SUMMARY AND EVALUATION OF 2018-2019 WINTER CLOUD SEEDING OPERATIONS FOR THE HIGH UINTAS PROGRAM IN UTAH

Prepared for

Central Utah Water Conservancy District
Division of Water Resources, State of Utah
Duchesne County Water Conservancy District
Uintah Water Conservancy District
Lower Colorado River Basin States

by

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Stephanie D. Beall
Mark E. Solak

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Sandy, Utah 84093

Report No. WM 19-13
NAWC Project No. 18-423, 18-430a

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GLOSSARY OF RELEVANT METEOROLOGICAL TERMS, ETC.

Advection: Movement of an air mass. Cold advection describes a colder air mass moving into the area, and warm advection is used to describe an incoming warmer air mass. Dry and moist advection can be used similarly.

Air Mass: A term used to describe a region of the atmosphere with certain defining characteristics. For example, a cold or warm air mass, or a wet or dry air mass. It is a fairly subjective term but is usually used in reference to large (synoptic scale) regions of the atmosphere, both near the surface and/or at mid and upper levels of the atmosphere.

Cold-core low: A typical mid-latitude type of low pressure system, where the core of the system is colder than its surroundings. This type of system is also defined by the cyclonic circulation being strongest in the upper levels of the atmosphere. The opposite is a warm-core low, which typically occurs in the tropics.

Cold Pool: An air mass that is cold relative to its surroundings, and may be confined to a particular basin

Condensation: Phase change of water vapor into liquid form. This can occur on the surface of objects (such as dew on the grass) or in mid-air (leading to the formation of clouds). Clouds are technically composed of water in liquid form, not water vapor.

Confluent: Wind vectors coming closer together in a two-dimensional frame of reference (opposite of diffluent). The term convergence is also used similarly.

Convective (or convection): Pertains to the development of precipitation areas due to the rising of warmer, moist air through the surrounding air mass. The warmth and moisture contained in a given air mass makes it lighter than colder, dryer air. Convection often leads to small-scale, locally heavy showers or thundershowers. The opposite precipitation type is known as stratiform precipitation.

Convergence: Refers to the converging of wind vectors at a given level of the atmosphere. Low-level convergence (along with upper-level divergence), for instance, is associated with lifting of the air mass which usually leads to development of clouds and precipitation. Low-level divergence (and upper-level convergence) is associated with atmospheric subsidence, which leads to drying and warming.

Deposition: A phase change where water vapor turns directly to solid form (ice). The opposite process is called sublimation.

Dewpoint: The temperature at which condensation occurs (or would occur) with a given amount of moisture in the air.

Diffluent: Wind vectors spreading further apart in a two-dimensional frame of reference; opposite of confluent

Entrain: Usually used in reference to the process of a given air mass being ingested into a storm system

Evaporation: Phase change of liquid water into water vapor. Water vapor is usually invisible to the eye.

El Nino: A reference to a particular phase of oceanic and atmospheric temperature and circulation patterns in the tropical Pacific, where the prevailing easterly trade winds weaken or dissipate. Often has an effect on mid-latitude patterns as well, such as increased precipitation in southern portions of the U.S. and decreased precipitation further north. The opposite phase is called La Nina.

Front (or frontal zone): Reference to a temperature boundary with either incoming colder air (cold front) or incoming warmer air (warm front); can sometimes be a reference to a stationary temperature boundary line (stationary front) or a more complex type known as an occluded front (where the temperature change across a boundary can vary in type at different elevations).

Glaciogenic: Ice-forming (aiding the process of nucleation); usually used in reference to cloud seeding nuclei

GMT (or UTC, or Z) time: Greenwich Mean Time, universal time zone corresponding to the time at Greenwich, England. Pacific Standard Time (PST) = GMT – 8 hours; Pacific Daylight Time (PDT) = GMT – 7 hours.

Graupel: A precipitation type that can be described as "soft hail", that develops due to riming (nucleation around a central core). It is composed of opaque (white) ice, not clear hard ice such as that contained in hailstones. It usually indicated the presence of convective clouds and can be associated with electrical charge separation and occasionally lightning activity.

High Pressure (or Ridge): Region of the atmosphere usually accompanied by dry and stable weather. Corresponds to a northward bulge of the jet stream on a weather map, and to an anti-cyclonic (clockwise) circulation pattern.

Inversion: Refers to a layer of the atmosphere in which the temperature increase with elevation

Jet Stream or Upper-Level Jet (sometimes referred to more generally as the storm track): A region of maximum wind speed, usually in the upper atmosphere that usually coincides with the main storm track in the mid-latitudes. This is the area that also typically corresponds to the greatest amount of mid-latitude synoptic-scale storm development.

La Nina: The opposite phase of that known as El Nino in the tropical Pacific. During La Nina the easterly tropical trade winds strengthen and can lead in turn to a strong mid-latitude storm track, which often brings wetter weather to northern portions of the U.S.

Longwave (or longwave pattern): The longer wavelengths, typically on the order of 1,000 – 2,000+ miles of the typical ridge/trough pattern around the northern (or southern) Hemisphere, typically most pronounced in the mid-latitudes.

Low-Level Jet: A zone of maximum wind speed in the lower atmosphere. Can be caused by geographical features or various weather patterns, and can influence storm behavior and dispersion of cloud seeding materials

Low-pressure (or trough): Region of the atmosphere usually associated with stormy weather. Corresponds to a southward dip to the jet stream on a weather map as well as a cyclonic (counter-clockwise) circulation pattern in the Northern Hemisphere.

Mesoscale: Sub - synoptic scale, about 100 miles or less; this is the size scale of more localized weather features (such as thunderstorms or mountain-induced weather processes).

Microphysics: Used in reference to composition and particle types in a cloud

MSL (Mean Sea Level): Elevation height reference in comparison to sea level

Negative (ly) tilted trough: A low-pressure trough where a portion is undercut, such that a frontal zone can be in a northwest to southeast orientation.

Nucleation: The process of supercooled water droplets in a cloud turning to ice. This is the process that is aided by cloud seeding. For purposes of cloud seeding, there are three possible types of cloud composition: Liquid (temperature above the freezing point), supercooled (below freezing but still in liquid form), and ice crystals.

Nuclei: Small particles that aid water droplet or ice particle formation in a cloud

Orographic: Terrain-induced weather processes, such as cloud or precipitation development on the upwind side of a mountain range. Orographic lift refers to the lifting of an air mass as it encounters a mountain range.

Pressure Heights:
(700 millibars, or mb): Corresponds to approximately 10,000 feet above sea level (MSL); 850 mb corresponds to about 5,000 feet MSL; and 500 mb corresponds to about 18,000 feet MSL. These are standard height levels that are occasionally referenced, with the 700-mb level most important regarding cloud-seeding potential in most of the western U.S.

Positive (ly) tilted trough: A normal U-shaped trough configuration, where an incoming cold front would generally be in a northeast– southwest orientation.

Reflectivity: The density of returned signal from a radar beam, which is typically bounced back due to interaction with precipitation particles (either frozen or liquid) in the atmosphere. The reflectivity depends on the size, number, and type of particles that the radar beam encounters

Ridge (or High Pressure System): Region of the atmosphere usually accompanied by dry and stable weather. Corresponds to a northward bulge of the jet stream on a weather map, and to an anti-cyclonic (clockwise) circulation pattern.

Ridge axis: The longitude band corresponding to the high point of a ridge

Rime (or rime ice): Ice buildup on an object (often on an existing precipitation particle) due to the freezing of supercooled water droplets.

Shortwave (or shortwave pattern): Smaller-scale wave features of the weather pattern typically seen at mid-latitudes, usually on the order of a few to several hundred miles; these often correspond to individual frontal systems

Silver iodide: A compound commonly used in cloud seeding because of the similarity of its molecular structure to that of an ice crystal. This structure helps in the process of nucleation, where supercooled cloud water changes to ice crystal form.

Storm Track (sometimes reference as the Jet Stream): A zone of maximum storm propagation and development, usually concentrated in the mid-latitudes.

Stratiform: Usually used in reference to precipitation, this implies a large area of precipitation that has a fairly uniform intensity except where influenced by terrain, etc. It is the result of larger-scale (synoptic scale) weather processes, as opposed to convective processes.

Sublimation: The phase change in which water in solid form (ice) turns directly into water vapor. The opposite process is deposition.

Subsidence: The process of a given air mass moving downward in elevation, such as often occurs on the downwind side of a mountain range

Supercooled: Liquid water (such as tiny cloud droplets) occurring at temperatures below the freezing point (32 F or 0 C).

Synoptic Scale: A scale of hundreds to perhaps 1,000+ miles, the size scale at which high and low pressure systems develop

Trough (or low pressure system): Region of the atmosphere usually associated with stormy weather. Corresponds to a southward dip to the jet stream on a weather map as well as a cyclonic (counter-clockwise) circulation pattern in the Northern Hemisphere.

Trough axis: The longitude band corresponding to the low point of a trough

Upper-Level Jet or Jet Stream (sometimes referred to more generally as the storm track): A region of maximum wind speed, usually in the upper atmosphere that usually coincides with the main storm track in the mid-latitudes. This is the area that also typically corresponds to the greatest amount of mid-latitude synoptic-scale storm development.

UTC (or GMT, or Z) time: Greenwich Mean Time, universal time zone corresponding to the time at Greenwich, England. Pacific Standard Time (PST) = GMT – 8 hours; Pacific Daylight Time (PDT) = GMT – 7 hours.

Vector: Term used to represent wind velocity (speed + direction) at a given point

Velocity: Describes speed of an object, often used in the description of wind intensities

Vertical Wind Profiler: Ground-based system that measures wind velocity at various levels above the site

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1.0 INTRODUCTION

Due to high natural precipitation variability and the increasing demand for water, cloud seeding has been conducted in some parts of Utah over 40 years (Stauffer, 2001) (Griffith, et al, 2009). The State of Utah Division of Water Resources has provided cost sharing support to these cloud seeding projects since 1976. North American Weather Consultants (NAWC) has been the contractor that has conducted essentially all of the operational winter cloud seeding projects in the mountainous areas of Utah, covering varying time periods since 1974. Figure 1.1 depicts the locations of the areas that have been the intended target areas for these projects.

The Duchesne County Water Conservancy District and the Uintah Water Conservancy District were joined by the Central Utah Water Conservancy District in supporting an operational seeding project beginning in the 2002-2003 winter season. The intended target area of this program is the south slope of the Uinta Mountains above 8,000 feet. The project, with the same sponsors, has continued during the 2004 - 2019 water years. The State of Utah, Division of Water Resources has provided cost sharing support to these projects. Beginning with water year 2005, additional seeding generators were added to target the Strawberry Divide areas providing runoff into Strawberry and Currant Creek Reservoirs. Under the primary contract, seeding operations have been conducted each season during the period of December 1 through April 30 as opportunities occur.

<u>Project Extension Period</u>

The demand for fresh water continues to grow in the southwest, and the Colorado River is an extremely important component of the surface water resources in the region. Colorado

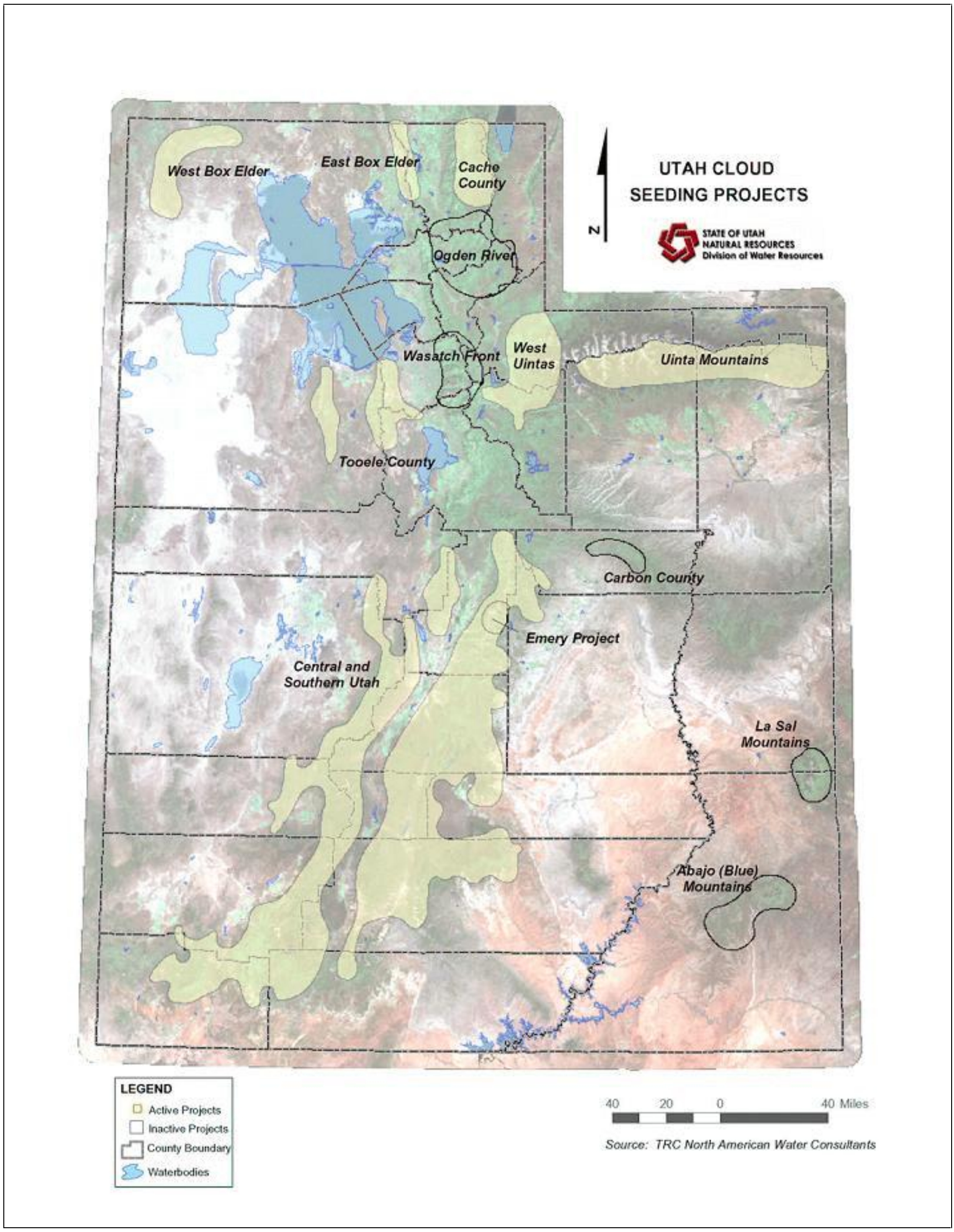


Figure 1.1 Winter cloud seeding target areas in Utah since 1974

River water interests have worked together in recent years to develop new or improved strategies aimed at enhancing the flow of the river and better managing the water resources. One of the most promising strategies is increasing the use of cloud seeding where viable opportunities occur. A 2006 NAWC study, "*The Potential Use of Winter Cloud Seeding Programs to*

Augment the Flow of the Colorado River" (Griffith and Solak, 2006), as well as some similar investigations by representatives of the Lower Colorado River Basin States, led to the addition of a time extension period to the High Uintas cloud seeding program funded by the Lower Basin States (LBS) interest group. Winter cloud seeding projects in other areas of Utah and Colorado were selected for receipt of the supplemental funding as well. The High Uintas Program is tributary to the Colorado River via the Green River, and LBS funds have been used to augment the program beginning in the 2010 water year. The extension period funded by Lower Basin States monies this season was at the beginning of the core project season, from November 1-30. The extension provided additional benefit to the primary project sponsors at no additional cost to them. As additional LBS funding benefits, two ground-based silver iodide generators have previously been added to the program, as well as strategically-located mountain ridge ice detector systems designed to help identify storm periods producing supercooled liquid water which is the target of the cloud seeding efforts.

This report provides information about operational cloud seeding conducted over the target watersheds in the 2018-2019 winter season, including the extension period. Section 2.0 describes the seeding project design and provides maps of the seeded target areas, as well as the locations of the ground-based seeding units (generators) with which the seeding was conducted. Section 3.0 describes the meteorological and computer forecast model data used in the conduct of operations, with some examples presented. Section 4.0 summarizes the seeding operations and documents the seeding generator usage by site and storm event. Section 5.0 provides statistical estimations of the effects of the cloud seeding on precipitation and the snow water content within the seeding target area. Section 6.0 provides conclusions and recommendations.

2.0 PROJECT DESIGN

2.1 Background

The general project design utilized for the High Uintas cloud seeding project is essentially the same as that which has been shown to be effective for over four decades of wintertime cloud seeding in other mountainous regions of Utah (Griffith et al, 2009). Estimations of seeding effectiveness for long-standing operational seeding projects in Utah have consistently indicated increases in wintertime precipitation and snow water content during the periods in which cloud seeding was conducted. These increases have averaged approximately 5-10% more than what would have been expected in the absence of seeding, as predicted by historical target/control linear regression analyses.

The target area for the High Uintas project is adjacent to the target area for the Upper Weber Basin Project (refer to Figure 1.1), which has also been conducted for a number of recent winter seasons. Some refinements to the general design of projects that NAWC has used in other regions of Utah were necessary in the High Uintas project design, to address some of the special issues raised in a North American Weather Consultants/Utah Division of Water Resources feasibility report for the project completed in the fall of 2002. These issues include 1) the prevalence of low elevation atmospheric inversions in the Uintah Basin during the coldest portion of the winter, 2) the extension of a productive precipitation regime through the month of April, and 3) two discrete prevailing wind regimes (southerly and northwesterly) during winter storms in the Uintas.

The target area was designed to include elevations of 8000 feet MSL or greater on the south slope of the Uinta Mountains containing river drainages that provide water to either of the sponsoring counties, plus areas providing runoff into Strawberry and Currant Creek Reservoirs. Figure 2.1 provides a map of the project area. In consideration of the first of the three special issues raised above (prevalent temperature inversions), it was decided it would be preferable to locate the ground-based silver iodide generators at elevations of 7000 feet or higher wherever possible. This would place the generators above the top of the inversions in the Uintah Basin about 50% of the time inversions exist, based on analysis of atmospheric sounding data obtained by NAWC in the Uinta Basin during years past. Further, due to the known atmospheric inversion situation, NAWC offered to operate a five-month project (December-April) on a four-month fixed price basis to offset any remaining concerns about low level atmospheric inversions detrimentally affecting the seeding operations during some of the winter months (especially January).

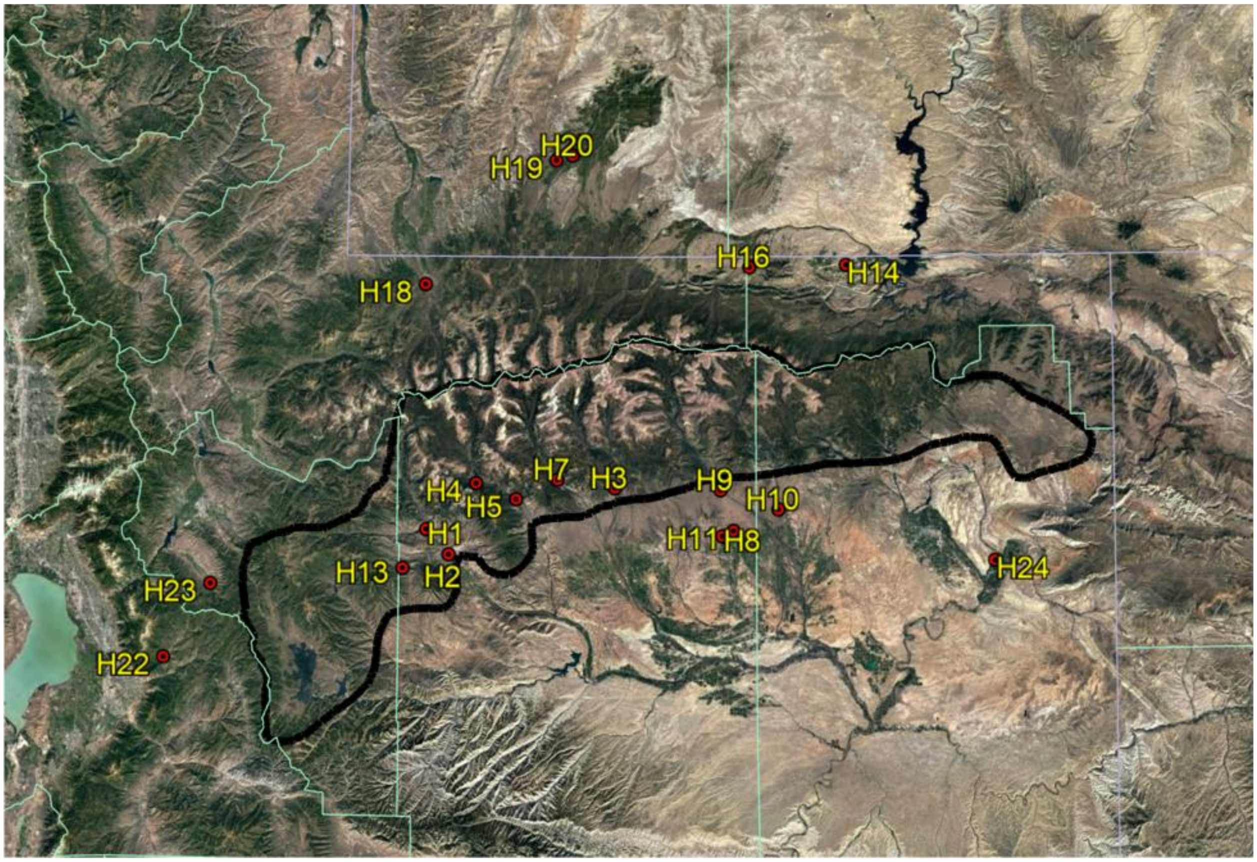


Figure 2.1 High Uintas target area and ground-based seeding generator locations. Sites labeled beginning with a "W" denote Western Uintas sites that are also commonly used to target the High Uintas program.

Regarding the second factor, project duration, Table 2-1 shows average monthly precipitation amounts at three high elevation NRCS SNOTEL sites located within the target area. The month of April is obviously a very productive period based on climatology. This information was used in specifying the cloud seeding project core operational period.

Table 2-1
Average Monthly Precipitation in the Target Area (inches)

Site	Elev.	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Chepeta	10,300	2.6	2.2	2.2	2.3	2.2	2.6	3.6	2.9
Five Pts.	11,000	2.9	2.3	2.8	2.5	2.2	2.8	2.7	2.9
Trout Cr.	9,400	1.7	1.8	1.7	1.8	2.0	2.5	2.6	2.3

Consideration of the third issue (wind direction) dictates that a majority of the generators should be placed at south flank locations, since the majority of the more productive storms have steering level winds from the southeast through west-southwest directions (from which the winds are blowing). A secondary maximum in potentially seedable storms occurs with northwesterly flow aloft, which supports location of some generators on the north slope of the Uintas for seeding under those conditions. Experience since the feasibility study has shown the storms with northerly-component air flow to be good seeding candidates, with the enhanced snowfall due to seeding on the northern slope carrying over onto the upper portion of the southern slope as well.

2.2 Seedability Criteria

NAWC has historically followed a selective seeding approach. This has proven to be the most efficient and cost-effective method, and has provided the most beneficial results. Selective seeding, or seeding only storms or storm periods in which precipitation has a reasonable chance of being enhanced, is based on several criteria which determine the seedability of the winter storms. These criteria deal with the structure of the airmass (temperature, stability, wind flow and moisture content), both in and below the precipitating clouds. Table 2-2 provides a summary of the generalized criteria that NAWC uses in the conduct of its wintertime projects in the intermountain west. These criteria are based upon the results obtained in a number of relevant research-oriented weather modification programs.

Table 2-2
NAWC Winter Cloud Seeding Criteria

1)	CLOUD BASES BELOW THE MOUNTAIN BARRIER CREST.
2)	LOW-LEVEL WIND DIRECTIONS AND SPEEDS THAT WOULD FAVOR THE MOVEMENT OF THE SILVER IODIDE PARTICLES FROM THEIR RELEASE POINTS INTO THE INTENDED TARGET AREA.
3)	NO LOW-LEVEL ATMOSPHERIC INVERSIONS OR STABLE LAYERS THAT WOULD RESTRICT THE VERTICAL MOVEMENT OF THE SILVER IODIDE PARTICLES FROM THE SURFACE TO AT LEAST THE -5°C (23°F) LEVEL OR COLDER.
4)	TEMPERATURE AT MOUNTAIN BARRIER CREST HEIGHT EXPECTED TO BE -5°C (23°F) OR COLDER.
5)	TEMPERATURE AT THE 700 MB LEVEL (APPROXIMATELY 10,000 FEET) EXPECTED TO BE WARMER THAN -15°C (5°F).

2.3 <u>Equipment and Project Setup</u>

During the off-season the ground-based generators are routinely removed from the field for maintenance and testing. NAWC began re-installing the generators in October 2018. The generators were placed at the locations shown in Figure 2.1.

2.3.1 Ground-Based Manual Generators

The cloud seeding equipment at each site consists of a cloud seeding generator unit and a propane gas supply. The seeding solution contains two percent (by weight) silver iodide (AgI), the active seeding agent, complexed with very small portions of sodium iodide and para-dichlorobenzene in solution with acetone. A paper published by Dr. William Finnegan, a well-respected cloud seeding formulation expert of the Desert Research Institute (Finnegan, 1999), indicates that this formulation is superior to others that produce pure silver iodide particles. The modified particles produced by combustion of the revised formulation act as ice nuclei much more quickly, and there are somewhat larger numbers of effective nuclei at warmer temperatures (e.g., about -5°C to -10°C). Figure 2.2 is a photograph of a manually operated, ground-based cloud seeding generator like those used in the High Uintas Program. Trained local operators are available to activate each seeding generator upon request from a NAWC meteorologist. A generator is activated by igniting a propane flame in the burn chamber, and then adjusting the flow of seeding solution through a flow rate meter. The propane gas also pressurizes the solution tank, which allows the solution to be sprayed into the burn chamber at a regulated rate, where microscopic sized silver iodide (AgI) crystals are formed. The crystals, which closely resemble natural ice crystals in structure, are released at a rate of 8 grams per hour when the 2% (AgI by weight) solution is used. These crystals become active as artificial ice forming nuclei at in-cloud temperatures between -5°C and -10°C (23°F to 14°F).

It is necessary that the AgI crystals become active in the region in the cloud which contains supercooled liquid water, at relatively low altitudes upwind of the mountain crest so that the available supercooled liquid water can be effectively converted to ice crystals in time to grow to snowflake sizes and fall out of the cloud onto the mountain barrier. If the AgI crystals take too long to become active, or if the temperature upwind of the crest is too warm, the plume will pass from the generator through the precipitation formation zone and over the mountain crest without producing any additional snowfall in the intended target region.

Figure 2.2 NAWC Manually Operated Silver Iodide Generator

Cloud seeding generators are maintained at approximately 20 locations specific to the High Uintas program, with the majority of these sites on the south and southwest side of the Uinta Range. There are 5 sites on the northern side of the target area. Two other sites are used primarily to target the Strawberry Divide area (sites H22 and H23), with many of the nearby Western Uintas sites utilized to target this area as well. The network of sites is designed to be effective in generating plumes of seeding material which will pass over the target area in a variety of wind flow situations. Several sites primarily designated for use in the Western Uintas Program (W prefix) are also utilized for seeding the High Uintas target area when conditions are favorable for this. Pertinent site information is listed in Table 2-3, corresponding to the site numbers shown in Figure 2.1.

Table 2-3
Cloud Seeding Generator Sites

Site ID	Site Name	Elevation (Ft)	Latitude (N)	Longitude (W)
H1	Hanna Pump House	7019	40°27.60'	110°49.56'
H2	Hanna	6781	40°24.64'	110°46.03'
H3	Yellowstone Canyon	7660	40°32.50’	110°20.30’
H4	Rock Creek Ranch	7988	40°33.02'	110°41.78'
H5	Robbins Ranch	7404	40°31.18'	110°35.64'
H7	Moon Lake	8100	40°33.25’	110°29.20’
H8	Bluebell	5840	40°21.52’	110°07.54’
H9	Uinta Power Plant	6932	40°32.27'	110°03.98'
H10	Farm Creek	6756	40°31.00'	109°55.00'
H11	Neola	6330	40°27.48'	110°02.93'
H13	Red Creek	7900	40°23.02’	110°53.06’
H14	Manila	6500	40°58.91'	109°44.36'
H16	Birch Creek	7634	40°58.64'	109°59.48'
H18	Bear River East	8223	40°56.54'	110°50.17'
H19	Black’s Fork	7509	41°11.39'	110°29.87'
H20	Robertson	7322	41°11.97'	110°27.31'
H22	Hobble Creek	5870	40°12.22'	111°30.14'
H23	Wallsburg	6175	40°20.95'	111°23.00'
H24	Jensen	4896	40°23.92'	109°21.49'
W4	Pineview	6407	40°56.39'	111°10.18'
W6	Oakley	6472	40°43.07’	111°18.00’
W7	Kamas	6489	40°38.43'	111°16.77'
W8	Kamas West	6472	40°38.16'	111°19.33'
W9	Woodland	6706	40°34.89'	111°13.81'
W10	Woodland East	7305	40°33.35'	111°06.80'
W11	Midway	5570	40°30.59'	111°28.64'
W12	Heber City	5810	40°29.73'	111°22.52'

Most of the winter storms that affect the northern Utah mountains are associated with synoptic weather systems that move into Utah from the Pacific Ocean from the northwest, west or southwest. They usually consist of a frontal system and/or an upper trough with the winds preceding the front or trough blowing from the south or southwest. As the system passes through the area, the wind flow typically changes to the west, northwest, or north. Clouds and precipitation may precede as well as follow the front/trough passage. For that reason, the seeding generators were situated to allow selective operations in the "southwesterly" flow ahead of the system and/or in the "northwesterly" flow following passage of a front/trough. A majority (over 60%) of the heavier precipitation events affecting the southern slopes Uintas occur in southwesterly flow regimes, thus the higher concentration of generator sites on the southern side of the mountain range.

In consideration of the Uinta Basin temperature inversion factor and the fact that human habitation is sparse in some areas where seeding generators could be helpful, an on-the-ground site survey investigating possible locations for remotely controlled seeding generators was conducted in the project area in August 2011. The initial investigations focused on site exposure and the expected transport of seeding material from the sites into the south slope target area. In all, thirteen candidate sites were identified, approximately evenly split between the north and south slopes. This initiative was supported by LBS funding. If supplemental funding becomes available for this purpose, some remotely controlled seeding sites could potentially be established.

2.3.2 Project Instrumentation

Some specialized instrumentation has been added over the past number of years to enhance cloud seeding guidance during operations within the High Uinta Program area. These include an icing rate detector and more recently a radiometer. Both instrument systems used during the 2018-2019 Program were supported by funding from the Lower Basin States.

2.3.2.1 Icing Rate Meter

An important addition was made to the program a number of years ago. An ice detector and associated meteorological observational equipment were installed at an open exposure, above timberline, high elevation site (11,540 feet) called Dry Ridge, added to an existing USFS tower-mounted communications system, allowing for real-time observation of supercooled liquid water (SLW) at the site. Other observations include: precipitation, temperature, wind direction and wind speed. Because SLW is the target of cloud seeding, such a sensor is of benefit both in terms of real-time operational decisions and for later analysis of the frequency of SLW occurrence in relation to winter storm periods. This sensor is similar to sensors which have been installed in two other seeding target areas in Utah. Analysis reports on the Utah ice detector data are available on the NAWC website at http://www.nawcinc.com/publications.html. Analyses of the data from these sites have provided valuable insight into the occurrence of SLW during winter storms. Figures 2.3 and 2.4 provide photographs of the installation. The funding for the equipment, installation and maintenance of this site was provided by three Lower Colorado River Basin States and administered by the Utah Department of Water Resources Division.

Figure 2.3 Icing Rate Meter Installation at the Dry Ridge Site

Figure 2.4   Dry Ridge Sensor Suite

2.3.2.2   Microwave Radiometer

In mid December of 2018, a microwave radiometer was installed at the Duchesne Water Conservancy District in Roosevelt, Utah. A photo of the radiometer located in Roosevelt can been seen in Figure 2.5. The purpose of this instrument was to observe the occurrence of supercooled liquid water, which the is the target of winter time cloud seeding operations. It also provides a vertical sounding (vertical profile) of the atmosphere in the area, including the presence of any low level stable layers or temperature inversions in the Uintah Basin, which can hinder cloud seeding operations by limiting the vertical transport of seeding material to the intended target, in this case, the higher elevations of the Uintah range.

Figure 2.5 Microwave Radiometer located in Roosevelt, Utah

The radiometer is a passive device that can provide an atmospheric profile of a number of different parameters, including temperature, relative humidity and liquid water. In addition, the radiometer has algorithms that can derive other products including inversions and stability that can assist in real time cloud seeding decisions making processes. Figure 2.6 shows an example of output from a computer program called the Universal Rawinsonde Observation Program (RAOB), that assisted in analyzing raw radiometer data.

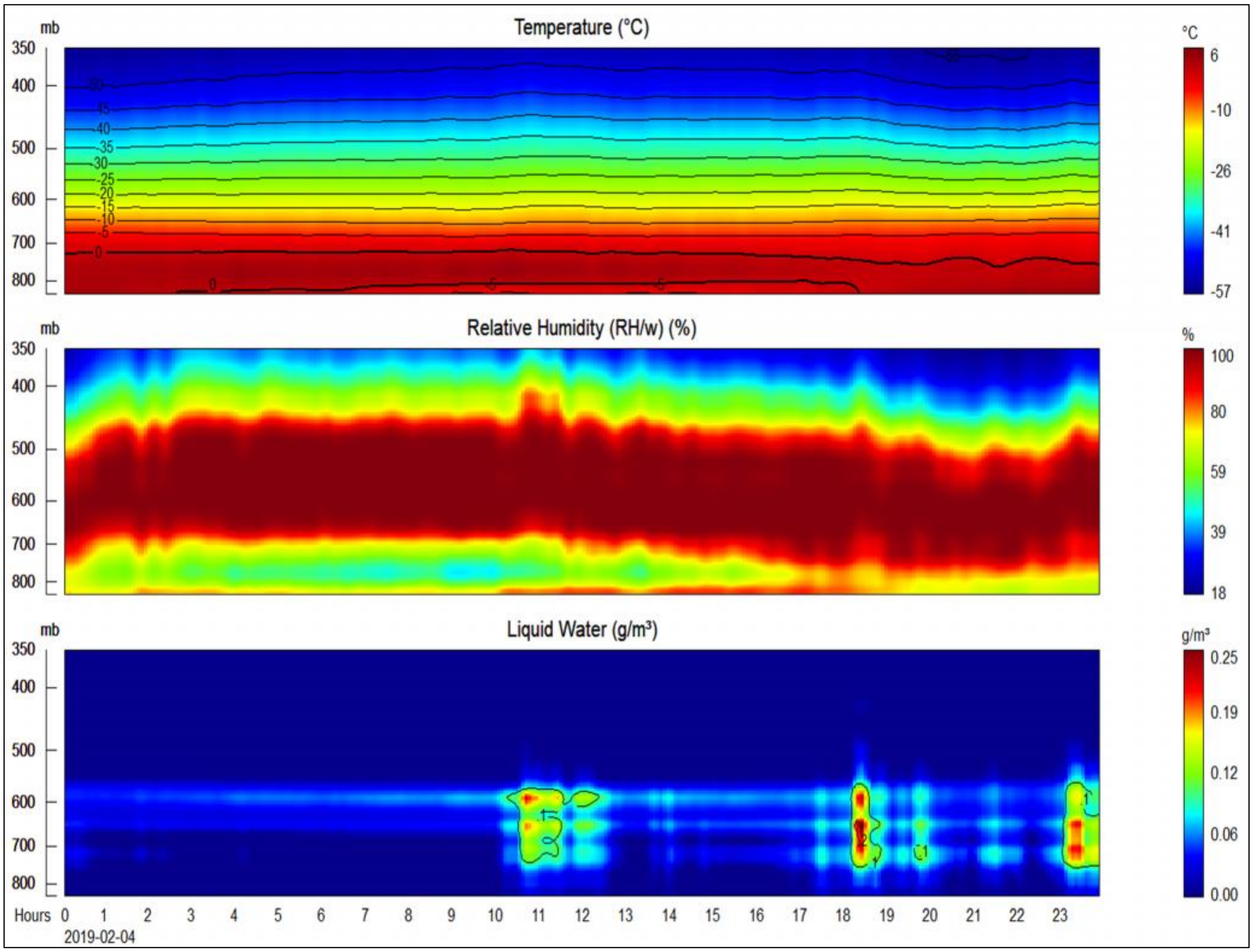


Figure 2.6 Radiometer output including temperature (top panel), Relative Humidity (middle panel) and Liquid Water occurrence (bottom panel)

Additional information pertaining to the radiometer and a brief analysis can be found in Appendix C.

2.3.3 Suspension Criteria

NAWC always conducts its projects within guidelines adopted to ensure public safety. Accordingly, NAWC has a standing policy and project-specific procedures for the suspension of cloud seeding operations in certain situations. Those criteria are shown in Appendix A. The criteria are an integral part of the seeding program. There was a seeding suspension for a portion of the target area late in the season (spring 2019), as described in more detail in Section 4.0.

3.0 WEATHER DATA AND MODELS USED IN SEEDING OPERATIONS

NAWC maintains a fully equipped project operations center at its Sandy, Utah headquarters. Meteorological information is acquired online from a wide variety of sources, including some subscriber services. This information includes weather forecast model data, surface observations, rawinsonde (weather balloon) upper-air observations, satellite images, NEXRAD radar information, and weather cameras. This information helps NAWC meteorologists to determine when conditions are appropriate for cloud seeding. Each of NAWC's meteorologists also has a fully capable computer system with internet access at home, to allow continued monitoring and conduct of seeding operations outside of regular business hours. Figures 3.1 – 3.3 show examples of some of the available weather information that was used in this decision-making process during the 2018-2019 winter season. Figure 3.4 provides predictions of ground-based seeding plume dispersion for a discrete storm period in central and southern Utah using the National Oceanic and Atmospheric Administration's HYSPLIT model (Appendix B). This model helps to estimate the horizontal and vertical spread of a plume from potential ground-based seeding sites in real-time, based on wind fields contained in the weather forecast models.

Global and regional forecast models are a cornerstone of modern weather forecasting, and an important tool for operational meteorologists. These models forecast a variety of parameters at different levels of the atmosphere, including winds, temperatures, moisture, and surface parameters such as accumulated precipitation. An example of a display from the Gobal Forecast Systems (GFS) model is shown in Figures 3.5.

A more recent product to which NAWC obtained access provides the ability to display a special High-Resolution Rapid Refresh (HRRR) model meteorological data in support of operations. The software used by NAWC was developed by Idaho Power Company in support of their cloud seeding operations primarily by providing analyses and forecasts of supercooled liquid water, temperature, moisture, and other parameters relevant to operations. The HRRR model does not forecast seeding effects, or the dispersion of seeding material such as the

HYSPLIT model does, but it contains important atmospheric parameters in much higher time and space resolution than other (e.g. global) weather forecast models. An example of HRRR products is shown in Figure 3.6, which include cross-section location and vertically integrated liquid (upper left), cross section of cloud liquid water and temperature (upper right), dew point depression (lower left), and a plot of liquid vs. ice (lower right).

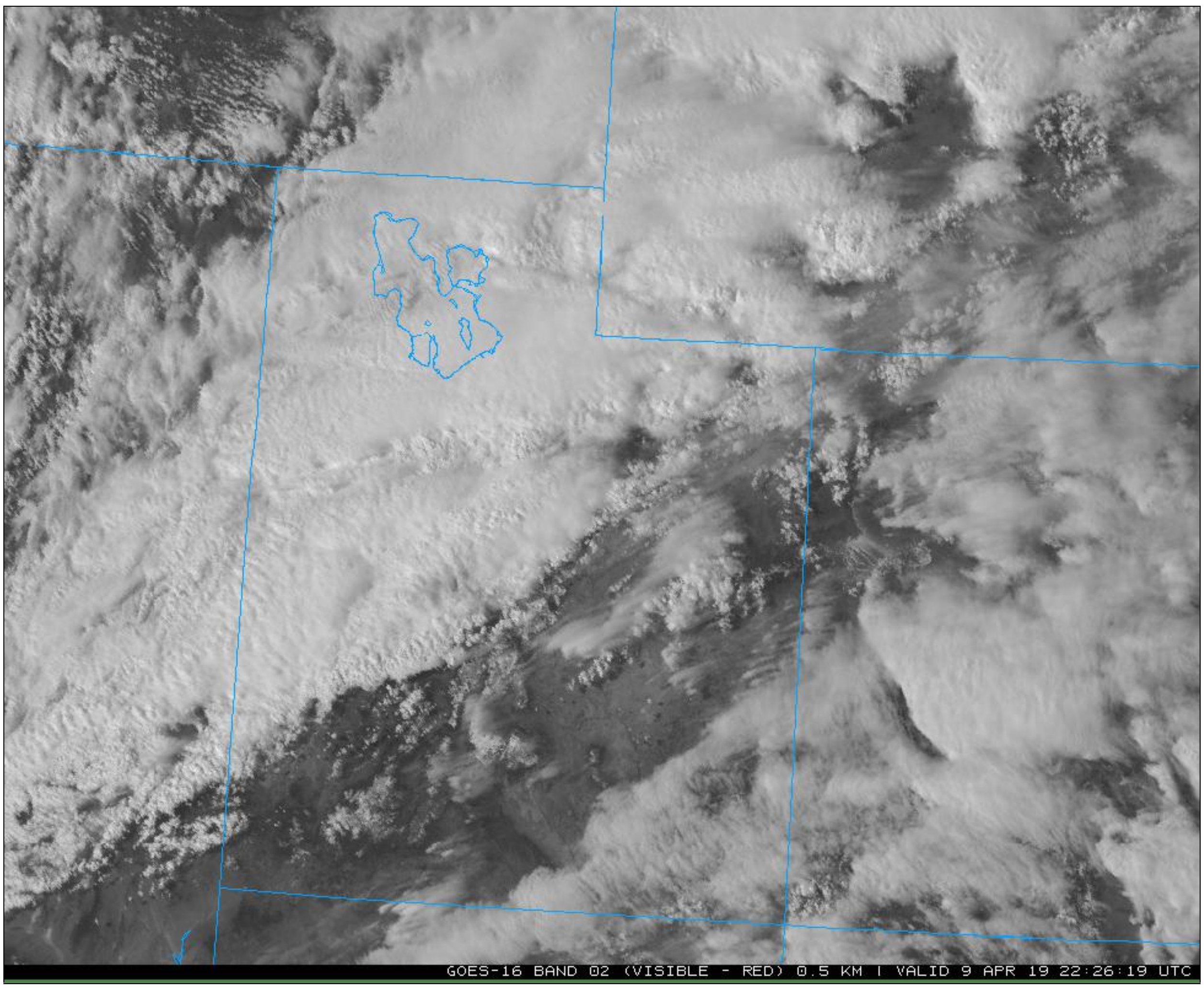


Figure 3.1 Visible spectrum satellite image on April 9, 2019 as a cold frontal boundary moved across Utah

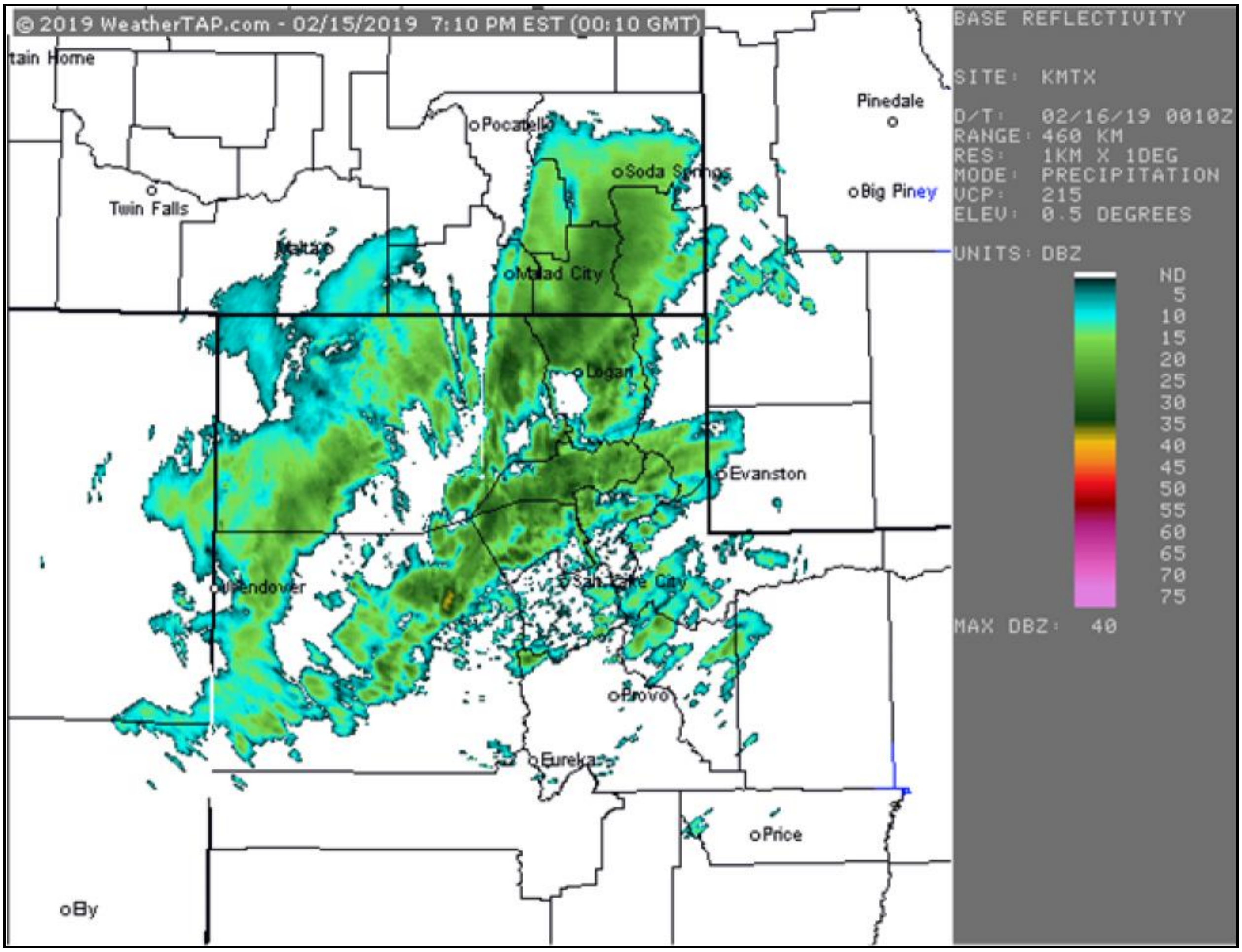


Figure 3.2 Weather radar image over northern Utah on February 16, 2019

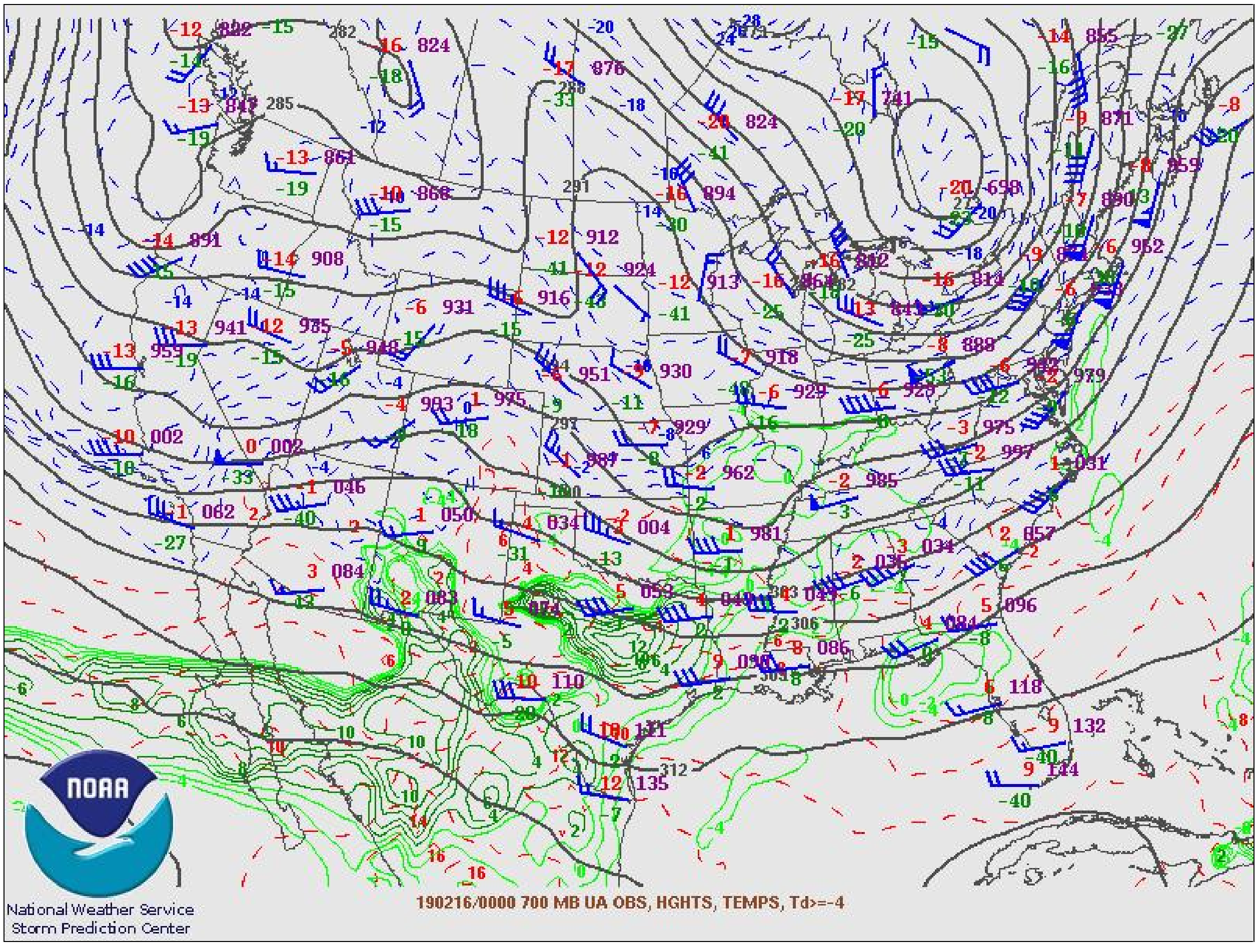


Figure 3.3 U.S. 700 mb map on February 16, 2019 at 1600 MST

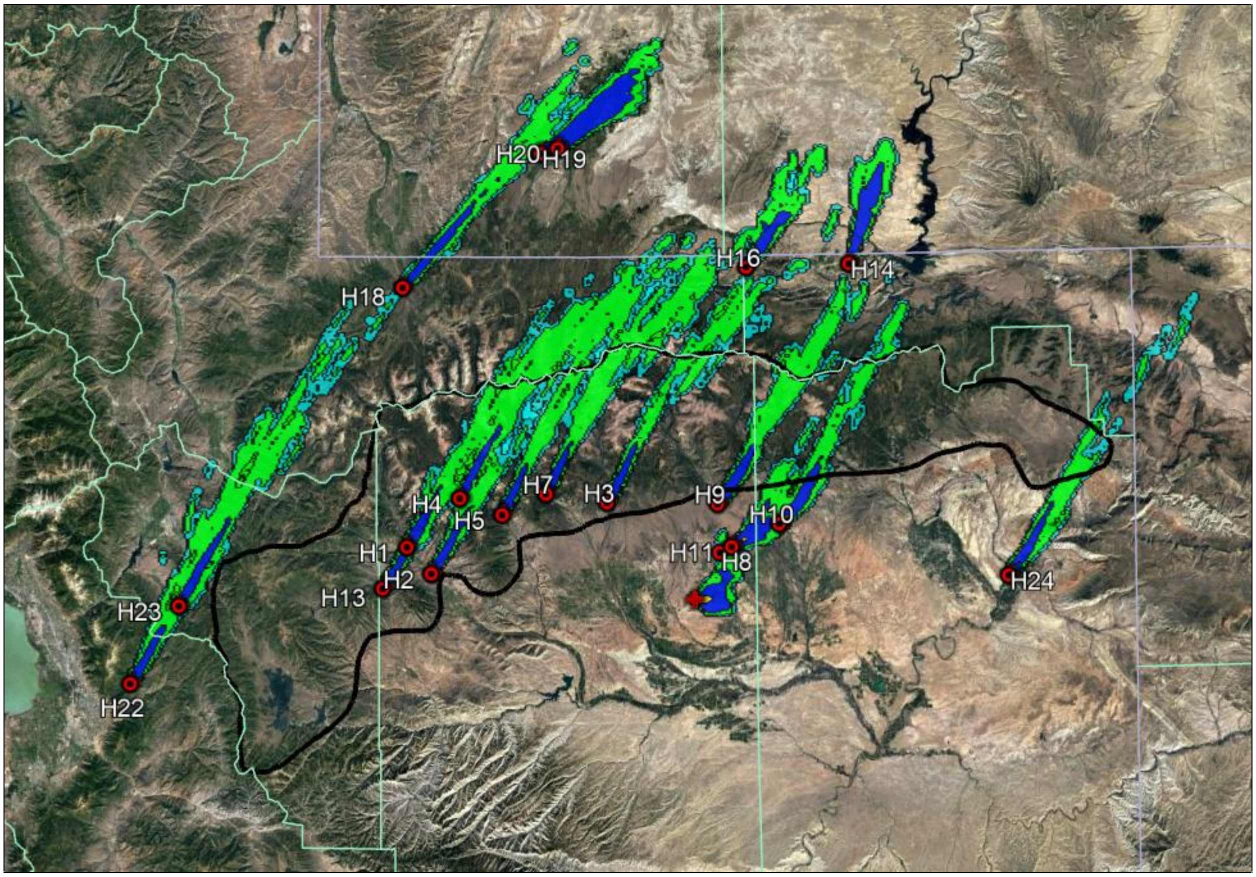
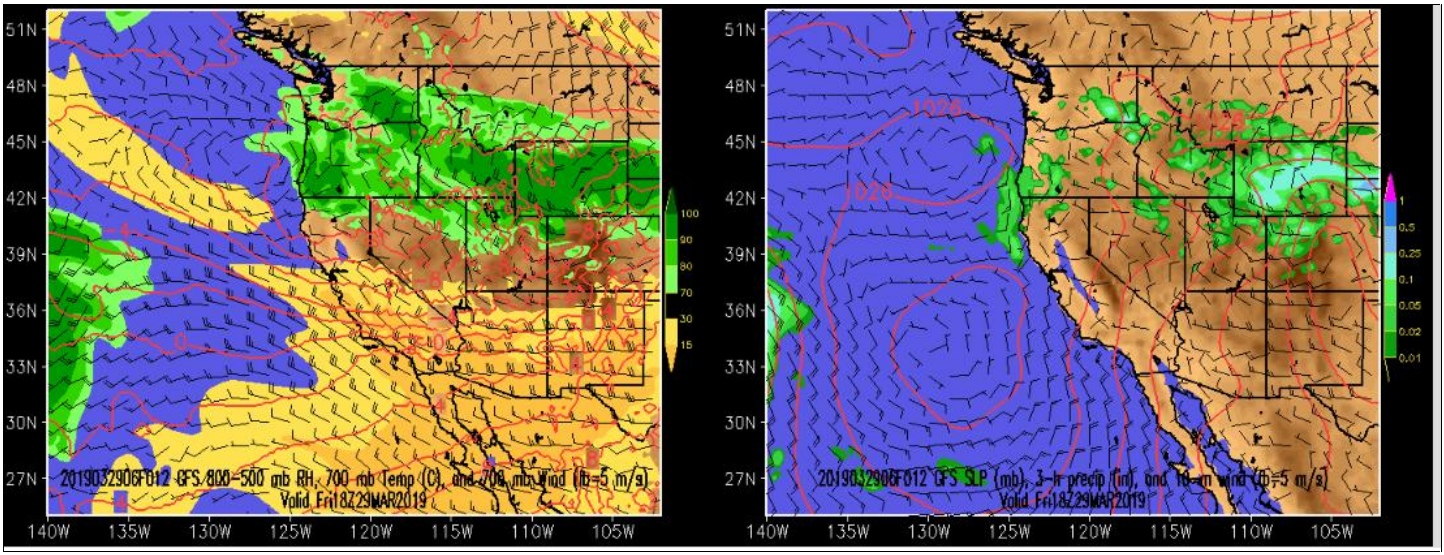


Figure 3.4 HYSPLIT plume dispersion forecast for seeding locations during a seeded storm event on February 5, 2019



Figures 3.5 GFS model plot during a storm event on March 29, 2019

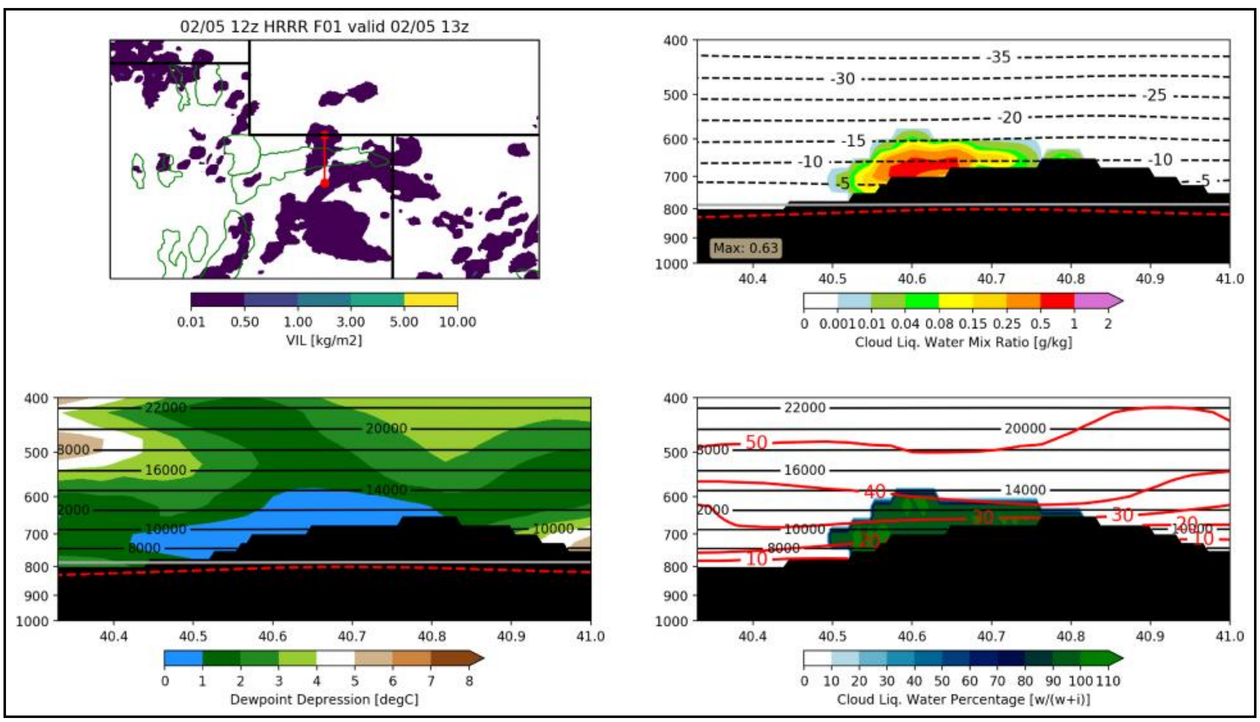


Figure 3.6 Data displays from the HRRR model from March 5, 2019

4.0 OPERATIONS

The core 2018-2019 cloud seeding program for the High Uintas was contractually scheduled to run from December 1, 2018 through April 30, 2019, with an extension period from November 1-30, 2018 that was funded by the Lower Basin States. A total of 28 storm periods were seeded during the entire operational season of November 1 – April 30, with 6 of these occurring during the extension period in November (including one seeded event that was split between the extension period and the core program which began on December 1). Altogether, there were six seeded storms were seeded in November, four additional storms in December (in addition to the event ending on December 1), six in January, four in February, six in March, and two in April. A cumulative 1,648.5 hours of ground seeding generator operations were conducted during the regular season, and an additional 312.25 hours during the extension period, for a total of 1,960.75 hours. There was a seeded suspension beginning on April 9 for the areas surrounding Strawberry Reservoir in the southwestern portion of the program, due to several SNOTEL sites that exceeded about 200% of the median snow water content beginning around that time. These mid-elevation sites included Currant Creek, Beaver Divide, Daniels-Strawberry, and Rock Creek, which of course did not have as high of absolute values of snow water content as higher elevation sites. However, SWE numbers ranging from about 12-22 inches at these sites were of potential concern in case the melt should happen quickly. For this reason, NAWC (with some discussion with DWR personnel) decided to suspend operations for this portion of the program. Snowpack percentages remained high through the end of the season in this area, and the suspension affected essentially only the final two storm events of the season.

Figure 4.1 is a graph of operations this season for the core High Uintas program, compared to a linear usage of the total budgeted hours. Table 4-1 shows the seeding dates and ground generator usage for the storm events, and Table 4-2 shows operation times for each of the CNG sites.

Precipitation/snowfall was above average nearly region-wide during the season. As of April 1, 2019, SNOTEL observations for the Natural Resource Conservation Service showed snow water content averaging about 148% of normal (median) for the Duchesne Basin and about 105%

of normal for sites in the Green River Basin portion of the Uintah Range. Water year precipitation percentages were 135% of normal (mean) for the Duchesne Basin and around 112% of normal for sites in the Green River Basin. By the end of the project (May 1), median snowpack percentages had increased to 159% for the Duchesne Basin and 123% for the Green River Basin. Water year to date percentages (of the mean) also remained high on May 1, 133% for the Duchesne Basin and 117% for the Green River Basin. Figures 4.2 to 4.4 show snow water content and water year precipitation accumulations, and normals, for October 1 through May 1 for target area SNOTEL sites. Figures 4.5 – 4.10 show regional monthly precipitation as a percent of normal for November through April.

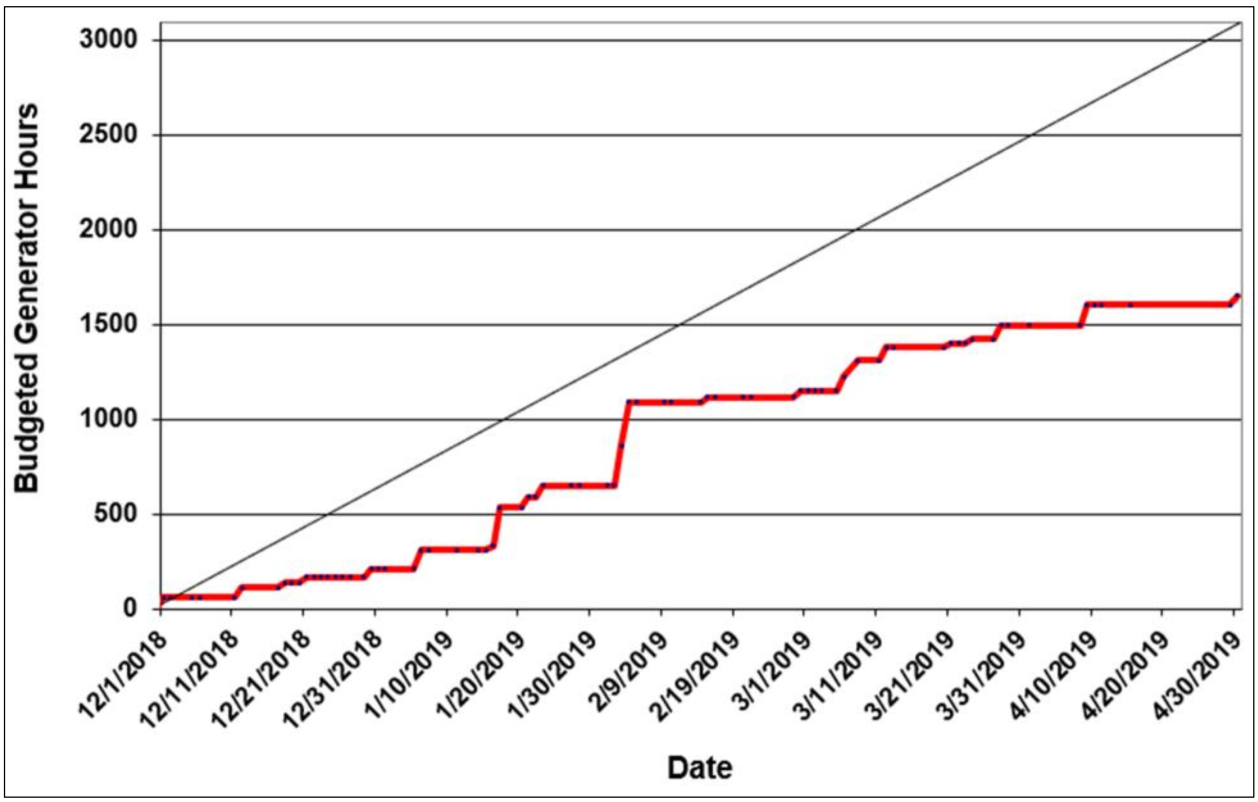


Figure 4.1 Seeding operations during the 2018-2019 season for the core program.

Table 4-1
Storm Dates and Number of Generators used in the High Uintas Program, 2018-2019 Season

Storm Number	Date	Number of Generators	Hours of Operation
1*	November 2-3	2	26
2*	November 4	3	22.5
3*	November 17	3	16.25
4*	November 22	9	90
5*	November 24	5	30.75
6**	Nov 29- Dec 1	11	183.75
7	December 12	7	51.5
8	December 18-19	3	25
9	December 21-22	3	29
10	December 30-31	3	46
11	January 6	2	7.25
12	January 6-7	5	91.75
13	January 16	3	19.75
14	January 17-18	11	203
15	January 21-22	5	57.25
16	January 23-24	4	58.25
17	February 3-4	9	214.25
18	February 4-6	10	228.25
19	February 15-16	3	26.75
20	February 28	4	30.5
21	March 6-7	6	73.5
22	March 8	9	87.25
23	March 12-13	5	70
24	March 21-22	1	22
25	March 24	3	21
26	March 28-29	2	74.5
27	April 9-11	4	106.25
28	April 30	8	48.5
Regular Season Total	---	---	1,648.5
Extension Total	---	---	312.25

* Seeding for Lower Basin-Funded Extension.

** Seeding for both the extension and core program.

Table 4-2a
Generator Hours for High Uintas Program, 2018-2019, Storms 1-10

Storm	1*	2*	3*	4*	5*	6**	7	8	9	10
Dates	Nov 2-3	Nov 4	Nov 17	Nov 22	Nov 24	Nov 29 – Dec 1	Dec 12	Dec 18-19	Dec 21-22	Dec 30-31
SITES										
H1				10	5					
H2				10	5					
H3				11	7	15				
H4										
H5										
H7				9.25	8.75	16.75				
H8				11.25		11				
H9				10						
H10				10						
H11										
H13				10						
H14			5.75							
H16			5.25				7			
H18	13		5.25			15	7	13		
H19							6.25			
H20							6.25			
H22						18			12	
H23				8.5	5	17			11	16
H24										
W3								5		
W4	13	4				17	8.25			
W6										
W7						18.75				
W8										
W9		9.5				19	7			14
W10		9								16
W11						17.25				
W12						19	9.75		6	
W14								7		
Storm	**27**	**23.5**	**16.25**	**90**	**30.75**	**183.75**	**51.5**	**25**	**29**	**46**

*****Seeding for Lower Basin Extension.
** Seeding for both the extension and core program

Table 4-2b
Generator Hours for High Uintas Program, 2018-2019, Storms 11-20

Storm	11	12	13	14	15	16	17	18	19	20
Dates	Jan 6	Jan 6-7	Jan 16	Jan 17-18	Jan 21-22	Jan 23-24	Feb 3-4	Feb 4-6	Feb 15-16	Feb 28 – Mar 1
SITES										
H1				16			24.5	15		2
H2				16			24.5	15		2
H3		25		24						15.75
H4		25	7	24			28	40		
H5		25	7.25	24			28	40		
H7										
H8							22.5	22		2.75
H9							26			
H10							26	21.75		
H11							23.75	18.75		
H13			5.5	10						
H14					2					
H16					15.25	13.75				
H18				6	15	15				
H19					12.5					
H20					12.5					
H22	4.25	8.75		16			11			
H23	3	8		20.75				18		8
H24								21.75		
W3										
W4										
W6									8	
W7										
W8						13.5				
W9						16			8	
W10										
W11				23						
W12				23.25				16	3	
W14									7.75	
Storm	**7.25**	**91.75**	**19.75**	**203**	**57.25**	**58.25**	**214.25**	**228.25**	**26.75**	**30.5**

Table 4-2c
Generator Hours for High Uintas Program, 2018-2019, Storms 21-28

Storm	21	22	23	24	25	26	27	28	
Dates	Mar 6-7	Mar 8	Mar 12-13	Mar 21-22	Mar 24	Mar 28-29	Apr 9-11	Apr 30	Site Total
SITES									
H1	17	10			7				106.5
H2	17	10			7				111.5
H3		12.5						5	115.25
H4		18		22				10	174
H5								10	134.25
H7								6	40.75
H8	6.5							3.5	79.5
H9									36
H10	16	9						4.5	87.25
H11	16	5						6.25	69.75
H13									25.5
H14			15				19		41.75
H16						24			65.25
H18			7			14.5	35		145.75
H19							26		44.75
H20							26.25		45
H22									70
H23	1				7				123.25
H24		10.75						3.25	35.75
W3									5
W4									42.25
W6									8
W7									18.75
W8									13.5
W9						12			85.5
W10			18						43
W11		6	12						58.25
W12		6	18			24			125
W14									14.75
Storm	**73.5**	**87.25**	**70**	**22**	**21**	**74.5**	**106.25**	**48.5**	

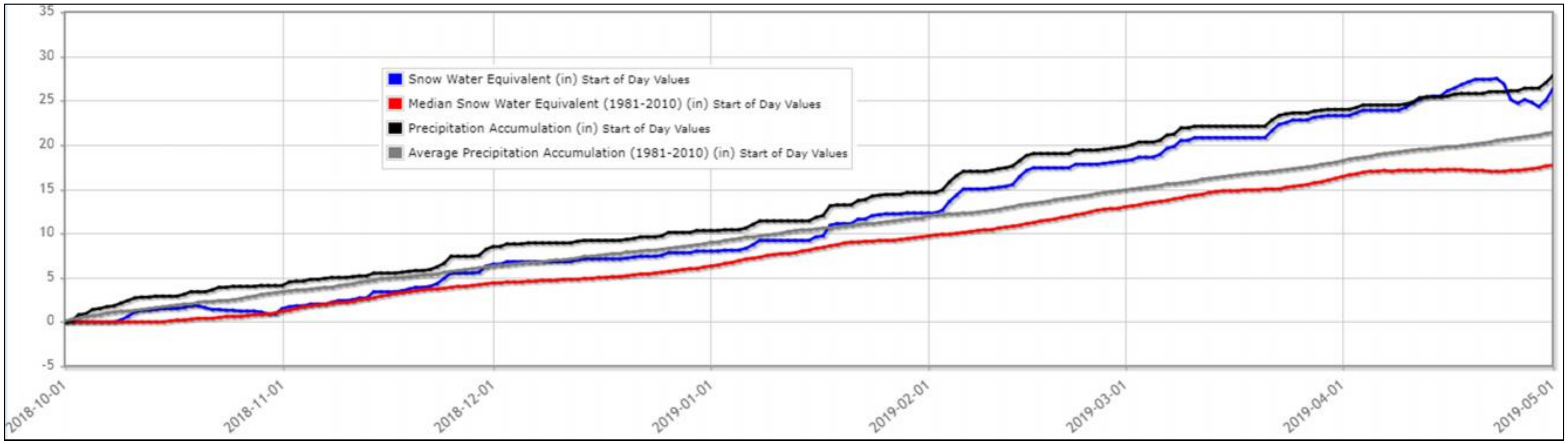


Figure 4.2 NRCS SNOTEL snow and precipitation plot for October 1, 2018 through May 1, 2019 for the Five Points Lake SNOTEL, UT.

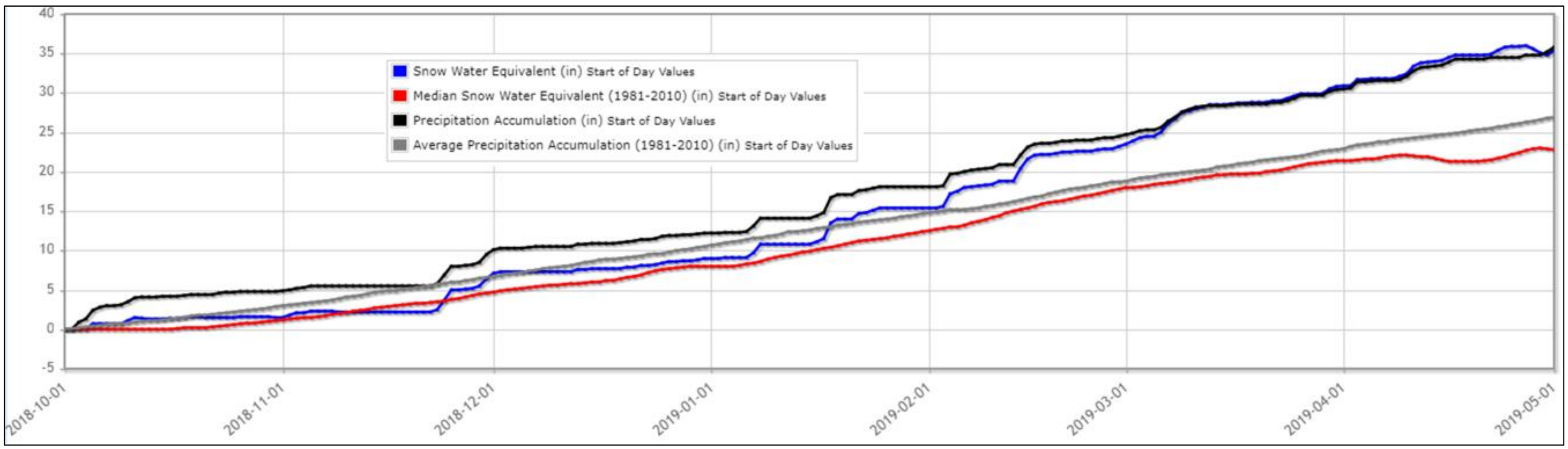


Figure 4.3 NRCS SNOTEL snow and precipitation plot for October 1, 2018 through May 1, 2019 for the Trial Lake SNOTEL, UT.

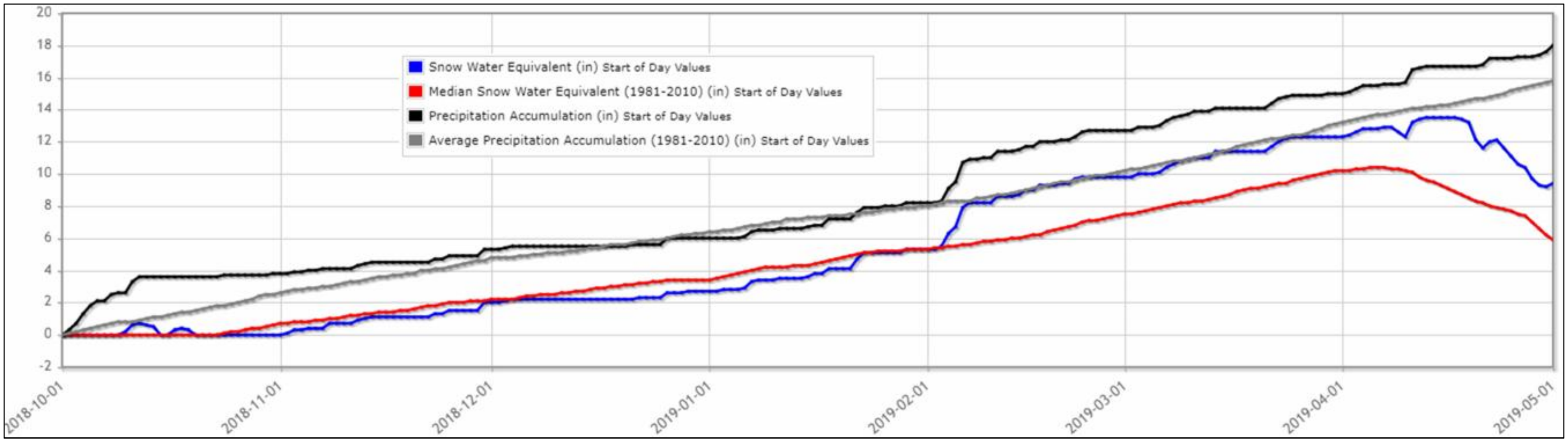


Figure 4.4 NRCS SNOTEL snow and precipitation plot for October 1, 2018 through May 1, 2019 for the Trout Creek SNOTEL, UT.

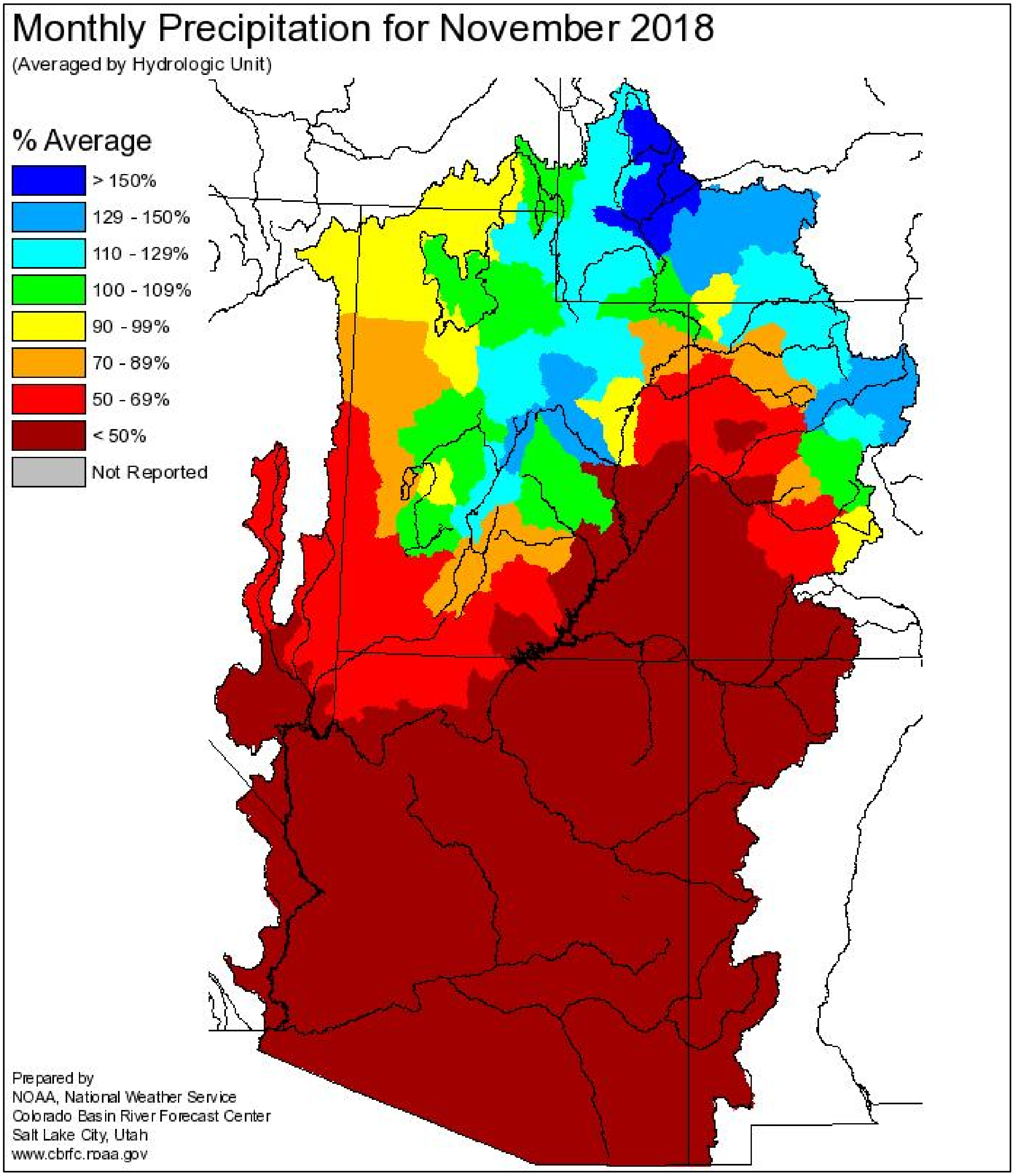


Figure 4.5 November 2018 precipitation, percent of normal

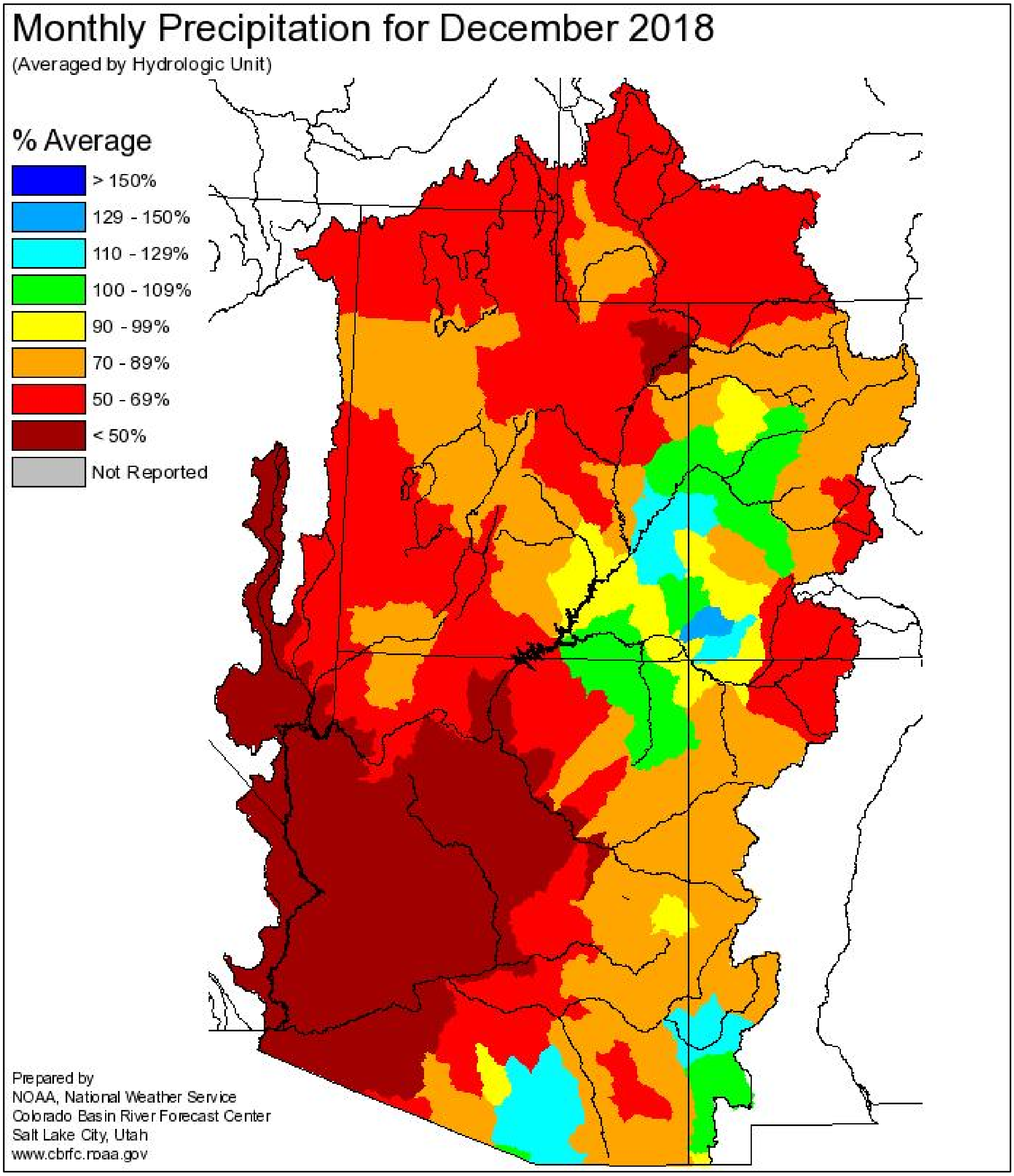


Figure 4.6 December 2018 precipitation, percent of normal

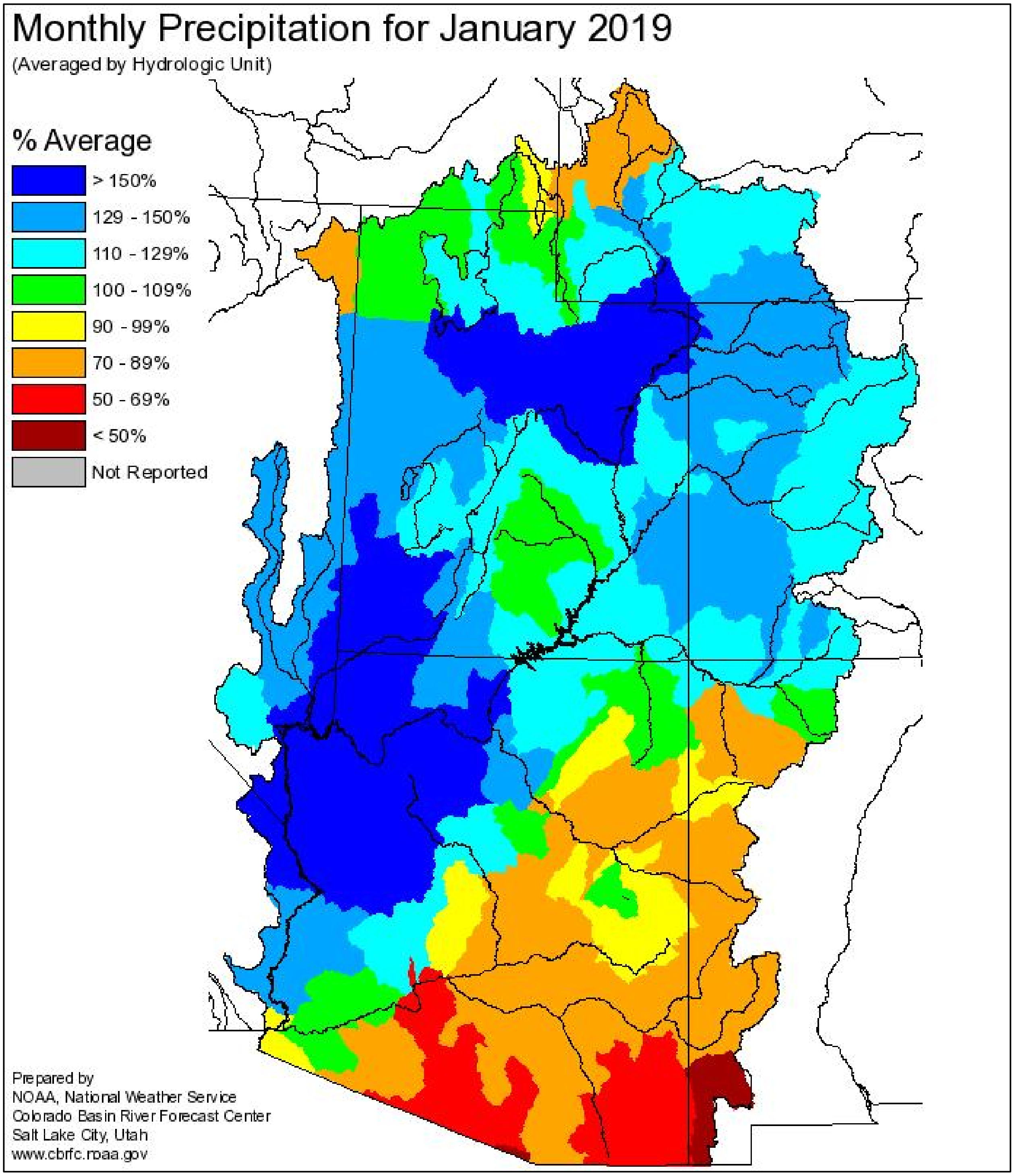


Figure 4.7 January 2019 precipitation, percent of normal

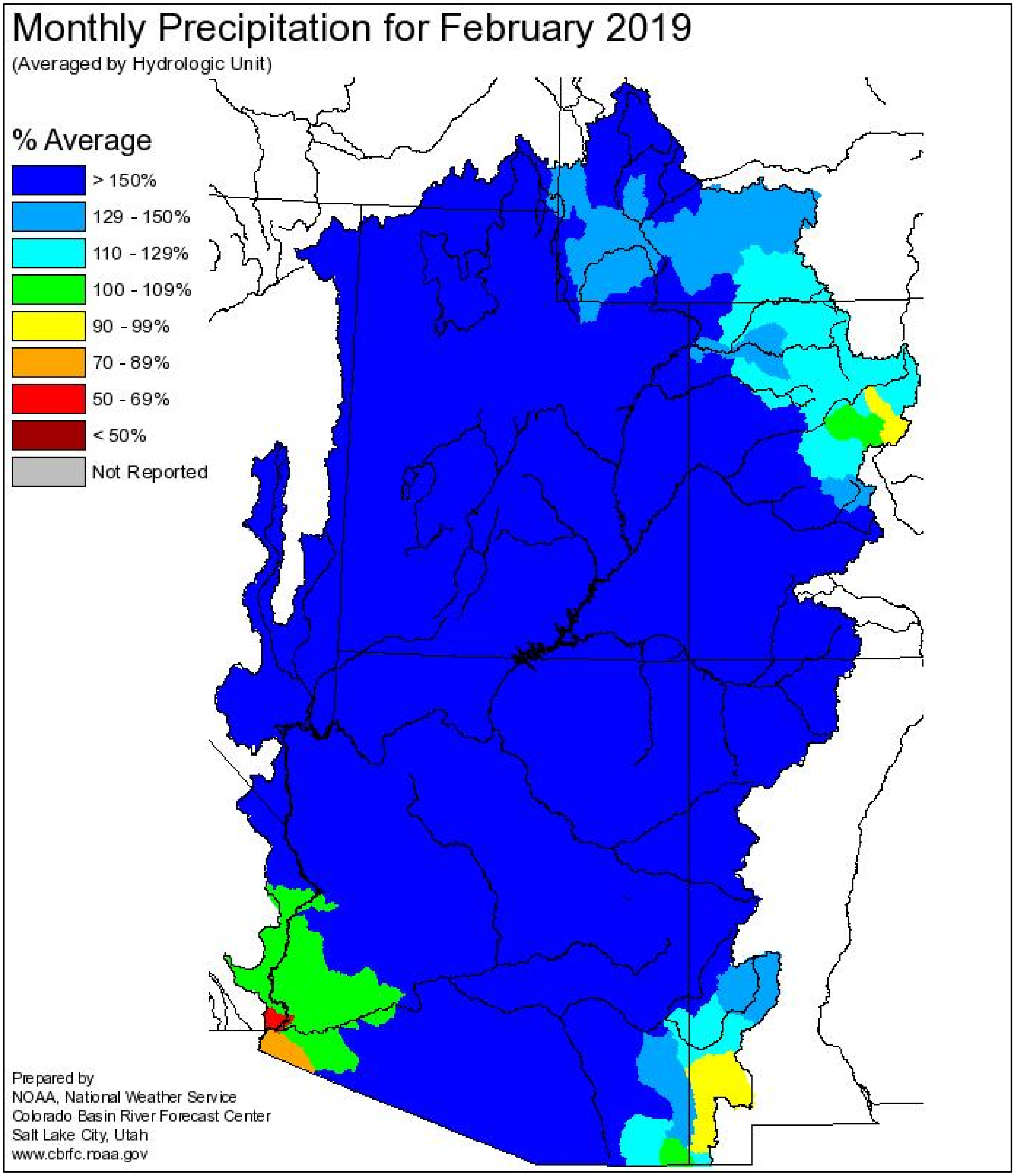


Figure 4.8 February 2019 precipitation, percent of normal

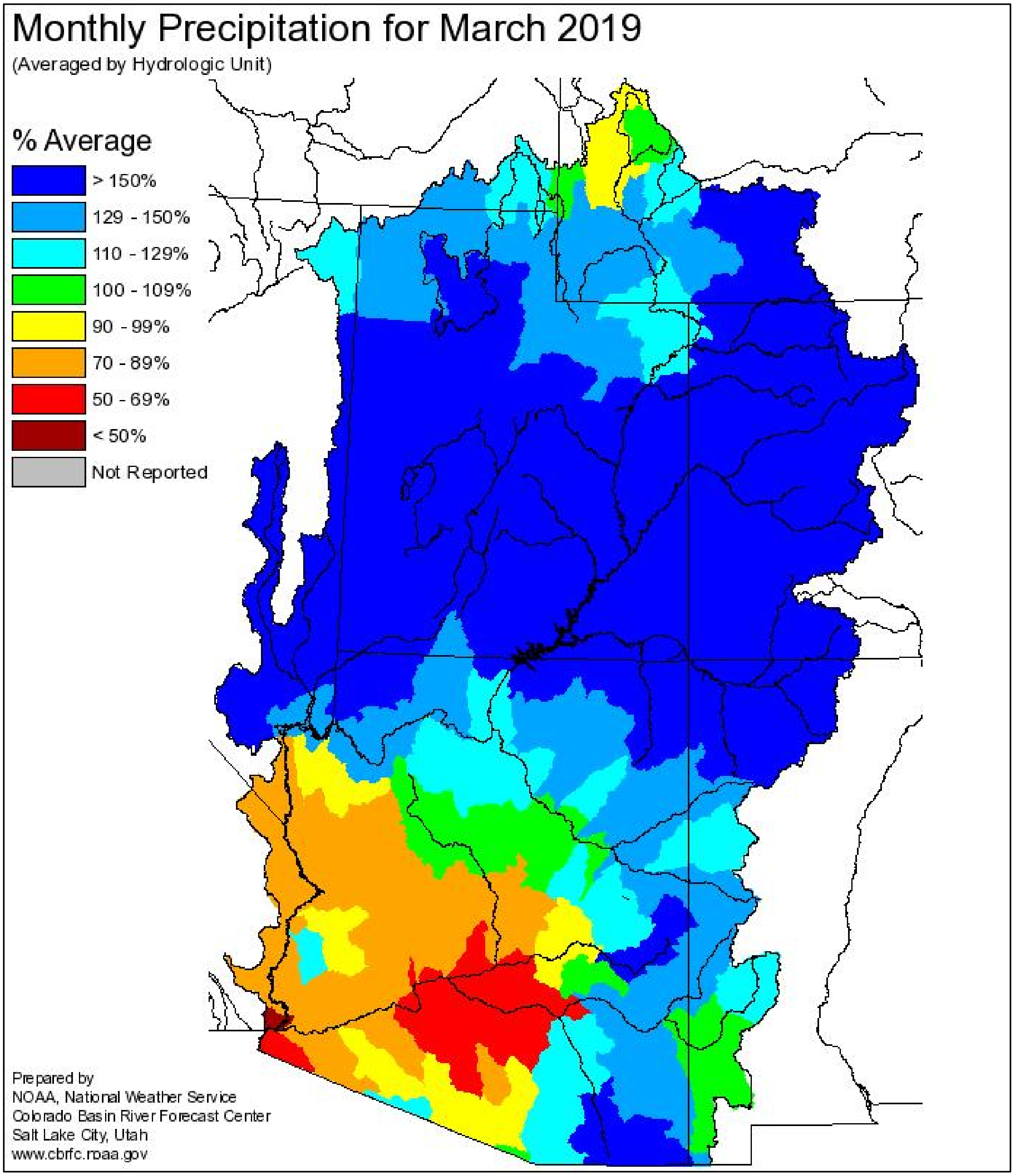


Figure 4.9 March 2019 precipitation, percent of normal

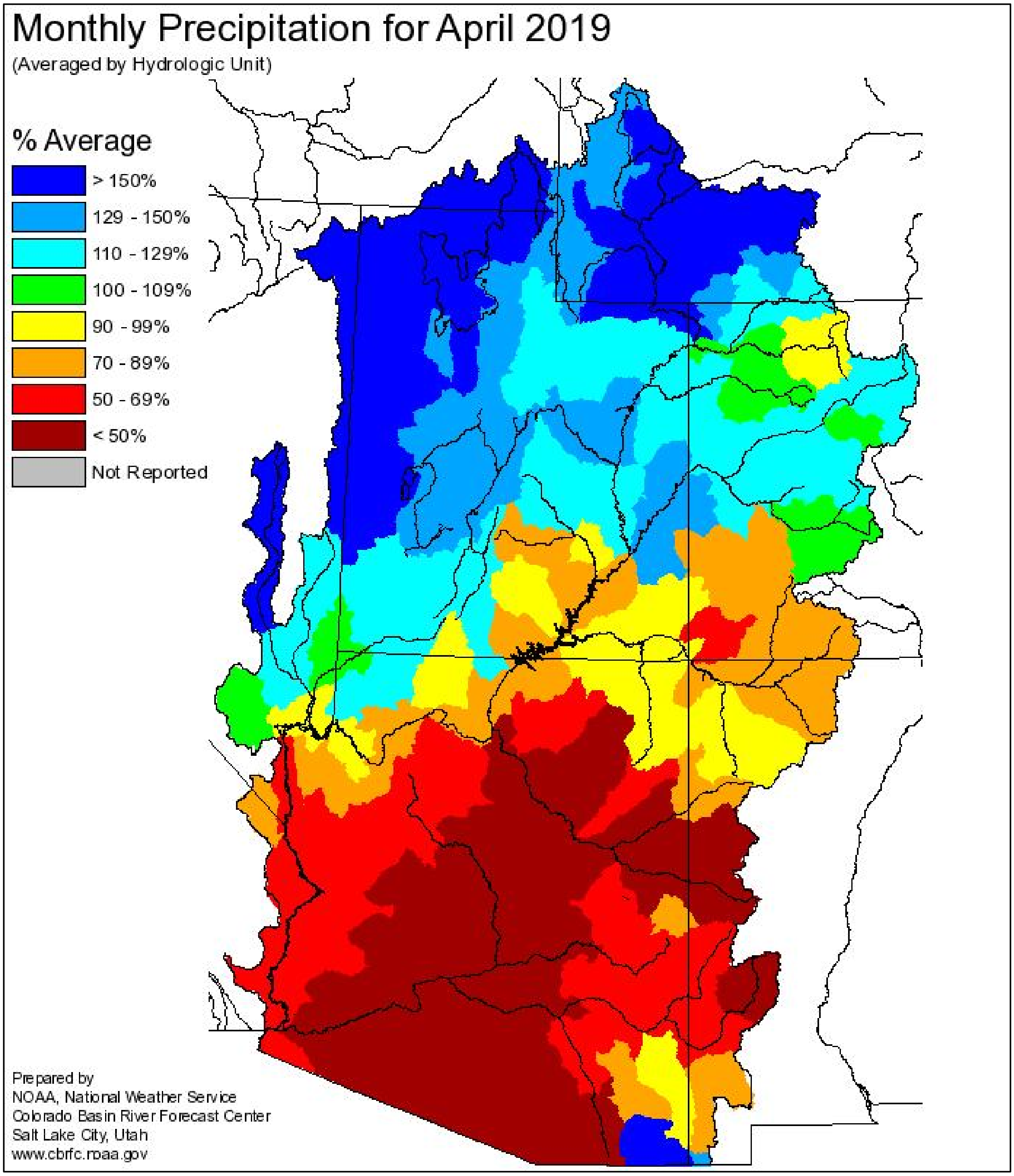


Figure 4.10 April 2019 precipitation, percent of normal

4.1 Operational Procedures

In typical operational practice, an approaching storm was monitored at the NAWC operations center in Sandy, Utah with the aid of continually updated online weather information. If the storm parameters met the seedability criteria presented in Table 2-1 of the previous section, and if no seeding curtailments or suspensions were in effect, an appropriate array of seeding generators was activated and adjusted as conditions warranted. Seeding continued as long as conditions were favorable. In a normal sequence of events, certain generators would be used in the early period of storm passage, some of which might be turned off as the wind direction changed, with other generators then used to target the area in response to the evolving wind pattern. Climatologically, the wind direction during productive storm periods in the Uintas favors a southwesterly direction, so that the generator sites on the southwestern side of the target would be used most often. Some time is required for vertical transport, nucleation, and precipitation fallout, and the seeding effects spread downwind for some distance, so seeding from the southwestern CNG group can affect the eastern portion of the target area as well. Generators located in the eastern portion of the southern slope array would be used less often because of the impact of this dominance of southwesterly flow on targeting of seeding effects. The CNG sites on the northern side of the range, however, may be used relatively often as well.

4.2 Operational Summary

A brief synopsis of the weather during the operational seeding period is provided below. All times reported are local, either in MST or MDT. When wind direction information is given it is the direction from which the wind is blowing. For example, a northwest wind is blowing from the northwest towards the southeast. The temperature at the 700 mb level (~9,500 feet above sea level during the winter) is commonly referenced, since temperature is an important factor when determining the seeding potential of an event. Data from the ice detector site at Dry Ridge (elevation 11,540 feet) can also be an important indicator of the presence of at least low altitude supercooled water in the target area, and thus seeding potential.

November 2018

November brought near normal to (in some portions of the target area) above normal precipitation and snowfall. Most of the November storm activity occurred during the latter portion of the month. Seeding was conducted for the Lower Basin early-season extension of the program, with a total of 6 seeded storm events. This includes one event that ended on December 1, and thus contained seeding hours for both the extension and core program.

A limited seeding opportunity, the first of the season, occurred on the night of November 2-3 with a weak system. Winds were from the west to northwest with a 700 mb temperature around -4°C. A couple of seeding sites on the northwestern side of the Uinta Range were favorable for seeding operations. Seeding ended early on the 3rd with clearing skies. Precipitation amounts were light, with about 0.1 – 0.2” of water content indicated at SNOTEL sites.

A weak and fast-moving system on November 4 provided another seeding opportunity. A few Western Uintas sites were utilized during the afternoon and evening hours, with westerly winds and a 700-mb temperature around -4°C. Precipitation and seeding ended later in the evening. Precipitation amounts were again light, around 0.2” in the western portion of the High Uintas. There were a few icing cycles at Dry Ridge during the morning although temperatures at that point were quite warm, near to above -5°C at the site.

A weak system dropped into the area from the north on November 17, with some north-side sites utilized during the late morning and afternoon hours. The 700 mb temperature was around -5 to -6°C, with up to a couple inches of snowfall observed mostly on the northern side of the Uintas. Precipitation was fairly minimal with the High Uintas target area, with water equivalent amounts of about 0.1 – 0.2” in some areas.

A colder and somewhat more significant storm event occurred on November 22, with more widespread seeding operations than in the earlier events. Seeding was conducted from about 1000 to 2000 MST at most western and southwestern sites, with the 700 mb temperature in the -6 to -10°C range. Several (at least 6) icing cycles were observed at Dry Ridge during the midday period, with a site temperature around -8°C during that time. Precipitation during this event was still rather light, with SNOTEL data indicated around a quarter inch of water equivalent in most of the target area.

A storm with significantly more moisture impacted the area on November 24, with snowfall beginning during a warm frontal pattern the previous night. Temperatures were warm initially, but seeding began on the morning of November 24. There were several icing cycles at Dry Ridge on the night of November 23-24, during the warm portion of the storm period. A cold front brought the 700 mb temperature down from near -2°C at 700 mb initially to below -8°C later in the day. Seeding was conducted through late morning to midday, ending during the afternoon hours with drying conditions. Higher elevation sites in the western half of the Uinta Range recorded about 1-2" of water equivalent, with lesser amounts at the lower sites and on the eastern side of the range. Approximately half of this precipitation likely occurred during the colder (seeded) portion of the event.

A storm system began to impact the area on November 29 with a relatively warm southerly wind pattern. Stable temperature profiles in the lower to mid levels of the atmosphere restricted seeding opportunity initially, although some higher elevation sides on the southern side were utilized on the night of November 29-30. On the 30th, winds became westerly with good mixing and cooling temperatures. Seeding was more widespread on the 30th, using southwestern as well as Western Uintas sites during the daytime hours. Orographic and convective precipitation activity (including some lightning) was noted on November 30, and appeared excellent for seeding operations. The 700-mb temperature cooled from about -5 to -8°C during the day on the 30th. Conditions remained favorable overnight and seeding operations continued into the early morning of December 1. The 700-mb temperature continued to fall from about -8° to -12° C during this period. Precipitation amounts with this event ranged from about 1.0 – 1.5" of water equivalent on the western side of the Uinta Range, gradually tapering down to around 0.5" totals on the eastern side.

December 2018

December brought somewhat below normal snowfall to the area, although there were several seeding opportunities. In addition to the storm event that ended on the morning of December 1, there were four seeded storm periods in December.

After a dry period with valley temperature inversions, a vigorous trough on December 12 brought a seeding opportunity. The 700-mb temperature cooled to about -12° C following a frontal passage, with excellent orographic and convective type snowfall apparent based on observations. This situation appeared quite good for seeding operations during the afternoon and early evening hours. Precipitation ended during the evening hours, with totals between about 0.1 – 0.3” of water equivalent at SNOTEL sites.

A moist northwesterly wind flow on the night of December 18-19 allowed for some limited seeding operations, with a 700 mb temperature about -6°C. A few sites on the northwestern side of the Uintas were run overnight. Precipitation was fairly minimal, averaged around 0.1” in the target area.

A weak system in westerly flow on the night of December 21-22 allowed for some limited seeding operations. The 700-mb temperature was around -6 to -8°C, and a few west side sites were utilized. Precipitation amounts were relatively light, with around 0.2” mostly on the western side of the Uinta Range.

There were a few other weak events in late December that were generally unfavorable for seeding in the High Uintas. The only additional December seeding with from a few sites on the west/southwest side of the range, in westerly flow as a trough moved into the area beginning on December 30. Seeding began during the afternoon hours and continued overnight, ending on the morning of December 31. The 700-mb temperature was around -8° C on the 30th and became quite cold (near -15°C) by the 31st. Precipitation amount were again light, with generally around 0.1 – 0.2” at SNOTEL sites.

January 2019

Snowfall was somewhat above the normal in January, with at least a couple of significant storm periods occurring. Some storm periods were on the warm side and others quite cold, but most of the major storm events had at least some periods that were favorable for seeding operations. There were six seeded storm periods in January.

A couple of fast-moving system provided some seeding opportunities early in the month, with some periods of at least moderate snowfall on January 6-7. Significant icing was noted at the Dry Ridge site on the night of January 5-6, prior to the main event. Temperature inversions had developed in the valleys prior to this, but were mixing out, with mixing conditions improving in most areas. The Uinta Basin remained cold with an inversion, however, which prevented any operations from many of the south-side sites. Seeding was conducted in westerly flow from a few sites during the midday and afternoon hours on January 6. Skies partially cleared by late afternoon, but seeding was initiated again overnight in southerly flow ahead of another system (utilized a few high elevation sites in the target area). On the 7th, seeding was expanded somewhat to include sites to the southwest of the target area. The 700 mb temperature was around -8°C, and precipitation totals during the January 6-7 period were near to above an inch at most SNOTEL sites in the western portion of the Uintas, and generally half an inch to near an inch in eastern portions.

A period of significant precipitation occurred in mid-January, consisting partially of a subtropical moisture plume that affected the area. Precipitation began on January 16, with a relatively warm/stable temperature profile in south to southwest flow. The 700 mb temperature was around -6°C but stability and poor mixing at lower and mid elevations limited seeding operations to a few of the high elevation sites within the target area. There was an icing cycle at Dry Ridge early in the morning of January 16. Seeding was conducted during the midday and afternoon hours on the 16th. Precipitation on January 16 amounts up to about a half inch of water equivalent were observed across most of the target area.

A mild and very moist system moved into Utah on January 17 with strong southwesterly winds, and the 700-mb temperature warming to around -4 to -5°C. Seeding initially began using the high elevation southwestern sites in and near the target area, as the lower and mid elevations of the Uinta Basin remained very cold with little or no mixing. Conditions improved later in the day with slow cooling at mid levels and a gradual shift to more westerly winds, and additional sites were activated on the southwestern side during the afternoon and the western side of the Uintas later in the day. There was an icing cycle at Dry Ridge just after 1600 MDT with a site temperature around -8°C. Convective activity was observed due to the cooling air mass aloft and abundant moisture, with even some thundershowers during the afternoon hours. Winds continued to shift to the west and then northwest by the morning of January 18, with steady cooling to around -8 to -10°C at 700 mb on the 18th. Seeding conditions remained generally excellent with good moisture and mixing, with seeding through the early afternoon hours on the 18th using favorable sites. Snow shower activity and seeding ended by mid-afternoon. Precipitation totals from this system ranged from over 2” of water equivalent at some sites on the far western side of the Uintas (such as Trial Lake) to between 1-2” in most of the target area, tapering down to about a half inch on the eastern end.

A deep trough developed over the Rockies on January 21-22 and resulted in a seeding opportunity using north-side sites. Winds shift from the north-northwest on the afternoon of the 21st to more northeasterly on the 22nd, with the 700 mb temperature falling from around -10°C initially to around -15°C on the 22nd. Despite the northerly wind pattern, there were a couple of icing cycles at Dry Ridge during the night and early morning hours of January 22. Most seeding ended on the morning of January 22, although one northeastern site remained on until later that day. Most SNOTEL sites observed roughly a half inch of water content from this storm, although there were some higher totals along the crest (and outside of the target area on the north side).

A weak system affected the area on the evening of January 23rd and overnight, with the 700 mb temperature near -8°C in west to northwest flow. Several sites were utilized, with seeding ending early on the morning of the 24th. There was one icing cycle at Dry Ridge during the early morning hours, around 0300- 0400 MST. Precipitation totals of 0.2 – 0.4” water content were observed at most SNOTEL sites in the target area.

February 2019

February brought above normal snowfall area-wide, with some significant early and mid-month storm events responsible for a large portion of the snow. Some of these events contained subtropical moisture or temperatures that were too warm for seeding, while others were on the cold end of the temperature spectrum. In total there were four seeded storm periods in February.

A plume of subtropical moisture moved into the area beginning on February 2nd, with widespread precipitation and temperatures initially on the warm side for seeding operations. However, the 700-mb temperature cooled to around -6 to -7°C on the 3rd and seeding was initiated, with winds remaining from the south to southwest. Seeding was conducted through the day on the 3rd and the following night, utilized sites on the south and southwest side of the Uintas. This included some of the Uinta Basin sites as mixing there appeared reasonably good. There was some orographic and convective type of precipitation as well, which enhanced the seedability of the event. By the morning of February 4th, winds had become even stronger and due southerly as a trough center deepened off the Oregon coast. Temperatures were also marginally warm, and seeding was terminated for a time on February 4th. Precipitation totals during this initial storm period were fairly substantial, with around an inch of water equivalent in the target area.

A strong southerly wind pattern and marginal temperatures continued for an extended time period as a deep trough remained near the west coast. Conditions became somewhat more favorable for operations again on the evening of February 4th, and seeding was conducted again initiated at many south-side sites. Winds on February 5th gradually became more southwesterly, and seeding ended at some of the south-side sites later in the day. However, widespread precipitation continued as the trough core moved inland overnight with a strong cold front and wind shift over Utah, bringing the 700 mb temperature down to around -16°C by the morning of the 6th. At this point, clouds appeared quite icy by observations and given the cold temperatures, all seeding was terminated on the morning of February 6. SNOTEL data indicated precipitation totals ranging up to 2” in higher portions of the target area during the February 4-6 seeded storm period.

A large amount of tropical/subtropical moisture was advected into portions of the southwestern U.S. during the February 13-14 period, with some of this moisture affecting Utah with fairly widespread precipitation. Temperatures during this period were warm, generally above -5°C at 700 mb, with widespread precipitation from a high cloud deck providing natural seeding of the storm. However, a strong cold front arrived on the evening of February 15th, with seeding operations initiated on the western side of the Uintas with the frontal passage as temperatures cooled into the desirable range, along with some convective storm activity. By early on the 16th, the 700 mb temperature had cooled all the way to about -15°C and cloud appeared very icy, so seeding operations were ended. There was icing observed at Dry Ridge during the early (warm) portion of the event, and also a little on the evening of the 14th and again the evening of the 15th near the time of the cold frontal passage. This long storm period as a whole provided between about 1.0 to 2.5" of water equivalent to the target areas, with likely about a half inch of this occurring during the seeding period toward the end of the event.

After a fairly extended period of very cold temperatures and only some sparse snowfall that did not appear to have any real seeding potential, a warmer system arrived beginning on February 27th. Conditions were not favorable for seeding initially, but on February 28th a moist southwesterly wind pattern and a 700 mb temperature around -5°C, combined with convective type showers, provided a seeding opportunity during the afternoon and evening hours utilizing available sites on the south and southwest side of the Uinta Range. Dry Ridge had three icing cycles on the afternoon of the 28th with a site temperature near -7°C, and another later (just before midnight). Precipitation totals during this event were fairly light, with an average of about a quarter inch of water equivalent measured.

March 2019

March was another above-normal month for snowfall, with the most consistent storm activity occurring in the first half of March. Many of the March events were favorable for seeding, with a total of six seeded storm periods.

Another large subtropical moisture plume affected the area on March 5-6, initiating widespread precipitation from primarily a higher cloud deck. Temperatures also warmed during this period, to above -3° C at 700 mb. Icing was observed at Dry Ridge on the night of March 5-6, during the warming phase of this storm event. By the evening of March 6th, convective precipitation in southwesterly flow combined with some cooling resulted in a seeding opportunity utilized several south-side sites. Seeding continued overnight and through much of the day on March 7th, with convective showers and a 700 mb temperature near -5°C in southwesterly flow. There were a few more icing cycles noted at Dry Ridge late on March 7th. Seeding operations ended by late afternoon on March 7th. Precipitation during the March 5-7 event was over an inch at nearly all sites, with up to about 2.5" of water content in some areas.

Another system in a series brought snowfall to the area on March 8th, with southerly winds initially, shifting around to the northwest by later in the day. Significant icing at Dry Ridge was also observed at the start of this event. Seeding was conducted through the day from south-side sites, with the 700 mb temperature falling from about -6°C to below -10° C. Snowfall and seeding ended during the evening with a shift to westerly winds at that time as well. Precipitation amounts were generally between about 0.4 – 0.8" on March 8th.

A trough over the western U.S. on March 12-13 resulted in some loosely organized areas of precipitation. Temperatures were on the warm side initially, above -5°C at 700 mb, but convective activity helped to make conditions more favorable for seeding at these temperatures and temperatures cooled considerably by March 13th. Seeding was conducted on the night of March 12-13 and through much of the day on the 13th, utilizing some west and north-side sites. Once icing cycle was observed at Dry Ridge overnight as the site temperature fell to around -10°C. Drying begin later in the afternoon on the 13th and seeding operations ended. This was a fairly limited opportunity with only light precipitation amounts, mostly under 0.2".

A trough provided limited seeding opportunity in a southerly wind pattern on the night of March 21-22, although cold temperatures and very stable conditions in the Uinta Basin limited site use to only a couple of high-elevation locations that were accessible. The 700 mb temperature was around -7°C, and precipitation ranged from about 0.1" up to locally about 0.5". There was intermittent icing at the Dry Ridge site during the evening and overnight hours. Additional precipitation continued in many areas through March 22th and overnight but was not favorable for seeding operations due to the observed cloud types and wind patterns.

On the morning of March 24, widespread precipitation was occurring with a 700 mb temperature around -6 to -7°C in southwesterly flow. Significant icing was observed at Dry Ridge just prior to this, on the night of March 23-24. Seeding was initiated from some sites on the southwest side of the Uintas, although several sites were inaccessible at this point due to deep snow cover. Seeding continued through most of the day as the winds gradually shifted from the southwest to more westerly with shower activity across the area. Seeding ended about sunset with gradually clearing skies. Precipitation totals were between about a quarter and a half inch of water equivalent during this storm period.

Seeding was conducted from sites on the western and northern sides of the Uintas beginning on the night of March 28-29, following a cold frontal passage. The 700 mb temperature dropped to around -8 to -10°C on the 29th with snow shower activity continuing in northwesterly flow. There was an icing cycle at Dry Ridge around 0400 MST on the morning of the 29th, with a site temperature of -11°C. Seeding continued through the day, ending during the evening hours. Precipitation totals were generally between about 0.2 to 0.6" of water equivalent in the target area with this event.

April 2019

April was a near-normal month overall across the Uintas. However, due to earlier heavy snowfall events, snowpack was much above normal and seeding was suspended for some portions of the target area beginning on April 9th. This affected the mid-elevation areas around Strawberry Reservoir and on the southwestern side of the Uinta Range where several SNOTEL sites had 150-200% or more of the normal snowpack for the remainder of April. Some of the April storm events were minor and did not present favorable seeding situations due to cloud types, wind, or temperatures (which were quite warm in some cases). However, there were two seeded storm periods during the month of April.

A deep trough over the Rockies on April 9-11 provided an extended period of seeding opportunity from the north and northwest side of the Uintas, beginning late on the evening of the 9th. 700-mb temperatures were generally about -5 to -8°C with winds almost due northerly for much of this time period. Orographic and some convective type clouds were apparent which appeared quite favorable for seeding operations. There were a few icing cycles at Dry Ridge on the night of April 10-11 with a site temperature just below -10°C. Seeding ended mid-morning on April 11th as snow showers had tapered off by that time. Operators at seeding sites on the north side of the Uintas reported about 12-20" of new snow accumulation, with SNOTEL sites along the Uinta Crest reported generally around an inch of water equivalent. Lower and mid-elevation sites on the southern side reported much lesser amounts, generally under a half and in some places very little at all, due to the northerly wind pattern and associated orographic patterns during this event.

A significant frontal system on April 30th resulted in a seeding opportunity from sites on the southern side of the target area during the afternoon and evening hours. The 700 mb temperature dropped from about 0 to -5°C during this period with convective activity aiding the vertical transport of seeding material. There was an icing cycle observed at Dry Ridge just before 6 pm with a site temperature near -6°C. Seeding operations ended late in the evening with drying and a shift to northwesterly winds overnight. Precipitation amounts were significant, with generally around an inch of water equivalent in target area from this event.

5.0 ASSESSMENT OF SEEDING EFFECTS

5.1 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. 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, i.e., basically a signal to noise ratio issue. Larger seeding effects can be detected more easily, and with a smaller number of seeded cases, than are required to detect smaller increases.

Historically, consistently positive seeding results have been observed in wintertime seeding programs in mountainous areas. However, the apparent differences due to seeding are relatively small, usually being of the order of a 5-15 percent seasonal increase. In part, this relatively small percentage increase accounts for the significant number of seeded seasons (often five years or more) required to establish these results with any certainty.

Despite the difficulties involved, some techniques are available for estimation of the effects of operational seeding programs. These techniques are not as statistically rigorous or scientifically desirable as the randomization technique used in research, where roughly half the sample of storm events is randomly left unseeded. However, most of NAWC's clients do not choose to cut the potential benefits of a cloud seeding project in half in order to better document the effects of the cloud seeding project. The less rigorous techniques can, however, potentially offer a reasonable indication of the long-term effects of seeding on operational programs.

A commonly employed technique, the one utilized by NAWC in this assessment and in evaluation of its other winter seeding projects, is a "target" and "control" comparison. This technique is described by Dr. Arnett Dennis (1980) in his book entitled “Weather Modification by Cloud Seeding”. The technique is based on the selection of a variable that would be affected by seeding (such as precipitation or snowpack). Records of the variable to be tested are acquired for an 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 not-seeded "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 project seeding (or seeding from other adjacent projects). The historical data in both the target and control areas are taken from past years that have not been subject to cloud seeding activities. These data are evaluated for the same seasonal period of time (months) as that when the seeding is to be or has been conducted. 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 natural precipitation, based on precipitation observed in the control area. This regression equation is then used during 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 work 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 areas selected too close to the target, 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.

Experience has shown that it is virtually impossible to provide a precise assessment of the effectiveness of cloud seeding over one or two winter-spring seasons. However, as the data sample size increases, it becomes possible to provide at least a reasonable estimate of seeding effectiveness.

5.2 Data Sets Used in the Target/Control Evaluations

5.2.1 Precipitation and Snowpack Data

The Natural Resources Conservation Service (NRCS) collects data from a number of precipitation and snow measurement sites. Most of these sites have been converted to automated SNOTEL sites in the last 30 years, although manual snow course measurements are still conducted in some locations. NAWC has utilized monthly precipitation and snow data from a number of these sites for use in seeding program evaluations. The number of sites operated by agencies such as the NRCS, especially manual snow course sites, has been gradually reduced. Even some cooperative observer sites, which are managed by the National Weather Service, have been either discontinued or have become inactive. Therefore, the selection of target and control sites first involves examination of the period of record of data at a given location, and changes to the set of target or control sites are sometime necessary in the event that measurements at a site are discontinued.

There have been, and continue to be, multiple cloud seeding programs conducted in the State of Utah. As a consequence, potential control areas that are truly unaffected by cloud seeding are somewhat limited in geographic area. This is complicated by the fact that the best correlated control sites are generally those closest to the target area. Many measurement sites in this part of the state, although not located within the boundaries of the intended area of effect of a seeding program, have been subjected to potential effects of numerous historical and current seeding programs. This renders such sites of questionable value for use as control sites. Studies of downwind seeding effects suggest that if we wish to consider any precipitation gauge sites downwind of the seeded area as control sites for the High Uintas project, they should be located at least 50-75 miles downwind of current or historic cloud seeding programs in Utah (or Idaho and Nevada) to avoid significant contamination.

Our normal approach in selecting control sites for a new project is to look for sites upwind or crosswind from the target area that will geographically bracket the intended target area. The reason for this approach is that we have observed that some winter seasons are dominated by one upper airflow pattern while other seasons are dominated by other flow patterns. The result of different upper airflow patterns and storm tracks often results in heavier precipitation in one area versus the other. For example, a strong El Niño pattern may favor the production of heavy winter precipitation in the southwestern United States while a strong La Niña pattern may favor the production of below normal precipitation in that region. Having control sites either side of the target area relative to the generalized flow pattern can improve the prediction of target area precipitation under these variable upper airflow pattern situations.

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 usually manifests itself in terms of missing data. The double mass plot is an engineering tool that will indicate any changes in relationships between two stations, and may be particularly useful if one or both stations have moved during their history. If 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 excluded from further consideration.

There are some things to consider when dealing with the two types of precipitation observations typically available from mountainous areas in the west: standpipe storage precipitation gauges and snow pillows. There are some potential problems associated with each type of observation. With the advent of the SNOTEL data acquisition system in the late 1970's, access to precipitation and snowpack (water equivalent) data in mountainous locations became routine. Before the SNOTEL system was developed, these data had to be acquired by actually visiting the site to make measurements. This is still required at some sites. Figure 5.1 is a photo of an NRCS SNOTEL site, with labels to allow the reader a better understanding of the two types of observation systems. The vertical tube is the standpipe storage gauge, which is approximately 12" in diameter. The gauges are approximately 20’ in height so that their sampling orifices remain above the snowpack surface. There are at least two types of potential problems associated with high elevation observations of the water equivalent of snowfall, as measured by standpipe precipitation storage gauges. The two areas of concern are clogging at the top of the standpipe storage gauge, and blow-by of snowflakes past the top of the standpipe gauge. Either situation would result in an underestimate of the actual precipitation that fell during such periods. In the fall, the storage gauge is charged with antifreeze, which melts the snow that falls to the bottom of the gauge. 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. Heavy, wet snow may accumulate around the top of the standpipe storage gauge, 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 gauge, 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 effects. Sites that are near or above timberline are more likely to be impacted by wind since properly sheltered sites may be difficult to find in these areas. The snow pillow, pictured on the pad at ground level in the foreground of Figure 5.1, 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.

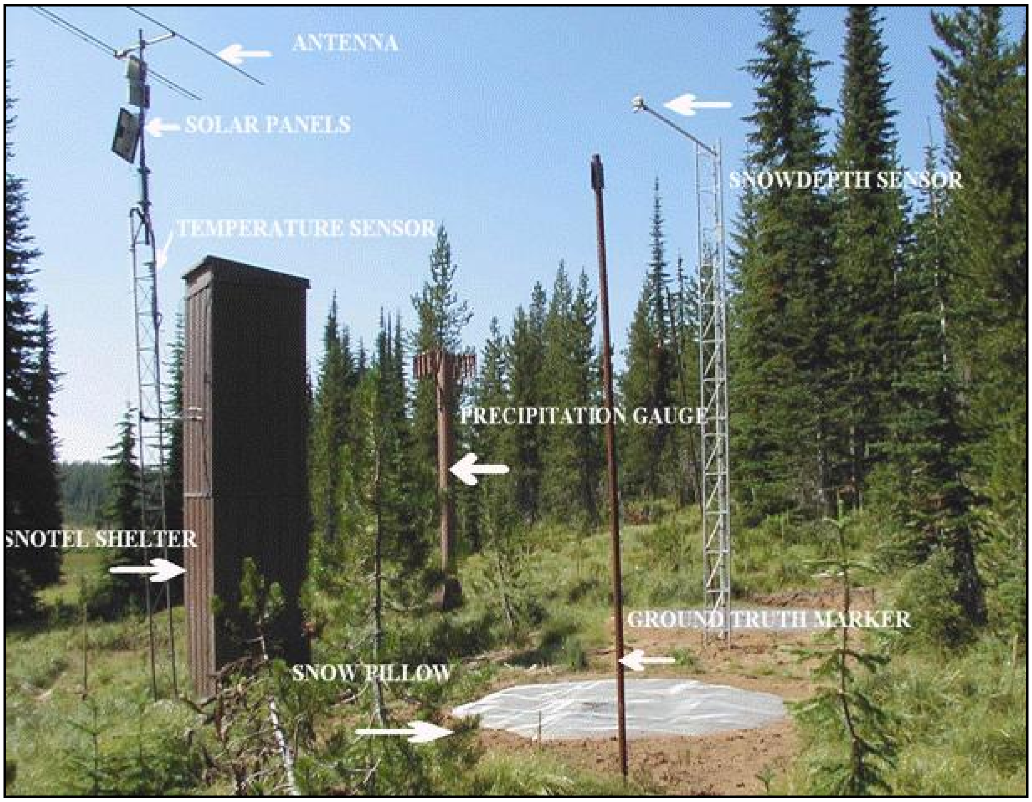


Figure 5.1 SNOTEL site

The water content within the snowpack is important since, after consideration of antecedent soil moisture conditions, it ultimately determines how much water will be available to replenish the supply when the snow melt occurs. Hydrologists routinely use snow water content measurements to forecast streamflow during the spring and early summer months. As with the precipitation storage gauge and SNOTEL precipitation gauge networks, Utah also has access to an excellent snow course and SNOTEL snow pillow reporting system via the NRCS. Many of the same reporting mountain sites are available for both precipitation and snowpack measurements. Consequently, it was judged worthwhile to evaluate the effects of seeding on snowpack as well.

There are some potential problems with snowcourse (manual) type of measurements that must be recognized when using those measurements to evaluate seeding effectiveness. Because not all winter storms are cold, sometimes rain as well as snow falls in the mountains. This can lead to a disparity between precipitation totals which theoretically measure everything that falls, and snowpack water content which measures only the water held in the snowpack. Warm periods can occur between snowstorms. If a significant warm period occurs, some of the precipitation that fell as snow will have melted or sublimated by the time the next snowcourse measurement is made. Thus, some of it may never be recorded, even though some of the melted snow may have gone into the ground to recharge the ground water. This can also lead to a greater disparity between the snow water content at higher elevations (where less snow will melt in warm weather) and that observed at lower elevations. These problems primarily apply to the older snowcourse measurements which were made at coarse (monthly) intervals compared to today's measurement capabilities. The newer daily SNOTEL measurements avoid some of these problems, but depletion of the snowpack can occur even with SNOTEL measurements when dealing with April 1st observations. We need to be concerned with both types of measurements since we often use snow course measurements to provide a longer historical data base from which the regression equations can be developed. In addition, some measurements are conducted manually at some mountain sites in the west up to the present time.

Another factor that can affect the indicated results of the snowpack evaluation is the date on which snow course measurements were made. Since the advent of SNOTEL, data are now available on a daily basis. However, prior to SNOTEL, and at those sites where snow courses are still measured by visiting the site, the measurement is recorded on the day it was made. In some cases, because of scheduling issues or stormy weather, these measurements have been made as many as 5-10 days before or after the end of the month. This can lead to a disparity in the snowpack water content readings when comparing one group (such as a control) with another control or target group. Normally, however, snowpack measurements are made within a few days of the intended date. Nonetheless, the measurement timing issue can affect the data. Only two manual snow course sites are used in this analysis, both of which are located in the target area.

Most of the snowpack data used in this analysis are from sites that were originally snow course sites and became SNOTEL sites after approximately 1980. It was recognized that this change could present a problem because of potential differences between the snow course and SNOTEL measurement techniques, so the NRCS collected concurrent data at the newly established SNOTEL sites using both measurement techniques for an overlap period of approximately 10 years in duration. They then developed mathematical correlations between the two types of measurements at each site and applied a correction factor at each site that converted the previous monthly snow course measurements to estimated values as though the SNOTEL measurements had been available at these sites for the full period of record. The resulting estimated data at some sites were very similar to the original snow course data, while at some sites there were differences of as much as 10-15%. After careful consideration, we decided to use these NRCS estimated data in place of the mixture of manual snow course and SNOTEL measurements. We believe that using these NRCS estimates can help eliminate any inherent systematic bias between data obtained using the snow course and SNOTEL measurement systems.

April 1 snowpack readings have generally become accepted as the conventional data set for snowpack water content since they usually represent the maximum snow accumulation for the winter season. Most streamflow and reservoir storage forecasts are made on the basis of the April 1 snowpack data. For that reason, and since five months of seeding are contained in the April 1 snowpack measurements, April 1st was selected as the most appropriate standardized date for snowpack analysis.

The bottom line is that it is difficult to accurately measure snow water equivalent at unmanned high-elevation sites. Both types of NRCS observations (gauge 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 the 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.

5.2.2 Streamflow Data

In addition to the precipitation and snow water equivalent data which are used in these evaluations, NAWC began to utilize streamflow data for use in target and control analyses for the program. Monthly streamflow data were obtained from the USGS (United States Geological Survey) website for sites that had a long history of unregulated streamflow measurements. Streamflow data can, under the right circumstances, directly address the issue of how much additional water is being produced by a seeding program. There are some potential difficulties here as well, including diversions for irrigation (which are present to some extent above even most of the "unregulated" sites), and significant carryover in streamflow from one season to another, which lowers the correlation between target and control sites. Overall, the best correlation between control and target sites is found with the precipitation data, followed by snow water equivalent, with streamflow correlations generally being the lowest of the three data types.

5.3 Evaluation Methodology

Using the target-control approach described earlier, the mathematical relationships for two variables (precipitation and snowpack) were determined between a group of sites in an unseeded area (the control group) and the sites in the seeded area (the target group), based upon records for a common period prior to any seeding in either area. From these data, prediction equations were developed whereby the amount of precipitation or snowpack observed in the unseeded (control) area was used to predict the amount of natural precipitation in the seeded (target) area. This "predicted" value is the amount of precipitation or snowpack that would be expected in the target area without seeding. The difference between the predicted amount and the observed amount in the target area is the excess, which may be the result of cloud seeding. Statistical tests have shown that such indications have little statistical significance for individual seasons, and usually fall within the standard deviation of the natural variability. However, more meaningful estimates can be obtained by combining the results of several or more seeded seasons.

5.3.1 Precipitation Target and Control Sites

Precipitation measurements were available from six sites within the target area (the same sites as used in the previous several years). There are additional SNOTEL sites in the target area (e.g., Chepeta), but they have shorter periods of record. Thus, they were not considered in this analysis. The sites selected for use in the evaluation work are shown in Figure 5.2, and are all higher elevation NRCS sites. The average elevation for the target area sites is 9,875 feet above mean sea level (MSL). Specifics in regard to location and elevation of these six target area sites are provided in Table 5-1.

For many years, winter cloud seeding in Utah was limited to mainly the central and southern portions of the State, although occasional winter seeding was conducted in the mountains of Tooele County (southwest of the Salt Lake area) in the late 1970’s and early 1980’s. However, beginning in the 1988 water year, winter cloud seeding programs became more widespread in northern Utah. The result of this increase in cloud seeding projects is that it has become more difficult to locate control areas that have not been contaminated by other cloud seeding programs. To further complicate the matter, some sites that had data available in the past have been eliminated over the years.

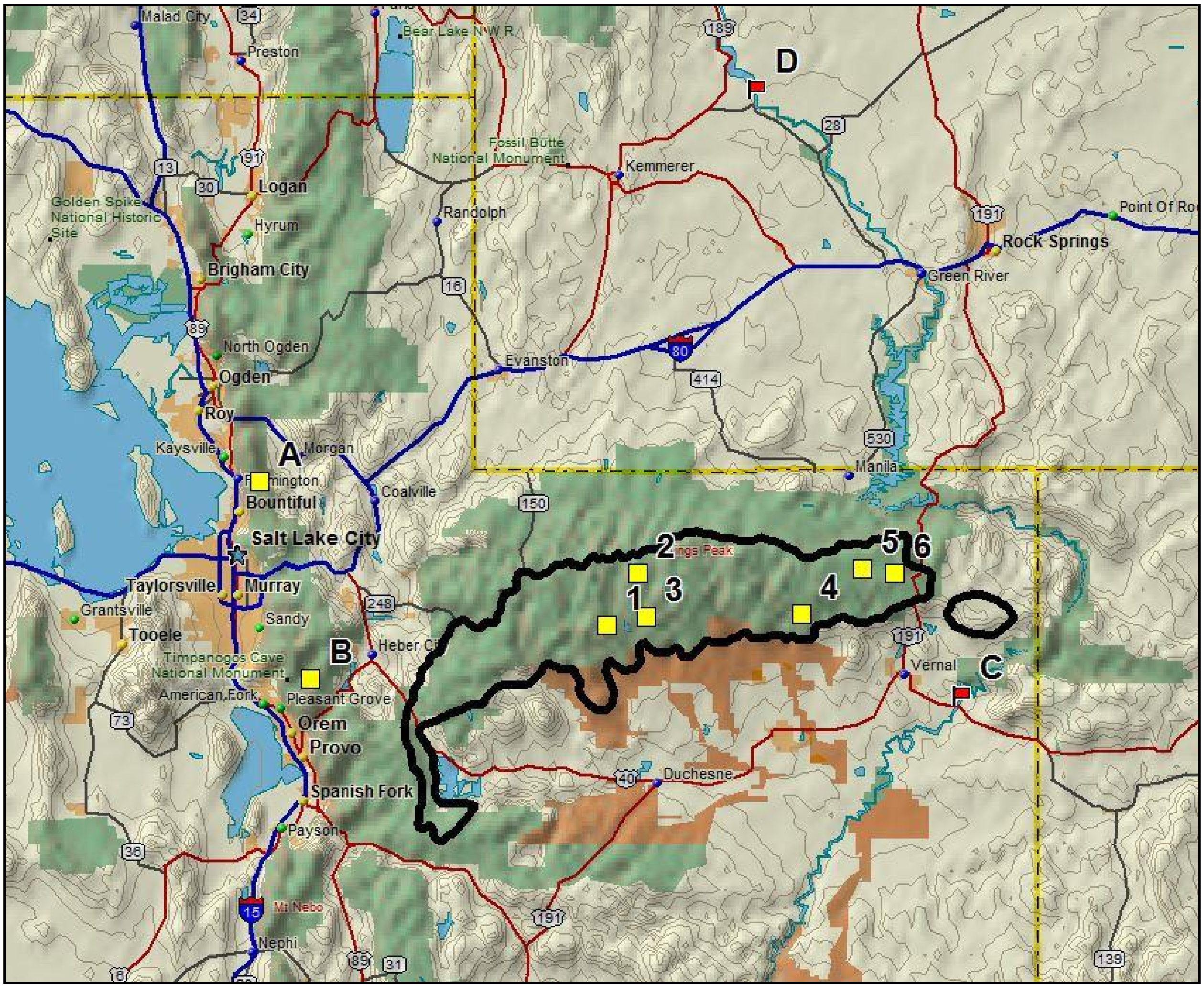


Figure 5.2 Precipitation gauges used as target area sites (number ID's) and control sites (letter ID's). The yellow boxes represent SNOTEL locations and the flag is an NWS co-op site.

The control gauge sites used in the evaluations were carefully selected according to the following criteria: 1) similarity to the target area sites, in terms of elevation and meteorology; 2) geographic bracketing of the target area; and 3) mathematical correlation of the data with that in the target area. The Strawberry Divide SNOTEL site was at one time included in the control group, but has been excluded from evaluations in recent years since it is now in part of the target area. Two cooperative (valley) reporting gauges, located at Heber and Vernal, were previously used as control sites, but have been discontinued because data are no longer available at these sites. The relationship of the control area gauges to the target area is shown in Figure 5.2, and the specifics in regard to the locations and elevations of the control sites are provided in Table 5-1.

Table 5-1
Control and Target Area Precipitation Gauge Sites

Group ID	Site Name	Site Number	Elevation (ft.)	Latitude (N)	Longitude (W)
Control					
A	Farmington Canyon	11J11S	8000	40°58'	111°48'
B	Timpanogos Divide	11J21S	8140	40°26'	111°37'
C	Jensen	424342	4750	40°22'	109°21'
D	Fontenelle Dam, WY	483396	6480	41°59'	110°04'
Target					
1	Brown Duck	10J30S	10600	40°35'	110°35'
2	Five Points Lake	10J26S	10920	40°43'	110°28'
3	Lakefork #1	10J10S	10100	40°36'	110°26'
4	Mosby Mountain	09J05S	9500	40°37'	109°53'
5	Trout Creek	09J16S	9400	40°44'	109°40'
6	King's Cabin	09J01S	8730	40°43'	109°33'

It is recognized that the group of control sites in Table 5-1 might provide a conservative estimate of the effects of seeding for the High Uintas, since there could have been some seeding effects impacting some of the control sites (e.g. seeding for the western Uintas project could impact the precipitation at Heber, and projects in eastern Tooele County and eastern and western Box Elder County could impact sites like Farmington Canyon). Those impacts would have the effect of raising the predicted target area precipitation and, thus, lowering the indicated effects of seeding in the High Uintas target area. The average elevation of all seven control sites is 6,842 feet, which is much lower than that of the target sites (9,875 feet). The large elevation difference is due in part to the fact that the Uinta Range is the highest mountain range in the region. The locations of the control sites are shown in Figure 5.2. Elevation differences are important in snow water content evaluations, since snowmelt may impact high and low elevation sites differently. The great elevation difference between the target and control sites is also of significance in the precipitation evaluations because of the potential for much windier exposures at the Uintas sites which are ~3,000 feet higher on average than the control sites. Gauge catch deficiency due to wind can be very high, and in some exposed areas it can be 50% or greater.

5.3.2 Snowpack Target and Control Sites

The procedure was essentially the same as was done for the precipitation evaluation, e.g., control and target area sites were selected, and average values for each were determined from the historical snowpack data. Due to concerns regarding potential contamination by other seeding projects, combined with some period of record limitations and consideration of site correlation values, a short 13-year historical period (1975-88) was used in most of the snow water content evaluations. The limited amount of historical data renders the equations using the historical regression technique questionable, as described in the earlier precipitation evaluation section. We prefer historical periods of at least 20 seasons duration when utilizing this technique. The years after the 1988 water year were excluded from the historical period in most of these evaluations, since a number of new seeding programs were activated in northern Utah beginning with the 1989 water year, especially along the Wasatch Range west of the Uintas. We took this step to eliminate concerns about potential contamination due to downwind effects impacting the control sites.

Four sites were selected as controls for the snowpack evaluation. The control group provides reasonably good correlations with the six-site target area group. The six snowpack target sites include four of the six sites used in the precipitation evaluations (data were unavailable back to 1975 for the Brown Duck and Five Points Lake sites), plus two additional manual snowcourse sites (Lakefork Mountain #3 and Spirit Lake). Spirit Lake is actually located on the north slope of the Uintas but is very close to the crest, so we believe it to be representative of the higher south slope area immediately south of its location. It should also be noted here that SNOTEL sites were installed in 2009 at the Lakefork Mountain #3 and Spirit Lake snow course locations, and data at these sites became SNOTEL-only beginning in 2011. The target and control area snowcourse/snow pillow site names, elevations and locations are summarized in Table 5-2, and site locations are shown in Fig. 5.3. The elevations of the control area sites averaged 8,184 feet. The target sites were significantly higher, averaging 9,405 feet. The relationship of the control area snowpack sites to the target area is shown in Figure 5.3.

Table 5-2
Control and Target Snowpack Sites

Group ID	Site Name	Site Number	Elevation (Ft)	Latitude (N)	Longitude (W)
Control					
A	Farmington Canyon Upper	11J11S	8000	40°58'	111°48'
B	Lookout Peak	11J64S	8200	40°50'	111°43'
C	Timpanogos Divide	11J21S	8140	40°26'	111°37'
D	Kelley RS, WY	10G12S	8180	42°15'	110°48'
Target					
1	Lakefork #1	10J10S	10100	40°36'	110°26'
2	Lakefork Mountain #3	10J12S	8400	40°33'	110°21'
3	Spirit Lake	10J55S	10300	40°50'	110°00'
4	Mosby Mountain	09J05S	9500	40°37'	109°53'
5	Trout Creek	09J16S	9400	40°44'	109°40'
6	King’s Cabin	09J01S	8730	40°43'	109°33'

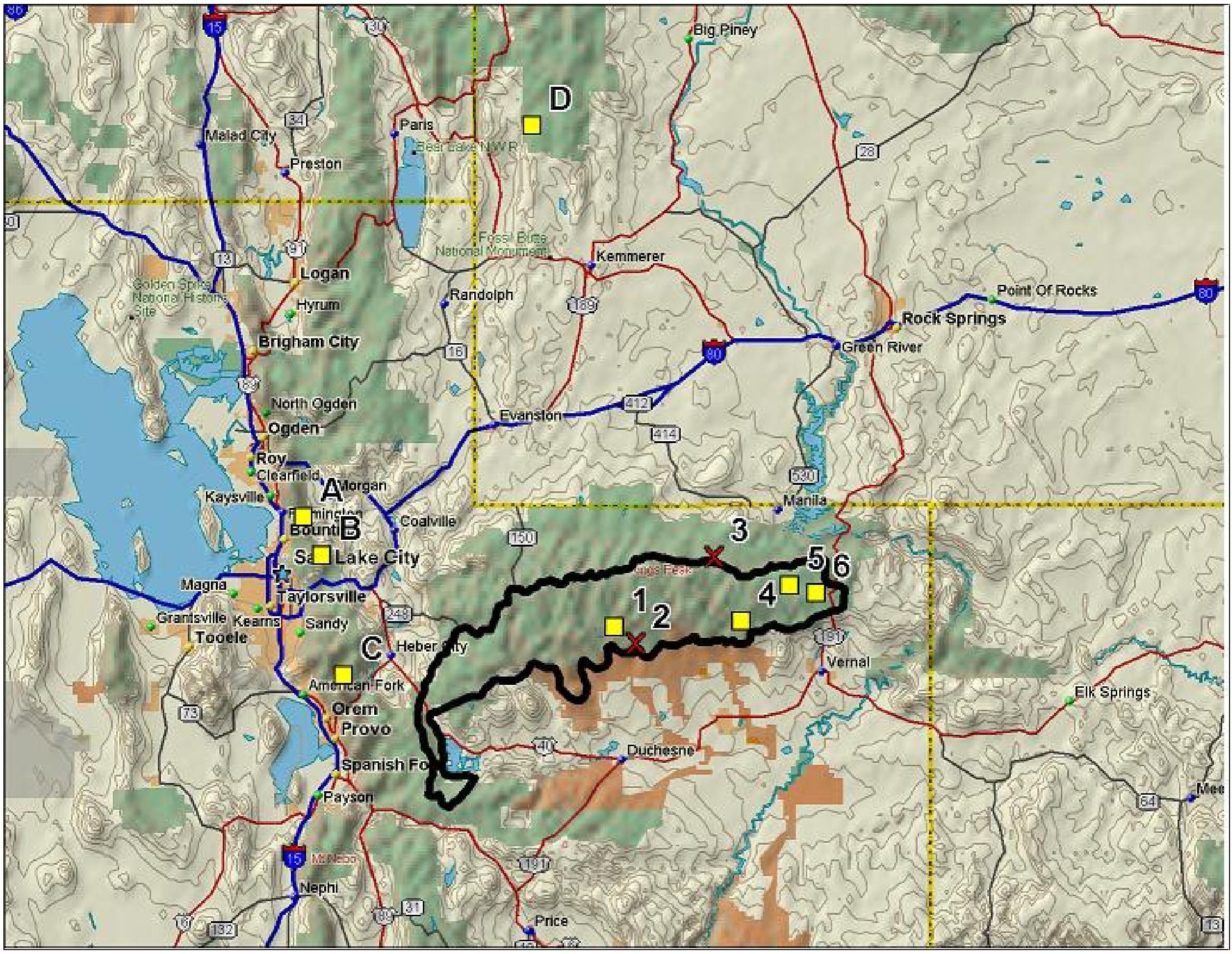


Figure 5.3 **Target sites (numbered) and control area snow sites (letters); squares are SNOTEL sites, and X's are snowcourses**

Due to the challenges involved in the target/control analyses for this program, including concern over short historical periods, a snow water content regression (linear and multiple linear) using fewer sites but a much longer historical regression period of 46 years was also conducted.

5.3.3 Streamflow Target and Control sites

NAWC has investigated numerous target/control type evaluation techniques, as well as multiple variations of existing techniques, in an attempt to provide the client with a reasonable estimate of precipitation increases resulting from the seeding program. One of these techniques is an evaluation based on March – July streamflow, utilizing several control sites that had essentially unregulated streamflow records. Three suitable control sites were located in western Wyoming, and two sites were similarly located in northwestern Colorado. Three suitable (unregulated) streamflow gauges were used to represent target area runoff (Yellowstone, Lake Fork and Ashley Creek drainages). Streamflow data at these sites have longer periods of record than SNOTEL snow and precipitation data, yielding a longer historical base period. The sites utilized in these streamflow comparisons have data back to at least 1964, allowing a 30 year base period to be established for the period prior to the beginning of the South Slope seeding program (certain years were excluded from the base period due to a historical seeding program affecting western Wyoming). There were two separate regions with unregulated streamflow gauges that were judged to be suitable for controls. One of these groups is in western Wyoming. Examination of the correlation between these and the target area sites, along with examination of double-mass plots, an engineering tool used to examine the consistency of an historical paired data set, resulted in three of these Wyoming gauges being selected as controls. Similarly, two control sites were selected from an available set in northwestern Colorado, which are unlikely to be affected by current or historical seeding programs. These sites are listed in Table 5-3, and shown on the map in Figure 5.4.

Table 5-3 Control and Target Streamflow Gauges
(Data obtained from the USGS website)

Group ID	Site Name	USGS Site Number	Latitude (N)	Longitude (W)
Control	**Wyoming and Colorado**			
A	Hams Fork, WY	09223000	42°07’	110°42’
B	Smiths Fork, WY	10032000	42°03’	110°24’
C	Fontenelle Creek, WY	09210500	42°06’	110°25’
D	Little Snake River, CO	09260000	40°33’	108°25’
E	White River near Meeker, CO	09304500	40°02’	107°51’
Target	**Utah**			
1	Lake Fork above Moon Lake	09289500	40°36’	110°32’
2	Yellowstone River	09292500	40°31’	110°20’
3	Ashley Creek	09266500	40°35’	109°37’

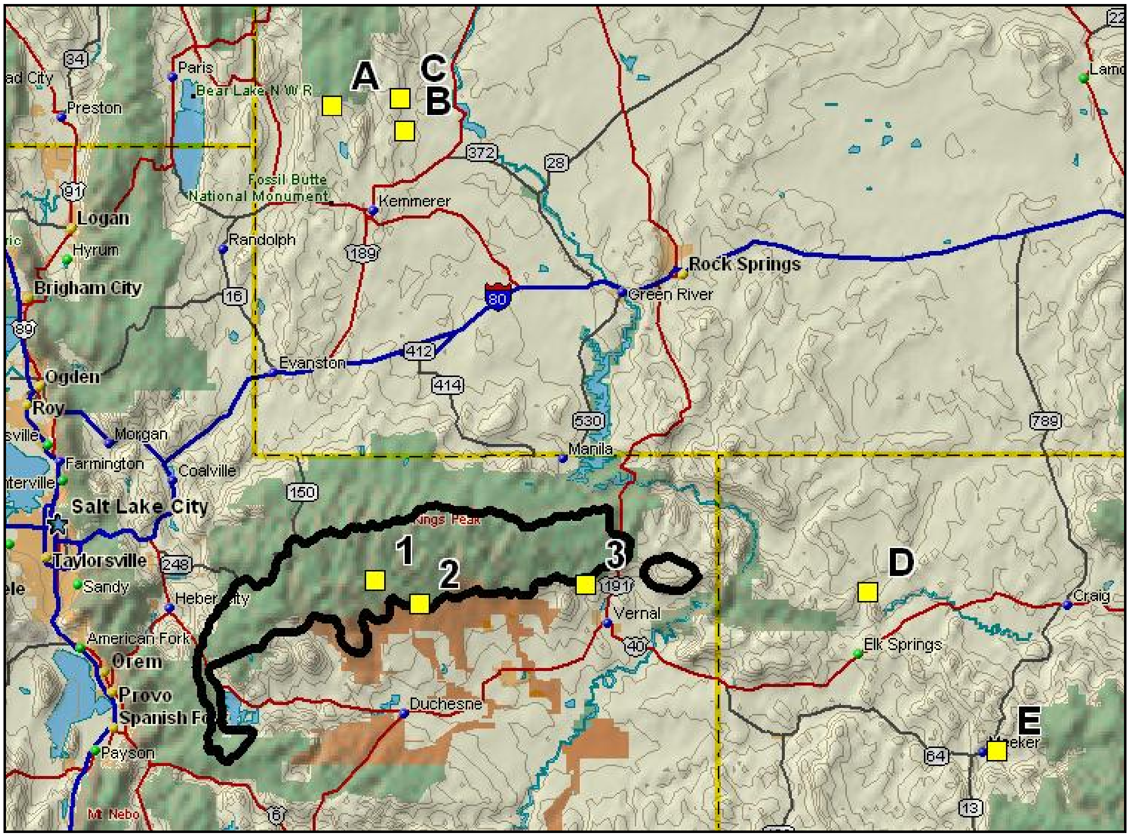


Figure 5.4 High Uintas streamflow target and control gauges

Over the years, several evaluation methods have been applied to the precipitation, snowpack and streamflow data. The results of the various evaluations are summarized in the following sub-sections, and Appendix B contains more detailed information for some of these evaluations.

5.3.4 Development of Regression Equations for the Target and Control Sets

NAWC compared various methods of analyzing the data, including the linear and multiple linear regression methods which have been used with this and similar programs. The target and control site historical (non-seeded) data for precipitation, snowpack, and streamflow were used to develop regression equations that describe the relationship between the control and target areas in the absence of cloud seeding. In the precipitation evaluation, for example, the monthly precipitation values were totaled at each gauge in the control and target areas for the December-April periods in each of the historical (not seeded) water years from 1980 - 1988, 1994, and 1996-2000, for a total of 15 seasons. The reasons for the short historical period are a) a lack of consistent precipitation measurements prior to the advent of the SNOTEL observations and b) the necessity of excluding winter seasons in which there were some seeding activities conducted in upwind areas that may have impacted precipitation in the High Uintas target area (e.g., projects in the western Uintas or the Wasatch Front area). Averages for each group were obtained, and predictor equations developed from these data for a five-month period (December through April). Appendix B contains details regarding some of the historical regression relationships that have been developed and applied to the seeded seasons.

Development of snowpack and streamflow regressions was similar. The snowpack analyses were based on snow water equivalent amounts measured on April 1 (using both the SNOTEL and snow course measurements). April 1 is important because it approximates the total seasonal snowpack accumulation fairly well in many areas, usually before significant melting begins. Also, many water supply forecasts are based on April 1 snow water content. The streamflow analysis utilized total streamflow (in acre-feet) during the March – July period. This period has been found to be one of the best correlated with winter season precipitation. April – July streamflow can be used for this as well, although the runoff can begin during March in some seasons, especially areas on a southerly exposure such as the southern slopes of the Uintas. The primary snowpack regression used for this program was based on only 13 historical seasons (water years 1975 – 1987), although an alternate snowpack regression that was also developed utilized long-term historical data available at only a small number of sites to produce a 46-year historical period. The streamflow regression was based on a fairly long historical period of 30 seasons. These include water years 1966, 1971-79, and 1983-2002. The historical regression periods were selected on the basis of data availability and avoidance of seasons where historical seeding programs would have directly impacted some or all of the control sites.

Multiple regression analyses relate each control site individually to the average of the target area sites, and these were conducted as well. This multiple regression analysis method was used because it provides a higher correlation between control and target sites, which can yield a better estimate of seeding effects if there is sufficient historical (non-seeded) data for a meaningful regression equation to be established using this method. For the precipitation and snowpack evaluations, a relatively short historical period makes this type of analysis somewhat questionable since the number of independent variables (control sites) in the equation becomes relatively large in comparison to seasons in the historical period. The results of the multiple regression analysis (for precipitation and snowpack) were still considered, but for this program the multiple regression method is better suited to the streamflow data set which has a much longer historical period.

5.4 Evaluation Results

Precipitation evaluation results have been examined for a period of 17 seeded seasons (2003-2019 water years). The seeded period used in one snowpack evaluation (with more sites but a short historical period) excludes the water year 2004, 2007, 2012, and 2015 seasons due to early melting in those years, and so includes only 13 seasons. The other long-term snowpack evaluation (few sites but 46 historical seasons) excludes these same seeded seasons due to early snow melt. This evaluation originally had three control sites but one snow course (White River #3) appears to have been discontinued in 2016 so the regression equation was re-established without this site. The streamflow evaluation currently has data available through 2018 for the March – July seasonal period, and so includes the 2003-2018 water years, for a total of 16 seasons.

The evaluation techniques as described yield an estimation of the observed/predicted amount of precipitation, snow water content, or streamflow for an individual season. Individual season results are included in the tables in Appendix B, in the “RATIO” column for the seeded seasons. Results for the 2018-2019 season are discussed below Table 5-4. A ratio of 1.05, for example, would suggest a 5% increase over the natural precipitation, snowpack, or streamflow

Table 5-4
Summary of High Uintas Evaluation Results

Evaluation Type	Method	Historical Years	Seeded Years	Correlation (R-value)	Resultant Ratio
Dec – Apr Precipitation	Linear Regression	15	17	0.86	**0.96**
Dec – Apr Precipitation	Multiple Linear	15	17	0.92	**0.95**
April 1 Snow Water Content	Linear Regression	13	13*	0.81	**0.93**
April 1 Snow Water Content	Multiple Linear	13	13*	0.94	**1.03**
April 1 Snow Water Content	Linear Regression	46	13*	0.84	**0.99**
April 1 Snow Water Content	Multiple Linear	46	13*	0.86	**1.05**
March – July Streamflow… 5 control 3 target	Linear Regression	30	16**	0.75	**0.96**
March – July Streamflow… 5 control 3 target	Multiple Linear	30	16**	0.79	**0.92**
March – July Streamflow… 3 control 3 target	Linear Regression	30	16**	0.61	**0.93**
March – July Streamflow… 3 control 3 target	Multiple Linear	30	16**	0.63	**0.91**

* Snowpack result excludes 2004, 2007, 2012, and 2015 due to early snow melt
** Streamflow evaluation includes seeded year data up through 2018, as the full March – July streamflow data for the current season is not yet available

predicted for the target area based on the historical regression equation. A ratio at or below 1.0 is not indicative of an increase over the natural precipitation or snowfall. An increase for an individual seeded season or combination of seeded seasons could be attributed to seeding effects. However, it is important to exercise caution in interpreting single-season statistical indications, since the natural variability of weather patterns between control and target areas will often outweigh the effects of seeding in a given year. This natural variability can result in a false or exaggerated positive indication, or in a low ratio (lack of indicated effects) when seeded effects were actually present. The strength of this type of evaluation is in multi-season indications over many seeded years.

Overall, indications from the various evaluation methodologies (linear regression and multiple linear regression) were mixed. Appendix B contains detailed evaluation results. Recall that a ratio greater than 1.0 is suggestive of a positive seeding effect. Overall, a majority of these observed/predicted ratios were in the 0.95 - 1.06 range, particularly for the evaluations that exhibit more stable mathematical characteristics (i.e. evaluations of December – April precipitation). Correlation (expressed as R-values) was generally highest for the precipitation evaluations, somewhat lower for the snowpack evaluations, and lowest for the various streamflow evaluations. Relatively low correlations (R values of much less than 1.0) indicate that there is considerable natural variability between the control and target areas, which for the South Slope of the Uintas target area is essentially unavoidable given its uniqueness in terms of meteorology, climatology and barrier orientation. Development and performance of the regression equations are greatly affected by the duration of the historic period; longer base periods are highly desirable. Because of this factor, NAWC included a long-term snowpack evaluation, as mentioned earlier, using a base period of 46 seasons and a limited number of target/control sites with long records, sites that are likely to be unaffected by surrounding seeding programs. The results of this evaluation (ratios of 0.98 for the linear and 1.04 for the multiple linear, for the average of the seeded seasons) are similar to most of the other evaluation results for the High Uintas seeding program. Snowpack evaluations were not meaningful for the 2004, 2007, 2012 and 2015 seasons due to substantial early snowmelt and those seasons were excluded from the snowpack evaluation results.

It is important to recall that, for the High Uintas program, there are a number of factors that make a meaningful analysis of the seeding effects difficult. These include the following: a) a relatively small number of seeded seasons, b) high seasonal variability between control and target areas, c) generally short historical periods without seeding from which regression equations can be developed, d) potential impacts on the historical regression equations from other NAWC winter seeding programs, e) sensitivity to early snowmelt issues at south-slope locations, and f) the possible long-term reduction of precipitation in the target area due to pollution as documented for precipitation sites slightly west of the High Uintas target area (Griffith, et al, 2005). Items b) and d) above are described more fully in sections below.

Seasonal Variability, Related to Storm Track and Barrier Orientation (item b)

From a meteorological standpoint, there are several possible reasons why target area precipitation was comparatively low on average during the seeding seasons compared to that observed in various control areas. The El Nino/La Nina phase and various other factors can affect the location and orientation of the primary storm track on a seasonal and multi-seasonal basis. This can lead to large (either negative or positive) precipitation anomalies in the High Uintas in comparison to the surrounding region, especially given the east-west orientation of the mountain barrier. Observations by NAWC during the seeded seasons, particularly over the last few seasons, have suggested that many of the major storm events in the region have been accompanied by a wind pattern moving essentially straight west to east, i.e., basically barrier-parallel. Although this type of pattern can present reasonable seeding opportunity for the target area, the base (natural) amount of precipitation falling in the High Uintas with this type of flow pattern is low compared to surrounding areas. This is because the predominantly north-south oriented mountain barriers in the intermountain region produce strong orographic (terrain-induced) lift in westerly air flow situations, while the west-east oriented Uinta Range produces minimal lift in those situations. The result is a minimal orographic component of the precipitation in the Uintas during periods of westerly flow. Given that the orographic component of precipitation is high in the mountains of Utah, approaching 75% of the winter precipitation in many areas, a persistent wind pattern that is even slightly anomalous can lead to a negative precipitation anomaly that may more than offset the actual seeding effects. In addition, there are indications that large, closed-circulation storm systems (so-called cutoff lows) during the spring, which climatologically contribute a substantial amount of snowfall over the Uinta Range particularly during the month of April, were relatively lacking during the seeded seasons. The effect of that sort of natural variation, again, can easily mask or outweigh the positive seeding effects obtained via the seeding program. Of course, precipitation increases obtained by cloud seeding would help to at least partially offset such negative anomalies.

Contamination by Other Seeding Projects (item d)

Other seeding programs being conducted in Utah may be impacting the apparent effects of seeding in the High Uintas. For example, the programs conducted in Tooele County and Box Elder County (which included seeding in both western and eastern portions of the county last winter) may be increasing the precipitation at some of the northern control sites (e.g., Farmington Canyon) and seeding in Juab and Sanpete Counties could be increasing precipitation at some of the southern control sites (e.g., Timpanogos Divide and Heber). Some of the Uinta program SNOTEL sites are within approximately 50 miles downwind of other seeding programs. Solak et al (2003) reported that precipitation appears to have been increased at similar downwind distances due to the cloud seeding program being conducted in central and southern Utah, with similar results in subsequent analyses up through 2018. For the High Uintas precipitation evaluation, 15 historical seasons were selected which exclude Water Years 1989 through 2002 since a number of seeding programs began in WY 1988 or 1989 in northern Utah, especially along the Wasatch Range west (upwind) of the Uintas. These seasons were excluded from the historical period due to potential contamination effects. Similar exclusions resulted in a 13-year historical data set for the snowpack evaluation, while the streamflow evaluation had a different set of historical seasons (during the 1970s and early 1980s) excluded because of the Bear River seeding program affecting portions western Wyoming where some of the streamflow control sites are located.

In order to illustrate the potential effects of contamination, assume that the average precipitation at the control sites was increased by 5%. This would also raise the predicted target area precipitation by 5%. **If** this were the case, it would cause a similar 5% precipitation increase in the High Uintas target area to be undetected in a more basic mathematical analysis. A final (and very important) consideration in the estimation of seeding effects for this program pertains to the results obtained from numerous similar programs in Utah and elsewhere in the western U.S. While each program is unique, evaluation results from most of these programs have ranged from approximately 5-10% increases over the estimated natural seasonal precipitation.

The Bottom Line

With consideration given to the meteorology and physiography of the Uintas, the range of results of various evaluations of seeding effects, the peculiarities of the seeded period, and results of similar programs, our best estimate is that the High Uintas seeding program has increased the project target area precipitation by approximately 3-5% on average during the seeded periods. Table 4-4 summarizes the results of the various evaluations conducted to date for the High Uintas program. More details regarding these evaluations are shown in Appendix B.

6.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

This was the 17th consecutive season of winter cloud seeding activities for the High Uintas using the current project design. Some limited seeding had previously been conducted in the area in 1977 and 1989 in response to drought conditions. In the current design, the areas targeted for seeding include the south slope river drainages of the Uinta Mountains above 8000 feet located in Duchesne and Uintah Counties. The seeding program utilizes a network of 20 manually operated, ground-based silver iodide generators. The design of this project is based on a feasibility assessment completed by NAWC and the State of Utah, Division of Water Resources in August 2002. NAWC project meteorologists monitor each winter storm as it passes through Utah and, if the storm satisfies NAWC's seedability criteria and no suspensions are in effect, appropriate cloud seeding generators are activated. The goal of the winter cloud seeding program is to augment wintertime precipitation and snowpack over the seeded watersheds.

The 2018-2019 cloud seeding program for the High Uintas was contractually scheduled to run from December 1, 2018 through April 30, 2019, with an extension period from November 1-30, 2018 that was funded by the Lower Basin States. A total of 28 storm periods were seeded during the entire operations period (November 1 – April 30), with six seeded storm events during the extension period in November. Altogether, there were six seeded storms were seeded in November, four additional storms in December (in addition to the event ending on December 1), six in January, four in February, six in March, and two in April. A cumulative 1,648.5 hours of ground seeding generator operations were conducted during the regular season, and an additional 312.25 hours during the extension period, for a total of 1,960.75 hours. There was a seeded suspension beginning on April 9 for the areas surrounding Strawberry Reservoir in the southwestern portion of the program, due to several SNOTEL sites that exceeded about 200% of the median snow water content beginning around that time. Details regarding seeding suspensions, storm dates and seeding generator usage are presented in Section 4.

Precipitation/snowfall was above average nearly region-wide during the season. As of April 1, 2019, SNOTEL observations for the Natural Resource Conservation Service showed snow water content averaging about 148% of normal (median) for the Duchesne Basin and about 105% of normal for sites in the Green River Basin portion of the Uintah Range. Water year precipitation percentages were 135% of normal (mean) for the Duchesne Basin and around 112% of normal for sites in the Green River Basin. By the end of the project (May 1), median snowpack percentages had increased to 159% for the Duchesne Basin and 123% for the Green River Basin. Water year to date percentages (of the mean) also remained high on May 1, 133% for the Duchesne Basin and 117% for the Green River Basin.

Estimates of the effectiveness of the cloud seeding program were attempted for the combined total of the seeded seasons. Various evaluations using linear regression, multiple linear regression, and double ratio methods were applied to December-April precipitation, April 1 snowpack, and March – July streamflow. There methodologies are described in Section 5 of the report.

For the High Uintas target area, there are a number of factors that make a meaningful analysis of the seeding effects difficult. These include a) a relatively small number of seeded seasons, b) high seasonal variability between control and target areas due to factors such as seasonal storm tracks and east-west orientation of the Uinta Range, c) short historical periods without seeding, from which regression equations were developed for the precipitation and snowpack evaluations, d) potential impacts on the historical regression equations of increases in control area precipitation due to the operation of other NAWC winter seeding programs (which would cause an underestimate of seeding effects in the High Uintas), e) sensitivity to early snowmelt issues at south-slope locations, and f) the possible long-term reduction of precipitation in the target area due to pollution as documented for precipitation sites slightly west of the High Uintas target area (Griffith, et al, 2005).

It is likely that the control sites selected for both the precipitation and snow water content analyses were again impacted by other seeding projects last winter (i.e., Eastern Tooele County, Box Elder County, Cache County, Juab County and Sanpete County). Assuming that the effect was to increase the precipitation or snow water content at some of these control sites, the regression equations used in the High Uintas Project evaluation would over-predict the amount of natural precipitation and snow water content in the target area. The net result would be an underestimate of the actual effects of seeding in the target area. Unfortunately, due to the fact that most of the mountainous areas of Utah have been seeded in recent years, there are few reasonably-well correlated precipitation measurement sites available that are likely not affected by seeding.

Indications from the various evaluation methodologies are mixed. Resulting observed/predicted ratios for the seeded seasons, which are potentially indicative of the effects of seeding, were under 1.0 for some of these evaluations, although some of the many variations NAWC examined (especially when comparing specific target and control sites) yielded ratios greater than 1.0. Recall that a ratio greater than 1.0 is potentially indicative of a positive seeding effect. Overall, a majority of these observed/predicted ratios are in the 0.95 - 1.05 range, particularly for evaluations that exhibit better target/control correlations as measured by R-values in the regression equations. R-values were generally highest (around 0.86) for the precipitation evaluations, around 0.81 - 0.83 for the snowpack evaluations, mostly in the 0.61 to 0.75 range for the various streamflow evaluations. Relatively low correlations (R-values of much less than 1.0) indicate that there is a large amount of natural variability between the control and target areas, which for the High Uintas target area is essentially unavoidable given its uniqueness in terms of meteorology, climatology and barrier orientation.

Section 4.4 contains a more detailed summary of the various evaluation techniques that were utilized, and Appendix B contains tables of results from many of these evaluations. The "RATIO" column in these tables, for the seeded seasons, contains observed/predicted ratios pertaining both to individual seasons as well as to the seeded period as a whole (highlighted in bold). **With consideration given to the meteorology of the Uintas and results of similar programs, our best estimate is that the High Uintas seeding program has increased the natural precipitation by approximately 3-5% on average during the seeded seasons.**

A feasibility study completed in August 2002 included an analysis of the estimated increases in annual streamflow in the Uinta Basin produced by an assumed 10% increase in April 1st snow water content. This estimate was approximately 64,000 acre-feet of water. **If a 5% increase is used in the calculations instead, the estimated increase in the average annual streamflow in the Uinta Basin due to the cloud seeding project would be 36,190 acre feet. Dividing that amount by the cost of the program would yield an estimated cost of approximately $2.50 per acre-foot for the additional streamflow.**

No attempt was made to evaluate the effects of seeding specific to the seeding period extension (November 1-30, 2015) separately. That extension was made possible through funding provided by the three Lower Colorado River Basin States. NAWC's experience has been that analyses of such short time periods provide lower correlations than in seasonal evaluations (e.g., the five-month period used by NAWC in the evaluation of this program) and is therefore even more difficult than evaluating entire seeded seasons.

One item of special note during the 2018-2019 season is a microwave radiometer that was sited in the Uinta Basin, in the town of Roosevelt. The operation of the Roosevelt radiometer allowed for a large data set of the atmospheric profile to be collected during the 2018-2019 winter season over the High Uintas target area. A very active weather pattern during the January through April time frame produced a number of storm periods where a threshold amount of 0.10 g/m^3 or greater of liquid water was detected by the radiometer. The analysis provided some insights into liquid water occurrence and seemed to correlate well with the Dry Ridge icing meter located nearby in the Uinta Range. For more information regarding the data and its associated analysis, please refer to Appendix C. Future funding from the Lower Basin States would likely allow for additional radiometer analyses to be conducted.

Conclusions

Assessment of seeding operations and evaluations of the effectiveness of the seeding efforts lead us to the following conclusions.

- The operational design of the seeding project and the array of ground-based seeding generators are appropriate for augmenting winter snowfall over the southern slope of the High Uintas.

- Available meteorological data are considered adequate for identification of storm periods that present favorable cloud seeding conditions. A specialized high elevation ice detector system, a helpful tool for seeding opportunity recognition, is located at Dry Ridge (elev. 11,450'), west of Moon Lake. The operation of the site and analysis of the collected data is funded by the Lower Colorado River Basin States. The site continues to provide data that are helpful in recognizing seeding opportunities.

- Given the area winter climatology, extension of the project seeding period made possible by funding support provided by the Lower Colorado River Basin States is of considerable value to the project.

- Due to a variety of factors, the ability to precisely quantify the effectiveness of the High Uinta seeding program is somewhat limited.

- The seeding operations are believed to be producing beneficial effects on precipitation within the intended target area. The magnitudes of the increases in precipitation and snowpack water content over the project's cumulative seeded winter seasons are estimated to be in the range of about 3% to 5%.

- Assuming a 5% increase of snow water content, the estimated resultant increase in average annual streamflow from the target area rivers and streams is a little over 36,000 AF.

- Factoring the cost of the seeding project and the estimated yield of enhanced streamflow indicates the cost of producing the additional surface water is about $2.50 per AF.

- If the value of the additional usable surface water is about $10 per AF, the benefit/cost ratio associated with the project is approximately 4.0/1.

Recommendations

It is recommended that the High Uintas cloud seeding program be continued, to provide additional water for the increasing water demands in the areas served by the drainage basins.

The precipitation (and snowpack) in Utah can often be subject to drought periods. Since such drought periods cannot be predicted with any degree of certainty and since many drainages in Utah could utilize additional water even in normal to above normal years, **we recommend that our clients consider conducting cloud seeding programs on a routine basis each year, as an integral part of their overall water management strategy**. This approach has proven to be very effective in southern and central Utah, where operational cloud seeding has been conducted since the 1970's, as well as in other parts of the western U.S. Provisions for suspension of the cloud seeding operations in very high water years or periods can be invoked as necessary.

This overall approach is recommended for several reasons:

- No one can accurately predict if precipitation during the coming winter season will be above or below normal. Having a cloud seeding program already operational will take advantage of each seeding opportunity.

- Seeding in normal to above normal water years will result in larger precipitation increases, which may provide additional carryover storage in surface reservoirs or underground aquifers that can be drawn from during dry years.

- The continuity of conducting cloud seeding programs each year can lead to planned budgets for such programs, avoiding the potential difficulties of attempting to obtain emergency funding in the midst of a drought situation.

- Conducting cloud seeding programs only after drought conditions are encountered may mean fewer cloud seeding opportunities and a late project start, leading to less additional precipitation being generated from cloud seeding program operations.

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APPENDIX A

UTAH WINTER CLOUD SEEDING SUSPENSION CRITERIA

Certain situations require temporary or longer-term suspension of cloud seeding activities, with reference to well-considered criteria for consideration of possible suspensions, to minimize either an actual or apparent contribution of seeding to a potentially hazardous situation. The ability to forecast (anticipate) and judiciously avoid hazardous conditions is very important in limiting any potential liability associated with weather modification and to maintain a desirable public image.

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

1. Excess snowpack accumulation
2. Rain-induced winter flooding
3. Severe weather

1. Excess Snowpack Accumulation

Snowpack begins to accumulate in the mountainous areas of Utah in November and continues through April. The heaviest average accumulations normally occur from January through March. Excessive snowpack water content becomes a potential hazard during the resultant snowmelt. The Natural Resources Conservation Service (NRCS) maintains a network of high elevation snowpack measurement sites in the State of Utah, known as the SNOTEL network. SNOTEL automated observations are now readily available, updated as often as hourly. The following set of criteria, based upon observations from these SNOTEL site observations, has been developed as a guide for potential suspension of operations.

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

Snowpack-related suspension considerations will be assessed on a geographical division or sub-division basis. The NRCS has divided the State of Utah into 13 such divisions as follows: Bear River, Weber-Ogden Rivers, Provo River-Utah Lake-Jordan River, Tooele Valley-Vernon Creek, Green River, Duchesne River, Price-San Rafael, Dirty Devil, South Eastern Utah, Sevier River, Beaver River, Escalante River, and Virgin River. 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.

Streamflow forecasts, reservoir storage levels, soil moisture content and amounts of precipitation in prior seasons are other factors which need to be considered when the potential for suspending seeding operations due to excess snowpack water content exists.

2. Rain-induced Winter Floods

The potential for wintertime flooding from rainfall on low elevation snowpack is fairly high in some (especially the more southern) target areas during the late winter/early spring period. Every precaution must be taken to insure accurate forecasting and timely suspension of operations during these potential flood-producing situations. The objective of suspension under these conditions is to eliminate both the real and/or perceived impact of weather modification when any increase in precipitation has the potential of creating a flood hazard.

3. Severe Weather

During periods of hazardous weather 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 and the attendant hazards. Each phenomenon is described in terms of criteria used by the NWS in issuing special weather bulletins. Those relevant in the conduct of winter cloud seeding programs include the following:

- **Snow Advisory** - This product is issued by the NWS when four to twelve inches of snow in 12 hours, or six to eighteen inches in 24 hours, are forecast to accumulate in mountainous regions above 7000 feet. Lower threshold criteria (in terms of the number of inches of snow) are issued for valleys and mountain valleys below 7000 feet.

- **Heavy Snow Warning** - This is issued by the NWS when it expects snow accumulations of twelve inches or more per 12-hour period or eighteen inches or more per 24-hour period in mountainous areas above 7000 feet. Lower criteria are used for valleys and mountain valleys below 7000 feet.

- **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 Warnings** - 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 are not limited to, fall or spring convective systems.

Seeding operations may be 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 (e.g., a heavy storm that impacts Christmas Eve travel).

Flash Flood Warnings are usually issued when intense convective activity causing heavy rainfall is expected or is occurring. Although the probability of this situation occurring during our core operational seeding periods is low, the potential does exist, especially over southern sections of the state during late March and early April, which can include the project spring extension period. The type of storm that may cause problems is one that has the potential of producing 1-2 inches (or greater) of rainfall in approximately a 24-hour period, combined with high freezing levels (e.g., > 8,000 feet MSL). Seeding operations will be suspended for the duration of the warning period in the affected areas.

NAWC's project meteorologists have the authority to temporarily suspend localized seeding operations due to development of hazardous severe weather conditions even if the NWS has not issued a warning. This would be a rare event, but it is important for the operator to have this latitude.

APPENDIX B

PRECIPITATION, SNOWPACK AND STREAMFLOW EVALUATION DATA AND RESULTS

Summary of High Uintas Evaluation Results

Evaluation Type	Method	Historical Years	Seeded Years	Correlation (R-value)	**Resultant Ratio**
Dec – Apr Precipitation	Linear Regression	15	17	0.86	**0.96**
Dec – Apr Precipitation	Multiple Linear	15	17	0.92	**0.95**
Dec – Apr Precipitation	Double Ratio	15	17	NA	**0.97**
April 1 Snow Water Content	Linear Regression	13	13*	0.81	**0.93**
April 1 Snow Water Content	Multiple Linear	13	13*	0.94	**1.03**
April 1 Snow Water Content	Double Ratio	13	13*	NA	**0.93**
April 1 Snow Water Content	Linear Regression	46	13*	0.83	**0.99**
April 1 Snow Water Content	Multiple Linear	46	13*	0.86	**1.05**
April 1 Snow Water Content	Double Ratio	46	13*	NA	**0.99**
March – July Streamflow… 5 control 3 target	Linear Regression	30	16**	0.75	**0.96**
March – July Streamflow… 5 control 3 target	Multiple Linear	30	16**	0.79	**0.92**
March – July Streamflow… 5 control 3 target	Double Ratio	30	16**	NA	**1.00**
March – July Streamflow… 3 control 3 target	Linear Regression	30	16**	0.61	**0.93**
March – July Streamflow… 3 control 3 target	Multiple Linear	30	16**	0.63	**0.91**
March – July Streamflow… 3 control 3 target	Double Ratio	30	16**	NA	**0.96**

* Snowpack result excludes 2004, 2007, 2012, and 2015 due to early snow melt

** Streamflow evaluation includes seeded year data up through 2018, as the full March – July streamflow data for the current season is not yet available

DETAILED EVALUATION DATA AND RESULTS

High Uintas December – April Precipitation, Linear Regression

Regression (non-seeded) period:

Water Year	Control Avg	Target Avg
1980	18.72	17.28
1981	11.03	9.75
1982	21.05	15.50
1983	16.37	13.12
1984	16.62	11.72
1985	10.70	11.50
1986	19.81	16.13
1987	7.85	9.78
1988	8.81	9.33
1994	12.22	10.95
1996	16.21	14.15
1997	18.09	16.83
1998	17.68	14.43
1999	14.03	15.32
2000	13.93	13.63
Mean	14.87	13.30

Seeded period:

Water Year	Control Avg	Target Avg	Predicted	Ratio	Increase
1989*	12.17	11.05	11.77	0.94	-0.72
1990*	10.68	13.47	10.92	1.23	2.54
1991*	12.21	11.62	11.79	0.99	-0.17
1992*	6.25	7.15	8.42	0.85	-1.27
1993*	15.77	16.45	13.80	1.19	2.65
1995*	15.80	15.15	13.82	1.10	1.33
2001*	12.27	13.93	11.83	1.18	2.11
2002*	11.15	7.83	11.19	0.70	-3.36
2003	9.32	9.40	10.16	0.93	-0.76
2004	13.84	12.15	12.71	0.96	-0.56
2005	18.91	17.20	15.57	1.10	1.63
2006	19.23	14.73	15.76	0.93	-1.02
2007	9.42	8.45	10.22	0.83	-1.77
2008	15.29	13.22	13.53	0.98	-0.31
2009	17.46	13.67	14.76	0.93	-1.09
2010	13.15	12.08	12.32	0.98	-0.24
2011	21.95	17.23	17.29	1.00	-0.06
2012	9.48	8.23	10.25	0.80	-2.02
2013	9.84	10.68	10.45	1.02	0.23

Water Year	**Control Avg**	**Target Avg**	**Predicted**	**Ratio**	**Increase**
2014	11.57	9.83	11.43	0.86	-1.60
2015	8.56	7.20	9.73	0.74	-2.53
2016	14.27	12.27	12.95	0.95	-0.69
2017	23.26	20.63	18.03	1.14	2.60
2019	19.35	16.17	15.82	1.02	0.35
Mean	**14.39**	**12.45**	**13.02**	**0.96**	**-0.57**

* Seeding conducted in nearby areas but not in target area

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.858476
R Square	0.736981
Adjusted R Square	0.716749
Standard Error	1.417657
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	73.20731	73.20731	36.42607	4.2E-05
Residual	13	26.12676	2.009751		
Total	14	99.33406			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	4.895582	1.439077	3.40189	0.004725	1.786645
X Variable 1	0.564797	0.093581	6.035401	4.2E-05	0.362628

High Uintas December – April Precipitation, Multiple Linear Regression

Regression (non-seeded) period:

Water Yr	Timp Div	Farm Cyn	Jensen	Font Dam	Target avg
1980	30.4	37.9	4.0	2.6	17.3
1981	18.3	21.0	2.8	2.1	9.8
1982	34.6	45.3	2.5	1.8	15.5
1983	22.5	36.6	3.5	2.8	13.1
1984	20.6	40.8	2.5	2.6	11.7
1985	18.9	19.6	3.4	0.9	11.5
1986	30.5	41.9	3.8	3.1	16.1
1987	10.6	16.8	2.4	1.6	9.8
1988	11.8	18.8	3.2	1.4	9.3
1994	18.8	27.2	1.7	1.2	11.0
1996	24.6	35.9	2.3	2.0	14.2
1997	28.0	37.6	4.0	2.7	16.8
1998	24.8	39.3	3.6	3.1	14.4
1999	18.9	30.1	3.8	3.4	15.3
2000	20.4	31.2	2.9	1.3	13.6
Mean	**22.2**	**32.0**	**3.1**	**2.2**	**13.3**

Seeded period:

Water Year	Timp Div	Farm Cyn	Jensen	Font Dam	Target avg	Predicted	Ratio	Increase
1989*	17.7	28.5	1.6	0.9	11.1	10.1	1.10	1.0
1990*	20.8	18.3	2.6	1.0	13.5	11.4	1.18	2.0
1991*	17.2	26.7	3.2	1.7	11.6	12.0	0.97	-0.4
1992*	9.2	13.0	1.8	1.0	7.2	7.6	0.94	-0.5
1993*	25.3	29.9	5.7	2.2	16.5	17.0	0.97	-0.6
1995*	25.3	32.2	2.9	2.8	15.2	13.9	1.09	1.2
2001*	16.9	28.1	2.1	2.0	13.9	10.7	1.30	3.2
2002*	13.3	28.2	1.2	1.9	7.8	8.7	0.90	-0.9
2003	11.0	21.8	2.7	1.8	9.4	9.7	0.97	-0.3
2004	17.6	32.0	2.3	3.4	12.2	11.6	1.05	0.6
2005	33.1	34.4	4.0	4.1	17.2	17.3	0.99	-0.1
2006	29.3	43.6	2.2	1.8	14.7	14.4	1.02	0.4
2007	12.8	20.8	2.8	1.3	8.5	10.1	0.83	-1.7
2008	21.4	33.5	4.6	1.6	13.2	15.0	0.88	-1.8
2009	25.7	38.1	4.4	1.7	13.7	15.9	0.86	-2.2
2010	21.5	25.0	3.9	2.2	12.1	13.8	0.88	-1.7
2011	36.0	45.5	4.4	1.8	17.2	18.7	0.92	-1.4

Water Year	Timp Div	Farm Cyn	Jensen	Font Dam	Target avg	Predicted	Ratio	Increase
2012	16.1	20.0	1.2	0.7	8.2	8.7	0.95	-0.5
2013	12.4	22.7	3.2	1.1	10.7	10.5	1.02	0.2
2014	16.3	25.6	2.5	1.8	9.8	10.9	0.90	-1.1
2015	11.4	19.9	1.7	1.3	7.2	8.4	0.86	-1.2
2016	20.4	30.8	2.9	3.0	12.3	12.7	0.96	-0.5
2017	37.9	44.5	3.8	6.8	20.6	19.2	1.07	1.4
2018	15.6	20.9	1.2	1.0	8.5	8.8	0.97	-0.2
2019	31.0	37.8	4.9	3.6	16.2	18.1	0.89	-1.9
Mean	21.7	30.4	3.1	2.3	12.5	13.2	**0.95**	**-0.7**

* Seeding conducted in nearby areas but not in target area

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.92059
R Square	0.84749
Adjusted R Square	0.78649
Standard Error	1.23083
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	84.18464	21.046	13.8924	0.0004
Residual	10	15.14942	1.5149		
Total	14	99.33406			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	2.50414	1.804771	1.3875	0.19543	-1.5171	6.5254	-1.517	6.525418
X Variable 1	0.22402	0.122163	1.8338	0.09658	-0.0482	0.4962	-0.048	0.496214
X Variable 2	0.05192	0.101297	0.5126	0.61938	-0.1738	0.2776	-0.174	0.277624
X Variable 3	1.21646	0.702718	1.7311	0.11412	-0.3493	2.7822	-0.349	2.782211
X Variable 4	0.186	0.78296	0.2376	0.81702	-1.5585	1.9305	-1.559	1.930547

April 1 Snowpack, Linear Regression Based on 13 Historical Seasons

Regression (non-seeded) period:

Water Year	Control avg	Target avg
1975	29.6	9.9
1976	24.8	10.0
1977	10.2	3.6
1978	29.9	10.5
1979	28.6	14.6
1980	35.3	18.4
1981	16.2	9.5
1982	34.9	14.0
1983	31.9	17.0
1984	27.8	12.2
1985	25.0	11.4
1986	35.1	14.3
1987	14.5	10.4
Mean	26.4	12.0

Seeded period:

Water Year	Control Avg	Target Avg	Predicted	Ratio	Increase
1989*	24.5	9.0	11.2	0.80	-2.3
1990*	18.6	10.6	9.0	1.18	1.6
1991*	19.9	10.1	9.5	1.06	0.6
1992*	13.8	8.4	7.2	1.16	1.2
1993*	29.2	14.6	13.0	1.12	1.6
1995*	28.7	15.2	12.8	1.19	2.4
2001*	16.6	10.2	8.3	1.23	1.9
2002*	21.2	6.8	10.0	0.68	-3.2
2003	17.0	9.4	8.4	1.11	1.0
2004**	24.6	7.9	11.3	0.70	-3.4
2005	37.0	20.5	15.9	1.29	4.6
2006	35.4	11.0	15.4	0.72	-4.3
2007**	16.7	6.5	8.3	0.79	-1.8
2008	27.4	11.9	12.3	0.97	-0.4
2009	28.5	7.7	12.7	0.60	-5.0
2010	17.2	9.4	8.5	1.11	0.9
2011	41.6	14.1	17.7	0.80	-3.6
2012**	16.1	5.9	8.1	0.73	-2.2
2013	17.4	7.0	8.6	0.81	-1.6

Water Year	Control Avg	Target Avg	Predicted	Ratio	Increase
2015**	12.6	2.3	6.8	0.34	-4.4
2016	21.7	10.1	10.2	0.99	-0.1
2017	32.0	14.8	14.1	1.05	0.7
2018	14.2	6.9	7.4	0.93	-0.5
2019	30.8	14.3	13.6	1.05	0.6
Mean	**26.4**	**11.1**	**12.0**	**0.93**	**-0.8**

* Seeding conducted in nearby areas but not in target area
** Not included in average due to very early and abnormal snow melt

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.807491
R Square	0.652042
Adjusted R Square	0.62041
Standard Error	2.344172
Observations	13

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	2.028078	2.285175	0.887493	0.393805	-3.00156
X Variable 1	0.376232	0.082868	4.540157	0.000844	0.193842

April 1 Snowpack, Multiple Linear Regression Based on 13 Historical Seasons

Regression (non-seeded) period:

Water Year	Timp Div	Farm Cyn	Lookout	Kelley RS	Target Avg
1975	31.6	40.6	25.8	20.5	9.9
1976	26.5	34.2	19.0	19.3	10.0
1977	7.9	17.6	8.8	6.5	3.6
1978	32.3	38.8	24.1	24.4	10.5
1979	33.2	38.7	24.8	17.7	14.6
1980	40.5	43.4	35.1	22.2	18.4
1981	18.3	24.0	13.5	8.9	9.5
1982	39.2	44.1	32.8	23.4	14.0
1983	36.6	43.5	29.9	17.6	17.0
1984	27.0	38.3	26.8	19.0	12.2
1985	25.1	34.3	26.7	13.9	11.4
1986	39.6	43.0	30.2	27.6	14.3
1987	11.6	20.1	16.9	9.3	10.4
Mean	**28.4**	**35.4**	**24.2**	**17.7**	**12.0**

Seeded period:

Water Year	Timp Div	Farm Cyn	Lookout	Kelley RS	Target Avg	Predicted	Ratio	Increase
1989*	19.3	36.5	25.3	16.8	9.0	7.4	1.21	1.5
1990*	21.7	23.7	16.4	12.4	10.6	11.5	0.93	-0.8
1991*	18.3	28.6	20.4	12.4	10.1	9.4	1.08	0.7
1992*	10.1	21.1	12.9	11.0	8.4	5.3	1.58	3.1
1993*	37.1	35.1	27.0	17.7	14.6	17.9	0.82	-3.2
1995*	28.0	39.2	31.5	15.9	15.2	13.8	1.10	1.4
2001*	8.2	27.5	20.3	10.5	10.2	5.0	2.05	5.2
2002*	13.9	34.0	24.1	12.7	6.8	6.4	1.07	0.5
2003	10.7	23.2	20.3	13.8	9.4	6.8	1.39	2.6
2004**	16.7	40.9	28.2	12.7	7.9	6.9	1.14	1.0
2005	40.6	53.1	36.6	17.5	20.5	16.9	1.21	3.6
2006	26.3	53.2	41.7	20.5	11.0	10.2	1.08	0.8
2007**	10.3	24.0	19.4	13.0	6.5	6.2	1.05	0.3
2008	26.7	37.7	29.5	15.6	11.9	13.0	0.92	-1.1
2009	23.6	43.8	30.3	16.3	7.7	9.2	0.84	-1.5
2010	17.8	22.9	18.2	9.8	9.4	11.2	0.84	-1.8
2011	43.7	56.4	44.6	21.5	14.1	19.1	0.73	-5.1
2012**	12.9	20.8	17.8	12.7	5.9	8.2	0.71	-2.4

Water Year	Timp Div	Farm Cyn	Lookout	Kelley RS	Target Avg	Predicted	Ratio	Increase
2014	12.7	31.7	28.2	19.1	7.5	6.0	1.25	1.5
2015**	4.8	20.0	14.1	11.5	2.3	3.2	0.74	-0.8
2016	16.5	30.4	25.4	14.2	10.1	9.1	1.11	1.0
2017	29.2	39.8	33.9	25.0	14.8	12.1	1.22	2.7
2018	8.8	19.6	15.2	13.2	6.9	5.3	1.29	1.6
2019	32.5	41.0	35.0	14.8	14.3	17.3	0.82	-3.0
Mean	**23.0**	**37.2**	**29.0**	**16.3**	**11.1**	**10.8**	**1.03**	**0.4**

* Seeding conducted in nearby areas but not in target area
** Not included in average due to very early and abnormal snow melt
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.93716
R Square	0.878269
Adjusted R Square	0.817404
Standard Error	1.625839
Observations	13

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	6.339979	3.026456	2.094853	0.069492	-0.63905	13.319	-0.63905	13.319
Timp Div	0.536956	0.221169	2.427815	0.041343	0.02694	1.046972	0.02694	1.046972
Farm Cyn	-0.36777	0.264512	-1.39037	0.201875	-0.97774	0.242197	-0.97774	0.242197
Lookout	0.388727	0.169898	2.288	0.051425	-0.00306	0.780512	-0.00306	0.780512
Kelley RS	-0.33837	0.174272	-1.9416	0.088128	-0.74024	0.063505	-0.74024	0.063505

April 1 Snowpack, Linear Regression Based on 46 Historical Seasons

Regression (non-seeded) period:

Water Year	Control Avg	Target Avg
1957	25.85	7.97
1958	32.65	10.80
1959	18.20	7.90
1960	22.35	5.87
1961	16.30	5.20
1962	32.75	16.23
1963	17.80	5.67
1964	20.40	5.27
1965	32.60	9.73
1966	21.75	9.10
1967	27.10	10.23
1968	27.70	10.60
1969	40.05	16.80
1970	24.15	8.07
1971	28.10	9.53
1972	28.25	7.60
1973	31.35	10.90
1974	24.40	5.03
1975	36.10	9.07
1976	30.35	8.93
1977	12.75	2.47
1978	35.55	9.87
1979	35.95	13.03
1980	41.95	17.67
1981	21.15	8.03
1982	41.65	12.50
1983	40.05	16.40
1984	32.65	11.50
1985	29.70	10.40
1986	41.30	12.53
1987	15.85	7.40
1988	13.40	5.27
1989	27.90	7.27
1990	22.70	8.60
1991	23.45	9.37
1992	15.60	7.07
1993	36.10	14.07
1994	21.90	7.70

Water Year	Control Avg	Target Avg
1996	28.05	8.03
1997	43.90	13.50
1998	33.35	10.10
1999	21.35	6.00
2000	28.60	10.33
2001	17.85	8.63
2002	23.95	5.93
Mean	**27.8**	**9.5**

Seeded period:

Water Year	Control Avg	Target Avg	Predicted	Ratio	Increase
2003	16.95	8.93	5.78	1.55	3.2
2004**	28.80	6.30	9.86	0.64	-3.6
2005	46.85	19.63	16.09	1.22	3.5
2006	39.75	10.33	13.64	0.76	-3.3
2007**	17.15	3.93	5.84	0.67	-1.9
2008	32.20	11.70	11.04	1.06	0.7
2009	33.70	6.67	11.55	0.58	-4.9
2010	20.35	8.07	6.95	1.16	1.1
2011	50.05	13.57	17.19	0.79	-3.6
2012**	16.85	3.87	5.74	0.67	-1.9
2013	20.20	6.10	6.90	0.88	-0.8
2014	22.20	6.47	7.59	0.85	-1.1
2015**	12.40	1.50	4.21	0.36	-2.7
2016	23.45	8.60	8.02	1.07	0.6
2017	34.50	13.77	11.83	1.16	1.9
2018	14.20	4.83	4.83	1.00	0.0
2019	36.75	13.57	12.60	1.08	1.0
Mean	**30.1**	**10.2**	**10.3**	**0.99**	**-0.1**

** Not included in average due to very early snow melt

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.836371208
R Square	0.699516797
Adjusted R Square	0.692687634
Standard Error	1.885329949
Observations	46

	Coefficients	*Standard Error*
Intercept	-0.07114187	0.987139943

X Variable 1	0.344927472	0.034081011

April 1 Snowpack, Multiple Linear Regression Based on 46 Historical Seasons

Water Year	Farmington Cyn	Timpanogos	Target Avg
1957	26.40	25.30	7.97
1958	33.90	31.40	10.80
1959	21.10	15.30	7.90
1960	25.40	19.30	5.87
1961	21.80	10.80	5.20
1962	35.40	30.10	16.23
1963	20.50	15.10	5.67
1964	23.90	16.90	5.27
1965	38.60	26.60	9.73
1966	22.10	21.40	9.10
1967	23.00	31.20	10.23
1968	30.50	24.90	10.60
1969	36.40	43.70	16.80
1970	30.30	18.00	8.07
1971	38.70	17.50	9.53
1972	37.60	18.90	7.60
1973	33.70	29.00	10.90
1974	30.90	17.90	5.03
1975	40.60	31.60	9.07
1976	34.20	26.50	8.93
1977	17.60	7.90	2.47
1978	38.80	32.30	9.87
1979	38.70	33.20	13.03
1980	43.40	40.50	17.67
1981	24.00	18.30	8.03
1982	44.10	39.20	12.50
1983	43.50	36.60	16.40
1984	38.30	27.00	11.50
1985	34.30	25.10	10.40
1986	43.00	39.60	12.53
1987	20.10	11.60	7.40
1988	16.10	10.70	5.27
1989	36.50	19.30	7.27
1990	23.70	21.70	8.60
1991	28.60	18.30	9.37
1992	21.10	10.10	7.07
1993	35.10	37.10	14.07
1994	25.70	18.10	7.70
1995	39.20	28.00	13.53

Water Year	Farmington Cyn	Timpanogos	Target Avg
1997	51.60	36.20	13.50
1998	43.50	23.20	10.10
1999	27.50	15.20	6.00
2000	39.20	18.00	10.33
2001	27.50	8.20	8.63
2002	34.00	13.90	5.93
Mean	**32.0**	**23.5**	**9.5**

Water Year	Farmington Cyn	Timpanogos	Target avg	Predicted	Ratio	Increase
2003	23.20	10.70	8.93	5.51	1.62	3.4
2004**	40.90	16.70	6.30	8.28	0.76	-2.0
2005	53.10	40.60	19.63	15.45	1.27	4.2
2006	53.20	26.30	10.33	11.65	0.89	-1.3
2007**	24.00	10.30	3.93	5.46	0.72	-1.5
2008	37.70	26.70	11.70	10.73	1.09	1.0
2009	43.80	23.60	6.67	10.31	0.65	-3.6
2010	22.90	17.80	8.07	7.38	1.09	0.7
2011	56.40	43.70	13.57	16.49	0.82	-2.9
2012**	20.80	12.90	3.87	5.94	0.65	-2.1
2013	30.70	9.70	6.10	5.74	1.06	0.4
2014	31.70	12.70	6.47	6.61	0.98	-0.1
2015**	20.00	4.80	1.50	3.73	0.40	-2.2
2016	30.40	16.50	8.60	7.53	1.14	1.1
2017	39.80	29.20	13.77	11.53	1.19	2.2
2018	19.60	8.80	4.83	4.77	1.01	0.1
2019	41.00	32.50	13.57	12.49	1.09	1.1
Mean	**37.2**	**23.0**	**10.2**	**9.7**	**1.05**	**0.5**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.859094313
R Square	0.738043039
Adjusted R Square	0.719331828
Standard Error	1.801747514
Observations	46

	Coefficients	*Standard Error*
Intercept	1.132749671	1.060535368
Farmington	0.066018713	0.045897051

Cyn		
Timpanogos	0.266315504	0.046335651

March – July Streamflow Linear Regression, with 5 Control and 3 Target Sites; units are in acre feet

Regression (non-seeded) Period:

Water Year	Control avg	Target Avg
1966	112936	49949
1971	261215	66992
1972	178150	59875
1973	193597	72462
1974	212877	43409
1975	197588	79701
1976	169736	48415
1977	44359	25649
1978	227917	53303
1979	191656	45339
1983	279948	96463
1984	331384	69498
1985	222233	57727
1986	276152	96943
1987	116536	64515
1988	139135	36566
1989	105895	32889
1990	89112	51965
1991	120377	54937
1992	81594	38662
1993	212713	78967
1994	83576	38992
1995	245111	105683
1996	189341	52819
1997	263786	76363
1998	215275	81533
1999	215124	75497
2000	120952	40342
2001	113842	62042
2002	58672	19379
Mean	**175693**	**59229**

Seeded Period:

Water Year	Control Avg	Target Avg	Predicted	Ratio	Increase
2003	123438	47931	47895	1.00	36
2004	90888	40375	40836	0.99	-460
2005	174888	101668	59055	1.72	42614
2006	152841	54263	54273	1.00	-10
2007	105346	33724	43971	0.77	-10248
2008	207348	45549	66095	0.69	-20546
2009	219964	54665	68831	0.79	-14166
2010	175017	51930	59082	0.88	-7152
2011	365025	103727	100293	1.03	3433
2012	79824	29931	38436	0.78	-8505
2013	80584	36523	38601	0.95	-2077
2014	177875	35639	59702	0.60	-24063
2015	149671	51525	53585	0.96	-2060
2016	178270	61738	59788	1.03	1950
2017	189133	83172	62144	1.34	21028
2018	94881	30575	41702	0.73	-11127
Seeded Mean	**160312**	**53934**	**55893**	**0.96**	**-1960**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.749069335
R Square	0.561104868
Adjusted R Square	0.545430042
Standard Error	14338.66364
Observations	30

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	21123.14391	6886.056	3.06752417	0.00475	7017.681
X Variable 1	0.216890053	0.036251	5.98302272	1.92E-06	0.142633

High Uintas March – July Streamflow Multiple Linear Regression, with 5 Control and 3 Target Sites; units are in acre feet

Regression (non-seeded) Period:

Water Year	Hams Fk	Fontenelle	Smiths Fk	Little Snake	White River	Target Avg
1966	44794	26481	69071	261819	162515	49949
1971	145432	70383	178721	590894	320645	66992
1972	103820	75862	158637	301634	250798	59875
1973	48082	29485	75594	476355	338467	72462
1974	80404	46964	127332	498440	311243	43409
1975	81706	45447	115301	396510	348975	79701
1976	75548	52151	120425	329104	271451	48415
1977	7077	7711	23732	85711	97566	25649
1978	93460	58383	142896	471055	373789	53303
1979	53667	33706	80654	396038	394214	45339
1983	102494	73684	153030	617221	453311	96463
1984	103004	56974	147686	809511	539744	69498
1985	49380	32445	86070	470868	472404	57727
1986	128700	95836	186880	499949	469394	96943
1987	36867	24696	51531	219782	249806	64515
1988	36184	24103	64874	298988	271525	36566
1989	46081	30952	84247	170223	197970	32889
1990	33395	23630	62426	171219	154892	51965
1991	44451	23899	77260	213547	242727	54937
1992	23469	10950	48549	140134	184870	38662
1993	69422	33656	122948	457750	379790	78967
1994	27123	17019	46243	176877	150618	38992
1995	57851	40953	106167	564912	455670	105683
1996	72113	40088	129123	364185	341195	52819
1997	91551	59499	165808	589422	412650	76363
1998	58520	41232	102936	458203	415485	81533
1999	80859	69012	137185	480812	307753	75497
2000	37484	23018	70236	244056	229966	40342
2001	20646	14235	44049	238488	251794	62042
2002	24183	18504	49405	93630	107637	19379
Mean	**62592**	**40032**	**100967**	**369578**	**305295**	**59229**

Seeded Period:

Water Year	Hams Fork	Fontenelle	Smiths Fork	Little Snake	White River	Target Avg	Predicted	Ratio	Increase
2003	26134	29925	57863	242638	260630	47931	57296	0.84	-9365
2004	30335	23304	60098	152754	187948	40375	43108	0.94	-2733

Water Year	Hams Fork	Fontenelle	Smiths Fork	Little Snake	White River	Target Avg	Predicted	Ratio	Increase
2005	76070	53163	113152	322611	309446	101668	63114	1.61	38554
2006	57043	43893	95628	235021	332619	54263	62867	0.86	-8604
2007	29811	19643	52585	215647	209043	33724	44970	0.75	-11247
2008	55706	33729	81623	512575	353108	45549	66147	0.69	-20598
2009	65884	41152	117741	542915	332130	54665	64093	0.85	-9428
2010	47569	34226	71247	470661	251381	51930	58728	0.88	-6797
2011	105799	82651	159392	943100	534183	103727	106706	0.97	-2980
2012	38298	23792	64335	134015	138679	29931	36367	0.82	-6436
2013	26722	17708	57232	121059	180197	36523	39053	0.94	-2529
2014	81110	53750	107247	324809	322459	35639	64300	0.55	-28661
2015	58245	39208	95950	237787	317166	51525	58174	0.89	-6649
2016	58245	34884	90428	420466	286091	61738	57181	1.08	4557
2017	58245	93600	183955	307629	237851	83172	79093	1.05	4079
2018	58245	32380	90296	142410	162616	30575	37738	0.81	-7163
Seeded Mean	**54999**	**41063**	**93673**	**332881**	**275972**	**53934**	**58601**	**0.92**	**-4667**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.788019316
R Square	0.620974442
Adjusted R Square	0.542010784
Standard Error	14392.49006
Observations	30

	Coefficients
Intercept	19093.5744
Hams Fork	-0.20489592
Fontenelle	0.648935056
Smiths Fork	-0.09760667
Little Snake	0.022804631
White River	0.093055464

High Uintas March – July Streamflow Linear Regression, with 3 Wyoming Control Sites and 3 Target Sites; units are in acre feet

Regression (non-seeded) Period:

Water Year	Control Avg	Target Avg
1966	46782	49949
1971	131512	66992
1972	112773	59875
1973	51054	72462
1974	84900	43409
1975	80818	79701
1976	82708	48415
1977	12840	25649
1978	98246	53303
1979	56009	45339
1983	109736	96463
1984	102555	69498
1985	55965	57727
1986	137139	96943
1987	37698	64515
1988	41720	36566
1989	53760	32889
1990	39817	51965
1991	48537	54937
1992	27656	38662
1993	75342	78967
1994	30128	38992
1995	68324	105683
1996	80441	52819
1997	105619	76363
1998	67563	81533
1999	95685	75497
2000	43579	40342
2001	26310	62042
2002	30697	19379
Mean	**67864**	**59229**

Seeded Period:

Water Year	Control Avg	Target Avg	Predicted	Ratio	Increase
2003	37974	47931	47492	1.01	439
2004	37912	40375	47468	0.85	-7093
2005	80795	101668	64307	1.58	37361
2006	65521	54263	58309	0.93	-4046
2007	34013	33724	45937	0.73	-12213
2008	57019	45549	54971	0.83	-9422
2009	74925	54665	62002	0.88	-7337
2010	51014	51930	52613	0.99	-683
2011	115947	103727	78110	1.33	25616
2012	42142	29931	49129	0.61	-19198
2013	33887	36523	45888	0.80	-9364
2014	80702	35639	64271	0.55	-28632
2015	64468	51525	57896	0.89	-6370
2016	61598	61738	56769	1.09	4969
2017	133395	83172	84962	0.98	-1790
2018	56460	30575	54751	0.56	-24177
Seeded Mean	**64236**	**53934**	**57805**	**0.93**	**-3871**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.609172
R Square	0.371091
Adjusted R Square	0.34863
Standard Error	17164.15
Observations	30

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	32580.86	7266.534	4.48368633	0.000114	17696.02
X Variable 1	0.392674	0.096607	4.06467088	0.000353	0.194784

High Uintas March – July Streamflow Multiple Linear Regression, with 3 Wyoming Control Sites and 3 Target Sites; units are in acre feet

Regression (non-seeded) Period:

Water Year	Hams Fork	Fontenelle	Smiths Fork	Target Avg
1966	44794	26481	69071	49949
1971	145432	70383	178721	66992
1972	103820	75862	158637	59875
1973	48082	29485	75594	72462
1974	80404	46964	127332	43409
1975	81706	45447	115301	79701
1976	75548	52151	120425	48415
1977	7077	7711	23732	25649
1978	93460	58383	142896	53303
1979	53667	33706	80654	45339
1983	102494	73684	153030	96463
1984	103004	56974	147686	69498
1985	49380	32445	86070	57727
1986	128700	95836	186880	96943
1987	36867	24696	51531	64515
1988	36184	24103	64874	36566
1989	46081	30952	84247	32889
1990	33395	23630	62426	51965
1991	44451	23899	77260	54937
1992	23469	10950	48549	38662
1993	69422	33656	122948	78967
1994	27123	17019	46243	38992
1995	57851	40953	106167	105683
1996	72113	40088	129123	52819
1997	91551	59499	165808	76363
1998	58520	41232	102936	81533
1999	80859	69012	137185	75497
2000	37484	23018	70236	40342
2001	20646	14235	44049	62042
2002	24183	18504	49405	19379
Average	**62592**	**40032**	**100967**	**59229**

Seeded Period:

Water Year	Hams Fork	Fontenelle	Smiths Fork	Target Avg	Predicted	Ratio	Increase
2003	26134	29925	57863	47931	52856	0.91	-4924
2004	30335	23304	60098	40375	49158	0.82	-8782
2005	76070	53163	113152	101668	65107	1.56	36561
2006	57043	43893	95628	54263	61159	0.89	-6896
2007	29811	19643	52585	33724	45597	0.74	-11874
2008	55706	33729	81623	45549	53019	0.86	-7470
2009	65884	41152	117741	54665	63245	0.86	-8580
2010	47569	34226	71247	51930	52717	0.99	-787
2011	105799	82651	159392	103727	83343	1.24	20384
2012	38298	23792	64335	29931	48385	0.62	-18453
2013	26722	17708	57232	36523	46693	0.78	-10170
2014	81110	53750	107247	35639	62524	0.57	-26885
2015	58245	39208	95950	51525	58683	0.88	-7158
2016	59483	34884	90428	61738	54856	1.13	6882
2017	122630	93600	183955	83172	90500	0.92	-7327
2018	46705	32380	90296	30575	57002	0.54	-26427
Seeded Mean	**57971**	**41063**	**93673**	**53934**	**59052**	**0.91**	**-5119**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.629376912
R Square	0.396115297
Adjusted R Square	0.326436293
Standard Error	17454.10769
Observations	30

	Coefficients	*Standard Error*
Intercept	30446.25283	9346.848154
Hams Fork	-0.26435458	0.430607215
Fontenelle	0.478306208	0.486930199
Smiths Fork	0.259311656	0.340472822

APPENDIX C

ROOSEVELT RADIOMETER RESULTS

Introduction

The operation of the Roosevelt radiometer allowed for a large data set of the atmospheric profile to be collected during the 2018-2019 winter season over the High Uintas target area. A number of cases were identified during the January through April period where a threshold amount of 0.10 g/m^3 of liquid water was detected by the radiometer. The radiometer was installed in mid-December but due to a technical issue with the computer that is required to archive the radiometer data, data was obtained starting in January. The radiometer observed a very active pattern during the January through April period, with a number of southerly track storms that impacted the High Uinta Range, allowing for the observation of liquid water.

Radiometer Liquid Water Plots

The radiometer was able to obtain a very accurate picture of super cooled liquid water occurrence during winter storms that affected not only the Uinta Basin but the higher elevations in the Uinta Range. As mentioned above, a number of cases were analyzed that showed the occurrence of liquid water when the radiometer was in the zenith angle (looking straight up) and when the radiometer was looking north, at a 20-degree angle above the horizontal. The subsequent paragraphs provide two examples of supercooled liquid water (SLW) occurrence observed by the radiometer, first in southerly flow and secondly in northerly flow, where a "spill over" effect seems to occur across the crest of the barrier onto the southern side.

Figure C-1 shows a radiometer data plot from February 5, 2019 looking at the 20-degree north angle, towards higher terrain. This plot shows liquid water occurrence beginning around 1200 UTC or 0500 MST. Liquid water occurs off and on throughout most of the day until around 2200 UTC or 1500 MST. This liquid water is, in fact, supercooled, as the temperature profile seen at the top panel of Figure 1 shows the -5°C level is located around 700 mb at 0500 MST, with cooling occurring throughout the day which lowered the -5°C level to 775 mb by 1500 MST. All of the liquid water occurrence between the 0500 and 1500 MST time window shows liquid water mainly occurring between 775 and 575 mb. For reference, the 700 mb level is near 10,000 feet above sea level while 600 mb is around 14,000 feet in elevation. The radiometer data was used during seeding operations to assist with assessing the seedability of this particular storm. Seeding operations occurred from a few sites on the 4th of February and additional sites were added with the additional consideration of the radiometer data that showed supercooled liquid water (SLW) was present. As SLW decreased later in the day, the radiometer (in combination with other data) gave the meteorologist good evidence for when seeding operations were to be terminated for this storm event.

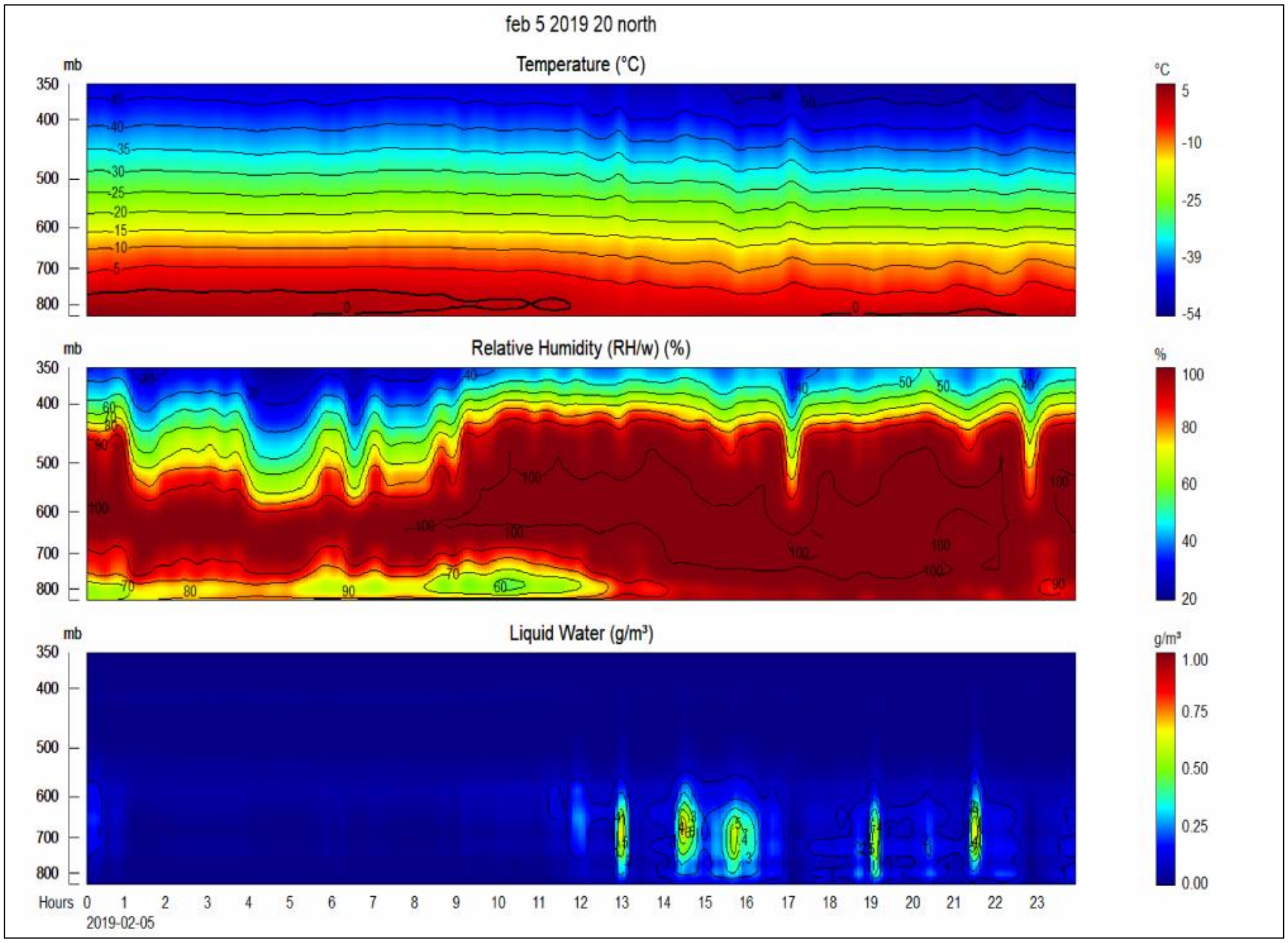

Figure C-1 Radiometer Plot from February 5, 2019 – 20 degree North Angle

Figure C-2 is another example of liquid water that was observed by the radiometer. However, in this case, the mean wind flow direction was out coming from the west/northwest. Spatially, it would make sense that the majority of the SLW observed would be on the north side of the barrier, however, this is not the case, as can been seen in Figure C-2. Liquid water values are considerably less than they would be in southerly or southwesterly flow, however, the values do exceed the threshold set for the definition of a liquid water occurrence case, per NAWC standards. LW values up to 0.25 g/m^3 were observed on January 21 and the temperature profile shows that the LW is in fact, supercooled, as the -5°C level was between 600 and 700 mb, the same range as the majority of the liquid water that was occurring between 1000 and 2000 UTC or 0300 and 1300 MST.

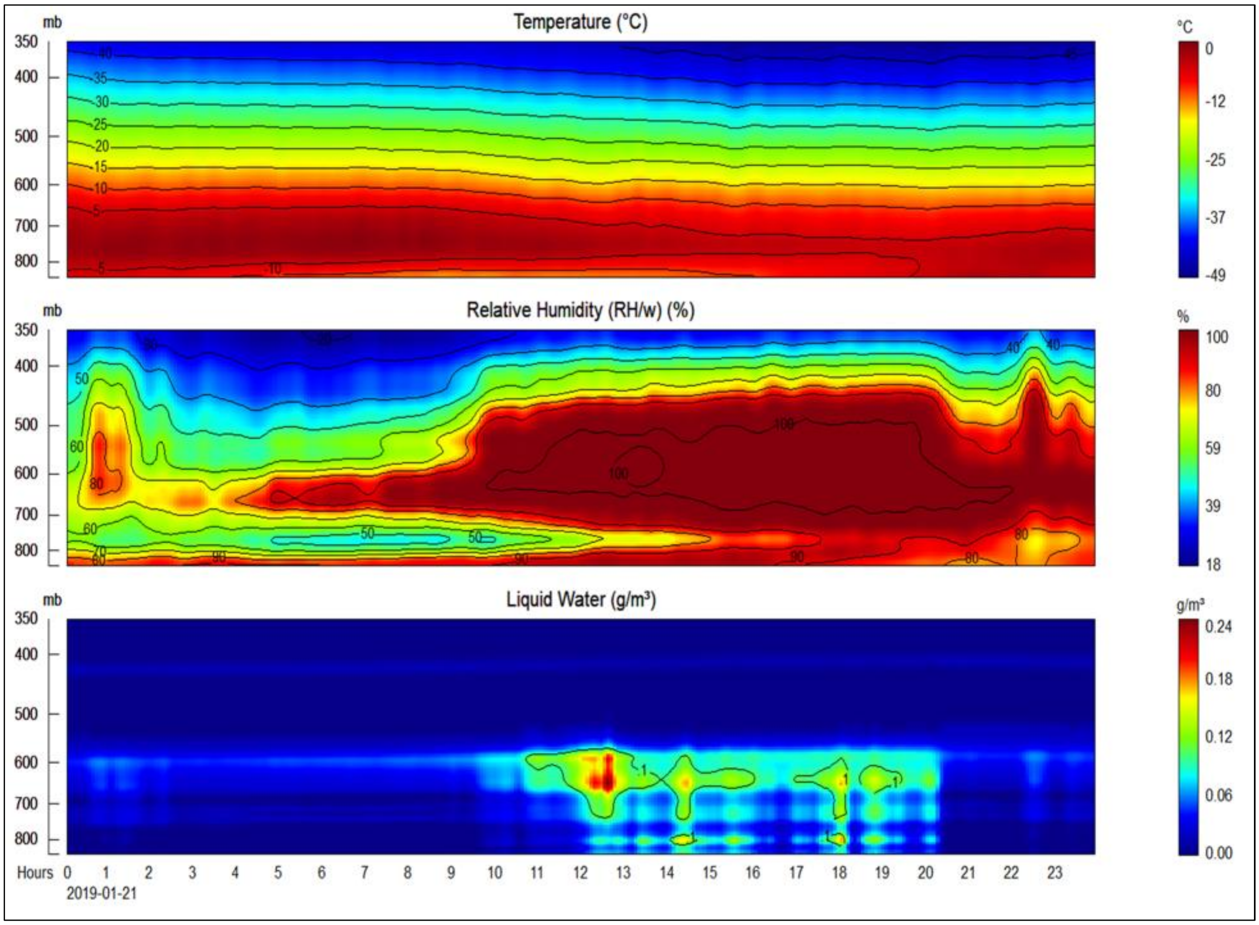

Figure C-2 Radiometer plot from January 21, 2019 – 20 degrees north angle

Radiometer Liquid Water and Inversion Plots

The Uinta Basin is no stranger to the occurrence of inversions during part of the winter storm season, which can not only reduce air quality but make seeding operations challenging as the ground based seeding method employed by NAWC relies solely on wind speed and direction, along with enough instability to allow for the vertical transport of the seeding material to the -5°C level, the temperature threshold at which seeding agents can become activated and increase snowfall. Figure C-3 is one such case from February 5, 2019 where the RAOB program can not only show temperature and liquid water but can also show the presence of any inversions. Interestingly enough, one can see an isothermal layer, where temperature remains constant with height on the temperature panel (top) and shows a surface-based inversion (bottomed panel) existing at the same time. At approximately 1200 UTC or 0500 MST, the inversion seems to dissipate and the presence of SLW shows up on the liquid water panel (middle). SLW values between 0.50 and 0.75 g/m^3 are evident on the liquid water panel (middle). This is a fairly common occurrence, whereas stability will be present before the main part of the storm comes through which not only brings precipitation and SLW, but also stronger winds that help to scour out any low or mid level stability that could inhibit seeding operations. This is why during seeding operations, it is imperative to take low level stability into account, along with other atmospheric criteria to ensure that the material is transported to the correct level for activation.

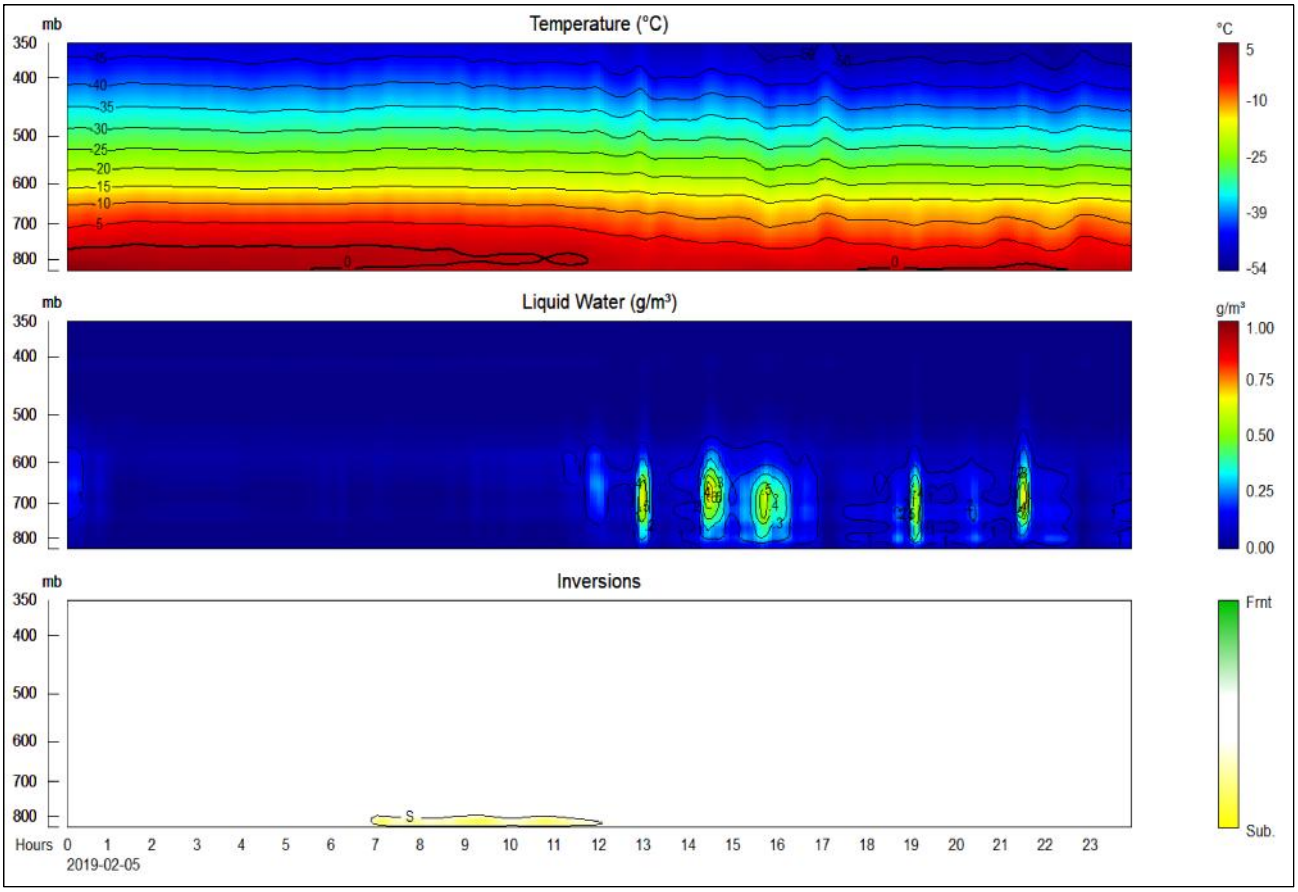

Figure C-3 Radiometer plot from February 5, 2019 – 20 degree north including any inversions

A seeding project feasibility study was conducted for the High Uintas project, focusing on the southern slope of the Uinta Range (NAWC Report 2002) It showed that inversions are fairly common in the Uinta Range, both at the surface and at locations above the surface (elevated) during stormy periods. The 2002 study referenced winter months' upper air balloon sounding data in the Basin obtained in an earlier study. This study showed that elevated inversions, with an average top height of 6,200 feet or 800 mb, were much more common (61% of cases) than surface based inversions, which had an average top height of 7,500 feet or 765 mb (13% of cases) and that no inversions (23%) occurred as well. Since the detailed balloon sounding data were obtained nearly 40 years ago – it would be interesting to see if this still holds true, with the use of newly acquired radiometer data. The radiometer also possesses the capability to produce a rawinsonde balloon sounding nearly continuously, which is helpful in remote locations far from a National Weather Service (NWS) rawinsonde site.

Radiometer and Dry Ridge Icing Meter Comparison

In the field of meteorology and weather modification, it is often beneficial to compare two real time observational systems, in order to verify the consistency and quality of data. For many years now, an icing meter has been located at Dry Ridge and has been providing continuous icing data during the winter seasons in conjunction with cloud seeding operations and has provided NAWC with valuable data regarding icing (NAWC report, WM-18-9). The comparison of the icing meter to the radiometer is a helpful one, even though it is cautioned that the icing meter is a point measurement and the radiometer gives a full atmospheric profile. Regardless, a few cases were analyzed to see how to see how well the two instruments compare during storm periods. The two instruments are about 38 miles apart, with the icing meter at an elevation of around 11,500 feet and the radiometer located in Roosevelt, Utah which has an elevation of around 5,100 feet. Figure C-4 shows the two locations of the instruments.

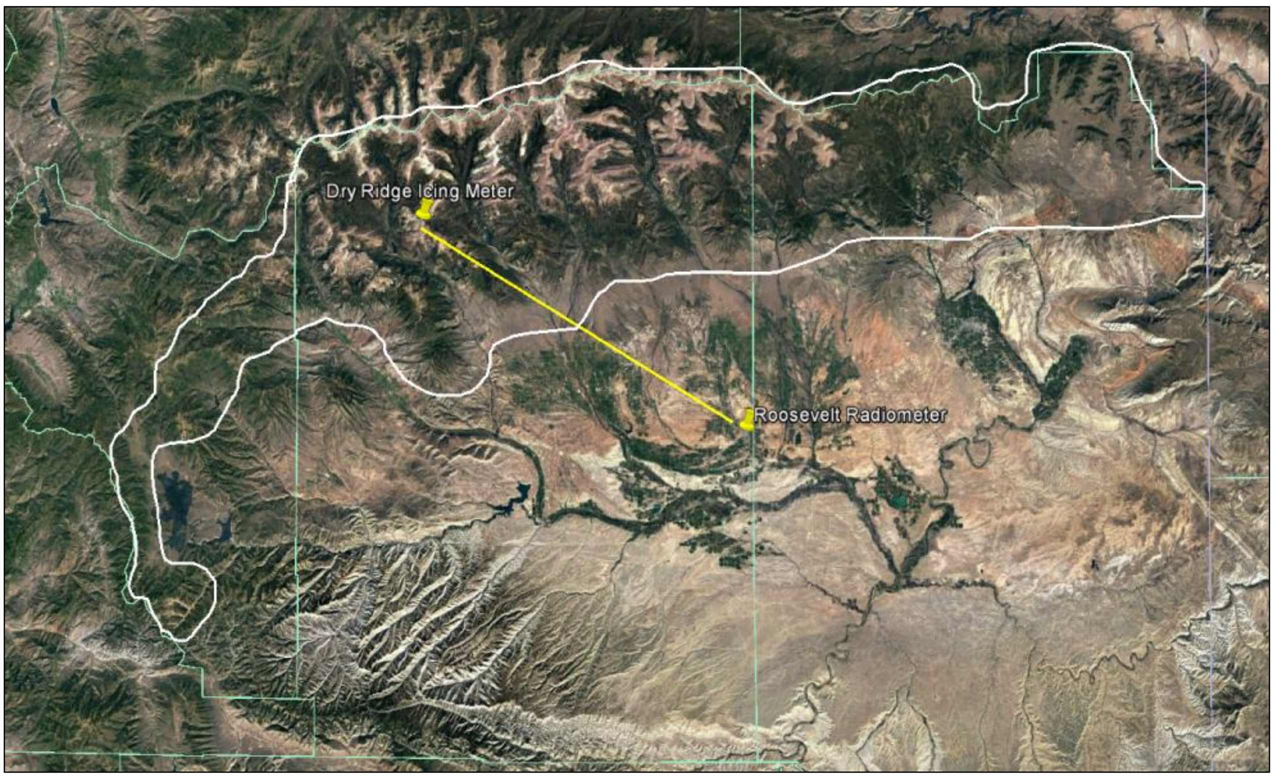

Figure C-4 Map showing location of Dry Ridge Icing Meter and the Roosevelt Radiometer Locations

Figure C-5 is the first case of the icing meter and the radiometer comparison, with the top panel showing liquid water observed by the radiometer, the middle panel showing the number of icing cycles at 15-minute intervals and the bottom panel showing the snowfall rate. From the figure, all three variables show amounts being reported around 1800 MST and continuing into the evening hours of February 16. The radiometer liquid water values are modest, with just under 0.20 g/m^3 observed but seem to coincide well with the occurrence of icing, and precipitation following after icing, as occurred at the Dry Ridge site. It should be noted for this and similar figures that the top panel (radiometer display) is in UTC time while the middle and lower panels (icing meter) are in MST, a difference of 7 hours.

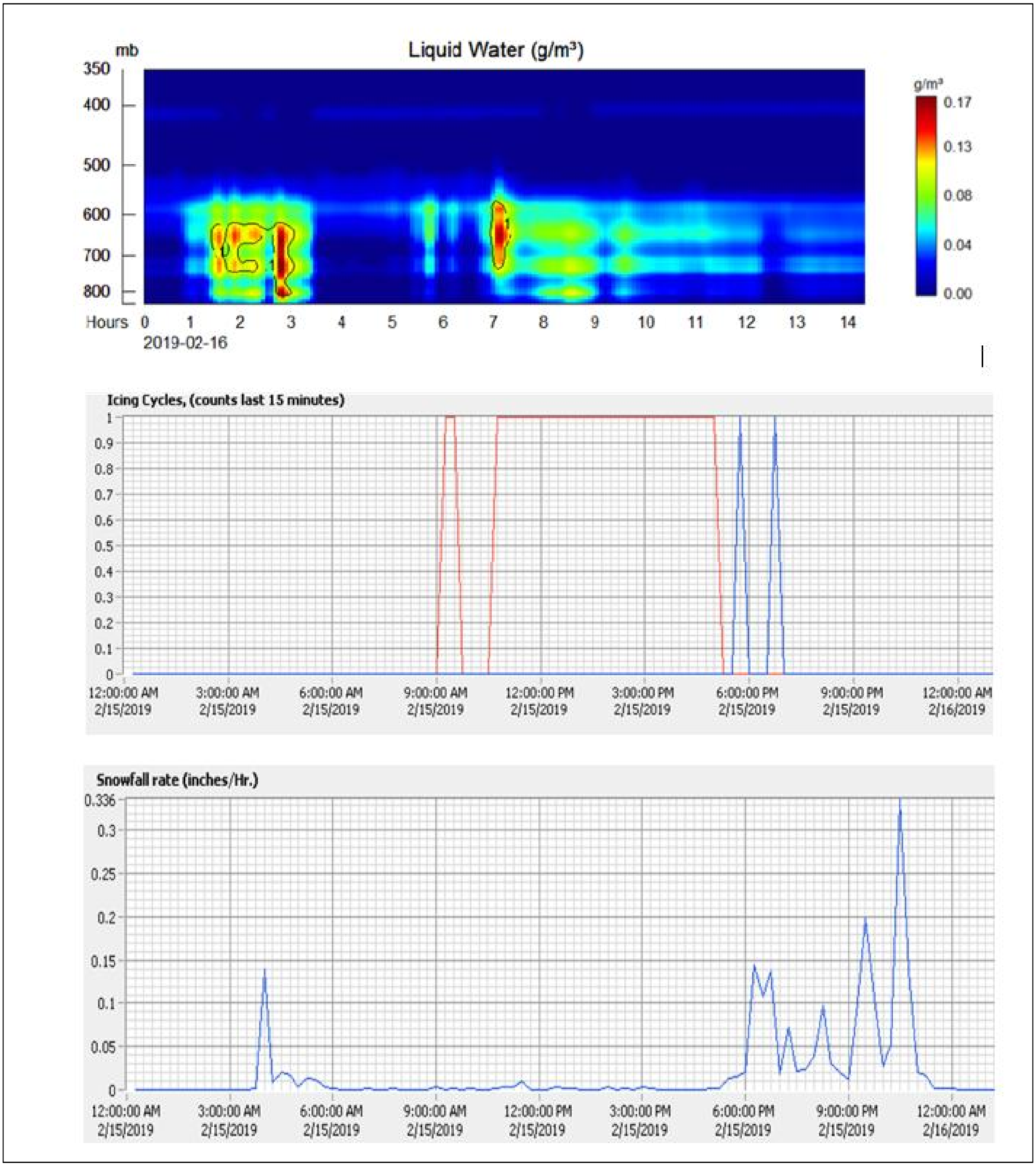

Figure C-5 Liquid water, icing data and snowfall rate plots from February 16, 2019

The next case examined took place during a storm event that occurred March 21st into the 22nd. Figure C-6 shows liquid water data from the radiometer, along with icing meter data and snowfall rates. Once again, the two instruments seem to correlate rather well, with liquid water plotted around 1700 MST from the radiometer and icing occurring nearly at the same time. The radiometer plot is at a 20-degree angle looking north, so the both measurements are sampling the atmosphere at about the same location. Precipitation lags behind the icing event, which tends to be rather common according to analyses conducted solely on years of data of the icing meters located in Utah, including the Dry Ridge site.

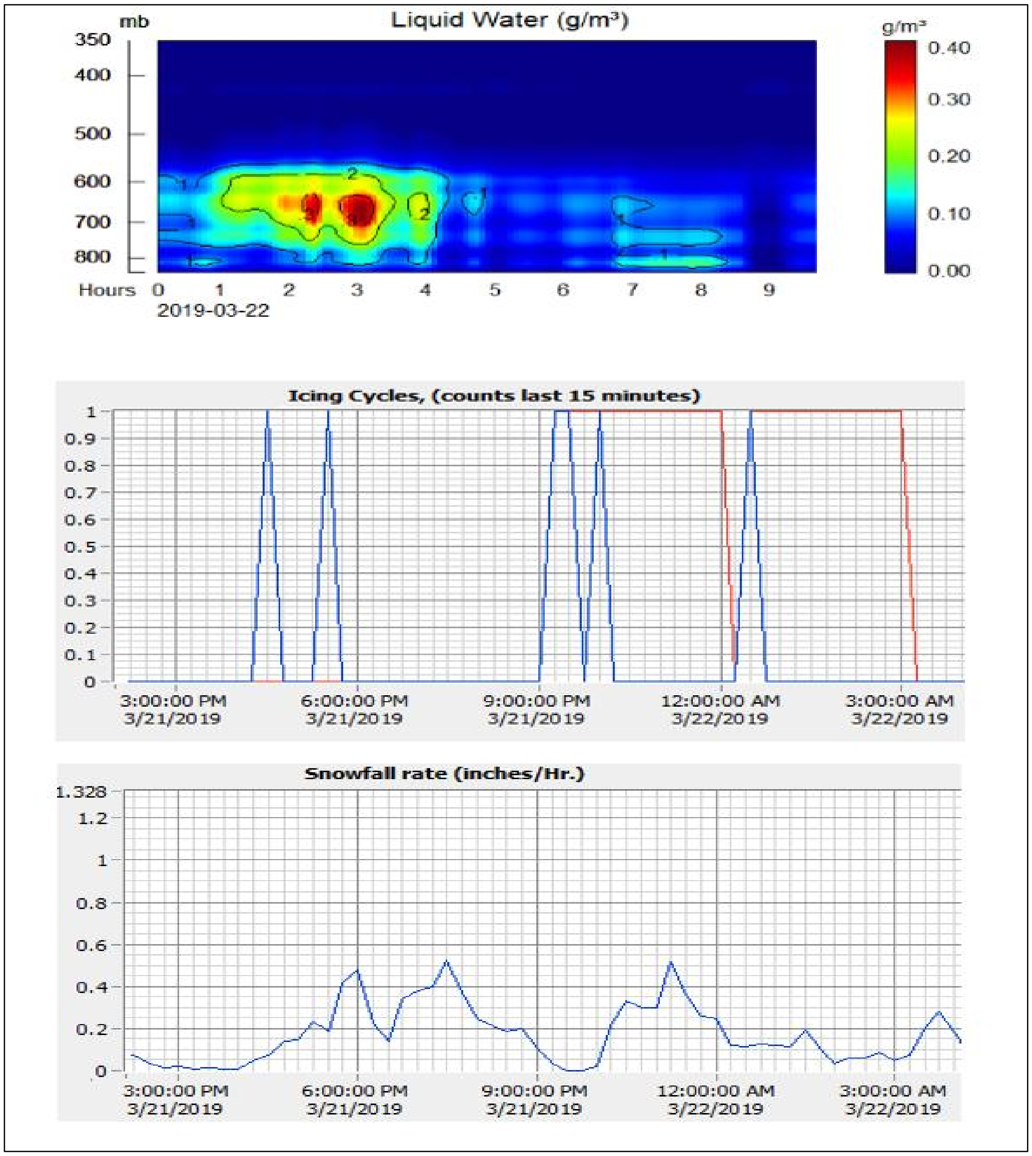

Figure C-6 Liquid water, icing data and snowfall rate plots from March 21-22, 2019

Summary

In conclusion, the radiometer has brought another level of observational data to assist with cloud seeding guidance during operational periods. Data are somewhat sparse in the Uinta Basin, particularly any data above the surface, including radar. The radiometer can help a meteorologist in the real-time decision making process during cloud seeding operations by providing valuable data regarding the vertical structure of the atmosphere. The radiometer can help shed light on stability issues, which can affect the Uinta Basin during the winter periods. It can help identify not only surface-based inversions, but any layers containing a lesser degree of stability (which may be elevated). This is another valuable tool during cloud seeding operations, as stability can inhibit the vertical transport of seeding material to the -5°C level, where SLW would be present, which is needed to activate the seeding material. Lastly, the comparison between the radiometer and icing meter showed somewhat surprising and encouraging correlation, as the two instruments display the occurrence of SLW in different spatial resolutions. The two cases examined in this analysis showed remarkable similarly, as did a third case not presented here. This gives a valuable insight into how the icing meter is behaving and observing SLW and icing, as it is a permanent instrument system included in the design of the High Uinta project. It is recommended that further analysis could be conducted to further analyze the correlation between these two devices, in order to strengthen confidence in the systems' data and the meteorological interpretation of those data.

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