Annual Cloud Seeding Report

Southern/Central Utah Program
2021-2022 Winter Season

Prepared For:

State of Utah Division of Water Resources

Utah Water Resources Development Corporation

Lower Colorado River Basin States

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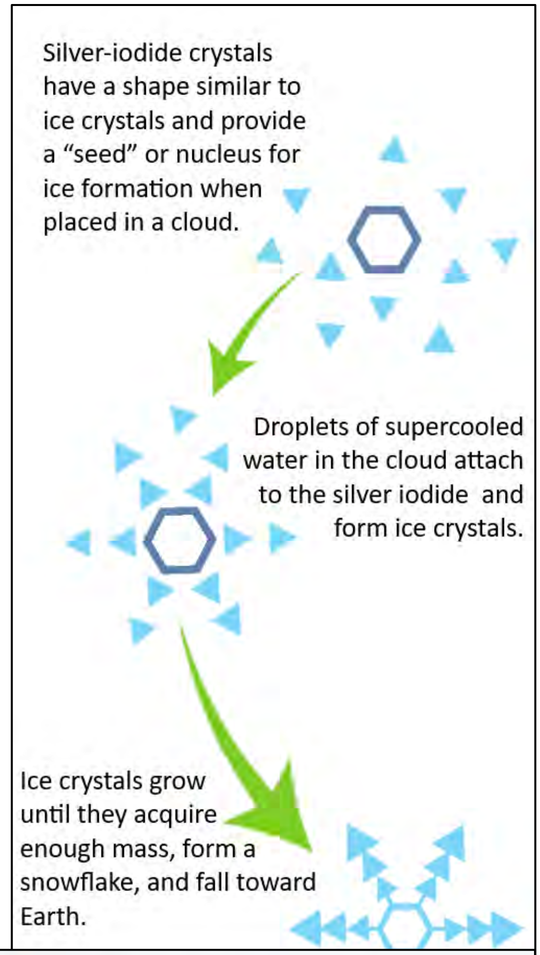
WEATHER MODIFICATION OVERVIEW

The Science

The cloud-seeding process aids precipitation formation by enhancing ice crystal production in clouds. When the ice crystals grow sufficiently, they become snowflakes and fall to the ground.

Silver iodide has been selected for its environmental safety and superior efficiency in producing ice in clouds. Silver iodide adds microscopic particles with a structural similarity to natural ice crystals. Ground-based and aircraft-borne technologies can be used to add the particles to the clouds.

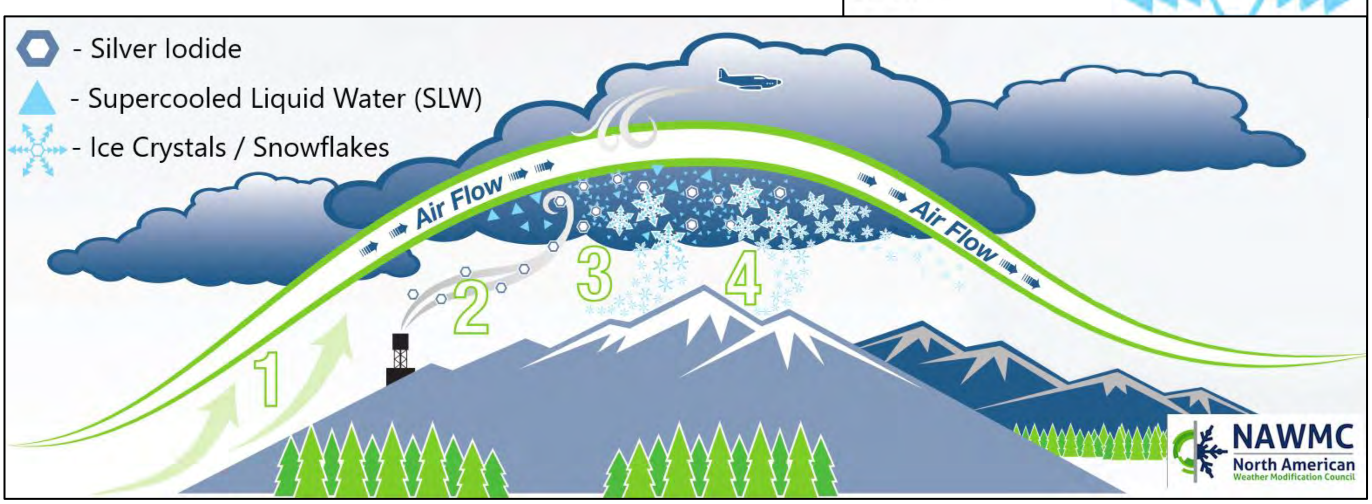


Safety

Research has clearly documented that cloud seeding with silver-iodide aerosols shows no environmentally harmful effect. Iodine is a component of many necessary amino acids. Silver is both quite inert and naturally occurring, the amounts released are far less than background silver already present in unseeded areas.

Effectiveness

Numerous studies performed by universities, professional research organizations, private utility companies and weather modification providers have conclusively demonstrated the ability for Silver Iodide to augment precipitation under the proper atmospheric conditions.



STATE OF THE CLIMATE

As reported last year, every ten years, the National Oceanic and Atmospheric Association (NOAA) releases a summary of various U.S. weather conditions for the past three decades to determines average values for a variety of conditions, including, temperature and precipitation. This is known as the U.S Climate normal, with a 30-year average, representing the "new normal" for our climate. These 30-year normal values can help to determine a departure from historic norms and identify current weather trends.

The recently released 30-year average ranges from 1990 – 2020. Images in Figure 1 and 2 show how each 30-year average for the past 120 years compares to the composite 20th century average for temperature and precipitation.

For the western U.S., the 1990-2020 average show much warmer than average temperatures. When comparing precipitation for the past 30 years to both the previous 30-year average and the 1901-2000 average, the American Southwest (including portions of Utah, Arizona, California and Nevada) has seen as much as a 10% decrease in average annual precipitation.

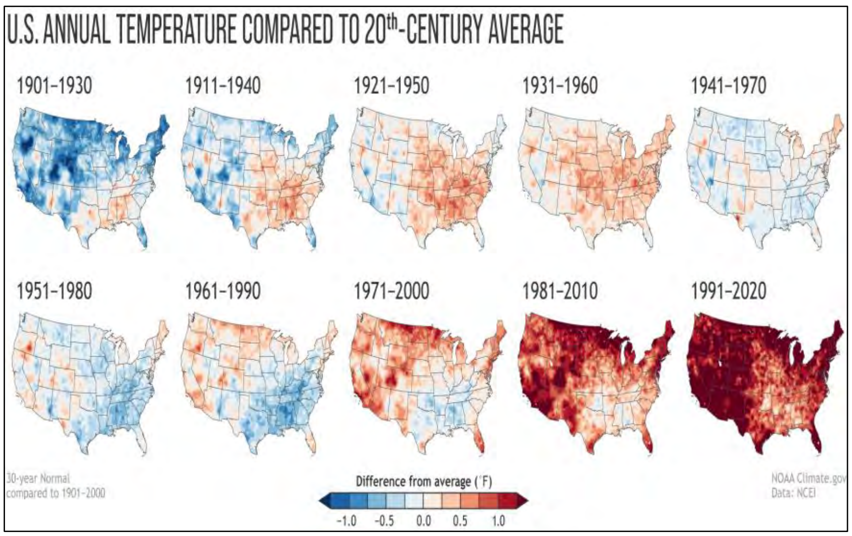


Figure 1 **U.S. Annual Temperature compared to 20th-Century Average**

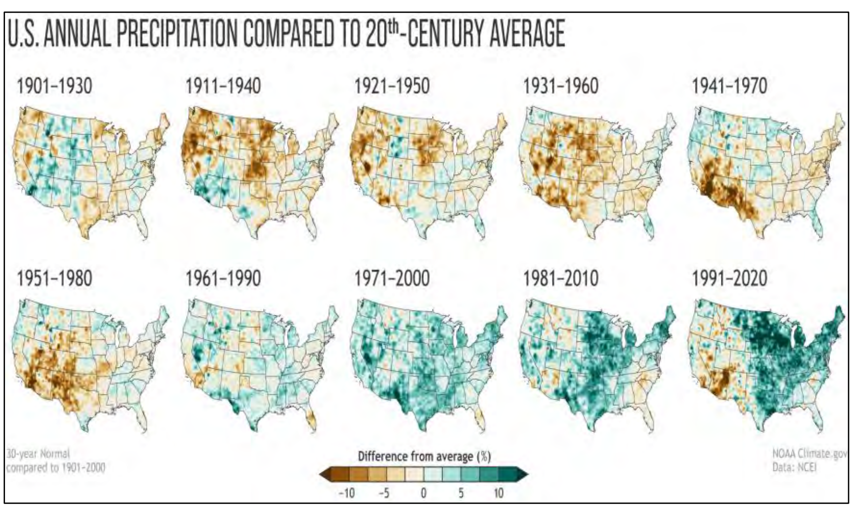


Figure 2 **U.S. annual precipitation compared to 20th-Century average.**

EXECUTIVE SUMMARY

In many past winter seasons, cloud seeding has been conducted in several different regions within central and southern Utah. Since the mid-1970s seeding has been concentrated in the mountainous watersheds from Millard and Sanpete Counties southward to the Pine Valley Mountains and Washington County and the headwaters of the Sevier River in Iron and Garfield Counties. The mountainous portions of Tooele and Juab Counties have been included as seeding target areas since 1988. The intended target areas of this program generally include terrain above 7,000 feet elevation. The Southern and Central Utah Seeding Program utilizes approximately 70 ground-based, manually-operated (Cloud Nuclei Generator, or CNG) sites, containing a 2% silver iodide solution. The goal of the seeding program is to augment wintertime snowpack/precipitation over the seeded watersheds. Cost sharing for the seeding program is provided by the Utah Division of Water Resources, and additional funds from the Lower Colorado River Basin States has resulted in early-season (November 1st-15th) and late season (March 16th - April 15th) extensions to the seeding program since 2010. Due to abnormally dry conditions this season and the past several years, the decision was made to extend the core seeding program through April 30th.

Precipitation and snowfall were well below normal during the 2021-2022 winter season. A total of 2678.5 CNG hours were conducted during 14 storm periods for the core program this season. An additional 681.25 hours of seeding were conducted during five late-season storm periods for the early and late season Lower Basin Extension periods. An additional 591.25 hours of seeding were conducted for the special core program extension through late March and April during some of these same late-season events. There were no seeding suspensions during the 2021-2022 season.

Evaluations of the effectiveness of the cloud seeding program were made for both the past winter season and for all seeded seasons combined. These evaluations utilize SNOTEL records collected by the Natural Resources Conservation Service (NRCS) at selected sites within and surrounding the seeded target area, as well as some seasonal streamflow data. Analyses of the effects of seeding on target area precipitation and snow water content have been conducted for this seeding program, utilizing target/control comparison techniques. **Evaluation of December – March precipitation data have suggested long-term seasonal increases averaging 12% for both Eastern Tooele County and the primary target areas of central and southern Utah. April 1st snowpack evaluations have suggested a 10% increase in Eastern Tooele County and 4% increases for the central and southern Utah watersheds**. As discussed in section 6.0 of the report, the precipitation evaluation results are stronger mathematically, and suggest roughly a 1.3-inch increase in seasonal precipitation in the target areas due to seeding. This would likely produce an average additional runoff of more than 70,000 acre-feet annually in these watersheds.

It is recommended that the currently designed winter seeding programs over the mountainous portions of central and southern Utah be continued. Routine application of weather modification technology each year can help stabilize and increase water supplies, both with surface and underground storage. Commitment to conduct a program each winter provides stability and acceptance by funding agencies and the general public. The program is designed so that it can be temporarily suspended or terminated during a given winter season, should snowpack accumulate to the point where additional water may not be beneficial.

1. INTRODUCTION

Since the mid-1970s, operational cloud seeding has been routinely conducted throughout the winter and early spring seasons over many of the mountainous watersheds of central and southern Utah. Water managers and others concerned about maintaining adequate water supplies have recognized that application of cloud seeding technology can be a viable method available to augment and help stabilize water supplies. By employing cloud seeding it could be possible to moderately increase the amount of precipitation and runoff beyond that which would have occurred naturally. Operations can be suspended in portions of or all of certain winter seasons that experience excessive amounts of precipitation. Cloud seeding suspensions, for example, were invoked in the 1982, 1983, 1993, 1995, 2005, 2008, 2010, 2011, 2017 and 2019 water years. Operations were suspended entirely in the 1984 water year due to abnormally wet conditions.

In a number of past winter seasons, cloud seeding has been conducted in many different regions within central and southern Utah. Since the mid-1970s seeding has been concentrated in the mountainous watersheds from Millard and Sanpete Counties southward to the Pine Valley Mountains and Washington County and the headwaters of the Sevier River in Iron and Garfield Counties. The mountainous portions of Tooele and Juab Counties have been included as seeding target areas since 1988. A map showing the current boundaries of these seeded target areas is provided in Figure 1.1. The target areas, generally terrain above 7,000 feet MSL, were selected as high-yield areas with substantial snowpack accumulation. These areas are the primary contributors to spring and summer streamflow. Figure 1.2 depicts the average annual precipitation for the State of Utah. This figure graphically demonstrates these higher-yield areas.

Traditionally, the sponsoring counties or water conservancy districts have contracted the cloud seeding program in central and southern Utah with the Utah Water Resources Development Corporation (UWRDC). The UWRDC, a non-profit organization, was formed in the 1950s to act as a liaison between the agencies desiring cloud seeding and the company providing the actual cloud seeding equipment and operations. North American Weather Consultants (NAWC) has been contracting with the UWRDC in this capacity. During the current water year, the State of Utah, through the Division of Water Resources, was again a co-sponsor of this program through 50% cost sharing.

Cloud seeding in Utah is regulated by the Utah Department of Natural Resources through the Division of Water Resources. Utah law requires that operators conducting cloud seeding have both a license and a site-specific permit for the area(s) to be seeded. The three Lower Colorado River Basin States (Arizona, California and Nevada), as in previous seasons, provided additional funding to extend the operational period in those areas of the southern target area, which contain tributaries to the Colorado River.

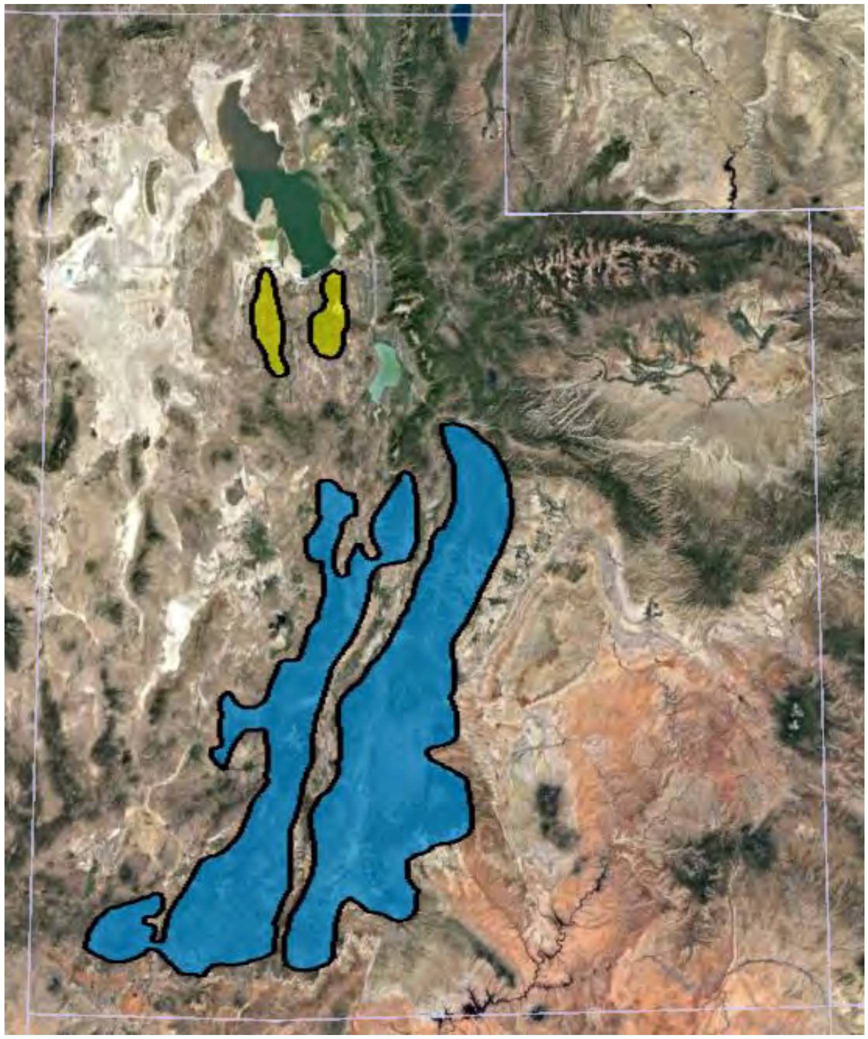


Figure 1.1 **Seeded target areas in central and southwestern Utah; Eastern Tooele Target (yellow) and Primary Target (blue)**

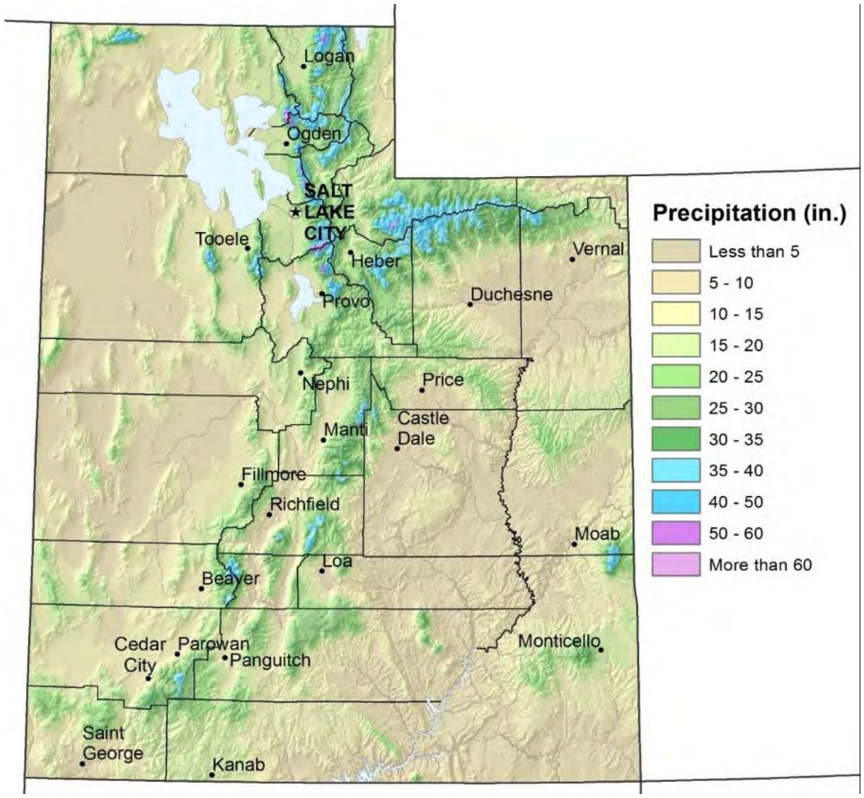


Figure 1.2 Utah average annual precipitation

1.1 Core Program and Extension Periods

As the demand for fresh water continues to grow in the southwest, the Colorado River is an extremely important component of the surface water supply in the region. Various Colorado River water interests (e.g. the Lower Basin States) 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 for precipitation augmentation where and when viable seeding opportunities occur.

The primary Central and Southern Utah Seeding Program, funded by various Utah water interests and the Division of Water Resources, was active from November 16 – March 15 this season. The Central/Southern Utah Project was one of two Utah projects selected to receive supplemental Lower Basin funding. Due to exceptionally dry conditions this year and the continuing drought situation, it was decided to extend seeding operations for the primary central and southern Utah Seeding Program through April 30 during the 2021-2022 winter season. This extension was in conjuncture with the extension periods funded by the Lower Basin States and Utah's Division of Water Resources, which ran from November 1-15 and March 16 – April 15, and allowed the entire target area to continue to be seeded through the end of April when favorable conditions occurred. Thus, additional benefit was realized while total costs remained well within the budgeted amounts for the program.

1.2 Installation and Operation of Icing Rate Meters

An earlier agreement with the three Lower Basin States provided funds to purchase some hardware for three remote icing rate meters. The Lower Basin States provided funds in the 2009 agreement to install and operate two of these sites beginning during the 2009-2010 winter season. One site was installed in central Utah in conjunction with a Utah Department of Transportation site (Skyline), a second site was established at the Brian Head ski area in southern Utah. Beginning with the 2012-13 winter season, a third icing meter site has been active at Dry Ridge in the Uintas (within the High Uintas seeding program target area). The icing rate meters detect the presence of supercooled liquid water (SLW) cloud droplets embedded in naturally occurring winter storms. These droplets are the target of the cloud seeding operations. Funds from the Lower Basin States are also provided for the analysis of the ice detector data to improve understanding of when/where SLW occurs in cold-season storm events. The Brian Head and Dry Ridge sites remained in operation this season. The Skyline site in central Utah was discontinued prior to the start of the 2020-21 season due to reallocation of funding from the Lower Basin States. However, at the beginning of the 2021-22 season the Skyline icing meter was moved to the northern slopes of the Uintas to work in conjunction with a National Resource Conservation Service SNOTEL site (Lily Lake).

2. PROJECT DESIGN

2.1 Background

Evaluations of this long-standing operational seeding project have consistently indicated increases in wintertime precipitation during the periods in which cloud seeding was conducted. Statistical analyses have suggested seasonal increases in precipitation that may be attributed to the cloud seeding program, averaging between 5% and 15% (Griffith et al., 2009). Operational procedures for Central/Southern Utah cloud seeding program utilize the basic principles of applying cloud seeding technology that have been shown to be effective during more than 40 years of wintertime cloud seeding for the mountainous regions of Utah. Continued increases in availability of weather data and forecast products have led to improved seeding opportunity recognition capabilities, and continued analysis of the effectiveness of operational cloud seeding projects is leading to improved confidence in the accuracy of the long-term average effects of the Central/Southern Utah Program. NAWC has incorporated observational, seeding method and evaluation enhancements into the project when they are believed to be of practical value to the project.

2.2 Seedability Criteria

NAWC conducts selective seeding during winter storm events, which is the most efficient and cost-effective method. Selective seeding means that seeding is conducted only during specific time periods and in specific locations where it is likely to be effective. This decision is based on several criteria which determine the seedability of the storm. These criteria deal with characteristics of the atmosphere including temperature, stability, and wind flow, both in and below the clouds. Moisture content of the atmosphere, including cloud types and occurrence of supercooled liquid water (SLW) are important factors during seeding operations. Some heavier storm periods may not be seeded due to factors which make the storm naturally efficient at producing precipitation. Other storm periods can be deemed unfavorable due to several factors including temperature, stability or wind direction. The general criteria are provided below. The use of this focused seeding method has yielded consistently favorable results with very high cost/benefit ratios in a number of NAWC projects conducted in the western U.S.

- Cloud bases are near or below mountain barrier height.
- Low level wind speed and direction that would favor the transport of silver iodide seeding material, from its release locations into the target area.
- The absence of low level inversions or stable layers that would restrict the vertical movement of silver iodide from the surface to the -5°C level (23°F) or colder.
- Temperatures at the 700-mb level are warmer than -15°C (5°F)

2.3 Equipment and Project Set-Up

During the Fall of 2021, following a period of off-season maintenance, NAWC technicians re-installed the ground-based cloud seeding generators at sites selected to produce seeding plumes over the target areas in various wind situations. The target areas are discussed in more detail in Section 4.0. The seeding generator site locations, approximately 70 in all, are shown in Figure 2.1. Information on these locations is provided in Table 2-1.

Eleven ground-based seeding sites were available in eastern Tooele County (ET) during the season, located throughout the Tooele Valley from Erda and Grantsville southward to Faust, with additional sites to the west of the Stansbury Range, in Skull Valley. These locations allow for targeting of this portion of the seeding target area (Oquirrh and Stansbury Mountains) during a variety of wind flow situations.

The second seeded target group is referred to as the Primary Target (PT). This target area covers a large portion of central and southwestern Utah, including the principal mountain ranges listed below.

- Wasatch Range - northeast of Nephi
- Wasatch Plateau - east of Mt. Pleasant to east of Manti
- San Pitch Mountains - east of Levan to Gunnison
- Fish Lake Hightop Plateau - east of Koosharem
- Pavant Range - east of Fillmore to Cove Fort
- Tushar Mountains - east of Beaver
- Sevier Plateau - east of Salina to Panguitch
- Valley Mountains - east of Scipio
- Paunsaugunt Plateau - east of Panguitch and Hatch
- Markagunt Plateau - east of Paragonah to Brian Head
- Pine Valley/Harmony Mountains - southwest of Cedar City to St. George
- Kolob Terrace - south of Cedar City to Springdale

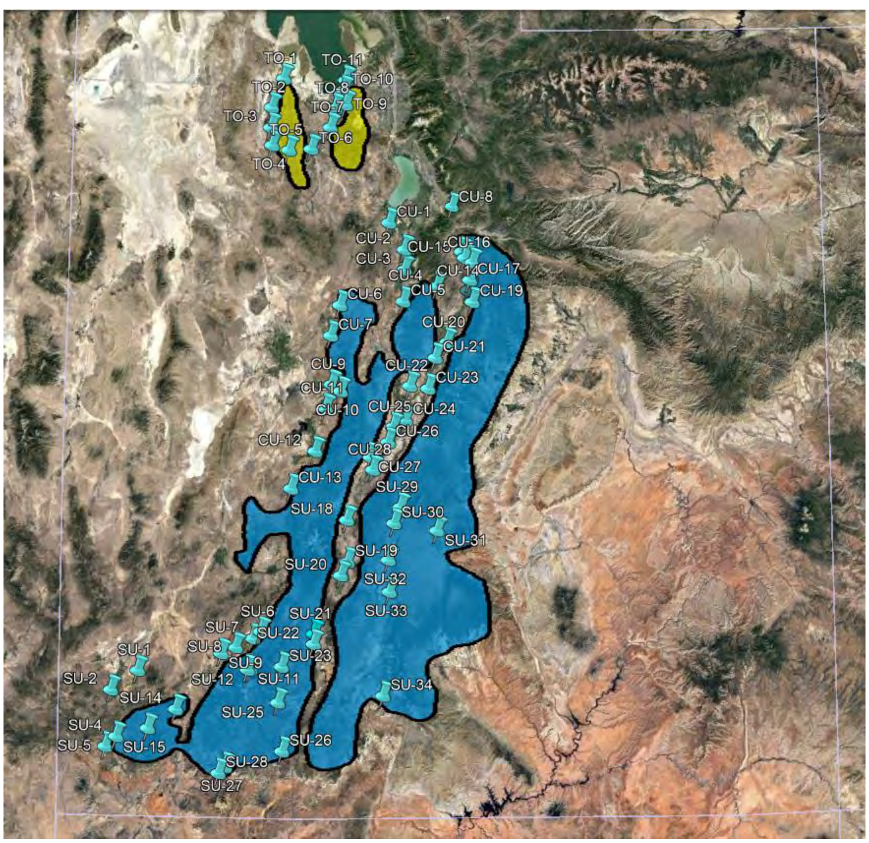


Figure 2.1 **Target areas and seeding site location**

Table 2-2
Seeding Site Locations

Site Number	Name	Latitude (N)	Longitude (W)	Elevation (feet)
TO-1	Skull Valley North	40°41.11'	112°40.10'	4289
TO-2	Skull Valley Central	40°32.20'	112°44.74'	4390
TO-3	Skull Valley #3	40°35.00’	112°41.00’	4300
TO-4	Skull Valley #4	40°23.87’	112°42.92’	4890
TO-5	Terra	40°19.12'	112°37.60'	5166
TO-6	Rush Valley	40°19.50'	112°28.75'	5342
TO-7	Stockton	40°26.12'	112°21.18'	5234
TO-8	Settlement Canyon	40°31.14’	112°18.16’	5140
TO-9	Pine Canyon	40°33.09'	112°15.15'	5095
TO-10	Erda	40°37.50'	112°16.97'	4415
TO-11	Lakepoint	40°40.85’	112°15.85’	4250
CU-1	Elberta	39°57.12'	111°57.72'	4732
CU-2	Mona	39°48.93’	111°51.61’	4943
CU-3	Nephi West	39°42.78'	111°51.56'	5042
CU-4	Fountain Green	39°37.69'	111°38.88'	5985
CU-5	Levan	39°33.17'	111°52.06'	5286
CU-6	Leamington	39°31.99'	112°16.92'	4721
CU-7	Oak City	39°22.76'	112°20.43'	5059
CU-8	Spanish Fork	40° 2.000'	111° 33.00'	5230
CU-9	McCornick	39°07.95'	112°20.01'	4848
CU-10	Holden	39°05.92'	112°16.49'	5077
CU-11	Fillmore	39°00.71’	112°22.30’	4879
CU-12	Kanosh	38°47.71'	112°26.20'	5048
CU-13	Cove Fort	38°36.35'	112°35.44'	5942
CU-14	Birdseye	39°55.70'	111°34.08'	5600
CU-15	Hideaway Valley	39°46.32'	111°27.90'	6300
CU-16	Milburn	39°44.88'	111°24.96'	6787
CU-17	Fairview	39°39.61’	111°25.87’	6125
CU-18	Fairview South	39°36.44'	111°26.71	5855
CU-19	Mt. Pleasant	39°32.46'	111°27.03'	5981
CU-20	Ephraim	39°20.73'	111°34.95'	5626
CU-21	Manti	39°16.08'	111°39.51'	5505
CU-22	Centerfield	39°07.60'	111°49.43'	5100
CU-23	Mayfield	39°06.97'	111°42.52'	5550
CU-24	Salina	38°57.22'	111°51.21'	5190
CU-25	Aurora	38° 55.83’	111° 55.58’	5176
CU-26	Sigurd	38°50.52’	111°57.90’	5220
CU-27	Richfield	38°45.96’	112°04.68’	5296

Site Number	Name	Latitude (N)	Longitude (W)	Elevation (feet)
CU-28	Annabella	38°42.17'	112°03.77'	5316
SU-1	Newcastle	37°40.61'	113°33.73'	5242
SU-2	Enterprise	37°34.50'	113°43.99'	5345
SU-4	Veyo	37° 20.17'	113° 41.42'	4487
SU-5	Gunlock	37°17.16'	113°45.88'	3638
SU-6	Paragonah	37°52.98’	112°46.56’	5880
SU-7	Parowan	37°50.88'	112°49.56'	5980
SU-8	Summit	37°48.04'	112°55.96'	6009
SU-9	Enoch	37°46.44'	113°01.55'	5566
SU-11	Brian Head Summit	37°41.64'	112°50.76'	9591
SU-12	Brian Head Store	37°41.58'	112°51.00'	9700
SU-14	New Harmony	37°29.05'	113°18.85'	5355
SU-15	Pine Valley	37°23.05'	113°29.57'	6579
SU-18	Marysvale	38°26.98'	112°13.72'	5870
SU-19	Kingston	38°12.40'	112°11.33'	6018
SU-20	Circleville	38°10.27'	112°16.03'	6082
SU-21	Spry	37°52.43'	112°26.24'	6564
SU-22	Panguitch	37°52.38'	112°23.88'	6610
SU-23	Panguitch Lake	37°42.39’	112°38.47’	8255
SU-25	Duck Creek	37°31.50’	112°39.80’	8451
SU-26	Orderville	37°16.62’	112°38.10’	5470
SU-27	Springdale	37°11.65'	112°59.83'	3987
SU-28	Rockville	37°09.70'	113°02.35'	3737
SU-29	Koosharem	38°30.87'	111°53.13'	6973
SU-30	Greenwich	38°26.00’	111°55.54’	6882
SU-31	Loa	38°23.83'	111°38.89'	7052
SU-32	Angle	38°14.91'	111°57.65'	6415
SU-33	Antimony	38°05.29'	111°57.25'	6661
SU-34	Henrieville	37°33.72’	112°59.64’	6000

The primary target area reaches from eastern Juab County in central Utah, southward to the northern portions of Washington and Kane Counties in southwestern Utah.

There are approximately 60 seeding generator sites available for the primary target areas. These generators extended roughly in north to south lines west of the target areas in eastern Juab and Millard well as throughout Sanpete, Sevier and Piute Counties. Further south, generators were located in Iron, Garfield, Kane, and Washington Counties. This equipment array provides various seeding options regardless of wind direction, as some generators are nearly always upwind of a portion of the target area during storms. It should be noted that winds during winter storms in Utah typically blow from the west toward the east, most commonly from the southwest before frontal passages and from the northwest following cold frontal passages.

The cloud seeding equipment at each site includes a cloud seeding generator unit and a propane gas supply tank. The seeding solution consists of two percent (by weight) silver iodide (AgI), complexed with small portions of sodium iodide and para-dichlorobenzene, in solution with acetone. This particular solution is used because it is formulated specifically to be a fast-acting nucleation agent via the condensation-freezing mechanism, rather than via the slower contact nucleation mechanism. This is an important characteristic, given the relatively narrow mountain barriers within the cloud seeding target areas in Utah. The 2% silver iodide solution has been used throughout most of the history of the program.

The seeding units are manually operated by a local operator igniting propane in a burn chamber, and then adjusting the flow of the seeding solution into the burn chamber through a flow rate meter. The propane gas pressurizes the solution tank, which causes the solution to be forced into the burn chamber. The regulated seeding solution is sprayed into the propane flame, where microscopic silver iodide crystals are formed through the combustion process. The silver iodide is released at a rate of eight grams per hour, and after combustion it produces these ice-forming nuclei crystals, which closely resemble natural ice crystals in structure. These crystals become active as ice-forming nuclei beginning at temperatures near -5°C (23°F) in-cloud. Since experience has indicated that seeding is most effective within a particular temperature range (Griffith et al., 2013), the seeding generators were operated only during those periods when the temperatures within the cloud mass were between about -5 and -25°C (+23 to –13°F). For the seeding to be effective, the AgI crystals must become active in the cloud region which contains supercooled liquid water droplets sufficiently far upwind of the mountain crest so that the available supercooled liquid water can be effectively converted to ice crystals which will then 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 freezing the cloud drops in time to affect precipitation in the desired area.

Most storms that affect Utah's mountains are associated with synoptic (large-scale) weather systems that move into Utah from the southwest, west, or northwest. They usually consist of a frontal system and/or an upper trough, with the air preceding the front or trough flowing from the south or southwest. As the front/trough passes through the area, the wind flow changes to the west, northwest, or north and the atmosphere cools. Clouds and precipitation may precede the front/trough passage, or they may mostly occur along the boundary of the colder air mass that moves into the region, and in some cases, continuing in the airmass behind the front or trough. For that reason, the seeding generators were situated to enable effective targeting in varying wind flow regimes, primarily ranging from southwesterly to northwesterly. Winds in meteorology are reported from the direction with which the winds are blowing. For example, a southwest wind means the winds are blowing towards the northeast.

The core 2021-2022 cloud seeding program for central and southern Utah began on November 15, 2021 and ended on March 15, 2022. However, due to exceptionally dry conditions over the past few years, it was decided to extend seeding operations for the core central and southern Utah Seeding program through April 30, 2022. This extension was in conjunction with the extension periods funded by the Lower

Basin States and Utah's Division of Water Resources, which ran from November 1-15 and March 16 – April 15. The seeding generators located in the central valley from approximately Milburn to Hatch were used in this program extension, as well as a few sites in the area near Koosharem, Antimony, and Loa, plus those in the vicinity of Brian Head and the Pine Valley Mountains. Seeding from the central valley sites would be expected to produce positive seeding effects on both the western and eastern slopes of the Wasatch Plateau. The eastern slopes of the Wasatch Plateau are tributary to the Colorado River. Seeding from these sites and those near Antimony would provide increases in precipitation on the western and eastern slopes of the Escalante Mountains (eastern slopes tributary to the Colorado River) and the Thousand Lakes and Boulder Mountains (also tributary to the Colorado River). Figure 2.2 is a map of the areas that contribute runoff to the Colorado River, areas where early and late-season time extensions to the seeding program were funded by the Lower Basin States. These areas are also included as part of the core program and so are subject to seeding operations during the entire seasonal period.

Figure 2.2 Portions of the Southern/Central Utah Program that contribute to the Colorado River

2.4 Suspension Criteria

NAWC has a standing policy of operating within guidelines adopted to ensure public safety. Accordingly, NAWC, working in conjunction with the Utah Division of Water Resources, has developed criteria and procedures for the suspension of cloud seeding operations (detailed in Appendix A). Due to a large number of wildfires during the past several years, NAWC's suspension criteria included situations that might impact several burn areas located with the central/southern Utah target areas during periods that might be conducive to debris flows. There were no seeding suspensions during the 2021-2022 season.

3. WEATHER DATA AND MODELS USED IN SEEDING OPERATIONS

NAWC maintains a 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 upper-air observations, satellite images, NEXRAD radar information, and local webcams. This information helps NAWC meteorologists to determine when conditions are appropriate for cloud seeding. Each of NAWC's meteorologists also has access to these same products at home, allowing 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 2021-2022 winter season.

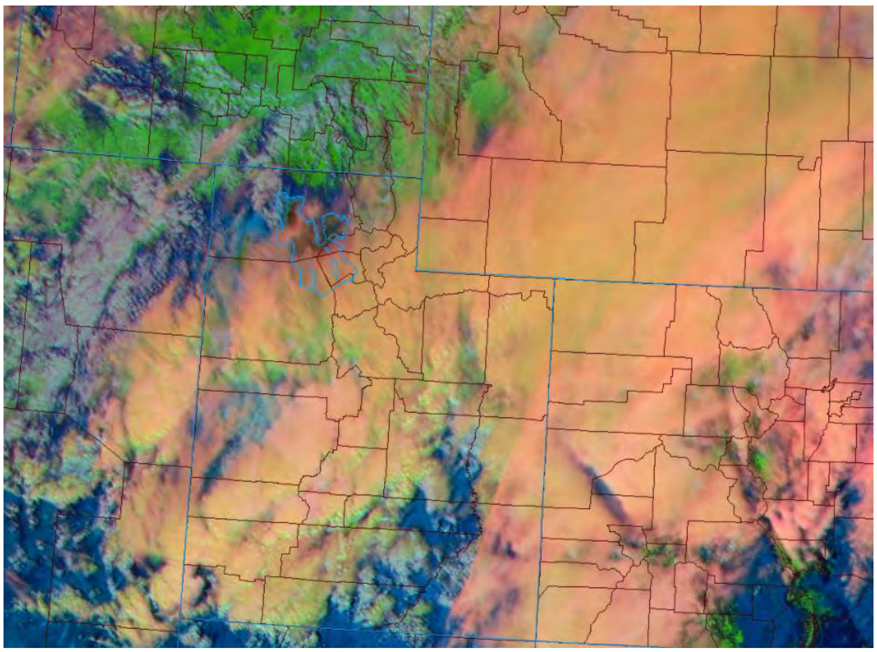


Figure 3.1 Visible spectrum satellite image at 1300 MST February 21, 2022 as a cold front moved southeast through Utah.

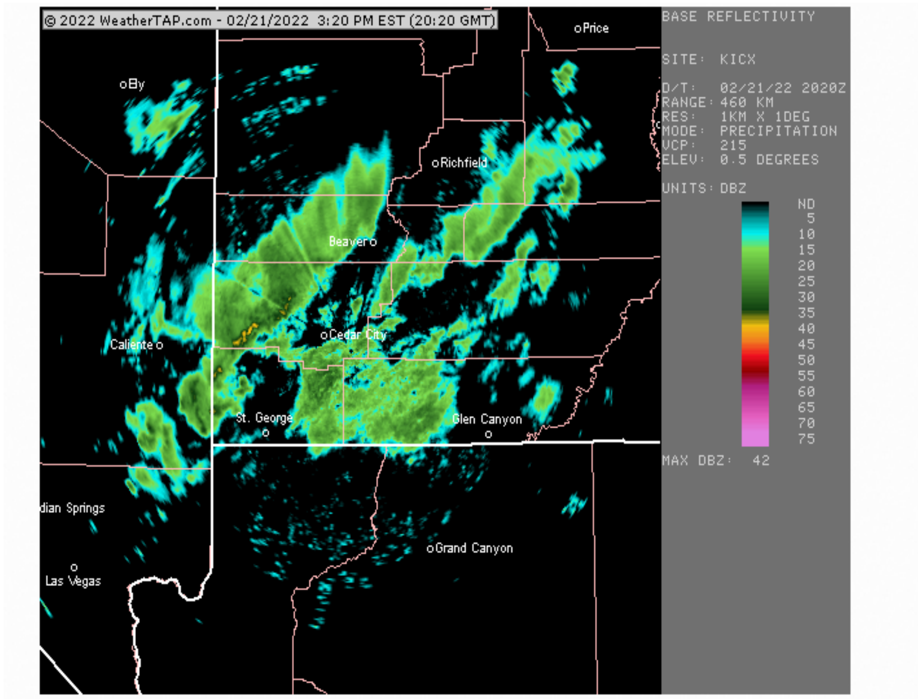


Figure 3.2 **Cedar City weather radar image at 1300 MST February 21, corresponding to satellite image in Fig 3.1**

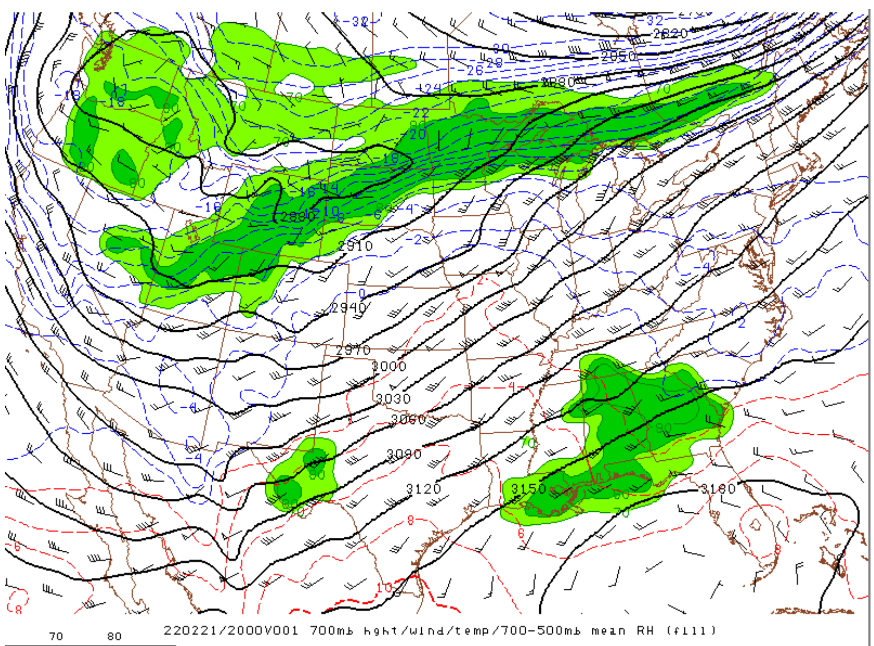


Figure 3.3 **700 mb map at 1000 MST on February 21, 2022, showing winds, temperatures, and moisture values at that level**

Global and regional forecast models are an important tool for operational cloud seeding decisions. 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 forecast from the North American Model (NAM) is shown in Figure 3.4.

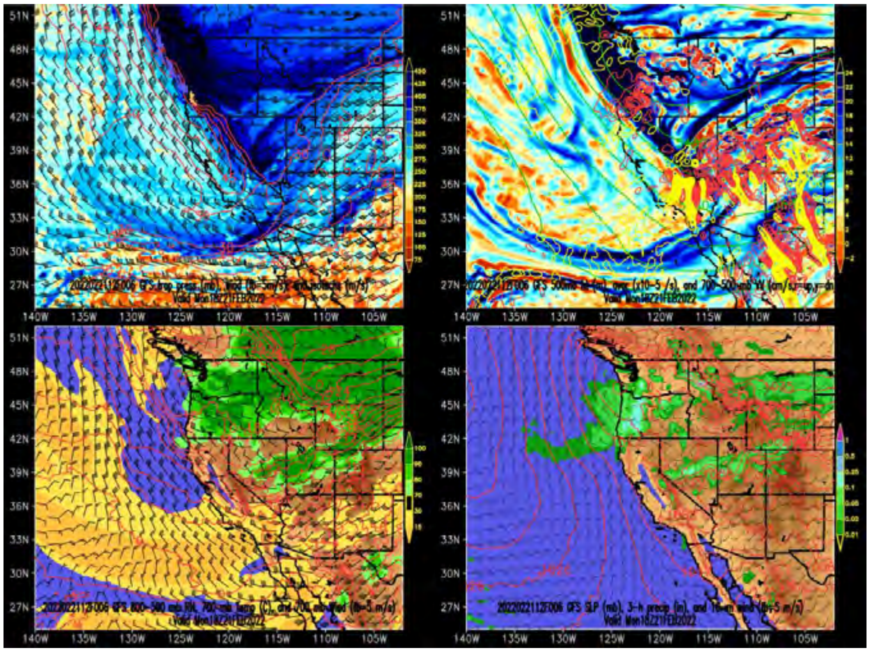


Figure 3.4 GFS model forecast (4-panel plot) during a storm event on February 21, 2022.

Figure 3.5 provides predictions of ground-based seeding plume dispersion for a storm period in central and southern Utah using the National Oceanic and Atmospheric Administration's HYSPLIT model (information provided in Appendix B). This model assists in estimating 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.

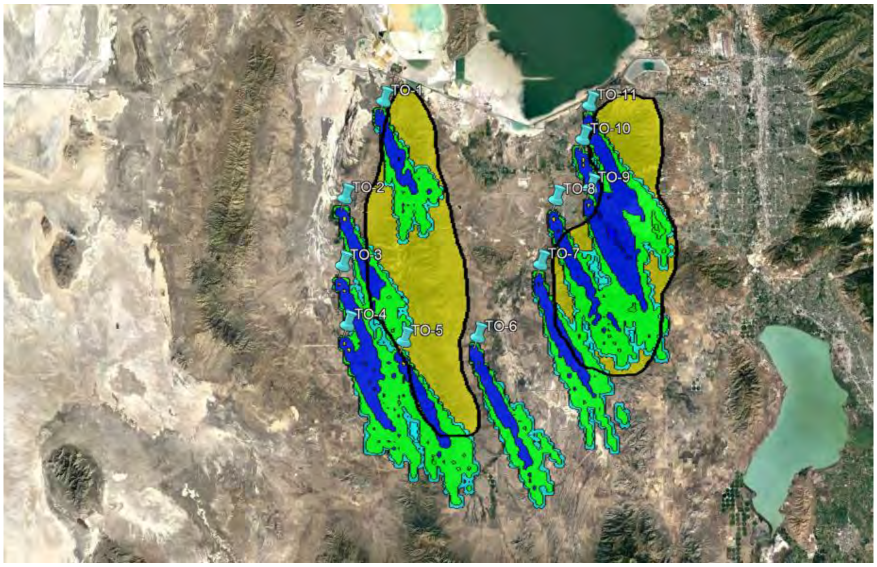


Figure 3.5 **HYSPLIT plume dispersion forecast from a seeding storm event on February 21, 2022, for the Tooele County target areas.**

An agreement between the three Lower Colorado River Basin States and the Utah Division of Water Resources has provided continued funding for icing rate meters and special precipitation detectors at two sites in Utah. One of them is located in the Central/Southern Utah project area, at Brian Head Ski Resort in southwestern Utah. The ice detectors are used to measure the occurrence of supercooled liquid cloud droplets, useful in making real-time seeding decisions, as well as for later analysis. The icing meter cycles when a certain amount of icing accumulates on a small probe. The probe is then heated briefly to de-ice the probe. Multiple cycles are indicative of likely favorable seeding situations, assuming that the other seeding criteria, especially temperature, are met. Figure 3.6 is a photograph of an installation at Brian Head, and Figure 3.7 is a close-up photo of the instrumentation at this site.

Figure 3.6 **Icing meter suite at Brian Head Ski Resort.**

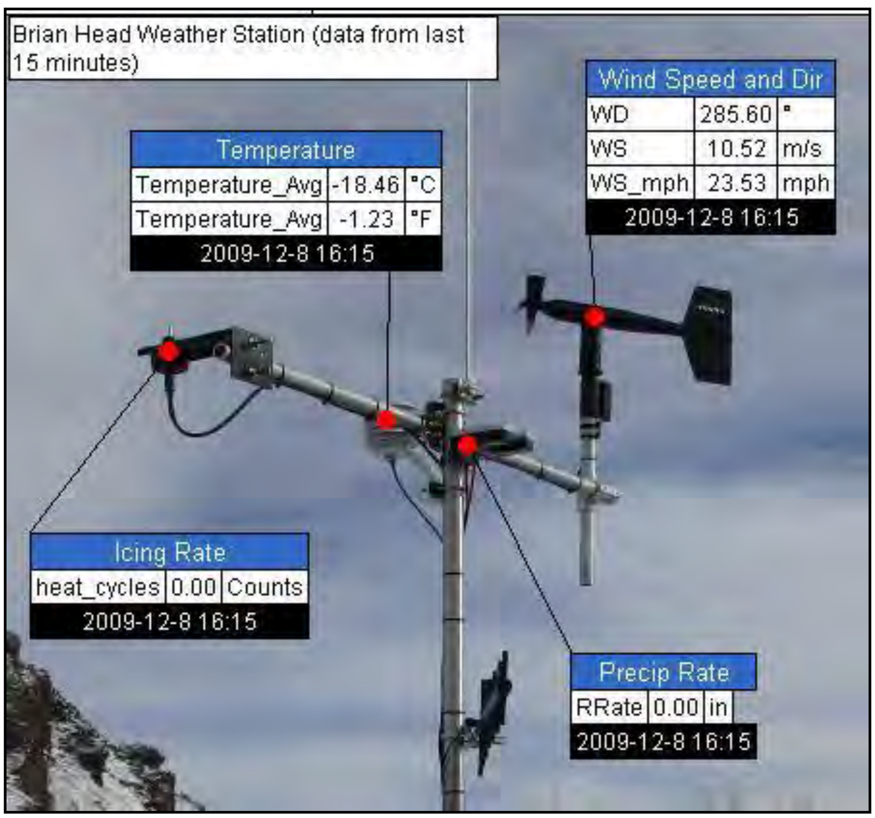


Figure 3.7 **Close-up photo of the special instrument suite at Brian Head.**

4. OPERATIONS

A total of 14 storm events were seeded during the main core program contract period (November 15th – March 15th), and 5 events were seeded during the Lower Basin extension period (March 16th – April 15th). There were no seeding opportunities during the November 1-15 portion of the Lower Basin States extension this season. In all, there were no seeded storm events in November, six events in December, two in January, three in February, seven in March, and two in April. For the regular contract period, a cumulative 2678.5 generator hours were utilized. For the Lower Basin extension, there was an additional 681.25 generator hours of seeding conducted. A special core program extension that ran during late March and April, intended to help alleviate severe drought conditions, resulted in an additional 591.25 generator hours of seeding. Figure 4.1 shows cumulative seeding hours for the core program this season with the special core program extension period of March 16 – April 30 included. Table 4-1 shows the dates and number of CNGs used for each of the storm events, and Appendix B shows detailed usage for the individual CNG sites.

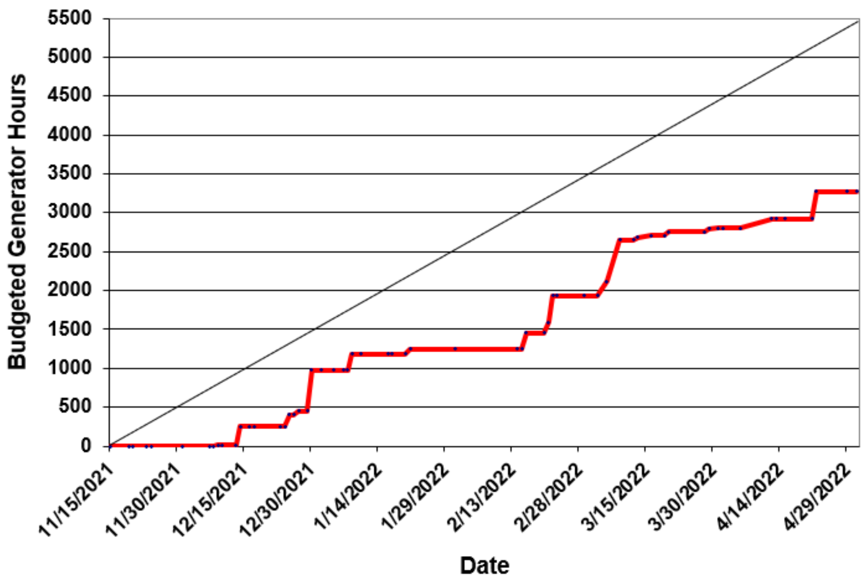


Figure 4.1 **Cumulative and budgeted seeding hours for the southern/central Utah core program and core program extension during the 2021-2022 season. Red line shows actual usage this season, while the black diagonal line depicts a linear usage of budgeted hours.**

Table 4-1
Storm dates and generator usage, 2021-2022 season

Storm No.	Date(s)	Number of CNG Sites		Number of Generator Hours		
			Primary Contract	Lower Basin Extension	Special Primary Extension	Total Hours
1	December 9	4	9.5			
2	December 14-15	19	239.5			
3	December 16	1	4.5			
4	December 25-26	11	146.5			
5	December 27-28	5	52			
6	December 30-31	35	527.25			
7	January 7-8	29	204.25			
8	January 20-21	9	66.25			
9	February 16	28	204			
10	February 21-22	16	136			
11	February 22-23	21	340.75			
12	March 5-6	26	183			
13	March 8-9	39	538.25			
14	March 13	4	26.75			
15	March 16	23		68.25	31.5	
16	March 20	31		101.5	45.5	
17	March 29-30	26		130	39.5	
18	March 31	15		89.5	4	
19	April 11-12	32		292	123.75	
20	April 22-23	37			347	
Total			2678.5	681.25	591.25	3951

As of April 1st, 2022, SNOTEL observations showed somewhat variable numbers for snowpack and cumulative water year precipitation, all below the seasonal average. The cumulative precipitation percentages of normal were higher than those of snowpack. This difference was largely due to a wetter than normal October, where a lot of precipitation fell as rain in the higher elevations. The lowest percentages overall for the season were in Tooele County, and the highest in Central Utah. The April 1 data are summarized in Table 4-2.

Table 4-2
Snowpack and Precipitation Percentages on April 1, 2022

River Basin	No. of Reporting Stations	Snow Water Percent of Median	Water Year Precipitation Percent of Average
Tooele County	**4**	**55%**	**85%**
Price - San Rafael	**8**	**86%**	**116%**
Beaver River	**3**	**103%**	**105%**
Upper Sevier River	**17**	**87%**	**94%**
Southwestern Utah	**10**	**70%**	**99%**

Figure 4.2 provides the percent of median values of April 1 snow water content for Utah. Figures 4.3 – 4.5 show October 1, 2021 – April 1, 2022 snow water equivalent, accumulated precipitation, and normal values for three SNOTEL sites.

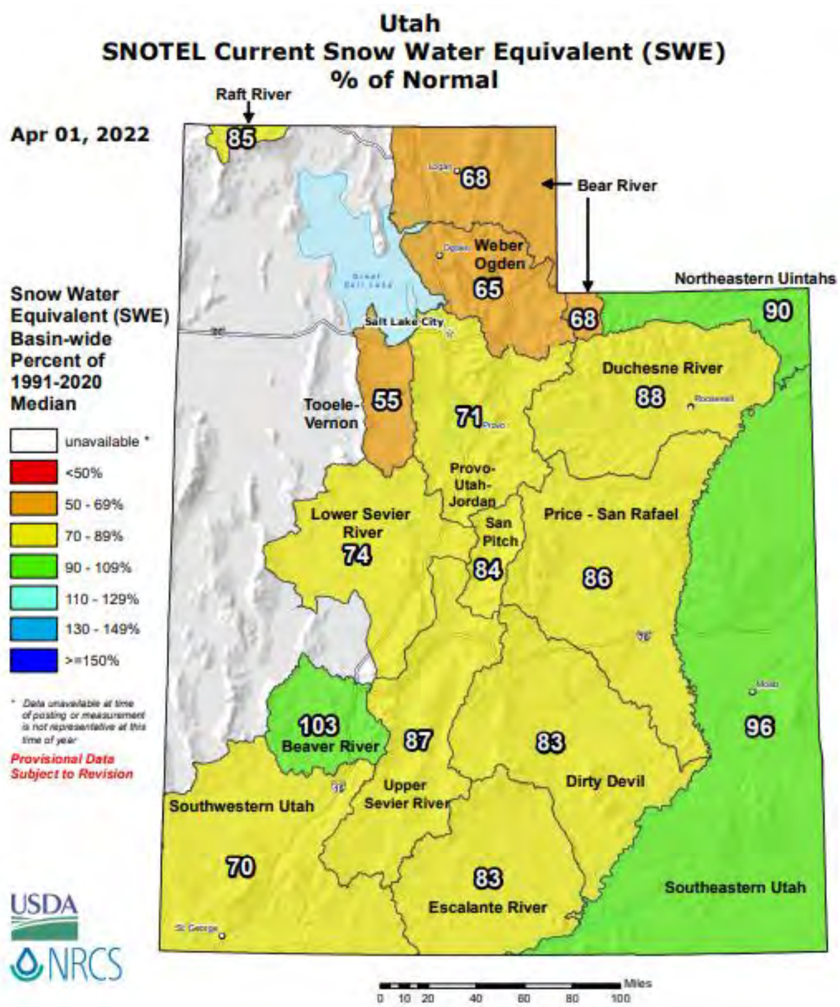


Figure 4.2 **Snow water content in Utah on April 1st, 2022 (percent of median)**

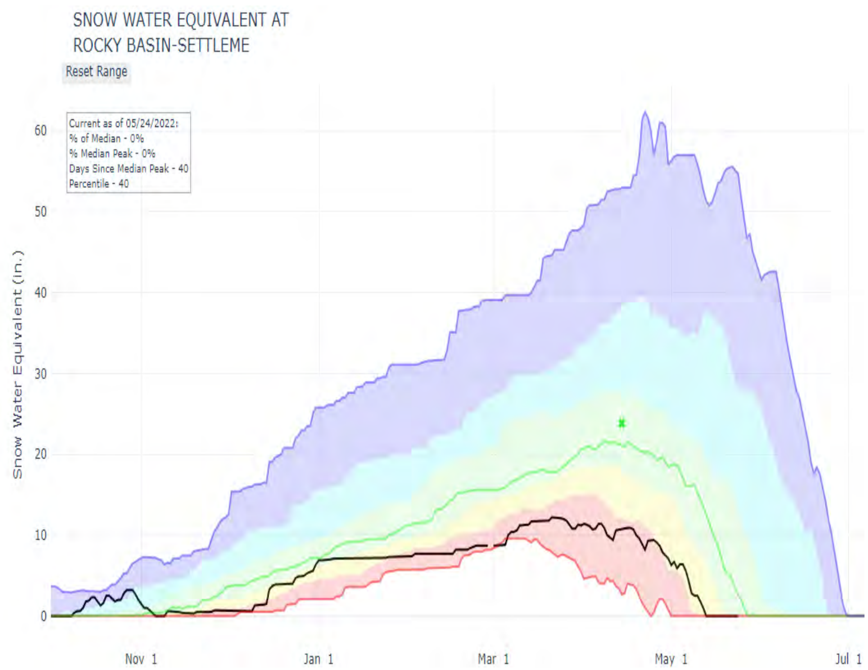


Figure 4.3 **NRCS SNOTEL snow water content plot for October 2021 through May 2022 for Rocky Basin-Settlement Tooele County. Black line is the 2021-22 season data.**

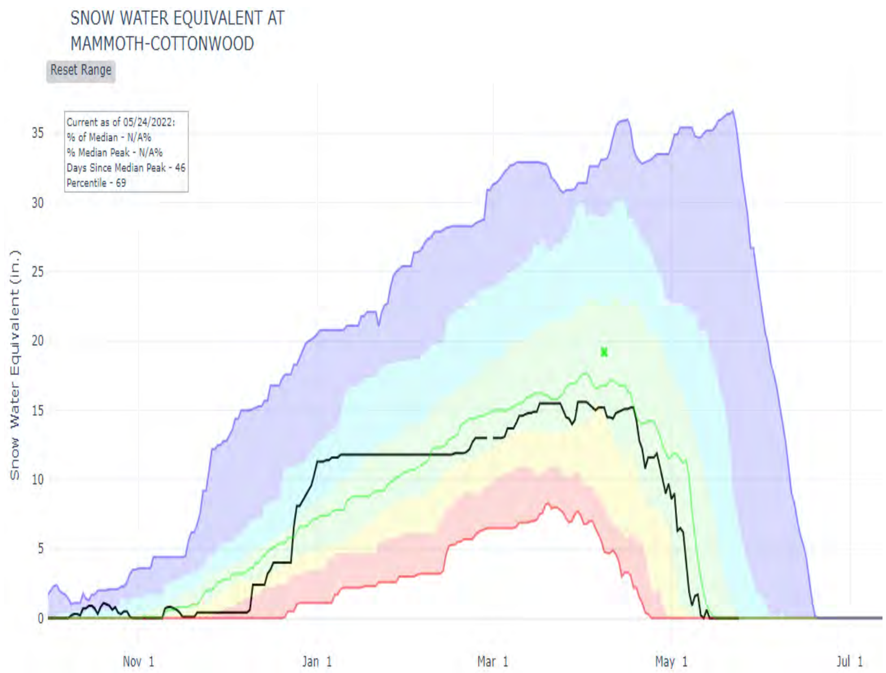


Figure 4.4 **NRCS SNOTEL snow water content plot for October 2021 through May 2022 for Mammoth-Cottonwood in Central Utah. Black line is the 2021-22 season data.**

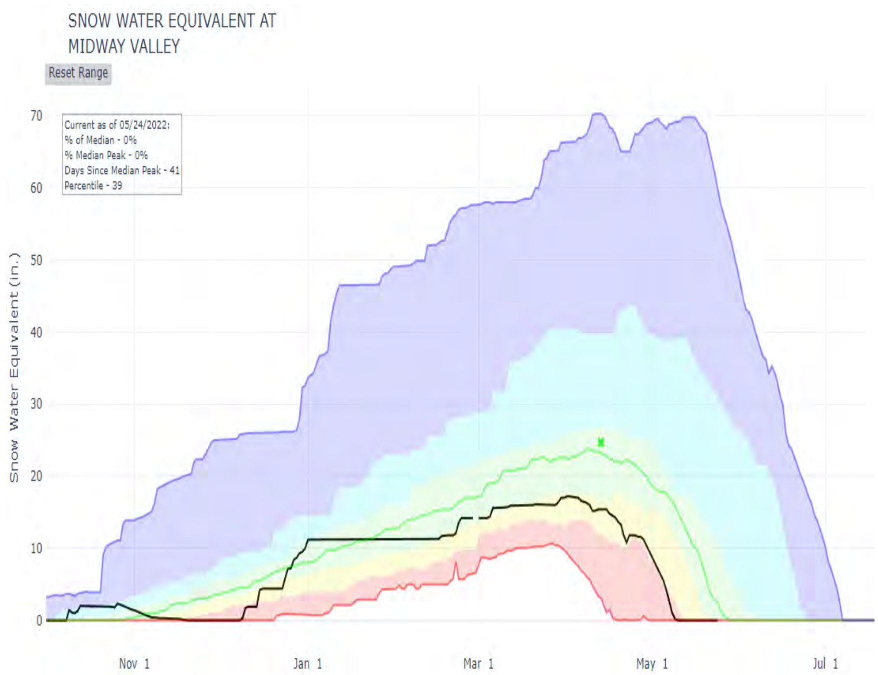


Figure 4.5 **NRCS SNOTEL snow water content plot for October 2021 through May 2022 for Midway Valley in southwestern Utah. Black line is the 2021-22 season data.**

4.1 Operational Procedures

In operational practice, an approaching storm was monitored at the NAWC operations center in Sandy with the aid of continually updated online weather information. Outside typical business hours, NAWC's meteorologists monitored the weather information using computer systems at their residences. If the storm parameters met the seedability criteria presented in Table 2-1 of Section 2 and no seeding curtailments or suspensions were in effect, an appropriate array of seeding generators was ignited and adjusted as conditions required. Seeding continued as long as conditions were favorable and precipitating clouds remained over the target areas. In a normal sequence of events, certain generators would be used in the early period of the storm passage, some of which might be turned off as the wind directions at various levels of the atmosphere changed, while others were used later to target the area in response to the evolving wind pattern. Some generator sites, due to their location, were used in a wider variety of wind flow situations than others and were thus used more often.

4.2 Operational Summary

A synopsis of the atmospheric conditions during operational seeding periods is provided below. All times reported are local, either in MST or MDT. This synopsis describes seeded storm periods, as well as some significant storm periods that were not seeded.

November 2021

The weather pattern through the month of November was largely dominated by high pressure and dry weather, with only a couple of weak storm systems pushing mostly dry cold fronts across the state. Figure 4.6 shows precipitation as a percentage of the average (mean) monthly values across the region in November. There no storms were seeded through the month of November.

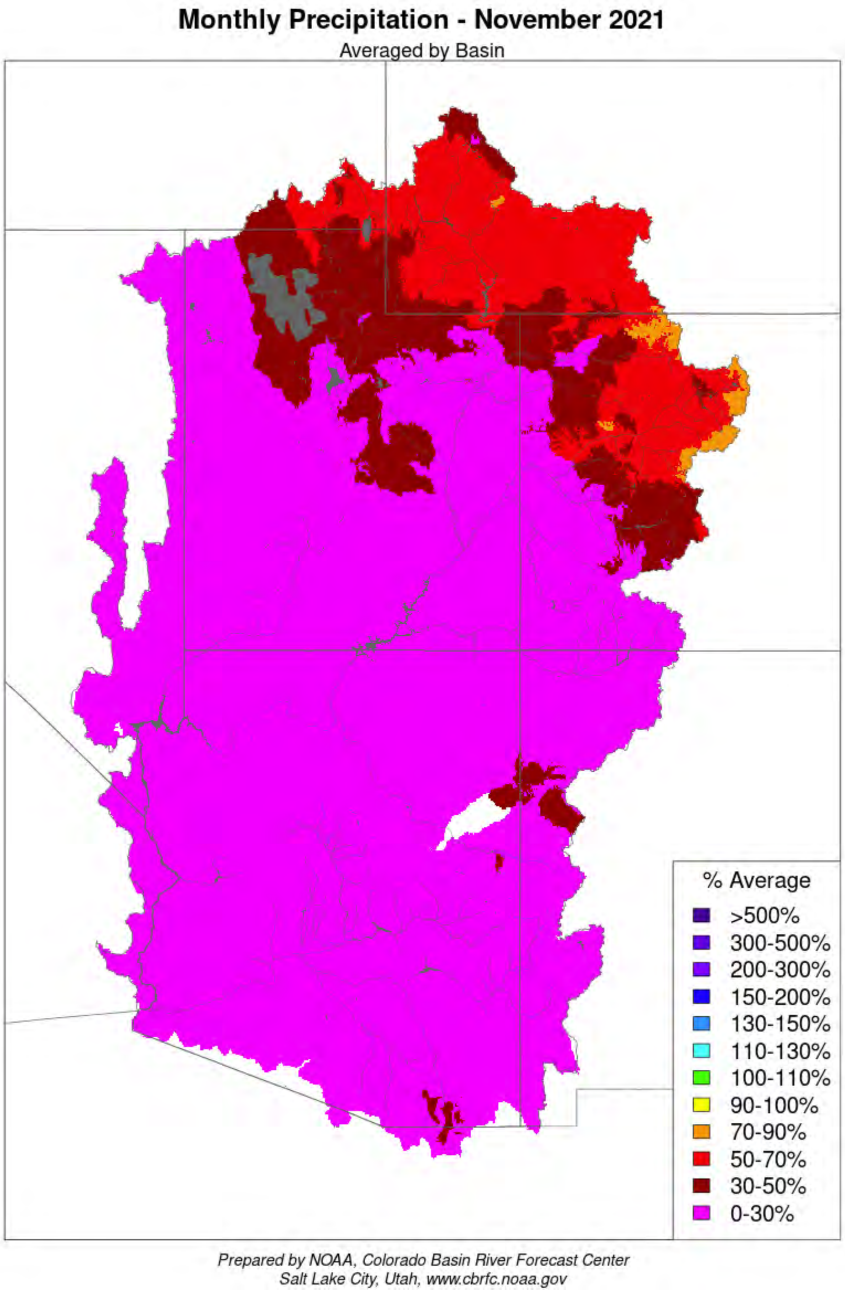


Figure 4.6 November 2021 precipitation, percent of normal

December 2021

December was characterized as a wet and active month with several moderate storms and a few stronger ones occurring. There were six seeding opportunities in December. Figure 4.7 shows December precipitation patterns as a percentage of the monthly average.

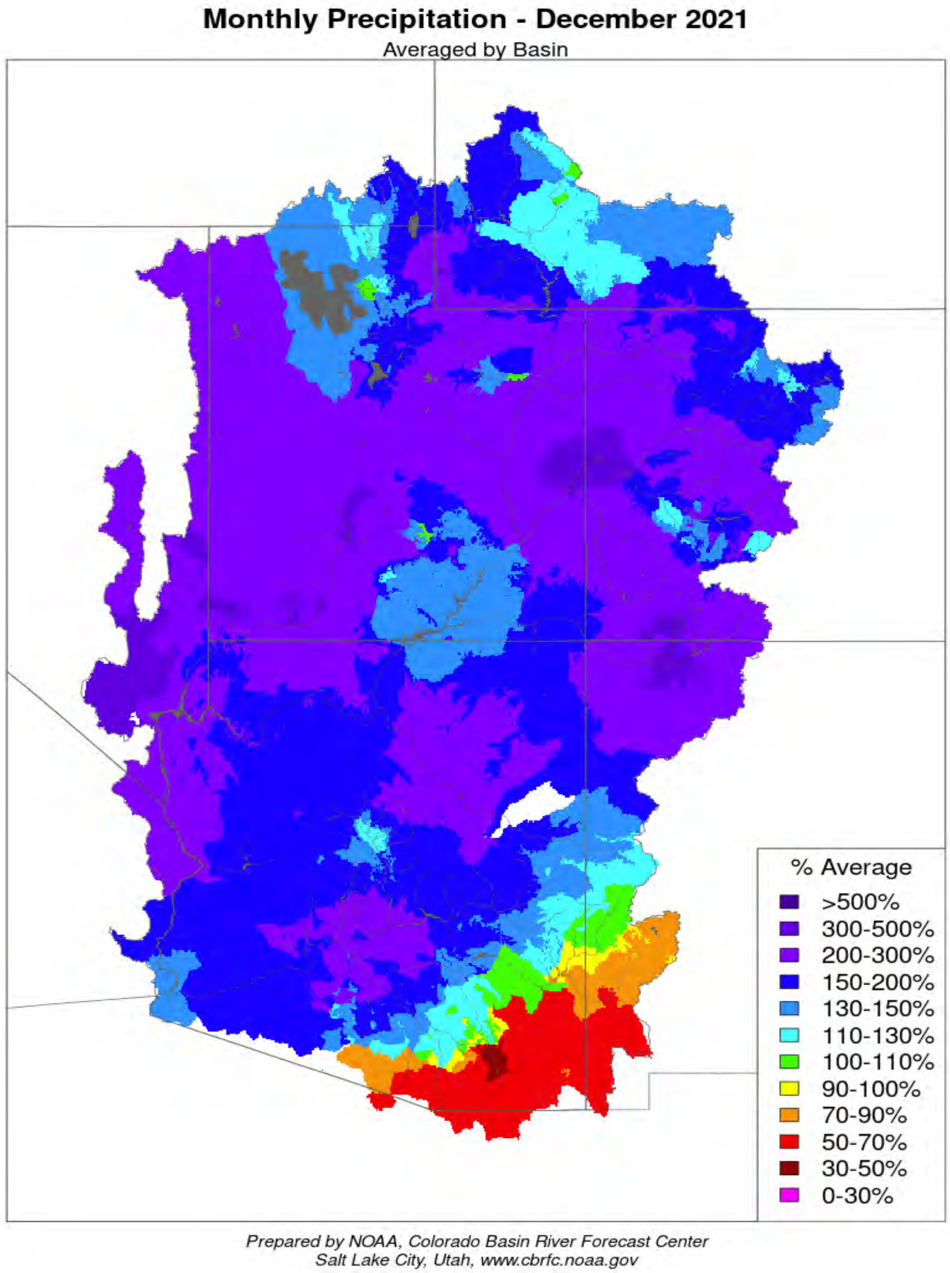


Figure 4.7 December 2021 precipitation, percent of normal

After dry weather in early December, a shortwave trough moved across the state December 8-9. As this trough approached the state on the evening of the 8th, it tapped into a plume of subtropical moisture that spread over northern Utah in a southwesterly flow pattern. This increase in moisture caused a shield of generally light snow to develop over northern Utah on the evening of the 8th. Generally light widespread snow continued overnight into the morning of the 9th while also progressing southward across the remainder of the state. 700-mb temperatures were initially too warm for seeding operations on the evening of the 8th with values reading around -3 to -4°C in northern Utah and around 0 to 2°C in central and southern Utah. Additionally, precipitation was originating form a high cloud deck which is unfavorable for cloud seeding due to natural self-seeding properties taking place within the storm. As colder temperatures filtered in across Utah on the 9th, 700-mb temperatures cooled down to near -10°C in northern Utah and down to around -4°C in southern Utah. Conditions had unfortunately begun to dry out over northern Utah by the time temperatures become favorable for seeding, but snow showers persisted across the southern portions of the state through the day in a southwesterly flow pattern. Seeding operations were initiated at some higher elevation sites near Brain Head due to temperatures being quite marginal. These sites ran for a few hours before snow showers ended early in the evening on the 9th. Precipitation totals with this system were around 0.6-2.0 inches of SWE in the Brian Head area and along the main spine of the Wasatch Range across central Utah, with much lighter amounts at lower elevations.

A rather strong and robust cold front quickly moved southeast and across the entire state of Utah on the evening of December 14. Somewhat warm and moist southerly flow developed out ahead of the cold front late in the afternoon hours on the 14th and resulted in snow showers over the mountains of far southern Utah (near Brian Head) and also over the Wasatch Range of northern Utah. 700-mb temperatures were initially on the warm side ahead of the front at around -3°C to -4°C, but radar returns showed that reasonable liquid water amounts were present and sites were activated. An abrupt wind shift to northwesterly was observed behind the frontal passage along with a rapid drop in temperatures, where 700-mb temperatures fell to near -11°C to -13°C. A narrow band of heavy snow with embedded thunderstorms also formed along and immediately behind the cold front as it progressed across the state. Additional sites were activated in Tooele County and in southern/central Utah to target the good mixing and high liquid water content that was embedded in this frontal band. Seeding operations continued overnight into the morning hours of December 15th as cold and moist northwesterly flow pattern kept orographic type snow showers going overnight for a majority of mountain locations. Seeding operations then ended by late morning on the 15th as drier conditions settle in. Storm totals were generally around 0.5 – 1.0 inches of SWE in most areas with some localized amounts to around 1.5 inches.

A weak trough moved across northern Utah on the evening of December 16th. Warm advection within a southwesterly flow pattern developed over the state on the morning of the 16th and allowed 700-mb temperatures to warm from around -12°C up to near -7°C. Light snow showers spread over northern Utah within this warm southwesterly flow pattern on the morning of the 16th, but conditions had become quite stable in the lower levels as a result. As the trough axis approached the northern portions of the state in the afternoon hours of the 16th, 700-mb temperatures cooled back down to near -12°C over northern Utah and instability increased. One site in Tooele County was activated around 1430 MST but was later turned off early in the evening by 1900 MST as radar data suggested that little liquid water was present with ongoing snow showers. Additionally, another stable layer in the lower levels had started to redevelop as the sun set. Precipitation totals from this system averaged about 0.1-0.2" of SWE in the Tooele County area.

The first in a series of shortwave troughs pushed a strong cold front southeastward and across Utah on the morning of December 26th. Strong southwesterly flow developed out ahead of this approaching storm on the evening of December 25th which spread a plume of moisture and a shield of snow over the mountain ranges of southern Utah. 700-mb temperatures ahead of the front were around -7°C and so a few sites across southwestern Utah that were favored in the southerly flow pattern were activated early in the evening on the 25th. Snow continued overnight across the southern portions of the state as moisture continued to stream up from the southwest. The strong cold front associated with the incoming trough then quickly moved across Utah from 0800-1100 MST on the morning of the 26th. A convective snow squall band developed along the leading edge of the frontal boundary which swept eastward and over the entire program area. Additionally, the flow quickly turned northwesterly behind the boundary and 700-mb temperatures rapidly fell to around -12°C to -14°C across the state. Numerous additional sites were activated in central and southern Utah to target the frontal boundary. No sites were activated in Tooele County as snow showers were briefly observed along the frontal boundary and conditions quickly dried out behind its passage. For southern Utah, seeding operations continued into the early afternoon hours before ending as quick drying ensued behind the frontal boundary. Precipitation totals from this system averaged about a half inch in central Utah and generally 0.5 – 1.0 inches in the southern mountains. Locally higher amounts up to 1.0-1.2 inches were noted in the Brian Head area.

The next in a series of storm systems brought another cold front across Utah on the evening of December 27th into the morning of the 28th. The cold front made its way across northern Utah around 1800 MST on the 27th and eventually across southern Utah around 0000-0100 MST on the 28th. A band of moderate and heavy snow developed along the frontal boundary as it quickly moved eastward and across the State. Similar to the storm on December 25-26, southwesterly flow ahead of the front quickly flipped northwesterly and 700-mb temperatures fell from around -10°C down to around -14°C. Moderate and heavy snow along the frontal boundary only lasted for a few brief hours, but orographic induced snow showers in cold and moist northwesterly flow behind the front kept snow showers going overnight into the morning hours of December 28th. No sites in Tooele County were activated again due to the very short duration of precipitation taking place. Several sites in southern and central Utah were activated around 2100 MST on the evening of the 27th and remained on overnight into the early morning hours of the 27th. Seeding operations then ceased after 0800 MST on the 28th as snow shower activity dried out and the storm moved eastward. Overall, the central and southern areas reported around 0.3-0.6 inches of SWE (Snow Water Equivalent) out of this storm.

The last in a series of storms finally moved across Utah on December 30-31. This last system came in three different features with seeding operations being conducted during only one of them. The first feature was a shortwave trough that moved through north and central Utah early in the morning of December 30. This produced a band of high based light snow across Tooele County. No seeding operations were conducted with this light band of snow as the cloud deck was measuring little to no liquid water and snow was originating from around 23,000 feet. The second feature was a closed low that was located off the coast of southern California. The position of this low forced warm and moist southwesterly flow to develop over the state late in the morning and afternoon hours on the 30th. This type of set up caused snow showers to fall over the mountain ranges of southern Utah. Snow showers were falling from a very thin and high cloud deck that had no measurable liquid water within it, so no seeding operations took place during this second feature either. The third and final feature was a cold short-wave trough, that swiftly swung southward and across Utah on the night of the 30th into the morning hours of the 31st. A 700-mb frontal boundary associated with this final feature also moved southward and over the state on the evening of the 30th. This frontal boundary was responsible for widespread snow shower activity that first developed over northern Utah around 1600 MST on the 30th and progressed southward into the evening hours. Sites in Tooele County were activated first around 1700-1800 MST on the 30th with sites in central and southern Utah being activated later around 2000-2100 MST. Broad southwesterly flow from earlier in the day turned northwesterly behind the frontal boundary and 700-mb temperatures cooled from around -6°C/-7°C down to near -8°C /-9°C. Seeding operations continued through the morning hours of the 31st as moist northwesterly flow kept snow shower activity going. An arctic airmass with 700-mb temperatures around

-14°C to -16°C then began to move in from the northwest during the afternoon hours of the 31st. This brought an end to seeding operations across the entire program area. Overall, Tooele County locations received around 0.25-0.7" of liquid precipitation accumulation with sites in central and southern Utah reporting around 0.7-1.8".

No icing meter data was available during the month of December 2021, due to the icing meter malfunctioning.

January 2022

January was a fairly dry month. The weather pattern for most of the month of January was largely dominated by high pressure and dry weather. A few weak and moisture starved storm systems were able to move through Utah at times, but often brought little more than a few high clouds and cooler temperatures. There were two storms that were seeded during the month of January. Figure 4.8 shows the monthly precipitation as a percentage of normal in January.

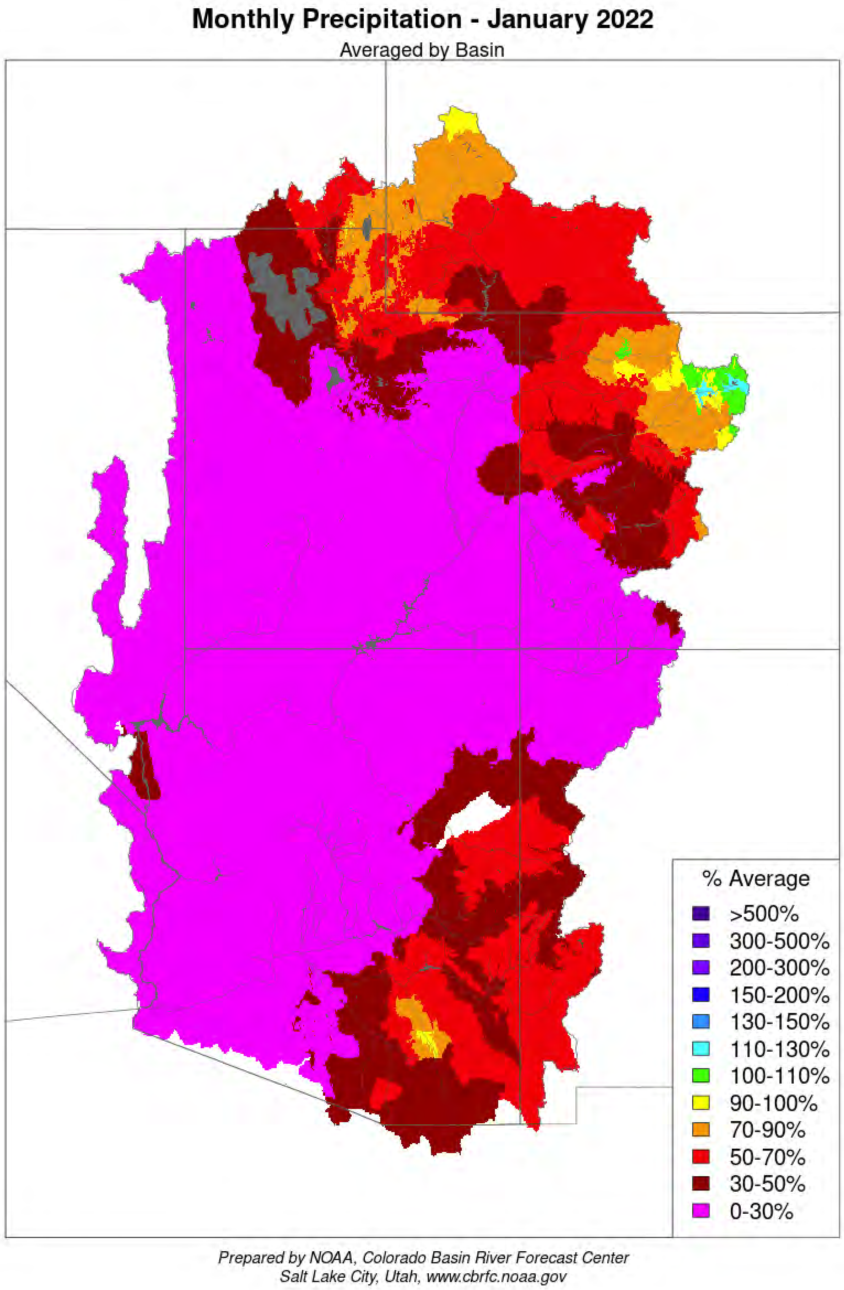


Figure 4.8 January 2022 precipitation, percent of normal

A weak trough and associated cold frontal boundary moved through northern and central Utah on the night of January 7-8. As the trough and associated frontal boundary began to move into northwest Utah on the evening of the 7th, the flow aloft turned northwesterly and 700-mb temperatures cooled from 2°C/4°C down to around -5°C/-6°C. Snow showers first started falling over far northwest Utah, but spread southward through the overnight hours. Sites favorable in northwesterly flow from Piute County northward were activated early in the evening and ran overnight. Observations in the early morning hours of January 8th revealed that conditions had largely dried out so seeding operations were ceased between 0800-1100 MST. Totals were around 0.2 inches or less.

After a couple weeks of dry weather, a weak shortwave trough moving southward along the Utah and Nevada border and brought a return of precipitation to central and southern Utah on January 21. As the trough moved southward during the morning hours on the 21st, snow showers developed over portions of southern Utah. The flow was mostly due northerly and 700-mb temperatures were generally around -10°C. Seeding operations were initiated at sites located in Iron and Garfield Counties around 0800 MST on the 21st, as this is where most of the snowfall activity was occurring. Seeding efforts continued until about 1700 MST, when conditions dried out and skies cleared. Precipitation totals ranged from about 0.05 to 0.3 inches of SWE in seeded portions of the target areas.

No icing meter data was available during the month of January 2022, due to the icing meter malfunctioning.

February 2022

February 2022 was another relatively dry month with only a few storm events impacting Central/Southern Utah, mainly during the second half of the month. As a result, there were only three storms that were seeded for the month of February. Figure 4.9 shows the February precipitation pattern across the region in comparison to average values.

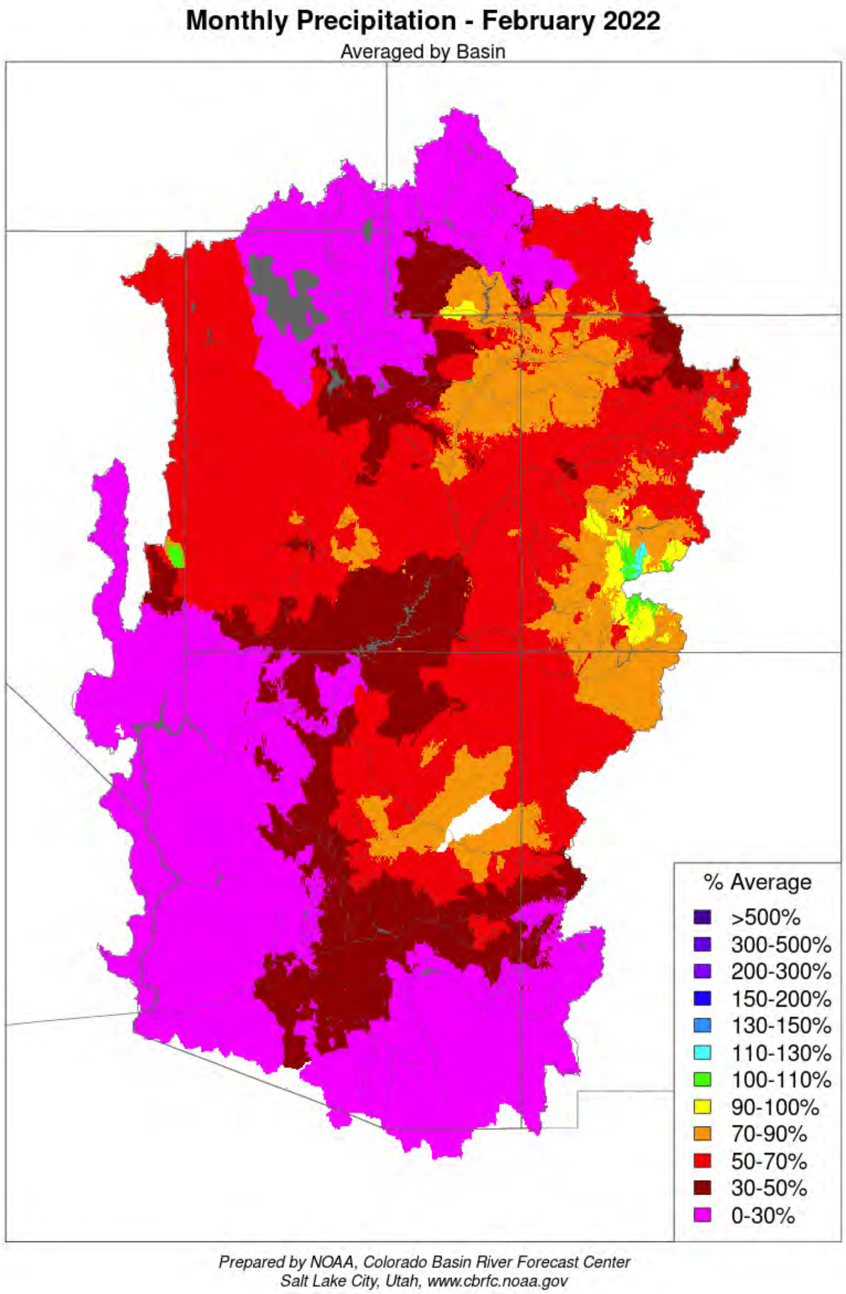


Figure 4.9 February 2022 precipitation, percent of normal

A shortwave trough propagated southward through the entire state of Utah on February 16th. The trough first moved through northern Utah early in the morning hours, then progressed southward into southern Utah and ultimately exited the state late in the evening hours. This shortwave provided forcing for ascent as it made its way through the state and allowed snow showers to develop. Cold advection associated with this wave (700-mb temperatures falling from about -6°C to -12°C) also increased instability that had previously been in place. Liquid water values were generally low within showers that developed, but seeing as it was the first storm to impact the state in almost a month, seeding operations were initiated. Sites in Tooele County were first turned on around 0900 MST with additional sites in Juab, Millard, Sanpete and Sevier Counties being activated around 1200 MST. Snow showers continued for most areas until about 1800 MST after which conditions dried out and seeding operations ended. Precipitation totals ranged from about 0.1 to 0.5 inches of SWE in Tooele County and around 0.1-0.6" in seeded portions of the central Utah.

A cold front started digging southward through Nevada on the morning of February 21. As this trough made its way southward through Nevada, it forced a previously stalled frontal boundary over northern Utah to restrengthen and to also start progressing southward. Snow showers initially began along the restrengthening frontal boundary over northern Utah early in the morning, but radar data indicated that these showers were lacking liquid water so no seeding operations were conducted in Tooele County. As the front slowly made its way into central and southern Utah, cooling aloft and better low level moisture improved cloud types for seeding operation, with more orographic and convective snow shower activity taking place. Seeding operations began late morning in central and southern Utah under a generally light northerly flow pattern. Seeding continued until about 2100 MST after which conditions dried out over most of the southern and central program areas. Precipitation totals with this system were mostly 0.2 – 0.5 inches with a few higher totals up to near 0.8 inches.

A mean longwave trough remained in place over the Western U.S. through February 22-23. Embedded within this longwave pattern were a couple of smaller troughs, one of which ejected northeast and through northern Utah prior to sunrise on the 22nd. Some light snow developed over Tooele County but no seeding operations took place as radar data and satellite imagery revealed that snow was falling from a high, thin, and icy cloud deck with cold 700-mb temperatures around -15°C. A second and more prominent trough then dove southward along the west coast during the afternoon hours of the 22nd and formed into a closed low overnight into the morning of the 23rd. As this trough propagated south on the 22nd it forced a warm front over Arizona to push northward and across Utah. 700-mb temperatures over southern and central Utah were in the -11°C to -12°C range ahead of the front but as it lifted northward, 700-mb temperatures warmed to up near -8°C. Moisture rich air within this warm boundary was forced up and over the cold air in place and caused moderate to heavy snow to fall over the mountain ranges of southern and central Utah. Generator sites in Washington, Iron, Garfield and Kane counties were activated around midday on the 22nd and were left on through the morning hours of the 23rd as periods of moderate to heavy snow continued to fall. Snow finally began to taper off around mid-morning on the 23rd and seeding operations were concluded. Precipitation totals with this system were mostly 0.6-0.8" in central Utah, but some locations (particularly Brian Head) received upwards of 2.0-2.5" of precipitation.

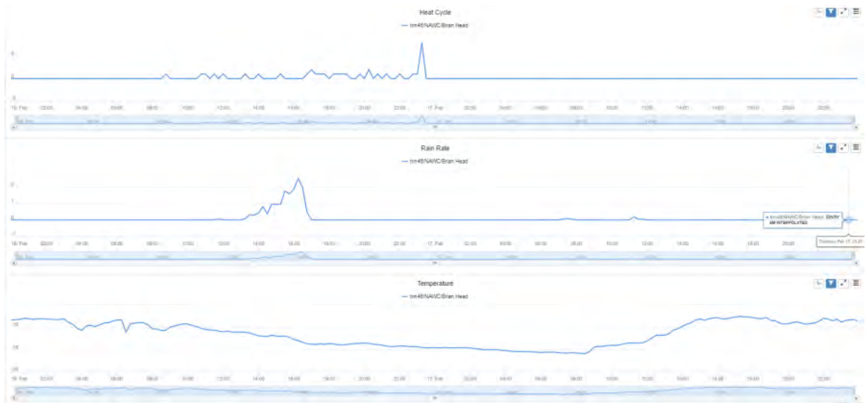


Figure 4.10 Brian Head precipitation, icing, and temperature for February 16

March 2022

The month of March was somewhat below average in terms of precipitation and snowfall, although the frequency of storm events was much more normal compared to January or February of this year. Snowpack accumulation followed a fairly typical pattern in early March, but a significant warm period later in the month reduced the snow water equivalent at many sites particularly at lower to mid elevations. Figure 4.11 shows monthly precipitation as a percentage of normal for March.

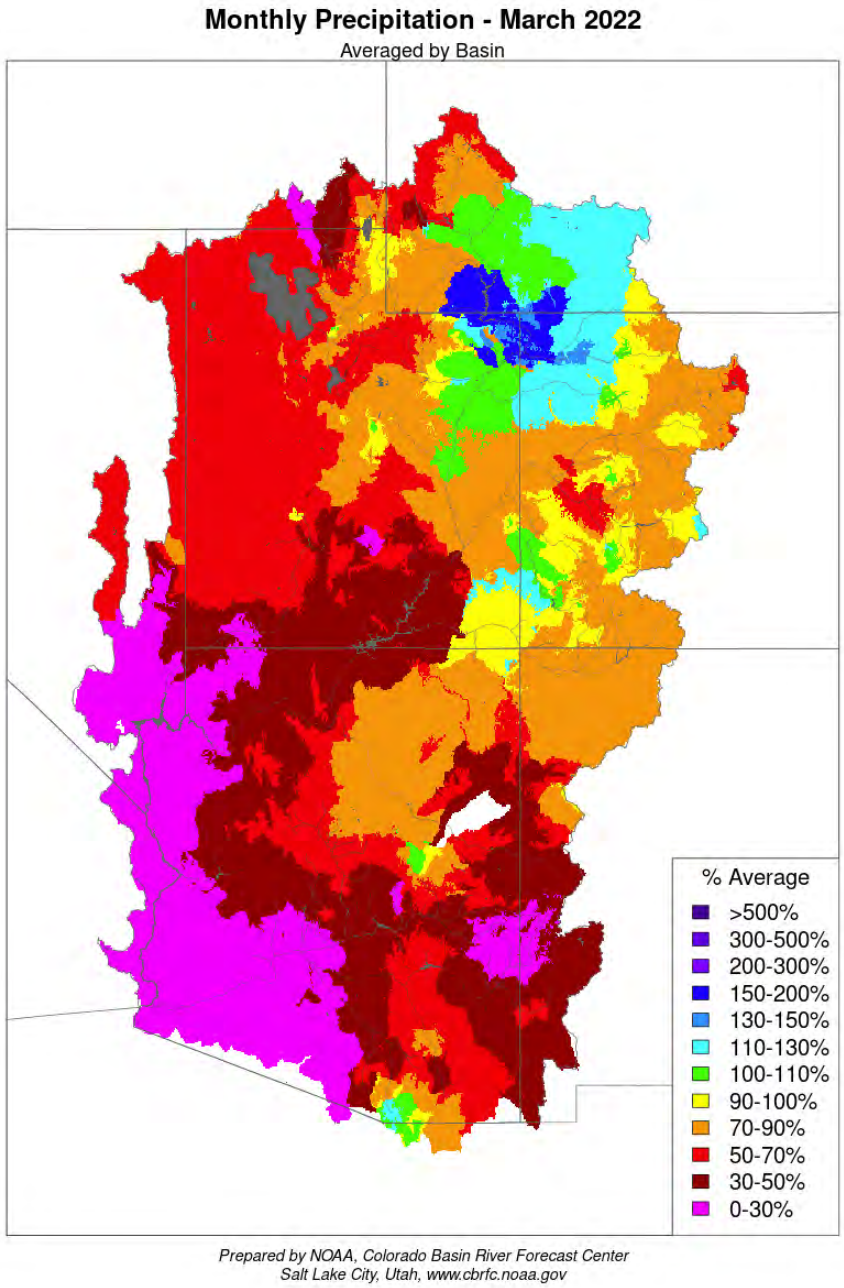


Figure 4.11 March 2022 precipitation, percent of normal

A broad and cold upper-level trough slowly made its way across southern Utah March 5-6. As the trough began to enter southern Utah from southern Nevada on the morning of the 5th, southerly flow out ahead of the system and its associated cold frontal boundary pulled a plume of moisture northward and over Utah. As moisture increased and spread northward through the morning and afternoon hours, widespread rain/snow showers and thunderstorms started developing. With 700-mb temperatures cooling to near -8°C as the trough and its associated cold front moved into Utah from the west, cloud seeding operations were initiated at sites favorable in southerly flow. Seeding operations continued into the early evening hours of the 5th, before ending across portions of central and southern Utah as showers and thunderstorms came to an end there. Further north, seeding operations continued in Tooele County overnight and into the morning of March 6 as the cold front had stalled over northern Utah and kept snow showers going in that area. The stalled frontal boundary then started progressing southeast and through Utah during the day on the 6th as the large trough moved eastward into southern Colorado and pulled the boundary along with it. This forced the flow across the state to turn northwesterly and also caused 700-mb temperatures to fall down to -14°C/-15°C. Snow showers continued across portions of Tooele County through about noon on the 6th before ending. Snow showers redeveloped across portions of Sanpete, Millard, Sevier and Piute counties as the flow turned northwesterly in the morning hours and continued through the early evening hours before ending there as well. As a result, seeding operations were re-activated for sites in these areas that do well in northwest flow and were terminated around 1700 MST on the 6th as conditions dried out. Observations revealed that around 0.8-1.5 inches of precipitation fell across Tooele County while locations in southern and central Utah received around 0.1-0.8 inches.

Another cold trough and its associated frontal boundary slowly moved southeast and across Utah March 8th through the 9th. Light snow within a westerly flow warm advection pattern began during the morning hours on the 8th. This snow was falling from a thin and icy stratus deck that was located at around 15,000 feet. Most of the falling snow was evaporating before reaching the ground due to a dry sub cloud environment that was in place so no seeding operations were activated. As the frontal boundary slowly worked its way southward into northern Utah during the evening hours on the 8th, it increased moisture and allowed snow shower activity to pick up, primarily over Tooele County and portions of Juab and Sanpete counties. Seeding operations were then activated at sites in these areas and continued overnight as snow showers persisted in a cold northwesterly flow pattern. Snow showers continued throughout the day on the 9th and also spread further south into central Utah as the cold front advanced southward across the state. Seeding operations continued through the day in Tooele County with a few additional sites being activated in Millard, Sevier, and Piute Counties as snow showers moved into those locations. By 2100 MST on the 9th, snow shower activity had started dwindling and as a result, cloud seeding operations were ceased.

A fast-moving trough swept across northern Utah on the 13th of March. Southwesterly flow ahead of the trough and its associated frontal zone spread moisture northward and over Utah. As a result, light snow developed over portions of Tooele and Juab Counties around 0800 MST on the 13th. Most of this light snow was falling from a cloud deck located at near 26,000 feet and with a dry sub cloud environment in place, most of the falling snow was evaporating before reaching the ground. By mid-morning the frontal boundary started to push into northern Utah and caused snow shower activity to increase. It also brought colder temperatures and forced 700-mb temperatures to drop from 0°C down to near -10°C. Several seeding sites were activated in Juab County through the afternoon hours, as numerous thunderstorms had popped up in this area. Seeding operations continued up until about 1900 MST as conditions began to dry out after that time. Locations in central Utah recorded around 0.2-0.3 inches of precipitation out of this storm.

A trough moving across Utah on the 16th cooled 700-mb temperatures down to near -8°C and also produced widespread showers and thunderstorms across portions of Utah. Cold advection in a northwesterly flow pattern provided a favorable environment for orographic snow showers across the northwest facing terrain of central and southern Utah. As a result, cloud seeding operations began around mid-morning and continued into the late afternoon hours. Seeding operations then gradually ended from north to south as snow shower activity dried out and shifted south into Arizona. Precipitation totals ended up being much higher than initially forecast with locations in southern and central Utah recording around 0.5-0.8 inches of SWE (Snow Water Equivalent).

A cold front pushed southeast and across Utah on March 20th. Strong and dry southwest flow ahead of the front early in the morning quickly turned northwesterly behind it and 700-mb temperatures fell from -2°C down to -8°C/-9°C. Rain/snow showers and a few thunderstorms developed along and immediately behind the frontal boundary. Seeding operations initially began in Tooele County at around 1000 MST as the front first made its way through northern Utah. Additional sites were then activated in central Utah and eventually southern Utah as the front progressed southward through the afternoon. Given that this was a fast-moving system, seeding operations only lasted a few hours before conditions quickly dried out on the back side of the front. Precipitation amounts were generally around 0.1-0.3 inches, but a few higher amounts up to near 0.8 inches were observed in southern Utah.

An open wave trough made its way through southern Utah on March 29th and then fully exited off to the east during the morning of March 30th. As the system made its way across southern Utah on the 29th, it spread a plume of moisture across the state and induced a northwesterly flow pattern. Cold advection within the northwesterly flow pattern combined with daytime heating and caused numerous showers and thunderstorms to break out over portions of southern and central Utah. Even though 700-mb temperatures were marginal and around -3°C to -4°C, seeding operations were activated at sites in Sevier, Millard, Iron, Kane and Piute Counties. Seeding operations continued into the early evening before activity wanned and conditions dried out after 2100 MST. A few of the higher elevation sites near Brain Head remained on overnight into the early morning hours of March 30th, as a few scattered showers persisted within the cold and moist northwest flow pattern. Precipitation totals with this system were mostly 0.2 – 0.6 inches.

A relatively weak trough crossed through Utah during the morning and afternoon hours on March 31. This system was lacking a frontal boundary but as 700-mb temperatures cooled down to near -4°C during the afternoon hours it caused scattered showers and thunderstorms to developed over locations in Tooele County as well as locations in central and southern Utah. Given that 700-mb temperatures were marginal for seeding, only a few sites were activated in Tooele County and in southern and Central Utah. As the sun set around 2000 MST, showers and thunderstorms dried out and seeding operations were terminated. Precipitation totals with this system were generally around 0.1 inches but a few higher totals near 0.5 inches were observed.

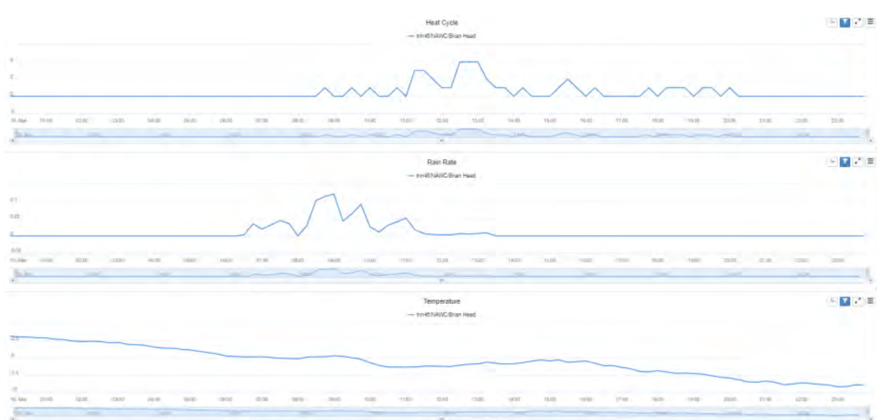


Figure 4.12 Brian Head icing, precipitaion, and temperature on March 16, 2022

April 2022

The weather pattern through the month of April was mostly dry across portions of southern and central Utah as the storm track remained largely focused over far northern Utah. Two separate storm systems were able to dig far enough south however, and brought two opportunities for seeding operations. One of the seeded periods in April occurred during the regular spring extension period funded by the Lower Basin States, with the other seeding period being conducted exclusively for the core program extension. Figure 4.13 shows precipitation patterns in April.

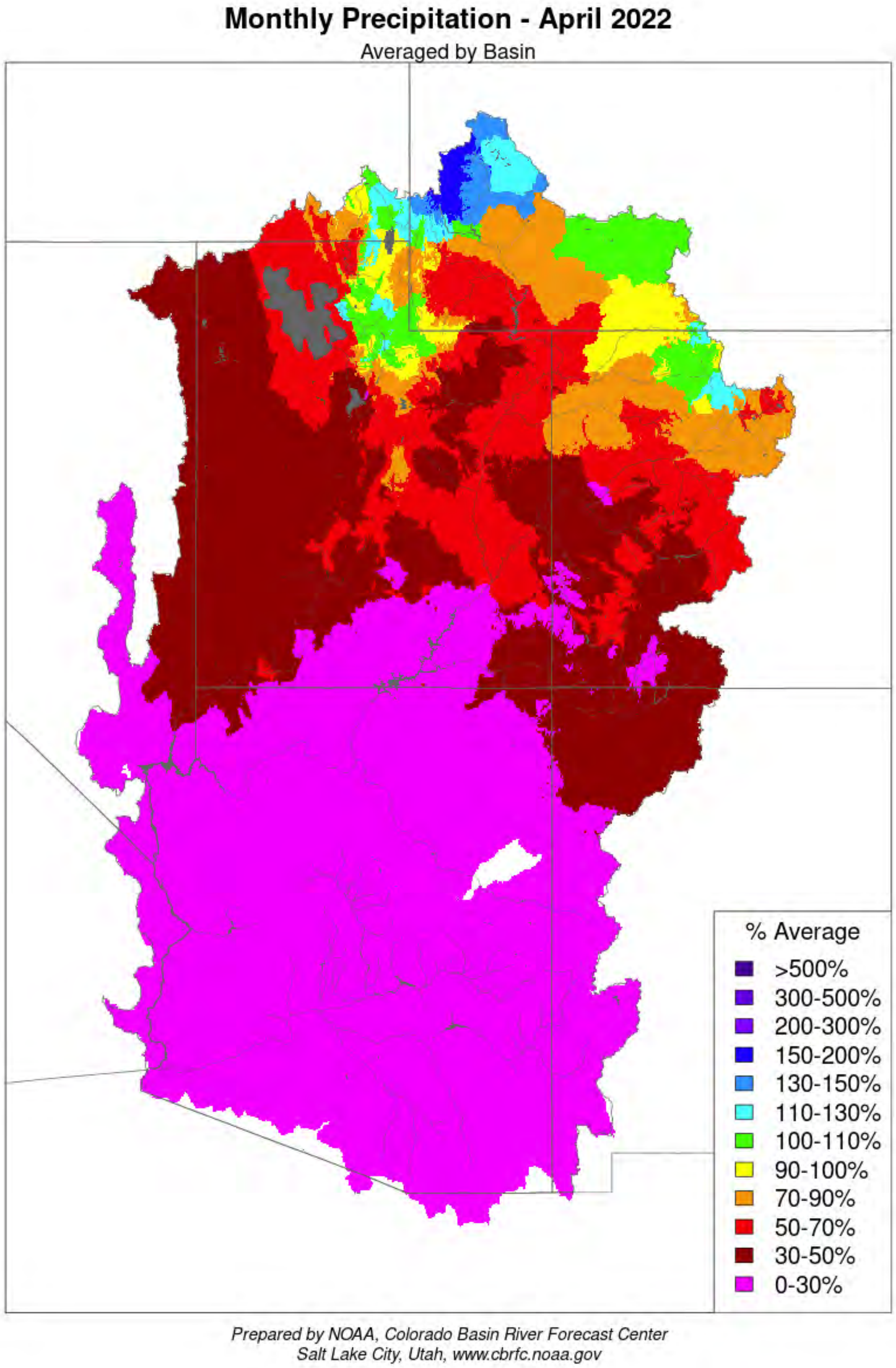


Figure 4.13 April 2022 precipitation, percent of normal

On the morning of April 11, a compact upper-level low moved southeast out of the Pacific Northwest and into the interior northern Rockies. An associated cold front pushed into far northwest Utah by mid-afternoon, then progressed southward through the state, reaching southern Utah by 2100 MST. A decaying atmospheric river within this system spread ample moisture out ahead of the cold front, and as a result, a band of moderate and heavy snow developed along the front. 700-mb temperatures were initially around 2°C ahead of the front but fell down to near -13°C behind it as much colder temperatures filtered in. Seeding operations began across Tooele County around 1700 MST on the 11th, with sites in central and southern Utah being activated around 1900-2100 MST as the front made its way into those areas during that time frame. Cold northwest flow behind the frontal passage kept snow showers going through the evening and overnight hours with seeding operations continuing into the early morning hours of April 12th. Around 0800 MST on the 12th, seeding operations ended in portions of southern Utah as conditions had dried out there. Seeding continued in Tooele County as well as in Sanpete County as lingering moisture and additional orographic instability in northwesterly flow kept showers going. All seeding operations then finally came to an end around 1700 MST on the 12th as snow showers had finally tapered off and the very cold air mass for mid-April settled in. Precipitation totals ranged from about 0.8 to 1.2 inches of SWE in Tooele County and around 0.1-1.8" in seeded portions of central and southern Utah.

The last and final storm of the 2021-2022 cloud seeding season took place April 22-23 as a trough moved through Utah. Modest upper-level lift from the incoming trough caused showers to develop over western Utah on the morning of the 22nd. Coverage of showers then spread eastward and over the remainder of Utah through the afternoon with numerous thunderstorms developing as instability increased from daytime heating. Given it was likely the last storm of the season and 700-mb temperatures were around -8°C, all available sites were activated. Seeding ended for sites located in Iron, Garfield, Kane, Piute and Millard Counties early in the evening hours on the 22nd, but continued overnight and through the 23rd for areas in Tooele and Sanpete Counties as unstable northwest flow and lake enhancement kept snow showers going in these areas. It wasn't until around 1700 MDT on the 23rd that all seeding operations were terminated as conditions had finally dried out. Precipitation totals ranged from about 0.5 to 1.0 inches of SWE in Tooele County and around 0.1-1.0" in seeded portions of the central and southern Utah.

Figure 4.14 Brian Head icing, precipitation, and temperature for April 22-23, 2022

5. ASSESSMENTS OF SEEDING EFFECTS

5.1 Background

The seemingly simple issue of determining the effects of cloud seeding has received considerable attention over the years. Evaluating the results of a cloud seeding program is often a rather difficult task, however, and the results, especially single-season indications, should be viewed with appropriate caution. The primary reason for the difficulty stems from the large natural variability in the amounts of precipitation that occur in a given area. The ability to detect a seeding effect becomes a function of the size of the seeding increase relative to the natural variability in the precipitation pattern. Larger seeding effects can be detected more readily, and with a smaller number of seeded cases than are required to detect smaller increases.

Historically, in weather modification, the most significant seeding results have been observed in wintertime seeding programs for snowpack augmentation in mountainous areas. The apparent increases due to seeding are generally less than 20% for individual seasons, and in the range of 5-15% for the long-term average. This section of the report summarizes statistical evaluations of the effects of the cloud seeding on the precipitation and snowpack within the higher elevations of this program's targeted areas. When expressed as percentages, the increases may not initially appear to be particularly high. However, when considering that these increases are area-wide averages covering thousands of square miles, the volume of the increased runoff is impressive.

NAWC has used a commonly employed evaluation technique since this seeding project was first evaluated following the 1978 water year. This technique, referred to as the target and control comparison, is based on evaluating the effects of seeding on a variable that would be affected by seeding (such as precipitation or snow water content). Records of the variable to be evaluated are acquired for an historical (non-seeded) period of sufficient duration, ideally 20 years or more. These records are partitioned into those that lie within the designated seeded target area of the project and those in appropriate control areas. Ideally the control sites are well-correlated with the target area sites but would be unaffected by the seeding. All the historical data, e.g., precipitation, in both the target and control areas are taken from a period that has not been subject to cloud seeding activities, since past seeding could affect the development of a relationship between the target and control areas. These two sets of data are analyzed mathematically to develop a regression equation which estimates (calculates) the most probable amount of natural target area precipitation, based on the amount of precipitation observed in the control area. This equation is then used during the seeded period to estimate what the target area precipitation should have been in the absence of cloud seeding. A comparison can then be made between the estimated natural target area precipitation and that which occurred during the seeded seasonal periods.

This target and control technique works well where a good statistical correlation can be found between the target and control area variables. Generally, the closer the control sites are to the seeding target area, the higher the correlation will be. Control sites which are too close to the target area, however, can be subject to contamination by the seeding activities. This can result in an underestimate of the seeding effect. For precipitation and snowpack assessments, correlations of 0.90 or better are considered excellent and correlations around 0.85 are good. A correlation of 0.90 indicates that over 80 percent of the variance (random variability) in the historical data set is explained by the regression equation.

Correlations less than about 0.80 are still acceptable, but it would likely take much longer (many more years of comparison) to attach any statistical significance to the apparent seeding results.

5.2 Evaluation Approach

With the establishment of the Natural Resources Conservation Service's (NRCS) SNOTEL automated data acquisition system in the late 1970's, access to precipitation and snowpack (water equivalent) data in mountainous locations became routine. Before the automated system was developed, these data had to be acquired by having NRCS personnel visit the site to make measurements. This is still done at some sites. Historically, Utah has had snowpack measurements taken at monthly intervals for many years and unlike many other states, precipitation measurements are available from some of these same high elevation sites. Precipitation and snowpack data used in the analysis were obtained from the NRCS and/or from the National Climatic Data Center. The current season NRCS data are considered provisional and subject to quality control analysis by the NRCS.

There have been, and continue to be, multiple cloud seeding programs conducted in the Utah and some surrounding states. As a consequence, potential control areas that are unaffected by cloud seeding are somewhat limited. This is complicated by the fact that the best correlated control sites are generally those closest to the target area, and most measurement sites in this part of the state have been subjected to contamination at some time by numerous historical and current seeding programs. This renders such sites of questionable value for use as control sites. The potential effects of other cloud seeding projects beyond (downwind) their intended target areas is a consideration especially when selecting control sites. Some earlier weather modification research programs have indicated that the precipitation can be affected in areas downwind of the intended target areas. Analyses of some of these programs have indicated increases in precipitation in these downwind areas out to distances of 50-100 miles. Thus, control sites for evaluation of the southern and central Utah seeding program are located in areas that are not expected to be significantly affected by any current or historical seeding operations.

Our normal approach in selecting control sites for a new project includes looking for sites 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 a particular upper airflow pattern while other seasons are dominated by other flow patterns. These different upper airflow patterns and resultant storm tracks often result in heavier precipitation in one area versus the other. For example, a strong El Nino pattern may favor the production of heavy winter precipitation in the southwestern United States while a strong La Nina pattern may favor the production of below normal precipitation in the southwest. Having control sites either side of the target area relative to the generalized flow pattern can improve the estimation of natural target area precipitation under these variable upper airflow pattern situations.

Another 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. Fortunately, missing data (typically on a daily basis) are noted in the historical data base so that sites can be excluded from consideration if they have much missing data. We normally eliminate a site if it has significant amounts of missing data. If a significant measurement site move (more than a mile or change in elevation of 100-200 feet) is indicated in the station records, this may also be a factor. The double-mass plot, an engineering tool, will indicate any systematic changes in relationships between the two stations. If changes (shown as inflections in the slope of the line connecting the points) are significant, a site or sites may be excluded from further consideration.

Using the target-control comparison described above, the mathematical relationships for two variables (precipitation and snow water equivalent, or SWE) were determined between a group of sites in an unseeded area (the control group) and the sites in the seeded area (the target group). From these data, regression equations were developed whereby the amount of precipitation or SWE observed in the unseeded (control) area was used to estimate the amount of natural precipitation in the seeded (target) area. This estimated value is the amount of precipitation or SWE that would be expected in the target area without seeding. The difference between the estimated amount and the observed amount in the target area is the excess, which may be the result of the seeding. Statistical tests have shown that such increases have very little statistical significance for an individual season, and usually fall within one standard deviation of the natural variability. However, an excess obtained by averaging the results of several seeded seasons is much more meaningful.

5.3 Evaluation of Precipitation in the Target Area

In past years several target areas have been evaluated to assess the efficacy of cloud seeding, by examining the precipitation observed at the gauges within the seeded targets. For the current water year, two target areas (see Figure 1.1) were again evaluated. An attempt has been made to consistently utilize the same groups of target and control sites from one season to the next, although there have been a few changes over the years as some sites were discontinued. The following describes the techniques that were used in selection of the target and control sites.

Precipitation Target Sites

The northernmost seeded target in the Central/Southern program is the East Tooele Target (ETT). That area contains the mountain watersheds of the Stansbury and Oquirrh Mountains, located in the eastern portions of Tooele County, south of the Great Salt Lake. Due to the scarcity of available target sites, this target group also includes a valley-level precipitation gauge (Tooele, just over 5,000 feet MSL), as well as a site (Vernon Creek) somewhat south of the official target areas. The locations of the three remaining precipitation gauges that were used in the evaluation for this target are listed in the target area portion of Appendix C and shown in Figure 5.1. The three target SNOTEL gauges are located in the Stansbury and Oquirrh Mountain ranges. The average elevation of the target gauges is 7,157 feet, MSL. Additional high elevation sites in the Stansbury and Oquirrh Mountain Ranges would be desirable in order to provide a more accurate evaluation of seeding effects in these target areas.

The Primary Target area is represented by 25 precipitation gauge sites. A few of the target site gauges are NWS cooperative observer sites, but the large majority consists of SNOTEL storage gauges. These sites are shown in Figure 5.2. The sites are located throughout the target area and should provide a representative data set for the evaluation. The average elevation for the target gauge array is about 8,800 feet MSL.

Precipitation Control Areas

The control site array for the precipitation evaluation of the Eastern Tooele Target seeding operation was the same group of control sites used in recent seasons' evaluations. The control group consists of six gauge sites, listed in Appendix C and shown in Figure 5.1. Four sites are located in eastern Nevada and two in northern Utah.

The precipitation evaluation control sites used for the Primary Target (PT) area evaluation are located in eastern Nevada and north central Arizona (bracketing the PT area on the northwest and southeast). The locations of these sites are shown in Figure 5.2.

Most of the sites in the control area are NRCS SNOTEL gauges at mountain locations, although in the case of the primary target area of southern/central Utah, other gage sites significantly help the control versus target correlation. These sites have generally remained the same for a significant number of years, except for any necessary changes due to discontinued sites or poor data quality. Elimination or replacement of some lower elevation (non-SNOTEL) co-op sites has been necessary in some cases, and in the past a few data estimates for individual co-op sites have been necessary to fill in small data gaps. During the past two seasons, a couple of existing control sites of this type, Caliente and McGill in eastern Nevada, did not have data available. A number of possibilities were examined, included simply dropping these sites and producing a new regression equation, or replacing them with other sites in eastern Nevada or western Utah, upwind of the target areas. However, most of the lower elevations sites correlate poorly to the much wetter seeding target areas, and all options explored for a revised control set resulted in lower correlation of the control/target set and a substantially higher year to year variability of the evaluation results. Because of this situation, data estimates were produced for these two control sites for this season based on data from the nearest available sites of similar type. This allows the control set that has been used previously to stay in use for the time being in this particular target/control evaluation. The Tooele County precipitation evaluation, and all those based on snowpack, have different control sets and so are unaffected by the missing data at these two sites.

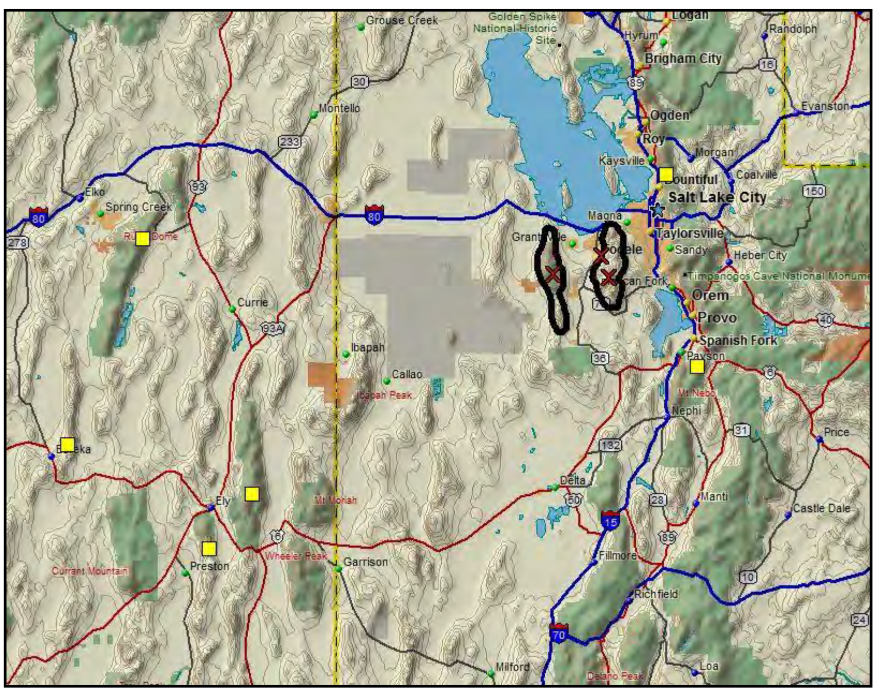


Figure 5.1 **Precipitation sites for Eastern Tooele target/control evaluation; control sites are depicted as squares and target sites with an X.**

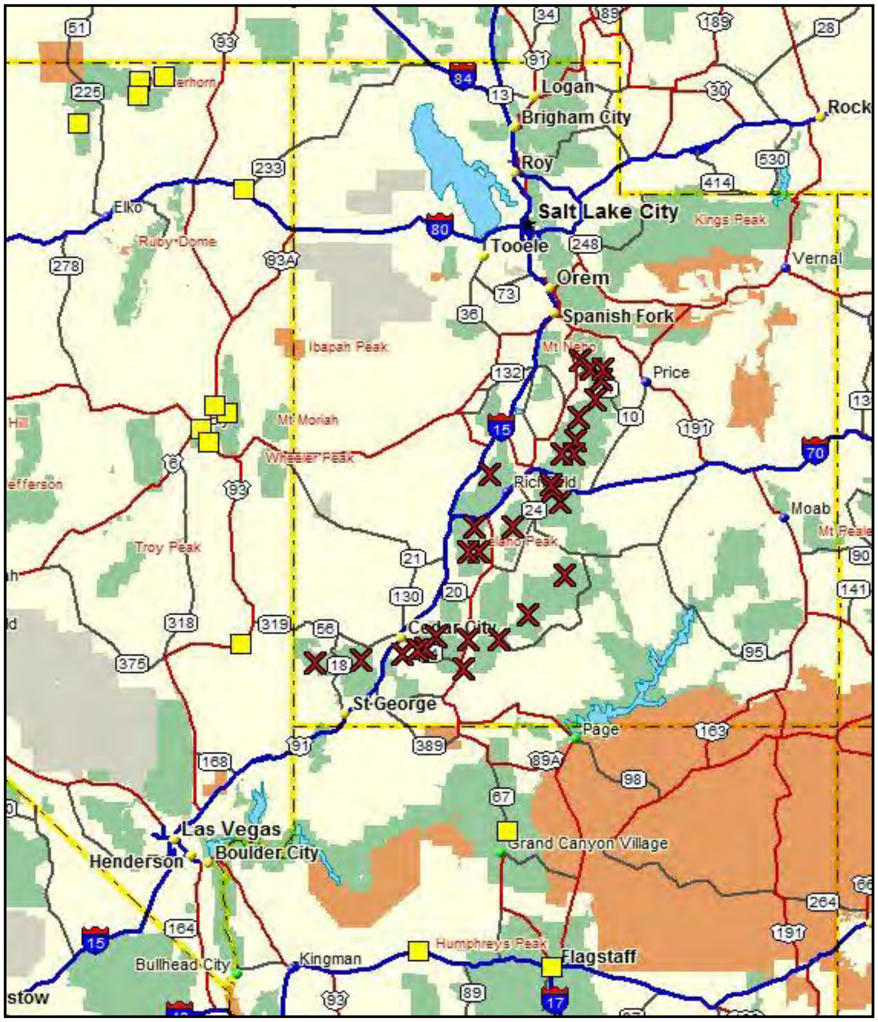


Figure 5.2 **Precipitation target (X) and control (square) sites, primary target area.**

Precipitation Data Compilation

The evaluation was conducted for the December through March period, which represents the period during which operational cloud seeding has been conducted in nearly all the seeded water years, although in a few historical years the latter half of March has not been seeded. Precipitation data for some of the higher elevation target sites were obtained from storage gauge sites. Observations were taken at approximately monthly intervals before the conversion to the NRCS SNOTEL technology, which (at most sites) occurred in the early 1980's. With the advent of the NRCS SNOTEL system, data are available on a daily and even hourly basis, which eliminates some of the timing problems in the earlier data sets. Precipitation amounts for the December-March period were summed for each station, in the two target areas and their respective control areas. Averages were calculated for each of the groups for each individual four-month (December-March) season. The four-month averages for the historical (unseeded) seasons were then used to develop a linear regression equation for the target, which was in turn used to estimate the target area natural precipitation for the seeded period.

In the ETT, the historical (non-seeded) base period includes 28 non-seeded seasons (1957-75, 1983-88, and 1993-95). Seeded years in the ETT target include water years 1976-1982, 1989-1992, and 1996-2022 (38 seeded seasons). A reasonably good correlation between the control and target stations was established, with a correlation coefficient (r value) of 0.78. Target and control sites are listed in Appendix C. The control area sites are shown schematically on Figure 4.1 relative to the East Tooele Target area. Their average elevation is 8,348 feet MSL.

The historical period in the PT consists of an 18-year period (1957-73, and 1984). Seeded years began in 1974 in the PT and continued through 1983. Although seeding resumed in the southern portion of the PT in 1985, it was not until 1988 that a majority of the PT was being seeded again. Therefore, the 1985-87 period has been excluded from the evaluation, with target-wide seeding resuming in 1988 and continuing through the current water year. This provides a total of over 40 seeded seasons for evaluation. The regression analysis between the 12-site control area and the 25-site target area for the 18-year historical period (December-March, 1957-73, 1984 water years) provided an excellent correlation between the two groups. The correlation coefficient (r) is 0.96. This is a very strong correlation and should provide an accurate assessment of predicted natural precipitation in the target area during seeded seasons. The sites that make up the control and target areas are listed in Appendix C. The control area sites (denoted by squares) are shown schematically on Figure 4.2 relative to the Primary Target area. Their average elevation is 7,032 feet MSL.

The linear regression equation developed from the historical relationship between the control and target groups is of the following form:

$$Y_C = A(X_O) + B$$

where Y_C is the calculated average target area precipitation (inches) for a specific period (e.g., December-March), and X_O is the control average observed precipitation for the same period. The coefficients A and B, the slope and y intercept values from the historic regression equation are constants.

The seeding effect (SE) can be expressed as the ratio (R) of the average observed target precipitation to the average calculated (estimated) natural target precipitation, such that:

$$SE = R = (Y_O)/(Y_C)$$

where Y_O is the target area average observed precipitation (inches) and Y_C is the target area average calculated precipitation (inches).

The seeding effect can also be expressed as a percent excess (or deficit) of the expected precipitation in the form:

$$SE = (Y_O – Y_C) / (Y_C \text{ x } 100)$$

The regression equations and the historical correlation coefficients for the two target areas are presented in Table 5-1. The stations which constitute each control/target group are listed in Appendix C.

Results of Precipitation Analyses

Table 5-2 provides the ratios of the observed average target area December-March precipitation to the calculated (from the regression equation described above) for the two target areas. A ratio equal to 1.0 would indicate no difference between the observed and predicted precipitation amounts. The difference between these values is also provided to show the average difference (inches) in precipitation during the seeded periods. Tables 5-3a and 5-3b list the results for each seeded season for the Eastern Tooele Target Area and Primary Target Area, respectively.

Table 5-1
Correlation coefficients, variances, and regression equations for precipitation evaluations

Target Group	Equation	Correlation Coefficient (r)	Variance (r^2)
Eastern Tooele (ETT)	$Y_C = 0.88(X_6) – 0.69$	0.78	0.61
Primary Target (PT)	$Y_C = 1.69(X_{12}) – 3.17$	0.96	0.91

Where:

Y_C = Average calculated precipitation for target (December - March)

X_6 = Average two state (NV/UT) control area observed precipitation for December - March for 6 sites

X_{12} = Average two state (AZ/NV) control area observed precipitation for December - March for 12 sites

Table 5-2
Precipitation evaluation results for the 2021-2022 December-March season and for all seeded seasons

Target Group	**Seeded Period**	**Ratio**	**Increase (inches)**
E. Tooele Co.	38 Seeded Water Years	1.12	1.3
	2022 Water Year	0.99	-0.1
Primary Target	45 Seeded Water Years	1.12	1.3
	2022 Water Year	1.44	3.4

The ratio shown in Table 5-2 is the ratio of average observed target area precipitation to average calculated target area precipitation, and the increase is the absolute increase in inches of water.

Table 5-3a
Eastern Tooele Co. (ETT) Target area
Summary of December - March precipitation evaluations

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
1976	10.3	9.4	1.10	0.9
1977	6.6	6.9	0.96	-0.2
1978	20.7	16.3	1.27	4.4
1979	12.5	11.5	1.09	1.0
1980	19.6	15.8	1.24	3.8
1981	8.9	9.3	0.95	-0.5
1982	15.5	16.3	0.95	-0.8
1989	11.0	10.8	1.02	0.2
1990	9.8	7.7	1.27	2.1
1991	8.4	7.4	1.13	1.0
1992	7.4	7.4	1.01	0.1
1996	14.2	14.2	1.00	0.0
1997	15.0	12.9	1.16	2.1
1998	20.2	14.6	1.39	5.6
1999	9.3	8.8	1.05	0.5
2000	15.2	12.5	1.21	2.6
2001	9.4	8.3	1.12	1.0
2002	8.4	8.4	1.00	0.0
2003	8.7	7.6	1.14	1.1
2004	15.0	11.1	1.34	3.8
2005	15.4	13.4	1.15	2.0
2006	15.4	14.7	1.05	0.7
2007	9.9	8.3	1.19	1.6
2008	14.7	12.7	1.15	2.0
2009	13.6	13.2	1.03	0.4
2010	11.5	11.2	1.03	0.3
2011	16.6	14.9	1.11	1.6
2012	8.5	7.1	1.19	1.3
2013	9.5	8.3	1.15	1.2
2014	10.4	9.0	1.15	1.3
2015	6.2	6.0	1.03	0.2
2016	13.2	11.9	1.10	1.2
2017	18.8	16.8	1.12	2.0
2018	8.6	7.8	1.10	0.8

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
2019	17.3	15.5	1.11	1.8
2020	8.4	8.6	0.98	-0.2
2021	9.4	9.0	1.04	0.4
2022	8.3	8.4	0.99	-0.1
Seeded Mean	**12.2**	**11.0**	**1.12**	**1.3**

Table 5-3b
Primary Target (PT) area
Summary of December - March precipitation evaluations

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
1974	11.3	11.3	1.00	0.0
1975	12.8	12.1	1.06	0.7
1976	9.9	9.9	1.01	0.1
1977	6.4	4.6	1.40	1.8
1978	20.3	18.7	1.08	1.6
1979	16.3	14.5	1.12	1.8
1980	20.5	16.7	1.23	3.9
1981	9.3	8.0	1.16	1.3
1982	16.9	16.1	1.05	0.8
1983	17.5	15.0	1.17	2.5
1988	9.8	7.2	1.36	2.6
1989	10.2	10.3	0.99	-0.1
1990	9.1	7.8	1.17	1.3
1991	10.8	8.0	1.34	2.7
1992	10.2	7.6	1.34	2.6
1993	19.7	19.0	1.04	0.7
1994	8.7	6.5	1.35	2.3
1995	14.0	12.0	1.17	2.0
1996	12.9	12.2	1.05	0.7
1997	12.2	11.6	1.05	0.5
1998	14.4	12.6	1.14	1.8
1999	6.9	6.4	1.07	0.4
2000	12.4	10.8	1.15	1.7

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
2001	9.5	6.8	1.39	2.7
2002	6.2	6.7	0.92	-0.6
2003	9.6	6.6	1.45	3.0
2004	11.0	9.2	1.20	1.8
2005	15.9	14.2	1.13	1.8
2006	13.7	13.1	1.04	0.5
2007	7.2	7.4	0.98	-0.2
2008	15.1	11.7	1.28	3.3
2009	13.1	11.6	1.13	1.5
2010	13.8	11.1	1.24	2.7
2011	16.6	14.3	1.16	2.3
2012	8.7	7.9	1.09	0.7
2013	9.2	8.9	1.04	0.4
2014	7.9	7.1	1.10	0.7
2015	8.4	7.7	1.09	0.7
2016	11.4	11.7	0.98	-0.3
2017	16.1	18.0	0.89	-2.0
2018	8.6	7.2	1.20	1.4
2019	15.7	15.3	1.03	0.4
2020	10.1	10.4	0.98	-0.2
2021	9.3	8.4	1.12	1.0
2022	11.0	7.6	1.44	3.4
Seeded Mean	12.0	10.7	1.12	1.3

Eastern Tooele Target Precipitation Results

Seeding began in the ETT in 1976 and continued through the 1982 water year. Seeding resumed in 1989 and continued through 1992. After a break in seeding during water years 1993-95, seeding resumed in the 1996 water year and has been conducted each year through the present. Thus, there are 38 seeded seasons and 28 non-seeded seasons in the regression period. For the single season (2021-2022) evaluation, the regression equation resulted in an observed/predicted ratio of 0.99 as shown in these Table 5-3a. This is a 1% decrease from that predicted by the control sites without seeding. It is important to remember that single-season evaluation results can vary significantly due to variability in precipitation patterns from one year to another, and, thus, a single-season result carries very little statistical significance. This variability primarily affects the results of the evaluation, not necessarily the actual effectiveness of the seeding. **During the 38 seeded seasons the observed precipitation within the target has averaged 12 percent greater than might have been expected from calculations based on the control**

precipitation averages. That increase is equal to an average additional 1.3 inches of water per seeded season. Note that the December-March evaluations do not estimate any possible additional effects of seeding which was conducted outside this four-month core evaluation period (e.g., November 15th-30th, April 1st-15th).

Figure 5.3 is a scatterplot showing a comparison between the seeded and non-seeded data sets in the eastern Tooele County precipitation linear regression. The linear regression equation (e.g. best linear fit to the historical non-seeded data, shown in black) is represented by the black diagonal line. Note that the vast majority of the seeded season data (red dots) lie above the regression line, indicative of greater target area precipitation in seeded seasons than that predicted from the regression equation based upon control area precipitation.

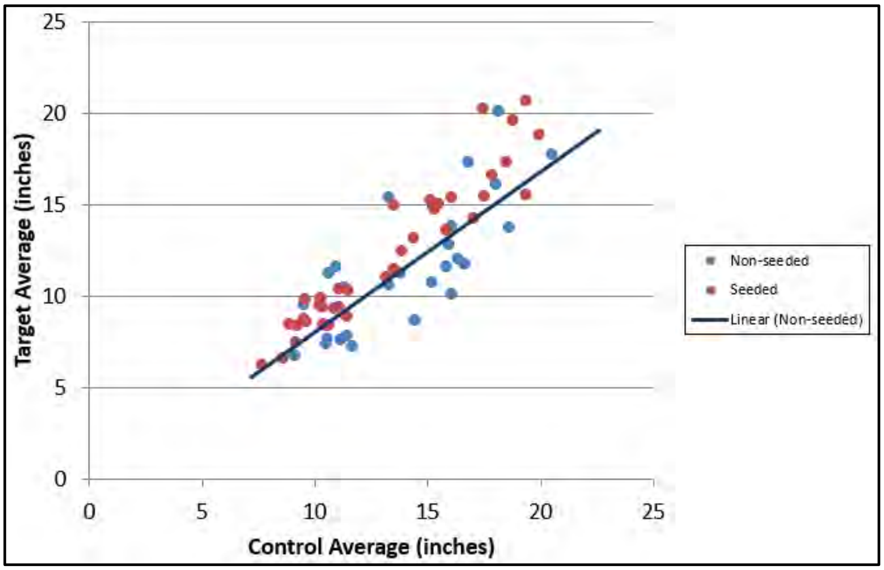


Figure 5.3 **Scatterplot of historical non-seeded (blue) vs seeded (red) data points for the eastern Tooele County precipitation evaluation. The diagonal line represents the linear regression equation for the non-seeded period.**

Primary Target Precipitation Results

Seeding was conducted in the target area beginning in the 1974 water year, continued until seeding was suspended in February 1983, and then discontinued entirely during water year 1984 because of excessively wet weather. However, seeding began again over portions of Washington County (mainly the Pine Valley Mountains) in 1985 and continued to spread northward in 1986 and 1987 into other parts of the target area. By 1988, seeding was again being conducted over essentially all of the previously seeded primary target area. The seeding program has continued to target most of the mountainous areas of central and southern Utah up through the current season. There have been 45 seeded seasons, excluding those when seeding was conducted over only a portion of the current target, and 18 seasons in the historical unseeded database. The 25 SNOTEL or cooperative observer sites located within the PT provide good coverage of the area targeted by cloud seeding. The high-density site coverage and distribution should ensure that the target area measurement sites are representative of the overall target area.

In the 2022 water year, the target/control precipitation evaluation results (from Table 5-2) yielded an observed/predicted ratio of 1.44, indicating that 44% more precipitation occurred in the target area than that predicted by control sites. As mentioned earlier, single-season results should be viewed with appropriate caution. **Over the 45 seeded years included in the long-term seeded record, 12 percent more precipitation has been observed (on average) than would have been expected from the control area-based predictions. This has provided an annual average excess of over 1.3 inches of water throughout the target area.** Statistical tests show the long-term average to be very meaningful (i.e., not the result of chance), even though individual-year results are not statistically significant. A one-tail significance test for the predicted vs. observed values (all seeded seasons) yielded a P value of 0.06 for this evaluation. This suggests only a 6% probability of the results of this one regression evaluation being due to chance. The December-March evaluations do not estimate any possible effects of seeding which was conducted outside of this four-month core evaluation period (e.g., November 15th-30th or during April).

Figure 5.4 is a scatterplot similar to Figure 5.3. Again, note that almost all of the seeded seasons are above the regression line indicating increases in precipitation. Appendix C contains the historical and seeded regression equation information for both target areas.

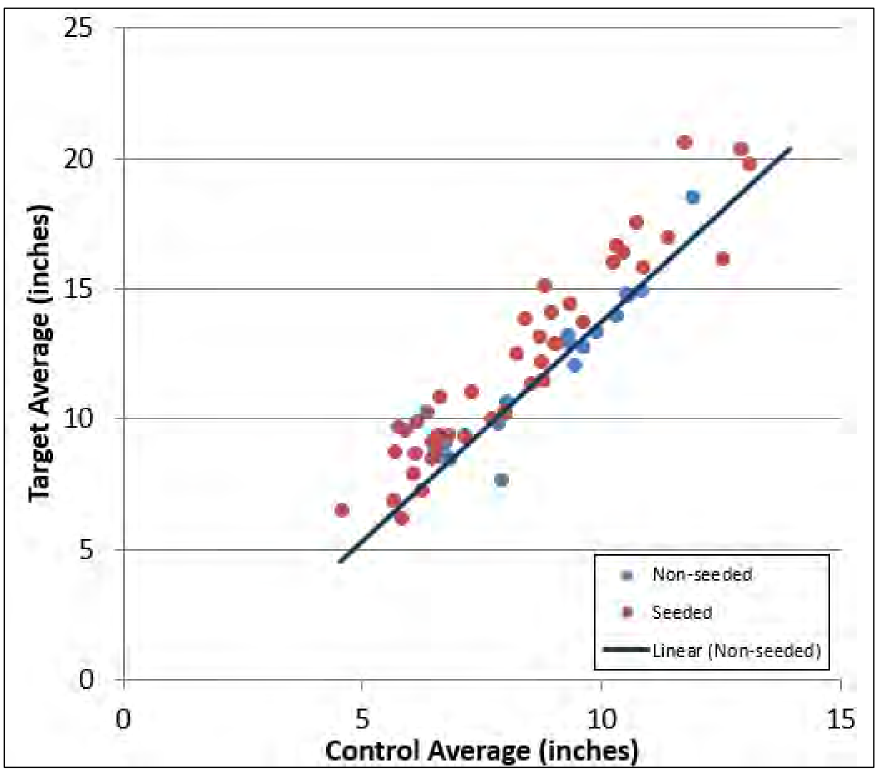


Figure 5.4 **Scatterplot of historical non-seeded (blue) vs seeded (red) data points for the primary target precipitation evaluation. The diagonal line represents the linear regression equation for the non-seeded period.**

5.4 Snow Water Equivalent (SWE) Evaluations

The procedure for evaluating the effect of cloud seeding on the snow water equivalent (SWE) as observed on April 1st was essentially the same as was done with the precipitation evaluations. In general, the control area snow sites have been drawn from approximately the same areas as were used in the precipitation evaluation, but they are limited to the availability of higher elevation sites which have significant SWE accumulation.

Target Area SWE Sites

Many of the same target sites, either snow course or SNOTEL, that were used in the precipitation evaluation were also used in the SWE evaluation. The four target SWE site locations used for the ETT are shown in Figure 5.5 as X's. Two of these target sites are snow courses, while the other two are SNOTEL sites. The average elevation for the four target sites is 7,463 feet MSL.

A total of 30 target area SWE measuring sites were utilized in the Primary Target. Figure 5.6 shows target and control site locations. The average elevation for the target area sites is approximately 9,090 feet MSL. Actual site locations and elevations are listed in Appendix C for both target areas.

Control Area SWE Sites

The selection of sites in the control group was determined primarily by their degree of correlation with each target area. Thus, control area sites (for the ETT and the PT) were selected individually from a large number of potential sites available in surrounding regions and assessed regarding their effects on the control vs. target group correlations.

The control group used in the SWE evaluation for the Eastern Tooele County target area (ETT) consists of five snow measurement sites. These sites extend from southern Idaho (one site) through eastern Nevada (three sites) into the Wasatch Mountains of Utah (one site southeast of the target area). The correlation coefficient (r) of 0.79 indicates a moderately good correlation between control and target areas and is slightly lower than that for the shorter regression period (0.82). Detailed information on the five SNOTEL/snow course sites utilized in this control is given in Appendix C, and the sites are shown in Figure 5.5. The average elevation of the control group about 8,050 feet MSL. Some data estimation was necessary for one of the sites (Vernon Creek) for the period prior to 1967, as SNOTEL/snow course data were unavailable. The estimation was based on data at two other target sites closest to Vernon Creek (Rocky Basin Settlement and Bevan’s Cabin).

The Primary Target control group consists of ten SNOTEL/snow course sites located from southern Idaho southward through eastern Nevada into north-central Arizona. This control group provided a good correlation (r = 0.94) with the Primary Target, with a variance (r^2) of 0.88, indicating that 88% of the variability in the historical data used to predict the expected snowpack was explained in the regression equation. The locations of the ten sites used as the control area are listed in the control section of Appendix C and are shown as yellow squares in Figure 5.6. The average elevation of this control group is 8,800 feet MSL.

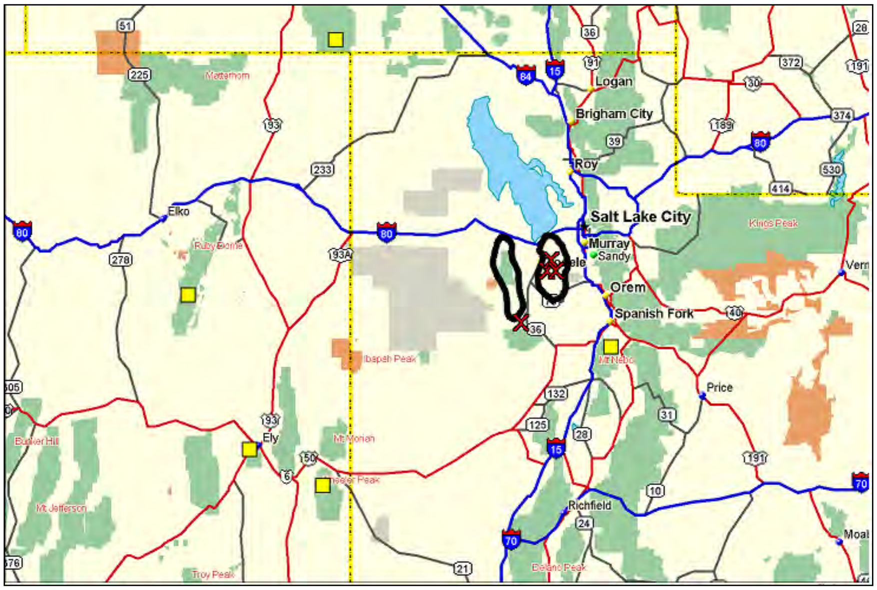


Figure 5.5 SWE sites for Eastern Tooele target/control evaluation (squares are control sites, X's are target sites).

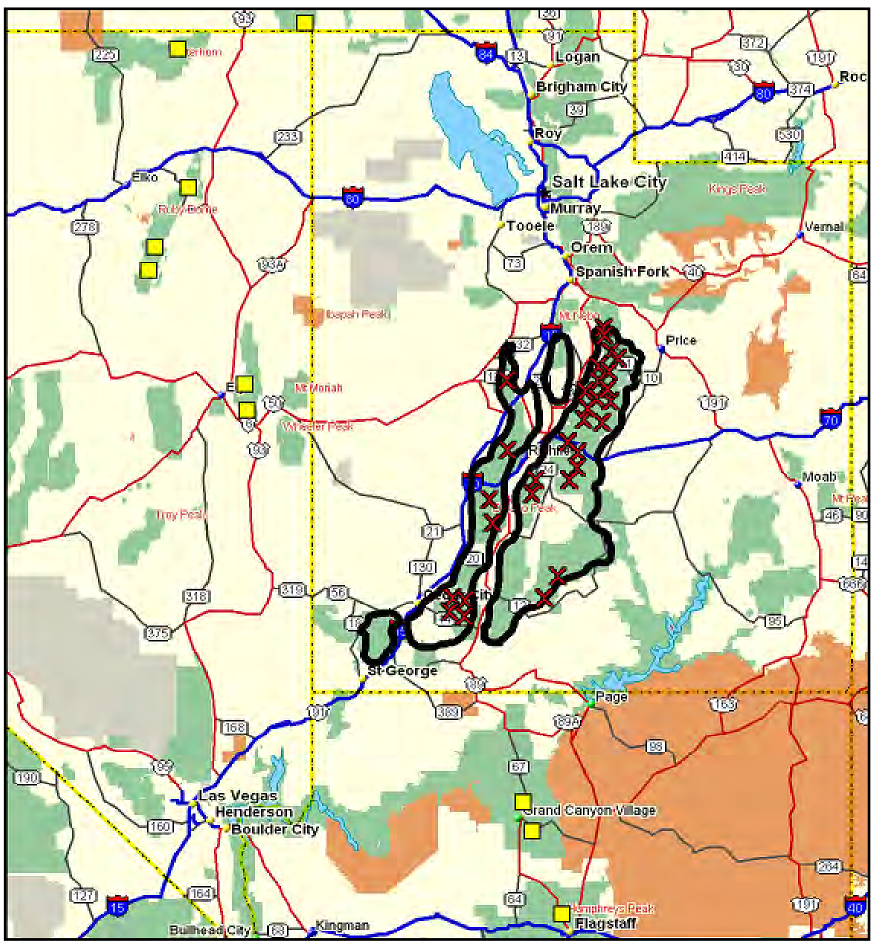


Figure 5.6 SWE sites for Primary Target evaluation (squares are control sites, X's are target sites)

SWE Regression Equation Development

The procedure was essentially the same as was done for the precipitation evaluation, i.e., control and target area stations were selected and average values for each were determined from the historical SWE data. The regression equation for the Tooele County SWE evaluation is based on a 29-year non-seeded period (1956-75, 1983-88, and 1993-95). The regression period for the primary target is shorter, consisting of 18 years (1957-73, and 1984). The SWE regression equations developed for the ETT and PT areas, using historical SNOTEL and estimated SNOTEL April 1st snow water content data, are provided in Table 5-4.

Table 5-4
Correlation coefficients, variances and regression equations for SWE evaluation

Target Group	Equation	Corr Coeff (r)	Variance (r^2)
Eastern Tooele (ETT)	YC = 1.069(X5) – 0.81	0.77	0.59
Primary Target (PT)	YC = 1.04(X10) - 0.38	0.94	0.88

Where:

Y_C = Average calculated SWE for target (April 1st)

X_5 = Average three state (ID/NV/UT) control area SWE (April 1st) for 5 sites

X_{10} = Average three state (AZ/ID/NV) control area SWE (April 1st) for 10 sites

Results of Snow Water Content Analyses

The results of the snow water evaluations for current water year and the average for all seeded seasons for the ETT and PT are presented in Table 5-5. In some seasons, including the 2021-2022 season, a large number of SNOTEL sites have experienced large decreases from peak SWE (10-50+%) prior to April 1st. For this reason, April 1st SWE evaluation results for water years 2007, 2012, 2015, 2017, and 2022 were excluded due to excessive pre-April 1st snow melt. Tables 5-6 and 5-7 list the results for each seeded season for the ETT and PT, respectively. Appendix D contains the historical and seeded year regression equation and evaluation result information for both target areas.

Table 5-5
Snow water content evaluation results for the 2021-2022 season, and for all seeded seasons

Target Group	Seeded Period	Ratio Y_o/Y_c	Increase Y_o-Y_c
Eastern Tooele (ETT)	34 water years*	1.09	1.1
	2022 water year	0.66	-2.8
Primary Target (PT)	41 water years*	1.04	0.5
	2022 water year	1.24	2.1

* 2007, 2012, 2015 and 2017 results not included in long-term mean due to excessive pre-April 1st snow melt

The ratios shown in Table 5-5 are ratios of average observed target area SWE to average calculated target area SWE. The increase is the average difference (in inches) between observed and calculated water content in snowpack at target gauges on April 1st.

Eastern Tooele Results

Table 5-5 shows the Eastern Tooele target group snow water evaluation results for the current water year and for all seeded seasons**.** As in the SWE evaluation for the Primary Target area, the 2007, 2012, 2015, 2017, and 2022 (April 1) Tooele County SWE evaluation results are excluded from the long-term mean due to excessive pre-April 1st snowmelt. Table 5-6 shows individual year results for the ETT SWE evaluation. The long-term result of this evaluation, a ratio of 1.09 equivalent to a 9% increase, is also close to the 1.12 ratio for the ETT precipitation evaluation (see Table 5-2 for comparison). The difference in observed versus calculated snow water (in inches of water) showed an average of about 1.1 inches more water observed than calculated per year for both (snow and precipitation) analyses in the Tooele County portion of the program. Results for the current season are also shown (a ratio of 0.66 which suggests an 34% decrease), although it should again be emphasized that single-season results carry very little statistical significance.

Table 5-6
Eastern Tooele Co. (ETT) Target area, April 1st snow water content evaluation

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
1976	15.6	16.0	0.98	-0.4
1977	9.3	5.8	1.59	3.5
1978	21.1	17.8	1.18	3.3
1979	18.0	19.4	0.93	-1.4
1980	24.4	19.5	1.25	4.8
1981	12.5	9.2	1.36	3.3
1982	19.6	22.1	0.89	-2.5
1989	9.9	14.1	0.70	-4.2
1990	12.4	10.7	1.16	1.7
1991	10.5	10.1	1.05	0.5
1992	10.3	8.5	1.21	1.8
1996	12.8	14.7	0.87	-1.9
1997	17.9	15.0	1.19	2.9
1998	23.4	15.0	1.56	8.4
1999	8.8	10.0	0.88	-1.2
2000	15.9	11.2	1.42	4.7
2001	11.4	8.5	1.35	3.0
2002	11.0	11.2	0.98	-0.2
2003	9.6	8.3	1.16	1.3
2004	15.0	10.1	1.49	4.9
2005	20.2	18.5	1.09	1.7

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
2006	16.3	17.0	0.96	-0.6
2007*	7.2	6.4	1.11	0.7
2008	17.5	14.4	1.21	3.1
2009	13.9	12.6	1.10	1.2
2010	13.0	12.2	1.06	0.8
2011	21.9	16.3	1.34	5.5
2012*	7.2	7.9	0.91	-0.7
2013	10.0	7.7	1.30	2.3
2014	8.3	9.9	0.83	-1.7
2015*	1.5	3.6	0.43	-2.0
2016	12.0	13.8	0.87	-1.8
2017*	13.8	13.0	1.06	0.8
2018	5.3	8.1	0.66	-2.8
2019	21.4	20.0	1.07	1.4
2020	11.5	10.7	1.08	0.8
2021	10.8	11.3	0.95	-0.5
2022*	5.4	8.2	0.66	-2.8
Seeded Mean	14.3	13.0	1.10	1.3

* Results excluded from long-term average due to excessive early-season snowmelt

Primary Target Results

Table 5-7 shows the individual and combined season results of the April 1st SWE evaluation for the Primary Target areas. As discussed in the previous section, the 2007, 2012, 2015 and 2017 April 1st SWE evaluation results are excluded from the long-term mean due to excessive early season snowmelt in those seasons. The data for the combined seeded seasons included in the evaluation indicates a ratio of observed to calculated snow water of 1.04. This ratio (1.04) is much less than the ratio of 1.12 for the precipitation evaluation for this primary target group, and the resulting statistical significance (one-tail P value of 0.29) is less as well. Indications of excess snow water content provided by the SWE evaluation are also less than in the precipitation results, with an average of 0.6 inches per year in the snow water analysis and 1.3 inches per year indicated by the precipitation evaluation. These differences are discussed in section 5.7.

Table 5-7
Primary Target (PT) area
April 1st snow water content evaluation

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
1974	15.6	14.0	1.11	1.6
1975	17.3	18.3	0.95	-1.0
1976	12.9	12.8	1.01	0.2
1977	8.2	8.0	1.02	0.2
1978	21.8	18.9	1.15	2.9
1979	21.4	18.2	1.17	3.2
1980	23.6	19.6	1.20	4.0
1981	10.2	9.6	1.06	0.6
1982	20.5	20.7	0.99	-0.2
1983	26.0	23.6	1.10	2.4
1988	13.1	10.5	1.25	2.7
1989	11.3	14.6	0.77	-3.4
1990	10.5	9.1	1.16	1.4
1991	12.8	12.3	1.04	0.5
1992	12.1	11.7	1.04	0.4
1993	21.3	20.4	1.04	0.9
1994	10.8	9.3	1.17	1.6
1995	16.6	18.0	0.92	-1.4
1996	14.6	13.8	1.06	0.8
1997	15.1	15.7	0.96	-0.6
1998	16.7	17.4	0.96	-0.7
1999	8.1	10.3	0.79	-2.2
2000	13.7	12.9	1.06	0.8
2001	11.3	10.8	1.04	0.5
2002	9.6	10.4	0.92	-0.8
2003	12.1	9.5	1.28	2.6
2004	10.2	9.2	1.11	1.0
2005	20.1	21.1	0.95	-1.0
2006	17.4	16.9	1.03	0.5
2007*	6.8	7.8	0.87	-1.0

Water Year	Observed	Predicted	Ratio Observed/Predicted	Excess Water Content (inches)
2008	16.1	15.2	1.06	0.8
2009	12.7	13.0	0.98	-0.2
2010	15.1	14.8	1.02	0.3
2011	20.1	16.2	1.24	3.9
2012*	7.9	7.1	1.11	0.8
2013	9.3	8.8	1.06	0.5
2014	9.9	9.4	1.05	0.5
2015*	6.1	4.7	1.28	1.3
2016	12.8	14.4	0.89	-1.5
2017*	13.9	16.6	0.84	-2.7
2018	7.9	8.1	0.97	-0.2
2019	19.5	18.9	1.03	0.6
2020	14.0	11.6	1.21	2.4
2021	11.0	10.9	1.00	0.1
2022	10.6	8.4	1.26	2.2
Seeded	14.5	13.8	1.05	0.6

* Results not included in long-term average due to excessive early-season snowmelt

5.5 Multiple Linear Regression Analyses

A variation of the linear regression technique is a multiple linear regression. In the linear regression averages of the control site data and target site data are used in development of the equation. In a multiple linear regression typically an average of all the target site data is correlated with each individual control site resulting in an equation with a number of terms depending upon the number of control sites. Past work with multiple linear regression evaluations highlighted some potential problems with this type of evaluation under certain circumstances. For example, a multiple linear regression equation containing independent control variables (such as single control sites) that are too similar to each other may yield an unrealistic regression equation. Such an equation typically produces highly variable results (that is, very high and/or very low individual season observed/predicted ratios) when applied to seeded season data.

One way to reduce or eliminate problems with the multiple regression analysis is to group control sites into two or more sets, with each set containing an average of a grouping of control sites. Ideally, control sites with similar characteristics (such as those at a higher latitude in comparison to much of the target area, and those at a lower latitude) can be grouped for this purpose, allowing the multiple linear regression equation to distinguish between the two groups in a meaningful way. Testing the standard deviation of the resulting individual seeded year ratios provides a useful comparison between a linear and corresponding multiple linear regression technique. Although a multiple linear regression equation containing the same control sites will typically have a better correlation (higher r-value) than the linear, ideally the resulting individual year observed/predicted ratios should have less variability (lower standard deviation) as well. This indicates that the multiple linear regression equation is helping to reduce some of the natural variability or "noise" inherent in the target /control relationship.

Most of the multiple linear regression equations developed for the southern/central Utah seeding program produced much more variable individual seeded season results than did the linear regression equations, and so the results from most of these have not been considered reliable for evaluation of this program. However, for the primary target area, it was found that a multiple linear SWE regression equation containing two control sets (one an average of the five northern-most control sites, and the other an average of the five southern-most sites) reduced the variability in the seeded season results slightly. For the combination of all seeded seasons, this multiple linear SWE regression produced an observed/predicted ratio of 1.04 (similar to the 1.05 long-term result for the linear regression equation).

5.6 Double Mass Plots

A double mass plot is an engineering tool designed to display data in a visual format in which it can readily be seen if there has been a change in the relationship between two variables. NAWC has applied this technique to the central/southern Utah cloud seeding program. Figures 5.7 and 5.8 provide plots of the data used by NAWC in target area evaluations of December – March precipitation, for the Primary Target and Eastern Tooele County Target areas. Target and control area-average seasonal values for both the historical (not-seeded) and the seeded periods are plotted on the figures. The December – March precipitation data are used in these plots since these data best represent the seeded season. The plotted values are cumulative; each new season is added to the sum of all of the previous seasons. In each figure, a line has been drawn through the points during the not-seeded base period. The plots show stable linear relationships prior to the beginning of cloud seeding. For comparison with the seeded period, the line describing the not-seeded period is extended at a constant slope through the seeded period. The Eastern Tooele County plot (Fig. 5.8) is more complex since there were two non-seeded intervals (from 1983-88 and 1993-95) even after the beginning of initial seeding operations in 1976. However, the line in this plot is drawn to fit the pre-seeding historical period of 1957-1975.

Figures 5.7 and 5.8 show a distinct change in the relationship between the target and control areas (a sustained change in the slope of the line representing the seeded seasons) that begins at approximately the same time as the start of the cloud seeding programs in the mid to late 1970s. Beginning at/near this time the plots in each case show generally greater precipitation in the target area compared to the control area. NAWC believes that this demonstrates evidence of a consistent positive seeding effect. A separate line could be drawn through the data points since seeding began in each case. Such a line would also have a fairly constant slope, departing from the slope of the line describing the not-seeded base period.

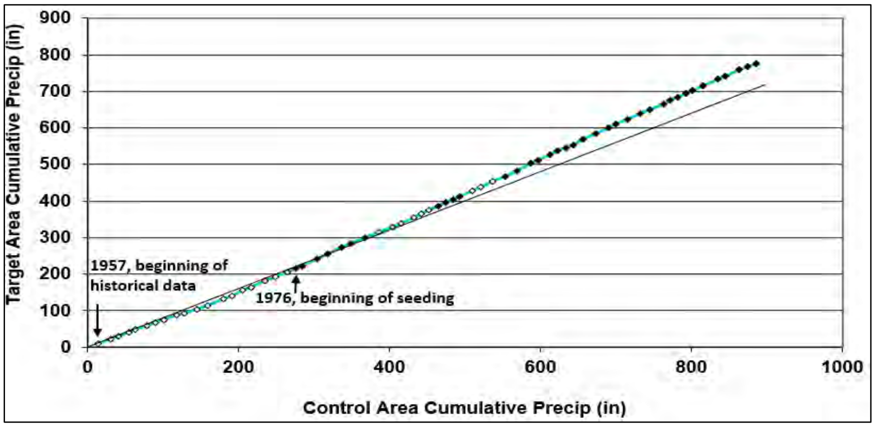


Figure 5.7 Double-Mass plot for Primary Target; all seasons shown after 1974 in this plot were seeded, and all the seasons plotted previous to this were not seeded.

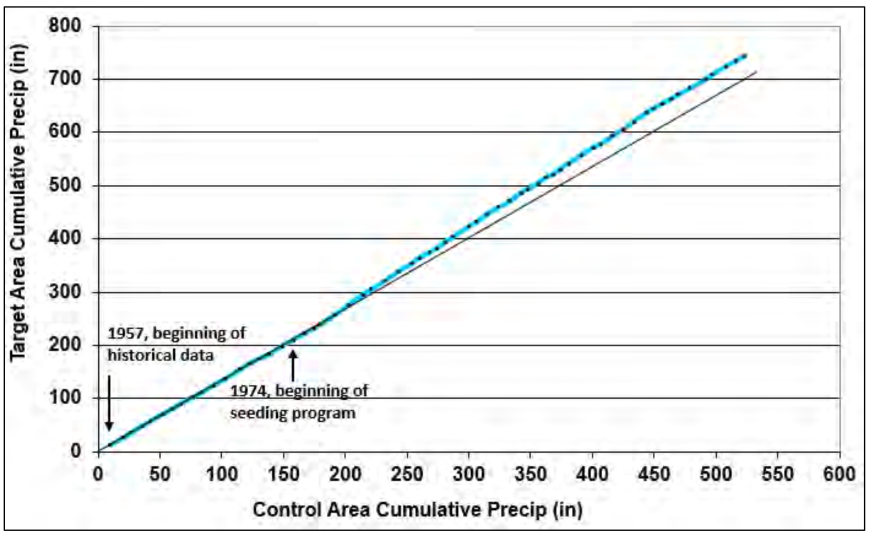


Figure 5.8 Double-Mass plot for Eastern Tooele County Target; smaller data points denote non-seeded seasons, and larger, darker points are the seeded seasons

Summary of Evaluation Results

Table 5-8 summarizes the results of the seeding evaluations, both for the ETT and PT target areas, for precipitation and SWE. Combined results of all seeded season evaluations suggest an approximate 10-12% increase in precipitation/snow water for the ETT, with a range of 3-12% increases indicated for the PT in the various linear and multiple linear regression evaluations.

Table 5-8
Summary of ratios from precipitation and SWE evaluations

	2022 Water Year	Long-term Average
ETT Precipitation Linear	0.99	1.12
ETT SWE Linear	0.66	1.10
PT Precipitation Linear	1.44	1.12
PT SWE Linear	1.26	1.05

The reader will note the significant differences in long-term average results between the precipitation and SWE analyses, which have persisted even though the target and control groups have had minor adjustments over time (usually due to loss of site data availability), resulting in various combination of sites having been examined in regression equations. One factor involved in this difference is that SWE accumulation usually begins before the seeded portion of the season, and therefore the seeding effects on snow water content are diluted by the early season non-seeded period. The seeding program in some years has ended by mid-March, making this a potential factor in the spring as well. Also, it was determined that the change in SWE measurement methods (the advent of SNOTEL) which occurred in about 1980, and the ensuing data adjustments applied by NRCS, may result in an underestimate of seeding effects in the SWE evaluation for the Primary Target, as was discussed in further detail in some past reports. Based on these considerations, it is concluded that (at least for the Primary Target area) the estimates of cloud seeding effectiveness based on December through March precipitation may be more reliable than those based upon April 1st snow water content.

As a side note, the December-March precipitation evaluations do not estimate any possible effects of seeding which was conducted outside of this four-month core evaluation period (e.g., November 15-30 or during April). NAWC performed an analysis of the potential increases in streamflow from these extension periods (Griffith et al., 2010) at the request of a Lower Basin States representative. This analysis provided estimates of **average** March – July increases in streamflow to Lake Powell (20,271 acre-feet) and to Lake Mead (8,331 acre-feet). The estimated cost per acre-foot of the calculated average increases were $1.22 per acre-foot for inflow to Lake Powell and $1.81 per acre-foot for inflow to Lake Mead.

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APPENDIX A: 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 positive public image.

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

1. Excess snowpack accumulation

2. Rain-induced winter flooding

3. Severe weather

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.

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, Southeastern Utah, Sevier River, Beaver River, Escalante River, and Virgin River. The Weber-Ogden and Provo River – Utah Lake – Jordan River criteria apply to suspension considerations for the Western Uintas project. 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. For the Southern and Central Utah Program, there are 10 listed SNOTEL sites with date-specific snow water equivalent criteria on which suspension decisions can be based.

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.

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.

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 that may be relevant in the conduct of winter cloud seeding programs include the following:

- 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 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: SEEDING OPERATIONS TABLES

Table B-1
Generator Hours – Central and Southern Utah, 2021-2022
Storms 1-9

Storm	1	2	3	4	5	6	7	8	9
Dates	Dec 9	Dec 14-15	Dec 16	Dec 25-26	Dec 27-28	Dec 30-31	Jan 7-8	Jan 20-21	Feb 16
SITES									
TO1		13.5							
TO2		13.5				15.5	13		
TO3						15.5	13		8
TO4		13							
TO5		3.5	4.5			16.25	13		8
TO6									
TO7									
TO8		12				16.25	13		8
TO9		10.5				15.25	13		6.25
TO10		11.5					13		6
TO11		11.5					13		6
CU1									
CU2							2		
CU3							5		
CU4							3		6.75
CU5							5		8.25
CU6							4		7.75
CU7							5		8.25
CU8						9			7
CU9						20	5		
CU10							12.75		8.25
CU11						7.25			
CU12						9.25	5		7.5
CU13					10	8.75	5		7.25
CU14						22	2.5		4
CU15						22			5
CU16						22	5		8

Storm	1	2	3	4	5	6	7	8	9
Dates	Dec 9	Dec 14-15	Dec 16	Dec 25-26	Dec 27-28	Dec 30-31	Jan 7-8	Jan 20-21	Feb 16
SITES									
CU17				4.5		22	5		7
CU18						22	5		8
CU19				5.75					9
CU20						23	6		
CU21						20	3.5		8.25
CU22						20			6
CU23						20	5		7.75
CU24							5.5		7.75
CU25							5		7.75
CU26							6		7.75
CU27							8		7.75
CU28							5		6.75
SU1									
SU2									
SU4									
SU5					10	20			
SU6					10	6.75			
SU7					10	6			
SU8						6.75			
SU9						5.75		5.75	
SU11	5	15.75						8.25	
SU12	4.5			15		20		8	
SU14									
SU15					12	20			
SU18									
SU19								7	
SU20								8	
SU21		14.5						7	
SU22								7.5	
SU23				15		20			
SU24									

Storm	1	2	3	4	5	6	7	8	9
Dates	Dec 9	Dec 14-15	Dec 16	Dec 25-26	Dec 27-28	Dec 30-31	Jan 7-8	Jan 20-21	Feb 16
SITES									
SU25		15.75		15.25					
SU26		14		15.5		20			
SU27		14		15.25		20			
SU28		14		15.25		20			
SU29		12.5		15		5.25			
SU30		12.5		15.25		6.25			
SU31									
SU32		12.5				6.75		7.5	
SU33		12.5				6.75		7.25	
SU34		12.5		14.75		20			
Storm Total	**9.5**	**239.5**	**4.5**	**146.5**	**52**	**527.25**	**204.25**	**66.25**	**204**

Table B-2
Generator Hours – Central and Southern Utah, 2021-2022
Storms 10-18

Storm	10	11	12	13	14	15	16	17	18
Dates	Feb 21-22	Feb 22-23	Mar 5-6	Mar 8-9	Mar 13	Mar 16	Mar 20	Mar 29-30	Mar 31
SITES									
TO1				24					2**
TO2				21					
TO3				21					
TO4			24.25	3.5					
TO5			23.25	2					
TO6			1.25						
TO7				22					
TO8			3.75	17					
TO9			4.75	21					
TO10							3.75**	6.75**	2**
TO11				21.5			3.25**	7.25**	
CU1					7.5	4.25**			

Storm	10	11	12	13	14	15	16	17	18
Dates	Feb 21-22	Feb 22-23	Mar 5-6	Mar 8-9	Mar 13	Mar 16	Mar 20	Mar 29-30	Mar 31
SITES									
CU2				24.5	7.25	2.5**	6**	5**	
CU3				24.5	7		2.75**	5.75**	
CU4				24.5		2.5*	6*		
CU5				23.5	5		6**	2**	
CU6				5					
CU7				12.5		4.25**	6.5**	5.25**	
CU8			4.25			5**		7.5**	
CU9				11					
CU10			3.25	7.5		5.25**	5.75**		
CU11				10.75		5**	5.5**		
CU12			4.5	12		5.25**	6**		
CU13			2.5	9.25					
CU14			4.5				5.5*		
CU15						5.75*	4.75*		
CU16				8					
CU17						4*	6.25*		
CU18			5	24.75		5.5*	6.25*		
CU19			5	23.25			3.75*		
CU20	9.25			12					
CU21	9.25			12.5		3.75*	6.25*		
CU22	9.25			6.5			4*		
CU23	8.75			6.25		5*	4.5*		
CU24	20.25			6		5*		3.5*	
CU25	9			7		4.5*		6.75*	4.25*
CU26	9.25			13.75		6*	4.5*	6.75*	6.5*
CU27	8.25			12		5.25*		6*	7*
CU28	8			11			3.75*	6.75*	
SU1		14.5					4*	6*	
SU2		5.25					3.75*	5.75*	
SU4									
SU5		21	7.75						

Storm	10	11	12	13	14	15	16	17	18
Dates	Feb 21-22	Feb 22-23	Mar 5-6	Mar 8-9	Mar 13	Mar 16	Mar 20	Mar 29-30	Mar 31
SITES									
SU6						4*	5*		5*
SU7	6.5						4.5*	6.5*	5*
SU8	4.5						5*	5*	10.75*
SU9							2.75*		
SU11		19.75	7.5				4.75*	19*	
SU12	5.25	14	7.75			3*	4.75*		
SU14		5.25							
SU15		20							
SU18	7.75	20		11.25		3.5*			7.5*
SU19	7.75	15		9		3.5*		7.25*	7.25*
SU20	7.75	14.5		10.5				6*	6*
SU21									7.75*
SU22	5.25	18.5	6.75				4*		8*
SU23			7.5						
SU24									
SU25		19.5	7.75					4*	
SU26		20	7.75						
SU27		18.75	5						
SU28		20.25							
SU29		15	6	12		3.5*	3.5*	7.25*	7.5*
SU30		14.75	5.5	12		3.5*	4*	5.5*	7*
SU31		14.5	6.5					6.75*	
SU32		14.5	6.5	11				7*	
SU33		14.75	6.5	11.5				7*	
SU34		21	8	11.25					
Storm Total	**136**	**340.75**	**183**	**583.25**	**26.75**	**99.75**	**147**	**169.5**	**93.5**
LBS Extension						**68.25**	**101.5**	**130**	**89.5**
Core Extension						**31.5**	**45.5**	**39.5**	**4**

***** Seeding hours funded through Lower Basin extension
** Seeding hours funded through Core Program special extension

Table B-3
Generator Hours – Central and Southern Utah, 2021-2022
Storms 19-20

Storm	19	20	Site Totals
Dates	Apr 11-12	Apr 22-23	
SITES			
TO1	9.5**	8.25**	57.25
TO2			63
TO3			57.5
TO4			40.75
TO5			70.5
TO6			1.25
TO7		8.25**	30.25
TO8			70
TO9			70.75
TO10	12**	7.5**	62.5
TO11			62.5
CU1			11.75
CU2	19**		66.25
CU3	13.75**	5.5**	64.25
CU4	14.25*	7**	64
CU5	15**		64.75
CU6			16.75
CU7	12**	9**	62.75
CU8		27.5**	60.25
CU9		9.25**	45.25
CU10	14.5**	2**	59.25
CU11	14**	9.25**	51.75
CU12	14**		63.5
CU13			42.75
CU14	15*		53.5
CU15	11*	19.5**	68
CU16	23*		66
CU17	14*		62.75
CU18	14*	28.75**	119.25
CU19	14*		60.75
CU20	12*	9.25**	71.5
CU21	12*		75.5
CU22	10.5*	9**	65.25
CU23	12*		69.25
CU24			48

Storm	19	20	Site Totals
Dates	Apr 11-12	Apr 22-23	
SITES			
CU25	12*	8.25**	64.5
CU26		9.5**	63.5
CU27	12*		65.75
CU28	12*	8.25**	68.5
SU1		7**	31.5
SU2		7**	21.75
SU4		7.5**	7.5
SU5		8**	66.75
SU6		10.75**	41.5
SU7		10.75**	49.25
SU8	12*		44
SU9			14.25
SU11		8.5**	88.5
SU12			82.25
SU14		10.5**	15.75
SU15		2.5**	54.5
SU18		10**	67.25
SU19	12*	9**	77.75
SU20	11.25*	9**	73
SU21	12*		41.25
SU22	12*		62
SU23		6.75**	49.25
SU24			0
SU25	12*		74.25
SU26		7.5**	84.75
SU27		4.5**	77.5
SU28		8.5**	78
SU29	11*	10.25**	108.75
SU30	11*	7.25**	104.5
SU31		7.25**	35
SU32	11*		76.75
SU33			66.25
SU34		8.5**	84.75
Storm Total	**415.75**	**347**	
LBS Extension	**292**		

Storm	19	20	Site Totals
Dates	Apr 11-12	Apr 22-23	
SITES			
Core Extension	123.75	347	

***** Seeding hours funded through Lower Basin extension

** Seeding hours funded through Core Program special extension

APPENDIX C: EVALUATION TARGET AND CONTROL SITES

PRIMARY TARGET - PRECIPITATION

Site	Lat(N)	Long(W)	Elev (Ft)
Control Sites			
Bear Creek Tel, Nv	41°50'	115°27'	8040
Berry Creek Tel, Nv	39°21'	114°39'	9100
Caliente, NV	37°37'	114°31'	4440
Ely, NV	39°17'	114°51'	6250
Flagstaff Airport, AZ	35°08'	111°40'	7000
Jacks Peak Tel, NV	41°32'	116°01'	8420
McGill, Nv	39°24'	114°46'	6340
Pole Creek RS, Tel Nv	41°52'	115°15'	8330
Seligman, Az	35°19'	112°53'	5250
Seventy-Six Ck Tel Nv	41°42'	115°28'	7100
Ward Mountain, Tel #2 Nv	39°08'	114°49'	9200
Wupatki NM, Az	35°31'	111°22'	4908
Target Sites			
Alton	37°26'	112°29'	7040
Beaver Dams	39°08'	111°33'	8000
Big Flat	38°18'	112°21'	10290
Black Fl. UM Ck.	38°41'	111°36'	9400
Box Creek	38°30'	112°02'	9300
Buck Flat	39°08'	111°27'	9800
Castle Valley	37°40'	112°44'	9580
Dills Camp	39°02'	111°28'	9200
Farnsworth Lake	38°46'	111°40'	9600
Gooseberry R.S.	38°48'	111°41'	7920
Hatch	37°39'	112°26'	6910
Kimberly Mine	38°29'	112°23'	9300
Kolob	37°32'	113°03'	9250
Little Grassy Ck.	37°29'	113°51'	6100
Long Flat	37°30'	113°25'	8000
Mammoth-Cottonwood	39°41'	111°19'	8800
Merchant Valley	38°18'	112°26'	8750
Midway Valley	37°34'	112°50'	9800
Pickle Keg Spring	39°02'	111°35'	9600
Pine Creek	38°53'	112°15'	8800

PRIMARY TARGET - PRECIPITATION (continued)

Site	Lat(N)	Long(W)	Elev (Ft)
Target Sites			
Red Pine Ridge	39°27'	111°16'	9200

Scofield-Skyland Mine	39°41'	111°12'	8710
Seeley Ck. R.S.	39°19'	111°26'	10000
Webster Flat	37°35'	112°54'	9200
Widtsoe-Esc. # 3	37°50'	111°53'	9500

EASTERN TOOELE TARGET - PRECIPITATION

Control Sites			
Berry Creek, NV	39°21'	114°39'	9100
Diamond Peak, NV	39°34'	115°51'	8040
Farmington Cyn Upr, UT	40°58'	111°48'	8000
Lamoille #3, NV	40°38'	115°24'	7700
Payson R.S., UT	39°56'	111°38'	8050
Ward Mtn #2, NV	39°08'	114°49'	9200
Target Sites			
Rocky Basin Setlmnt, UT	40°26'	112°13'	8900
Tooele, UT	40°32'	112°18'	5072
Vernon Creek, UT	39°56'	112°25'	7500

PRIMARY TARGET - SNOW COURSE AND SNOW PILLOW

Site	Lat(N)	Long(W)	Elev (Ft)
Control Sites			
Bright Angel Sc, Az	36°13'	112°04'	8400
Grand Canyon Sc, Az	35°58'	111°58'	7500
Snowbowl #2 Sc, Az	35°19'	111°42'	11,200
Bostetter RS Pil, Id	42°10'	114°11'	7500
Berry Creek, Pil, Nv	39°21'	114°39'	9100
Dorsey Basin Pil, Nv	40°53'	115°12'	8100
Site	**Lat(N)**	**Long(W)**	**Elev (Ft)**
Green Mountain Pil, Nv	40°23'	115°32'	8000
Corral Canyon Pil, Nv	40°17'	115°32'	8500
Ward Mountain #2 Pil, Nv	39°08'	114°49'	9200
Pole Creek RS, Pil, Nv	41°52'	115°15'	8330
Target Sites			
Beaver Dams Pil	39°08'	111°33'	8000
Big Flat Pil	38°18'	112°21'	10290
Black Fl UM Creek Pil	38°41'	111°36'	9400
Box Creek Pil	38°30'	112°02'	9300
Buck Flat Pil	39°08'	111°27'	9800
Dill's Camp Pil	39°03'	111°27'	9200
Farnsworth Lake Pil	38°46'	111°40'	9600
Fish Lake Sc	38°33'	111°43'	8700
GBRC Alp Mead. Sc	39°18'	111°27'	10000

GBRC Headqts. Sc	39°19'	111°29'	8700
Gooseberry RS Pil	38°47'	111°41'	8400
Huntington Hrshoe Sc	39°37'	111°19'	9800
Kimberly Mine Pil	38°29'	112°23'	9300
Mammoth-Ctnwood Pil	39°41'	111°19'	8800
Mt. Baldy RS Sc	39°08'	111°30'	9500
Oak Creek SC	39°21'	112°21'	7760
Pickle Keg Spring Pil	39°02'	111°35'	9600
Pine Creek Pil	38°53'	112°15'	8800
Red Pine Ridge Pil	39°28'	111°16'	9200
Seeley Creek R.S. Pil	39°19'	111°26'	10000
Box Springs Pil*	38°30'	112°00'	9300
Thistle Flat Sc	39°14'	111°37'	8500
Upper Joes Valley Sc	39°26'	111°15'	8900

PRIMARY TARGET - SNOW COURSE AND SNOW PILLOW (continued)

Site	Lat(N)	Long(W)	Elev (Ft)
Wrigley Creek Sc	39°09'	111°20'	9000
Bryce Canyon Sc	37°38'	112°12'	8000
Castle Valley Pil	37°40'	112°44'	9500
Long Flat Pil	37°30'	113°25'	8000
Midway Valley Pil	37°34'	112°51'	9800
Tall Poles Sc	37°43'	112°51'	8800
Webster Flat Pil	37°59'	112°54'	9200
Widtsoe Esc. #3 Pil	37°50'	111°53'	9500
Yankee Res. Sc	37°32'	112°48'	8700

EASTERN TOOELE TARGET - SNOW COURSE AND SNOW PILLOW

Site	Lat(N)	Long(W)	Elev (Ft)
Control Sites			
Baker Creek #2, NV	38°58'	114°17'	8950
Bostetter RS, ID	42°10'	114°11'	7500
Corral Canyon, NV	40°17'	115°32'	8500
Murray Summit, NV	39°14'	114°58'	7250
Payson R.S., UT	39°56'	111°38'	8050
Target Sites			
Bevan's Cabin, UT	40°28'	112°15'	6450
Rocky Basin Settlement, UT	40°26'	112°13'	8900
Vernon Creek, UT	39°56'	112°25'	7500

APPENDIX D: EVALUATION RESULTS TABLES

Primary Target Linear Regression
Dec-Mar Precipitation

Non-seeded period:

Year	Control	Target	Predicted	Ratio	Increase
1957	9.6	12.7	13.1	0.97	-0.4
1958	10.3	13.9	14.3	0.98	-0.3
1959	6.6	8.8	7.9	1.11	0.9
1960	9.3	13.2	12.6	1.05	0.6
1961	6.6	8.5	8.0	1.06	0.5
1962	10.9	14.9	15.2	0.98	-0.3
1963	6.7	9.0	8.2	1.10	0.8
1964	6.9	8.4	8.4	1.00	0.0
1965	9.9	13.3	13.6	0.98	-0.3
1966	7.2	9.3	8.9	1.04	0.4
1967	9.5	12.0	12.8	0.94	-0.8
1968	9.3	12.9	12.6	1.03	0.3
1969	11.9	18.4	17.0	1.09	1.5
1970	8.0	10.6	10.4	1.02	0.2
1971	7.9	9.7	10.1	0.96	-0.4
1972	8.0	7.6	10.3	0.74	-2.7
1973	10.6	14.7	14.7	1.00	0.0
1984	10.6	14.8	14.6	1.01	0.1
Mean	8.9	11.8	11.8	1.00	0.0

Seeded period:

Year	Control	Target	Predicted	Ratio	Increase
1974	8.6	11.3	11.3	1.00	0.0
1975	9.1	12.8	12.1	1.06	0.7
1976	7.7	9.9	9.9	1.01	0.1
1977	4.6	6.4	4.6	1.40	1.8
1978	13.0	20.3	18.7	1.08	1.6
1979	10.5	16.3	14.5	1.12	1.8
1980	11.8	20.5	16.7	1.23	3.9
1981	6.6	9.3	8.0	1.16	1.3
1982	11.4	16.9	16.1	1.05	0.8
1983	10.8	17.5	15.0	1.17	2.5
1988	6.2	9.8	7.2	1.36	2.6
1989	8.0	10.2	10.3	0.99	-0.1
1990	6.5	9.1	7.8	1.17	1.3
1991	6.6	10.8	8.0	1.34	2.7
1992	6.4	10.2	7.6	1.34	2.6
1993	13.1	19.7	19.0	1.04	0.7
1994	5.7	8.7	6.5	1.35	2.3
1995	9.0	14.0	12.0	1.17	2.0
1996	9.1	12.9	12.2	1.05	0.7
1997	8.8	12.2	11.6	1.05	0.5

1998	9.4	14.4	12.6	1.14	1.8
1999	5.7	6.9	6.4	1.07	0.4
2000	8.3	12.4	10.8	1.15	1.7
2001	5.9	9.5	6.8	1.39	2.7
2002	5.9	6.2	6.7	0.92	-0.6
2003	5.8	9.6	6.6	1.45	3.0
2004	7.3	11.0	9.2	1.20	1.8
2005	10.3	15.9	14.2	1.13	1.8
2006	9.7	13.7	13.1	1.04	0.5
2007	6.3	7.2	7.4	0.98	-0.2
2008	8.8	15.1	11.7	1.28	3.3
2009	8.7	13.1	11.6	1.13	1.5
2010	8.4	13.8	11.1	1.24	2.7
2011	10.3	16.6	14.3	1.16	2.3
2012	6.6	8.7	7.9	1.09	0.7
2013	7.2	9.2	8.9	1.03	0.3
2014	6.1	7.9	7.1	1.10	0.7
2015	6.5	8.4	7.7	1.09	0.7
2016	8.8	11.4	11.7	0.98	-0.3
2017	12.6	16.1	18.0	0.89	-2.0
2018	6.1	8.6	7.2	1.20	1.4
2019	10.9	15.7	15.2	1.03	0.5
2020	8.0	10.1	10.4	0.98	-0.2
2021	6.8	9.3	8.4	1.12	1.0
2022	6.4	11.0	7.6	1.44	3.4
Mean	8.2	12.0	10.7	1.122	1.3

*Seeding conducted in adjacent areas, but not target area

SUMMARY OUTPUT

Regression Statistics	
Multiple R	**0.955721**
R Square	**0.913403**
Adjusted R Square	0.907991
Standard Error	0.901939
Observations	18

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Upper 95.0%*
Intercept	**-3.173422**	1.173074	-2.705219	0.015604	-5.660227	-0.68662	-0.68662
X Variable 1	**1.688715**	0.129992	12.99091	6.46E-10	1.413144	1.964286	1.964286

Eastern Tooele Target Linear Regression
Dec-Mar Precipitation

Non-seeded period

Year	Control	Target	Predicted	Ratio	Increase

1957	13.3	10.6	10.9	0.97	-0.4
1958	16.7	11.7	13.9	0.84	-2.2
1959	10.5	8.4	8.4	0.99	-0.1
1960	13.8	11.2	11.4	0.98	-0.2
1961	9.2	6.7	7.3	0.92	-0.6
1962	15.8	11.6	13.2	0.88	-1.6
1963	10.6	7.7	8.6	0.89	-0.9
1964	11.4	7.8	9.3	0.84	-1.5
1965	16.4	12.0	13.6	0.88	-1.6
1966	10.5	7.4	8.5	0.87	-1.1
1967	16.1	10.1	13.4	0.75	-3.3
1968	15.2	10.7	12.6	0.85	-1.9
1969	20.6	17.7	17.3	1.02	0.4
1970	11.7	7.2	9.5	0.76	-2.3
1971	13.3	15.4	11.0	1.40	4.4
1972	11.2	7.6	9.1	0.84	-1.5
1973	18.2	20.1	15.2	1.32	4.9
1974	14.5	8.7	12.0	0.73	-3.3
1975	16.0	12.8	13.3	0.96	-0.5
1983	18.1	16.1	15.1	1.06	1.0
1984	18.7	13.7	15.6	0.88	-1.9
1985	11.0	11.6	8.9	1.29	2.6
1986	16.1	13.8	13.4	1.03	0.4
1987	10.6	11.2	8.6	1.30	2.6
1988	9.5	9.5	7.6	1.25	1.9
1993	16.9	17.3	14.1	1.23	3.3
1994	11.4	10.4	9.3	1.13	1.2
1995	15.3	14.8	12.6	1.17	2.2
Mean	14.0	11.6	11.6	1.00	0.0

Seeded period:

Year	Control	Target	Predicted	Ratio	Increase
1976	11.5	10.3	9.4	1.10	0.9
1977	8.6	6.6	6.9	0.96	-0.2
1978	19.4	20.7	16.3	1.27	4.4
1979	13.9	12.5	11.5	1.09	1.0
1980	18.8	19.6	15.8	1.24	3.8
1981	11.5	8.9	9.3	0.95	-0.5
1982	19.4	15.5	16.3	0.95	-0.8
1989	13.2	11.0	10.8	1.02	0.2
1990	9.6	9.8	7.7	1.27	2.1
1991	9.3	8.4	7.4	1.13	1.0
1992	9.2	7.4	7.4	1.01	0.1
1996	17.1	14.2	14.2	1.00	0.0
1997	15.5	15.0	12.9	1.16	2.1
1998	17.5	20.2	14.6	1.39	5.6
1999	10.9	9.3	8.8	1.05	0.5
2000	15.1	15.2	12.5	1.21	2.6
2001	10.3	9.4	8.3	1.12	1.0

2002	10.4	8.4	8.4	1.00	0.0
2003	9.5	8.7	7.6	1.14	1.1
2004	13.5	15.0	11.1	1.34	3.8
2005	16.1	15.4	13.4	1.15	2.0
2006	17.6	15.4	14.7	1.05	0.7
2007	10.3	9.9	8.3	1.19	1.6
2008	15.4	14.7	12.7	1.15	2.0
2009	15.9	13.6	13.2	1.03	0.4
2010	13.6	11.5	11.2	1.03	0.3
2011	17.9	16.6	14.9	1.11	1.6
2012	8.9	8.5	7.1	1.19	1.3
2013	10.3	9.5	8.3	1.15	1.2
2014	11.1	10.4	9.0	1.15	1.3
2015	7.7	6.2	6.0	1.03	0.2
2016	14.4	13.2	11.9	1.10	1.2
2017	20.0	18.8	16.8	1.12	2.0
2018	9.7	8.6	7.8	1.10	0.8
2019	18.5	17.3	15.5	1.11	1.8
2020	10.6	8.4	8.6	0.98	-0.2
2021	11.1	9.4	9.0	1.04	0.4
2022	10.4	8.3	8.4	0.99	-0.1
Mean	13.3	12.2	11.0	**1.12**	**1.3**

* Seeding in other parts of Utah but not target area, so excluded from the mean

SUMMARY OUTPUT

Regression Statistics	
Multiple R	**0.782368**
R Square	**0.612099**
Adjusted R Square	0.59718
Standard Error	2.231851
Observations	28

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	**-0.69476**	1.959753	- 0.354514	0.725813	-4.72309	3.33357	-4.72309	3.33357
X Variable 1	**0.875061**	0.136616	6.405266	8.73E-07	0.594243	1.15588	0.594243	1.15588

Primary Target
Apr 1 Snow Water Content Linear Regression

Non-seeded period:

Year	Control	Target	Predicted	Ratio	Increase
1956	14.9	12.3	15.1	0.82	-2.7
1957	15.3	16.9	15.4	1.10	1.5
1958	20.2	20.6	20.5	1.00	0.1
1959	9.6	10.4	9.6	1.09	0.8
1960	12.4	13.9	12.5	1.11	1.4
1961	12.7	11.3	12.7	0.89	-1.4
1962	20.3	20.1	20.6	0.98	-0.5
1963	8.9	10.3	8.8	1.17	1.5
1964	12.0	11.4	12.1	0.95	-0.7
1965	16.2	17.9	16.4	1.09	1.5
1966	11.2	10.5	11.2	0.93	-0.7
1967	11.5	10.8	11.5	0.94	-0.7
1968	13.5	16.8	13.6	1.24	3.3
1969	21.0	23.1	21.4	1.08	1.7
1970	14.3	15.2	14.4	1.06	0.8
1971	14.9	14.4	15.1	0.96	-0.6
1972	12.2	8.8	12.3	0.72	-3.5
1973	21.6	20.7	21.9	0.94	-1.2
1984	23.8	24.1	24.2	0.99	-0.2
Mean	15.1	15.2	15.2	1.00	0.0

Year	Control	Target	Predicted	Ratio	Increase
1974	13.9	15.6	14.0	1.11	1.6
1975	18.0	17.3	18.3	0.95	-1.0
1976	12.7	12.9	12.8	1.01	0.2
1977	8.1	8.2	8.0	1.02	0.2
1978	18.6	21.8	18.9	1.15	2.9
1979	18.0	21.4	18.2	1.17	3.2
1980	19.3	23.6	19.6	1.20	4.0
1981	9.6	10.2	9.6	1.06	0.6
1982	20.3	20.5	20.7	0.99	-0.2
1983	23.1	26.0	23.6	1.10	2.4
1985*	16.3	16.5	16.5	1.00	0.0
1986*	13.8	15.7	13.9	1.13	1.8
1987*	11.2	13.0	11.2	1.17	1.9
1988	10.5	13.1	10.5	1.25	2.7
1989	14.5	11.3	14.6	0.77	-3.4
1990	9.2	10.5	9.1	1.16	1.4
1991	12.3	12.8	12.3	1.04	0.5
1992	11.7	12.1	11.7	1.04	0.4
1993	20.1	21.3	20.4	1.04	0.9
1994	9.3	10.8	9.3	1.17	1.6

1995	17.8	16.6	18.0	0.92	-1.4
1996	13.7	14.6	13.8	1.06	0.8
1997	15.5	15.1	15.7	0.96	-0.6
1998	17.1	16.7	17.4	0.96	-0.7
1999	10.3	8.1	10.3	0.79	-2.2
2000	12.8	13.7	12.9	1.06	0.8
2001	10.8	11.3	10.8	1.04	0.5
2002	10.4	9.6	10.4	0.92	-0.8
2003	9.5	12.1	9.5	1.28	2.6
2004	9.3	10.2	9.2	1.11	1.0
2005	20.8	20.1	21.1	0.95	-1.0
2006	16.7	17.4	16.9	1.03	0.5
2007**	7.9	6.8	7.8	0.87	-1.0
2008	15.1	16.1	15.2	1.06	0.8
2009	12.9	12.7	13.0	0.98	-0.2
2010	14.7	15.1	14.8	1.02	0.3
2011	16.0	20.1	16.2	1.24	3.9
2012**	7.3	7.9	7.1	1.11	0.8
2013	8.9	9.3	8.8	1.06	0.5
2014	9.5	9.9	9.4	1.05	0.5
2015**	5.0	6.1	4.7	1.28	1.3
2016	14.2	12.8	14.4	0.89	-1.5
2017**	16.4	13.9	16.6	0.84	-2.7
2018	8.2	7.9	8.1	0.97	-0.2
2019	18.7	19.5	18.9	1.03	0.6
2020	11.5	14.0	11.6	1.21	2.4
2021	10.9	11.0	10.9	1.00	0.1
2022	8.5	10.6	8.4	1.26	2.2
Mean	13.7	14.5	13.8	1.05	0.6

* Seeding conducted in adjacent areas but not target area, so not included in mean
** Results not included in mean due to early snowmelt

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.935556396
R Square	0.87526577
Adjusted R Square	0.867928462
Standard Error	1.740763607
Observations	19

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Upper 95.0%*
Intercept	-0.378966405	1.483944	-0.25538	0.801495	-3.50982	2.751883	2.751883
X Variable 1	1.035560851	0.094814	10.92199	4.19E-09	0.83552	1.235602	1.235602

Primary Target

Apr 1 Snow Water Content Multiple Regression with Two Control Groups (North, South)

Non-seeded period:

YEAR	North Ctrl	South Ctrl	YOBS	YCALC	RATIO	EXCESS
1956	20.5	9.3	12.3	14.5	0.85	-2.2
1957	16.8	13.7	16.9	15.9	1.06	1.0
1958	25.5	14.9	20.6	20.3	1.02	0.3
1959	12.3	6.9	10.4	9.5	1.10	0.9
1960	13.7	11.2	13.9	12.9	1.08	1.0
1961	17.6	7.7	11.3	12.3	0.93	-0.9
1962	22.8	17.7	20.1	21.1	0.96	-0.9
1963	10.2	7.6	10.3	9.1	1.14	1.2
1964	17.1	6.9	11.4	11.5	0.99	-0.1
1965	20.0	12.4	17.9	16.4	1.09	1.5
1966	11.1	11.3	10.5	11.9	0.88	-1.4
1967	14.4	8.5	10.8	11.4	0.94	-0.7
1968	12.6	14.3	16.8	14.6	1.16	2.3
1969	21.1	21.0	23.1	22.5	1.03	0.6
1970	18.1	10.4	15.2	14.3	1.07	1.0
1971	21.0	8.9	14.4	14.4	1.00	0.0
1972	19.1	5.4	8.8	11.3	0.78	-2.5
1973	20.9	22.3	20.7	23.3	0.89	-2.6
1984	36.7	10.9	24.1	22.3	1.08	1.8
Mean	18.5	11.6	15.2	15.2	1.00	0.0

Seeded Period:

YEAR	North Ctrl	South Ctrl	YOBS	YCALC	RATIO	EXCESS
1974	20.9	7.0	15.6	13.1	1.19	2.5
1975	24.4	11.6	17.3	17.7	0.98	-0.4
1976	18.2	7.1	12.9	12.1	1.07	0.8
1977	9.9	6.3	8.2	8.1	1.01	0.1
1978	19.5	17.7	21.8	19.7	1.11	2.1
1979	19.0	17.0	21.4	19.0	1.13	2.4
1980	19.6	19.0	23.6	20.6	1.15	3.0
1981	10.1	9.1	10.2	10.1	1.01	0.1
1982	25.8	14.9	20.5	20.4	1.00	0.0
1983	24.6	21.6	26.0	24.4	1.06	1.6
1985*	17.8	14.9	16.5	17.1	0.97	-0.5
1986*	16.2	11.3	15.7	14.0	1.12	1.6
1987*	12.2	10.2	13.0	11.6	1.12	1.4
1988	13.5	7.4	13.1	10.3	1.27	2.8
1989	20.7	8.3	11.3	13.9	0.81	-2.7
1990	11.3	7.0	10.5	9.2	1.15	1.4
1991	12.7	11.9	12.8	13.0	0.99	-0.1
1992	10.0	13.3	12.1	12.8	0.95	-0.7
1993	17.2	22.9	21.3	22.2	0.96	-0.9
1994	9.9	8.7	10.8	9.7	1.12	1.1

1995	15.7	19.8	16.6	19.5	0.85	-2.9
1996	20.4	7.0	14.6	12.9	1.13	1.7
1997	19.7	11.3	15.1	15.5	0.97	-0.4
1998	18.3	15.9	16.7	18.0	0.93	-1.3
1999	14.8	5.7	8.1	9.7	0.83	-1.6
2000	16.0	9.6	13.7	12.8	1.07	0.9
2001	11.3	10.3	11.3	11.3	1.00	0.0
2002	15.8	5.0	9.6	9.7	0.99	-0.1
2003	10.1	8.9	12.1	9.9	1.22	2.2
2004	12.7	5.9	10.2	8.9	1.15	1.3
2005	18.4	23.1	20.1	22.8	0.88	-2.7
2006	23.9	9.4	17.4	16.0	1.09	1.4
2007**	11.2	4.5	6.8	7.4	0.91	-0.6
2008	17.7	12.5	16.1	15.4	1.04	0.6
2009	15.3	10.5	12.7	13.1	0.97	-0.4
2010	14.0	15.3	15.1	15.8	0.95	-0.7
2011	19.6	12.4	20.1	16.2	1.24	3.9
2012**	9.5	5.1	7.9	7.1	1.12	0.9
2013	12.0	5.8	9.3	8.6	1.08	0.7
2014	14.1	4.8	9.9	8.8	1.12	1.0
2015**	6.0	3.9	6.1	4.9	1.26	1.2
2016	21.0	7.4	12.8	13.5	0.95	-0.6
2017**	18.8	13.9	13.9	16.9	0.82	-3.0
2018	12.1	4.3	7.9	7.7	1.03	0.3
2019	21.9	15.4	19.5	19.2	1.02	0.4
2020	14.3	8.7	14.0	11.5	1.21	2.4
2021	15.4	6.4	11.0	10.4	1.05	0.5
2022	10.3	6.7	10.6	8.5	1.24	2.1
Mean	16.4	11.1	14.5	14.0	1.04	0.5

* Seeding conducted in adjacent areas but not target area, so not included in mean
** Results not included in mean due to early snowmelt

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.949996055
R Square	0.902492504
Adjusted R Square	0.890304067
Standard Error	1.586464815
Observations	19

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Upper 95.0%*
Intercept	**-0.260923565**	1.353562	-0.19277	0.849566	-3.13035	2.6085	2.6085
North Ctrl	**0.417766179**	0.064075	6.519931	7.06E-06	0.281933	0.5536	0.5536
South Ctrl	**0.666458753**	0.08255	8.073371	4.93E-07	0.49146	0.841457	0.841457

Eastern Tooele Target
Apr 1 Snow Water Content

Regression (non-seeded) period:

Year	Control	Target	Predicted	Obs/Pred Ratio	Increase
1956	16.3	8.9	16.7	0.54	-7.7
1957	14.2	16.0	14.4	1.11	1.6
1958	20.9	16.2	21.6	0.75	-5.4
1959	10.6	10.2	10.5	0.97	-0.3
1960	12.0	16.2	12.0	1.35	4.2
1961	12.8	10.5	12.9	0.82	-2.3
1962	20.7	18.8	21.3	0.88	-2.5
1963	7.9	7.1	7.6	0.93	-0.5
1964	13.8	14.0	14.0	1.00	0.0
1965	17.0	16.3	17.4	0.93	-1.1
1966	11.1	9.4	11.1	0.85	-1.6
1967	12.7	11.9	12.7	0.93	-0.9
1968	12.5	14.0	12.6	1.12	1.4
1969	22.4	25.5	23.2	1.10	2.3
1970	14.7	11.9	14.9	0.79	-3.1
1971	16.6	16.6	17.0	0.98	-0.4
1972	15.3	8.7	15.5	0.56	-6.9
1973	20.4	32.1	21.0	1.53	11.1
1974	17.2	13.1	17.6	0.74	-4.5
1975	18.1	20.1	18.6	1.08	1.5
1983	22.4	21.0	23.2	0.90	-2.2
1984	27.1	30.8	28.1	1.10	2.7
1985	15.0	20.3	15.2	1.33	5.1
1986	16.0	12.8	16.3	0.79	-3.5
1987	11.3	15.3	11.3	1.36	4.0
1988	11.7	12.2	11.7	1.05	0.6
1993	16.1	19.9	16.4	1.21	3.5
1994	10.0	11.5	9.9	1.16	1.6
1995	13.8	17.0	13.9	1.22	3.1
Mean	15.5	15.8	15.8	1.00	0.0

Seeded period:

Year	Control	Target	Predicted	Obs/Pred Ratio	Increase
1976	15.7	15.6	16.0	0.98	-0.4
1977	6.2	9.3	5.8	1.59	3.5
1978	17.4	21.1	17.8	1.18	3.3
1979	18.9	18.0	19.4	0.93	-1.4
1980	19.0	24.4	19.5	1.25	4.8
1981	9.3	12.5	9.2	1.36	3.3
1982	21.4	19.6	22.1	0.89	-2.5
1989	13.9	9.9	14.1	0.70	-4.2

1990	10.7	12.4	10.7	1.16	1.7
1991	10.2	10.5	10.1	1.05	0.5
1992	8.7	10.3	8.5	1.21	1.8
1996	14.5	12.8	14.7	0.87	-1.9
1997	14.8	17.9	15.0	1.19	2.9
1998	14.8	23.4	15.0	1.56	8.4
1999	10.1	8.8	10.0	0.88	-1.2
2000	11.2	15.9	11.2	1.42	4.7
2001	8.7	11.4	8.5	1.35	3.0
2002	11.2	11.0	11.2	0.98	-0.2
2003	8.5	9.6	8.3	1.16	1.3
2004	10.2	15.0	10.1	1.49	4.9
2005	18.0	20.2	18.5	1.09	1.7
2006	16.6	16.3	17.0	0.96	-0.6
2007*	6.8	7.2	6.4	1.11	0.7
2008	14.3	17.5	14.4	1.21	3.1
2009	12.6	13.9	12.6	1.10	1.2
2010	12.2	13.0	12.2	1.06	0.8
2011	16.0	21.9	16.3	1.34	5.5
2012*	8.2	7.2	7.9	0.91	-0.7
2013	7.9	10.0	7.7	1.30	2.3
2014	10.1	8.3	9.9	0.83	-1.7
2015*	4.1	1.5	3.6	0.43	-2.0
2016	13.6	12.0	13.8	0.87	-1.8
2017*	12.9	13.8	13.0	1.06	0.8
2018	8.3	5.3	8.1	0.66	-2.8
2019	19.5	21.4	20.0	1.07	1.4
2020	10.7	11.5	10.7	1.08	0.8
2021	11.3	10.8	11.3	0.95	-0.5
2022*	8.4	5.4	8.2	0.66	-2.8
Mean	12.9	14.3	13.0	1.10	1.3

* Not included in mean due to early-season snowmelt

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.766963
R Square	0.588233
Adjusted R Square	0.572982
Standard Error	3.975414
Observations	29

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.80605	2.774503	-0.29052	0.773637	-6.49886	4.886756	-6.49886	4.886756
X Variable 1	1.068717	0.172081	6.210555	1.22E-06	0.715637	1.421798	0.715637	1.421798

APPENDIX E: GLOSSARY

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.

Dew point: 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