable sites within the target area and ten in upwind control areas. The same sites excluded in the snow water analysis for potential contamination effects were excluded from this analysis. A shorter data set was available for this analysis since the snow water content analysis could use manually observed snow course data available prior to the advent of the SNOTEL technology. SNOTEL site installation began in the early 1980's. As a consequence, the seven possible target and ten possible control sites had data available beginning in water year 1983. Data were accumulated for each of the potential target and control sites for the period of November through March. The November – March period was selected as a likely core operational period. The following water years were excluded due to seeding within or near the potential target areas, as was done in the snow water content analysis: 1988-1990, 1992-1993, and 1995. The historical data set then consisted of seventeen seasons. Seasonal averages were then obtained for the target and control groupings. Double mass plots were prepared using the resulting data set. There were some minor irregularities with a couple of the potential control sites, but it was decided these irregularities were not significant enough to cause their exclusion from the analysis. Tables 11-4 and 11-5 contain listings of the target and control sites.

Table 11-4 SNOTEL Precipitation Target Sites

Site Name	Lat (N)	Long (W)	Elevation	Start Date
Blind Bull Sum	42^0 58'	110^0 37'	8650'	Oct. 1981
Cottonwood Cr.	42^0 39'	110^0 49'	7670'	Oct. 1981
Indian Cr.	42^0 18'	110^0 41'	9425'	Oct. 1981
Kelley R.S.	42^0 16'	110^0 48'	8180'	Oct. 1981
Snider Basin	42^0 30'	110^0 32'	8060'	Oct. 1981
Spring Cr. Div.	42^0 32'	110^0 40'	9000'	Oct. 1981
Willow Creek	42^0 49'	110^0 50'	8380'	Oct. 1981

The data were then used to develop a linear regression equation relating the target and control areas, for November – March precipitation. The resulting equation was y = .95 (x) + 1.91. This equation had an r^2 value of 0.88. Information concerning this regression equation is provided in Table 11-6. As was mentioned regarding the regression equation that was developed for the snow water content analysis, data could be added to the core period of November through March should a longer operational period be implemented.

Table 11-5 SNOTEL Precipitation Control Sites

Site Name	Lat (N)	Long (W)	Elevation	Start Date
Base Camp, WY	43^0 56'	110^0 26'	7030'	Oct. 1981
Emigrant Summit, ID	42^0 22'	111^0 34'	7390'	Oct. 1981
Giveout, ID	42^0 25’	$111^0$10’	6930’	Oct. 1982
Grassy Lk., WY	44^0 08'	110^0 50'	7265'	Oct. 1981
Oxford Spring, ID	42^0 16’	112^0 08’	6740’	Oct. 1981
Philips Bench, WY	43^0 31'	110^0 55'	8200'	Oct. 1981
Sheep Mtn, ID	43^0 13’	$111^0$41’	6570’	Oct. 1982
Slug Creek, ID	42^0 34’	111^0 18’	7225’	Oct. 1981
Somsen Rch., ID	42^0 57'	111^0 22'	6800'	Oct. 1981
Wildhorse Div., ID	42^0 45'	112^0 29'	6490'	Oct. 1981

Table 11-6

Linear Regression Equation Data for November - March Precipitation (inches)

Regression (non-seeded) period:

YEAR	CONTROL (XOBS)	TARGET (YOBS)	YCALC	RATIO	EXCESS
1983	18.40	18.87	19.38	0.97	-0.50
1984	22.12	22.00	22.91	0.96	-0.91
1985	15.95	16.83	17.05	0.99	-0.22
1986	24.76	31.09	25.41	1.22	5.67
1987	10.34	12.93	11.72	1.10	1.21
1991	15.51	15.49	16.63	0.93	-1.15
1994	13.24	14.70	14.48	1.02	0.22
1996	24.04	25.21	24.73	1.02	0.48
1997	30.73	29.14	31.08	0.94	-1.94
1998	19.17	18.70	20.11	0.93	-1.41
1999	21.46	22.74	22.28	1.02	0.46
2000	17.56	18.70	18.58	1.01	0.12
2001	11.24	12.90	12.58	1.03	0.32
2002	16.61	15.96	17.68	0.90	-1.72
2003	16.67	19.07	17.73	1.08	1.34
2004	18.89	17.44	19.84	0.88	-2.40
2005	13.89	15.53	15.09	1.03	0.44
Mean	18.27	19.25	19.25	1.00	0.00

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.938159
R Square	0.880142
Adjusted R Square	0.872152
Standard Error	1.881531
Observations	17

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	389.942	389.942	110.1482	2.64E-08
Residual	15	53.10239	3.540159		
Total	16	443.0444			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	1.905361	1.714751	1.111159	0.283994	-1.74955
X Variable 1	0.949542	0.090474	10.49515	2.64E-08	0.756701

11.3 Randomization

Randomization of experimental units, where approximately half of the events are seeded and the other half are not, is a tool used in the conduct of research programs. Normally, approximately a five-season period is needed to demonstrate statistically significant results from the conduct of such a program. It is understood that the five-year pilot program recently approved for the Wind River, Sierra Madre/Medicine Bow Ranges will employ randomization. This type of research program is much more costly to conduct than one where every potentially favorable event is seeded. The tradeoff is that when a randomized approach is applied, the determination of the results of seeding is more certain. This study assumes that randomization will not be employed for the SRWR area, should the decision be reached to proceed with a winter cloud seeding program.

11.4 Silver in Snow Evaluations

The results from a statistical evaluation, such as a target/control analysis, can be strengthened through supporting physical studies. This recommended was made by the Weather Modification Association, in its website response to a National Research Council Report (2004). One technique that has been employed by the Desert Research Institute (DRI) in the assessment of the effectiveness of at least the targeting (if not the magnitude) of seeding effects of winter programs is that of analyzing samples of snow from the target area during seeded periods to determine whether silver is present in projects that use silver iodide as the seeding agent (Warburton, et al, 1996) (Warburton, et al, 1995b).

The revision to the ASCE Manual 81(ASCE, 2006) contains the following summary of this technique.

> *"Occasionally, samples of newly fallen snow are collected for an analysis of silver content. This is an evaluation technique encountered more frequently in research projects due to the expense involved. Snow samples collected prior to cloud seeding or from non-seeded storms are analyzed to establish the natural background silver content (if measurable with available analysis techniques) for comparison with snow samples taken from seeded storms. This technique is only valid for projects using silver iodide as the cloud seeding agent, although some analysis techniques are applicable to other possible cloud seeding agents as well (i.e., lead iodide). Several analysis techniques have been developed for use in such analyses, including neutron activation, proton excitation, and flameless atomic absorption. An example of an analysis of the downwind transport of silver iodide outside of primary target areas is given by (Warburton 1974). Warburton, et al, (1996) demonstrates how trace chemical assessment techniques strengthen traditional target and control precipitation analyses.*
>
> *A modification of this trace chemistry assessment technique involves the simultaneous release of a control aerosol along with an active*

seeding aerosol (Warburton, et al. 1995). Such tracers have properties very similar to the seeding agent, with the key exception that it does not nucleate ice. It is insoluble in water, has an extremely low natural background in precipitation and is only removed from the atmosphere by passive precipitation scavenging mechanisms. Both the seeding agent and tracer are transported and scavenged in very similar manners when conditions are not conducive for effective seeding. Given similar release rates, detecting the same concentrations of silver and indium in precipitation samples at downwind locations indicates that the two aerosols were most likely removed from the atmosphere solely by scavenging. On the other hand, when sufficient supercooled liquid water (SLW) exists and temperatures are cold enough for the active seeding material to nucleate new ice crystals, the ratio of silver to tracer in target area precipitation samples can be much greater than unity. This indicates that some fraction of the seeding material was directly responsible for the nucleation of ice crystals that eventually produced additional snowfall."

This technique may be of potential value on the SRWR project should the decision be made to proceed with this project. The combination of silver in snow along with model predictions of the transport of seeding plumes over sampling sites (i.e., Section 11.5) would provide support to the indications of positive effects of seeding that may be provided through statistical evaluations (i.e., Section 11.2).

11.5 Computer Simulations

Those designing operational programs need to stay abreast of new developments in this field or related fields that have the potential to improve the performance of existing project designs. Such improvements could include the use of computer models to predict the transport of seeding plumes and fallout of artificially created precipitation, or the use of snow chemistry to estimate the effectiveness of the seeding operations. The use of computer models, while intriguing, can provide pitfalls if model results are accepted at face value without independent validation via observations. For example, the plume transport type output is much more acceptable if a tracer is released and tracked through the clouds of interest to verify the model predictions. Some work of this type utilizing SF_6 to depict seeding plumes was conducted on some Utah storm events (Holroyd, et al, 1995; Heimbach, et al, 1997).

Sophisticated atmospheric models have the potential to calculate the amounts of natural precipitation for short intervals (e.g., 6 hours, 12 hours) in mountainous areas. **If** these predictions were accurate and had been validated by observations, they could be compared with the amount of precipitation that fell during seeded periods within the intended target area to determine the impact of seeding on target area precipitation. An attempt to verify the output of the Regional Atmospheric Modeling System (RAMS) computer model developed at Colorado State University versus observed and predicted modified precipitation due to cloud seeding was made for the 2003-2004 winter season in central Colorado, with rather mixed results. Some of the conclusions from the final report (Colorado Water Conservation Board, 2005):

- When model simulated precipitation was compared to measured 24 hour precipitation at 61 SNOTEL sites the model exhibited a mean precipitation bias of 1.88.
- Comparison of model-predicted precipitation (control) versus seeded precipitation revealed that there was essentially no difference between the 86-day seed and control average totals.

Reasons given why there were no differences between seed and control precipitation included:

- The model-predicted seedability could be real; however, because of the model over-prediction bias and low amounts of supercooled liquid water content, this possibility is doubtful.
- There is circumstantial evidence that the model-predicted supercooled liquid water content is too low, thereby underestimating seedability.
- The low-level warm temperature bias in the model results in delayed AgI nuclei activation and reduced effectiveness of the seeding agent in the model.

Some commercial cloud seeding operators believe that computer models have not progressed to the stage that they can be used to quantitatively evaluate operationally conducted winter cloud seeding programs. They certainly hold considerable promise for use in this way in the future. Some existing models, such as DRI's Lagrangian particle dispersion model (LAP), have been used to predict the plume transport from ground based silver iodide generators. Some of these simulations have been subject to indepenedent verification though studies of the silver content of snow. There is additional discussion of the use of DRI's model used to provide simulations of plume transport for the SRWR area in section 6.8.This model, however, has not been applied to the perhaps more difficult problem of attempting to evaluate the effectiveness of seeding to produce increases in precipitation.

12.0 POTENTIAL BENEFITS/HYDROLOGIC ASSESSMENT (Note: A significant portion of this section was provided by Mr. Bruce Brinkman, a hydrologist with the WWDC)

The challenge of studying the non-linear feedback between increases in snowpack due to seeding operations and the ensuing runoff is a sizable task that requires both atmospheric and hydrologic-based modeling. Reliable results would take months and possibly years to achieve. In the interim, an estimate based on results in Section 6 (Table 6-8) of 10 percent increase in snowpack due to a successful seeding program will be used in this section as basis for investigation. Runoff data was obtained from the US Geological Survey (USGS) website for Wyoming located at: http://nwis.waterdata.usgs.gov/nwis. Figure 12.1 shows the gages used in this analysis and the basins they represent. Table 12-1 provides details of the selected gaging stations.

Annual runoff data from each USGS site represents the total amount of water that flowed past the given streamflow gaging station. Several historic gaging sites were found around the Salt River/Wyoming Ranges and it was possible to select a series of basins that cover a majority of this area of interest. A few of these gages are still active today. The records of these sites were used to build historic flow records for each basin. In order to represent target areas that may be impacted by significant snowpack increases, the basin areas closest to the national forest within the ranges were selected. These sites were also selected as high in the mountain ranges as possible to eliminate as many man made effects as possible.

The site monthly averages, in units of cubic feet per second, were obtained from the USGS website for the period of record for each gaging station. These averages were converted to acre-feet based on the number of days in the month using the equation:

$$\text{Runoff (in ac-ft)} = \text{Runoff (in ft}^3\text{/s)} * 1.983 * \text{number of days}$$

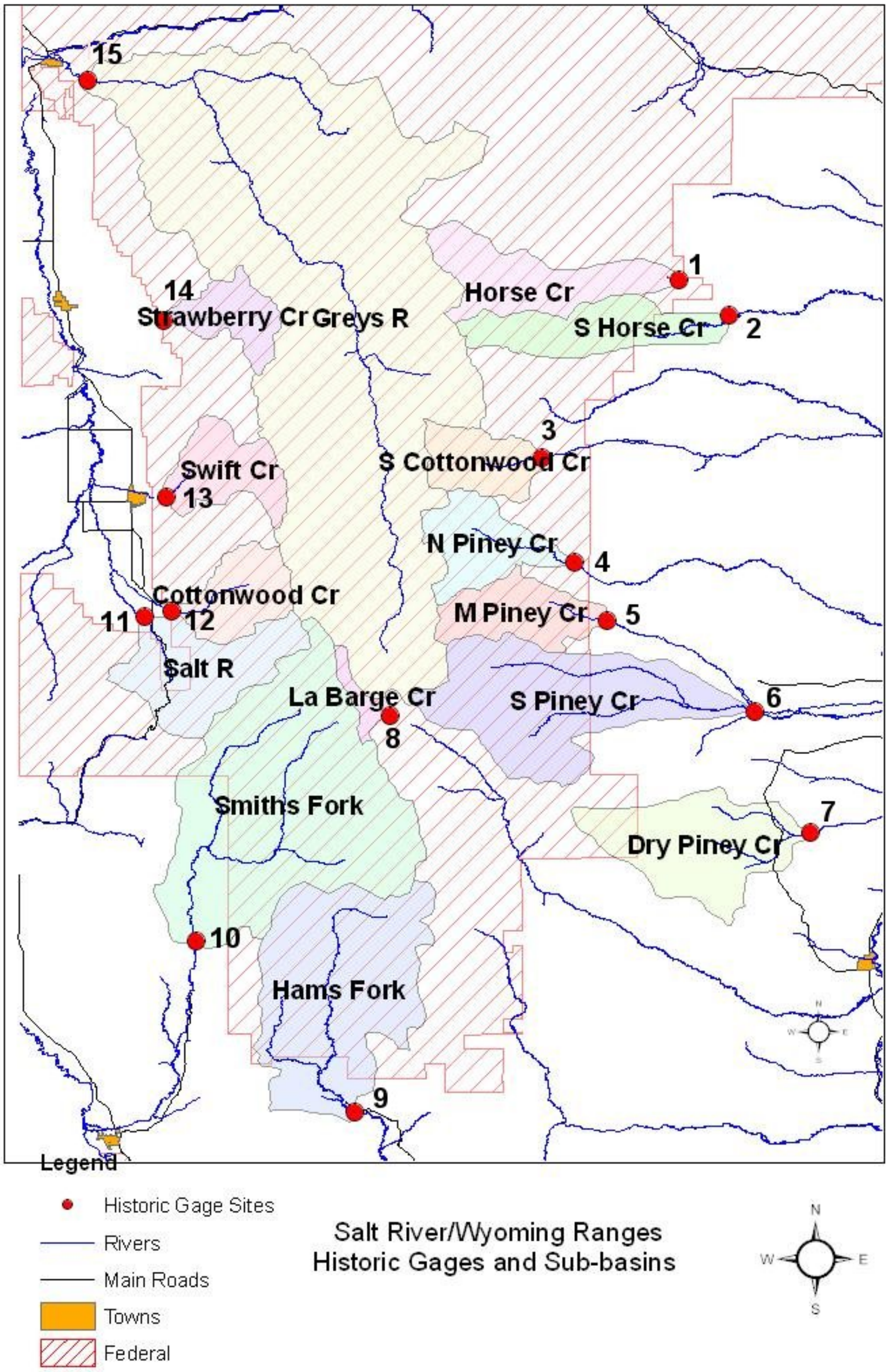

Figure 12.1 Location of Gages and Basins in the Salt River/Wyoming Ranges. Gage numbers correspond to information provided in Tables 12.1 and 12.2. (Source: Bruce Brinkman, WWDC).

Table 12-1
Summary of Gaging Stations and Basins in the Salt River/Wyoming Ranges shown in Figure 12.1

Area Number (shown in Figure), Stream Gage Location and WY population center the gage is near	USGS Station Identifier	Drainage Area (sq. mi)	Period of Record Utilized
1. HORSE CREEK AT SHERMAN RANGER STATION, WY	09189500	43.0	1955-1974
2. SOUTH HORSE CREEK NEAR MERNA, WY	09189550	33.3	1983
3. SOUTH COTTONWOOD CREEK NEAR BIG PINEY, WY	09191300	21.4	1983
4. NORTH PINEY CR AB APPERSON CR, NR MASON, WY	09205490	29.6	1983
5. MIDDLE PINEY CR BEL SOUTH FORK, NR BIG PINEY, WY	09206000	34.3	1942-1954
6. SOUTH PINEY CREEK NR BIG PINEY, WYO	09207500	117.0	1939-1941
7. DRY PINEY CREEK NEAR BIG PINEY, WYO.	09207700	67.0	1966-1972
8. LA BARGE CRK NR LA BARGE MDWS. RANGER STA, WY	09208000	6.3	1951-1981
9. HAMS FORK BELOW POLE CREEK, NEAR FRONTIER, WY	09223000	128.0	1953-2004
10. SMITHS FORK NEAR BORDER, WY	10032000	165.0	1943-2003
11. SALT RIVER NEAR SMOOT, WY	13024000	47.8	1933-1957
12. COTTONWOOD CREEK NEAR SMOOT, WY	13024500	26.3	1933-1957
13. SWIFT CREEK NEAR AFTON, WY	13025000	27.4	1943-1971
14. STRAWBERRY CREEK NEAR BEDFORD, WYO.	13027000	21.3	1933-1943
15. GREYS RIVER AB RESERVOIR NR ALPINE WY	13023000	448.0	1954-2004

The cumulative sum of the monthly averages for each site was then calculated from the monthly averages in ac-ft. The sums per basin were also normalized to a 72 year mean. This was done to reduce potential high and low biases from data taken during wet and dry years respectively. There were no sites found with records that ran consistently from 1933 to 2004 and that were located high in the Salt River/Wyoming Ranges above any man-made flow alterations. Therefore, several of the areas gaging site records were combined through regression and other methods to find the best long period record. The best fit came from USGS Station #13024500 Cottonwood Creek Near Smoot, Wyoming (number 12 in Table 12.2) from 1933-1957 and the USGS Station #13023000 Greys River Above Reservoir Near Alpine, Wyoming (number 15 in Table 12-1) from 1954-2004. These two sites have basins that are located entirely within the national forest and have a combined record covering the period from 1933 to 2004. The cumulative basin runoff values were then summed to provide an estimate of annual runoff from these basins. It should be noted that representative streamflow data were not available for all of the streams that originate in the proposed target areas. For example, measurements were not available for Fontenelle or LaBarge Creeks. Therefore, the following analyses of potential increases in streamflow due to cloud seeding will tend to be on the conservative side.

For many streams in Wyoming, the majority of the runoff and groundwater recharge occurs during the snowmelt runoff period that generally begins in April or May and ends in late July. A summary of the data for the Salt River/Wyoming Ranges is provided in Table 12-2.

Table 12-2

Summary of Annual and April through July Runoff for the Salt River/Wyoming Ranges shown in Figure 12.1

Area Number (shown in Figure), Stream Gage Location and WY population center the gage is near	Cumulative Annual Runoff (acre-feet)	Cumulative Apr. – Jul. Runoff (acre-feet)
1. HORSE CREEK AT SHERMAN RANGER STATION, WY	49,940	46,676
2. SOUTH HORSE CREEK NEAR MERNA, WY	15,585	13,584
3. SOUTH COTTONWOOD CREEK NEAR BIG PINEY, WY	25,535	18,099
4. NORTH PINEY CREEK NEAR MASON, WY	40,278	28,991
5. MIDDLE PINEY CR BEL SOUTH FORK, NR BIG PINEY, WY	18,285	13,515
6. SOUTH PINEY CREEK NR BIG PINEY, WYO	33,716	20,687
7. DRY PINEY CREEK NEAR BIG PINEY, WYO.	2,593	2,143
8. LA BARGE CREEK NR LA BARGE MDWS. RANGER STA, WY	10,187	7,799
9. HAMS FORK BELOW POLE CREEK, NEAR FRONTIER, WY	80,323	69,385
10. SMITHS FORK NEAR BORDER, WY	134,443	94,371
11. SALT RIVER NEAR SMOOT, WY	25,552	21,140
12. COTTONWOOD CREEK NEAR SMOOT, WY	30,946	20,766
13. SWIFT CREEK NEAR AFTON, WY	59,354	37,469
14. STRAWBERRY CREEK NEAR BEDFORD, WYO.	49,245	26,822
15. GREYS RIVER AB RESERVOIR NR ALPINE WY	467,575	327,145
TOTALS	1,043,557	748,590

Annual runoff in the Salt River/Wyoming Ranges (Table 12-2) varies by sub-basin from 2,600 ac-ft at Dry Piney Creek near Big Piney to 468,000 ac-ft in the Greys River above the reservoir near Alpine. Using the numbers presented in Table 12-2, the average annual runoff for the Salt River/Wyoming mountain ranges is approximately 1,043,555 ac-ft and the average April through July runoff is 748,590 ac-ft. The average April through July runoff represents approximately 72% of the average annual water year runoff in this area.

Some research studies in weather modification have used sophisticated hydrologic models to simulate what the potential increases in streamflow might be with an assumed increase in precipitation due to the cloud seeding. (references). Such detailed hydrologic modeling is beyond the scope of this study. A simpler technique has been used on some previous studies (Stauffer and Williams, 2000). This technique consists of utilizing linear regression techniques to develop a correlation between streamflow and precipitation. A common measure of precipitation that has been used in these studies is the average April 1st snow water content from representative sites in the area. If an acceptable correlation is established, assumed increases in snow water content can be inserted into the equations and then compared to calculated average flows. That approach was adopted for this study. Average monthly flows for the Greys River gaging station for the period 1937-2005 were selected for analysis. Five SNOTEL sites located within or near the Greys River drainage were then selected to correlate with runoff. The five selected stations were Blind Bull Summit, Cottonwood Creek, Snider Basin, Spring Creek Divide, and Willow Creek (locations were provided previously in Figure 5.3). Data from all five sites were available beginning in water year 1983. The April 1st snow water content values at these five sites were averaged for each season from 1983-2005 (23 years of record). Linear regression equations were then developed for the 23-year period relating: 1) the annual water year runoff from the Greys River site and 2) the April-July runoff with the average April 1st snow water contents. Tables 12-3 and 12-4 provide the results. High r^2 values (a measure of the goodness of fit of the regression) were obtained; 0.83 for water year values and 0.88 for April through July values. An r^2 value of 0.88 indicates 88% of the variance is explained by the regression equation. A perfect predictor would have an r^2 value of 1.0.

Table 12-3
April 1 SWE and Water Year Streamflow Correlation

	X obs	Y obs	Y calc	Ratio	Difference
Year	**Apr 1 SWE**	**Water Yr AF**	**Water Yr AF**	**Yobs/Ycalc**	**AF**
1983	24.2	615,389	488,309	1.26	127,080
1984	24.1	600,097	485,766	1.24	114,331
1985	18.9	420,994	375,997	1.12	44,996
1986	34.3	708,627	702,759	1.01	5,868
1987	15.2	327,251	297,168	1.10	30,083
1988	19.0	350,924	377,269	0.93	-26,345
1989	25.9	440,675	524,757	0.84	-84,082
1990	17.7	326,464	350,992	0.93	-24,529
1991	18.9	381,534	374,726	1.02	6,808
1992	14.2	255,136	276,401	0.92	-21,265
1993	22.8	475,259	457,794	1.04	17,465
1994	16.9	339,777	334,040	1.02	5,737
1995	22.9	465,551	461,184	1.01	4,366
1996	32.3	601,005	659,954	0.91	-58,949
1997	34.8	720,264	711,660	1.01	8,604
1998	21.5	511,346	429,822	1.19	81,524
1999	26.8	548,424	543,405	1.01	5,019
2000	22.6	427,317	453,556	0.94	-26,239
2001	15.0	273,997	293,777	0.93	-19,781
2002	18.6	314,621	369,216	0.85	-54,596
2003	23.1	357,535	464,999	0.77	-107,464

2004	18.7	342,938	370,912	0.92	-27,974
2005	20.8	415,172	415,836	1.00	-664
Mean	22.1	444,360	444,361	1.0	-0.2
SUMMARY OUTPUT	For Water Year runoff				
Regression Statistics					
Multiple R	0.909				
R Square	0.827				
Adjusted R Square	0.819				
Standard Error	56,912.018				
Observations	23				
ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	3.25122E+11	3.E+11	100.378114	1.87443E-09
Residual	21	6.80E+10	3.24E+09		
Total	22	3.93141E+11			
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	-24,932.63	48,320.69	-1	6.11E-01	-1.25E+05
X Variable 1	21,190.79	2,115.08	10	1.87E-09	1.68E+04

Table 12-4
April 1 SWE and April – July Streamflow Correlation

	X obs	**Y obs**	**Y calc**	**Ratio**	**Difference**
Year	**Apr 1 SWE**	**Apr - Jul AF**	**Apr - Jul AF**	**Yobs/Ycalc**	**AF**
1983	24.2	419,773	343,290	1.22	76,483
1984	24.1	399,033	341,174	1.17	57,859
1985	18.9	276,977	249,852	1.11	27,125
1986	34.3	540,944	521,703	1.04	19,241
1987	15.2	188,546	184,269	1.02	4,277
1988	19.0	246,305	250,910	0.98	-4,605
1989	25.9	311,425	373,613	0.83	-62,188
1990	17.7	207,403	229,049	0.91	-21,646
1991	18.9	268,844	248,794	1.08	20,050
1992	14.2	146,180	166,992	0.88	-20,812
1993	22.8	354,429	317,903	1.11	36,526
1994	16.9	230,117	214,945	1.07	15,172
1995	22.9	330,881	320,724	1.03	10,157
1996	32.3	438,942	486,091	0.90	-47,149
1997	34.8	534,317	529,108	1.01	5,209
1998	21.5	339,857	294,631	1.15	45,226
1999	26.8	384,346	389,127	0.99	-4,782

2000	22.6	283,171	314,377	0.90	-31,206
2001	15.0	167,968	181,448	0.93	-13,480
2002	18.6	217,358	244,210	0.89	-26,853
2003	23.1	251,080	323,897	0.78	-72,817
2004	18.7	231,231	245,621	0.94	-14,390
2005	20.8	285,586	282,996	1.01	2,590
Mean	22.1	306,726	306,727	1.0	-0.5
SUMMARY OUTPUT	For April - July				
Regression Statistics					
Multiple R	0.941				
R Square	0.886				
Adjusted R Square	0.881				
Standard Error	37,092.232				
Observations	23				
ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2.25033E+11	2.25033E+11	163.5611975	2.23011E-11
Residual	21	28892506959	1375833665		
Total	22	2.53926E+11			
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	-83,704.09	31,492.86	-2.66	0.01	-1.49E+05
X Variable 1	17,629.77	1,378.50	12.79	0.00	1.48E+04

The equation for the annual runoff, y = 21,191(x) – 2493, was applied to the average April 1st snow water content of 22.1 inches for the 23-year period. The predicted average annual runoff for the Greys River was 443,389 ac-ft. If the 22.1 inch value was increased by 10% (an assumed cloud seeding effect) then this equation yielded an estimated annual runoff value of 490,009 ac-ft. If the calculated natural amount (443,389 ac-ft) is divided into the calculated augmented amount, the result is 1.105 or a 10.5% increase. In other words, a 10% increase in average April 1st snow water content is predicted to increase the average annual runoff for the Greys River by 10.5%. Similarly, for the average April through July runoff, y = 17,630(x) – 83,704 or 305,919 ac-ft. Increases in the April 1st snow water content by 10% results in an estimated increase in average April-July runoff of 12.7%.

These results were applied to each of the project area sub-drainages to estimate potential increases in streamflow due to a 10% increase in April 1st snow water content. Results are provided in Tables 12-5 and 12-6. It should be noted that we did not develop a separate regression equation for each basin. The assumption was that the results obtained for the Greys River were representative of the other drainages. The results provided in Tables 12-5 and 12-6 do not contain any allowance for possible reductions in additional streamflow due to cloud seeding suspension criteria. The most likely impact of suspensions would be in very wet winter seasons when the snowpack percentage thresh-holds are exceeded (section 7.3 discusses proposed suspension criteria).

Table 12-5
Summary of <u>Annual Runoff</u> for the Salt River/Wyoming Ranges shown in Figure 12.1. Additional Runoff calculated assumes a 10% increase in April 1st snowpack, which would produce approximately a 10.5% increase in runoff.

Area Number (shown in Figure), Stream Gage Location and WY population center the gage is near	Cumulative Annual Runoff (acre-feet)	Additional Runoff (acre-feet)
1. HORSE CREEK AT SHERMAN RANGER STATION, WY	49,940	5,244
2. SOUTH HORSE CREEK NEAR MERNA, WY	15,585	1,636
3. SOUTH COTTONWOOD CREEK NEAR BIG PINEY, WY	25,535	2,681
4. NORTH PINEY CREEK NEAR MASON, WY	40,278	4,229
5. MIDDLE PINEY CR BEL SOUTH FORK, NR BIG PINEY, WY	18,285	1,920
6. SOUTH PINEY CREEK NR BIG PINEY, WYO	33,716	3,540
7. DRY PINEY CREEK NEAR BIG PINEY, WYO.	2,593	272
8. LA BARGE CREEK NR LA BARGE MDWS. RANGER STA, WY	10,187	1,070
9. HAMS FORK BELOW POLE CREEK, NEAR FRONTIER, WY	80,323	8,434
10. SMITHS FORK NEAR BORDER, WY	134,443	14,117
11. SALT RIVER NEAR SMOOT, WY	25,552	2,683
12. COTTONWOOD CREEK NEAR SMOOT, WY	30,946	3,249
13. SWIFT CREEK NEAR AFTON, WY	59,354	6,232
14. STRAWBERRY CREEK NEAR BEDFORD, WYO.	49,245	5,171
15. GREYS RIVER AB RESERVOIR NR ALPINE WY	467,575	49,095
TOTALS	**1,043,557**	**109,573**

Table 12-6
Summary of <u>April-July Runoff</u> for the Salt River/Wyoming Ranges shown in Figure 12.1. Additional Runoff calculated assumes a 10% increase in April 1st snowpack, which would produce approximately a 12.7% increase in runoff.

Area Number (shown in Figure), Stream Gage Location and WY population center the gage is near	Cumulative April-July Runoff (acre-feet)	Additional Runoff (acre-feet)
1. HORSE CREEK AT SHERMAN RANGER STATION, WY	46,676	5,928
2. SOUTH HORSE CREEK NEAR MERNA, WY	13,584	1,725
3. SOUTH COTTONWOOD CREEK NEAR BIG PINEY, WY	18,099	2,299
4. NORTH PINEY CREEK NEAR MASON, WY	28,991	3,682
5. MIDDLE PINEY CR BEL SOUTH FORK, NR BIG PINEY, WY	13,515	1,716

6. SOUTH PINEY CREEK NR BIG PINEY, WYO	20,687	2,627
7. DRY PINEY CREEK NEAR BIG PINEY, WYO.	2,143	272
8. LA BARGE CREEK NR LA BARGE MDWS. RANGER STA, WY	7,799	990
9. HAMS FORK BELOW POLE CREEK, NEAR FRONTIER, WY	69,385	8,812
10. SMITHS FORK NEAR BORDER, WY	94,371	11,985
11. SALT RIVER NEAR SMOOT, WY	21,140	2,685
12. COTTONWOOD CREEK NEAR SMOOT, WY	20,766	2,637
13. SWIFT CREEK NEAR AFTON, WY	37,469	4,759
14. STRAWBERRY CREEK NEAR BEDFORD, WYO.	26,822	3,406
15. GREYS RIVER AB RESERVOIR NR ALPINE WY	327,145	41,547
TOTALS	**748,590**	**95,069**

Some may question how a 10% increase in April 1st snow water content can result in more than a 10% increase in streamflow. This result has been observed in modeling studies that used more sophisticated hydrologic models. The explanation given for such an outcome is that a higher percent of the increased snow water runs off because base conditions account for most of the losses such as infiltration and evaporation (Stauffer and Williams, 2000).

The estimated total annual water year and April – July increases due to cloud seeding found in Tables 12-5 and 12-6 (109,973 and 95,070 ac-ft respectively) can be broken down into estimates of increased streamflow by seeding mode. This information is provided in Table 12-7. The estimated incremental contribution of each seed mode is discussed in section 6.11.

Table 12-7 Estimated Streamflow Increases (acre feet) by Seeding Mode

Contribution to 10% SWE Increase	**Manual Generators (7.07%)**	**Remote Generators (1.18%)**	**Aircraft (1.75%)**	**Total (10.0%)**
Water Year Runoff	77,468	12,930	19,175	109,573
Apr. – Jul. Runoff	67,214	11,218	16,637	95,069

The percentages for each of the three seeding modes add up to the estimated total increase of 10% found in Tables 12-5 and 12-6. An assumption of a 10.5% increase in runoff resulting from a 10% increase in SWE (as reported earlier in this section, based on hydrologic analysis) was used in the calculations in Table 12-7. This information will be utilized in section 14.0 in an attempt to provide some preliminary benefit/cost information by seeding mode.

13.0 COST ESTIMATES

Preliminary cost estimates have been prepared for: 1) a pre-seeding season of sampling, 2) annual cost of a program only utilizing manually operated, ground based silver iodide generators (core program) 3) the annual cost of adding five remotely operated, ground based silver iodide generators to the core program, and 4) the annual cost of adding one turbine cloud seeding aircraft to the core program. Costs are provided for a five-month operational period (tentatively Nov. 15 – Apr. 15). Costs include estimates of the reimbursable expenses of seeding (e.g., seeding materials and flight hours).

13.1 Estimated Cost to Conduct One Winter Season of Preliminary Data Acquisition

As mentioned in Section 6.7 NAWC recommends one winter season of project specific data collection prior to the beginning of any seeding activities. Data of primary interest will be the presence, frequency and magnitude of supercooled liquid water (slw) in winter clouds over and upwind of the proposed target areas and the temperature, moisture and wind structure of the lower atmosphere during winter storm periods. It is proposed that a passive microwave radiometer and one icing rate meter be utilized to collect the slw information and that rawinsondes be launched every six hours during storm periods. The radiometer and radiosonde receiver would be located at a suitable location in Star Valley and the icing rate meter installed at an exposed mountainous ground location that is accessible and has electrical power available. It is proposed that these systems be operated for the five-month period of November through March. The preliminary estimated costs for the three systems are as follows:

Microwave Radiometer, Icing Rate Meter and Rawinsondes

Set-up, Take-Down, Data Analysis and Reporting

Personnel		$14,200
Direct		
Land leases		$ 3,000
Travel/per diem		$ 1,000
Report		$ 750
	Total	$18,950

Five Months of Operations (Nov-Mar)

Rawinsonde Observations		$100,000
Radiometer Observations		$ 45,000
Icing Rate Meter Observations		$ 20,000
	Total	$165,000
	Grand Total	**$183,950**

Rawinsonde observations are budgeted for 100 releases during the November through March period. Radiometer observations would be acquired using a dual channel (water vapor and water liquid) microwave radiometer. The three types of observations are listed in descending order of priority. In other words, rawinsonde observations are listed as the first priority. This was done in case financial resources are not available to fund all three types of observations.

13.2 Manually Operated Silver Iodide Ground Generator Program (Core Program)

Assumptions: Five month program (Nov. – Mar.), 16 ground based generators sited at suitable local residences; estimated 3,000 seeding hours; local, part-time technician performing generator installation and removal, re-charging and maintenance tasks; direction of seeding activities from the contractor's headquarters; annual final report preparation including an analysis of possible effectiveness of the seeding operations, attendance at public meetings regarding the program as needed.

Set-up, Take-down and Reporting Costs

Personnel		$30,250
Direct		
Equipment (generators, propane tanks)		$10,100
Mileage, public meetings		$ 3,200
Insurance		$ 2,500
Final Report		$ 1,500
	Sub-total	$17,300
	Total	$47,550

Five Months Fixed Costs

Personnel		$60,225
Direct (technician travel, per diem, telephone calls, computer use charges, etc.)		$ 8,000
	Total	$68,225

Estimated Five Months Reimbursable Costs

Generator Usage, 3000 hours at $6.00/hr.		$18,000
	Grand Total	**$133,775**

13.3 Addition of Five Remotely Controlled, Silver Iodide Ground Generators to Core Program (13.2)

Assumptions: 5 remote generators purchased by program in first year of operation but costs amortized over a five year period, suitable sites can be found and leased on private lands, no EA or EIS required, servicing during the winter by snowmobile or helicopter, estimated 2400 seeding hours, operations directed from contractor's headquarters. Costs will inflate 5% for second and subsequent years.

Set-up, Take-down (first year)

Personnel		$ 55,000
Direct		
Acquisition of 5 remote generators		$200,000
Installation of generators		$ 20,000
	Sub-total	$220,000
	Total	$275,000

Five Months Operations

Personnel		$ 10,000
Direct		
Helicopter servicing		$ 20,000
	Total	$ 30,000

Estimated Reimbursable Costs

Generator Usage, 2400 hours at $12.00/hr.		$ 28,800
	Grand Total	**$333,800**

Set-up, Take-down costs (second year)

Personnel		$ 13,650
Direct		
Generator servicing		$ 10,500
	Sub-total	$ 24,150

Five Months Operations (second year)

Same as first year + 5%		$31,500

Estimated Reimbursable Costs (second year)

Same as first year + 5%	$30,240
Grand Total	**$85,890**

13.4 Addition of One Seeding Aircraft to Core Program (section 13.2)

Assumptions: lease of turbine engine aircraft equipped with acetone/silver iodide generators for 5 months, one aircraft pilot , base of operations established at suitable airport near target areas, project meteorologist stationed at operations base (seeding decisions will be made from this location), one project meteorologist assistant, no project dedicated weather radar (NWS NEXRAD radar to be used).

Set-up, Take-down

Personnel	$10,000
Direct	
Development of aircraft tracking software	$ 7,000
One-half month lease of aircraft	$25,000
Pilot, meteorologist per diem and travel	$ 3,000
Sub-total	$45,000

Five Months Operations

Personnel	$ 74,500
Direct	
Aircraft lease	$250,000
Office, hangar, computers, utilities	$ 10,000
2 vehicles	$ 7,500
pilot/meteorologist per diem	$ 20,000
Sub-total	$362,000

Estimated Reimbursable Costs

100 Flight hours @ $300/hr	$ 30,000
80 hours of airborne generator usage @ $80/hr	$ 6,400
Sub-total	$ 36,400
Grand Total	**$443,400**

13.5 Environmental Analyses

At this time it is unclear what, if any, environmental analyses may be required to activate the proposed program. If special use permits are required for siting of remotely controlled generators on federal lands, an environmental analyses complying with the National Environmental Policy Act (NEPA) will have to be conducted. For planning purposes a minimum supplemental budget of $100,000 is suggested, to cover these additional activities.

14.0 PRELIMINARY BENEFIT/COST ANALYSIS

The information presented in sections 12.0 and 13.0 of this feasibility study can be combined to provide initial benefit/cost estimates for the preliminary cloud seeding program design that has been developed for the SRWR.

Potential economic benefits from the conduct of the seeding project are estimated for an average winter season. The value of water can vary somewhat according to the basic principles of supply and demand, i.e., during dry and wet years, especially serial occurrence of dry or wet conditions. It is beyond the scope of this study to quantify that variability. Rather, we base our estimates on averages for the seeding effect during an average runoff year, the resultant average augmented runoff, and the average value of the additional water in a primary use context. Many secondary benefits result from increases in water availability and enhanced stability of fresh water supplies, but quantifying them can be laborious, so they are not included in the estimations in this study. Thus, the findings reported here are considered to be conservative.

The costs associated with the conduct of seeding operations and all the attendant logistics, data acquisition and a practical (historical target-control regression) seeding effectiveness evaluation, as shown in section 13.0, are included, tiered according to the core project concept. The preliminary project design recommends a first-season campaign of project area-specific data acquisition toward finalization of the design, but no routine operational seeding is envisioned for that season, so no benefit/cost estimates are made for that season.

14.1 Allocation of Water Use

Our simple economic value model allocates the runoff from the SRWR target area under average conditions as shown in Table 14-1. Runoff from the seeding project target area contributes to four rivers as shown in a stylized manner in Figure 14.1. The proportion of runoff allocated to the primary first uses varies from basin to basin, with one-time hydroelectric power generation residing at the downstream end in this exercise. First, estimates were made regarding the proportion of the augmented runoff that would be available for the region's hydroelectric power generating facilities, i.e., the proportion not withdrawn for consumptive uses. These estimates were based on general understandings of water use in the region, not on a detailed analysis. Then the upstream consumptive uses were in-house estimates of first-use categories for each sub-basin, those withdrawals split uniformly, with 90% allocated to agriculture and 10% to municipal use, applying state-wide average estimates provided by WWDC. Secondary and tertiary uses/benefits, etc, of the water were not considered.

Table 14-1
Estimated Allocation of Augmented Runoff to Primary First Uses

	Agricultural	Municipal	Hydroelectric
Green River	54%	6%	40%
Bear River	67%	8%	25%
Salt River	63%	7%	30%
Greys River	5%	0%	95%

Agriculture constitutes the greatest proportional use of the water, with the exception of the Greys which drains from its mountain-bound basin essentially directly into Palisades Reservoir without any significant upstream consumptive uses.

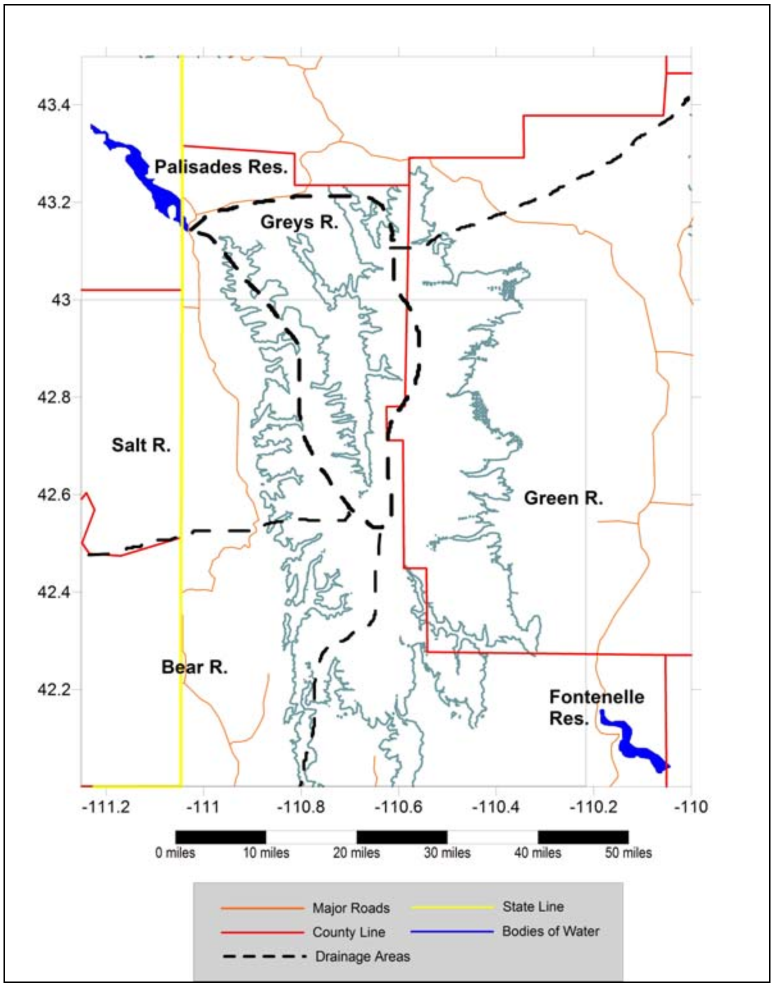

Figure 14.1 Stylized Depiction of the Drainages Receiving Runoff From the Project Target Area

14.2 Economic Value of Water in the Region

In this assessment, the economic value of the augmented runoff is limited to primary first uses. The many additional benefits of the augmented water supplies are not factored into the calculations in this section of the study. For each use, the value is expressed in dollars per acre-foot (AF).

Agriculture

An estimate of the value of water to agricultural interests in the region was obtained from Harvey Economics of Denver, via a referral from the WWDC. They provided a "transaction cost" estimate of $10-$12 per AF. An average value of $11 per AF was selected for this exercise. This is consistent with the value used in the weather modification feasibility study conducted for the Wind River and Medicine Bow/Sierra Madre Ranges (WMI, 2005).

Hydroelectric Power Generation

Electrical power rates fluctuate widely, depending on demand. In the intermountain west, the value of the power generated from hydroelectric facilities can vary from as low as $25 per mwh during off-peak demand periods to well over $100 during peak demand. Estimates of average annual values were obtained from a number of sources applicable to the region, ranging from $20-$50 per mwh. We have elected to use the average of $35 per mwh in this feasibility study, despite the fact that the timing of snowmelt runoff provides water during the beginning of the peak summer demand period and could theoretically be held in storage for meeting peak demand. To arrive at a value per AF of additional water we used an average value for turbine efficiency (power production) of 0.1875 mwh per AF from a range of 0.1 to 0.275 reported for USBR facilities in Wyoming (WMI, 2005). The calculation thus yields a value of $6.56 per AF for use in the SRWR feasibility study.

Municipal Water Supply

Estimates of the value of water for consumptive use by municipalities in Wyoming, as provided by Harvey Economics, range from $75 to $100 per AF. Again, we selected the mid-point, $87.50, in our economic benefit estimations. This is consistent with the value used in the weather modification feasibility study conducted for the Wind River and Medicine Bow/Sierra Madre Ranges (WMI, 2005).

14.3 Augmented Runoff Amounts and Values

Table 14-2 presents the economic value assigned to each primary use for each river flowing from the seeding project target area. Average values for a fully-implemented seeding project, i.e., with three seed modes employed, are shown.

Augmented runoff values are obtained by applying a 10.5% increase (resulting from a 10% increase in SWE due to cloud seeding) to the mean annual runoff. For the three primary first uses for the water, the economic values are obtained by multiplying the augmented runoff values by the corresponding water allocation percentages from Table 14-1 and the dollar values per AF of water.

Table 14-2
SRWR Snowmelt Runoff Augmented Amounts and Values
(average annual runoff)

	Greys	Salt	Green	Bear	Total
Avg Annual (AF)	467,575	165,097	276,442	134,443	1,043,557
Augmented (AF)	49,095	17,335	29,026	14,117	109,573
Ag Value ($11.00/AF)	$27,002	$120,132	$172,414	$104,042	$423,590
Muni Value ($87.50/AF)	0	$106,177	$152,387	$98,819	$357,383
Hydroelectric Value ($6.56/AF)	$305,960	$34,115	$76,164	$23,152	$439,391
Total Value	$332,962	$260,424	$400,965	$226,013	$1,220,364

The total first use economic benefit from a fully-implemented operational cloud seeding project for the SRWR is estimated at $1.22 million. As has been noted earlier, the additional economic benefits downstream of the hydroelectric power plants are not factored here. If the value of the additional water volume to recreation, fisheries, tourism, threatened and endangered species, and downstream uses could readily be quantified and included, the projected value would be even greater. Good examples are the value of the additional water to agricultural interests below Palisades and Fontenelle Reservoirs. In the particular case of the Greys River, a very large percentage of its augmented flow would be available below the powerplant for agricultural and municipal uses along the Snake River. Thus, the economic benefits reported here are conservative. These economic values are used later in this section in combination with estimated costs associated with the various cloud seeding methods and their incremental contribution to the augmented water supply, to estimate a) the cost per AF to produce the additional water and b) the benefit/cost aspect of the project operations.

Table 14-3 presents the costs for five years of seeding operations according to a tiered concept which has use of manually-operated ground-based seeding generators as its foundation, i.e., the core program. The addition of remotely controlled ground-based generators and one high performance seeding aircraft are shown as incremental cost increases. In all cases, a 5% annual inflationary increase is applied. Equipment lease and installation costs are included for the core program. The remotely-controlled generator option includes acquisition costs for these generators. The aircraft costs assume a turnkey lease for that portion. The average values shown for each component assume a five-year project.

Table 14-3
Seeding Program Costs

	Core Program*	Add Remotes*+	Add Aircraft
Year 1	$133,775	$173,800	$ 443,400
Year 2	$140,464	$125,890	$465,570
Year 3	$147,487	$132,185	$488,849
Year 4	$154,861	$138,794	$513,291
Year 5	$162,604	$145,733	$538,955
Average	$739,191/5= $147,838	$716,402/5= $143,280	$2,450,065/5= $490,013

* Includes equipment acquisition and installation costs amortized over 5-year period
\+ Does not include additional costs of environmental analyses if sited on federal lands.

The cost of producing the augmented runoff during an average runoff year and the benefit/cost ratios associated with conduct of the core seeding program and additions to it are derived using the 5-year average project costs and the proportional contribution of each seeding system to the augmented runoff, according to the percentages shown in Table 14-4 (also appears as Table 12-7 in this study). The core program using manual generators is thought to produce about 70.7% of the total average seasonal augmentation potential; remote generators add 11.8%; aircraft add 17.5%). The resultant costs per AF of additional water and overall estimated benefit/cost values are shown in table 14-5.

Table 14-4 Estimated Annual Streamflow Increases by Seeding Mode

Contribution to 10% SWE Increase	**Manual Generators (7.07%)**	**Remote Generators (1.18%)**	**Aircraft (1.75%)**	**Total (10%)**
Water Year Runoff	77,468	12,930	19,175	109,573
Apr. – Jul. Runoff	67,214	11,218	16,637	95,069

Table 14-5
Estimated Costs to Produce Additional Water and Estimated Benefit/Cost Ratios

	Core Program (CP)	CP Plus Remote CNG's	CP Plus Aircraft	CP Plus Remotes and Aircraft
Ave. Cost to Produce Extra Water	$147,838	$291,118	$637,851	$781,131
Ave. Water Year Streamflow Increase	77,468	90,398	96,643	109,573
Cost Per AF	$1.91	$3.22	$6.60	$7.13
Benefit	$862,797	$1,006,800	$1,076,361	$1,220, 364
Benefit / Cost	5.8	3.5	1.7	1.6

The reader is reminded that these values apply to an average winter precipitation and runoff season. Average values were used for the economic value of the additional runoff and only direct first use of the water was considered. In addition, some drainages do not have any historical streamflow records (i.e., LaBarge Creek). Thus, the values in the table are conservative.

Not surprisingly, the core program cost to produce additional water and benefit/cost ratio are the most attractive, since manually operated ground-based generators are the least costly of the seeding systems in terms of acquisition and operating costs. Analyses of atmospheric stability during storm periods indicated that use of manually operated generators could achieve about 70% of the potential seasonal runoff augmentation potential.

Addition of remotely controlled ground-based generators raises the percentage of attainable potential augmentation to about 84% and the benefit/cost ratio remains above 3. Addition of a high-performance aircraft, whether to just the core program or in combination with remotely controlled generators, decreases the overall project benefit/cost ratio to less than 2, but the overall cost to produce the additional water remains well below $8.00 per AF.

The costs and benefit/cost estimates could be refined by more in-depth analysis, especially into some of the more prominent secondary economic benefits, and the results would look even more favorable. The reader is reminded that the American Society of Civil Engineers (2006) recommends a 5/1 benefit/cost ratio at the design stage of a program to consider the program potentially feasible. If their criterion were used, only the core program using manually operated silver iodide ground generators would be considered economically viable. However, it is obvious that any decision regarding the value and economic viability of the program rests with the prospective program sponsors.

It is possible that a larger network of remotely controlled silver iodide generators could be used in place of a core program using manually operated generators. It is likely, however, that the approach would not yield a 5/1 benefit/cost ratio.

15.0 REPORTS AND EXECUTIVE SUMMARIES

A variety of reports and summaries with a specified number of copies were outlined in the RFP. These reporting requirements have been completed and are summarized in Table 15-1.

Table 15-1
Reports and Summaries

Type	Provisions	Word Processing	Number of Copies	Number of CDs
Draft Report	Results of Work	Word and Adobe Acrobat	15	0
Final Report	Incorporation of Technical Review Comments	Word and Adobe Acrobat	25 1 unbound	12
Executive Summary (less than 10 pages)	Summarize purpose, findings, recommendations, project configuration and costs	Word and Adobe Acrobat	1 unbound	12

The final report addresses comments and suggestions offered by WWDC staff and members of the weather modification Technical Advisory Team comprised of individuals from the Wyoming State Engineers office, University of Wyoming, U.S. Forest Service and a representative of the Star Valley Conservation District. The efforts of these individuals are appreciated.

16.0 CLIMATOLOGICAL MONITORING OF THE STUDY AREA

NAWC began the collection and archiving of pertinent climatological information for the study area beginning November 1, 2005. Types of data that were archived include surface and upper air data, precipitation data, fine scale model prediction fields, satellite and radar data and avalanche advisories. This archival process was continued through April, 2006. This information would assist in the implementation of the proposed pilot project(s).

17.0 SUMMARY AND CONCLUSIONS

The Wyoming Water Development Commission (WWDC) contracted with North American Weather Consultants (NAWC) of Sandy, Utah for performance of a comprehensive study of the feasibility of applying modern cloud seeding methodology for winter snowpack augmentation in the Salt River and Wyoming Ranges (SRWR) and development of a preliminary operational cloud seeding project design. This section presents the key elements, findings, conclusions and recommendations of the feasibility study. The study includes a survey of relevant prior research and operational seeding programs, considerable analysis of project area-specific historical weather data, computer modeling and assessment of potential cloud seeding methods, plus evaluation techniques. Analyses of various meteorological data indicate that the winter storms in the region frequently exhibit characteristics favorable for snowfall augmentation via cloud seeding. A core operational project design is presented. The study also includes hydrologic estimates of the potential project yield in terms of additional runoff and the estimated costs associated with conduct of the project. Preliminary benefit/cost estimates for the proposed project design are presented.

17.1 Project Area

The project target area consists of the terrain above 8,000 feet elevation in the parallel, north-south oriented Salt River and Wyoming Ranges in western Wyoming near the border with Idaho, comprising an area of about 3,590 square miles. The target area is shown in Figure 17.1. The Greys and Salt Rivers originate in the target area, draining north to join the Snake River at Palisades Reservoir. Several streams drain from the eastern slopes of the Wyoming Range, contributing to the Green River and Fontenelle Reservoir. Both Palisades and Fontenelle have hydroelectric power generation facilities, as do the Hams and Smiths Forks which flow from the southern portion of the target. Runoff from the target area is also of benefit to agriculture and municipalities, as well as recreational interests. Approximately 75% of the annual precipitation in the target area accumulates during the October-April period, with area average snowpack water equivalent on April 1 of about 22 inches.

17.2 Potential Yield/Benefits

The policy statements of the Weather Modification Association and the American Meteorological Society state that there is statistical evidence that precipitation from supercooled (clouds whose temperatures are colder than 32^0 F) orographic clouds (clouds that develop over mountains) has been seasonally increased by about 5% to 15%. A similar statement published by the World Meteorological Organization also indicates that there is statistical evidence for precipitation increases from supercooled orographic clouds although not stating a range of effect. The American Society of Civil Engineers supports and encourages development of atmospheric water (also known as weather modification or cloud seeding) for beneficial uses, and has published a standard and manual of professional practice for cloud seeding for the purpose of precipitation enhancement.

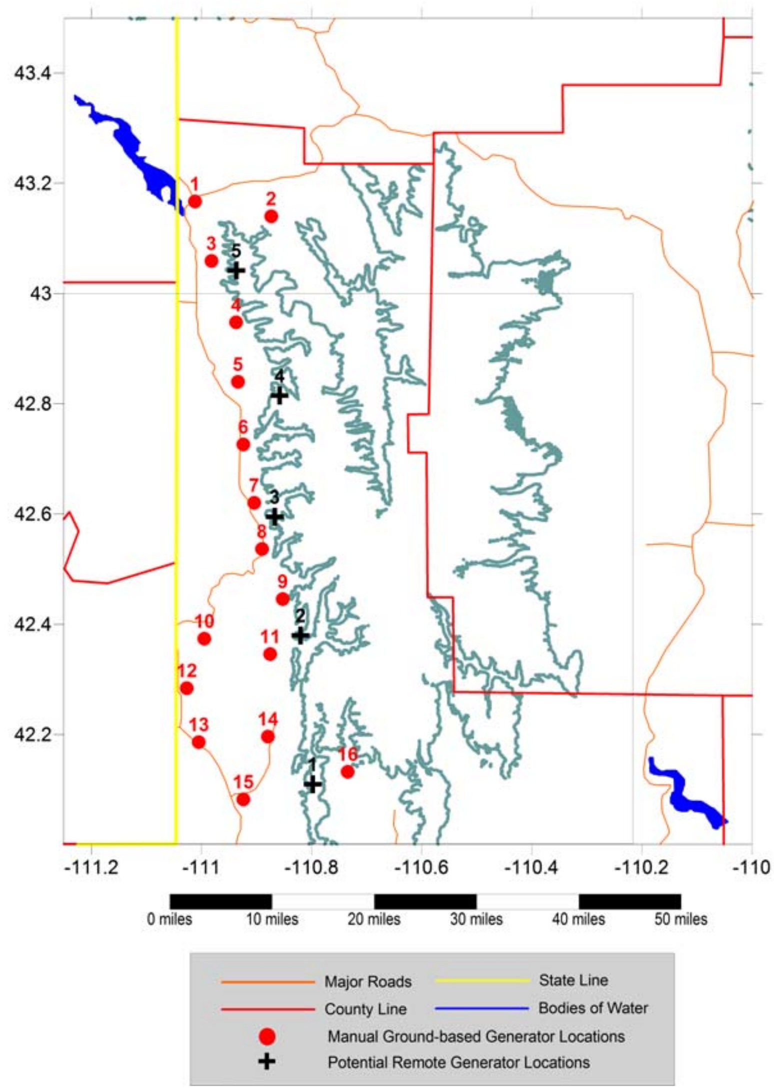

Figure 17.1 Proposed Target Area (8000 foot contour), Manual (red circles) and Remote (black crosses) Generator Sites

A review of the estimated results of several similar winter orographic seeding projects conducted in the western states, some for decades, supports the potential for precipitation augmentation ranging from about 5% to 15%, as referenced and cited earlier in this report.

A reasonable expectation of the average effect is of about a 10% increase in area average snow water equivalent in the SRWR, which would amount to a little over two additional inches of water content in the project area snowpack as of April 1.

Using real data, analysis of the variability in storm temperature structure over the project area for a ten year period was performed and then applied in conjunction with cloud top temperature partitioned seeding results from a research program in Colorado (Climax) to estimate the anticipated effects for the SRWR project. The analysis applied the varying Climax seeding effects within cloud top temperature categories according to their seasonal occurrence in the SRWR cloud top temperature data during the ten year period. Some in the scientific community have expressed some reservation regarding the absolute values of seeding effect from the Climax experiments. That fact notwithstanding, the importance of distinguishing between cloud top temperature classes is well established, and it is thought that the values from Climax are reasonable approximations. Using that Climax method, the ten-season average estimated (calculated) increase for the SRWR target area is 10%. That factor was applied at twelve surface measurement sites in the target area, yielding estimated increases in average April 1 snowpack water equivalent ranging from 1.27" to 3.05" and a target area average difference (increase) of 2.17" (55mm) of water due to seeding.

Hydrologic evaluations indicate that the estimated 10% increase in April 1st snowpack water equivalent (content) in the SRWR would result in an average water year increase in runoff from the proposed seeding target area of the order of 109,573 acre feet. Estimated average increase in April through July runoff would be 95,070 acre feet. The estimated incremental contribution of each seed mode as discussed in section 6.11 is provided in Table 17-1. For example, a core seeding program using lower elevation generators is predicted to result in approximately a 7% increase in April 1st snow water content with the associated runoff shown in the table. The addition of remote generators to this core program is estimated to result in an additional 1.2% increase in April 1st snow water content. Likewise, the addition of a seeding aircraft is estimated to result in a 1.8% increase. The approach proposed is that lower elevation manually operated ground generators would be used when it is expected that they would be effective during the seedable periods. If they are not expected to be effective, then higher elevation remote generators or aircraft might be effective. If low elevation generators were not proposed, then the remote generators and/or aircraft would be used more frequently resulting in higher percentage increases than those indicted in Table 17-1. In other words the percentages and increases in this table are additive starting from the increases predicted to result from the lower elevation core program design.

Table 17-1 Estimated Streamflow Increases by Seeding Mode

Contribution to 10% SWE Increase	Manual Generators (7.07%)	Remote Generators (1.18%)	Aircraft (1.75%)	Total 10%
Water Year Runoff	77,468	12,930	19,175	109,573
Apr. – Jul. Runoff	67,214	11,218	16,637	95,069

17.3 Project Goals and Scope

The WWDC indicated that the project feasibility and preliminary design considerations should be focused on operational aspects, rather than carrying a strong ongoing research component. **Accordingly, the primary project goal is stated as increasing winter snowpack in the target area at a favorable benefit/cost ratio without producing any significant negative environmental impacts, and its scope reflects that primary goal.** Seeding operations are to be conducted on a non-randomized basis. Randomization is a technique often used in the conduct of research programs whereby approximately one-half of the potential seed cases are left unseeded to allow a comparison with the seeded cases. Evaluation efforts are to be developed and incorporated. Limited investigational elements are included in the design, whereby measurements highly focused on a) identifying the presence of supercooled liquid water, the substance targeted by glaciogenic (ice forming) seeding methods and b) characterizing the vertical atmospheric structure via project specific rawinsonde (balloon) soundings are recommended for conduct on a phased rather than ongoing basis, to help maintain program cost effectiveness. Beyond the core program, "piggybacked" research components could be added on a non-interference basis if interest develops and adequate additional funding from other sources is obtained.

17.4 Desert Research Institute Modeling Work

The Desert Research Institute (DRI) served as a subcontractor to NAWC on this study. DRI's task was to utilize atmospheric modeling on two storm case studies to examine the meteorological features of these storms of importance to cloud seeding potential and targeting of seeding materials. Meteorological parameters of interest included: 1) presence of supercooled liquid water (the primary ingredient necessary for there to be a potential to modify the clouds artificially) 2) low and mid level wind flows and 3) vertical temperature structure. The latter two parameters are important in terms of activation of seeding materials and the transport and diffusion of these materials. DRI used two models in the performance of this work: 1) a well known prediction model called MM5 and 2) a DRI proprietary model known as the Lagrangian Random Particle model (LAP). The second model is used to predict the transport and diffusion of seeding particles released from ground locations during storm periods. This model does not predict the nucleation, growth and fallout of ice crystals formed by the seeing materials.

Two winter storm cases (chosen from storms that occurred during the 2004-2005 winter season) were analyzed. Verification of MM5 predictions included comparisons with synoptic maps, NWS soundings and precipitation observations in the Salt River Range. Verification of variables such as wind fields near the surface and cloud water over the mountains was not possible since little or no observational data existed. Likewise plume dispersion predicted by LAP could not be verified by observations.

For both case studies MM5 predicted orographic cloud water development over the Salt River and Wyoming Ranges. The duration of cloud water in both cases was not unlike observations within storms over other mountainous regions (see e.g., Super, 1999), and indicated the potential for cloud seeding was satisfied in that regard. The location of cloud water over upwind slopes was also similar to what has been observed in field studies in other mountainous regions, although the simulated depth and magnitude of the cloud water tended to be larger.

The seeding plume simulations from numerous ground locations in and around the Salt River and Wyoming Ranges were semi-quantitative in nature. They addressed the temporal evolution of seeding plumes over the target ranges and provided a visual representation of plume transport and the horizontal and vertical dispersion of plumes under a variety of wind conditions. The absolute concentrations of aerosols over the target ranges was not evaluated, nor was the potential concentration of active ice nuclei considered at the temperatures encountered by the plumes. The two cases produced a fairly limited range of temperatures at mountain top level. Case 1 mountain top temperatures were -8^0 to -10^0 C during the period when cloud water was predicted by MM5, so any plume transport to mountain top level or above would have encountered temperatures favorable for cloud seeding using silver iodide. Case 2 temperatures were higher, generally -5^0 to -6^0 C at mountain top level with an additional 500-600 m of vertical transport needed to reach the more favorable -8^0 C level.

Three sets of ground seeding sites were considered. High altitude sites, or mountain sites (M sites) were within the Salt River Range slightly upwind of the crest line. They were positioned to test the feasibility of seeding the Wyoming Range from the Salt River Range. If used in operations, they would need to be installed in the late summer or fall and operated remotely during the winter months. Sites in a second set of ground generators were mainly positioned on the west slope (W sites) of the Salt River Range above the valley but below the high altitude sites. Some of these were also on minor ridges and isolated hills to the west of the main range. It is suspected that most of these sites would also require remotely- controlled operation. In Case 2 a similar set of sites was positioned on the east slope (E sites) of the Wyoming Range. The final set of sites was positioned in the valley west of the Salt River Range along the main north/south road (R sites), mostly close to small towns.

The plume simulations using the LAP particle dispersion model indicated that the high altitude M-sites were potentially the most effective for ground-based seeding to target either the Salt River or Wyoming Ranges. In southwesterly to northwesterly airflow, transport over the Wyoming Range was predicted, and vertical dispersion was generally adequate to reach temperatures where silver iodide has significant activity. In addition to being above stable layers in the upwind valleys these sites were also frequently shown to be at or above the liquid cloud base. Case 2 indicated these sites would also be the most effective in southerly airflow where plumes were carried along the length of the Salt River Range. In the early situation in Case 2 where low-level easterly winds were predicted, these higher sites were experiencing more southerly flow and therefore several still showed plume transport over the target range.

The western slope W sites were potentially most effective with westerly winds. With the exception of the two most southerly sites and one site at the north end of the range, plumes moved across the target ranges. At times vertical transport was aided when plumes from the sites to the west of the Salt River Range were caught in a wave to the lee of one of the upwind ranges. In the early part of Case 1 where southwesterly flow was encountered at 3 km, winds to a depth above most of the W sites were channeled along the valley orientation and plumes from generators on the ridges and hills to the west of the Salt River Range were carried to the north and not across the target ranges. A few W sites on the west slope of the Salt River Range did show plume transport across the target. The southerly flow situation in Case 2 produced similar results, but in this case none of the W sites produced plumes that crossed the target.

Valley R sites were the least effective in southerly to southwesterly flow, mainly because they were more frequently subject to the channeling of winds moving north through the upwind valleys. Although not encountered in the two case studies it is likely that a similar pattern, but opposite in direction, would be produced by northwesterly and northerly winds. With the exception of the two most southerly sites, the valley sites showed their most favorable transport and dispersion over the targets in the westerly flow at the end of Case 1. This was also the most unstable period of the Case 1 storm. Due to light winds and unfavorable wind directions, valley sites appeared to be ineffective throughout Case 2. The possible exception was during a period when cloud water bands advected into the region and valley plumes showed adequate vertical transport to interact with these bands upwind of the target ranges.

The visual indications of plumes merging in the current case studies suggest a ground generator spacing of about 10 km would be needed to completely cover the target ranges with spreading and merging plumes of seeding aerosols. This takes into account only the physical dimensions of plumes, and not temperature considerations, silver iodide activity and the concentrations of ice particles that might be expected. Based on the simulated plume behavior in the valleys upwind of the target ranges it would not be advisable to position generators further upwind to increase the horizontal dimension over the target. It is unlikely that the plumes would be carried toward the target in most situations, and concentrations would likely too low to significantly modify ice particle concentrations.

17.5 Comments on DRI Modeling Work

Analyses of longer-term weather data would at first glance appear to present a somewhat different picture than that predicted by DRI through the use of atmospheric models to examine two specific case studies. The main difference between the evaluation described earlier in the overall study and the DRI modeling study is as follows. The main study produced an indication that valley (actually foothill) silver iodide generators would be effective approximately 67% of the time that seedable conditions are present. DRI's analysis, although based on only two case studies, would seem to indicate a lower effectiveness for low elevation generators. In the case of both analyses, there was no site-specific meteorological information available to compare with predictions or interpretations from adjacent or ancillary data sets. The primary questions are: 1) does supercooled liquid water occur frequently over the Salt River and Wyoming Ranges during the winter and if so what are the associated temperatures, 2) are there low level temperature inversions in Star Valley during winter storms and, if so, how often do they occur when supercooled liquid water is present and 3) what is the low-level wind structure during these events? It is precisely for these reasons that it is proposed that one season of project area specific data collection be conducted prior to the finalization of a seeding project design. Data would be collected on supercooled liquid water and on the temperature and wind structure of the lower atmosphere in Star Valley.

Furthermore, additional verification of the transport and diffusion predictions of the LAP is desirable before such predictions are accepted as being accurate. Unfortunately, this is a rather difficult task for two reasons: 1) atmospheric tracers are probably the only direct method through which these predictions could be validated (obtaining tracer data during storms from aircraft is difficult to accomplish safely over mountainous areas) and 2) the LAP model predicts only the transport and diffusion of seeding material, it does not predict the nucleation, growth and fallout of artificially generated ice crystals. As a consequence, it is unknown where the artificially generated ice crystals would be expected to fall. Finally, two case studies are not considered to be an adequate basis for the design of a seeding generator network. Many more such cases would be needed to develop a representative climatology assuming one were to accept the model predictions as being adequately accurate. Unfortunately, such modeling activities to develop such a climatology would be expensive.

It is strongly believed that as atmospheric models are improved and verified they will provide the ideal tool to accomplish many of the tasks related to development and conduct of winter cloud seeding programs.

Since there is some uncertainty regarding the effectiveness of valley/foothill based generators, additions to such a ground generator network through potential inclusion of higher elevation remotely operated ground generators and/or the use of a cloud seeding aircraft have also been proposed for consideration. The preliminary design that is summarized in the following section adopts this approach.

17.6 Seeding Project Preliminary Design

Seeding Methods and Materials

Prevailing temperature regimes favor use of silver iodide, the most commonly used glaciogenic seeding agent, as the most effective seeding material. Evaluation of representative atmospheric soundings, which document the vertical structure of the winter storm environment, suggests that effective seeding can frequently be accomplished using ground-based silver iodide nuclei generators. Analysis of atmospheric stability data during seedable storm situations shows that in about two-thirds (67%) of these seedable storm periods manually operated generators (the most cost effective release method) at lower elevations can be effective. That seeding method has been used for decades to good effect on a seeding project for the Smiths Fork portion of the SRWR target from the 1950's through the mid-1980's as well as in other climatologically and topographically similar areas of the west. Recommended locations are in the foothills and near the mouths of canyons. The "core" operational project design, therefore, incorporates this method as its foundation. A network of about sixteen sites is recommended, with approximate locations shown in Figure 17.1. The generator locations reflect the prevailing westerly-component flow during winter storms. Given the relatively narrow mountain barriers in the target area, use of a fast-acting silver iodide solution formulation is recommended.

Atmospheric temperature inversions could inhibit the vertical transport of seeding materials from lower elevations to the supercooled liquid water regions over the upwind barrier slopes in some of the storm periods. This factor was identified and documented in analysis of atmospheric soundings and in computer modeling studies for the area. Further, some areas where ground-based seeding would be desirable are not readily accessible during the winter months. For these reasons, it is recommended that an array of approximately five remotely controlled ground-based generators be considered for installation along the upwind (western) side of the Salt River Range at mid-barrier elevations. Their approximate locations are shown in Figure 17.1. Given the relatively narrow mountain barriers in the target area, use of a fast-acting silver iodide solution formulation is recommended. The recommendation of remotely-controlled systems is predicated on a favorable benefit/cost ratio being associated with their inclusion and with the assumption that special use permits can be obtained for the desired locations. Data analysis indicates that use of remotely controlled ground-based generators would enable seeding of an additional 17% of the total number of seedable storm periods, beyond the 67% considered to be effectively seedable using manually operated, lower elevation generators.

Airborne seeding with silver iodide may be conducted when the temperatures near the mountain crest height are too warm for silver iodide released from ground-based sites to be effective. Assuming the ability to fly safely in the desired areas upwind of the intended target area, aircraft can be flown at a temperature level appropriate for activation of the temperature dependent silver iodide nucleation process. Data analysis indicates that use of aircraft seeding would enable seeding of an additional 16% of the total number of seedable storm periods, beyond the 84% considered to be effectively seedable using manually operated lower elevation generators and remotely controlled ground-based generators. The area storm climatology indicates that airborne seeding could be of particular benefit during the month of April if operations are extended beyond the recommended core project period of November – March. This is due to the typically warmer storm conditions in April and the aircraft's ability to place the seeding material in more elevated supercooled liquid water zones. If airborne seeding is to be conducted, it is recommended that turbine engine aircraft be used. This recommendation is based primarily on aircraft performance as it relates to safety considerations, given the airframe icing that occurs during seeding operations. Potential bases of operations for aircraft include airports at Pocatello and Idaho Falls in Idaho and Jackson, Wyoming. A decision regarding inclusion of aircraft seeding in the project design can be made at the sponsor's discretion, if a benefit/cost analysis of this option is favorable. It is conceivable that the core program utilizing manually operated ground generators could be augmented by aircraft seeding without the use of remotely controlled, ground based silver iodide generators. This combination may result in the ability to seed a large majority of the seedable events.

Potential use of additional seeding methods was considered, including dry ice dispensed from aircraft, venting of liquid propane from mid-high elevation ground sites, and ground-launched rockets. For lack of evidence of significant large area positive effects, logistical issues, and benefit/cost considerations, these seeding methods are not recommended at this time for implementation in the SRWR project.

Based on the variability in plume behavior under different wind conditions it would be advisable to have meteorological measurements sufficient to characterize the surface and upper-air conditions during storm periods. Current networks (such as the BLM RAWS network) might be adequate for surface conditions, but an upper air sounding near the target ranges would be very useful. As suggested in the original Wyoming Feasibility Study (WMI, 2005), some type of dispersion or particle trajectory model, capable of being run in near real time, would be very helpful in determining what generators, if any, to operate in a specific storm situation. In addition a microwave radiometer to verify the presence of supercooled liquid water would also be helpful.

Operational Period

The primary seedable period extends from November through March. Although some seeding opportunities can occur outside the period, that five-month period is recommended for active operations because it typically includes the majority of the seedable storms.

Supplemental Meteorological Measurements

One winter season of supplemental data collection specific to the project area is proposed prior to a decision being made whether the fully operational SRWR seeding program should be implemented. Measurements would include rawinsonde (balloon) soundings to better characterize the structure of the storm environment, especially levels below mountain crest height. A strategically located ridge-top icing rate detector site would document the occurrence of supercooled liquid water. Microwave radiometer observations would document the vapor and liquid water in the winter storms. Analysis of data from these systems will help fine-tune the preliminary operational design. Comparison of the ice detector records with the radiometer data will indicate the extent to which a permanent ice detector site would be helpful in real time operational cloud seeding decision-making. This season of data collection would provide information to complete the preliminary design presented in this document.

Seeding Effectiveness Evaluation

Evaluations of the effectiveness of the cloud seeding program will be based on historical target and control techniques (target and control sites with the corresponding regression equations are provided in the report), plus some snow chemistry analyses verifying that silver above background levels is observed at various sampling points in the target areas.

17.7 Key Elements of Preliminary Seeding Project Design

- The suggested target area includes elevations above 8,000 feet located in Lincoln and Sublette Counties.
- Ground-based manually operated silver iodide generators are the core program release method.
- Supplemental mid-high elevation remotely controlled silver iodide generators are recommended for consideration, subject to benefit/cost considerations.
- Fast-acting silver iodide seeding solution formulations are recommended.
- Airborne seeding may be considered, subject to benefit/cost considerations.
- Seeding operations should be conducted full-time, with no randomization.
- Seeding suspension criteria will be followed with primary emphasis on percent of normal snowpack values and avalanche concerns.
- The primary seeding season will be November through March, with possible extension into April.

- Radar data from the National Weather Service radars can be used to view storms approaching the project area; a project-specific radar is not considered necessary.
- A one season campaign of rawinsonde, radiometer and ice detector measurements is recommended. Analysis of the one-season specialty measurements, in conjunction with other routinely available meteorological information, will assist in completion of the final project design.
- Surface snow chemistry sampling and analyses should be used to verify seeding material targeting.
- Historical target and control regression methods should be used to estimate seeding effectiveness.

17.8 Concluding Remarks

This feasibility and preliminary design study has concluded that an effective winter cloud seeding program can be established and operated for the Salt River and Wyoming Ranges. The program has the potential to enhance the snowpack by ~10% during an average winter season, with the resultant additional runoff estimated to be about 109,573 acre-feet. The cost of producing the additional runoff is estimated to range from approximately $2.00 to a little over $7.00 per acre-foot, which is a function of the seeding methodology that is employed. The core program, using only manually operated ground based silver iodide generators, is the most cost effective. This core program results in an attractive estimated project benefit/cost ratio of about 5.8/1, yielding an estimated 77,468 acre feet of additional runoff in an average year. The addition of higher elevation remote ground generators and or aircraft seeding to the core program results in higher estimated costs per acre foot and lower benefit/cost ratios. The additional water would benefit regional water supplies for agricultural and municipal use, hydroelectric generation and recreation. The benefit/cost estimates only considers potential primary benefits although there would be a number of secondary benefits as well. Conduct of the proposed single winter season of area-specific meteorological monitoring prior to the start of operational seeding would serve to refine the preliminary project design.

ACKNOWLEDGEMENTS

The guidance of Barry Lawrence of the Wyoming Water Development Commission (WWDC) helped us in the performance of this study. The assistance of Bruce Brinkman of the WWDC in providing hydrologic data and analysis was also quite beneficial. Harvey Economics of Denver, Colorado provided helpful information. The input from the Technical Advisory Team is also acknowledged. The cover photo was provided by Dave Bell of Pinedale, Wyoming (Dave Bell Photos.com). It was taken in the Bear Creek Drainage in the Salt River Range. The assistance of Meteorological Solutions, Inc. of Salt Lake City, Utah, acting as a sub-contractor to NAWC, in preparing a number of the graphics contained in this report and archiving of 2005-2006 winter season meteorological data is also acknowledged.

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Appendix A

Technical Advisory Team

Scott Armentrout, Medicine Bow Routt National Forest, Saratoga, WY
John Barnes, Wyoming State Engineer's Office, Cheyenne, WY
Greg Bevenger, Shoshone National Forest, Cody, WY
Dan Clark, Wyoming Department of Environmental Quality, Cheyenne, WY
Jane Darnell, USFS Wyoming Capital City Coordinator, Cheyenne, WY
Terry Deshler, University of Wyoming Dept. of Atmospheric Sciences, Laramie, WY
John Eise/David Copley, National Weather Service, Cheyenne, WY
Tom Florich/Liz Moncrief, Medicine Bow Routt National Forest, Laramie, WY
Lee Hackleman/Terry Gonzales, USDA Natural Resources Conservation Service, Casper, WY
Janet Kurman, Bureau of Land Management, Cheyenne, WY
Janine Powell/Robert Musselman, US Forest Service Rocky Mountain Research Station, Fort Collins, CO
Rick Schuler, Bureau of Land Management, Cheyenne, WY
Ken Shultz/Jeff Frazier, Wyoming Dept. of Transportation, Cheyenne, WY
Vern Stelter/Rick Huber, Wyoming Game and Fish Department, Cheyenne, WY
Joe Sullivan, National Weather Service, Riverton, WY
Michael Sweat, US Geological Survey, Cheyenne, WY
Craig Trulock, Bridger-Teton National Forest, Pinedale, WY
Eric Winthers, Bridger-Teton National Forest, Jackson, WY

Appendix B

Scoping Meeting Attendees

Afton, WY - Tuesday, July 19, 2005 3 P.M.

Don Griffith, North American Weather Consultants, Sandy, UT
Beth Thomas, USFS-Bridger Teton NF, Jackson, WY
Leron Allred, Star Valley Conservation District, Afton, WY
Rosalyn Allred, Dry Creek Irrigation, Afton, WY
Ross Turner, Lincoln County, Afton, WY
Jim Montuoro, WYDOT, Rock Springs, WY
Charlene Bucha Gentry, USFS-Bridger Teton NF, Afton, WY
Gregg R. Wilkes, Town of Afton, Afton, WY
Harry LaBonde, WY State Engineer's Office, Cheyenne, WY
Don DeLong, USFS-Bridger Teton NF, Afton, WY
Barry Lawrence, WY Water Development Commission, Cheyenne, WY

Marbleton, WY - Wednesday, July 20, 2005 10 A.M.

Harry LaBonde, WY State Engineer's Office, Cheyenne, WY
Barry Lawrence, WY Water Development Commission, Cheyenne, WY
Don Griffith, North American Weather Consultants, Sandy, UT
Eric Winthers, USFS-Bridger Teton NF, Jackson, WY
Terry Svalberg, USFS-Bridger Teton NF, Pinedale, WY
Paul McCarthy, PMPC Engineers, Saratoga, WY

Appendix C

Desert Research Institute (DRI) Modeling Case Studies

MM5 and Particle Dispersion Case Study 1: 7-10 December 2004

The first mesoscale modeling case study to investigate wind patterns and cloud water development over the Salt River and Wyoming Ranges covered the period from 00 UTC (Coordinated Universal Time) on 7 December to 00 UTC on 10 December 2004. The DRI Lagrangian particle dispersion model (LAP) was also used to study transport and dispersion of ground-released cloud seeding aerosols. The LAP runs included releases from high altitude generators in the target ranges themselves, lower sites at the upwind edges of the target ranges and separate ridges west of the target ranges, and a set of low altitude sites along the valley west of the main target ranges. The study area is shown in Fig. 1, where the area outlined in black is the inner domain of MM5.

For the storm period of interest, the western U.S. was in a pattern of moderate westerly flow. The dynamic forcing that led to cloud development and precipitation was contributed by two minor short wave troughs moving through the mean upper level flow. The first shortwave on 7-8 Dec was accompanied by a minor surface trough that eventually deepened to the lee of the Rockies. The second shortwave on 8-9 December strengthened the height gradient and winds over Wyoming, but had no distinct surface features. Winds aloft over the target ranges were predominantly westerly to west-southwesterly until the second trough passage, then veered to the northwest as a ridge developed behind the trough.

The MM5 run was initialized with NCEP reanalysis data beginning at 00 UTC on 7 December. The model was updated with new data every 12 hours and run through 00 UTC on 10 December. The model was run with three nested domains at horizontal grid spacings of 9-km (Domain 1), 3-km (Domain 2) and 1-km (Domain 3). Domain 3 was centered on the Salt River and Wyoming mountain ranges (Fig. 1). There were 38 vertical (sigma) levels with midpoints between 10 m and 14.55 km AGL.

Once MM5 was run for Case 1, the output was used to create model soundings at three NWS upper air sites; Boise, Salt Lake and Riverton. Model wind, temperature and humidity profiles compared remarkably well with observations. In like manner 500 mb model height patterns also compared well with synoptic maps at similar time periods. Model cloud liquid water predictions had no similar data set for comparison. However, model precipitation predictions at SNOTEL sites in the target ranges showed good correspondence in timing, but under predicted amounts by 30% or less. An example comparison using the Indian Creek SNOTEL snow water equivalent (SWE) accumulation is shown in Fig. 2.

In assessing cloud seeding feasibility, winds, temperature and cloud water development are three of the most important variables to consider. Based on the MM5 results, winds and temperature at cloud level were favorable for transporting seeding material over the target and producing ice nucleation by AgI provided supercooled cloud liquid was available. The model results indicated cloud liquid development was minimal, and confined mainly to the highest ridges (cap clouds) until after 06 UTC on 8 December. Figure 3 shows the wind and cloud liquid pattern at the 3-km level and 1-sigma level (surface to ~15m AGL) at 18 UTC on 8 December. The sites used as simulated AgI release points are shown as black dots. The black line segments in Fig. 3 (also shown in Fig. 1) are the locations where vertical cross-sections were created at 3-hour intervals throughout the simulation period. Winds at the 3-km level appeared to be favorable for aerosol transport across the target; however the low level winds were predicted to be light and directed along the upwind valleys, indicating aerosol transport from the lowest seeding sites to the liquid water regions shown at the 3-km level might not have been feasible.

Figure 4 shows the vertical cross-section constructed along the southwest to northeast line in Figs. 1 and 3. The wind and temperature were favorable for AgI seeding from sites W5 and M4, particularly from M4 which is shown to be at the -8^{o} C level and within the supercooled liquid cloud layer. Only the horizontal extent of cloud liquid could have inhibited ice particle growth.

By 06 UTC on 9 December winds and cloud water were predicted to be much more favorable for ground-based seeding operations (Fig. 5). As in Fig. 3, the cloud water is closely tied to the regions of higher terrain, but the amount and horizontal extent of the water is much larger than at the earlier time. The vertical structure of these variables is shown in the west-to-east cross-section at 06 UTC in Fig. 6. The orographic cloud water region over the target range appears to be enhanced by the broad wave induced by the mountain. Three ground generator sites (W4, R6 and M4 in Fig. 1) along the cross-section are also shown. The position of the generators, particularly the one at highest altitude (M4), relative to the cloud water, and the temperature structure suggest seeding from the ground would have been possible during this phase of the storm. The M4 site appears to be particularly well positioned in westerly flow, since the gap between the two ranges is minimal and nucleated ice particles would experience less downward motion in traversing the ranges.

Particle dispersion model simulations were used to confirm what the meteorological predictions suggested. The LAP model was initiated at 12 UTC on 8 December, near the time that MM5 predicted the first significant cloud liquid development. The model was run first to simulate aerosol plume dispersion from the higher altitude generator sites (W1-10 and M1-9), and then run again for simulations with the lower valley sites (R1-10). The model was run at 15-min time steps using the MM5 output files. Figure 7 shows a plan view and tilted perspective view of plumes from the higher sites at 18 UTC on 8 December; six hours after the simulated releases had begun. The indication is that only the highest sites (M2-M8) within the Salt River Range itself produced plumes that would have interacted with cloud liquid above the mountains, and that were transported in the proper direction. All other plumes either moved along the western edge of the range, or actually moved north and west of their points of origin. The plumes from lower sites also tended to move down into the valleys rather than up and over the main target ranges. This trend was even more evident with the lowest "valley" generator sites (R sites in Fig. 1) as shown by the perspective plume view in Fig. 8. Here plumes from sites to the west of the main range were transported north along the valley, and plumes from two sites at the southern end of the range moved around the target ranges into the adjacent valley to the east.

Figures 9 and 10 show how plume transport changed markedly during the latter part of the storm. Most plumes from the higher sites (Fig. 9) were carried across the target ranges. The exceptions were W2 whose plume remained in the valley to the west, and the two southernmost plumes (W9 and M7) which appear to skirt around the southern end of the target ranges. Vertical dispersion appears to be adequate to interact with the cloud water layer depicted in Fig. 6. The top panel of Fig. 9 also provides a means to estimate the generator spacing that would be required with the use of sites very close to the intended target regions. With sites slightly to the west of the main range, like W3, W4 and W5, the plumes (in this particular wind regime) tend to merge over the Salt River Range. The average spacing between these three generator sites is about 10 km. For sites like M2 and M3 which can potentially be used to seed the Wyoming Range, the proper spacing for coverage of the second range also appears to be about 10 km.

Figure 10 shows plume locations for the "valley" generator sites. Five of the eight sites shown produced plumes that were transported over the main target ranges, although concentrations over the mountains are indicated to be lower than for the sites in Fig. 9. This appears to be because the lower plumes are transported along the valley initially, and then up and over the mountains. They are therefore dispersed to some extent before moving into the cloud water regions. The three southernmost sites produced plumes that were transported too far south to affect the main ranges.

Based on the MM5 predictions for this case, the cloud water was generated by orographically-forced lifting, although mountain waves appeared to enhance the cloud water depth at times. There were a few isolated occurrences of cloud water in gravity waves induced by the mountains, but these were very short-lived and not positioned to provide viable cloud seeding opportunities using ground generators or aircraft. The cross-section analysis suggests that aircraft seeding might have been feasible, but only marginally so, for the time period between 00 and 09 UTC on 9 December. Figure 6 shows a cloud water region 20-25 km in width, extending up to a height up to about 5 km and centered over the target ranges. Assuming a Minimum Obstruction Clearance Altitude (MOCA) of 14-15,000 feet (4.3-4.6 km), a seeding aircraft might have been able to seed the western edge of these cloud water regions to enhance snowfall over the Wyoming Range. However, for fallout to occur over the target, the average wind speed between the seeding altitude and the mountain top would need to be 15 ms^{-1} or less. Cloud water extending further to the west of the target ranges would be preferable, and it is possible that MM5 under predicted the extent of the upwind cloud liquid.

The MM5 and LAP analyses indicated that ground seeding would have been feasible for up to 18 hours of the total storm period, with the best conditions occurring over the last 12 hours. The LAP analysis indicated seeding from the sites at the western edge of the Salt River Range and from sites within the Salt River Range (to target the Wyoming Range) was preferable to seeding from the upwind valleys. The highest altitude sites (M1-M9) produced the best results in all storm situations, with model results showing the sites to be frequently above cloud base and at temperatures at which AgI is an effective ice nucleant. There was also a period during the latter part of the storm when some valley sites produced plumes that were transported into the cloud water over the target ranges. Careful selection of sites would be needed to make use of any valley locations.

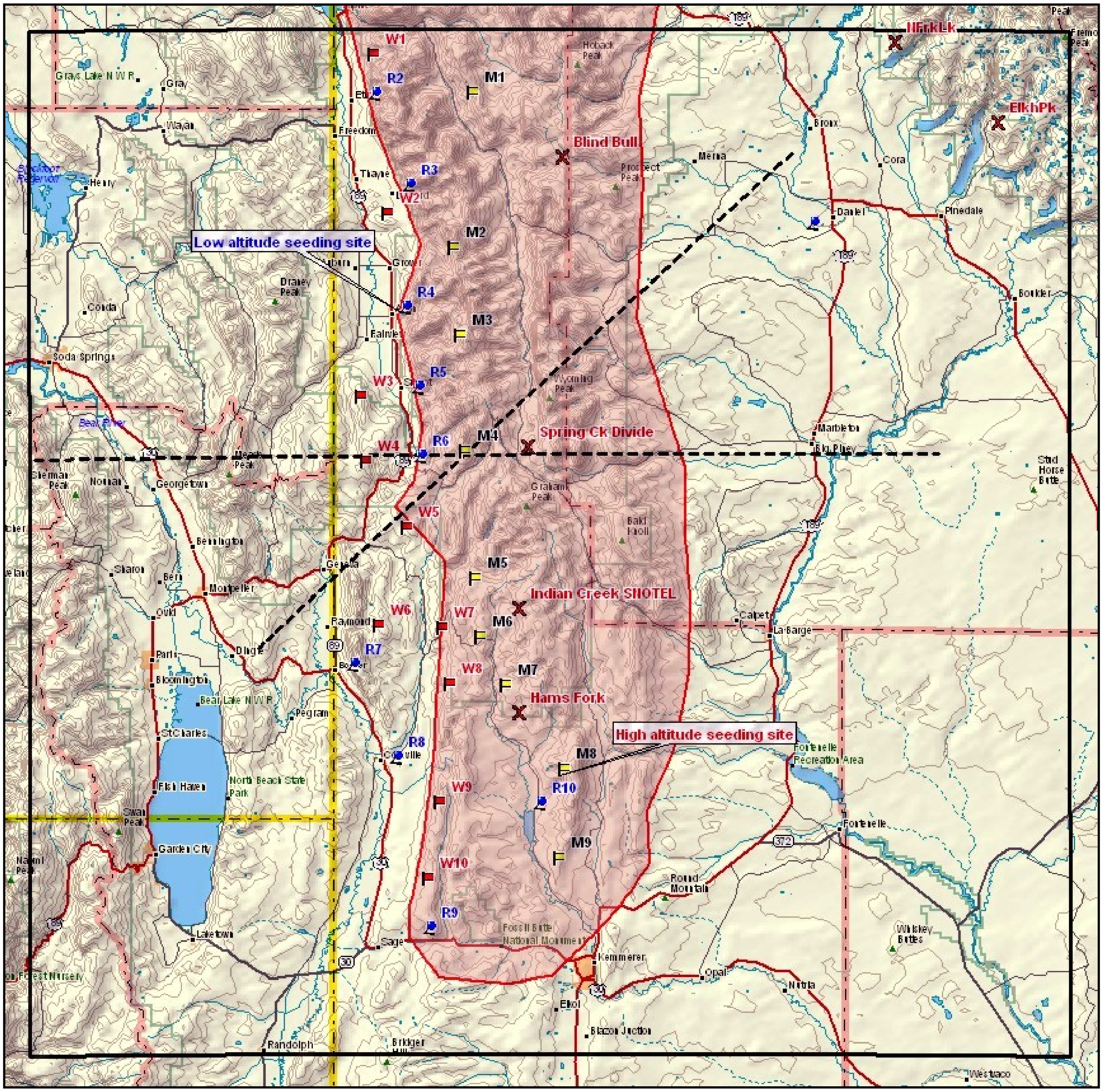


Figure 1. Map showing a portion of western Wyoming including most of the Salt River and Wyoming Ranges. The shaded region is the approximate target area for a snowfall enhancement project. The black square is the innermost domain of the MM5 model that used a grid spacing of 1-km. Black dashed lines are locations where vertical cross-sections were constructed from MM5 output. Simulated seeding aerosol releases were made from sites marked by pins and flags. W1-W10 are at the west edge of the target at altitudes somewhat higher than the valleys between mountain ranges. M1-M9 are within the Salt River Range at relatively high altitude, positioned to potentially seed the Wyoming Range. R1-R10 are low altitude sites mainly in the valley adjacent to the Salt river Range. The red X's are SNOTEL site locations, where ones in the upper right are in the Wind River Range.

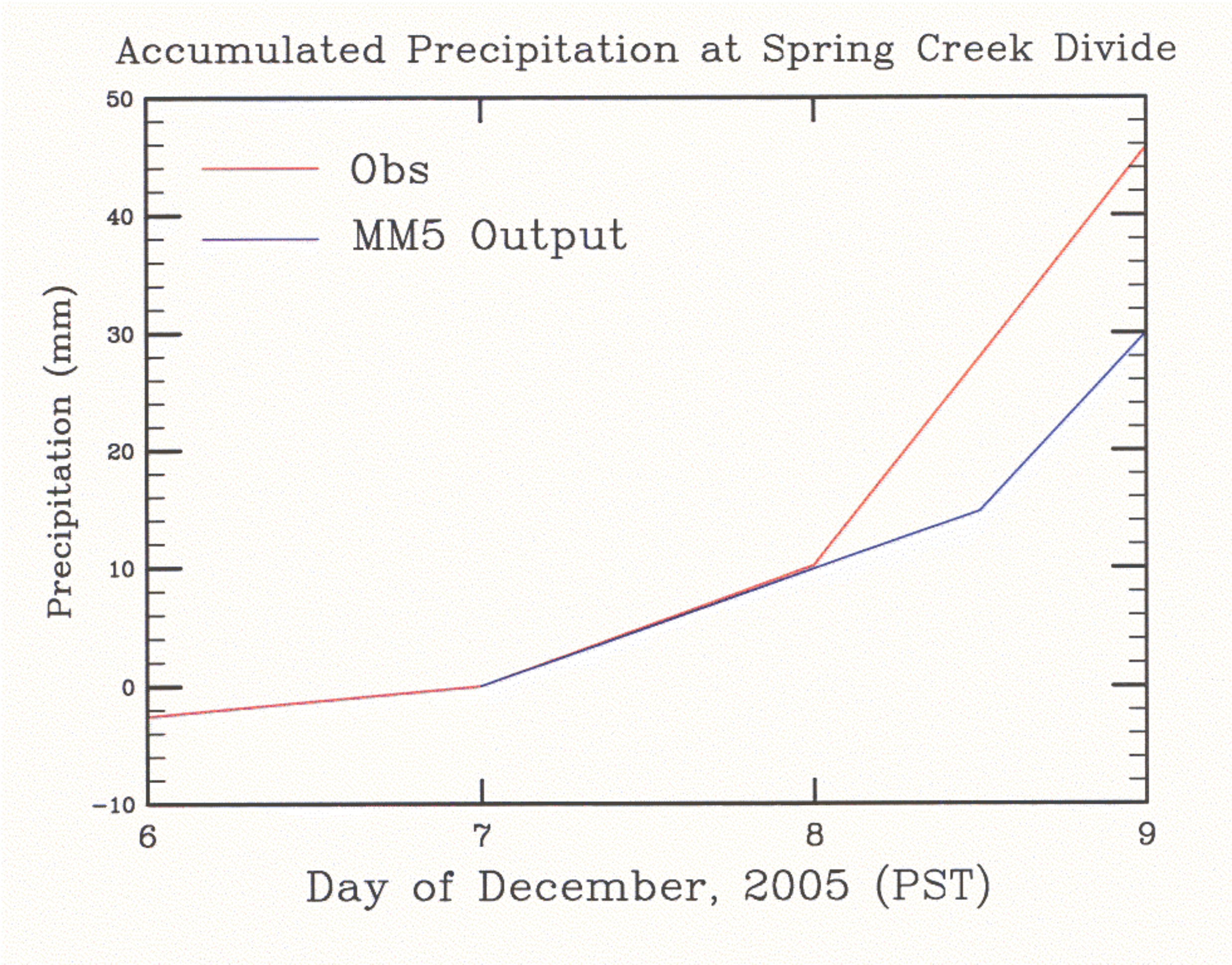


Figure 2. Comparison of MM5 precipitation accumulation (blue line) with SWE accumulation at the Spring Creek SNOTEL site (see Fig. 1). SWE was adjusted to zero at 00 UTC on 7 December, the start of the MM5 simulation.

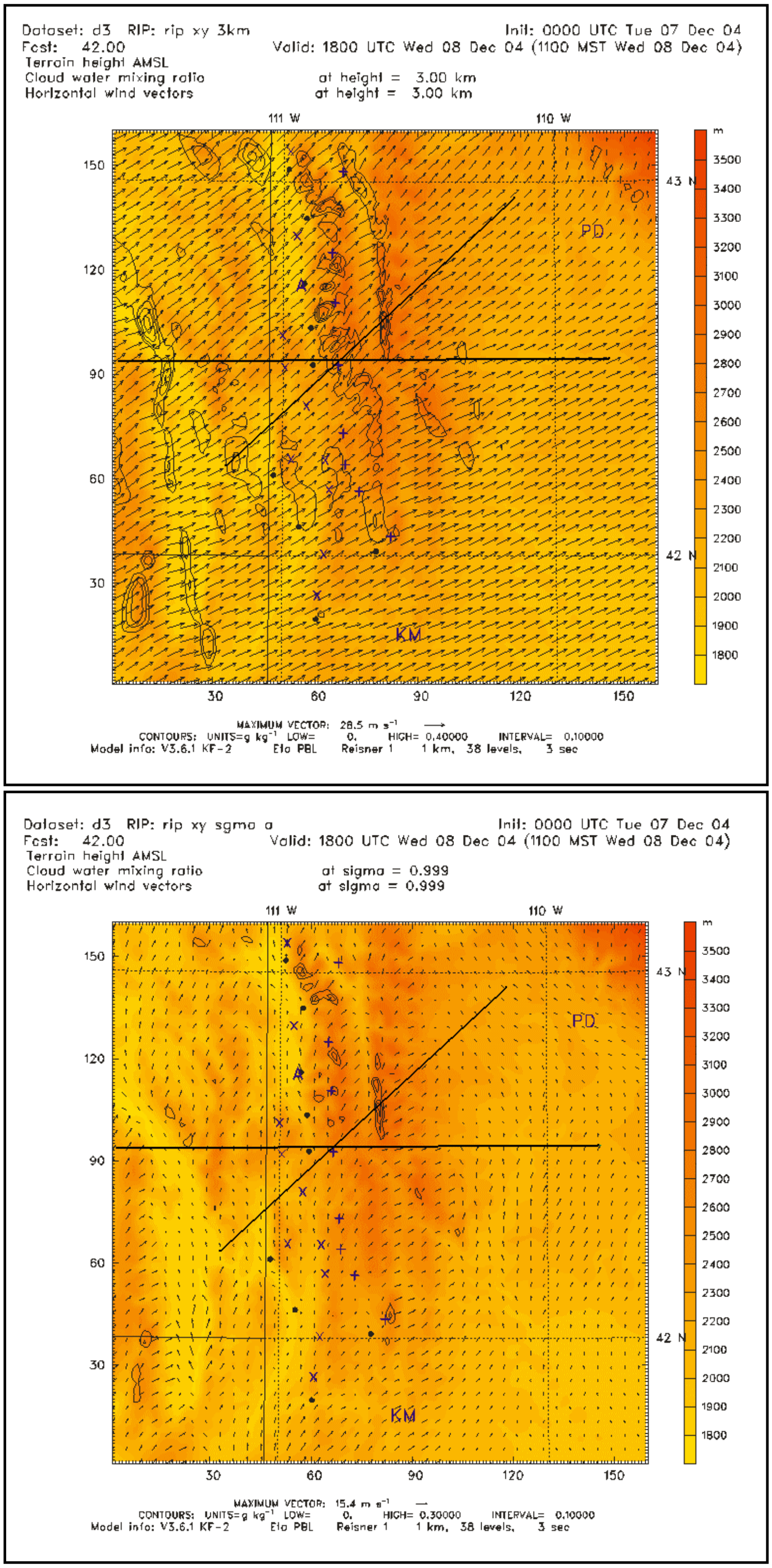


Figure 3. MM5 plots of wind vectors and cloud water mixing ratio over the inner domain at 18 UTC on 8 December at the 3-km MSL level (top) and at the first sigma level (first height level above ground, bottom). Terrain height is according to the scale at the right. Black line segment from southwest to northeast is the location of the vertical cross-section in Fig. 3. X's, +'s and circles are simulated seeding sites as in Fig. 1. Landmarks include Wyoming towns of Afton (A), Pinedale (PD) and Kemmerer (KM).

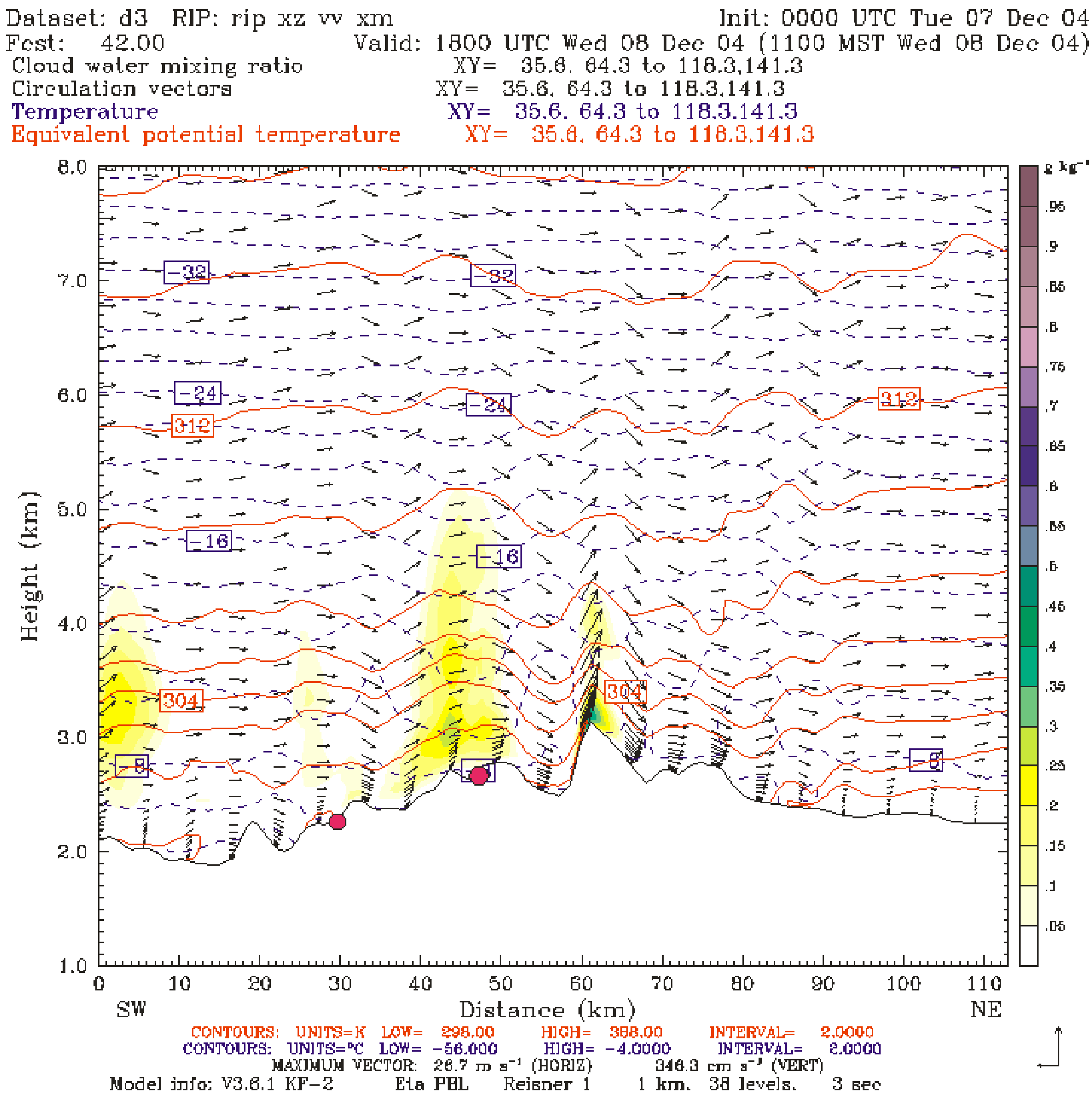


Figure 4. Vertical cross-section of cloud water mixing ratio (color shading), wind vectors, potential temperature (red lines) and temperature (black dashed lines) constructed along the southwest to northeast line segment shown in Figs. 1 and 3. Time is 18 UTC on 8 December 2004. Red circles show the positions of simulated seeding generator sites W5 and M4 (Fig. 1).

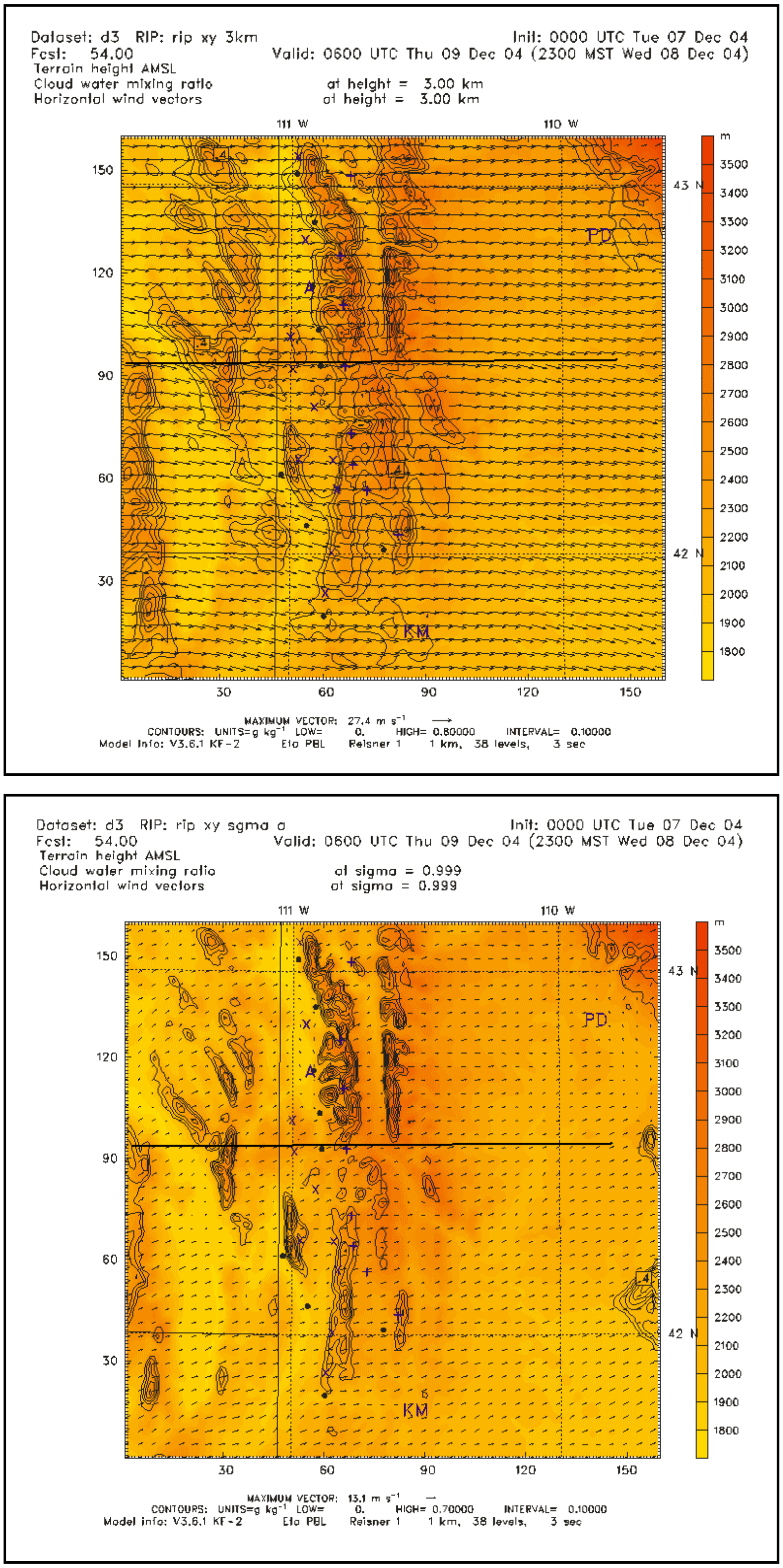


Figure 5. As in Fig 2, except showing cloud water mixing ratio and wind vectors at 06 UTC on 9 December. Black line segment from west to east is the location of the vertical cross-section in Fig. 6.

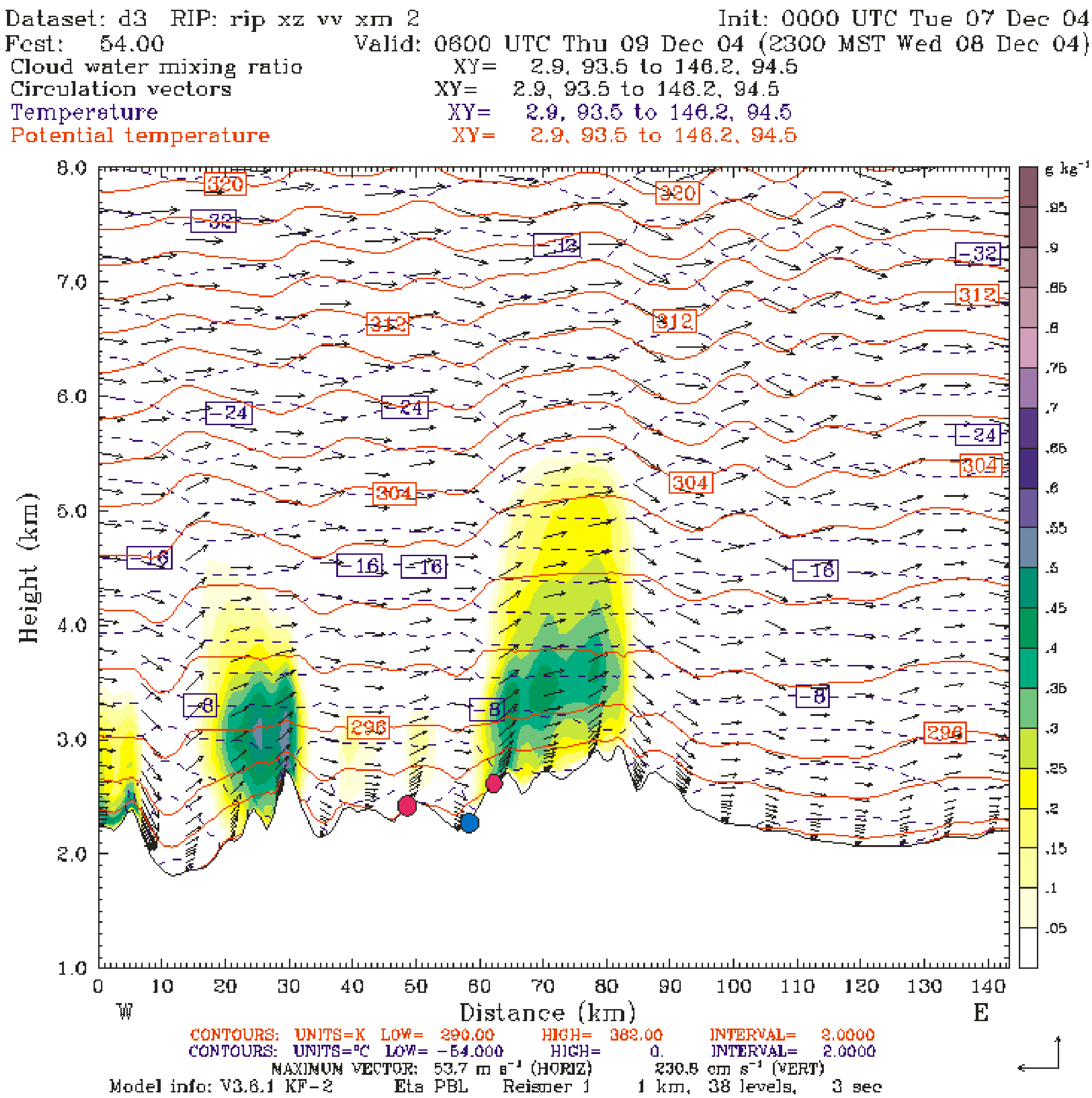


Figure 6. Vertical cross-section of cloud water mixing ratio (color shading), wind vectors, potential temperature (red lines) and temperature (black dashed lines) constructed along the west to east line segment shown in Figs. 1 and 5. Time is 06 UTC on 9 December 2004. Red circles show locations of seeding sites W4 and M4 and blue circle show location of the valley site R6 (see Fig. 1).

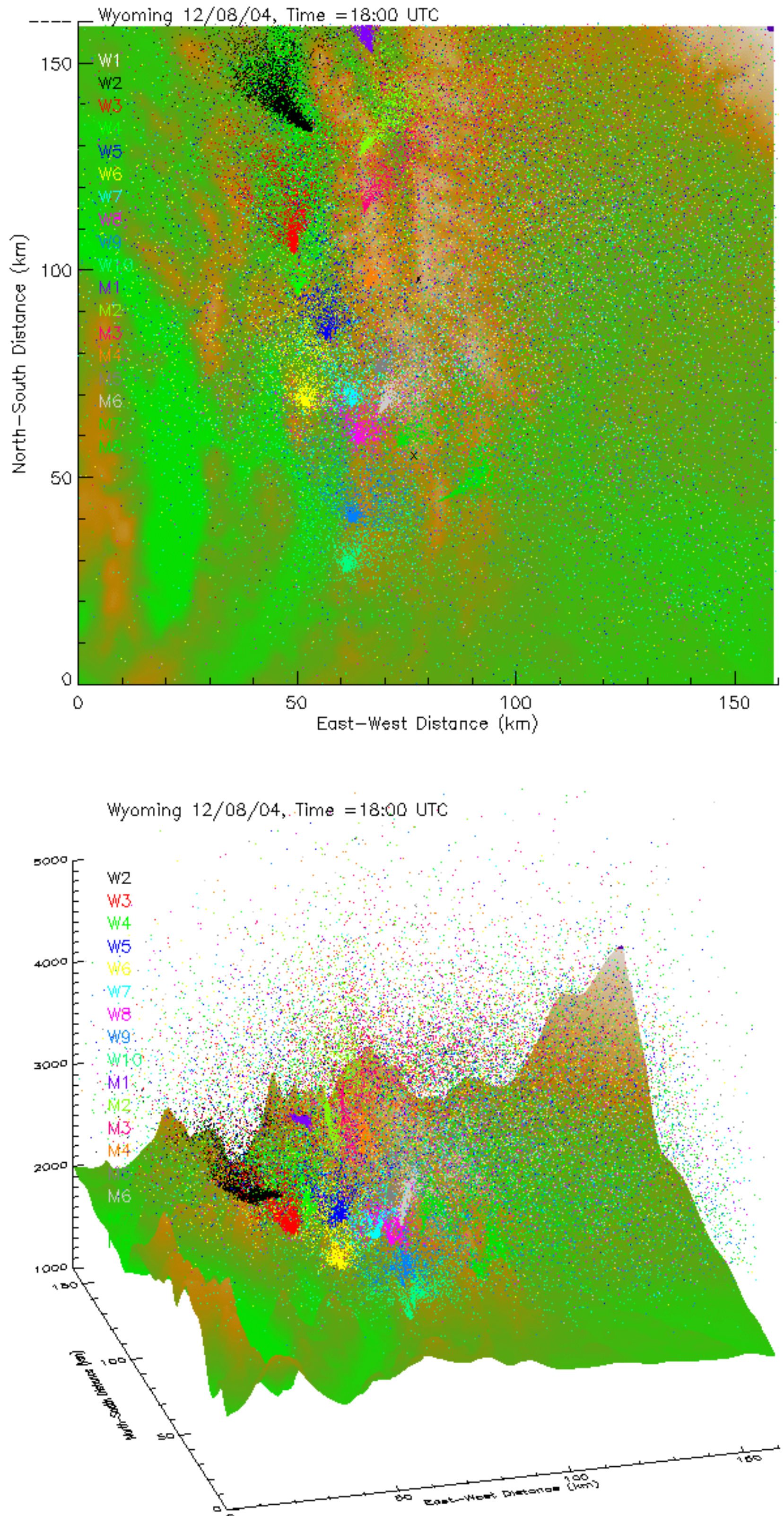


Figure 7. LAP plume predictions at 18 UTC on 8 December 2004 for all W and M sites in Fig. 1. Top panel shows plan view of simulated seeding plumes and bottom panel shows a 3-dimensional perspective view. The number of particles released is in proportion to the actual mass release rate of seeding material (25 grams per hour).

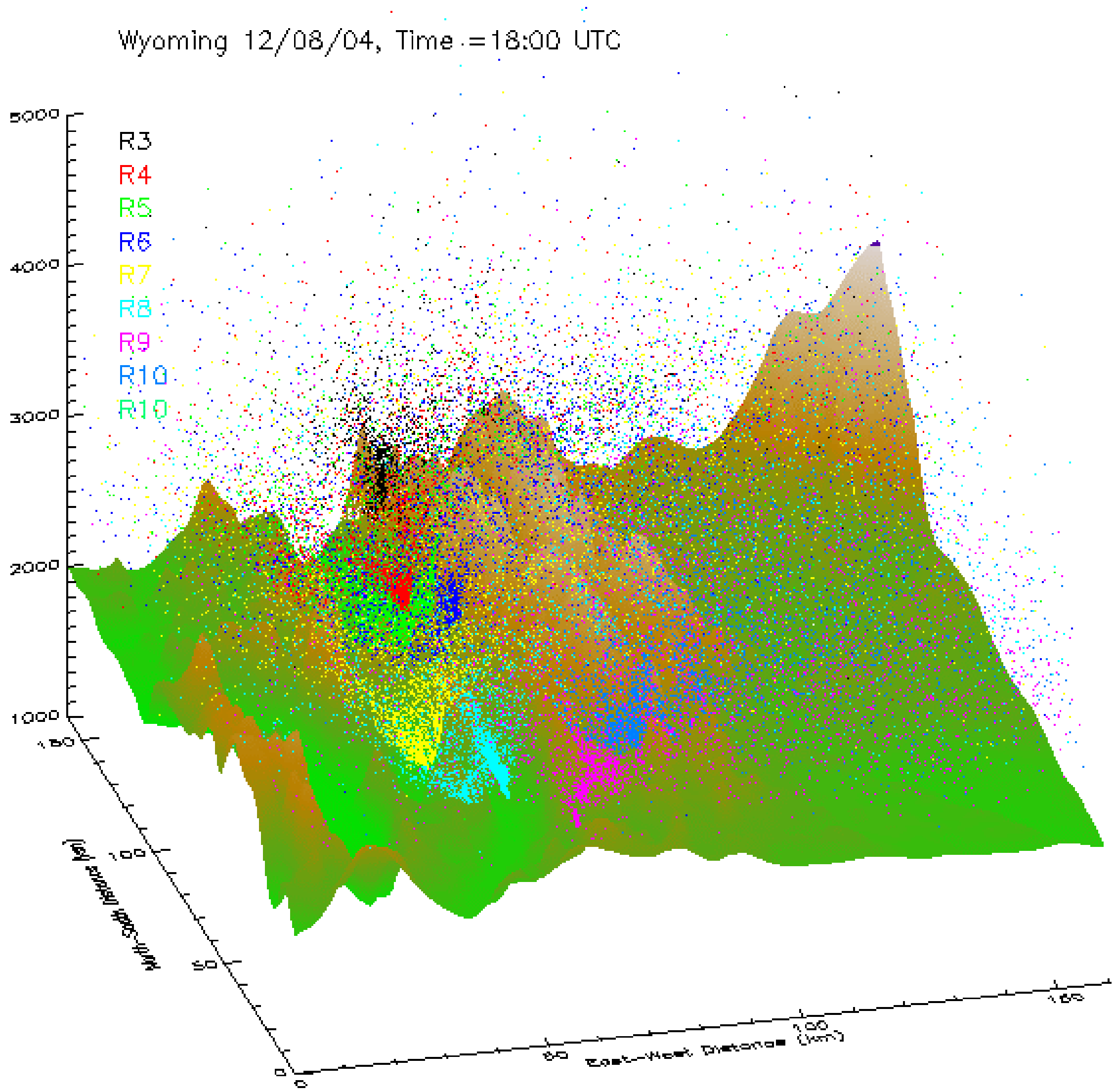


Figure 8. As in the bottom panel of Fig. 7, except showing simulated plumes from the lowest generator sites (R3-R10 in Fig. 1) at 18 UTC on 8 December 2004.

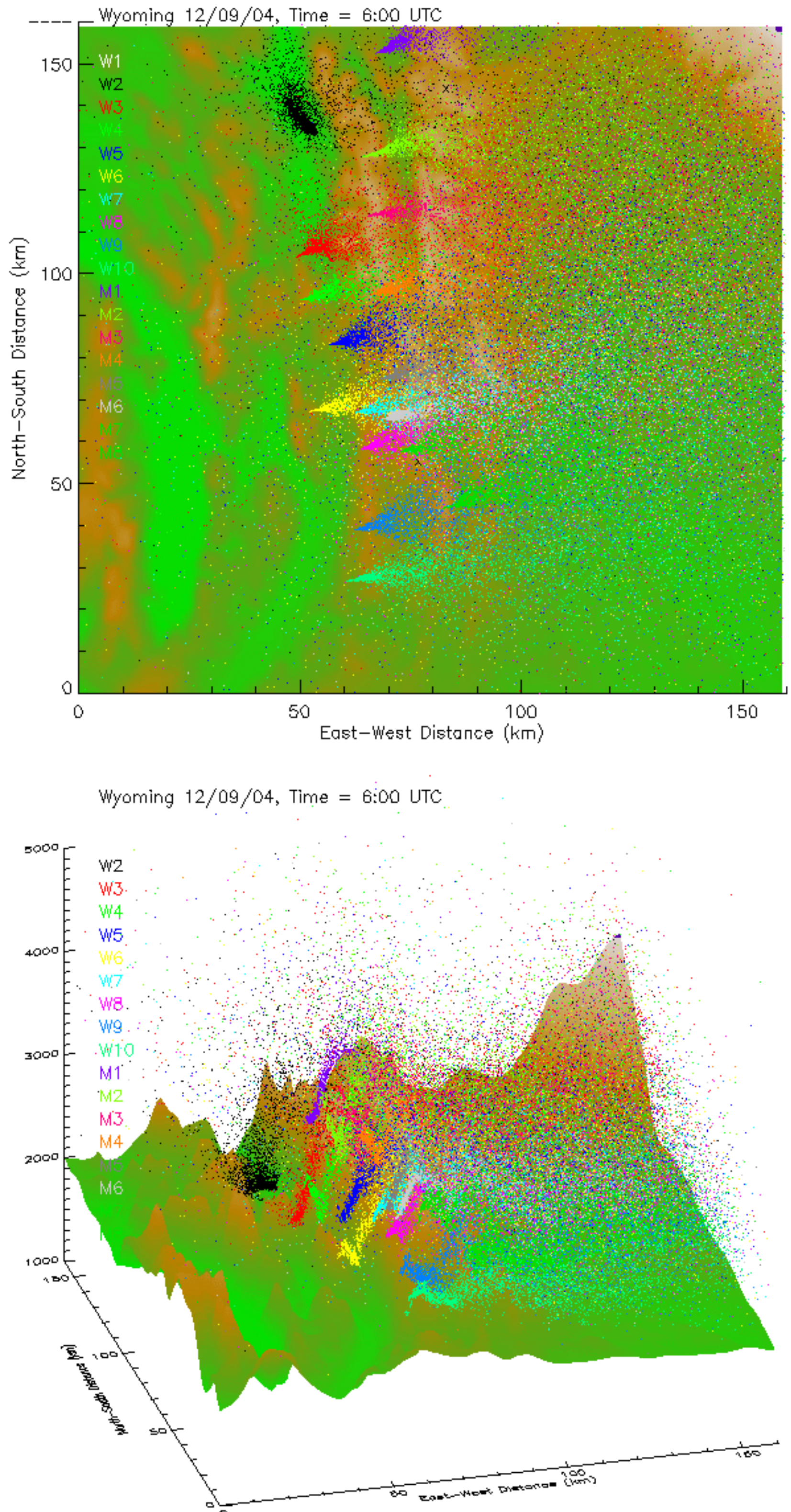


Figure 9. As in Fig. 7, except showing simulated plume locations at 06 UTC on 9 December 2004.

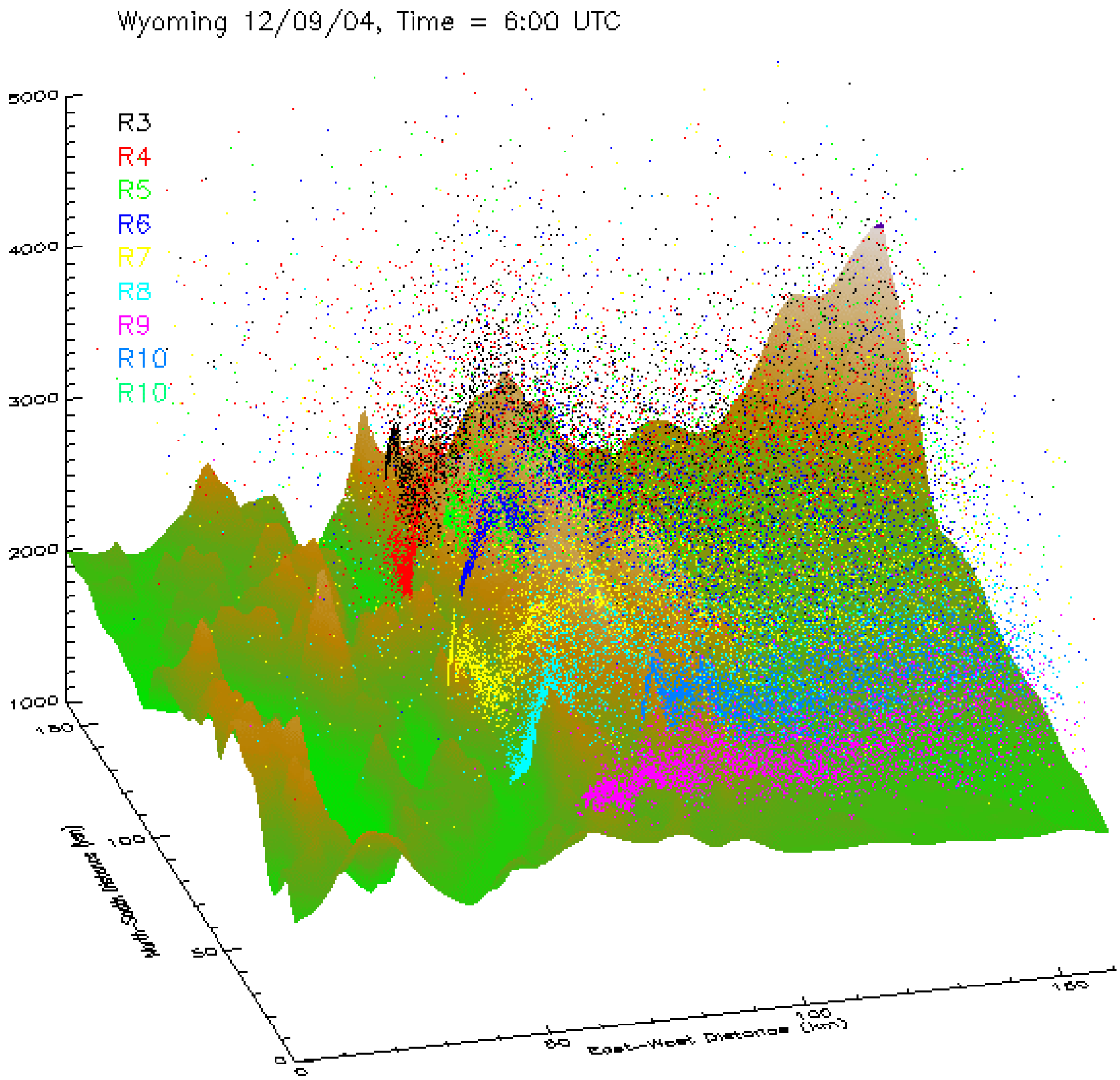


Figure 10. As in the bottom panel of Fig. 6, except showing simulated plume locations from the lowest "valley" generator sites.

MM5 and Particle Dispersion Case Study 2: 22 – 24 March 2005

The second mesoscale modeling case study to investigate wind patterns and cloud water development over the Salt River and Wyoming Ranges covered the period from 12 UTC on 22 March to 12 UTC on 24 March 2005. The MM5 model and the DRI Lagrangian particle dispersion model (LAP) were set up and run for this case in nearly the same way as with Case Study 1. However, in addition to the LAP runs for the simulated seeding sites used in Case 1, an additional set of sites was used for releases from the east side of the Wyoming Range due to low level winds during some storm periods exhibiting an easterly wind component. The study area with the additional east slope sites is shown in Fig. 11.

For this second storm period of interest, there was initially (12 UTC on 22 March) a deep trough along the west coast with an accompanying cloud band that extended from Idaho southwestward and across central California. A split in the upper level flow over Wyoming led to very weak winds and no clouds over the target ranges. By 00 UTC on 23 March the colder clouds from the approaching storm covered western Wyoming and Utah. The geopotential height gradient over Wyoming increased markedly ahead of a cold front over central Nevada. A separate stationary cold front was also positioned to the north over southern Montana.

MM5 cloud water first appeared between 00 and 03 UTC on 23 March in southerly flow at the 3-km level. Cloud water appeared in bands and also in orographically enhanced regions over the target ranges between 03 and 09 UTC as MM5 predicted 3-km winds to shift to slightly east of south. Between 09 and 12 UTC on 23 March MM5 analyses showed large areas of cloud water moving into the area from the south-southwest, but with little orographic enhancement. This corresponded to a period when satellite observations showed cloud bands over much of Wyoming, Idaho, Nevada and Utah. The trough was centered over Nevada by 12 UTC and the cold front was along the Nevada/Utah border. The arctic front to the north had moved to a location across the northwest corner of Wyoming.

By 00 UTC on 24 March satellite images showed the main frontal cloud feature over Montana, Wyoming and Idaho. The trough had deepened and broadened so that the strongest air flow was over the southwest U.S. Winds aloft over the target areas were southerly at about 20 knots and the arctic front had moved to just south of Riverton, with surface winds over northern Wyoming coming from the north. The MM5 cloud water bands continued through this time, often as features oriented NNE/SSW, with some of the bands merging with orographic cloud water features.

During the last 12 hours of the storm period a large split developed in the westerly winds leading to very light winds (5 kt at 500 mb) over the target region. The surface cold front progressed to the southern border of Wyoming with low level winds from the north behind the front. This latter period was dominated by orographic cloud water patterns in the MM5 analyses that shifted from the southern regions of the target ranges to the west and northwest regions as the winds gradually shifted. Overall the storm presented a much more complicated pattern of air flow and cloud water development than had been observed and simulated in Case 1, where winds were generally westerly and relatively strong for the entire storm.

Precipitation over the target ranges was somewhat less for Case 2, but the agreement between MM5 predictions and observations was actually better. The comparison between SNOTEL SWE and MM5 predictions at three sites is shown in Fig. 12. Both the timing and the amounts were in good agreement.

The description of MM5 results begins at 06 UTC on 23 March, about six hours after cloud water was initially predicted by MM5. (Note that MM5 was always initialized prior to any observed cloud development over the target ranges.) Figure 13 shows the wind and cloud liquid pattern at the 3-km level and 5th-sigma level (centered at 94 m AGL) at 06 UTC on 23 March. The sites used as simulated AgI release points are shown as black dots. The black line segments in Fig. 13 (also shown in Fig. 11) are the locations where vertical cross-sections were created at 3-hour intervals throughout the simulation period. At the lower level (top panel of Fig. 13) winds were relatively light and showed the effects of channeling through the valleys between mountain ranges. To the east of the Wyoming Range winds had a pronounced easterly component which led to the appearance of cloud water on the eastern slope of these mountains. At the 3-km level (bottom panel of Fig. 13) winds were stronger and from the south to south-southwest. A portion of the cloud water at this level was not tied to the terrain, but was being advected into the region from the south. An interesting feature in both panels of Fig. 13 is the lack of cloud water over the center of the target ranges. The orographic cloud water appears to be tied to minor topographic features on both the west and east sides of the ranges.

Figure 14 shows the vertical cross-section constructed along the southwest to northeast line in Figs. 11 and 13. Several cloud water maxima (near 30, 68 and 120 km) were associated with terrain features, while one prominent maximum (near 57 km) was a region with an elevated base that was moving into the target from the south. Of the four seeding sites shown in the cross-section it appears that only the high altitude site (M4 in Fig. 11) was positioned to take advantage of one of the cloud water regions, but the horizontal extent of the region and the relatively mild temperature (only about -5^o C near mountain top) could have inhibited ice nucleation, growth and fallout over the target. The east slope site (E2) appears to be too low for transport to the -6^o C level, particularly with the downward motion expected as terrain decreases in height to the north.

The cloud liquid pattern changed markedly by 12 UTC on 23 March. The coverage at the 3-km and 5-sigma levels is shown in Fig. 15. The lower level (bottom panel) shows some cloud liquid associated with the higher terrain, mainly to the southwest of the target ranges. The 3-km level (top panel) reveals much larger cloud liquid regions advecting into the region that were not generated by orographic lifting. The wind patterns were very similar to those predicted at 06 UTC; the main difference was the appearance of the elevated cloud liquid layers. These can be seen more clearly in Fig. 16, the vertical cross-section along the southwest to northeast line in Fig. 15. The region between 40 and 75 km was likely enhanced by the orographic lift. However, if the liquid bases were elevated above the terrain as suggested in Fig. 15, ground-based seeding might not have been effective. The temperature structure also indicates 500-700 m of lift would have been required from the highest generator to reach the -6^o C level. Aircraft seeding of the liquid water regions upwind of the target, along north to south flight tracks over the upwind valley, might have been more effective in this situation.

The cloud liquid regions evolved into banded features roughly parallel to the wind direction by 18 UTC on 23 March. As at 12 UTC, the 3-km and 5-sigma cloud water patterns in Fig. 17 indicate much of the cloud water was not associated with orographic lift, although the band elements were enhanced with passage over the higher terrain. The southwest-northeast cross-section in Fig. 18 shows one of the bands from 0 – 20 km range, but misses the region over the target range where band liquid and orographic liquid might have merged, as suggested by the 3-km plot in the region just southeast of Afton in Fig. 16. Between 12 and 18 UTC the -6^o C level lowered somewhat, suggesting ground seeding from the higher seeding sites might have been more effective. As at 12 UTC aircraft seeding of the cloud water bands just upwind of the target area might also have been possible.

Figure 19 shows that by 03 UTC on 24 March the cloud water was again mostly orographic in nature. The winds at 3-km and the 5-sigma level had veered to the west and cloud liquid was generally on the windward sides of the mountains. This cloud water pattern persisted through the end of the model simulation at 12 UTC on 24 March, as winds continued to veer to a more northerly direction. The west to east cross-section in Fig. 20 shows the cloud water base had lowered since 18 UTC, and the -5^o C level was now near mountain top level. Winds and temperatures favored ground seeding, at least from the higher sites, while the depth of cloud liquid, and the lack of upwind extension, indicated aircraft seeding would not have been feasible.

Based on the initial appearance of MM5 cloud liquid, the LAP model was initiated at 00 UTC on 23 March. As with Case 1, the model was run first to simulate aerosol plume dispersion from the higher altitude generator sites (W1-10 and M1-9), and then run again for simulations with the lower valley sites (R1-10). Also, due to the prediction of easterly component winds, LAP was also run using a set of simulated seeding sites (E1-E7) on the east side of the Wyoming Range (see Fig. 11). Figure 21 shows plan and tilted perspective views of plumes from the higher sites (left panels) and the valley sites (right panels) at 06 UTC on 23 March. Figure 22 shows plumes from the east side sites.

Plume animations showed that, for the period from 06–12 UTC, plumes from the west side valley sites were carried away from the target areas by the low level easterly winds at the south end of the ranges, and then northward along the valleys west of the Salt River Range. For the same period plumes from the somewhat higher west slope sites (W1-W10) were also initially carried northward along the west flank of the Salt River Range, then after 09 UTC were transported to the northwest. Only the high altitude sites (M1-M8) produced plumes that would potentially have interacted with clouds over the target, as shown in Fig. 13. From 06 to 09 UTC the plumes from M2, M3 and M4 were transported along the length of the ranges increasing the time available for ice particle growth. For this particular case, the vertical transport shown in Fig. 21 (bottom left) appears to take some seeding material as high as the -8^{o} C level, but with the bulk of material residing below the -6^{o} C level. After 09 UTC plumes from the high altitude sites also went to the northwest away from the targets. Figure 22 indicates that several plumes from the east slope sites could also have interacted with the cloud water shown in Fig. 13, and to generally the same temperature levels. For the same six-hour period, E1 through E5 showed transport to heights above 3 km over the Wyoming Range. E6 did so intermittently, but E7 plumes moved around the ranges to the valley west of the Salt River Range. For the latter part of this period, however, recall that orographic cloud water was minimal on both the east and west slopes.

For the period from 12-18 UTC on 23 March that was dominated by the bands of cloud water, the dispersion from ground sites was as follows. Figures 23 and 24 show dispersion patterns at 12 UTC and Figs. 25 and 26 show patterns at 18 UTC. As winds became more southerly the plumes from the higher altitude W and M sites began to be transported over the west slopes of the Salt River Range. The cloud water pattern also favored the western slopes in this period. Only W7, W8 and W9 showed transport over the higher terrain, while all the M sites showed good transport and dispersion to heights above 3 km where plumes could have interacted with either orographic or band-generated cloud water over the Salt River Range. None of the plumes moved across to the Wyoming Range. Valley site plumes were not transported over the target ranges in this period, however vertical dispersion at times was adequate to potentially interact with the bands of cloud water upwind of the Salt River Range. At the beginning of the period (through 15 UTC) a few east slope plumes (E1-E4) dispersed over the east slope of the Wyoming Range, but later all these plumes moved more to the north-northeast. Cloud water also diminished on the east side as winds began to veer more to the south.

Between 18 UTC on 23 March and 03 UTC on 24 March seeding sites to the west of the ranges were preferable for targeting. The plumes from these western sites are shown in Figs. 25 and 26. East slope sites are not shown since none produced plumes that impacted the target ranges for the remainder of the simulation period. Plumes from the higher altitude sites showed a gradual turning toward the northeast after about 2030 UTC. By 0130 UTC the plumes from high altitude M sites were oriented nearly west to east, and by the end of the period most of the W sites had plumes with similar orientations (Fig. 25). The transport and dispersion was favorable for interaction with cloud water that had become much more confined to the western slopes by this time (Figs. 19 and 20). As demonstrated in Case 1, several of the sites to the west of the Salt River Range (mainly W2, W3, and W4) produced plumes that stayed in the upwind valleys for much of the period. Two valley R sites (R9 and R10) near the southern end of the Salt River Range produced plumes that were transported across the target for much of the period. The remainder only showed reasonable westward transport after 03 UTC on 24 March. Vertical dispersion from the valley sites after about 01 UTC was quite good, particularly from sites R3 and R6. For this period when simulated seeding sites were aligned across the prevailing wind direction, a generator spacing of about 10 km appeared to be adequate to cover the intended target areas. This was similar to the finding in Case 1 where winds were generally westerly.

The second case study was much more complicated than the first. Both cloud water and plume dispersion varied markedly throughout the storm period. The period after about 00 UTC on 24 March, with generally westerly airflow and cloud water being mainly produced by orographic lift, was similar to Case 1. This amounted to about 12 of the 24 hours when cloud liquid was predicted to be over the target ranges by MM5. This appears to be a situation where many of the simulated seeding sites to the west of the target ranges would produce plumes that would interact with supercooled cloud water over the western slopes with sufficient time for nucleated ice particles to grow and fall out over the two target ranges. Case 2 presented a somewhat less favorable seeding opportunity due to the critical isotherm (-6^{o} C) being generally higher than in Case 1. The dispersion patterns in both cases, when westerly winds were prevalent, indicated a ground generator spacing of about 10 km was needed to adequately cover the target areas.

The early portion of Case 2 displayed winds with an easterly component and accompanying cloud water over the eastern slope of the Wyoming Range. Simulations suggested that this water could have been reached by plumes from seeding sites on the eastern side of the Wyoming Range, but how frequently this situation might occur is not known from the two mesoscale model simulations.

The southerly flow and generally weak winds later in Case 2 showed reasonable plume transport mainly from the highest seeding sites. This period also showed cloud liquid mainly in bands that advected into the region, where aircraft seeding might have been preferable, provided suitable flight tracks could be designed. As with Case 1 valley-positioned generators were not nearly as effective in producing plumes that would interact with cloud water over the target ranges, however the vertical dispersion in the latter part of Case 2 was greater than Case 1, and indicated (as did Case 1) that some periods are potentially seedable from valley sites.

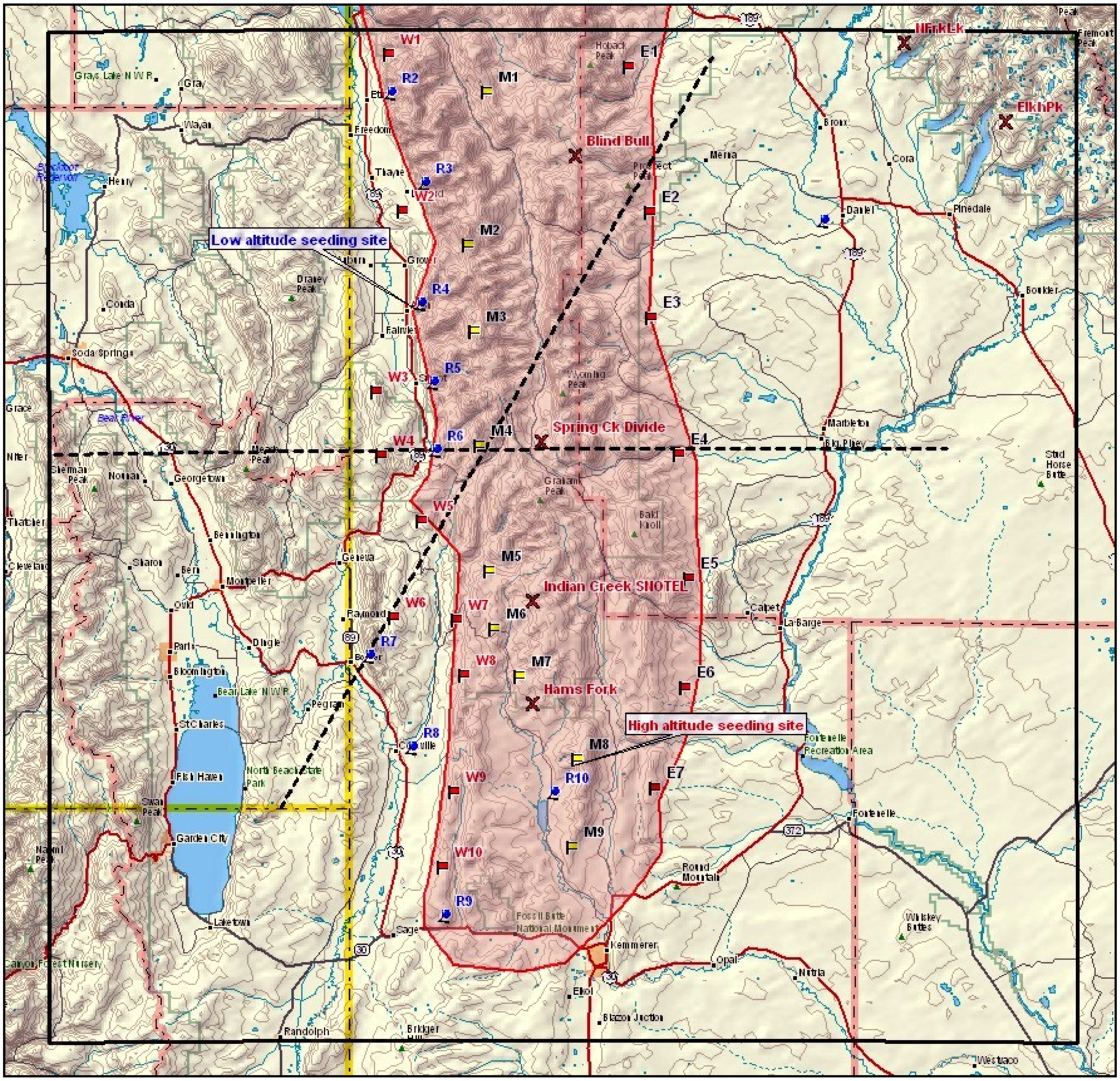


Figure 11. Map showing a portion of western Wyoming including most of the Salt River and Wyoming Ranges. The shaded region is the approximate target area for a snowfall enhancement project. The black square is the innermost domain of the MM5 model that used a grid spacing of 1-km. Black dashed lines are locations where vertical cross-sections were constructed from MM5 output. Simulated seeding aerosol releases were made from sites marked by pins and flags. W1-W10 are at the west edge of the target at altitudes somewhat higher than the valleys west of the target. M1-M9 are within the Salt River Range at relatively high altitude, positioned to potentially seed the Wyoming Range. R1-R10 are low altitude sites mainly in the valley adjacent to the Salt river Range. Sites E1-E6 are east slope sites similar to W1-W10. The red X's are SNOTEL site locations, where ones in the upper right are in the Wind River Range.

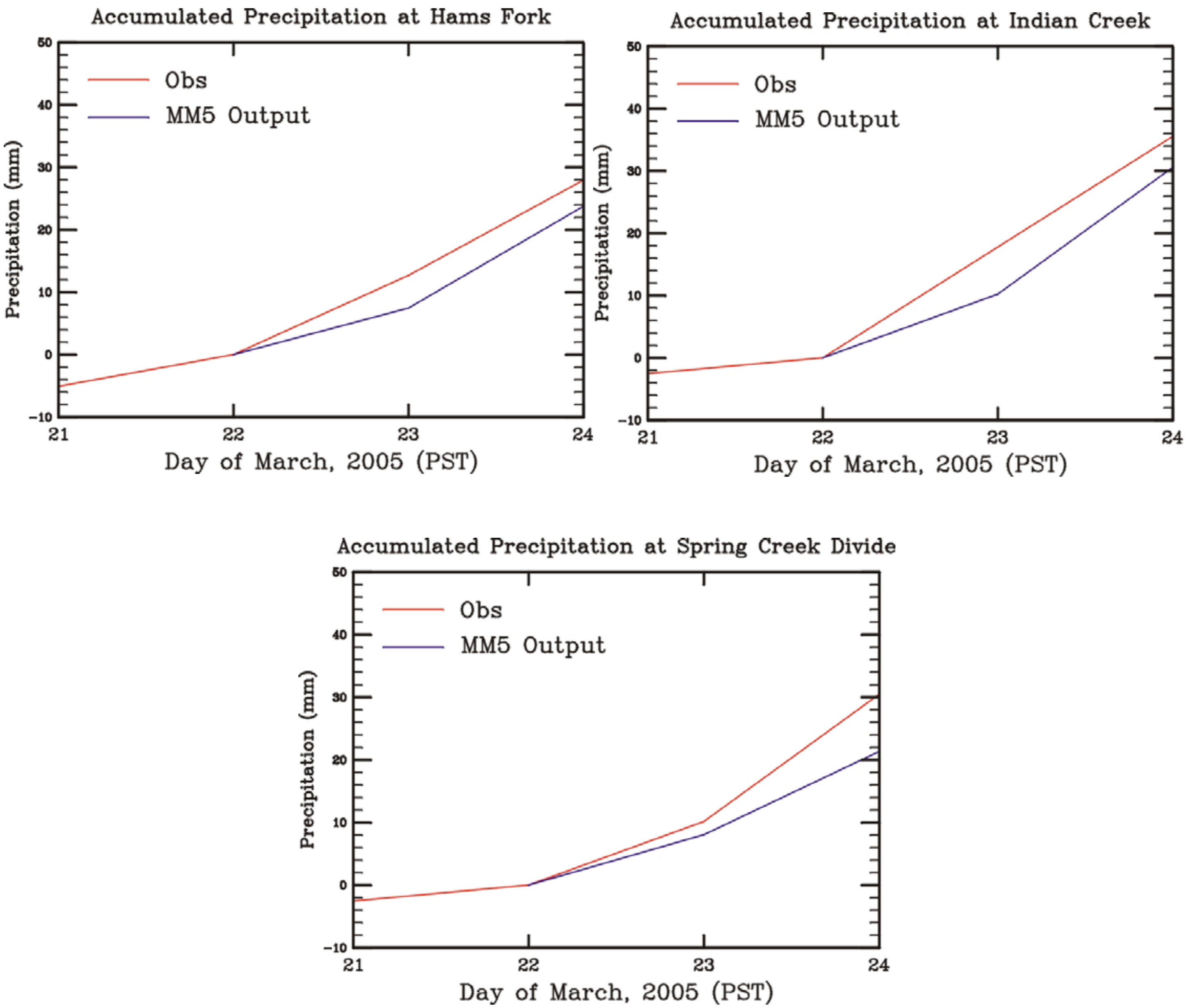


Figure 12. Comparison of MM5 precipitation accumulation predictions (blue lines) with SWE accumulation at three SNOTEL sites (red lines); Hams Fork, Indian Creek and Spring Creek (see Fig. 11). SWE was adjusted to zero at 00 UTC on 22 March, the start of the MM5 simulation.

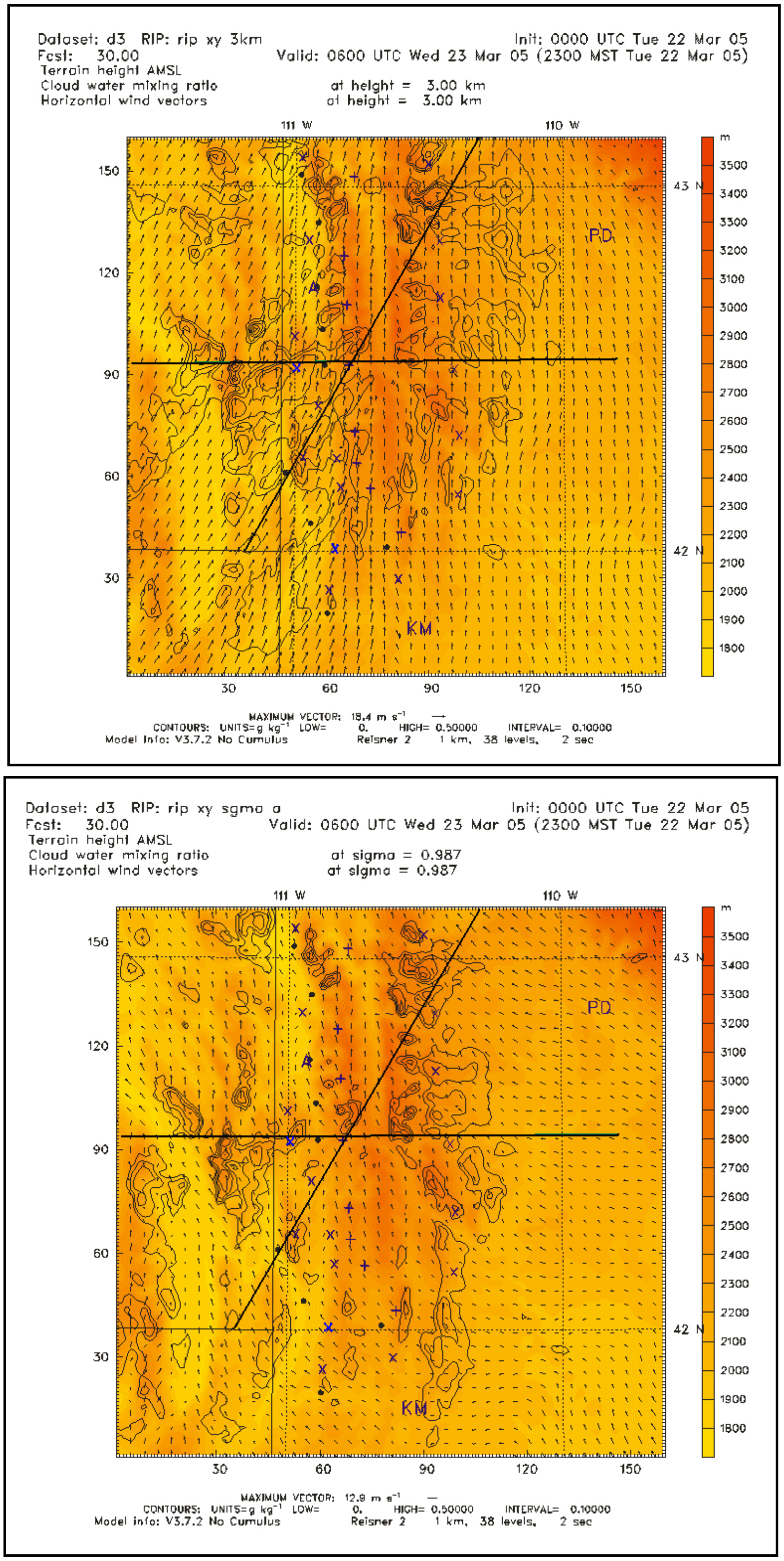


Figure 13. MM5 plots of wind vectors and cloud water mixing ratio over the inner domain at 06 UTC on 23 March at the 3-km MSL level (top) and at the fifth sigma level above ground (~95 m AGL, bottom). Terrain height is shaded according to the scale at the right of each figure. Black line segment from southwest to northeast is the location of the vertical cross-section in Fig. 14. X's, +'s and circles show simulated seeding sites as in Fig. 11. Landmarks include Wyoming towns of Afton (A), Pinedale (PD) and Kemmerer (KM).

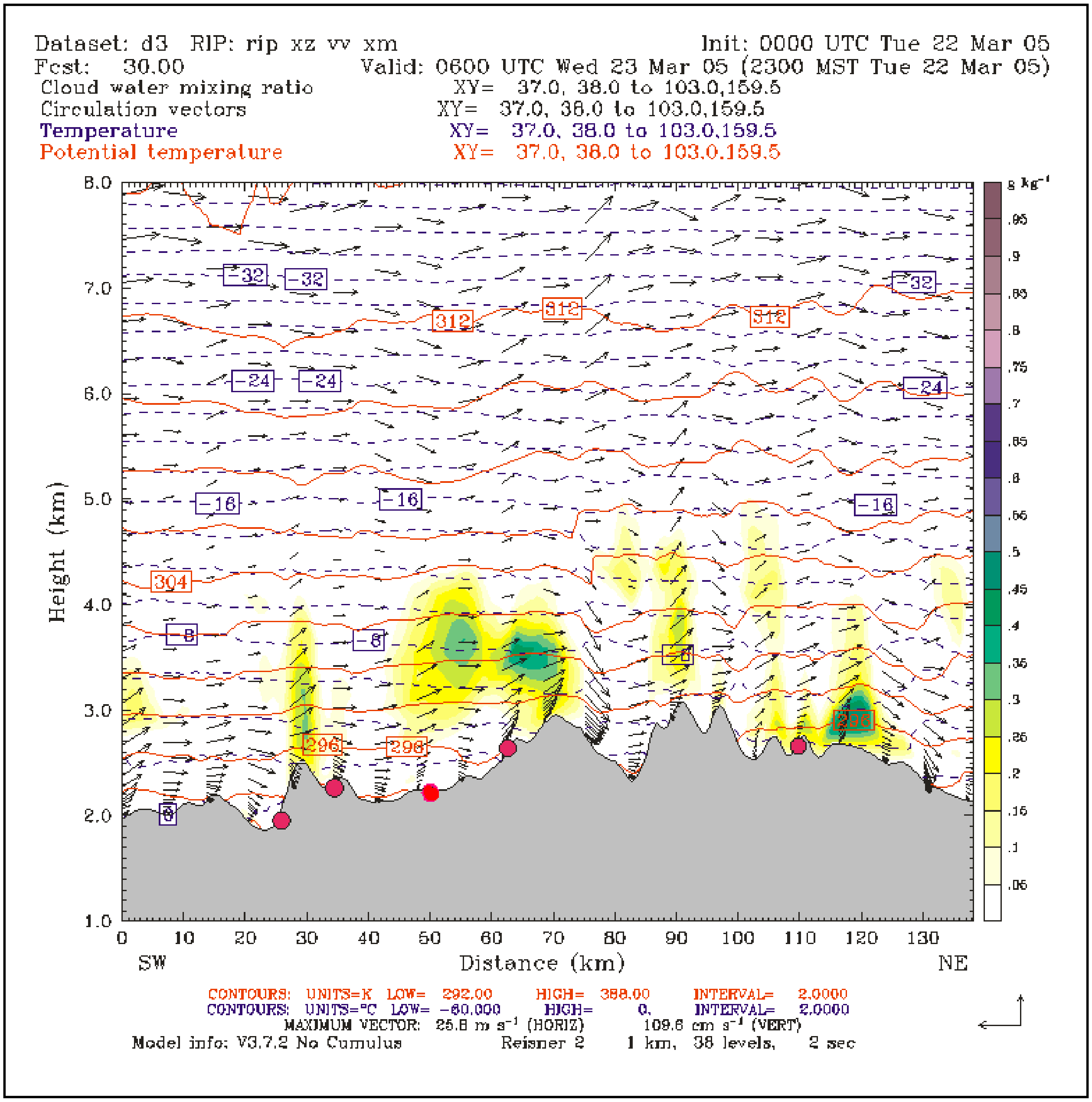
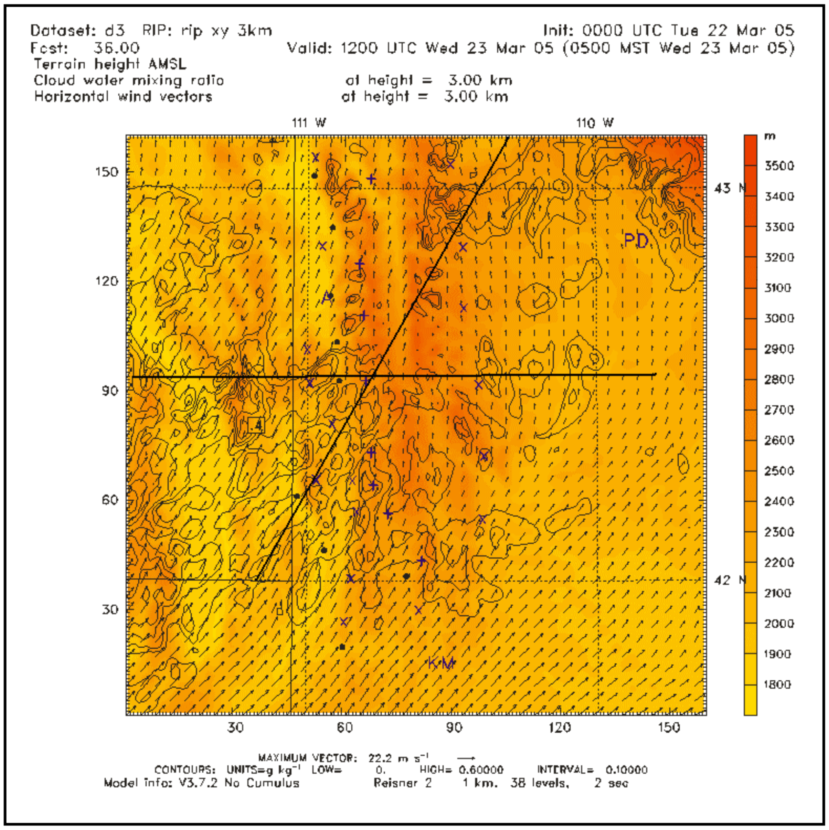


Figure 14. Vertical cross-section of cloud water mixing ratio (color shading), wind vectors, potential temperature (red lines) and temperature (black dashed lines) constructed along the southwest to northeast line segment shown in Figs. 11 and 13. Time is 06 UTC on 23 March 2005. Red circles show the positions of simulated seeding generator sites from left to right R7, W6, W5, M4 and E2 (Fig. 11).



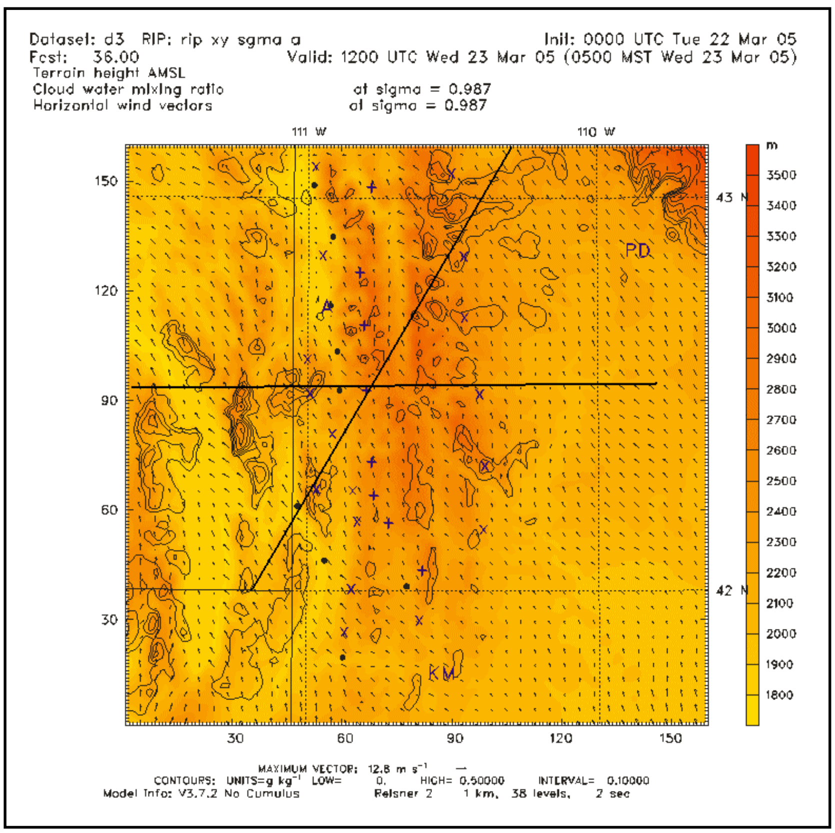


Figure 15. As in Fig 13, except showing cloud water mixing ratio and wind vectors at 12 UTC on 23 March 2005. Black line segment from southwest to northeast is the location where the vertical cross-section in Fig. 16 was constructed.

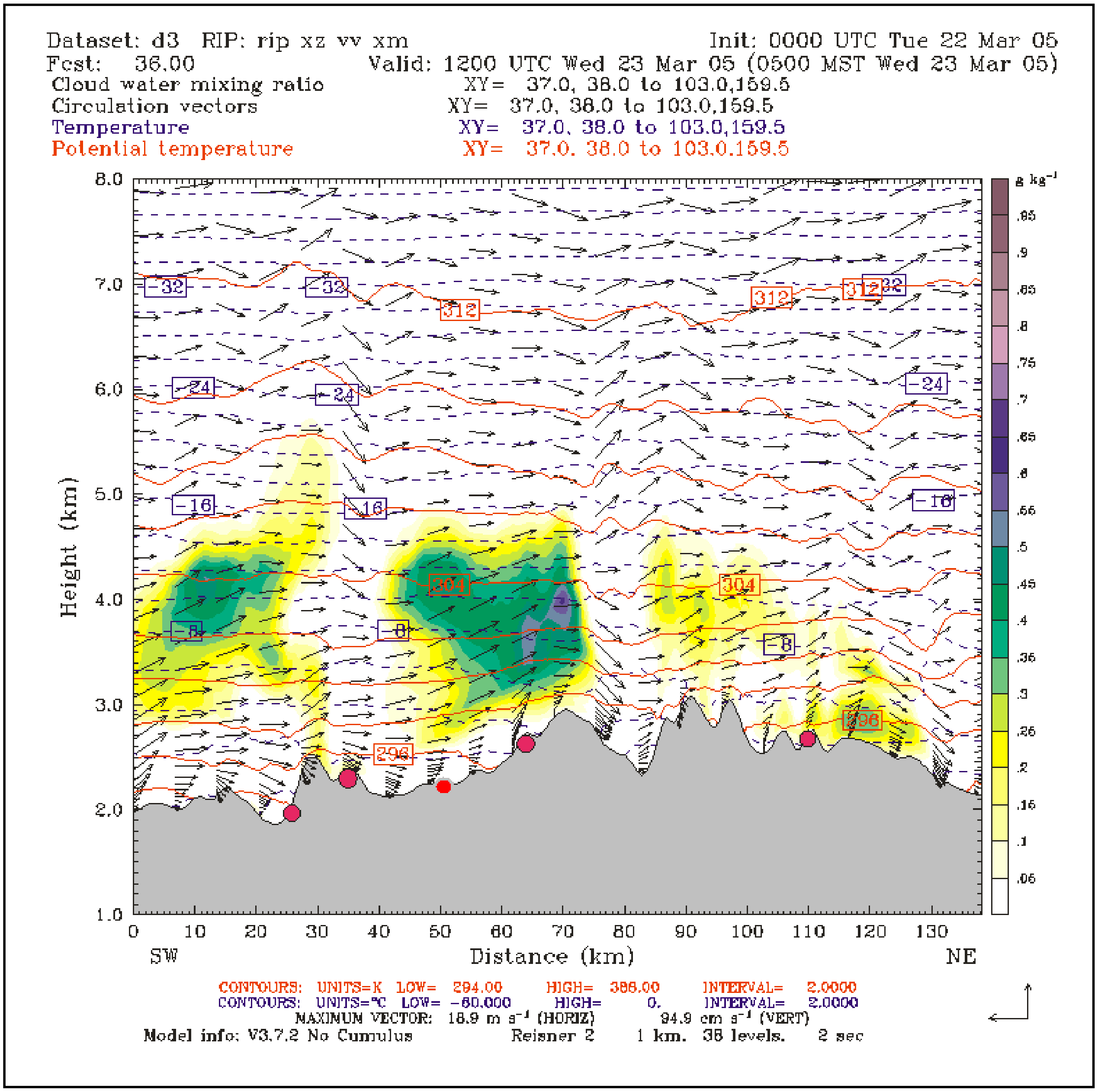


Figure 16. Vertical cross-section of cloud water mixing ratio (color shading), wind vectors, potential temperature (red lines) and temperature (black dashed lines) constructed along the southwest to northeast line segment shown in Figs. 11 and 15. Time is 12 UTC on 23 March 2005. Red circles show locations of seeding sites, from left to right, R7, W6, W5, M4, and E2 (see Fig. 11).

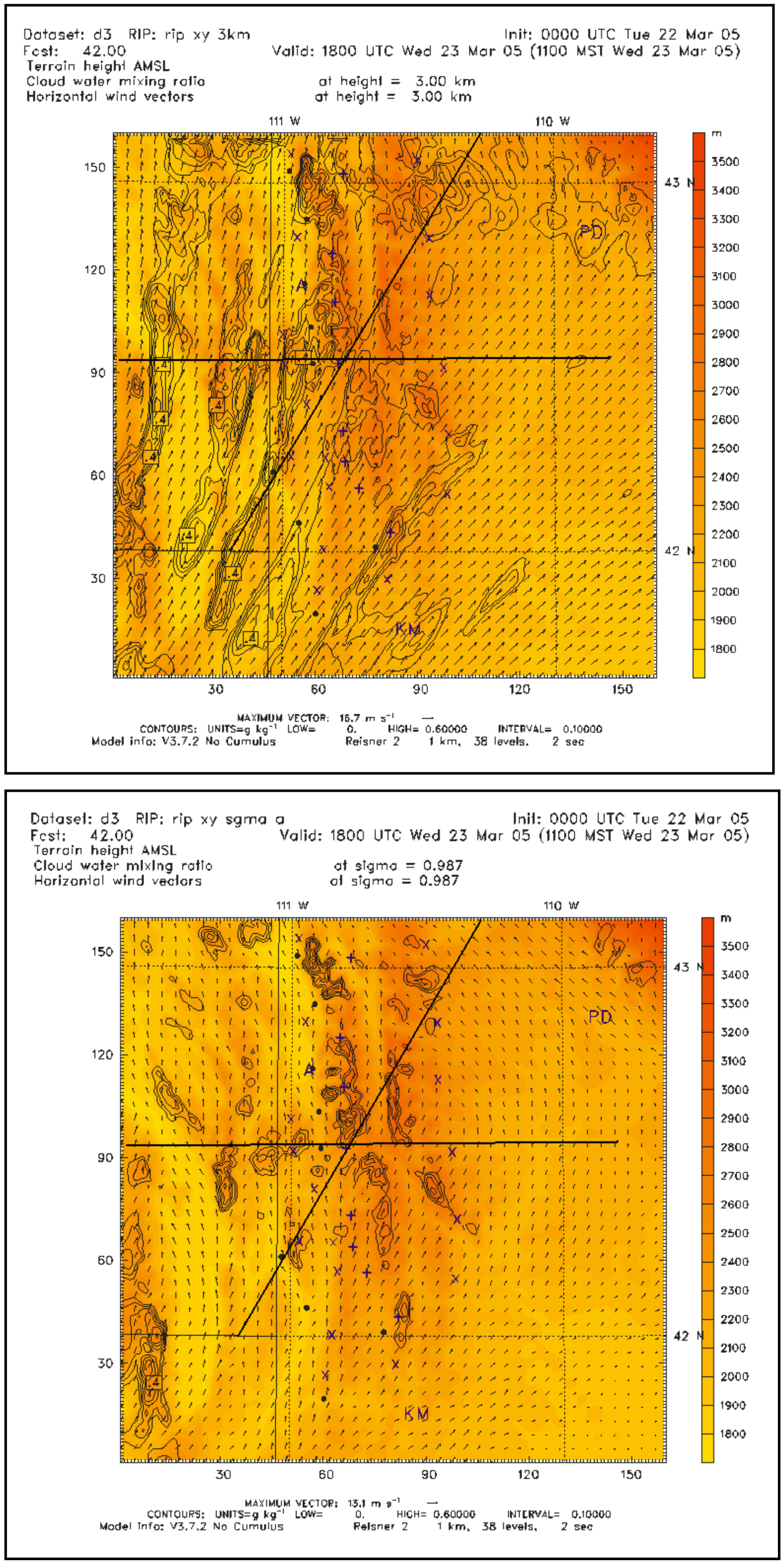


Figure 17. As in Fig 13, except showing cloud water mixing ratio and wind vectors at 18 UTC on 23 March 2005. Black line segment from southwest to northeast is the location where the vertical cross-section in Fig. 18 was constructed.

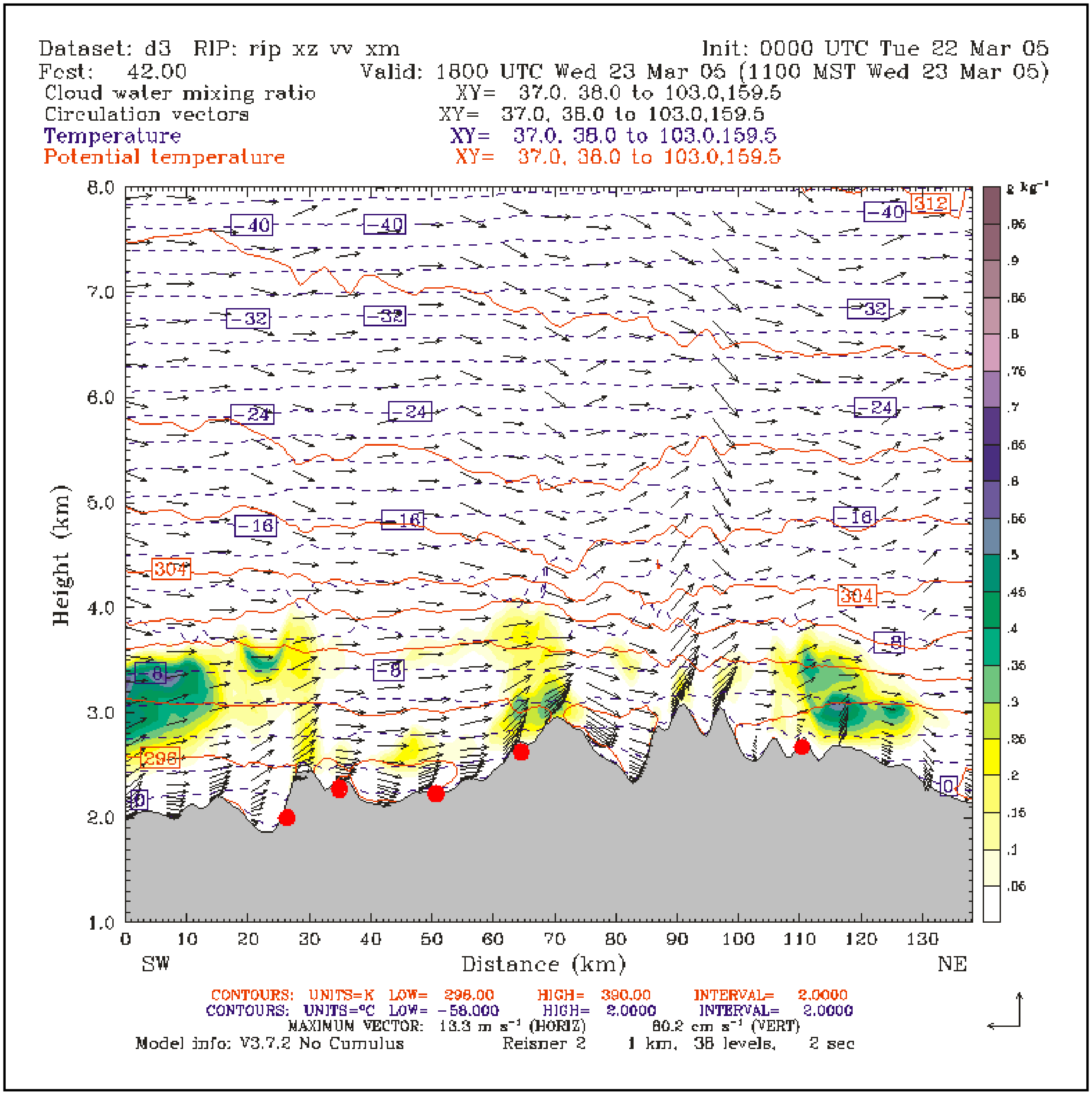
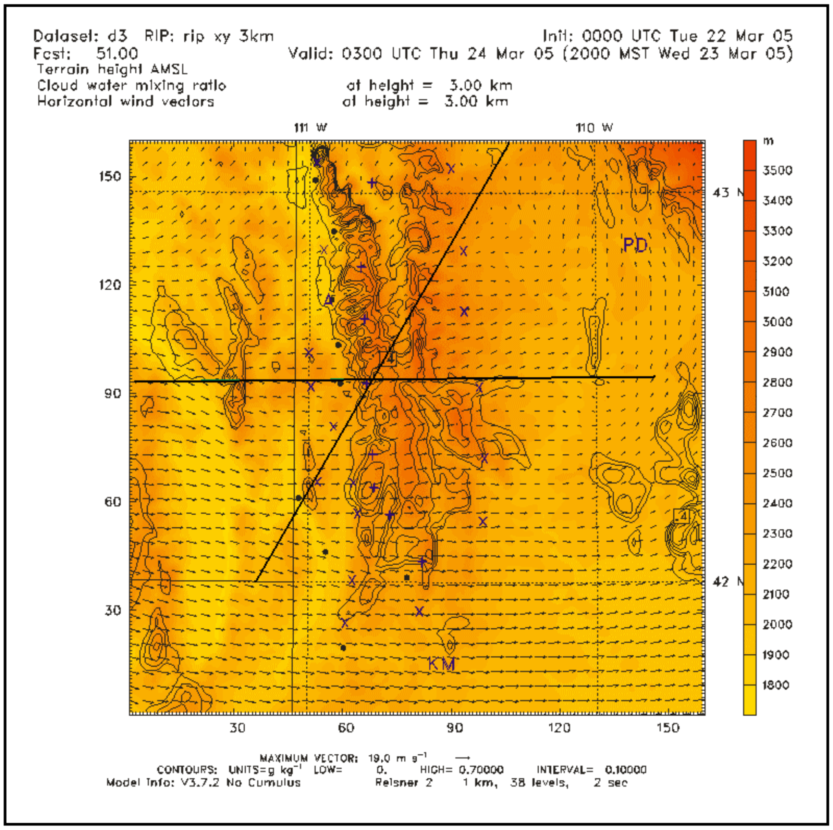


Figure 18. Vertical cross-section of cloud water mixing ratio (color shading), wind vectors, potential temperature (red lines) and temperature (black dashed lines) constructed along the southwest to northeast line segment shown in Figs. 11 and 15. Time is 18 UTC on 23 March 2005. Red circles show locations of seeding sites, from left to right, R7, W6, W5, M4, and E2 (see Fig. 11).



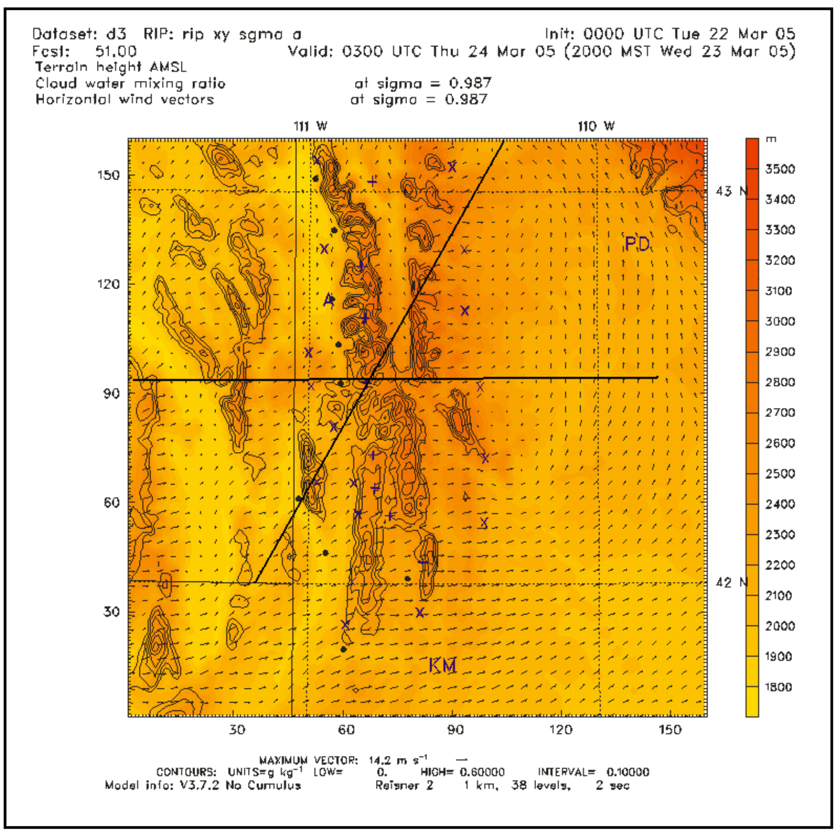


Figure 19. As in Fig 13, except showing cloud water mixing ratio and wind vectors at 03 UTC on 24 March 2005. Black line segment from west to east is the location where the vertical cross-section in Fig. 20 was constructed.

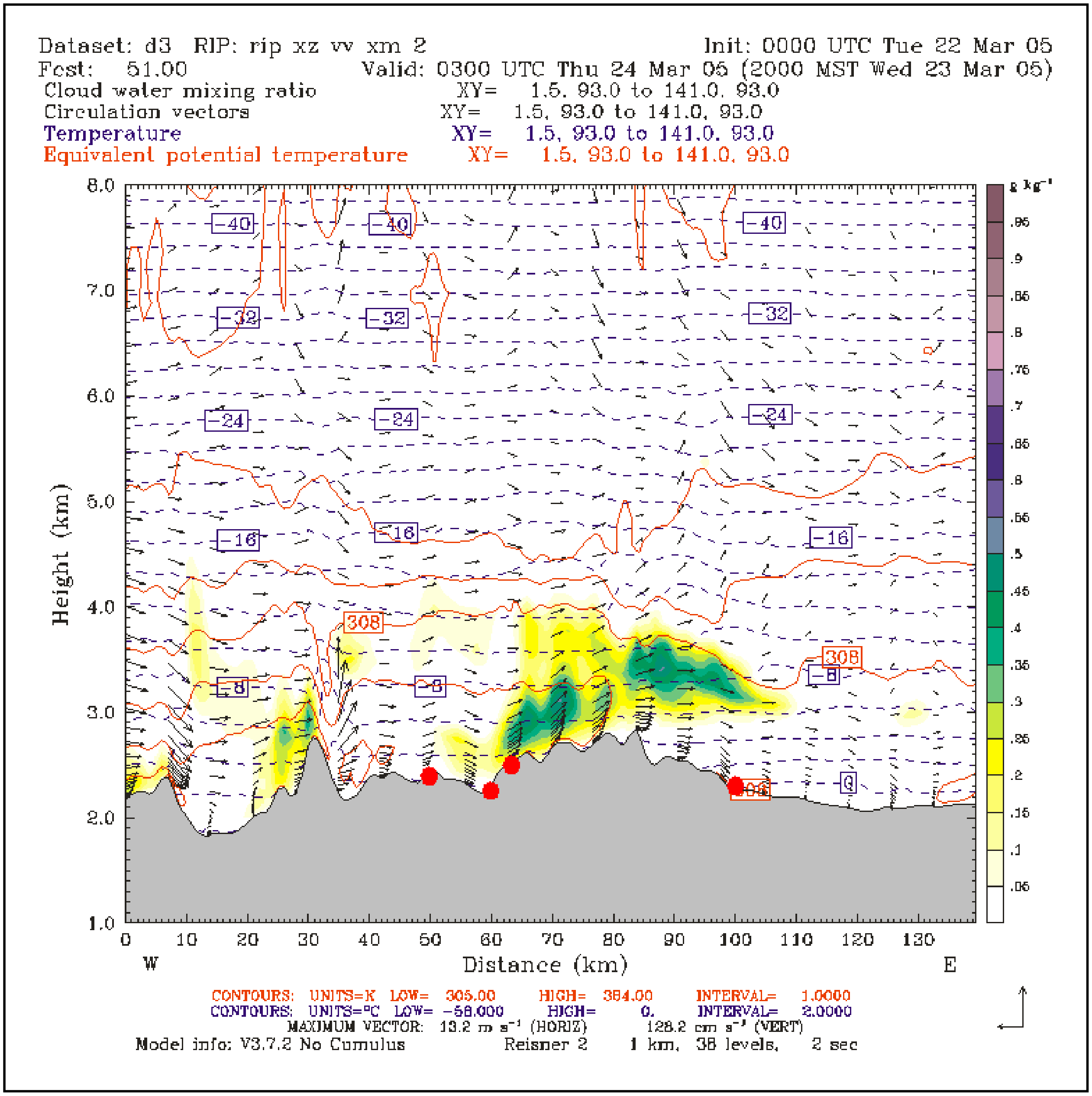


Figure 20. Vertical cross-section of cloud water mixing ratio (color shading), wind vectors, potential temperature (red lines) and temperature (black dashed lines) constructed along the west to east line segment shown in Figs. 11 and 19. Time is 03 UTC on 24 March 2005. Red circles show locations of seeding sites, from left to right, W4, R6, M4, and E4 (see Fig. 11).

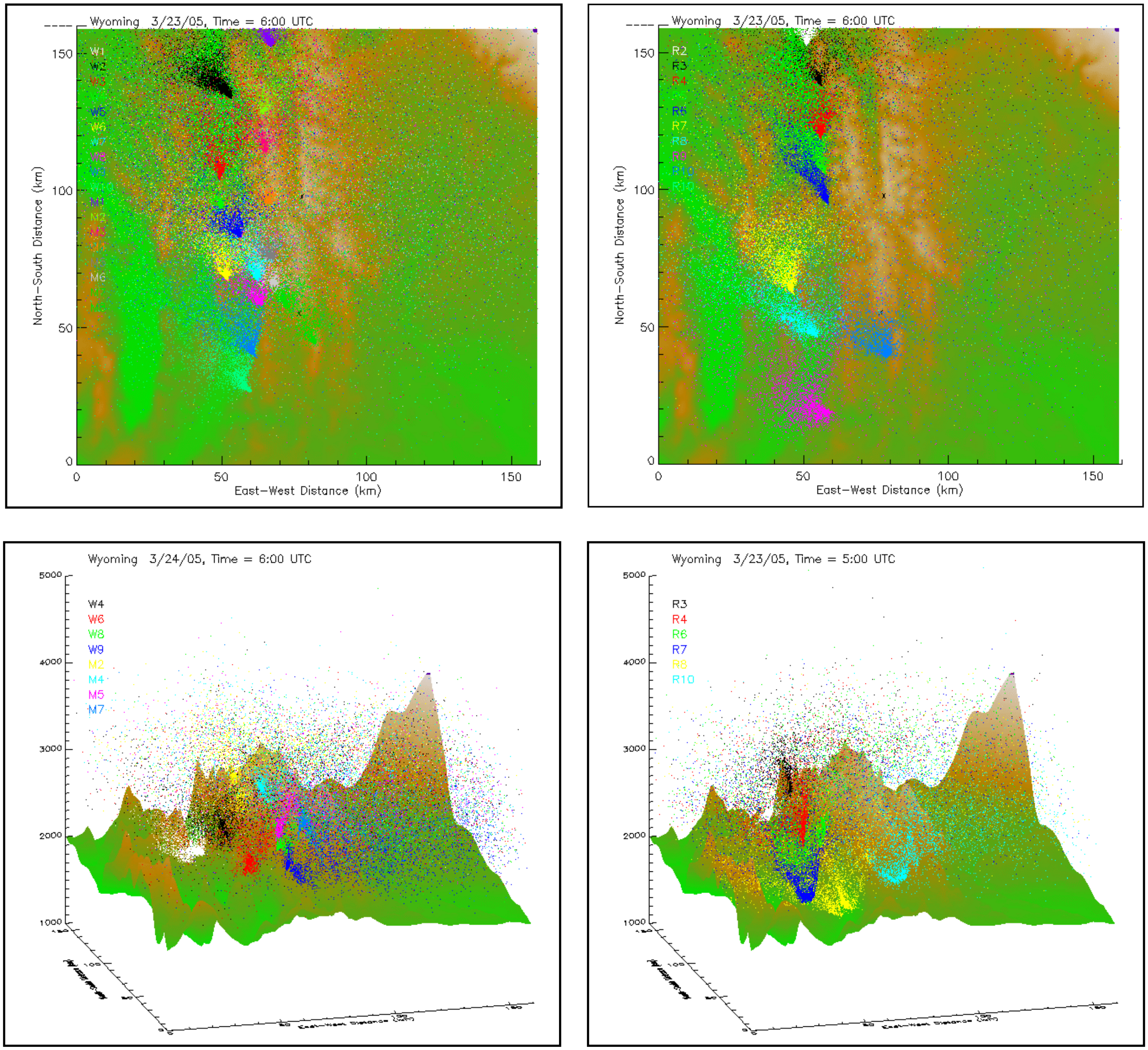


Figure 21. LAP plume predictions at 06 UTC on 23 March 2005 for W and M sites (left side) and R sites (right side). Top panels show the plan view of plumes and bottom panels show the perspective view. Black X's in top panels are the three SNOTEL site locations compared with MM5 in Fig. 12.

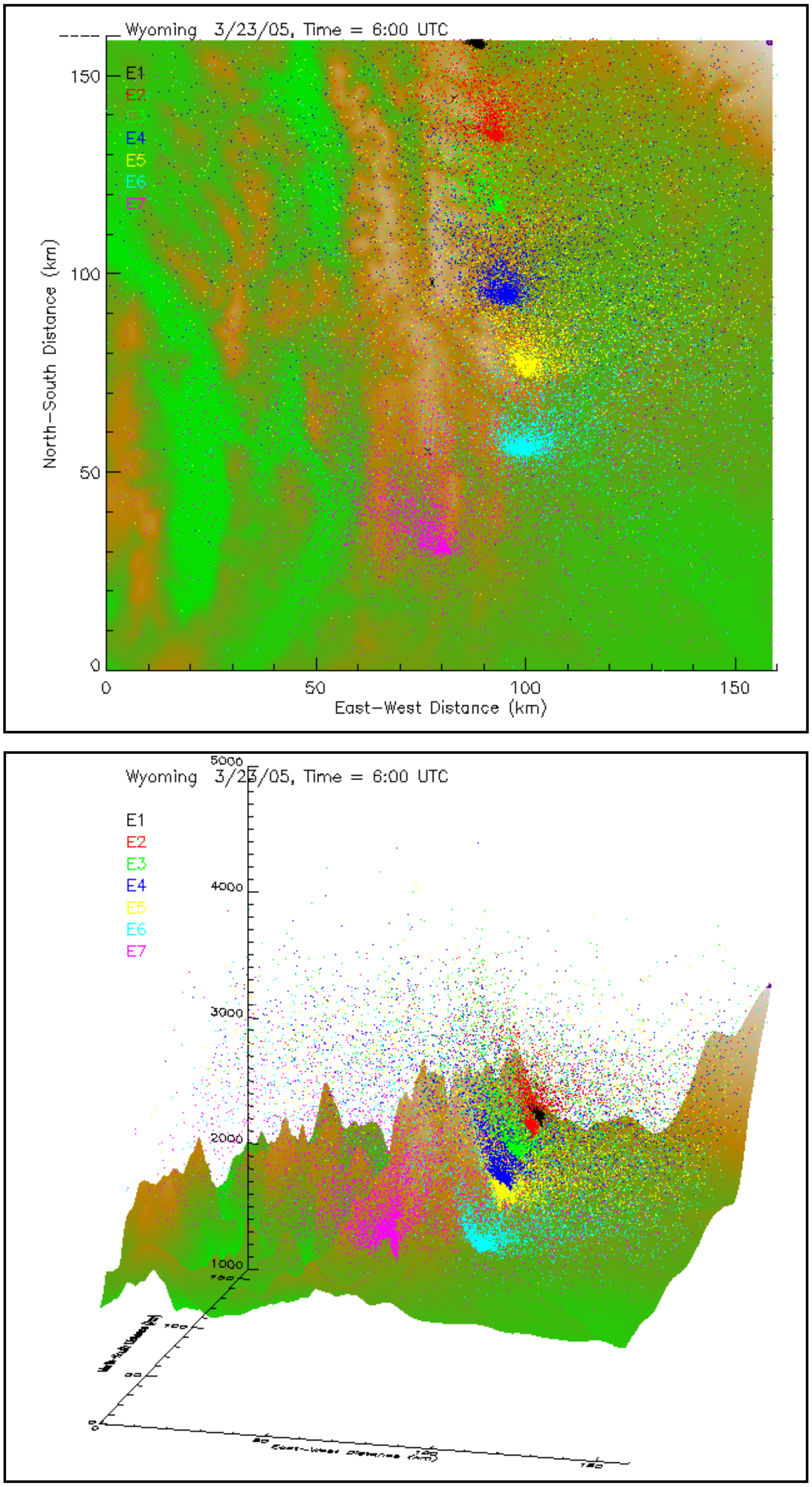


Figure 22. As is Fig. 21, except for showing LAP plumes from simulated seeding sites on the east side of the Wyoming Range (E sites in Fig. 11).

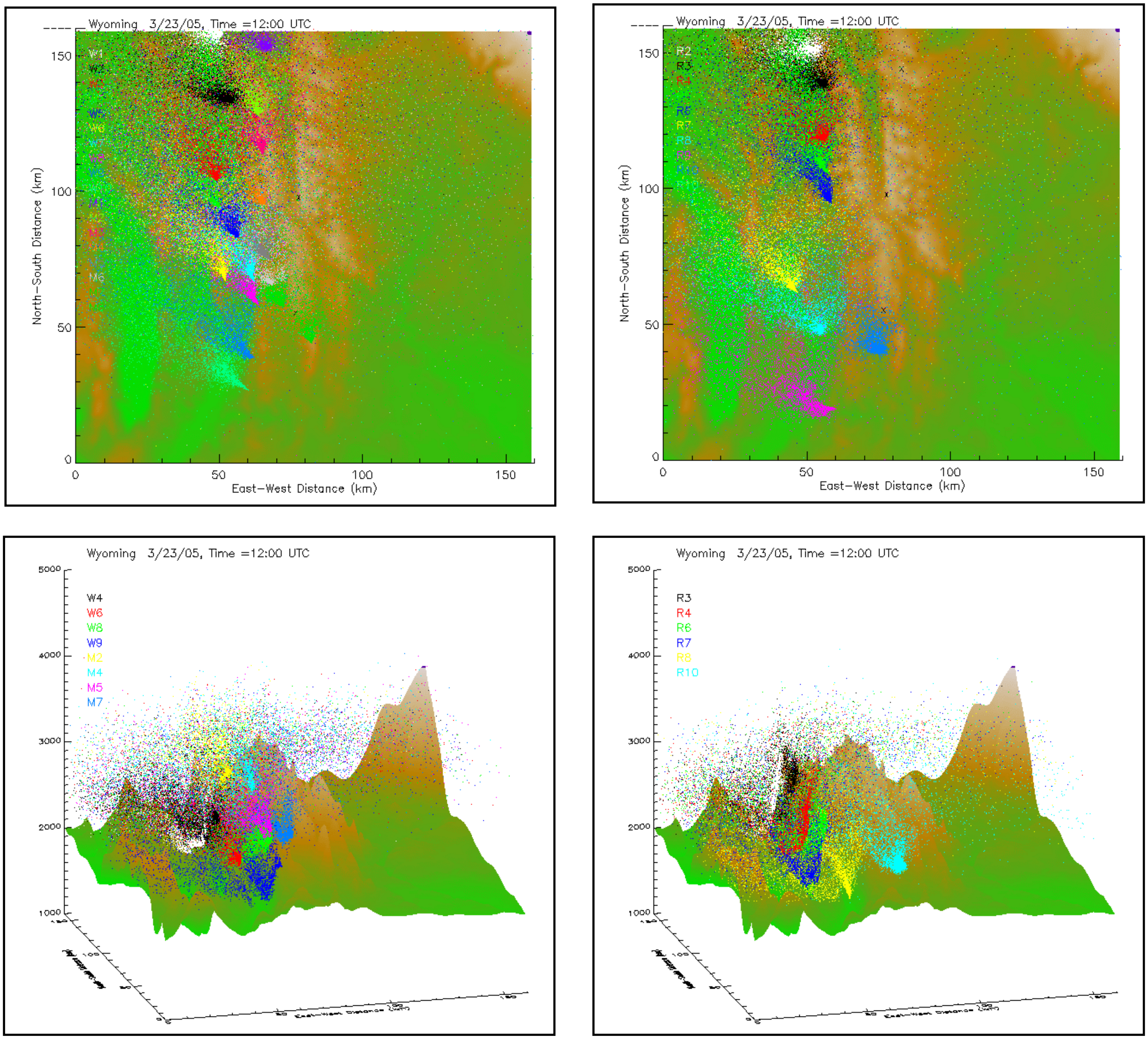


Figure 23. LAP plume predictions at 12 UTC on 23 March 2005 for W and M sites (left side) and R sites (right side). Top panels show the plan view of plumes and bottom panels show the perspective view.

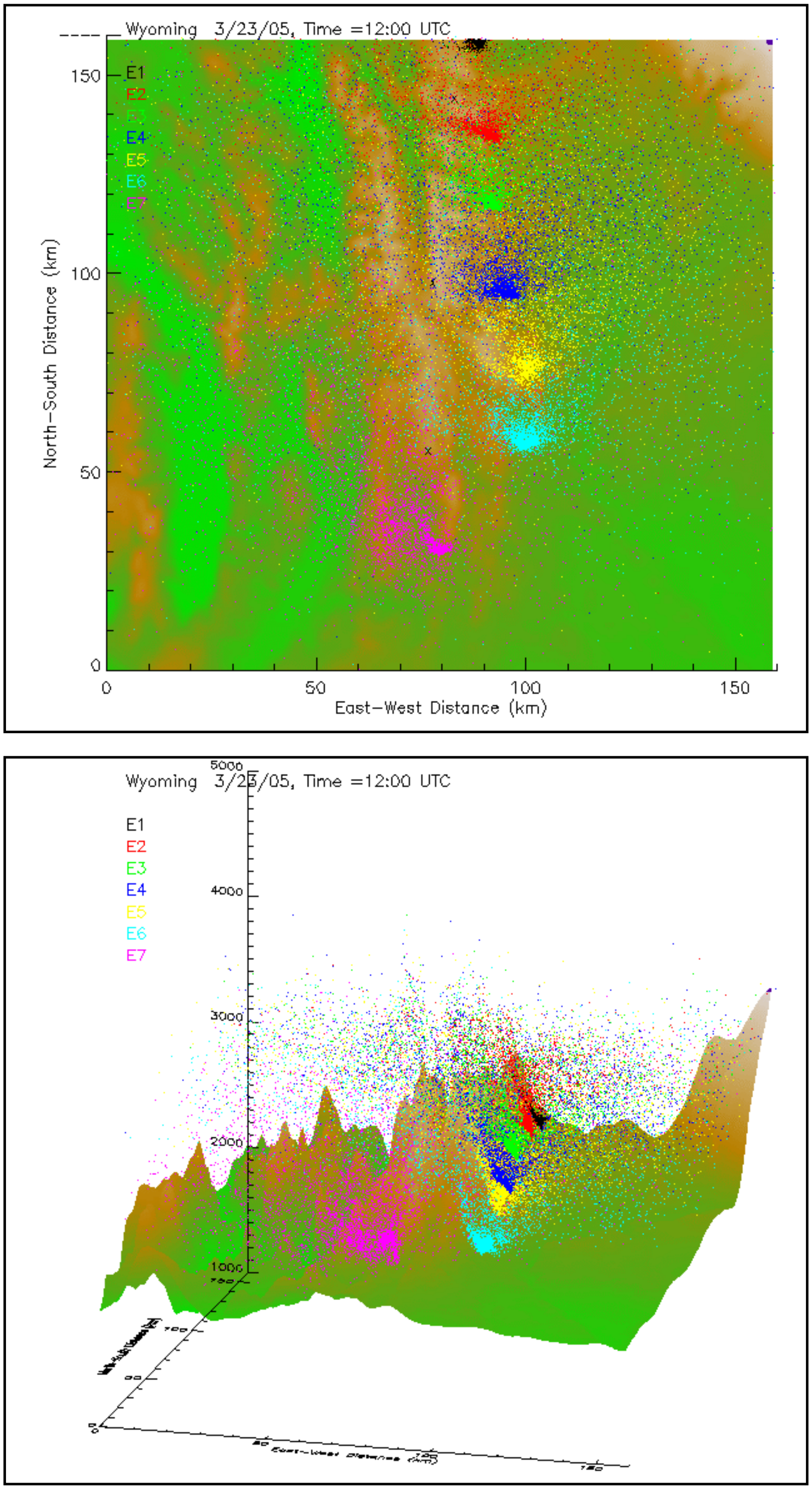


Figure 24. As is Fig. 23, except for showing LAP plumes from simulated seeding sites on the east side of the Wyoming Range (E sites in Fig. 11) at 12 UTC on 23 March.

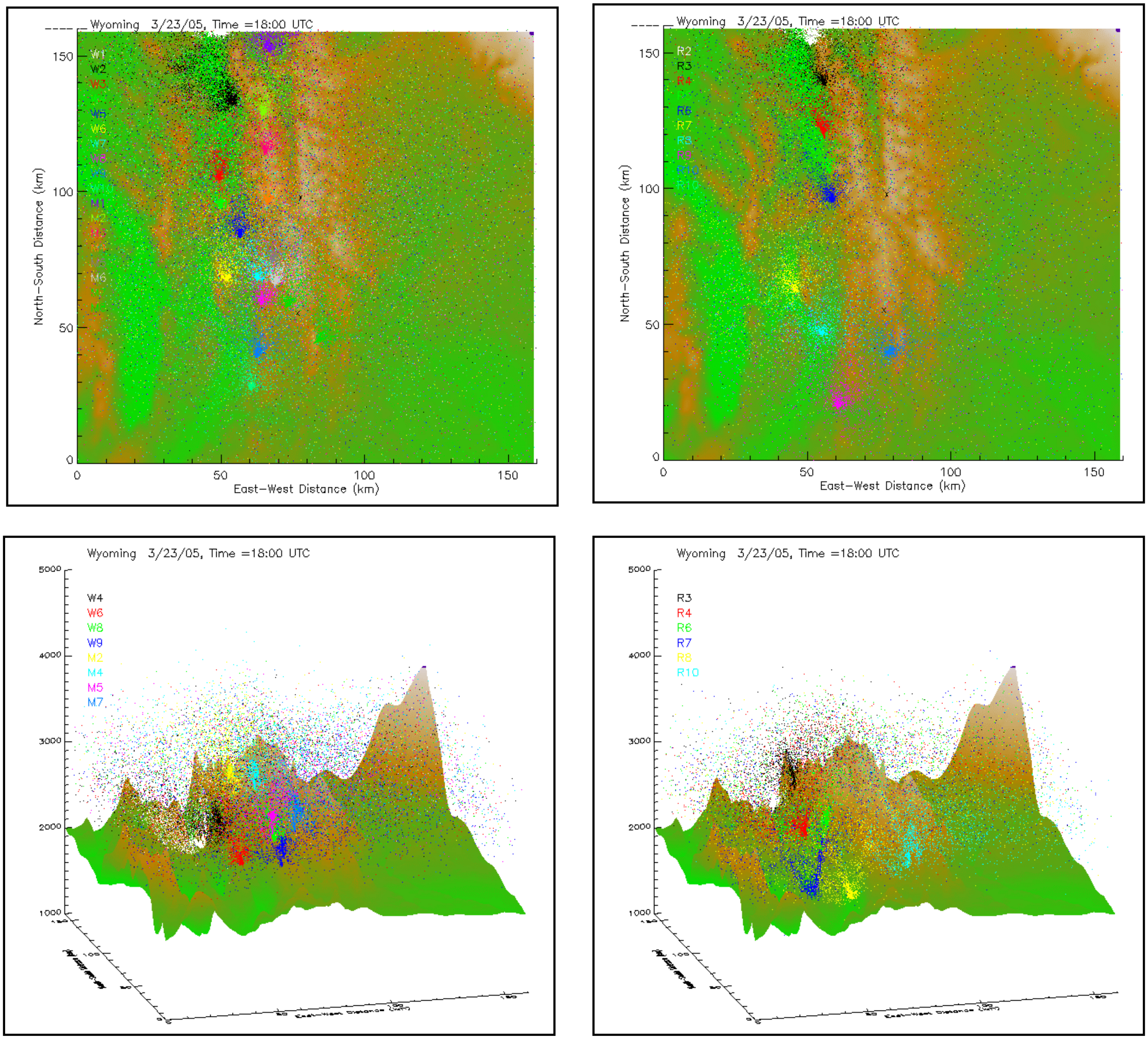


Figure 25. LAP plume predictions at 18 UTC on 23 March 2005 for W and M sites (left side) and R sites (right side). Top panels show the plan view of plumes and bottom panels show the perspective view.

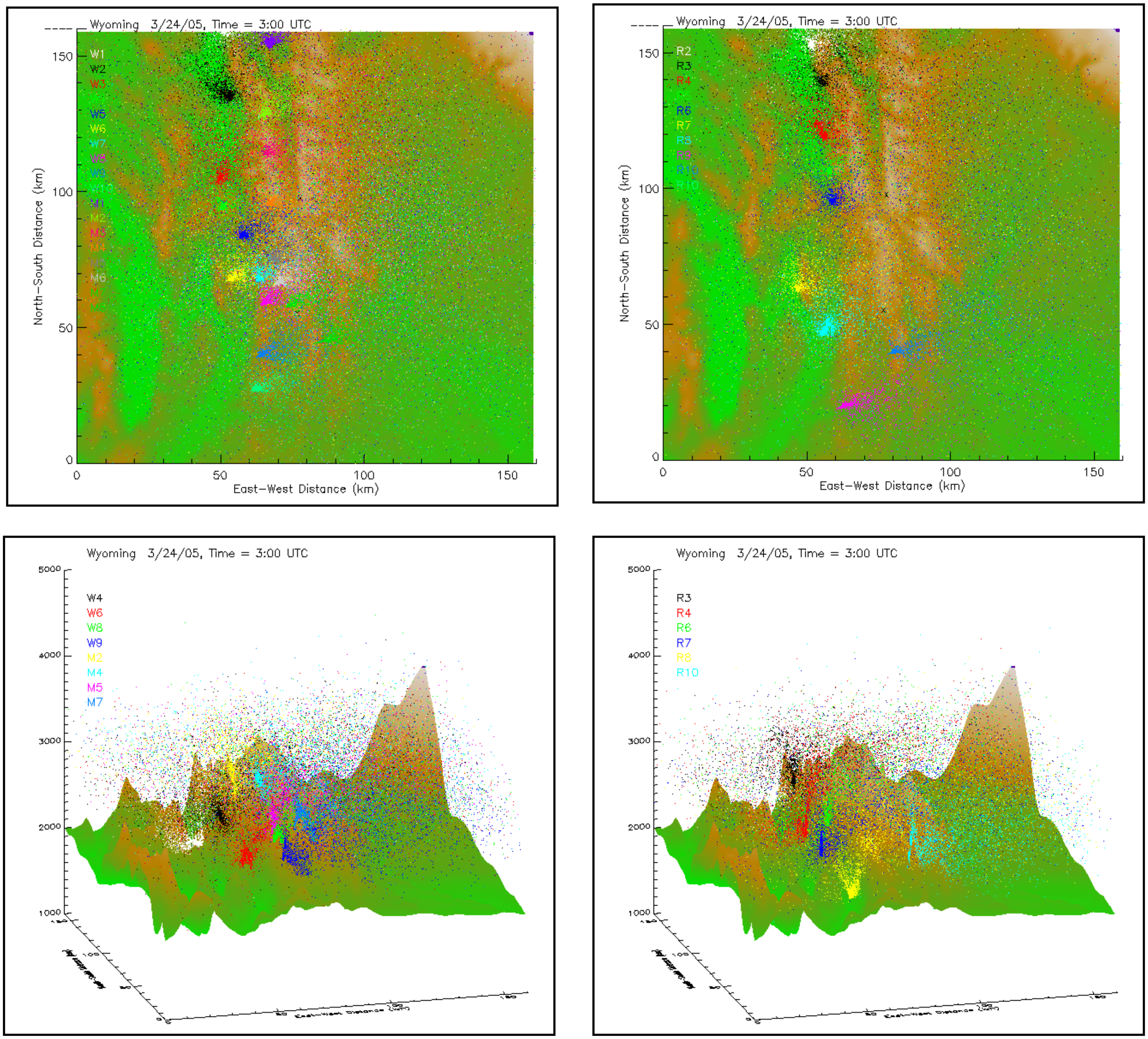


Figure 26. LAP plume predictions at 03 UTC on 24 March 2005 for W and M sites (left side) and R sites (right side). Top panels show the plan view of plumes and bottom panels show the perspective view.

Summary, Conclusions and Recommendations

Two winter storm cases were analyzed using the MM5 model and a Lagrangian particle dispersion model. Verification of MM5 predictions included comparisons with synoptic maps, NWS soundings and precipitation observations in the Salt River Range. Verification of variables such as wind fields near the surface and cloud water over the mountains was not possible since little or no observational data existed. Likewise plume dispersion predicted by LAP could not be verified by observations. Given the relatively good comparisons of MM5 output with the larger scale data sets and with precipitation observations, and given that plume patterns from LAP have been verified in similar situations in the Sierra Nevada, the LAP plume predictions should offer reasonable estimates of transport and dispersion for this feasibility study.

For both case studies MM5 predicted orographic cloud water development over the Salt River and Wyoming Ranges. The duration of cloud water in both cases was not unlike observations within storms over other mountainous regions (see e.g., Super, 1999), and indicated the potential for cloud seeding was satisfied in that regard. The location of cloud water over upwind slopes was also similar to what has been observed in field studies in other mountainous regions, although the simulated depth and magnitude of the cloud water tended to be larger. Observations of liquid water in winter storms in Utah (Sassen and Zhao, 1993; Huggins, 1995) indicated supercooled cloud liquid was mainly in the lowest 500-800 m above the terrain, with short-term episodes showing liquid to 1000 m or higher. In the MM5 simulations cloud liquid was often predicted to depths greater than 1000 m and to mixing ratios greater than 0.3 g kg^{-1}. Short-term observations have shown depths and concentrations of this magnitude, but long-term averages have generally been lower. The possible overestimates of cloud water depth should not affect the feasibility of ground seeding operations, but could impact the potential for seeding cloud liquid regions using aircraft. In summarizing observations over the Wasatch Plateau in Utah, Super (1999) noted that even with a special waiver to fly within 300-600 m of the terrain, both cloud liquid and seeding plumes were often below the aircraft flight level.

MM5 predicted cloud water in waves induced by the mountains on occasion, mainly in the first case study where stronger westerly flow across the north/south oriented ranges existed. As with the wave positions, the liquid regions tended to be quite variable in location and quite narrow in horizontal dimension. There also appeared to be times when the wave location enhanced the vertical motion over the upwind side of the target range, leading to a greater depth of the orographic cloud water layer. Such periods might be seedable by aircraft if they can be recognized in real time, and if suitable flight tracks can be designed. Based on the predictions from the two cases studied here, however, aircraft seeding to specifically target liquid regions in gravity waves does not appear to be a viable option for enhancing precipitation over the Salt River and Wyoming Ranges.

The seeding plume simulations from numerous ground locations in and around the Salt River and Wyoming Ranges were semi-quantitative in nature. They addressed the temporal evolution of seeding plumes over the target ranges and provided a visual representation of plume transport and the horizontal and vertical dispersion of plumes under a variety of wind conditions. The absolute concentrations of aerosols over the target ranges was not evaluated, nor was the potential concentration of active ice nuclei considered at the temperatures encountered by the plumes. The two cases produced a fairly limited range of temperatures at mountain top level. Case 1 mountain top temperatures were -8^o to -10^o C during the period when cloud water was predicted by MM5, so any plume transport to mountain top level or above would have encountered temperatures favorable for cloud seeding using silver iodide. Case 2 temperatures were higher, generally -5^o to -6^o C at mountain top level with an additional 500-600 m of vertical transport needed to reach the more favorable -8^o C level. Information elsewhere in this report provides estimates of the frequency of heights various temperatures over this region of Wyoming.

Three sets of ground seeding sites were considered. High altitude sites, or mountain sites (M sites) were within the Salt River Range slightly upwind of the crest line. They were positioned to test the feasibility of seeding the Wyoming Range from the Salt River Range. The mean height of these sites was 2515 m (8250 ft). If used in operations, they would need to be installed in the late summer or fall and operated remotely during the winter months. Sites in a second set of ground generators were mainly positioned on the west slope (W sites) of the Salt River Range above the valley but below the high altitude sites. Some of these were also on minor ridges and isolated hills to the west of the main range. The mean altitude of sites in this second set was 2262 m (7420 ft). It is suspected that most of these sites would also require remotely-controlled operation. In Case 2 a similar set of sites was positioned on the east slope (E sites) of the Wyoming Range. The final set of sites was positioned in the valley west of the Salt River Range along the main north/south road (R sites), mostly close to small towns. The mean height of R sites was 2005 m (6577 ft). These sites could be operated manually or remotely.

The plume simulations using the LAP particle dispersion model indicated that the high altitude M-sites were potentially the most effective for ground-based seeding to target either the Salt River or Wyoming Ranges. In southwesterly to northwesterly airflow transport over the Wyoming Range was predicted, and vertical dispersion was generally adequate to reach temperatures where silver iodide has significant activity. In addition to being above stable layers in the upwind valleys these sites were also frequently shown to be at or above the liquid cloud base. Case 2 indicated these sites would also be the most effective in southerly airflow where plumes were carried along the length of the Salt River Range. In the early situation in Case 2 where low-level easterly winds were predicted, these higher sites were experiencing more southerly flow and therefore several still showed plume transport over the target range.

The western slope W sites were potentially most effective with westerly winds. With the exception of the two most southerly sites and one site at the north end of the range, plumes moved across the target ranges. At times vertical transport was aided when plumes from the sites to the west of the Salt River Range were caught in a wave to the lee of one of the upwind ranges. In the early part of Case 1 where southwesterly flow was encountered at 3 km, winds to a depth above most of the W sites were channeled along the valley orientation and plumes from generators on the ridges and hills to the west of the Salt River Range were carried to the north and not across the target ranges. A few W sites on the west slope of the Salt River Range did show plume transport across the target. The southerly flow situation in Case 2 produced similar results, but in this case none of the W sites produced plumes that crossed the target.

Valley R sites were the least effective in southerly to southwesterly flow, mainly because they were more frequently subject to the channeling of winds moving north through the upwind valleys. Although not encountered in the two case studies it is likely that a similar pattern, but opposite in direction, would be produced by northwesterly and northerly winds. With the exception of the two most southerly sites, the valley sites showed their most favorable transport and dispersion over the targets in the westerly flow at the end of Case 1. This was also the most unstable period of the Case 1 storm. Due to light winds and unfavorable wind directions, valley sites appeared to be ineffective throughout Case 2. The possible exception was during a period when cloud water bands advected into the region and valley plumes showed adequate vertical transport to interact with these bands upwind of the target ranges.

Finally, a situation with low-level easterly flow was encountered in Case 2. The plumes from the E sites on the eastern slope of the Wyoming Range (similar in altitude to the W sites) showed transport into the low level cloud water over the eastern slopes. However, for this case it didn't appear likely that the plumes would have reached sufficiently cold temperatures to nucleate ice from silver iodide aerosols, mainly because the layer with easterly flow was too shallow and did not penetrate to cloud regions over the higher terrain of the target. This one case is probably not adequate to fully evaluate storms with easterly flow.

LAP plume shapes from Cases 1 and 2 allow for an estimate of the ground generator spacing that might be required to completely target the Salt River and Wyoming Ranges. The LAP plumes simulated during southwesterly to westerly airflow and moderate wind speeds behaved in a manner similar to plumes that have been documented with measurements in other mountainous areas. The example shown in Fig. 9 shows horizontal spreading that fits within the range of plume dimensions documented by Bruintjes et al (1995) over the mountains of north-central Arizona, Holroyd et al

(1988) over the Grand Mesa of Colorado and Huggins (1996) over the Wasatch Plateau in central Utah. The latter two cases also involved relatively high altitude releases of silver iodide. The vertical extent of the LAP plumes was also similar to observations made by aircraft over the Wasatch Plateau, in that the bulk of the LAP particles were generally found within 1 km of the top of the Salt River and Wyoming Mountains.

The visual indications of plumes merging in the current case studies suggest a ground generator spacing of about 10 km would be needed to completely cover the target ranges with seeding aerosols. This takes into account only the physical dimensions of plumes, and not temperature considerations, silver iodide activity and the concentrations of ice particles that might be expected. Based on the simulated plume behavior in the valleys upwind of the target ranges it would not be advisable to position generators further upwind to increase the horizontal dimension over the target. It is unlikely that the plumes would be carried toward the target in most situations, and concentrations would likely too low to significantly modify ice particle concentrations.

Based on the variability in plume behavior under different wind conditions it would be advisable to have meteorological measurements sufficient to characterize the surface and upper-air conditions during storm periods. Current networks (such as the BLM RAWS network) might be adequate for surface conditions, but an upper air sounding near the target ranges would be very useful. As suggested in the original Wyoming Feasibility Study, some type of dispersion or particle trajectory model, capable of being run in near real time, would be very helpful in determining what generators, if any, to operate in a specific storm situation. In addition a microwave radiometer to verify the presence of supercooled liquid water would also be helpful.

APPENDIX D

Historical Wyoming Cloud Seeding Permits

1	Water Resources Development Corporation	Denver, CO	21-Apr-51	Campbell, Johnson, Crook, Niobrara, Sheridan, Weston
2	Water Resources Development Corporation	Denver, CO	21-Apr-51	Albany, Goshen, Laramie, Platte, Carbon
3	Water Resources Development Corporation	Denver, CO	5-Jun-51	Park Big Horn, Washakie, Hot Springs
4	North American Weather Consultants	Pasadena, CA	24-Mar-52	Platte, Goshen, Laramie
5	North American Weather Consultants	Pasadena, CA	2-Apr-52	Campbell
6	North American Weather Consultants	Pasadena, CA	23-Apr-52	Sheridan
7	Water Resources Development Corporation	Denver, CO	14-May-52	Converse, Niobrara, Weston
8	Johnson County Weather Modification, Inc.	Buffalo, WY	16-Sep-52	Johnson
9	Water Resources Development Corporation	Denver, CO	12-May-53	Converse, Weston, Goshen, Niobrara, Platte, Laramie, Sheridan
10	Water Resources Development Corporation	Denver, CO	15-Feb-54	Campbell, Crook, Weston, Niobrara, Converse, Carbon, Albany, Platte, Goshen, Laramie, Sheridan, Johnson
11	North American Weather Consultants	Altadena, CA	9-Dec-54	Unita, Lincoln
12	Water Resources Development Corporation	Denver, CO	29-Dec-54	Sweetwater, Platte, Carbon, Albany, Laramie
13	Water Resources Development Corporation	Denver, CO	25-Jan-55	Carbon, Albany, Sweetwater, Laramie
14	Weather Modification Company	San Jose, CA	11-Apr-56	Goshen
15	Weather Engineers, Inc.	Sacramento, CA	7-Jun-57	Goshen
16	Grazing, Inc.	Alzada, MT	21-Jun-61	Crook, Campbell, Weston
17	The Boeing Company	Seattle, WA	22-Jan-62	Yellowstone Park
18	Natural Resources Research Institute	Laramie, WY	12-Feb-63	Carbon, Albany, Sublette, Fremont
19	North American Weather Consultants of Nevada	Goleta, CA	30-Sep-63	Lincoln
20	Natural Resources Research Institute	Laramie, WY	26-Nov-63	Carbon, Albany, Sublette, Fremont
21	North American Weather Consultants of Nevada	Goleta, CA	6-Dec-63	Lincoln
22	Natural Resources Research Institute	Laramie, WY	2-Nov-64	Carbon, Albany, Sublette, Fremont
23	North American Weather Consultants of Nevada	Goleta, CA	26-Oct-64	Lincoln
24	North American Weather Consultants of Nevada	Goleta, CA	20-Jan-65	Lincoln
25	Natural Resources Research Institute	Laramie, WY	18-Mar-69	Sublette (Eden ID)
26	Natural Resources Research Institute	Laramie, WY	18-Mar-69	Carbon, Albany
27	EG&G, Inc., Environmental Service Operation	Boulder, CO	19-Dec-69	Teton (Teton Village Ski Area)
28	Natural Resources Research Institute	Laramie, WY	4-Dec-70	Sublette (Eden ID)
29	Natural Resources Research Institute	Laramie, WY	4-Dec-70	Albany
30	University Corporation for Atmospheric Research	Boulder, CO	7-May-71	Laramie
31	University Corporation for Atmospheric Research	Boulder, CO	30-Dec-71	Laramie
32	University Corporation for Atmospheric Research	Boulder, CO	12-Oct-72	Laramie
33	Jackson Hole Ski Corporation	Jackson, WY	19-Dec-72	Teton
34	U of W - Dept of Atmospheric Sciences	Laramie, WY	3-Jan-73	Carbon, Albany
35	U of W - Dept of Atmospheric Sciences	Laramie, WY	3-Jan-73	Sublette (Eden ID)
36	U of W - Dept of Atmospheric Sciences	Laramie, WY	13-Nov-73	Carbon, Albany
37	U of W - Dept of Atmospheric Sciences	Laramie, WY	13-Nov-73	Sublette (Eden ID)
38	University Corporation for Atmospheric Research	Boulder, CO	11-Mar-74	Laramie

39	U of W - Dept of Atmospheric Sciences	Laramie, WY	12-Nov-74	Sublette (Eden ID)
40	Colorado International Corp of Delaware	Boulder, CO	29-Nov-74	Teton (Teton Village Ski Area)
41	Eden Valley I&D Dist	Farson, WY	27-Jun-75	Sublette (Eden ID)
42	University Corporation for Atmospheric Research	Boulder, CO	25-Feb-76	Hail Research
43	Colorado International Corp	Boulder, CO	7-Dec-76	Teton (Teton Village Ski Area)
44	Eden Valley I&D Dist	Farson, WY	29-Dec-76	Sublette (Eden ID)
45	Colorado International Corporation	Boulder, CO	10-Feb-77	Carbon, Albany
46	Colorado Internation Corporation	Boulder, CO	2-Mar-77	Sublette, Sweetwater
47	Eden Valley I&D Dist	Farson, WY	28-Jul-77	Sublette (Eden ID)
48	Colorado International Corporation	Boulder, CO	7-Nov-77	Teton (Teton Village Ski Area)
49	North American Weather Consultants, Inc.	SLC, UT	24-Feb-78	Uinta
50	State University of New York at Albany	Albany, NY	7-Mar-78	Front Range of Wyoming
51	Eden Valley I&D Dist	Farson, WY	24-Aug-78	Sublette (Eden ID)
52	Colorado International Corporation	Boulder, CO	18-Oct-78	Teton (Teton Village Ski Area)
53	Eden Valley I&D Dist	Farson, WY	30-Aug-79	Sublette (Eden ID)
54	Colorado Internation Corporation	Boulder, CO	11-Oct-79	Teton (Teton Village Ski Area)
55	North American Weather Consultants, Inc.	SLC, UT	25-Oct-79	Lincoln
56	Eden Valley I&D Dist	Farson, WY	28-Aug-80	Sublette (Eden ID)
57	North American Weather Consultants, Inc.	SLC, UT	6-Oct-80	Lincoln
58	North American Weather Consultants, Inc.	SLC, UT	21-Oct-81	Lincoln
59	Eden Valley I&D Dist	Farson, WY	28-Oct-81	Sublette (Eden ID)
60	Eden Valley I&D Dist	Farson, WY	27-Sep-82	Sublette (Eden ID)
61	Eden Valley I&D Dist	Farson, WY	15-Dec-83	Sublette (Eden ID)
62	Eden Valley I&D Dist	Farson, WY	5-Sep-84	Sublette (Eden ID)
63	Eden Valley I&D Dist	Farson, WY	24-Sep-85	Sublette (Eden ID)
64	Eden Valley I&D Dist	Farson, WY	24-Sep-86	Sublette (Eden ID)
65	Eden Valley I&D Dist	Farson, WY	17-Sep-87	Sublette (Eden ID)
66	Eden Valley I&D Dist	Farson, WY	16-Nov-88	Sublette (Eden ID)
67	North American Weather Consultants, Inc.	SLC, UT	26-Oct-88	Lincoln
68	North American Weather Consultants, Inc.	SLC, UT	10-Oct-89	Lincoln
69	Eden Valley I&D Dist	Farson, WY	9-Nov-89	Sublette (Eden ID)
70	Eden Valley I&D Dist	Farson, WY	15-Oct-90	Sublette (Eden ID)
71	Eden Valley I&D Dist	Farson, WY	26-Aug-91	Sublette (Eden ID)
72	Eden Valley I&D Dist	Farson, WY	19-Oct-92	Sublette (Eden ID)
73	North American Weather Consultants, Inc.	SLC, UT	8-Jan-93	Lincoln
74	Eden Valley I&D Dist	Farson, WY	7-Oct-93	Sublette (Eden ID)
75	Eden Valley I&D Dist	Farson, WY	7-Oct-94	Sublette (Eden ID)
76	Eden Valley I&D Dist	Farson, WY	21-Sep-95	Sublette (Eden ID)
77	Eden Valley I&D Dist	Farson, WY	4-Nov-96	Sublette (Eden ID)
78	Eden Valley I&D Dist	Farson, WY	26-Sep-97	Sublette (Eden ID)
79	Eden Valley I&D Dist	Farson, WY	23-Oct-98	Sublette (Eden ID)
80	Eden Valley I&D Dist	Farson, WY	24-Sep-99	Sublette (Eden ID)
81	Eden Valley I&D Dist	Farson, WY	3-Nov-00	Sublette (Eden ID)
82	Eden Valley I&D Dist	Farson, WY	26-Sep-01	Sublette (Eden ID)
83	Eden Valley I&D Dist	Farson, WY	19-Sep-02	Sublette (Eden ID)
84	Eden Valley I&D Dist	Farson, WY	9-Sep-03	Sublette (Eden ID)
85	North American Weather Consultants	Sandy, UT	14-Nov-03	Robertson (Duchesne, Uinta UT)

86	Eden Valley I&D Dist	Farson, WY	27-Aug-04	Sublette (Eden ID)
87	North American Weather Consultants	Sandy, UT	12-Nov-04	Robertson (Duchesne, Uinta UT)
88	Eden Valley I&D Dist	Farson, WY	14-Oct-05	Sublette (Eden ID)
89	North American Weather Consultants	Sandy, UT	4-Nov-05	Robertson (Duchesne, Uinta UT)
90	Weather Modification, Inc.	Fargo, ND	17-Jan-06	Carbon, Albany

Appendix E

Glossary of Terms

A majority of these definitions were originally provided in the WMI Final Feasibility Report for the Medicine Bow, Sierra Madre and Wind River Ranges, WMI, 2005.

Definitions are those found within the Glossary of Meteorology, where applicable. Italicized print in this section indicates an alternative glossary entry that the reader may also wish to review.

acoustic ice nucleus counter – Sometimes called an "NCAR counter", this instrument can be operated either on the ground of on an airplane. It is used to sample the atmosphere and "count" *ice nuclei*. The acoustic ice nucleus counter will count both natural and artificial ice nuclei, but cannot distinguish between them.

Advect or advection – The process of transport of an atmospheric property (e.g. temperature) by the horizontal or vertical motions (winds) of the atmosphere. Vertical transport due to buoyancy is a specialized form of advection known as *convection*.

AF – acre-foot or acre-feet.

AgI – see *silver iodide*.

AMS – American Meteorological Society, 45 Beacon Street, Boston, MA 02108-3693.

anemometer – The general name for instruments designed to measure the wind.

BLM – Bureau of Land Management, U.S. Department of the Interior.

BuRec – United States Bureau of Reclamation, Department of the Interior.

CCN – Cloud condensation nuclei. The tiny particles, either liquid or solid, upon which condensation of water vapor first begins in the atmosphere, they are necessary for the formation of cloud droplets.

cloud condensation nuclei – See *CCN*.

cell – A convective element (cloud) which in its life cycle, develops, matures, and dissipates, usually in about 30 min.

cloud droplet – A particle of liquid water from a few microns to tens of microns in diameter formed by condensation of atmospheric water vapor and suspended in the atmosphere with other droplets for form a cloud. These liquid water droplets are too small to precipitate.

cloud model – Physical description of cloud processes programmed into a computer to simulate cloud development and evolution. Very useful in understanding the relative importance of the many factors that influence cloud development, and the only way in which *exactly the same cloud* can be both seeded and unseeded (see also *targeting model*).

coalescence – In cloud physics, the merging of two water drops into a single larger drop. This occurs through the collision or two drops, which then unite.

convection – Vertical transport of an atmospheric property (e.g. temperature) by the vertical motions (winds) in the atmosphere driven by buoyancy.

EA – Environmental Assessment. A preliminary assessment of potential environmental impact of a planned activity. An EA will result in either the conduct of an *EIS*, or a *FONSI*.

EIS – Environmental Impact Statement. A detailed environmental study pertaining to planned activities, conducted after an *EA*, in accordance with *NEPA*.

FAA – Federal Aviation Agency, U.S. Department of Transportation.

FBO – Fixed-base operator. Airport-based business which provides fuel, maintenance, and often other aviation-related services.

glaciogenic – Causing the formation of ice.

glaciogenic seeding – Treatment of clouds with materials intended to increase and/or initiate the formation of ice crystals.

grid spacing – The distance between two points in a numerical (computer) model grid. Calculations derived from atmospheric theory and pertinent to the solution of the model are performed at each grid point by the computer.

ground generator – An ice nucleus generator operated on the surface.

hail – Precipitation in the form of balls or irregular lumps of ice, always produced by convective clouds, nearly always by cumulonimbus. An individual unit of hail is called a hailstone. By convention, hail has a diameter of 5 mm or more.

hydrometeor – Any product of condensation or deposition, or condensation and freezing, in the atmosphere. This includes cloud water or ice of any size, either suspended in the air or precipitating.

hygroscopic – Pertaining to a marked ability to accelerate the condensation of water vapor; having the property of attracting water, or having the effect of encouraging the formation of larger droplets.

hygroscopic seeding – Treatment of clouds with hygroscopic materials which encourage the formation of larger droplets, changing the cloud droplet spectrum in such a way as to enhance development of precipitation through coalescence.

ice nucleus – Any particle that serves as a nucleus for the formation of ice crystals in the atmosphere.

IFR – Instrument Flight Rules. The FAA regulations pertaining to flight at altitudes of 18,000 feet above mean sea level or higher over U.S. airspace, or in any meteorological conditions necessitating the use of aircraft instrumentation for safe navigation.

***in situ* measurement** – Measurements made within the portion of the atmosphere or cloud of interest.

inversion - a departure from the usual decrease in temperature with an increase in altitude.

mb – Millbar. A unit of pressure equal to one hecto-Pascal (hPa). Standard sea-level pressure is 1013.25 mb.

mesoscale – Weather features on the order of 1 to 100 km in horizontal dimensions.

microphysical – Very small scale features of a system, in this case, a cloud. These features include the sizes, shapes, and number of raindrops, cloud drops, ice, snow, graupel, and hail.

MSL – Mean Sea Level.

MST – Mountain Standard Time. Seven hours slower than GMT, CUT, and UTC. For example, 3:00 p.m. MDT equals 10 p.m. (22:00) UTC.

NAWC - North American Weather Consultants, Sandy, Utah.

NCAR – National Center for Atmospheric Research, Boulder, Colorado.

NEPA – National Environmental Policy Act. Federal environmental study rules and regulations employed whenever any action is planned that may affect federal lands.

nesting – A process where one grid cell for a numerical model is split into the designated number in the nesting ratio. For example, if the ratio is 3-to-1, the original cell would be split into three, at computations would be performed at all three points. This is a way to increase the resolution of a model over a specific region of interest.

NEXRAD – Next generation radar. Federally operated, sophisticated weather radar systems.

NOAA – National Oceanic and Atmospheric Administration, U.S. Department of Commerce. The parent agency of the National Weather Service (NWS).

NRC – National Research Council, Washington, D.C.

NRCS – Natural Resources Conservation Service.

nucleation – The initial formation of a cloud droplet or ice crystal.

NWS – National Weather Service, a division of *NOAA*.

orographic cloud – A cloud formed by terrain induced lifting of moist air, for example, air forced to rise to pass over a mountain.

orography – Topography, terrain, vertical relief.

pyrotechnic – Special flare designed to produce *glaciogenic* or *hygroscopic* nuclei.

radiometer – A device which passively senses microwave radiation at varying wavelengths as it passes through the atmosphere from space. Certain atmospheric constituents, for example liquid water and water vapor, attenuate the incoming radiation. Thus, these quantities can be measured by radiometers.

radiosonde (**or rawinsonde**) – An instrument package that senses and transmits weather information such as pressure, temperature, and humidity. Radiosondes are carried aloft by weather balloons twice daily from numerous sites all over the world, and can also be employed by projects to bolster local forecasting efforts.

RAMS – Regional Atmospheric Modeling System. A widely-used numerical model developed by Colorado State University scientists.

reflectivity (or equivalent radar reflectivity factor, Z_e) – The energy, first transmitted by a weather radar, reflected back toward the radar. In general, the more "dense" the reflecting cloud mass, the greater will be the reflectivity. Ice reflects about one-fifth the energy reflected by water, however, so reflectivities from snow are accordingly less.

remote sensing – The remote measurement of properties of interest, as with radar and satellite. Compare *in situ measurement*.

seeding agents – Agents dispensed by any means in or near a cloud volume which are intended to modify (seed) the cloud characteristics.

silver iodide – AgI, a common glaciogenic seeding agent.

SLW – Supercooled liquid water, see *supercooled water*.

SNOTEL – Snow measurement and telemetry site operated by the *NRCS*.

SRWR – Salt River and Wyoming Ranges.

stability - Resistance to vertical motion in the atmosphere due to thermodynamic structure.

supercooled liquid water – Water, still in liquid state, at temperatures less than 0^oC (32^oF). Under ideal conditions in the free atmosphere, water may exist in a supercooled state to temperatures as cold as -40^oC (-40^oF).

SWE – Snow water equivalent.

synoptic scale – Weather features of horizontal dimensions greater than 100 km.

target area – The area for which cloud seeding operations are targeted, usually near a *control area* similar in character and climatology. The behavior of treated storms over the target area is compared to untreated storms over the control area, to assess differences and thus measure project effectiveness. See also, *control area*, *seeding area*, and *seeded area*.

targeting model – Computer modeling in which terrain and winds are used to project when and where cloud seeding upwind of a target area should be conducted.

terminal velocity – The particular falling speed, for any given object moving through a fluid of specified physical properties, at which the drag forces and buoyant forces exerted by the fluid on the object just equal the gravitational force acting on the object. For hydrometeors, the greatest fall speed relative to the surrounding air that a hydrometeor will attain, as determined by the mass of the particle and frictional drag of the air through which it is falling.

tracer – An inert (non-reactionary) substance or aerosol that is dispersed into the atmosphere, commonly used to reveal wind flow patterns. In numerical modeling, there are no other calculations performed for tracers other than horizontal and vertical advection.

USFS – United States Forest Service, a division of the *USDA*.

UTC – Universal Time Coordinates. See also *GMT*, *CUT*. Seven hours ahead of Mountain Standard Time; for example, 10:00 p.m. UTC (22:00) equals 3:00 p.m. (17:00) MST.

VFR – Visual flight rules established by the *FAA* that state the requirements for flight in “visual” conditions.

wing-tip generator – Ice nucleus generators mounted at the tips of aircraft wings, or sometimes below the wings (usually near the ends).

WMA – Weather Modification Association, P.O. Box 26926, Fresno, CA 93729-6926.

WMI – Weather Modification, Inc., Fargo, North Dakota.

WRF – The Weather Research and Forecasting Model employed by RAL to study wind flow, transport and dispersion of seeding agents, and precipitation development within (and beyond) the areas of interest.

WWDC – Wyoming Water Development Commission, Cheyenne, Wyoming.

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