Annual Cloud Seeding Report
High Uintas Program
2023-2024 Winter Season

Prepared For:

Duchesne County Water Conservancy District

Uintah Water Conservancy District

State of Wyoming

Metropolitan Water District of Southern California

State of Utah, Division of Water Resources

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EXECUTIVE SUMMARY

Program History

The Duchesne County Water Conservancy District and the Uintah Water Conservancy District were joined by the Central Utah Water Conservancy District in supporting an operational seeding project, beginning in the 2002-2003 winter season. The intended target area of this program has been the southern slope of the Uinta Mountains above 8,000 feet. The High Uintas program currently utilizes 20 ground-based, manually operated Cloud Nuclei Generator (CNG) sites, along with a remotely operated site located at Moon Lake. Some sites established for the adjacent Western Uintas seeding program are also utilized to target the High Uintas. 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, with additional funds from the Lower Colorado River Basin States providing for an early-season extension to the seeding program.

A total of 1721.5 CNG hours were conducted during 30 storm periods for the core High Uintas program this season. An additional 350 hours of seeding were conducted during 3 storm periods in November for the Lower Basin States sponsored extension period. The seeding hours for the new remotely operated generators are excluded, as the hours for those are counted and billed separately. There were no seeding suspensions for the High Uintas program during the 2023-2024 season.

Precipitation and snowfall began below average for the start of the 2023-2024 winter season, but improved to above average beginning in mid-January 2024 and remained above average through April 2024. There was an El Niño pattern in place this winter season, in contrast to the past few seasons which observed a La Niña pattern. As of April 1, 2024, SNOTEL observations for the Natural Resource Conservation Service showed snow water content averaging about 133% of normal (median) for the Duchesne Basin and about 122% of normal for sites in the portions of the Uinta Range that compose the Green River Basin. Water year precipitation percentages were 121% of the median for the Duchesne Basin and around 111% of normal for sites in the Green River Basin.

Results

To evaluate the increase in snowpack and precipitation resulting from cloud seeding, long term Target/Control evaluations have been performed during both seeded and non-seeded years for the High Uintas cloud seeding program. Results of these evaluations indicate a 3% increase in precipitation and/or snowpack resulting from cloud seeding. This additional 3% increase in snowpack yields 0.4-1 inches of SWE to the target area, depending on overall seasonal trends.

The relationship between snowpack and realized streamflow is generally not linear (improved efficiency at higher runoff rates). Additional evaluations were, therefore, conducted to determine the projected increase in runoff resulting from a 3% increase in snowpack. These mathematical evaluations yielded an expected 2-4% increase in streamflow for Ashely Creek, Yellowstone River, and Lake Fork River (depending on overall seasonal performance).

These results are discussed in more detail in the Assessment of Seeding Effects section of the report.

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.

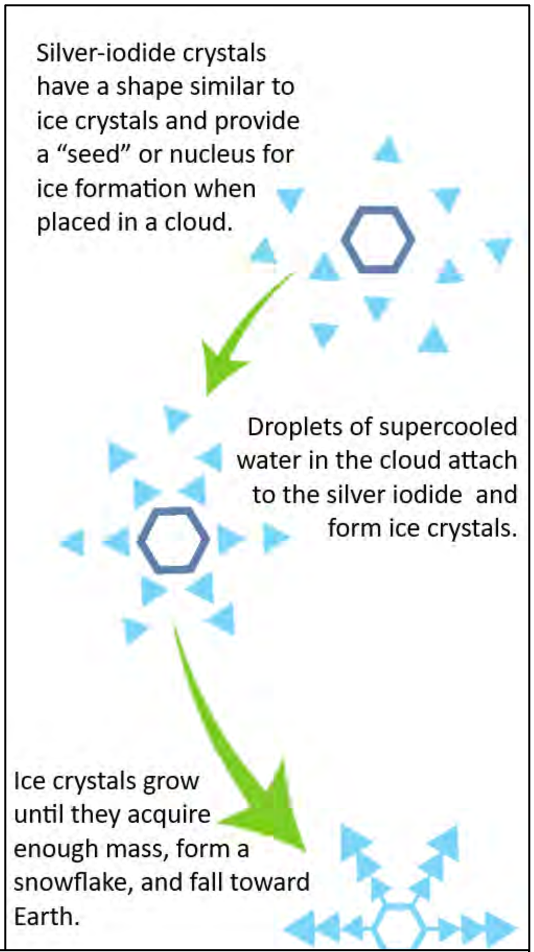
Silver iodide has been selected for its environmental safety and superior efficiency in producing ice in clouds. Silver iodide adds microscopic particles with a structural similarity to natural ice crystals. Ground-based and aircraft-borne technologies can be used to add the particles to the clouds.

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.



INTRODUCTION

Due to high natural precipitation variability and the increasing demand for water, cloud seeding has been conducted in some parts of Utah for well over 40 years. Cloud seeding in Utah is regulated by the Utah Department of Natural Resources through the Division of Water Resources. After complying with various permit requirements, NAWC was granted a license and permit to conduct cloud seeding for the High Uintas Program watersheds.

The Duchesne County Water Conservancy District and the Uintah Water Conservancy District were joined by the Central Utah Water Conservancy District in supporting an operational seeding project beginning in the 2002-2003 winter season. The state of Utah, through the Utah Division of Water Resources and the Lower Colorado River Basin States (LBS) collectively reimburse up to 50% of the cost of this program, and provide funding for an extension period that permits the continuation of the program through the month of April.

The intended target area of this program has been only the south slope of the Uinta Mountains above about 8,000 feet. However, a recent feasibility analysis and discussions with the Division of Water Resources resulted in the addition of the north slope of the Uintas (on the Utah side of the state line) to the program beginning in the 2019-2020 season. For the 2021-2022 water year, the LBS and the UDWR provided funds for the acquisition of a remotely operated ground seeding generator that was placed at Moon Lake. This generator releases higher concentrations of seeding solution than manual generators and permits more regular and consistent operation during the winter months when the road leading up to Moon Lake is frequently closed due to snow pack. This remote generator was once again for the 2022-2023 winter season in conjunction with the manual sites.

The High Uintas Program is tributary to the Colorado River via the Green River, and LBS funds have been used to augment the program beginning in the 2010 water year. The extension period funded by Lower Basin States has been at the beginning of the core project season for the High Uintas, during the month of November each season. The extension provides additional benefit to the primary project sponsors at no additional cost to them. As additional LBS funding benefits, additional ground-based silver iodide generators have previously been added to the program, as well as strategically-located mountain ridge ice detector systems designed to help identify storm periods producing supercooled liquid water which is the target of the cloud seeding efforts.

This report provides information about operational cloud seeding conducted over the target watersheds in the 2023-2024 winter season, including the extension period. Project Design describes the seeding project design and provides maps of the seeded target areas, as well as the locations of the ground-based seeding units (generators) with which the seeding was conducted. Weather Data and Models describes the meteorological and computer forecast model data used in the conduct of operations, with some examples presented. Operations summarizes the seeding operations and documents the seeding generator usage by site and storm event. Assessment of Seeding Effects provides an overview of statistical evaluations of the effects of the cloud seeding program.

PROJECT DESIGN

Background

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

The target area for the High Uintas project is adjacent to the target area for the Upper Weber Basin (Western Uintas) Project as seen in (Figure 2.1), which has also been conducted for a number of recent winter seasons. As discussed earlier the program was previously expanded for the 2020-2021 water year to incorporate the Northern Slope of the Uinta Mountain Range.

The target area was designed to include elevations of 8000 feet MSL or greater on the south slope of the Uinta Mountains containing river drainages that provide water to either of the sponsoring counties, plus areas providing runoff into Strawberry and Currant Creek Reservoirs. To overcome the impacts of the thermal inversions that is common in the valley south of the Uinta Mountain Range during the winter, NAWC recommends placing ground generators at or above about 7,000 feet in elevation. Due to the prevalence of national forests and Native American Reservations at upper elevations the placement of ground generators above the inversion is no simple task. This was the primary motivation for the LBS to sponsor the deployment of a remotely operated generator near Moon Lake on the southern side of the Uinta Range.

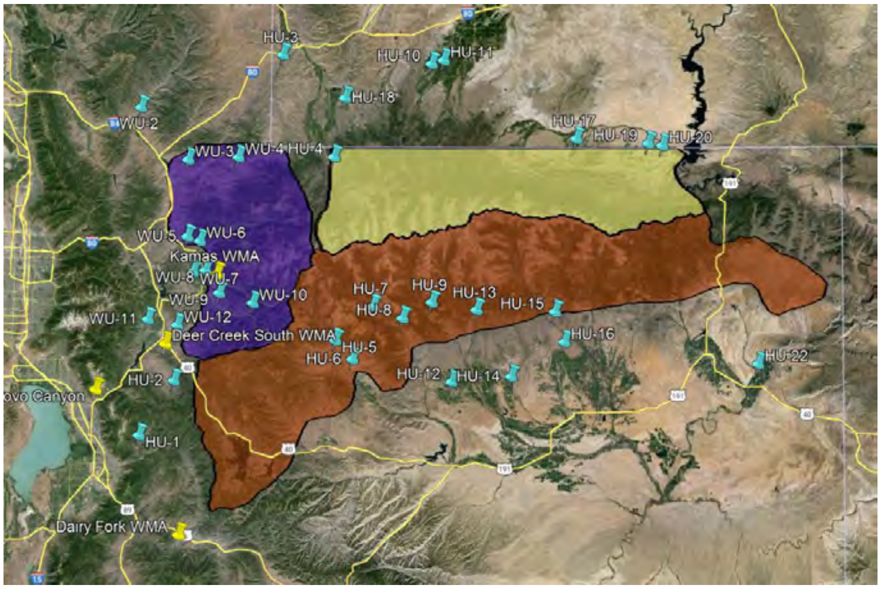


Figure 2.1 **Western Uinta Program (purple), High Uinta Program (orange), Northern Slope Extension (yellow). Blue pins denote existing generator locations while yellow pins show new remote sites**

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

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

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

Consideration of the third issue (wind direction) dictates that a significant number of generators should be placed at south flank locations, since a number of the more productive storms have steering level winds from the southeast through west-southwest directions. Another maximum in potentially seedable storms occurs during westerly to west-northwesterly winds, which supports frequent usage of sites on the western side of the Uinta Range. Some seedable situations involve winds with a more significant northerly component (i.e. from northwesterly to northeasterly), and this supports the location of seeding sites on the northern side of the Uinta Range. Operational experience with this program has shown that storms with northerly-component winds may be good seeding candidates, with the enhanced snowfall on the northern slope of the Uintas that frequently carries over to the upper portion of the southern slope (within the target area) as well.

Seedability Criteria

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

NAWC Winter Cloud Seeding Criteria

- Cloud bases are near to (ideally) below the mountain barrier crest.
- Low-level wind directions and speeds would favor the movement of the silver iodide particles from their release points into the intended target area.
- No low-level atmospheric inversions or stable layers that would restrict the upward vertical transport of the silver iodide particles from the surface to at least the -5°C (23°F) level or colder.
- Temperature at mountain barrier crest height expected to be -5°C (23°F) or colder.
- Temperature at the 700mb level (approximately 10,000 feet) expected to be warmer than -15°C (5°F).

Equipment and Project Setup

During the off-season, the ground-based seeding equipment is routinely removed from the field for maintenance and testing. NAWC began re-installing the manually operated generators in October 2023 and also began installing the new remotely operated sites in November 2023. The seeding sites were placed at the locations shown in Figure 2.1.

The cloud seeding equipment at each manually operated site consists of a cloud nuclei generator (CNG) unit and a propane gas supply. The cloud seeding equipment for a remotely operated (CNG) consists of a solution tank, datalogger, cellular communication modem, pressure control module, battery unit, camera for visual observations, a radio antenna, and a propane gas supply. The seeding solution for both manual and remote CNG's contains two percent (by weight) silver iodide (AgI), the active seeding agent, complexed with very small portions of sodium iodide and para-dichlorobenzene in solution with acetone. A paper published by Dr. William Finnegan, a well-respected cloud seeding formulation expert of the Desert Research Institute (Finnegan, 1999), indicates that this formulation is superior to others that produce pure silver iodide particles. The modified particles produced by combustion of the revised formulation act as ice nuclei much more quickly, and there are somewhat larger numbers of effective nuclei at warmer temperatures (i.e., about -5°C to -10°C). It is necessary that the AgI crystals become active in supercooled clouds at relatively low altitudes upwind of (or over) the mountain crest. This allows the available supercooled liquid water to be effectively converted to ice crystals which can grow to snowflake size and precipitate onto the mountain barrier. If the AgI crystals take too long to become active, or if the temperature upwind of the crest is too warm, the plume will pass from the generator through the precipitation formation zone and over the mountain crest without producing any additional snowfall in the intended target area.

Figure 2.2 is a photograph of a manually operated (CNG) while Figure 2.3 is a photo of a remotely operated unit.

Figure 2.2 **NAWC manually operated cloud nuclei generator (CNG)**

Figure 2.3 Photo of a NAWC remotely operated Cloud Nuclei Generator (CNG)

Manually operated CNGs are maintained at 21 locations specific to the High Uintas program, with in addition to the remotely operated equipment that was installed at Moon Lake on the southern flank of the target area in the fall of 2021. There are now eight sites on the northern side of the target area. Two other sites are used primarily to target the Strawberry Divide area (sites HU1 and HU2), with many of the nearby Western Uintas manually operated sites and nearby new remotely operated sites utilized to target this area as well. The network of sites is designed to be effective in generating plumes of seeding material which will pass over the target area in a variety of wind flow situations. Pertinent site information is listed in Table 2-2, corresponding to the site numbers shown in Figure 2.1.

Table 2-2
Cloud Seeding Generator Sites

Site ID	Site Name	Elevation (Feet)	Latitude (N)	Longitude (W)
HU1	Hobble Creek	5870	40°12.22'	111°30.14'
HU2	Wallsburg	6175	40°20.95'	111°23.00'
HU3	Evanston	7000	41°12.70’	111°01.13’
HU4	Bear River East	8223	40°56.54'	110°50.17'
HU5	Hanna Pump House	7019	40°27.60'	110°49.56'
HU6	Hanna	6781	40°24.64'	110°46.03'
HU7	Rock Creek Ranch	7988	40°33.02'	110°41.78'
HU8	Robbins Ranch	7404	40°31.18'	110°35.64'
HU9 Remote	Moon Lake	8100	40°33.25’	110°29.20’

HU10	Black’s Fork	7509	41°11.39'	110°29.87'
HU11	Robertson	7322	41°11.97'	110°27.31'
HU12	Talmage	6945	40°21.53’	110°27.28’
HU13	Yellowstone Canyon	7660	40°32.50’	110°20.30’
HU14	Bluebell	5840	40°26.85'	110°03.72'
HU15	Uinta Power Plant	6932	40°32.27'	110°03.98'
HU16	Neola	6330	40°27.48'	110°02.93'
HU17	Birch Creek	7634	40°58.64'	109°59.48'
HU18	Gilmore Ranch	7550	41°05.91’	110°47.96’
HU19	Manila	6500	40°58.91'	109°44.36'
HU20	Manila East	6230	40°58.57’	109°41.38’
HU22	Jensen	4896	40°23.92'	109°21.49'
W4	Pineview	6407	40°56.39'	111°10.18'
W6	Oakley	6472	40°43.07’	111°18.00’
W7	Kamas	6489	40°38.43'	111°16.77'
W8	Kamas West	6472	40°38.16'	111°19.33'
W9	Woodland	6706	40°34.89'	111°13.81'
W10	Woodland East	7305	40°33.35'	111°06.80'
W11	Midway	5570	40°30.59'	111°28.64'
W12	Heber City	5810	40°29.73'	111°22.52'
DN_0014 Remote	Kamas WMA	7018	40° 37.89'	111° 14.34'
DN_0016 Remote	Deer Creek WMA	6664	40° 26.78'	111° 24.90'
DN_0015 Remote	Provo Canyon WMA	5515	40° 19.38'	111° 39.28'
DN_0018 Remote	Dairy Fork WMA	6242	39° 56.60'	111° 21.59'

Project Instrumentation

Some specialized instrumentation has been added over the past number of years to enhance cloud seeding guidance during operations within the High Uinta Program area. This includes icing rate meters and, during a previous season (2021-2022), a radiometer was located on the northern side of the Uinta Range. Both instrument systems were supported by funding from the Lower Basin States. Because SLW is the target of cloud seeding, such a sensor is of benefit both in terms of real-time operational decisions and for later analysis of the frequency of SLW occurrence in relation to winter storm periods. This sensor is similar to sensors which have been installed in other seeding target areas in Utah. Analyses of the data from these sites have provided valuable insight into the occurrence of SLW during winter storms. Figures 2.4 and 2.5 provide photographs of the installation. The funding for the equipment, installation and maintenance of this site was provided by three Lower Colorado River Basin States and administered by the Utah Department of Water Resources Division.

Figure 2.4 **Icing Rate Meter Installation at the Dry Ridge Site**

Figure 2.5 **Dry Ridge Sensor Suite**

Suspension Criteria

NAWC always conducts its projects within guidelines adopted to ensure public safety. Accordingly, NAWC has a standing policy and project-specific procedures for the suspension of cloud seeding operations in certain situations. Those criteria are shown in Appendix A, and have recently been updated in coordination with the Utah Division of Water Resources. The criteria are an integral part of the seeding program. There were no suspensions of seeding operations during the 2023-2024 season.

WEATHER DATA AND MODELS USED IN SEEDING OPERATIONS

NAWC maintains a fully equipped project operations center at its Sandy, Utah headquarters. Meteorological information is acquired online from a wide variety of freely available sources and subscriber services. This information includes weather forecast model data, surface observations, rawinsonde (weather balloon) upper-air observations, satellite images, NEXRAD radar information, and weather cameras. This information helps NAWC's meteorologists to determine when conditions are appropriate for cloud seeding. NAWC's meteorologists are able to access all meteorological products from their homes, 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. Figure 3.4 provides predictions of ground-based seeding plume dispersion for a discrete storm period in the High Uintas using the National Oceanic and Atmospheric Administration's HYSPLIT model. This model helps to estimate the horizontal and vertical spread of a plume from potential ground-based seeding sites in real-time, based on wind fields contained in the weather forecast models.

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

During the summer of 2022, NAWC built an in-house Python script that has the ability to ingest 3-km High-Resolution Rapid Refresh (HRRR) model data readily available online. This script allows the user to define a grid where seeding operations and liquid water could be occurring. The user can specify a cross section over any location in the continental U.S. or Canada. This model data was used during cloud seeding operations as a guidance. In these cross sections, liquid water is plotted as a function of distance and height, with temperatures (red dashed lines), wind directions and speed (wind barbs) and potential temperatures (solid black lines) also being displayed. This model was utilized on a variety of different areas where NAWC conducts cloud seeding operations. The script has the ability to be run for one specific forecast hour. Figure 3.6 shows an example of the cross-section plot during a seeded event from this past winter season that includes liquid water occurrence, temperature, wind direction, wind speed and potential temperatures as a function of height. The map inset located in the upper left corner of the cross-section plot shows a map of where the cross section was taken within the state of Colorado. It is important to notice how much of the predicted liquid water is tied to underlaying terrain due to orographic forcing (lifting of the airmass as winds force it over the underlaying terrain). Also notice that much of the predicted liquid water is at temperatures of -5° C or colder which is an important feature since the silver iodide nuclei released from the remote generators mush reach this level in order for the nuclei to become active freezing nuclei. This model will continue to be utilized in future winter seasons and possibly lead to further verification techniques.

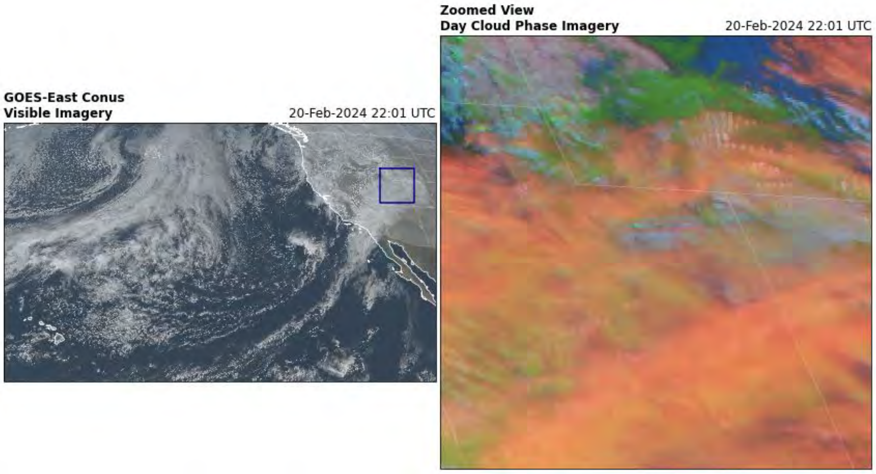


Figure 3.1 Zoomed satellite image of Utah on the afternoon of February 20, 2024 during a seeded event.

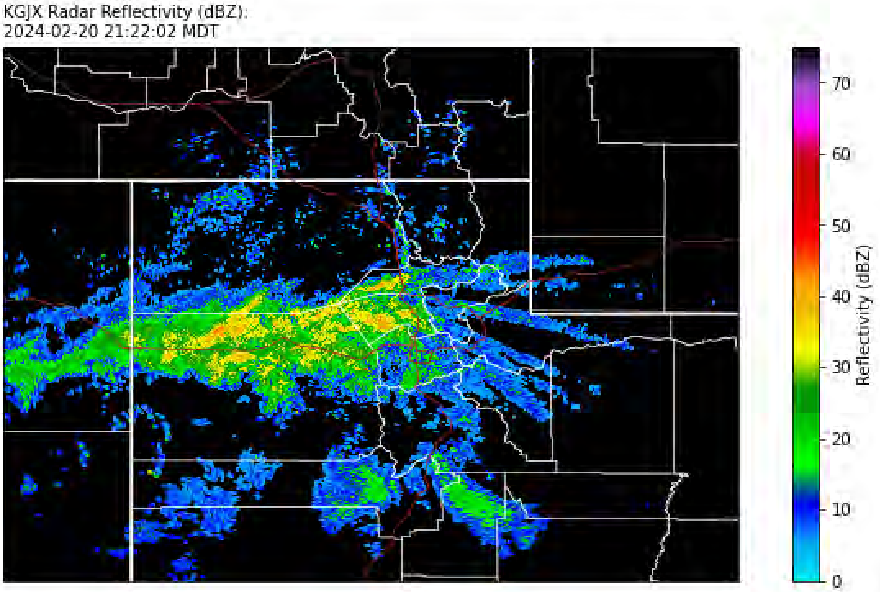


Figure 3.2 Weather radar image over northern Utah during the evening of February 20, 2024.

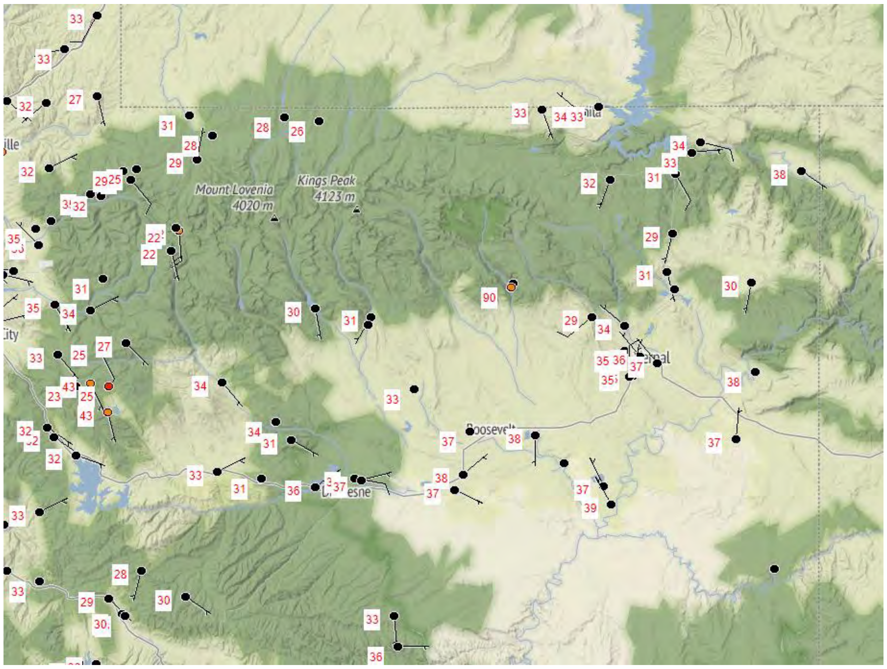


Figure 3.3 Surface map on the evening of February 20, 2024 showing winds and temperatures at a variety of automated sites in an around the Uinta Range.

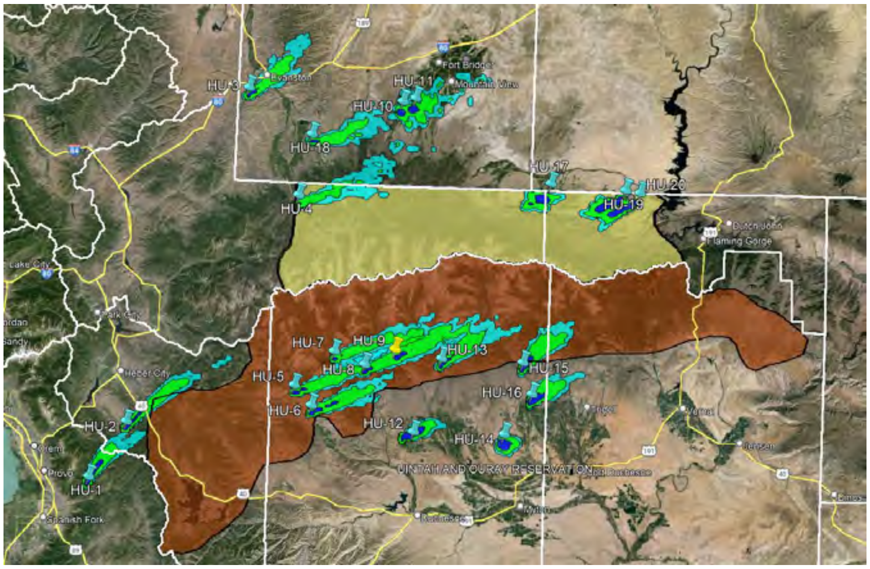
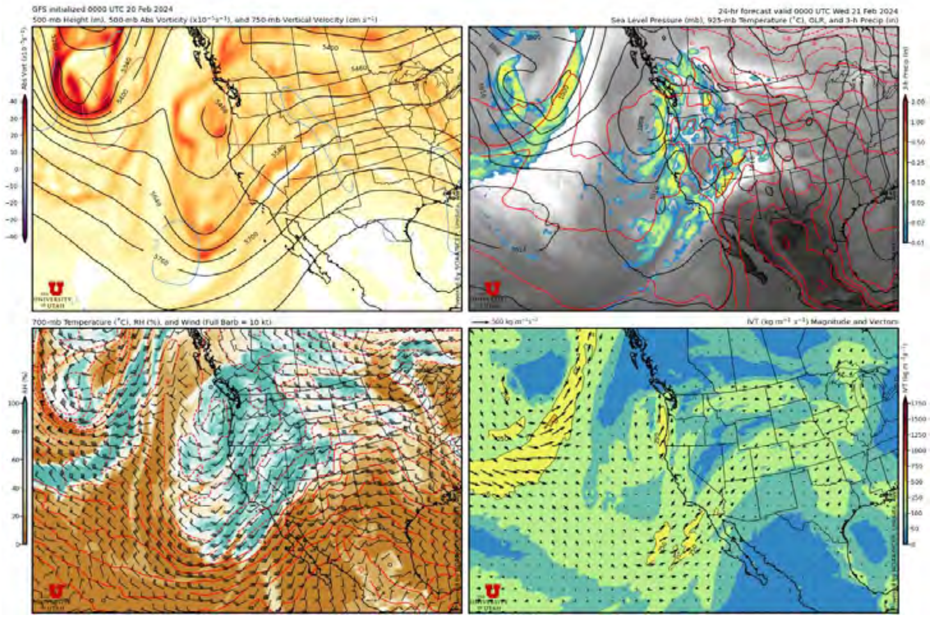


Figure 3.4 HYSPLIT plume dispersion forecast for potential seeding locations during a storm on the evening of February 20, 2024. This is a tool that can be used to help select appropriate sites for a given situation.



Figures 3.5 GFS model 4-panel data display during a storm event on February 20,2024. The lower left panel shows winds, moisture, and temperature at the 700-mb level which are especially useful for seeding operations.

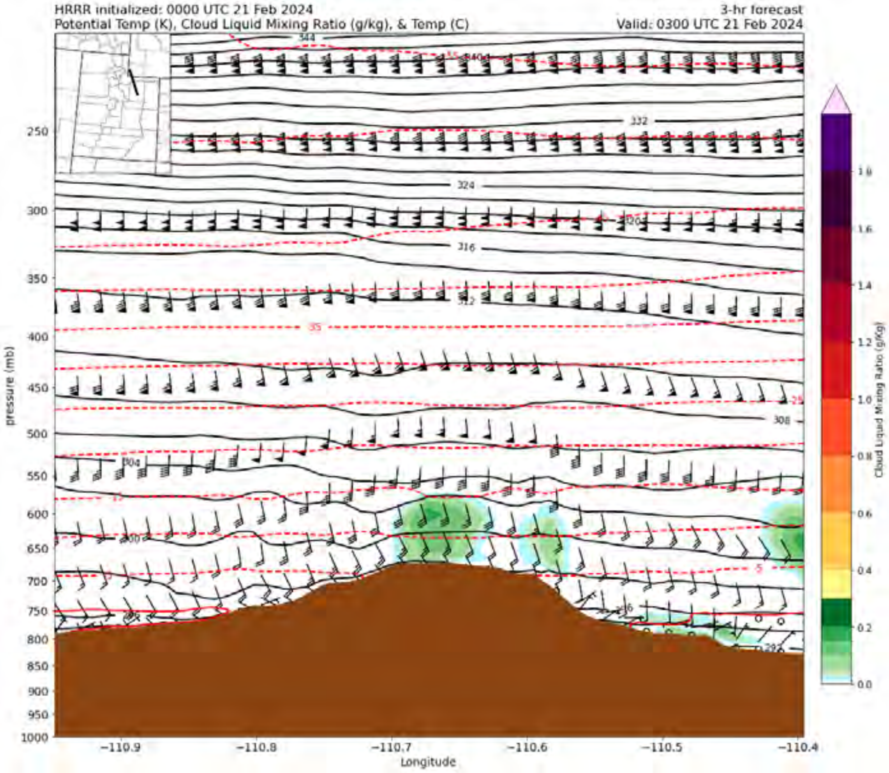


Figure 3.6 HRRR modeled Cross Section of Liquid Water on February 21, 2024 – Valid at 2100 MST

OPERATIONS

The core 2023-2024 cloud seeding program for the High Uintas was operated from December 1, 2023 through April 30, 2024, with an extension period from November 1-30, 2023 funded by the Lower Basin States. During the entire operational season of November 1 – April 30, seeding operations took place over 33 storm periods, with three of these occurring during the extension period in November. Altogether, there were three seeded storms in November, four in December, four in January, eight in February, ten in March, and four in April. A cumulative 1721.5 hours of ground seeding generator operations were conducted during the regular season, and an additional 350 hours during the extension period, for a total of 2071.5 hours. Seeding was also conducted from the four new remotely operated cloud seeding generators: however, the hours for these remotes are funded and counted separately so the hours are excluded from this report. Figure 4.1 is a graph of operations this season for the core High Uintas program, compared to a linear usage of the total budgeted hours. Table 4-1 shows the seeding dates and ground generator usage for the storm events.

Precipitation and snowfall began below average for the start of the 2023-2024 winter season, but improved to above average beginning in mid-January 2024 and remained above average through April 2024. There was an El Niño pattern in place this winter season, in contrast to the past few seasons which observed a La Niña pattern. As of April 1, 2024, SNOTEL observations for the Natural Resource Conservation Service showed snow water content averaging about 133% of normal (median) for the Duchesne Basin and about 122% of normal for sites in the portions of the Uinta Range that compose the Green River Basin. Water year precipitation percentages were 121% of the median for the Duchesne Basin and around 111% of normal for sites in the Green River Basin. Figures 4.2 to 4.4 show snow water content and water year precipitation accumulations, and normal, for October 1 through May 1 for target area SNOTEL sites.

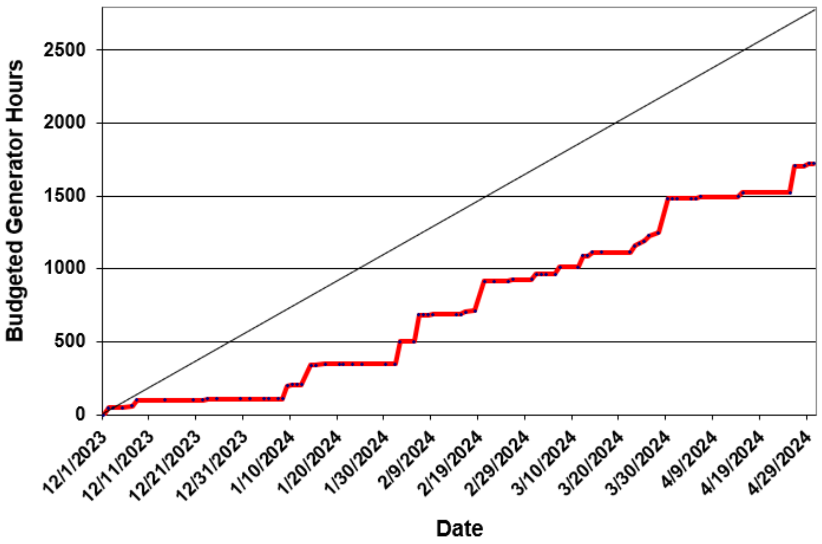


Figure 4.1 Seeding operations during the 2023-2024 season for the core program (red). Diagonal black line shows a linear usage of total budgeted hours, as a reference.

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

Storm Number	Date	Number of Generators	Operational Hours
1*	November 7	4	39
2*	November 16	2	7
3*	November 18-20	22	304
4	December 2-3	3	48
5	December 7	2	12.75
6	December 8	4	38.5
7	December 23	1	6.5
8	January 9-10	5	92.5
9	January 10	2	8.25
10	January 13-15	7	131
11	January 17	2	8
12	February 1-3	9	155.5
13	February 5	1	7.75
14	February 6-7	8	180.75
15	February 9	2	7.5
16	February 16	2	13.5

Storm Number	Date	Number of Generators	Operational Hours
17	February 18	3	11
18	February 20-21	9	201.75
19	February 26-27	1	9.75
20	March 2-3	9	39.25
21	March 7	5	48.25
22	March 12-13	7	74.25
23	March 14	3	27.5
24	March 23	8	45
25	March 24	3	14.5
26	March 25	2	15
27	March 26	6	38.75
28	March 28	4	18
29	March 30-31	9	235
30	April 6	2	12.5
31	April 15	5	29
32	April 26-27	16	182.25
33	April 29	4	16
Core Program Total	---	---	**1721.5**
Extension Total	---	---	**350**

*** Seeding during Lower Basin extension period**

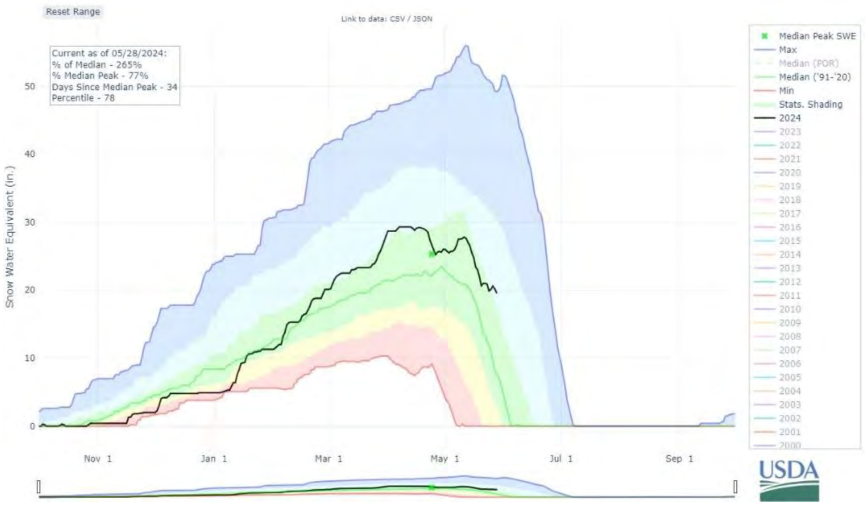


Figure 4.2 NRCS SNOTEL snow water content plot for October 1 through May 28 2024 for the Trial Lake SNOTEL, UT in the western Uintas. Black line is the 2023-24 season data. Green represents the median, and purple and red are the historical maximum and minimum values respectively.

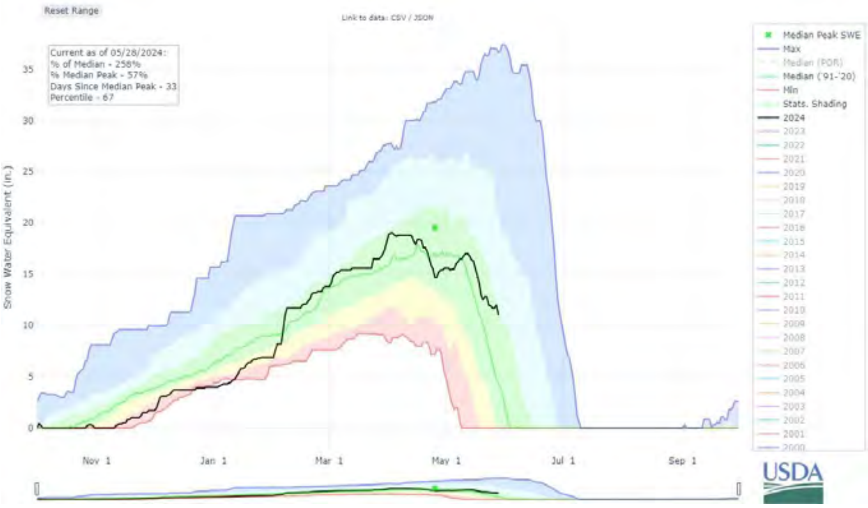


Figure 4.3 NRCS SNOTEL snow water content plot for October 1 through May 28 2024 for the Five Points Lake SNOTEL, UT in the central portion of the Uintas. Black line is the 2023-24 season data. Green represents the median, and purple and red are the historical maximum and minimum values respectively.

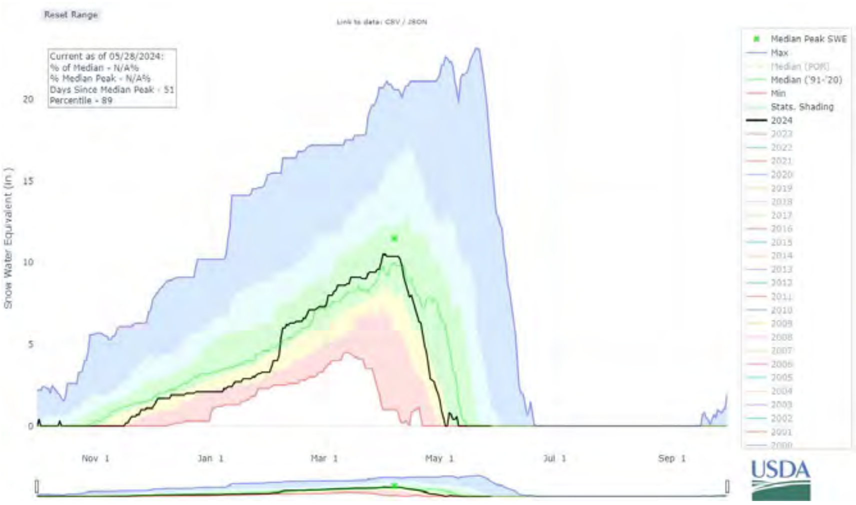


Figure 4.4 **NRCS SNOTEL snow water content plot for October 1 through May 28 2024 for the Trout Creek SNOTEL, UT on the eastern side of the Uintas. Black line is the 2023-24 season data. Green represents the median, and purple and red are the historical maximum and minimum values respectively.**

Operational Procedures

In operational practice, the project meteorologist, with the aid of continually updated online weather information, monitored each approaching storm. If the storm parameters met the seedability criteria presented in the seedability criteria secton, and if no seeding curtailments or suspensions were in effect, an appropriate array of seeding generators was ignited and then adjusted as evolving conditions required. Seeding continued as long as conditions were favorable and precipitating clouds remained over the target area. The operation of the seeding sites is not a simple “all-or-nothing” situation. Individual seeding sites are selected and run based on their location, and targeting considerations based on storm attributes.

Operational Summary

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

November 2023

There were three seeded storm events for the High Uintas program in November. Seeding during storms in November was somewhat limited by wind direction and temperatures, which were quite warm in some events. There was also a temperature inversion that developed in the Uinta Basin later in the month and limited use of sites there.

The first seeded event of the season occurred on November 7th as a weak frontal boundary slowly tracked southeast through Utah during the morning and afternoon hours. The front produced a band of light precipitation as it pushed through the region and brought a drop in temperatures. Southwesterly winds ahead of the front shifted northwesterly in direction around 1100 MST and 700 mb temperatures fell to around -4/-5°C. Seeding operations were conducted from a couple sites on the northern side of the program as well as from several sites located in the Western Uintas program until conditions began to dry out after 2000 MST. Precipitation totals for this storm event range from about 0.2-0.5”.

Some light showers and marginal temperatures on November 16, with winds shifting to the northwest by midday and as well as some weak convective type clouds, produced somewhat suitable conditions for seeding during the late morning to midafternoon hours. Much of the moisture was of subtropical origin but a shortwave trough moving across the area produced enough cooling and mixing for some seeding operations to occur from several sites located in the Western Uintas program from roughly 1200-1530 MST. Precipitation amounts were between 0.4-0.8” for the storm event as a whole.

A compact and vigorous trough moved southeastward across the Great Basin on November 18-20. Ahead of the incoming trough, convective showers developed over the western half of the Uintas in southwesterly flow pattern. 700 mb temperatures were initially on the mild side but the atmosphere was well mixed so seeding operations were conducted during the afternoon and early evening hours on the 18th. The 700 mb temperature then dropped to below -8 C after midday on the 19th with winds becoming northwesterly, and almost due northerly by the night of November 19-20 as the trough moved through Utah. Seeding was again conducted during the daytime hours on the 19th, but this time from several sites on the northern and western side of the program, and continued until the morning of November 20 with some lingering snowfall in a cold advection northerly flow pattern. Precipitation totals for the event as a whole ranged from about 0.4 – 1.1 inches of water equivalent.

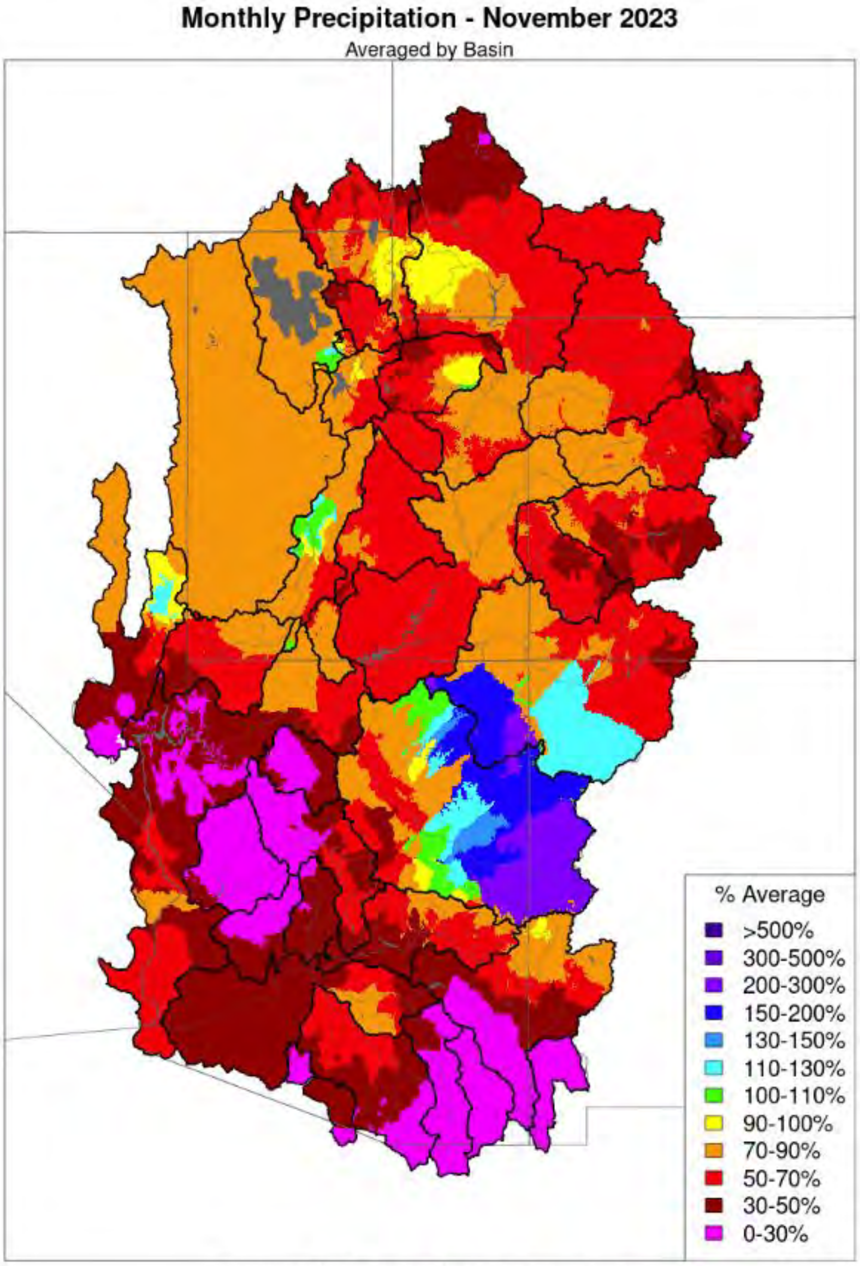


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Figure 4.5 November 2023 precipitation, percent of normal

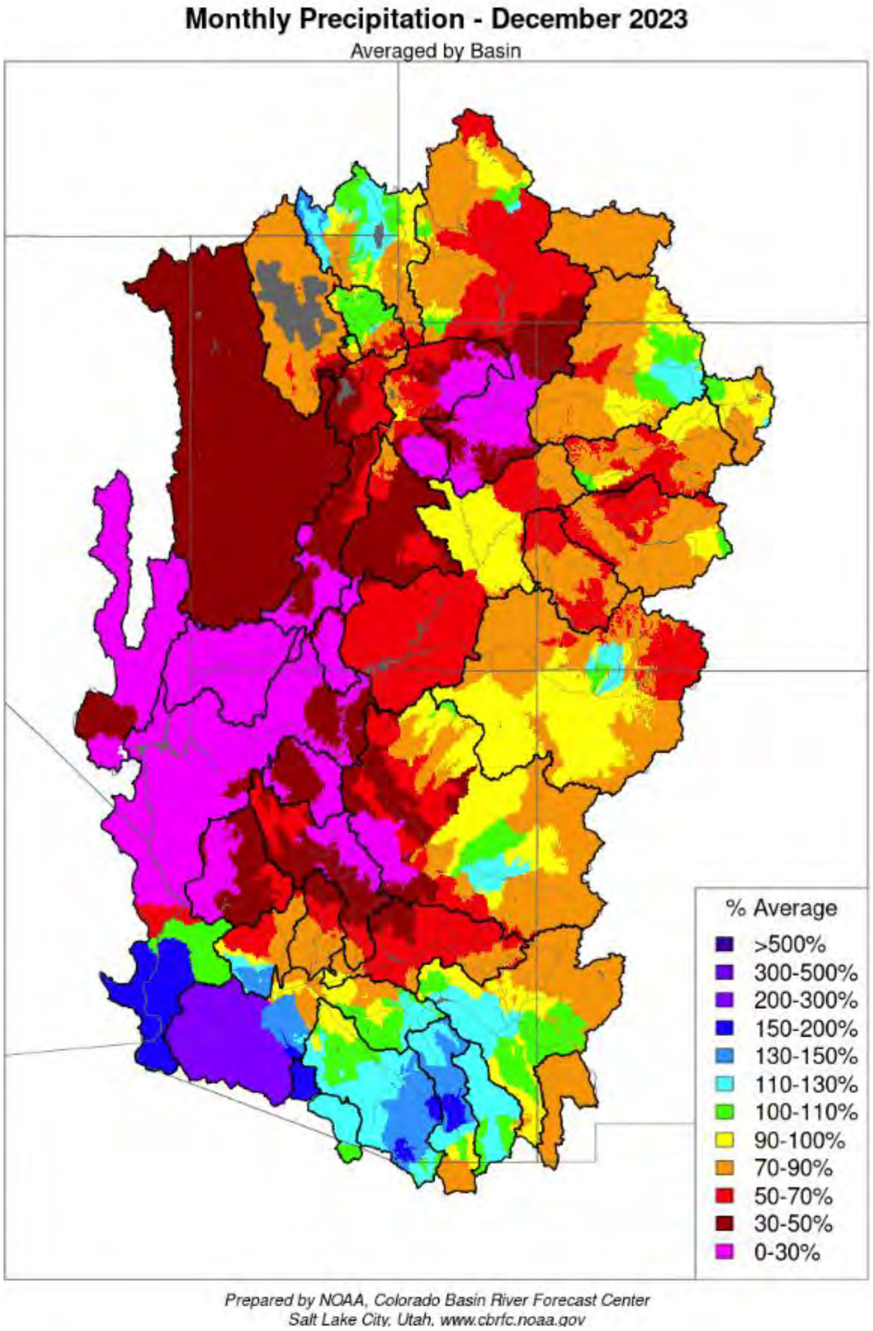
December 2023

December was the first month of operations for the core program for the High Uintas cloud seeding program. December produced below normal precipitation and snowpack across the area (shown in Figure 4.6), with a dry start to the season. In fact, at the end of 2023 many SNOTEL sites were close to the climatological minimum values in the Uintas region with December 2023 recording record breaking warmth across the entire Contiguous United States. There were four seeding opportunities for the High Uintas program in December.

A westerly wind pattern on December 2-3 was accompanied by gradually warming temperatures, from about -8 to -6° C at the 700 mb level. Moisture increased and conditions became favorable for seeding for the western portions of the target area on the night of December 2. Snowfall and seeding continued for much of the day on December 3, and, although precipitation amounts were decent, seeding conditions were only fair as a higher cloud deck was producing most of the snowfall. Seeding ended by mid-afternoon with storm precipitation totals ranging from about 0.9 - 1.7 inches of snow water content at target area SNOTEL sites.

A couple of fast-moving shortwave frontal systems produced seeding opportunities on December 7-8, with the first frontal passage on the 7th. The 700 mb temperature dropped to around -8° C behind the front with only some light snow showers and seeding during the morning to early afternoon for the western and northwestern portions of the target area. After a break, another system spread snow into the area on the night of December 7-8. Seeding began in westerly flow overnight, with winds becoming northwesterly and the temperature dropping further to around -12° C at 700 mb on December 8. A good orographic and somewhat convective snowfall pattern was observed on the morning of the 8th, but by mid-afternoon the clouds became quite icy in appearance with a lack of liquid water and seeding was terminated at that point. Precipitation totals, mainly with the second of these systems, exceeded a half inch of water content in northwestern portion of the target area, but amounts were light (near 0.1 inch) over southern and eastern portions.

After a period of dry weather with some strong temperature inversions in the Uintah Basin, a frontal snow band moved into northern Utah on December 23. Seeding was initiated from sites on the northern and western side of the program in the morning and the 700 mb temperature dropped from about -5 to -12° C during the day. Snow showers decreased during the afternoon hours following the main band, with snow and seeding activity ending by late afternoon. Precipitation with this system was light in the target area, with about 0.1 – 0.2 inches of water content.



Monthly Precipitation - December 2023

Averaged by Basin

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Figure 4.6 **December 2023 precipitation, percent of normal**

January 2024

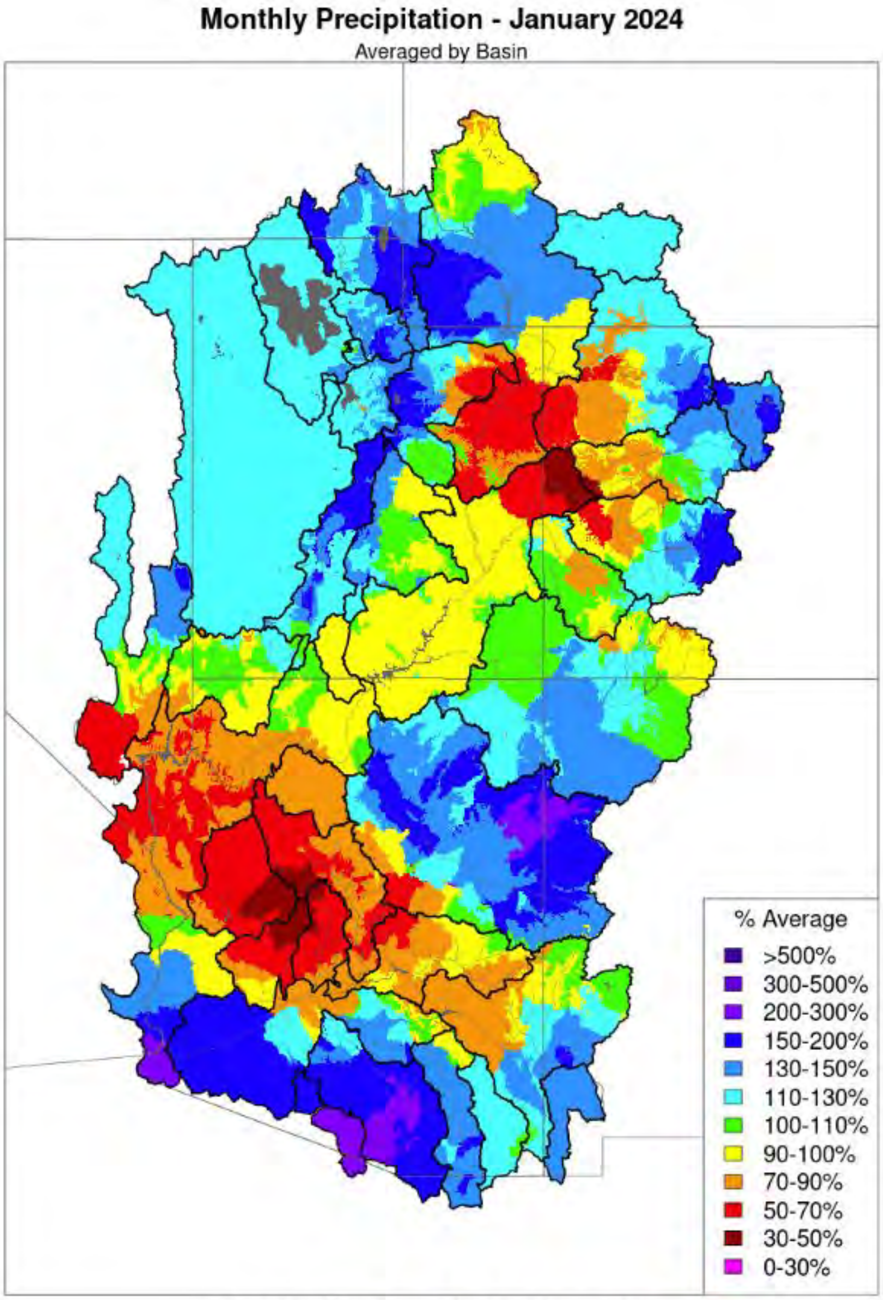
After a very dry start to the season, the weather pattern changed in January and brought much more frequent storm events to the region. As a result, precipitation and snowfall trended up to near normal or only slightly below normal in January (shown in Figure 4.7), which began a recovery from the low early season snowpack. The High Uintas program had 4 seeding storm periods in January.

After some weak and disorganized systems that did not prove favorable for seeding during the first week or so of January, a strong and fast-moving cold front arrived on January 9. Although temperatures were on the cold side, falling to near -15° C at 700 mb with the frontal passage, the front produced a zone of strong lift with a fairly intense snow squall that arrived in the western portion of the target area just after sunset. Seeding began during the early evening hours, and continued overnight into the early morning of January 10 at some sites located on the western and northern portions of the target area as additional snow shower activity lingered. Precipitation totals with this frontal passage amounted to about 0.5 – 0.8 inches of water content in the target area.

A frontal system brought additional periods of snowfall on the afternoon and evening of January 10. Temperatures warmed somewhat (to around -12° C at 700 mb) during the afternoon, but then fell back to below -15° C on the night of January 10 behind a cold front. Seeding was conducted for a short time period during the late afternoon to early evening when conditions appeared favorable with at least some embedded liquid water in the clouds on the western and northern side. Precipitation totals amounted to about 0.2 – 0.6 inches of snow water content.

A moist system moved onshore into Oregon and northern California on January 13, with moisture and southerly flow increasing although with an initially cold air mass over Utah. Limited seeding began from the southern side of the program on the night of January 13, with better lower level mixing and more moisture on January 14 as winds became northwesterly. More widespread seeding was conducted on the 14th from the northern side with 700 mb temperatures around -8° C during that time period. Snowfall and seeding continued overnight, ending the morning of January 15. Precipitation totals ranged from about 0.8 – 1.7 inches of water content with this system during about a 36 to 48-hour period.

A weak system brought some snowfall on January 17, with seeding initially conducted during a frontal snowfall band during the late morning to early afternoon hours. The 700 mb temperature was near -6 C during that period. After a break in activity, another short wave trough brought additional light snowfall with similar temperature on the night of January 17-18. However, precipitation was largely tied to the far western end of the program and there was no good wind direction for targeting the program. As such, seeding operations ended on the evening of January 17. Precipitation amounts in general were between about 0.1 – 0.4 inches of water content.


Monthly Precipitation - January 2024

Averaged by Basin

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Figure 4.7 January 2024 precipitation, percent of normal

February 2024

February was an active weather month that brought up to twice the normal monthly snowfall to portions of the Uintas (shown in Figure 4.8), and a consistently active weather pattern through the month. Snowpack values improved into the normal seasonal range from their low beginning, and there were eight seeded storm periods in February.

Widespread, light precipitation began on the evening of February 1 and was associated with a fairly warm air mass and precipitation from a higher cloud deck that was occurring ahead of a large trough over northern California. Seeding initially began from higher elevation sites located on the southern side on the evening of the 1st and carried over into the morning of the 2nd, as the Dry Ridge icing meter indicated high values of supercooled liquid water being present in the cloud deck. The passage of the trough axis through the area then resulted in northwesterly winds by the evening of February 2nd into the morning of February 3rd, with the 700 mb temperature falling to around -8° C. Snow and seeding ended on the morning of February 3rd, with precipitation totals from the storm period in general between about 0.5 – 1.5 inches of water content.

A large trough near the California coast brought a significant subtropical moisture plume into Utah on February 5-6. Initially, temperatures were warm and lower levels somewhat dry with unfavorable conditions for seeding. Rain and snow increased on the 6th with south to southwest winds and a 700 mb temperature near -3° C. Temperature remained fairly warm with lower levels winds mostly southeasterly even into the night of February 6, with very limited seeding opportunity. On February 7, the core region of the complex trough had moved inland and was crossing Utah and Arizona. Temperatures cooled somewhat (to near -6° C at 700 mb) with better mixing and widespread precipitation at times, although seeding was mainly targeted to the western end. Seeding was conducted through most of the day, ending in the evening, with precipitation totals from this event as a whole ranging from about 0.7 - 1.7 inches in the target area.

A weak trough crossing northern Utah on the 9th brought a brief seeding opportunity during the afternoon hours. Light snow developed over the western and northern portions of the target area in a westerly flow pattern by midday with 700mb temperatures lowering to near -12° C. Seeding began around 1200 MST as the Dry Ridge icing meter indicated the presence of super cooled liquid water. Seeding was then quickly concluded after 1600 MST satellite imagery and radar returns showed shower activity was weakening. Precipitation amounts ranged from 0.1-0.2” with this event.

A northwesterly flow pattern was in place across Utah on the morning of February 16th as another trough was digging southeast through Idaho. Ample moisture streaming into the area in the lower to mid-levels of the atmosphere was generating strong orographic lift and leading to the development of moderate precipitation over the northern and northwestern facing terrain of the program. A few seeding sites were turned on around 1400 MST and remained on until shower activity tapered off after 2000 MST. 700 mb temperatures were around -8° C in the morning but gradually lowered to near -10° C in the afternoon, just as precipitation was ending. SNOTEL sites in the region reported that the target area received between 0.1-0.3” of SWE.

Another weak trough crossed southern Idaho and far northern Utah on February 18th. Ample low level moisture streaming into northern Utah under a southwesterly flow pattern generated orographic showers during the morning hours with some showers becoming convective during the afternoon. Seeding was conducted from several sites on the southern and southwestern side, from roughly 1100 MST until shower activity diminished after 1900 MST. Precipitation totals from this storm period were between 0.1 – 0.4 inches of water content.

A large longwave trough remained centered near the Oregon coast on the morning of February 20th. Downstream of this large trough, a southwesterly flow pattern was pumping subtropical moisture into Utah and was causing widespread precipitation to occur over the state. 700 mb temperatures around -4°C were considered on the warm side for seeding, although weak embedded convective activity developed later in the afternoon and led to initiation of seeding operations after 1300 MST. The longwave trough axis ejected inland to the Desert Southwest on the evening of the 20th into the afternoon of the 21st. A jet streak on the southern side of this large low pivoted across the Desert Southwest and an associated cold front was forced west to east across Utah. Strong lifting dynamics from this complex system kept widespread and heavy precipitation going across northern Utah with intermittent periods of seeding activity continuing overnight and throughout the morning and afternoon of February 21st. 700 mb temperatures additionally lowered throughout the event, dropping from near -4°C on the 20th to near -7°C on the 21st. Seeding operations finally ended around 1700 MST on the 21st after snow shower activity tapered off. Observations revealed that the program received between 0.3-1.0” of liquid water content.

A cold frontal boundary made its way across northern Utah on the evening of February 26, causing 700 mb temperatures to drop from -5°C to near -14°C and winds to shift from south-southwesterly to west-northwesterly. A band of moderate to heavy precipitation initially accompanied the frontal passage with orographic enhanced showers continuing through the morning of February 27 in the cold and unstable post frontal environment. A couple sites were activated around 2000 MST on the 26th to target the precipitation occurring along the frontal passage. Several sites on the western and northern side of the program then remained on overnight into the morning of the 27th to target lingering showers in the post frontal northwesterly flow environment. All sites were then turned off around 0700 MST, just as precipitation was drying out. Between 0.1-0.7” of SWE was observed across the program.

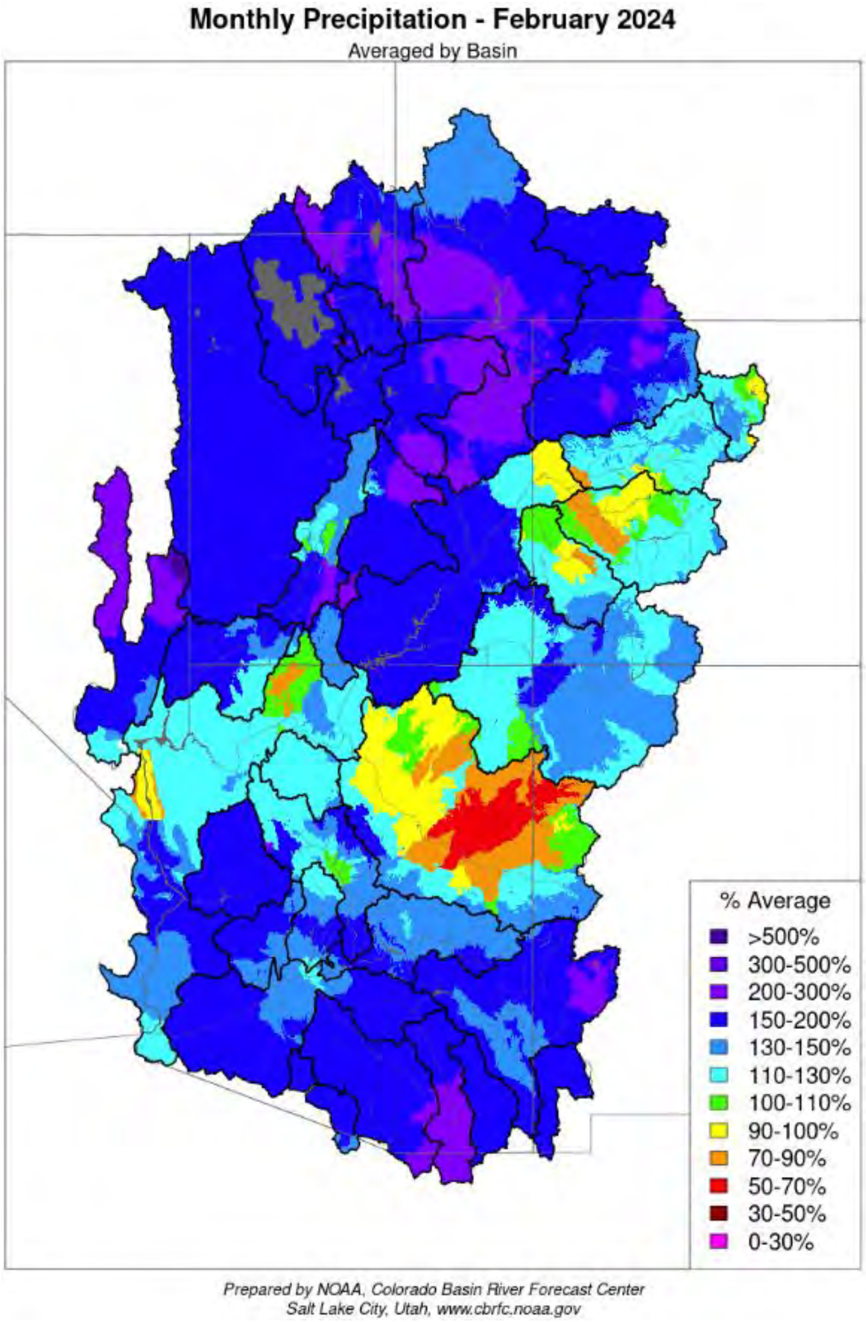


Figure 4.8 **February 2024 precipitation, percent of normal**

March 2024

March was another active month with above average snowfall (Figure 4.9) and a total of 10 seeded storm periods for the High Uintas program. While a number of these events had limited seeding opportunity due to wind direction and other factors, there were some major events with prolonged seeding operations at a number of sites. Snowpack remained above the seasonal average (median) values in essentially all areas, and has increased dramatically since about the beginning of 2024.

Very strong winds were occurring on the morning of March 2nd as a potent cold front moved into eastern Nevada. Widespread wind gusts of 55-70 mph were being observed ahead of the front, with a snow squall feature developing along the leading edge of the boundary as it moved into the Wasatch Front by midday. High values of super cooled liquid water developed in the leading edge of the frontal boundary, and as a result, seeding sites on the southern and western side of the program were activated to target its passage. Seeding continued until the early evening hours, after which, the front had passed, the flow aloft had shifted northwesterly in direction and winds had calmed considerably in strength. The change in wind direction and speed proved unfavorable for targeting the program area, so seeding operations were concluded by 2000 MST. Total snow water equivalent (SWE) for this event ranged from 0.4-1.0”.

A weak shortwave trough moving through far northern Utah caused snow showers to develop across portions of northern Utah after 0700 MST on March 7th. Conditions were somewhat stable in the lower levels of the atmosphere through the morning hours but as daytime heating became maximized by midday, instability increased and several convective type showers developed over the Uintas. Several seeding sites in the western portion of the program area were turned on after 0800 MST and ran until skies cleared out after 1900 MST. Upwards of 0.3” of SWE was observed across the program target area.

The front edge of a Pacific Northwest trough approached northern Utah on the morning of March 12 with an initial frontal boundary having already moved into northwest Utah as of 0400 MDT. This first boundary brought a swath of valley rain/snow and mountain snow to the program area, but strong stability in the lower levels and 700mb temperatures around -3°C limited seeding operations to only higher elevation sites. As the core of the trough moved into western Utah later on in the afternoon, a secondary frontal feature swept eastward across the West Desert. This secondary frontal boundary experienced frontogenesis as it moved eastward across northern Utah and prompted a snow squall to develop along its leading edge. Numerous seeding sites were activated to target the passage of the snow squall/cold front and remained on in the post frontal environment as additional snow shower activity continued to linger in a northwesterly flow pattern. Shower activity then began to dwindle and dry out after 2000 MDT, after which seeding operations ended. Total snow water equivalent (SWE) for this event ranged from 0.2-1.0”.

A closed low developed over Arizona on morning of the 14th of March. The placement of the low induced a northeasterly flow pattern across the Uinta range, which led to the development of heavy snowfall on the northern facing slopes near Manila, Utah. Temperatures were fairly cold with 700 mb temperatures hovering around -14°C and the storm appeared to be generating lots of super cooled liquid water. Seeding generator sites were turned on beginning around 0700 MDT and remained on until it appeared that snow showers were tapering off after 1700 MDT. Total snow water equivalent (SWE) for this event ranged from 0.6-1.5” with the highest amounts localized on the northeast side of the Uintas.

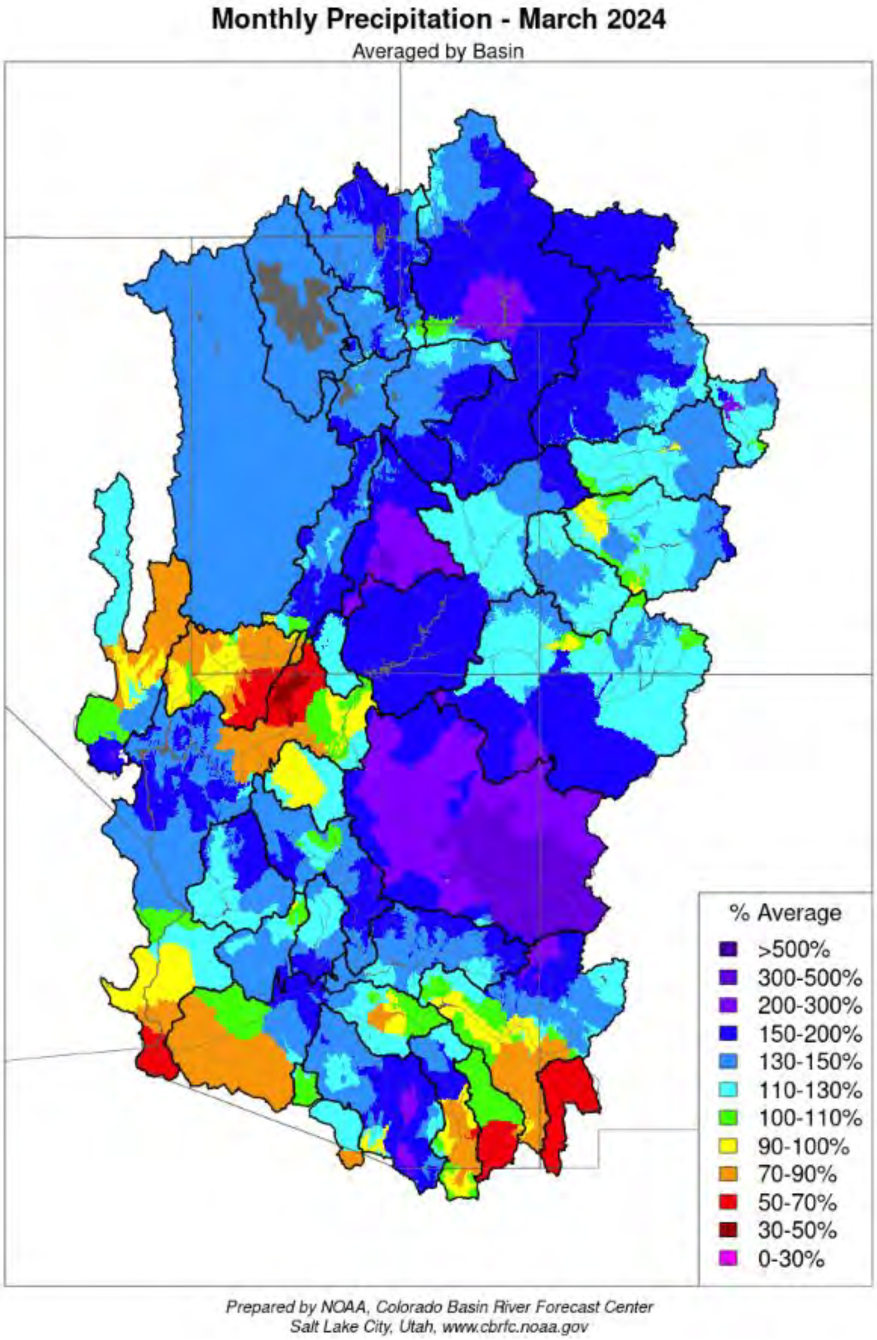
A strong cold front pushed eastward across northern Utah between 1700 MDT and 2100 MDT on the 23rd of March. The front was accompanied by moderate to heavy precipitation, a quick transition from southwest to northwesterly winds and a drop in temperatures. 700 mb temperatures fell from -1°C ahead of the front to near -8°C behind it. Seeding began from several sites around 1500 MDT as the front was first pushing into the eastern Utah and continued until conditions dried out after 2200 MDT. This storm system produced a quick 0.1-0.7" of liquid water content across the program.

A broad longwave trough upper-level trough encompassed the entire western United States on the morning of March 24th with Utah remaining under a moist northwesterly flow pattern in the wake of the frontal passage that moved through on the evening of March 23rd. The deep and moisture rich northwesterly flow pattern that was in place combined with daytime heating and caused scattered convective showers to pop up during the afternoon hours. Conditions were favorable for using several seeding sites on the western and northern end of the target area, from roughly 1400 MDT until shower activity tapered off after sunset near 1900 MDT. Between 0.1-0.2" of SWE was observed across the program with this shower activity.

A broad trough continued to remain over the Pacific Northwest March 25th through the 26th with Utah being stuck in a cold, moist northwesterly flow pattern. Diurnal shower activity was observed during the afternoon and early evening hours of each day which brought ideal conditions for seeding operations on the western end of the program. As such, seeding activity was conducted from roughly 1300-1800 MDT on the 25th and again between 1030-2000 MDT on the 26th. 700mb temperatures averaged around -10°C through both days and precipitation totals were in the 0.2-0.7" range.

Another large trough centered off the Pacific Northwest coast brought a frontal passage to northern Utah during the morning and afternoon hours of March 28. A good frontal precipitation band was noted with the 700 mb temperature dropping to around -7° C behind the front. Seeding was conducted at numerous sites from approximately 1300 MDT to 1900 MDT, with drying later in the evening. Precipitation totals ranged from about 0.1 – 0.4 inches of water equivalent.

Another large trough moving onshore near California brought some precipitation in southerly flow on March 30. Although temperature were considered somewhat warm, seeding was conducted beginning early in the morning of the 30th from sites that are favorable at targeting the program in southerly flow. Seeding continued overnight and through the 31st as another shortwave disturbance rotated through northern Utah and kept snow showers lingering in a southerly flow pattern. Seeding activity was then concluded in the evening hours of the 31st after conditions began to dry out. Total snow water equivalent (SWE) for this event ranged from 0.3-1.0" on the northern side to 0.9-1.9" on the southern side.


Monthly Precipitation - March 2024

Averaged by Basin

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Figure 4.9 **March 2024 precipitation, percent of normal**

April 2024

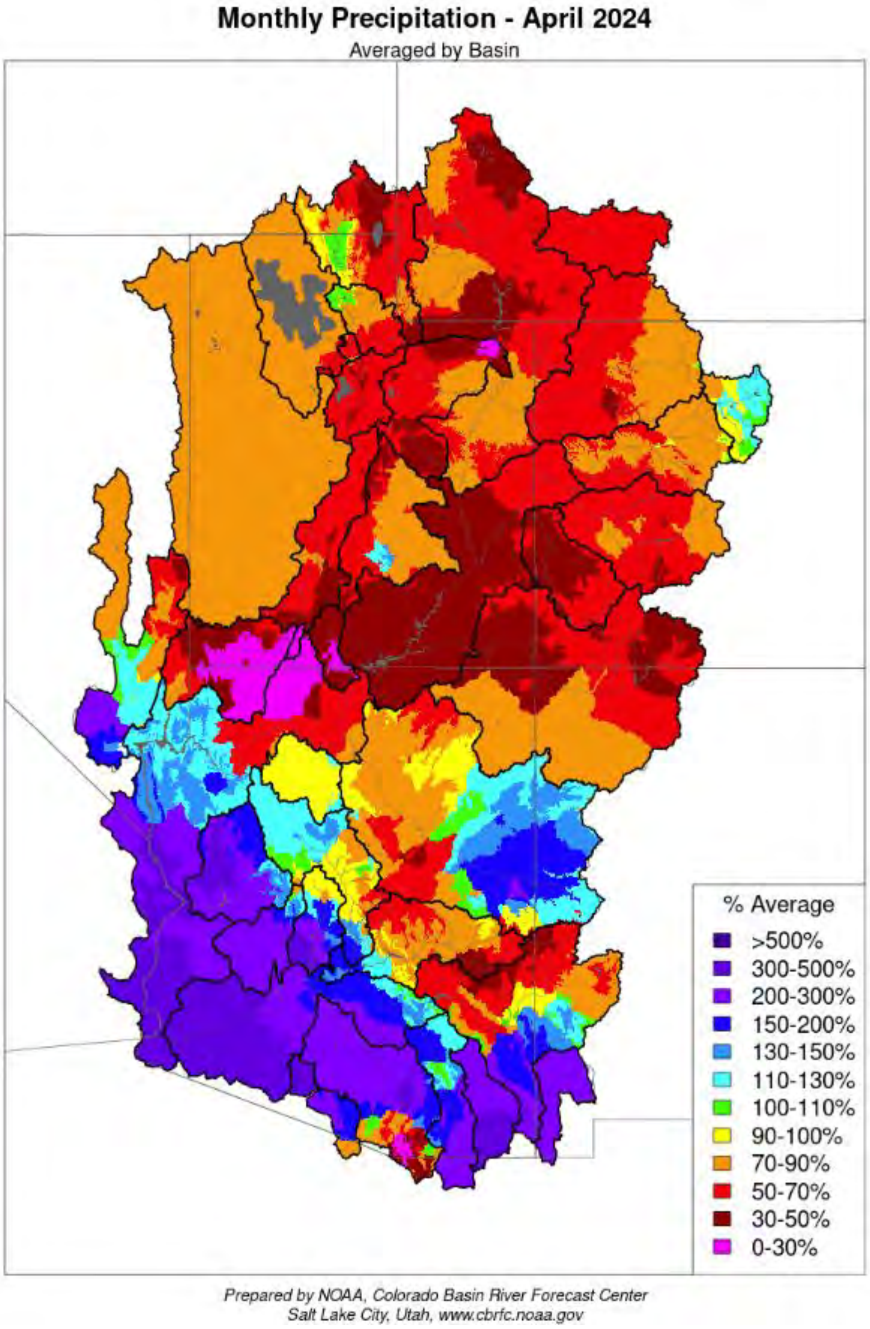
April was a fairly dry month across the Uintas region (Figure 4.10), although there were four seeded storm periods during the month.

A deep and cold trough moved through California and Nevada on April 5-6. A cold front associated with this trough swept east across northern Utah on the afternoon of the 5th but stalled out as it reached the I-15 corridor. As such, the Uinta range remained on the dry and mild side of the frontal boundary through the early morning hours of the 6th. The trough and front then finally kicked east and across the remained of Utah on the afternoon of the 6th with the flow transitioning from southwesterly to northwesterly and 700mb temperatures lowering from 2°C to -6°C. Seeding began from several sites on the western side of the Uinta range around midday on the 6th as convective type snow showers popped up in the cold northwesterly flow regime. Seeding continued up until snow shower activity died out around 2000 MDT. This storm system produced a quick 0.1-0.3" of liquid water content across the program.

The next seeded event of April occurred on April 15, with a trough producing semi-convective shower activity and a 700 mb temperature near -5° C. Showers continued in northwesterly flow, with seeding during the daytime hours, mostly ending by late evening. The High Uintas area received around 0.3 – 0.8 inches of water content from this event.

A fairly extensive trough moved across the Great Basin region April 26-27. 700mb temperatures fell from 5C to 0C on the morning of the 26th as the trough was inducing weak cold advection. Scattered snow showers and thunderstorms developed over the southern side of the program on the afternoon of the 26th and shower activity continued up until midnight of the 27th before ending. Seeding initially began from several sites on the southern side around 0930 MDT and were turned off late in the evening hours of the 26th. A cold and moist airmass entrenched across Utah allowed convective type showers to redevelop over the higher terrain during the afternoon hours of the 27th, although the flow had shifted northwesterly and 700 mb temperatures lowered to near -2/-3°C. Seeding was conducted again on the 27th, roughly from midday until late evening from sites on the western and northern side of the program. Between 0.3-1.0 inches of liquid precipitation was observed across the program.

The last seeded event of the season occurred on April 29 as a cold frontal boundary swept through northern Utah in the late afternoon hours. Scattered convective showers developed ahead of the front in a slightly warm airmass (0 to -1°C). As the front moved into eastern Utah later on, the flow aloft shifted northwesterly and 700mb temperatures lowered to near -4°C. Convective type showers transitioned to orographically enhanced showers. Seeding operations were conducted to target the ongoing showers ahead of and behind the front from roughly 1600-2100 MDT. The High Uintas area received around 0.1 – 0.5 inches of water content from this event.



Monthly Precipitation - April 2024

Averaged by Basin

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Figure 4.10 April 2024 precipitation, percent of normal

ASSESSMENT OF SEEDING EFFECTS

Background

The task of determining the effects of cloud seeding has received considerable attention over the years. Evaluating the results of a cloud seeding program for a particular season is rather difficult. The primary reason for the difficulty stems from the large natural variability in the amounts of precipitation that occur in a given area and between one area and another during a given season. The ability to detect a seeding effect becomes a function of the magnitude of the seeding increase and the number of seeded events, compared with the natural variability in the precipitation pattern. This can be described as a (seeding effect) signal to noise ratio issue. Larger seeding effects can be detected more easily, and with a smaller number of seeded cases, than are required to detect smaller increases.

Historically, consistently positive results have been observed in wintertime seeding programs in mountainous areas. However, the apparent differences due to seeding are relatively small, usually of the order of a 5-10 percent seasonal increase. In part, this relatively small percentage increase accounts for the significant number of seeded seasons (often ten years or more) required to establish these results for a particular program with any confidence.

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

A commonly employed technique, the one utilized by NAWC in this assessment and in evaluation of its other winter seeding projects, is a "target" and "control" comparison. This technique is described by Dr. Arnett Dennis (1980) in his book entitled “Weather Modification by Cloud Seeding”. The technique is based on the selection of a variable that would be affected by seeding (such as precipitation or snowpack). Records of the variable to be tested are acquired for an historical period of many years’ duration (20 years or more if possible). These records are partitioned into those located within the designated "target" area of the project and those from well-correlated "control" sites located well outside of the target area.

Ideally the control sites should be selected in an area meteorologically similar to the target, but one which would be unaffected by the project seeding (or seeding from other adjacent projects). The historical data in both the target and control areas are taken from past years that have **not been subject to cloud seeding activities**. These data are evaluated for the same seasonal period of time (months) as that when the seeding is to be, or has been, conducted. The target and control sets of data for the unseeded seasons are used to develop a mathematical model (typically a linear regression), which predicts the amount of target area natural precipitation, based on precipitation observed in the control area. This mathematical model is then used to analyze the selected variable in years where seeding **did not** occur in the control but **did** occur in the target areas. From the model and available data for the control area, we can predict what would likely have transpired in the target area had no seeding occurred, then compare this to what actually happened in the designated target area. Consistent differences between these predicted and observed values may be attributed to cloud seeding effects, although with a low level of confidence until sufficient seeded season data is accumulated.

This target and control technique works well where a good historical correlation can be found between target and control area precipitation. Generally, the closer the target and control areas are geographically, and in terms of elevation, the higher the correlation will be. Control areas selected too close to the target, however, can be subject to contamination by the seeding activities. This can result in an underestimate of the seeding effect. For precipitation and snowpack assessments, a correlation coefficient (r) of 0.90 or better would be considered excellent. A correlation coefficient of 0.90 would indicate that over 80 percent of the variance (r^2) in the historical data set would be explained by the regression equation used to predict the variable (expected precipitation or snowpack) in the seeded years. An equation indicating perfect correlation would have an r value of 1.0.

Experience has shown that it is virtually impossible to provide a precise assessment of the effectiveness of cloud seeding based on a small number of seeded seasons. However, as the data sample size increases, it becomes possible to provide at least a reasonable estimate of seeding effectiveness.

Selecting Target and Control Evaluations – Precipitation and Snowpack Data

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

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

Our normal approach in selecting control sites for a new project is to look for sites upwind or crosswind from the target area that will geographically bracket the intended target area. The reason for this approach is that some winter seasons are dominated by one upper-level wind (jet stream) pattern while other seasons are dominated by other flow patterns. The result of these differing weather patterns and storm tracks often results in heavier precipitation in one area versus the other. For example, a strong El Niño pattern may favor below normal precipitation in one region more than in another. Having control sites on either side of the target area relative to the generalized flow pattern can improve the prediction of target area precipitation under these variable upper air weather patterns.

An additional consideration in the selection of control sites for the development of an historical target/control relationship is one of data quality. A potential control or target site may be rejected due to poor data quality if the data significantly diverges over time from other sites in the area. SNOTEL sites, the type used in the evaluation of the High Uintas program, typically have reliable long-term records with external variables (such as terrain aspect and surrounding vegetation) carefully selected or maintained. The double mass plot is an engineering tool that will indicate any changes in relationships between two stations, and may be particularly useful if one or both stations have moved during their history. If a site exhibits either an abrupt change due to relocation, or long-term trends that differ substantially from other sites in the area, it may be excluded from further consideration.

There are some things to consider when dealing with the two types of precipitation observations typically available from mountainous areas in the west: standpipe storage precipitation gauges and snow pillows. There are some potential problems associated with each type of observation. With the advent of the SNOTEL data acquisition system in the late 1970's, access to precipitation and snowpack (water equivalent) data in mountainous locations became routine. Before the SNOTEL system was developed, these data had to be acquired by actually visiting the site to make measurements. This is still required at some sites. Figure 5.1 is a photo of an NRCS SNOTEL site, with labels to allow the reader a better understanding of the two types of observation systems. The vertical tube is the standpipe storage gauge, which is approximately 12" in diameter. The gauges are approximately 20' in height so that their sampling orifices remain above the snowpack surface. There are at least two types of potential problems associated with high elevation observations of the water equivalent of snowfall, as measured by standpipe precipitation storage gauges. The two areas of concern are clogging at the top of the standpipe storage gauge, and blow-by of snowflakes past the top of the standpipe gauge. Either situation would result in an underestimate of the actual precipitation that fell during such periods. In the fall, the storage gauge is charged with antifreeze, which melts the snow that falls to the bottom of the gauge. A pressure transducer records the weight of the solution. The weight of the antifreeze is subtracted from the total weight, giving the weight of the water, which is then converted into inches. Heavy, wet snow may accumulate around the top of the standpipe storage gauge, either reducing or stopping snow from falling into the standpipe and resulting in an underestimate of precipitation. Snow that falls with moderate to strong winds may blow past the top of the gauge, which can also result in an underestimate of precipitation. NRCS sites are normally located in small clearings in forested areas to help reduce the impacts of wind effects. Sites that are near or above timberline are more likely to be impacted by wind since properly sheltered sites may be difficult to find in these areas. The snow pillow, pictured on the pad at ground level in the foreground of Figure 5.1, is filled with antifreeze. This system weighs the snowpack, providing time-resolved records of the snowpack water content. Snow pillows can also have difficulty in providing accurate measurements of snow water content, because of wind either adding or removing snow from the measurement site when snow conditions are favorable for drifting.

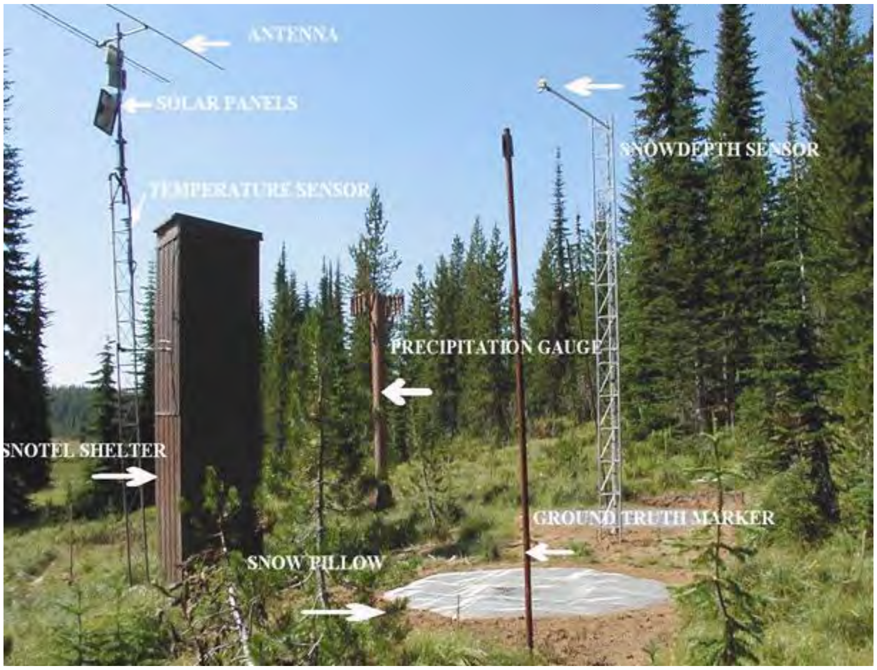

Figure 5.1 **Equipment at a SNOTEL site**

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

There are some potential problems with snow course (manual) type of measurements that must be recognized when using those measurements to evaluate seeding effectiveness. Because not all winter storms are cold, sometimes rain as well as snow falls in the mountains. This can lead to a disparity between precipitation totals which theoretically measure everything that falls, and snowpack water content which measures only the water held in the snowpack. Warm periods can occur between snowstorms. If a significant warm period occurs, some of the precipitation that fell as snow will have melted or sublimated by the time the next snow course measurement is made. Thus, some of it may not be recorded in the snow water content measurements. This can also lead to a greater disparity between the snow water content at higher elevations (where less snow will melt in warm weather) and that observed at lower elevations. The newer daily SNOTEL measurements avoid some of these problems, but depletion of the snowpack can occur even with SNOTEL measurements when dealing with April 1st observations. We are concerned with both types of measurements since we often use snow course measurements to provide a longer historical data base from which the regression equations can be developed. In addition, snowpack measurements are still conducted manually at a few mountain sites up to the present time.

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

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

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

Target and Control Sites - Precipitation

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

For many years, winter cloud seeding in Utah was limited to mainly the central and southern portions of the State, although occasional winter seeding was conducted in the mountains of Tooele County (southwest of the Salt Lake City area) in the late 1970's and early 1980's. However, beginning in the 1988 water year, winter cloud seeding programs became more widespread in northern Utah. The result of this increase in cloud seeding projects is that it has become more difficult to locate control areas that have not been affected by other cloud seeding programs. Also, some (non-SNOTEL) precipitation gage sites used as controls no longer have ongoing data collection.

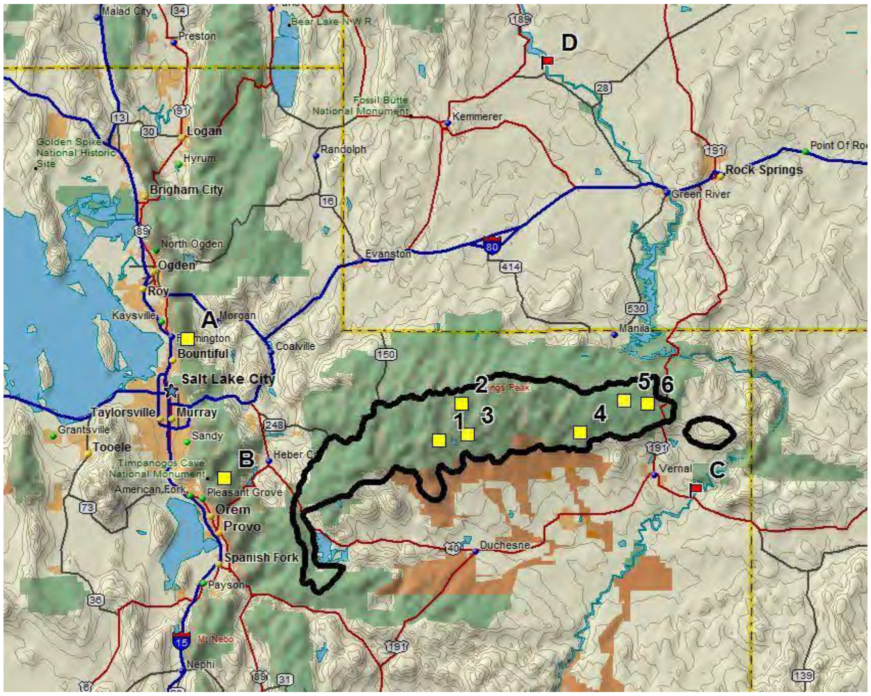

Figure 5.2 **Precipitation gauges used as target area sites (number ID's) and control sites (letter ID's). The yellow boxes represent SNOTEL locations and the flag is an NWS co-op site.**

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

Table 5-1
Control and Target Area Precipitation Gauge Sites

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

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

Target and Control Sites - Snowpack

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

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

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

Table 5-2
Control and Target Snowpack Sites

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

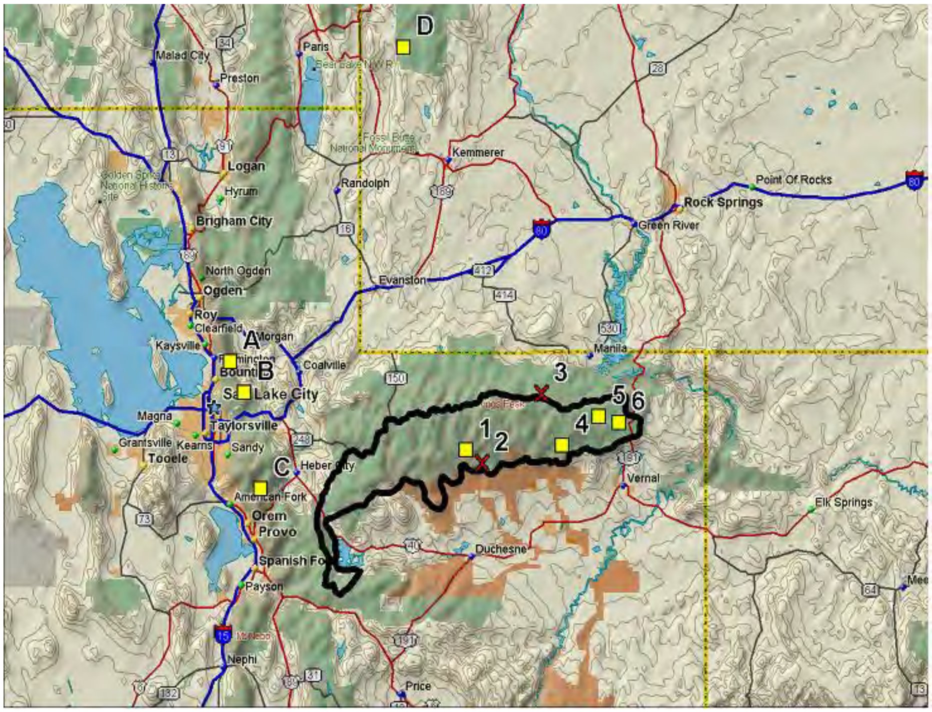

Figure 5.3 Target sites (numbered) and control area snow sites (letters); squares are SNOTEL sites, and X's are snow courses

Target and Control Sites – Streamflow vs. Streamflow

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

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

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

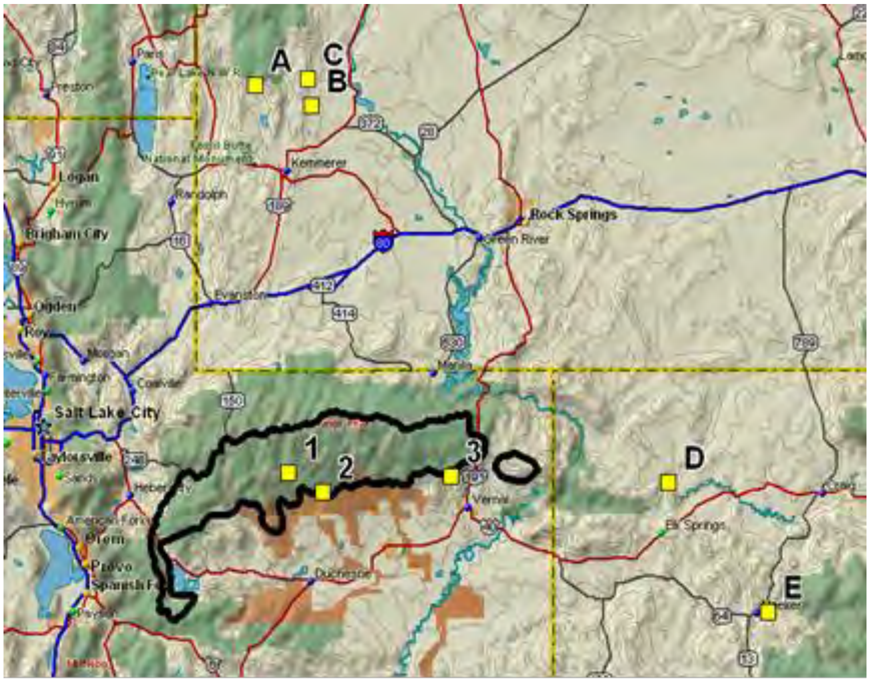

Figure 5.4 **High Uintas streamflow target and control gauges**

Development of Regression Equations

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

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

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

Precipitation evaluation results have been examined for a period of 21 seeded seasons (2003-2023 water years). The seeded period used in one snowpack evaluation (with more sites but a short historical period) excludes the water year 2004, 2007, 2012, and 2015 seasons due to early melting in those years, and so includes only 15 seasons. The other long-term snowpack evaluation (few sites but 46 historical seasons) excludes these same seeded seasons due to early snow melt. This evaluation originally had three control sites but one snow course (White River #3) appears to have been discontinued in 2016 so the regression equation was re-established without this site.

The evaluation techniques as described yield an estimation of the observed/predicted amount of precipitation, snow water content, or streamflow for an individual season. For past historical results and previous streamflow vs. streamflow evaluations please reference the 2022-2023 High Uintas cloud seeding report. A ratio of 1.05, for example, would suggest a 5% increase over the natural precipitation, snowpack, or streamflow predicted for the target area based on the historical regression equation. A ratio at or below 1.0 is not indicative of an increase over the natural precipitation or snowfall. An increase for an individual seeded season or combination of seeded seasons could be attributed to seeding effects.

Table 5-4
Summary of High Uintas Evaluation Results

Evaluation Type	Method	Pre-Seeded Years	Seeded Years	Correlation (R-value)	Resultant Ratio
Dec – Apr Precipitation	Linear Regression	15	21	0.86	0.96
Dec – Apr Precipitation	Multiple Linear	15	21	0.92	0.95
April 1 Snow Water Content	Linear Regression	13	17*	0.81	0.97
April 1 Snow Water Content	Multiple Linear	13	17*	0.94	1.02
April 1 Snow Water Content	Linear Regression	46	17*	0.83	1.04
April 1 Snow Water Content	Multiple Linear	46	17*	0.86	1.10
March – July Streamflow 5 control 3 target	Linear Regression	30	20**	0.75	0.99
March – July Streamflow 5 control 3 target	Multiple Linear	30	20**	0.79	0.98
March – July Streamflow 3 control 3 target	Linear Regression	30	20**	0.61	0.95
March – July Streamflow 3 control 3 target	Multiple Linear	30	20**	0.63	0.93

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

** Streamflow evaluation includes seeded year data up through 2022, as the full March – July streamflow data for the current season is not yet available

Seasonal Variability, Related to Storm Track and Barrier Orientation

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

Historic Evaluation Data

For the 2024 winter season the State of Utah and local sponsors significantly expanded seeding along the Wasatch Front. Many of the SNOTEL sites used as non-seeded "control" sites for seasonal evaluations are now in areas targeted by seeding operations. This includes Farmington Upper, Timpanogos Divide, and Lookout Peak. As such, target vs. control evaluations will no longer be performed on an annual basis. Rather, the average result of the historic target vs. control studies (evaluating the predicted increase in snowpack and precipitation) for the High Uintas seeding program will be used to derive the estimated increases in streamflow resulting from cloud seeding in a given season.

The historical studies, over the seeded period (2003-2023, as referenced above) indicate that an average increase in snowpack and seasonal precipitation resulting from cloud seeding of 3%.

For a more detailed explanation of these historic results and previous streamflow vs. streamflow evaluations please reference the 2022-2023 High Uintas cloud seeding report. This result is in line with the derived increase estimates for neighboring programs, with much longer periods of uninterrupted cloud seeding and larger target vs control data sets.

Determining the Impact of Cloud Seeding on Streamflow

To better understand the value and impact of cloud seeding program, research has been conducted every year to estimate the increase in runoff that occurs because of cloud seeding. The analysis is accomplished, first by, tabulating actual snowpack and seasonal precipitation values for the seeded period. Second, using the aforementioned results from the long-term target control study, predicting the increase in SWE and precipitation (measured value) that resulted from cloud seeding. Third, analyzing the relationship between snowpack/precipitation and runoff for the watershed and defining that relationship with a mathematical regression. Fourth, using the new regression (correlating snowpack/precipitation and streamflow) to determine how much a 3% reduction in the actual snowpack/precipitation values would have affected runoff.

This form of analyses does require that runoff be measured in largely unregulated waterways, not downstream from a reservoir with heavily controlled discharge rates. In the case of relatively small diversions (such as for city water use or local agriculture) upstream from the gauge, a strong correlation between snowpack/precipitation and runoff may be found. However, the larger the upstream diversion, the more prone to inaccuracies the results will be due to errors that arise in upscaling.

Results – Impact of Cloud Seeding on Runoff

Streamflow gauges used to derive runoff increases from this program, are located on Ashley Creek near Vernal Utah (USGS site #09266500), on Lake Fork River above Moon Lake (USGS site #09289500), and on Yellowstone River near Altonah (USGS site #09292500. Streamflow totals (generally reported in acre-feet) are collected for the March – July period. This period tends to produce the highest correlation to wintertime snowpack and precipitation. Regression equations having a good correlation (generally, an R value of about 0.80 or higher) should be reasonable for this analysis. In the case of Ashely Creek, both streamflow and corresponding SNOTEL data was available beginning in 1980, and for Lake Fork River and Yellowstone River, both streamflow and corresponding SNOTEL data was available beginning in 1990 and 1982 respectively.

For the Ashley Creek gauge, the streamflow gauge correlated well with the Trout Creek SNOTEL precipitation (Nov-Apr), with an R value of around 0.80. For snowpack (Apr 1), the correlation was much lower and around 0.65. In the headwaters of the Lake Fork River, the Lake Fork Basin SNOTEL site has the longest record (back to 1990) with the correlation between this site's seasonal precipitation and snowpack data and resulting streamflow being 0.75 and 0.77 respectively. Lastly, for the Yellowstone River gauge, the streamflow gauge correlated best with the Lakefork #1 SNOTEL site. For snowpack, the correlation was 0.79 and precipitation had an R value of around 0.74.

Utilizing these equations for Ashley Creek, a 3% increase in April 1 snowpack yielded an estimated 2% increase in streamflow and a 3% increase to November – April precipitation yielded an estimated 4% increase in stream flow. The average (base) streamflow at this gauge is over 48,000 AF. These equations predict an additional 1100-2000 AF, respectively in increased runoff resulting from cloud seeding over the head waters of Ashely Creek.

For the Lake Fork River gauge, application of a 3% increase in SWE and seasonal precipitation would lead to a similar 3-4% or more increase in streamflow at this gauge site. When applied to an average long-term seasonal (March – July) streamflow of over 60,000 AF at this gauge, seeding increase estimates yielded about 2000 to 2400 additional AF seasonally, considered representative of an average year.

Similarly for the Yellowstone River gauge, a 3% increase in SWE and seasonal precipitation corresponded to streamflow increases of 3-4%. When applied to an average long-term seasonal (March – July) streamflow of over 64,000 AF at this gauge, seeding increase estimates yielded about 2000 to 2500 additional AF seasonally, considered representative of an average year.

The results for Ashley Creek, Lake Fork River, and Yellowstone River collectively provide a good indication of the impact on cloud seeding in this watershed. With relative confidence the data suggests that cloud seeding results in an 2-4% increase in runoff across all major runoff channels in the High Uintas target area. It may be noted that drier portions of a watershed produce more inefficient runoff and may generate higher resultant streamflow percentage increases to streamfow in such analyses. Thus, the typically somewhat lower percentage runoff increases pertaining to major rivers are likely the most accurate for application to the watershed as a whole, if a percentage increase is scaled to the entire watershed. In either case, a higher percentage increase to streamflow (than the applied percentage increase to precipitation/snowpack) is an expected result.

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APPENDIX A: SUSPENSION CRITERIA

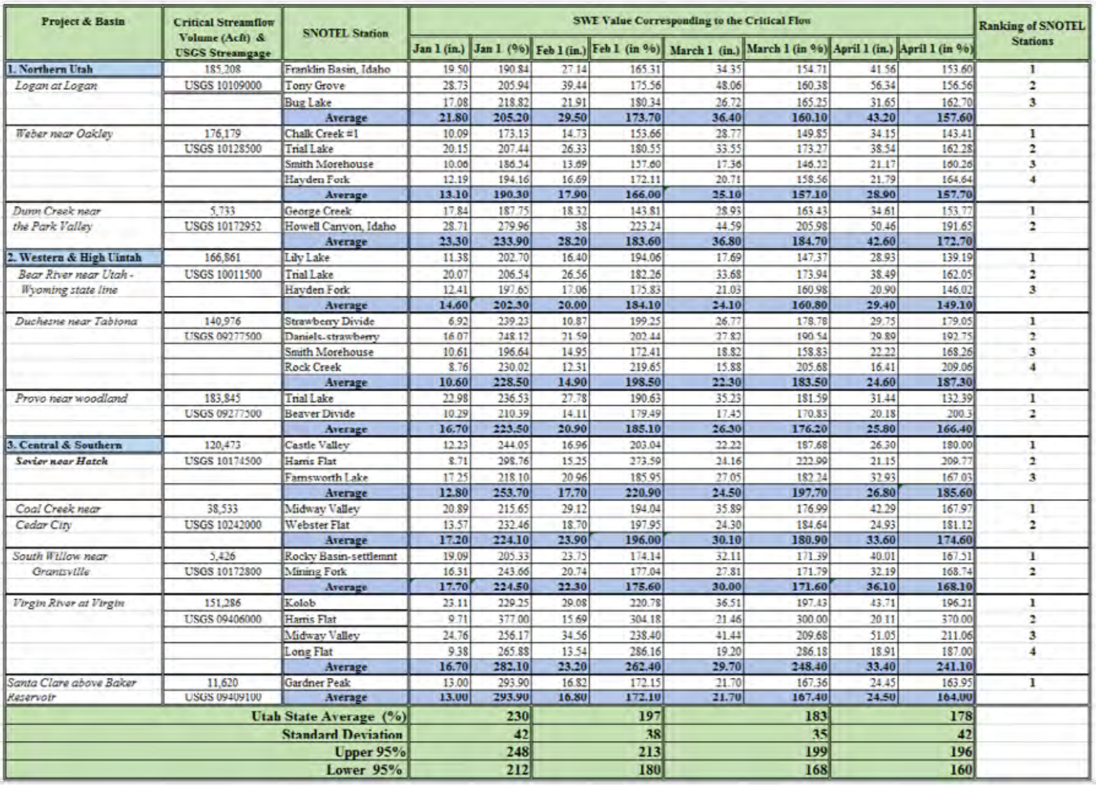
Certain situations require temporary or longer-term suspension of cloud seeding activities, with reference to well-considered criteria for consideration of possible suspensions, to minimize either an actual or apparent contribution of seeding to a potentially hazardous situation. The ability to forecast (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 are:

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.



Project & Basin	Critical Streamflow Volume (Acft) & USGS Streamgage	SNOTEL Station	SWE Value Corresponding to the Critical Flow								Ranking of SNOTEL Stations
			Jan 1 (in.)	Jan 1 (%)	Feb 1 (in.)	Feb 1 (in %)	March 1 (in.)	March 1 (in %)	April 1 (in.)	April 1 (in %)	
1. Northern Utah	185,208	Franklin Basin, Idaho	19.50	190.84	27.14	165.31	34.35	154.71	41.56	153.60	1
Logan at Logan	USGS 10109000	Tony Grove	28.73	205.94	39.44	175.56	48.06	160.38	56.34	156.56	2
		Bug Lake	17.08	218.82	21.91	180.34	26.72	165.25	31.65	162.70	3
		Average	**21.80**	**205.20**	**29.50**	**173.70**	**36.40**	**160.10**	**43.20**	**157.60**	
Weber near Oakley	176,179	Chalk Creek #1	10.09	173.13	14.73	153.66	28.77	149.85	34.15	143.41	1
	USGS 10128500	Trial Lake	20.15	207.44	26.33	180.55	33.55	173.27	38.54	162.28	2
		Smith Morehouse	10.06	186.34	13.69	137.60	17.36	146.32	21.17	160.26	3
		Hayden Fork	12.19	194.16	16.69	172.11	20.71	158.56	21.79	164.64	4
		Average	**13.10**	**190.30**	**17.90**	**166.00**	**25.10**	**157.10**	**28.90**	**157.70**	
Dunn Creek near	5,733	George Creek	17.84	187.75	18.32	143.81	28.93	163.43	34.61	153.77	1
the Park Valley	USGS 10172952	Howell Canyon, Idaho	28.71	279.96	38	223.24	44.59	205.98	50.46	191.65	2
		Average	**23.30**	**233.90**	**28.20**	**183.60**	**36.80**	**184.70**	**42.60**	**172.70**	
2. Western & High Uintah	166,861	Lily Lake	11.38	202.70	16.40	194.06	17.69	147.37	28.93	139.19	1
Bear River near Utah -	USGS 10011500	Trial Lake	20.07	206.54	26.56	182.26	33.68	173.94	38.49	162.05	2
Wyoming state line		Hayden Fork	12.41	197.65	17.06	175.83	21.03	160.98	20.90	146.02	3
		Average	**14.60**	**202.30**	**20.00**	**184.10**	**24.10**	**160.80**	**29.40**	**149.10**	
Duchesne near Tabiona	140,976	Strawberry Divide	6.92	239.23	10.87	199.25	26.77	178.78	29.75	179.05	1
	USGS 09277500	Daniels-strawberry	16.07	248.12	21.59	202.44	27.82	190.54	29.89	192.75	2
		Smith Morehouse	10.61	196.64	14.95	172.41	18.82	158.83	22.22	168.26	3
		Rock Creek	8.76	230.02	12.31	219.65	15.88	205.68	16.41	209.06	4
		Average	**10.60**	**228.50**	**14.90**	**198.50**	**22.30**	**183.50**	**24.60**	**187.30**	
Provo near woodland	183,845	Trial Lake	22.98	236.53	27.78	190.63	35.23	181.59	31.44	132.39	1
	USGS 09277500	Beaver Divide	10.29	210.39	14.11	179.49	17.45	170.83	20.18	200.3	2
		Average	**16.70**	**223.50**	**20.90**	**185.10**	**26.30**	**176.20**	**25.80**	**166.40**	
3. Central & Southern	120,473	Castle Valley	12.23	244.05	16.96	203.04	22.22	187.68	26.30	180.00	1
Sevier near Hatch	USGS 10174500	Harris Flat	8.71	298.76	15.25	273.59	24.16	222.99	21.15	209.77	2
		Farnsworth Lake	17.25	218.10	20.96	185.95	27.05	182.24	32.93	167.03	3
		Average	**12.80**	**253.70**	**17.70**	**220.90**	**24.50**	**197.70**	**26.80**	**185.60**	
Coal Creek near	38,533	Midway Valley	20.89	215.65	29.12	194.04	35.89	176.99	42.29	167.97	1
Cedar City	USGS 10242000	Webster Flat	13.57	232.46	18.70	197.95	24.30	184.64	24.93	181.12	2
		Average	**17.20**	**224.10**	**23.90**	**196.00**	**30.10**	**180.90**	**33.60**	**174.60**	
South Willow near	5,426	Rocky Basin-settlemnt	19.09	205.33	23.75	174.14	32.11	171.39	40.01	167.51	1
Grantsville	USGS 10172800	Mining Fork	16.31	243.66	20.74	177.04	27.81	171.79	32.19	168.74	2
		Average	**17.70**	**224.50**	**22.30**	**175.60**	**30.00**	**171.60**	**36.10**	**168.10**	
Virgin River at Virgin	151,286	Kolob	23.11	229.25	29.08	220.78	36.51	197.43	43.71	196.21	1
	USGS 09406000	Harris Flat	9.71	377.00	15.69	304.18	21.46	300.00	20.11	370.00	2
		Midway Valley	24.76	256.17	34.56	238.40	41.44	209.68	51.05	211.06	3
		Long Flat	9.38	265.88	13.54	286.16	19.20	286.18	18.91	187.00	4
		Average	**16.70**	**282.10**	**23.20**	**262.40**	**29.70**	**248.40**	**33.40**	**241.10**	
Santa Clare above Baker	11,620	Gardner Peak	13.00	293.90	16.82	172.15	21.70	167.36	24.45	163.95	1
Reservoir	USGS 09409100	**Average**	**13.00**	**293.90**	**16.80**	**172.10**	**21.70**	**167.40**	**24.50**	**164.00**	
		Utah State Average (%)		**230**		**197**		**183**		**178**	
		Standard Deviation		**42**		**38**		**35**		**42**	
		Upper 95%		**248**		**213**		**199**		**196**	
		Lower 95%		**212**		**180**		**168**		**160**	

Snowpack-related suspension considerations will be assessed on a geographical division or sub-division basis. The NRCS has divided the State of Utah into 13 such divisions as follows: Bear River, Weber-Ogden Rivers, Provo River-Utah Lake-Jordan River, Tooele Valley-Vernon Creek, Green River, Duchesne River, Price-San Rafael, Dirty Devil, South Eastern Utah, Sevier River, Beaver River, Escalante River, and Virgin River. 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 High Uintas Program, SNOTEL sites including Lily Lake, Trial Lake, Hayden Fork, Strawberry Divide, Daniels-Strawberry, and Rock Creek have 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 Warning - This is issued by the NWS when flash flooding is imminent or in progress. In the Intermountain West, these warnings are generally issued relative to, but 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: GLOSSARY OF RELEVANT METEOROLOGICAL TERMS

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