SUMMARY OF A WEATHER MODIFICATION FEASIBILITY/DESIGN STUDY FOR WINTER SNOWPACK AUGMENTATION IN THE UPPER BOISE RIVER BASIN, IDAHO

Don A. Griffith, David P. Yorty, and Mark E. Solak
North American Weather Consultants, Inc.
Sandy, Utah 84093

ABSTRACT. North American Weather Consultants (NAWC) performed a feasibility/preliminary design study of potential means of augmenting an existing operational winter cloud seeding program in the Upper Boise River Basin (UBRB) program in Idaho by extending the base project period of November through March by one month (April) and possibly adding remote generators and seeding aircraft to the existing lower elevation manual generator network. This study was performed for the Idaho Water Resources Board (IWRB). The IWRB noted that the upper Boise, including the North Middle and South Forks, and Mores Creek supplies 90% of the water for the lower Boise Basin. The UBRB ranges in elevation from approximately 915 m (3,000 feet) MSL at Lucky Peak Dam to crest elevations of approximately 2590 – 2700 m (8,500 to 9,500 feet) MSL between the Boise River and Big Wood River Basins. NAWC recommended that the intended target area for the UBRB program be defined as those regions in the basin that are above 1524 m (5,000 feet) MSL. The primary program goal would be to increase winter snowpack in the target area through operational cloud seeding. The resulting augmented spring and summer stream flow would be used in a number of ways including augmented hydroelectric power production and agricultural irrigation.

Average increases of 4.7% in April 1st snow water contents from cloud seeding were estimated through transference of the indicated results from the Climax I and II research programs. Simulations using empirically derived snowpack-stream flow relations yielded estimated average increases in March-July stream flow from three seeding modes totaling approximately 1.004×10^8 m^3 (81,425 acre-feet). The costs of the estimated increases in March-July stream flow range from \$0.003 to \$0.01 per cubic meter (\$3.29 to \$12.45 per acre-foot) of additional water in an average water year. A preliminary design for an augmented operational winter cloud seeding program is described.

1. INTRODUCTION

The Idaho Water Resource Board (IWRB) contracted with North American Weather Consultants (NAWC) of Sandy, Utah for the performance of a comprehensive study of the feasibility/design of applying modern cloud seeding methodologies for winter snowpack augmentation in a portion of the Upper Boise River Basin located in southwestern Idaho (Griffith and Yorty, 2009a). This paper presents the key elements, findings, conclusions and recommendations of that feasibility/design study. The study included a survey of relevant prior research and operational seeding programs, considerable analysis of program area-specific historical weather data, assessment of potential cloud seeding methods, plus evaluation techniques. Procedures and recommendations of the ASCE publication entitled "Standard Practice for the Design and Operation of Precipitation Enhancement Projects" were utilized where appropriate (ASCE, 2004).

An interesting aspect of the Upper Boise River Basin feasibility/design work is that NAWC had already conducted operational winter cloud seeding programs in this area. NAWC conducted five-month programs during the water years of 1992-1996, 2001-2005, and 2007-2009 (Griffith and Solak, 2002, Griffith, et al, 2009) and a three month program during the 2010 - 2011 water year (Griffith, et al, 2011). In recent seeded seasons, a network of approximately 20 manually operated, ground based silver iodide generators have been used in the conduct of this operational program. Therefore, the design of the program that is considered in this study is focused upon potential means of augmenting or enhancing this existing operational cloud seeding program.

A preliminary operational program design, including identification of permit and reporting requirements, was prepared. The study also included hydrologic estimates of the potential program yield in terms of additional runoff and the estimated costs associated with conduct of the program, based on different seeding modes.

The tasks specified by the IWRB in the performance of this feasibility/design study included:

- Review and Analysis of Climatology of the Target Area
- Review and Assessment of the Existing Program
- Evaluate Enhancements of the Existing Program
- Establish Criteria for Program Operation
- Development of Monitoring and Evaluation Methodology
- Development of Operational Suspension Criteria
- Preparation of a Final Report including an Executive Summary

Summaries of prior applicable research and operational programs and environmental and legal considerations were included in the final report. This information had been generated in the performance of similar feasibility/design studies conducted for the IWRB focused on the Eastern Snake River Basin in Idaho (Griffith, et al, 2010) and the Salt and Wyoming Ranges in southwestern Wyoming conducted for the Wyoming Water Development Commission (Griffith, et al, 2007).

2. PROGRAM GOALS AND SCOPE

The stated goal of the proposed seeding program is to increase winter snowpack in the target area to provide additional spring and summer stream flow and recharge of underground aquifers at a favorable benefit/cost ratio without the creation of any significant negative environmental impacts. 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 (Hess, 1974). Evaluation procedures, based upon an historical target and control approach, were developed and incorporated in the program design. 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 program specific rawinsonde (balloon) soundings are recommended for conduct on a phased rather than ongoing basis, to help maintain program cost effectiveness.

3. TARGET AREA

The Idaho Water Resources Board (IDWR) specified the area of interest to be the Upper Boise River Basin (UBRB). This area lies within portions of Boise, Camas and Elmore Counties. The IDWR noted that the upper Boise, including the North Middle and South Forks, and Mores Creek supplies 90% of the water for the lower Boise Basin. The UBRB ranges in elevation from approximately 915 m (3,000 feet) MSL at Lucky Peak Dam to crest elevations of approximately 2591 to 2744 m (8,500 to 9,500) feet MSL between the Boise River and Big Wood River Basins. NAWC recommended that the intended target area for the UBRB program be defined as those regions in the basin that are above 1524 m (5,000 feet) MSL since a high percentage of the runoff originates from regions above this elevation. This area is outlined in Figure 1.

Runoff from this target area benefits hydropower production, agriculture (both surface runoff and ground water recharge), municipalities (drinking water), as well as recreational interests. Approximately 70 - 80% of the annual precipitation in the target area accumulates during the October-April period, with area average snowpack water equivalent on April 1 of 64.5 cm (25.4 in).

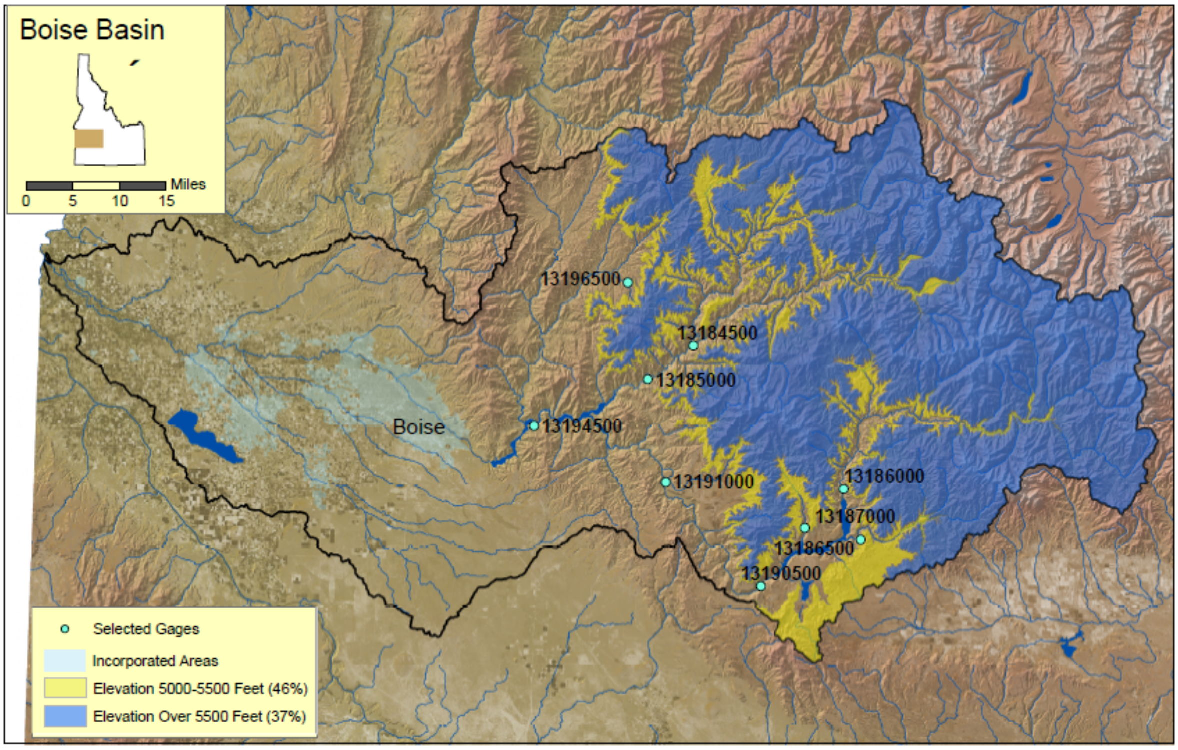

Figure 1. Proposed Target Area above 1524 meters (area includes those areas outlined in yellow and blue, black line outlines the Boise River Basin.)

4. REVIEW AND ANALYSIS OF THE CLIMATOLOGY OF THE TARGET AREA

The meteorological parameters of greatest interest in this feasibility study are: precipitation, surface and upper-level wind directions and velocities, 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 area is 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 and winds 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 -5^0 C (23^0 F) are important for one of the primary seeding materials (silver iodide), since this is the warmest temperature at which silver iodide begins to be active as an ice or freezing nuclei. Another consideration is 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 (colder than freezing) cloud droplets will likely be present in the storm clouds. It is the presence of these supercooled cloud droplets that determines whether there is any seeding potential within the clouds. Clouds that are naturally efficient in producing precipitation reaching the ground will contain few or no supercooled cloud droplets; inefficient clouds will have higher concentrations of supercooled cloud droplets. 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. Information on these parameters of interest is provided in the following sections. This feasibility/design study was defined as a wintertime activity. We have therefore provided information for the October through April time frame.

4.1 Precipitation and Snow Water Content

Data on the natural precipitation in the target area provides useful information concerned with the different types of storms that impact this area. 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 50 cm (20 inches) of precipitation during the winter months and if our analyses indicate 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 6.0 cm (2.4 inches) of additional precipitation. This estimate may then be used to provide estimates of resultant increases in stream flow. Observations of precipitation in the higher elevation target area have primarily been made 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.

Five NRCS sites located in the proposed target area were selected to provide monthly and seasonal data on precipitation and snow water content. Tables 1 and 2 provide these data.

Table 1. Average Monthly Precipitation at Five SNOTEL Sites (inches)

Site	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Oct.-Apr.	Water Year
Atlanta Sum.	2.5	6.3	6.5	6.8	4.9	5.9	2.9	35.8	44.2
Soldier R.S.	1.2	2.9	3.2	3.3	2.3	2.0	1.6	16.5	23.2
Mores Ck Sum.	2.2	6.8	6.9	7.7	5.7	4.8	3.1	37.2	45.7
Camas Ck Div	1.3	2.9	3.3	3.3	2.2	1.8	1.5	16.3	21.9
Trinity Mtn	2.6	8.3	8.7	8.5	7.0	5.2	3.3	43.6	52.7

Table 2. First of the Month Average Cumulative Snow Water Content at Five SNOTEL Sites (inches)

Site	**Oct.**	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**
Atlanta Sum.	0.0	1.4	7.0	13.4	20.1	26.2	31.9	31.1
Soldier R.S.	0.0	0.3	2.3	5.8	9.2	12.0	10.0	0.0
Mores Ck Sum.	0.0	0.8	6.3	13.7	21.7	29.2	34.6	31.0
Camas Ck Div.	0.0	0.0	1.6	5.1	9.3	11.7	11.0	3.0
Trinity Mtn.	0.0	2.0	9.1	17.0	25.5	33.4	39.5	40.5

From Table 1 the October through April average precipitation produces approximately 80% of the annual average water year precipitation. From Table 2, the average April 1st snow water content is 64.5 cm (25.4 in).

4.2 Specialized (Storm Period-Specific) Climatological Information

A detailed analysis of storm periods affecting the target area was conducted for an eight-season period (water years 2001-2008) for the October-April season. Precipitation data from several SNOTEL sites were considered and six-hour time blocks were selected when precipitation was clearly occurring in the target area. Data were examined from three SNOTEL sites: Atlanta Summit, Soldier R.S., and Mores Creek Summit. The SNOTEL data ranged from hourly to six-hourly in resolution and were obtained from the Natural Resources Conservation Service (NRCS).

A total of 386, six-hour periods were selected for analysis, generally corresponding to precipitation at the SNOTEL sites averaging more than about 0.1” and generally with precipitation evident in the data for at least two of the sites. These six-hour periods were matched as closely as possible to Boise weather balloon soundings, which we believe provide a good representation of the target area.

These soundings were used to derive temperature and wind data at the 700-mb and 500-mb levels, which are at approximately 3050 m (10,000’) and 5490 m (18,000’) MSL. The soundings also provided moisture (dewpoint) values, and a general idea of low to mid-level atmospheric stability. Estimates of the -5^0 C isotherm height and cloud-top temperature were also obtained from these sounding profiles.

4.2.1 Storm Precipitation

Figure 2 provides the number of six-hour periods in the analysis (by month) for four different ranges of precipitation amounts in inches (0.10 - 0.19, 0.20 - 0.29, 0.30 - 0.39 and 0.40 or greater). The highest frequency is in the 0.20-0.29” range. This suggests that the precipitation rates are usually rather light, a common feature of winter storms in many of the mountainous areas of the Intermountain West.

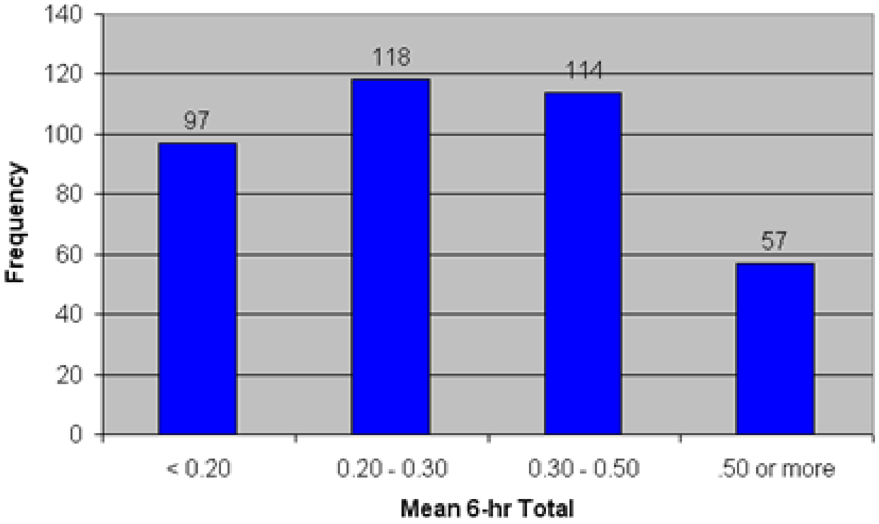

Figure 2. Frequency of 6-hour Storm Events by Precipitation Amount (inches)

4.2.2 700 mb Storm Winds

NAWC has utilized the 700 mb level as an index of important meteorological features regarding targeting of the seeding effects. First, the 700 mb wind is considered a good steering winds indicator, i.e., an approximation of the direction along which storm elements will move. 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, eight-season sample-described above were used to generate wind roses that graphically display the average information for each of three potential seeding modes: 1) lower elevation, ground based generators, 2) higher elevation, remotely operated ground generators, and 3) airborne seeding. Discussions of these three seeding modes are provided in Sections 5.1 – 5.3. The wind roses provide the frequency of wind direction and speeds by 22.5^0 wind sectors. The velocities on these wind roses are plotted in knots. Figure 3 provides an example of one of these plots. This information is useful in the potential siting of ground generators and selecting aircraft seeding tracks.

4.2.3 700 mb Storm Temperatures

A plot of the average 700-mb temperatures during the six-hour precipitation periods by month was prepared (Figure 4). NAWC uses temperatures at this level in helping decide whether a specific storm period is considered seedable using ground-based silver iodide generators, since 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 to approximately 300-600 m (1000-2000 feet) above the mountain crest heights (Super, 1999). Silver iodide becomes an active ice nucleant at temperatures of about -4 to -5^{0} C. These factors indicate that the 700-mb temperature should be approximately -5^{0} C or colder in order for ground seeding to have an appreciable effect.

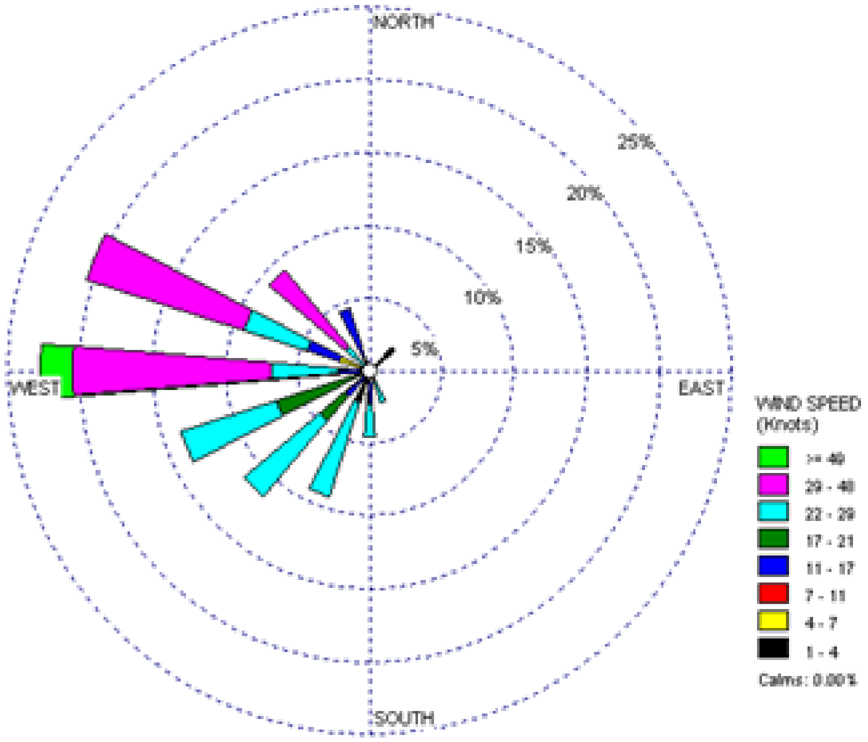

Figure 3 700-mb Storm Wind Rose for Ground-based Seedable Events

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 4 indicates that 700-mb temperatures did, in general, average –5^{0} C or colder during the precipitation events. The month of October was marginally warm on average.

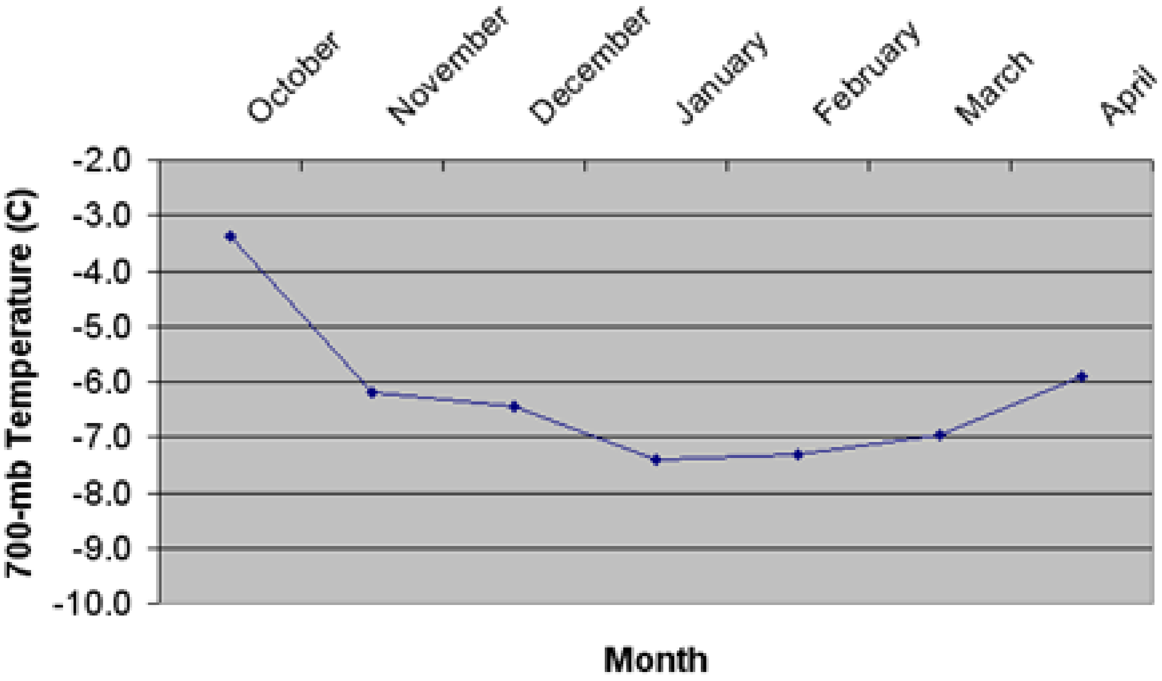

Figure 4. Mean 700-mb Temperature during Storm Periods by Month

4.2.4 <u>700 mb Storm Stability</u>

Another meteorological feature of special interest and importance 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 seedable cloud regions.

An analysis was performed to examine whether low-level stability might present a problem in seeding from ground generators in the UBRB. For this analysis, atmospheric stability (between the surface and 700 mb) was determined for the 386, six-hour precipitation events with concurrent Boise rawinsonde observations. Surface temperature, wind and dewpoint observations were also utilized in conjunction with the Boise sounding profiles to obtain better estimates of low-level stability issues and wind patterns. Low-level stability (which could prevent seeding material from reaching the -5^0 C level over the target area) was classified into four categories: Well-mixed or <u>neutral</u> conditions (no stability problems evident), which should mean that silver iodide particles released near the surface should be transported over the mountain barriers by the storm winds), slightly stable, moderately stable, and very stable. These categories correspond roughly to situations where less than 2^0 C of surface heating or upper level cooling would be necessary to mix out the atmosphere (slightly stable), 2 - 4^0 C (moderately stable), and more than 4^0 C (very stable). Cases that were well mixed or slightly stable were considered suitable for lower elevation ground-based seeding, while more stable cases would require remotely operated high-elevation ground generators or aircraft seeding.

The more-stable situations are cases where lower elevation ground-based seeding would probably not be attempted due to stability considerations. Figure 5 is a plot of the frequency of "neutral" stability below 700 mb for the seedable periods. Seedable periods are defined as those storm events that have estimated cloud top temperatures between -5^0 and -25^0 C (refer to Section 5.4). As shown in the figure, the most favorable category of stability (neutral) averages about 28% of the seedable cases during the October - April (and November - April) period, and is only about 21% of all seedable cases when considering only the November - March period. This analysis suggests that low-level stability presents significant problems during the winter months. These are the months that have the highest average amounts of precipitation.

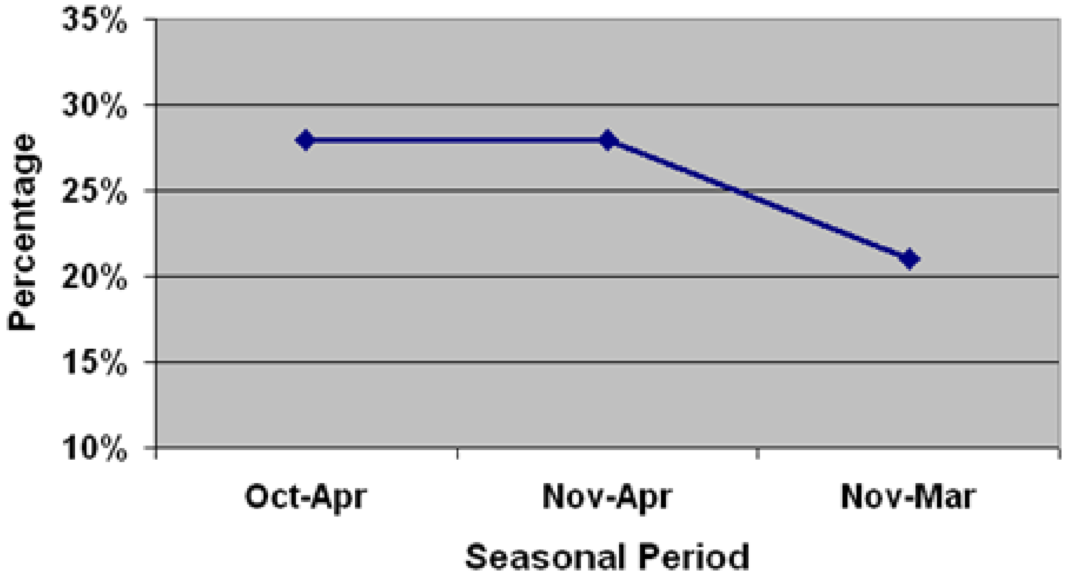

Figure 5. Percentage of Seedable Periods with a "Neutral" Stability Profile by Different Seasonal Time Periods

5. SEEDING PROGRAM RECOMMENDED DESIGN

5.1 Conceptual Model

The basic conceptual model upon which the UBRB cloud seeding program was based can be summarized as follows:

Some winter storms or portions of naturally occurring winter storms that pass over Idaho contain/produce supercooled cloud droplets. Some of these droplets are not converted to ice crystals as they pass over the mountainous areas of Idaho. The presence of supercooled cloud droplets over the crests of these mountain barriers indicates that these storms or portions of storms are inefficient in the production of precipitation. This inefficiency is attributed to the lack of sufficient natural ice nuclei (also called freezing nuclei) to covert these supercooled cloud droplets to ice crystals which, given the right conditions, could develop into snowflakes that would fall on the mountain barriers.

The deficit in natural ice nuclei occurs primarily in the range 0 to -15^0 C cloud temperatures. Introduction of silver iodide particles into cloud systems that contain supercooled cloud droplets in approximately the –5 to -15^0 C range will artificially nucleate some of the supercooled cloud droplets. The -5^0 C temperature is considered the nucleation threshold of silver iodide. At temperatures below approximately -15^0 C there are normally adequate numbers of natural ice nuclei to freeze the supercooled cloud droplets.

The artificially created ice crystals then have the potential to grow into snowflakes through vapor deposition and riming processes. If the ice crystals are generated in the rightgeographic locations, the artificially generated snowflakes will fall onto the targeted mountain barriers, resulting in increases in precipitation above what would have occurred naturally. Super and Heimbach, 2005, provide a more detailed discussion of the various microphysical processes pertaining to the conceptual model as summarized in the above text.

Research conducted in Utah and other Intermountain West locations (e.g., Super, 1999; Reynolds, 1988; Solak, et al, 1988 and 2005) has verified the presence of supercooled cloud droplets over or upwind of mountain barrier crests in a large number of winter storm periods. Research in a variety of locations has indicated the background concentrations of ice nuclei are low in the warmer portions of the atmosphere but increase exponentially at colder temperatures. Dennis, 1980, states "the concentration of active ice nuclei increases by about a factor of 10 for each temperature drop of 3.5 to 4^0 C. Prior research conducted in cloud chambers and in the atmosphere have demonstrated the ability of silver iodide nuclei to serve as ice nuclei in significant concentrations beginning near the -5^0 C level and increasing exponentially to the -2^0 to -25^0 C level (Garvey, 1975).

5.2 Operational Period and Selection and Siting of Equipment

An operational period of November through April was recommended based upon the precipitation and temperature climatologies of the area and the likelihood of generating positive seeding effects during this period. NAWC recommended silver iodide as the seeding agent to be used in the conduct of the enhanced UBRB program. The current program utilizes ground based, manually operated silver iodide generators. In terms of suggested enhancements, we recommend the potential addition of remotely operated, ground based generators and airborne seeding to the existing program if the perceived value of these additions exceeds the potential cost of such additions by a favorable margin as determined through a benefit/cost analysis.

5.3 Remotely Controlled, High Elevation Ground Based Silver Iodide Generators

Data presented in section 4 suggests that remotely controlled, high elevation ground based seeding and airborne seeding could be used to enhance the existing program. Figure 4 indicates that the 700 mb prevailing wind directions when remote generators are considered to be effective are predominately from the west-southwest to westerly directions. NAWC recommends that approximately five remotely controlled silver iodide generators be installed on the windward slopes of the target area mountains at higher elevations as far upwind of the barrier crest as possible. The crosswind spacing of the generators should be spaced approximately 8km apart. This spacing is somewhat greater than that indicated from an analysis of SF6 plumes observed in a Utah research program conducted over the Wasatch Plateau in Utah in the 1990's (Griffith, et al, 1992). This analysis suggested spacing of approximately 4-5 km apart.

5.4 Airborne Silver Iodide Seeding

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 and the clouds are seedable (e.g., they contain supercooled liquid water). Airborne seeding could also be effective in conditions where low elevation inversions exist. It appears from NAWC's analyses that low-level atmospheric temperature inversions are common in the Boise River valley during active winter storm periods. 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 immediate activation of the temperature dependent silver iodide nuclei. Convective clouds could also be seeded at their tops through aircraft penetrations as the tops pass through the -100 C level. 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 commonly occurs during seeding operations. Given the size of the target area and from some analyses of the timing of the seedable events, it appears one aircraft could seed a large majority of these events (i.e., two aircraft would not be required). The suggested base of operations would be at the Boise Air Terminal/Gowen Field Airport.

5.5 Opportunity Recognition Criteria

For the proposed UBRB program, 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" based on cloud top temperatures, 700 mb temperatures, winds and low level stability. Section 6.1 contains the rationale of using cloud top temperature to help determine "seedability". These criteria have been partitioned 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). These criteria are listed in Tables 3 - 6.

Table 3. Manually Operated Low Elevation Ground Generators Seeding Criteria

1. Cloud top temperatures expected to be ≥ - 26^0 C.
2. 700 mb level temperatures expected to be ≤ - 5^0 C.
3. Low-level atmospheric stability neutral to 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 4. Remotely Operated High Elevation Ground Generators Seeding Criteria

1. Cloud top temperatures expected to be ≥ - 26^0 C.
2. 700 mb level temperatures expected to be ≤ - 5^0 C.
3. Low-level atmospheric stability moderately 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 5. Aircraft Seeding Criteria

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).

5.6 Summary of Proposed Design

Components of the basic program design of the existing cloud seeding program in the Boise River Basin plus means of augmenting this basic design are summarized as follows:

- The target area will be the upper Boise River Basin above 1524 m (5,000 feet) MSL.
- The primary operational period will be November through March.
- Silver iodide will be the seeding agent. A formulation that produces fast acting ice nuclei is recommended (Finnegan, 1998).
- The existing program, that utilizes lower elevation ground based generators, will be augmented by extending the operational programs seeding period by one month. The existing program could also be enhanced through the addition of higher elevation remotely controlled ground based generators and aerial seeding.
- The UBRB would be operationally oriented, with the following goals: The stated goal of the program is to increase winter snowpack in the target area to provide additional spring and summer stream flow and recharge under-ground aquifers at a favorable benefit/cost ratio,without the creation of any significant negative environmental impacts.
- Due to the operational nature of the proposed program, i.e., the interest in producing as much additional water as possible, the seeding decisions would not be randomized. In other words, all suitable seeding opportunities would be seeded appropriately. In addition, there would not be an ongoing research component built into the program, although “piggyback” research components could be added to the core operational program if interest and additional funding from other sources is 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 (six state research program conducted from 2002-2006).
- 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 were provided in the final report), and possibly some snow chemistry analyses verifying that silver above background levels is being observed at various sampling points in the target area.
- A qualified/experienced meteorologist should direct the seeding operations.
- If aerial cloud seeding is employed, a winter season program field office should be established near the target area. The logical location of this program office would be at the Boise Air Terminal/Gowen Field.

6. POTENTIAL INCREASES IN PRECIPITATION AND SEASONAL STREAM FLOW

6.1 Estimated Increases in Precipitation

Analysis of the variability in storm temperature structure over the proposed target area for an eight winter season period was performed and then applied in conjunction with cloud top temperature partitioned seeding results from a research program in Colorado (Climax I and II; Mielke, et al, 1981, and Hess, 1974) to estimate the anticipated seeding effects for the UBRB. The analysis applied the varying Climax seeding effects within cloud top temperature categories according to their seasonal occurrence in the UBRB cloud top temperature data that were identified during a multi-year analysis period.

NAWC performed an analysis of a number of the six-hour events (refer to section 4.2) that had cloud top temperatures in a “seedable” range of –5^0 to –25^0 C based upon the activation threshold of silver iodide and Climax I and II results. The lower limit of –25^0 C is similar to indications of seedable conditions in northern Utah (Hill, 1980) and northern Colorado (Rauber, et al, 1986), both of which determined conditions to be seedable when the 500-mb temperature was –22^0 C or warmer. Of the 386, 6-hour periods examined, 109 periods, only 28%, were considered “seedable” based on having cloud-top temperatures between -5 and -25^0 C. Based upon the Climax I and II results, the seeding potential was considered to be +25% when cloud-top temperature was between –5^0 C and –20^0 C, +10% for cloud-top temperatures of –21^0 to –25^0 C, and 0% for cloud-top temperatures of –26^0 C or colder (or warmer than –5^0 C). This seeding potential was then sub-divided between different seeding modes or methods, including low elevation manual ground-based, high elevation remote ground-based, and aircraft seeding.

The seeding potential for a given 6-hour time period was assigned to ground-based seeding if a) the low-level air mass was classified as well-mixed or only slightly stable, and b) The 700-mb temperature was –5^0 C or colder. Similarly, the seeding potential was assigned to remote, high-elevation seeding sites if low-level stability was classified as “moderate” or higher and the 700-mb temperature was –5^0 C or colder. Seeding potential was assigned to aircraft-only for cases where the 700-mb temperature was above –5^0 C regardless of stability considerations (Tables 3 – 5 summarize these categories). The percentages of “seedable” events by seeding modes were approximately 44% for manual ground based generators, 27% for remote ground based generators and 29% for aircraft.

An indication of average percent increases for the November through March period for all seeding modes combined was 4.7%. The breakdown in these estimated percent increases by seeding mode was as follows: 1.7% for lower elevation manual ground based (which is the mode currently being used in the conduct of the basic program), 1.6% for higher elevation remote ground based, and 1.5% for aircraft based upon consideration of Tables 3-5 which indicate under what conditions each seeding mode could be utilized. These estimated increases were then applied to the average April 1st snow water contents to estimate the potential average increases in snow water content values. Table 6 provides these results listed by seeding mode. Similar calculations were made for increases in November through April precipitation, with results provided in Table 7. Obviously, different seeding modes can be used in combination which may potentially provide additional increases in precipitation not indicated in this analysis. For example, using a combination of low elevation manual and high elevation remote generators may produce higherincreases than only considering the contribution of remote generators when manual generators are considered ineffective. In other words seeding with both manual and remote generators when conditions are favorable for manual generators would be conditions that are also favorable for remote generators. In this context, the results provided in Tables 6 and 7 are likely conservative since the cumulative effects of using multiple seeding modes are not considered.

Table 6. Estimates of Average Increases in April 1st Snow Water Content (inches) by Seeding Mode (Based on November-March storm periods)

Site	Apr 1 SWE	Total Increase (4.7%)	Ground (1.7%)	Remote (1.6%)	Air (1.5%)
Atlanta Summit	31.9	1.50	0.54	0.51	0.48
Soldier R.S.	10.0	0.47	0.17	0.16	0.15
Mores Creek Sum	34.6	1.63	0.59	0.55	0.52
Camas Creek Div	8.2	0.39	0.14	0.13	0.12
Trinity Mtn	39.5	1.86	0.67	0.63	0.59
Average	24.84	1.17	0.42	0.40	0.37

Table 7. Estimates of Average Increases (inches) in November-April Precipitation by Seeding Mode

Site	Nov-Apr Precip	Total Increase (5.1%)	Ground (1.7%)	Remote (1.5%)	Air (1.9%)
Atlanta Summit	33.3	1.70	0.57	0.50	0.63
Soldier R.S.	15.3	0.78	0.26	0.23	0.29
Mores Creek Sum	35.0	1.79	0.60	0.53	0.67
Camas Creek Div	15.0	0.77	0.26	0.23	0.29
Trinity Mtn	41.0	2.09	0.70	0.62	0.78
Average	27.92	1.42	0.47	0.42	0.53

6.2 Estimated Increases in Stream Flow

The estimated increases in snow water content (April 1st) and November through April precipitation were then used to estimate the potential average increases in March through July surface runoff based upon the three different seeding modes. Linear regression correlations and relationships between April 1st snow water content, November through April precipitation and March through July stream flow were calculated. Historical stream flow measurements were available at two points (USGS Station numbers 13185000, Middle Fork and 13186000, South Fork) above Lucky Peak Dam plus estimates of additional stream flow contributing inflow to Lucky Peak Dam below these stations. The average April 1st snow water content (representing an average season) or average November through April precipitation was increased by the calculated seeding effect. This value was then entered into regression equations to calculate the amount of augmented stream flow. Tables 8 and 9 provide these results. Again it should be noted that different seeding modes can be used in combination which may potentially provide additional increases in stream flow not indicated in this analysis. As in prior NAWC design studies in the Intermountain West, the calculated percentage increases in stream flow were higher than the calculated increases in snow water content or precipitation. For example, from Table 6, a 4.7% increase in April 1st snow water content resulted in an estimated increase in stream flow of 5.6% from Table 8. We believe this to be due to the fact that any evapo-transpiration and ground water recharge requirements are met by the non-augmented (or natural) snowpack such that increases assumed to be produced by cloud seeding are added to the snowpack after these base requirements are met.

Table 8. Estimates of Increases in Average March-July Stream Flow (acre-feet) based upon Estimated Increases in April 1st Snow Water Content

Stream Gage	Total Increase (5.6%)	Ground (2.0%)	Remote (1.9%)	Air (1.7%)
USGS#13185000	33,292	11,791	11,097	10,404
USGS#13186000	26,058	9,229	8,686	8,143
2-Gage Subtotal incr	59,350	21,020	19,783	18,547
Est Additional incr*	22,075	7,818	7,358	6,898
Est Total Incr	81,425	28,838	27,141	25,445

* Estimates of additional stream flow contributing inflow to Lucky Peak Dam below the two USGS stations.

Table 9. Estimates of Increases in Average March-July Stream Flow (acre-feet) based upon Estimated Increases in November – April Precipitation

Stream Gage	Total Increase (6.8%)	Ground (2.3%)	Remote (2.0%)	Air (2.5%)
USGS#13185000	40,967	13,656	12,049	15,262
USGS#13186000	31,361	10,454	9,224	11,684
2-Gage Subtotal incr	72,328	24,110	21,273	26,946
Est Additonal incr*	26,902	8,967	7,912	10,022
Est Total Incr	99,230	33,077	29,185	29,185

* Estimates of additional stream flow contributing inflow to Lucky Peak Dam below the two USGS stations.

Data from Table 8 (based upon estimated increases in April 1st snow water content) suggest that the estimated amount of average additional March-July stream flow being produced by the existing program, which uses manual generators, is 3.49×10^7 m^3 (28,838 acre-feet). The estimated increase in average March through July stream flow achieved by extending the seeding program into the month of April is 5.30×10^6 m^3 (4,239 acre-feet). Data from Table 8 suggest that the estimated amount of average additional March-July stream flow that could be produced by adding remotely controlled ground generators and aircraft seeding is 6.48×10^7 m^3 (52,586 acre-feet). As suggested in Section 6.1, this estimate is likely conservative since the cumulative effects of using multiple seeding modes were not considered in this analysis.

6.3 Cost Considerations

Table 10 provides estimates of the annual cost of producing the estimated increases in average March through July stream flow by the two alternate seeding modes (remote generators and aircraft). The estimated increases in stream flow are taken from Table 9, which is based upon estimates of increases in November through April precipitation. The estimated cost of additional runoff ranges from \$0.005 to \$0.01 per cubic meter (\$5.94 to \$12.45 per acre-foot). For comparison purposes, the calculated cost of increases using manual generators is \$0.003 per cubic meter (\$3.29 per acre-foot). The values in Table 10 are for an average water year. Estimated costs per acre-foot would likely decline in above normal water years and increase in below normal water years due to the application of a fixed assumed percentage increase applied to lower and higher than normal base amounts.

It was beyond the scope of this feasibility study to estimate the potential value of the increased runoff. Should such an analysis be attempted, estimations of benefit/cost ratios could be calculated. The additional water would benefit regional water supplies for agricultural and municipal use as well as hydroelectric power generation. If the value of the additional water volume to recreation, fisheries, tourism, threatened and endangered species, and other downstream uses could be quantified and included, the projected value would be even greater.

Table 10. Estimated Annual Average Costs to Produce Additional March – July Stream Flow, Remote Generators or Aircraft

	Remote Generators*	**Aircraft****
Ave. Cost to Produce Extra Water	$173,350	$460,400
Ave. Mar. – July Stream flow Increase	29,185 a.f.	36,968 a.f.
Cost Per Acre-foot	$5.94	$12.45

* It is assumed that a five-year program would be conducted and that the initial remote generator acquisition, siting and installation costs would be amortized equally over the five-year period ($45,000 per year).

** One aircraft may not be capable of seeding all the suitable storm events so these estimates may be somewhat optimistic.

7.0 Concluding Remarks

This feasibility/design study has determined that extending the time period being seeded and adding enhancements to the operational program (adding high elevation ground based remote generators and a seeding aircraft) could augment an operational winter cloud seeding program currently using lower elevation ground generators that targets the upper Boise River Basin. These additions to the basic operational program have the potential to increase the average November through April precipitation by an additional 3.4%, which is estimated to produce a 4.5% increase in March through July runoff in an average water year. The resultant estimated increase in March through July runoff is 8.16 x 10^7 m^3 (66,153 acre-feet) in an average water year. The estimated average cost to achieve these increases in March through July stream flow is $0.008 per cubic meter ($9.58 per acre-foot).

NAWC completed a feasibility/design study, similar to this study, for the Big and Little Wood River Basins in central Idaho (Griffith and Yorty, 2009b). Since the Big Wood River Basin is directly downwind of the upper Boise River Basin, the cloud seeding enhancements mentioned in this study would also impact the Big Wood River Basin and to a lesser extent the Little Wood River Basin. As a consequence, the expense to add these enhancements to the upper Boise River Basin program could perhaps be shared between the Boise River and Wood River interests in some prorated fashion.

REFERENCES

ASCE, 2004: Standard Practice for the Design and Operation of Precipitation Enhancement Projects. *ASCE/EWRI Standard* **42-04**, Reston, Virginia, 63 pp.

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

Finnegan, W. G., 1998: Rates and Mechanisms of heterogeneous ice nucleation on silver iodide and silver chloroiodide particulate substrates. *J. Colloid Interface Sci.*, **202**, 518-526.

Garvey, D.M., 1975: Testing of Cloud Seeding Materials at the Cloud Simulation and Aerosol Laboratory. *J. Appl. Meteor,* **14**, pp. 883-890.

Griffith, D. A., and M. E. Solak, 2002: Economic Feasibility Assessment of Winter Cloud Seeding in the Boise River Drainage, Idaho. *J. Wea. Mod.*, **34**, pp. 39-46.

Griffith, D. A., G.W. Wilkerson, W.J. Hauze and D.A. Risch, 1992: Observations of Ground Released Sulfur Hexaflouride Tracer Gas Plumes in two Utah Winter Storms. *J. Wea. Mod.*, **24**, pp. 49-65.

Griffith, D. A., and M. E. Solak, 2002: Economic Feasibility Assessment of Winter Cloud Seeding in the Boise River Drainage, Idaho. *J. Wea. Mod.*, **34**, pp. 39-46.

Griffith, D.A., M.E. Solak, D. P. Yorty, and B. Brinkman, 2007: A Level II Weather Modification Feasibility Study for Winter Snowpack Augmentation in the Salt and Wyoming Ranges in Wyoming. *J. of Wea. Mod.*, **39**, pp. 76 - 83.

Griffith, D.A., D.P. Yorty, W. Weston, and M.E. Solak, 2009: Summary and Evaluation of the Winter 2008-2009 Cloud Seeding Program in the Upper Boise River Drainage. NAWC Report No. WM 09-10 to the Boise Project Board of Control, 60pp.

Griffith, D.A. and D.P. Yorty, 2009a: Weather Modification Feasibility Study for the Big and Little Wood River Basins in Idaho. NAWC Report No. WM 09-11 to the Idaho Water Resource Board, 93pp.

Griffith, D.A. and D.P. Yorty, 2009b: Weather Modification Feasibility Study for the Upper Boise River Basin, Idaho. NAWC Report No. WM 09-12 to the Idaho Water Resource Board, 123pp.

Griffith, D.A., M.E. Solak, and D. P. Yorty, 2010: Summary of a Weather Modification Feasibility Study for Winter Snowpack Augmentation in the Eastern Snake River Basin, Idaho. *J. of Wea. Mod.,* **42**, pp. 115-123.

Griffith, D.A., D.P. Yorty, and M.E. Solak, 2011: Summary and Evaluation of the Winter 2010-2011 Cloud Seeding Program in the Upper Boise River Drainage. NAWC Report No. WM 11- 06 to the Boise Project Board of Control, 31pp.

Hess, W. N., 1974: Weather and Climate Modification. John Wiley & Sons, Inc., New York, New York, 842 pp.

Hill, G.E., 1980: Seeding Opportunity Recognition in Winter Orographic Clouds. *J. Appl. Meteor.*, **19**, 1371-1381.

Mielke, P.W., G.W. Brier, L.O. grant, G.J. Mulvey, and P.N. Rosenzweig, 1981: A statistical reanalysis of the replicated Climax I & II wintertime orographic cloud seeding experiments. *J. Appl. Meteor.*, **20**, 643-659.

Rauber, R.M., L.O. Grant, D. Feng and J.B. Snider, 1986: The characteristics and distribution of cloud water over the mountains of northern Colorado during wintertime storms. Part I: temporal variations. *J. Cli. Appl. Meteor.*, **25**, pp. 469-488.

Reynolds, D.W., 1988: A Report on Winter Snowpack Augmentation. Bull. *Amer. Meteor. Soc.*, pp. 1290-1300.

Solak, M.E., R.B. Allan and T.J. Henderson, 1988: Ground-Based Supercooled Liquid Water Measurements in Winter Orographic Clouds. *J. Wea. Mod.*, **20**, pp.9-18.

Solak, M.E., D.P. Yorty and D.A. Griffith, 2005: Observations of Rime Icing in the Wasatch Mountains of Utah: Implications for Winter Season Cloud Seeding. *J. Wea. Mod.*, **37**, 28-34.

Super, A. B., 1999: Summary of the NOAA/Utah Atmospheric Modification Program: 1990-1998. J. Wea. Mod., 31, pp. 51-75.

Super, A.B. and J.A. Heimbach, 2005: Randomized Propane Seeding Experiment: Wasatch Plateau, Utah. J. Wea. Mod., 37, pp.35-66.