Annual Cloud Seeding Report

Western Uintas Program

2023-2024 Winter Season

Prepared For:

Weber Basin Water Conservancy District

Central Utah Water Conservancy District

Provo River Water Users Association

State of Utah, Division of Water Resources

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CLOUD SEEDING 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.

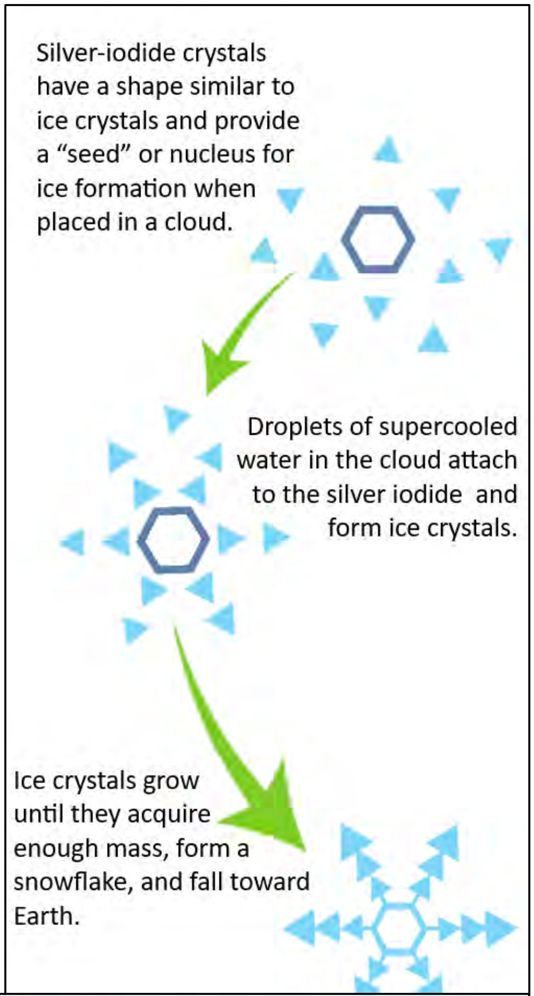
Silver iodide has been selected for its environmental safety and superior efficiency in producing ice in clouds. Silver iodide adds microscopic particles with a structural similarity to natural ice crystals. Ground-based and aircraft-borne technologies can be used to add the particles to the clouds.

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

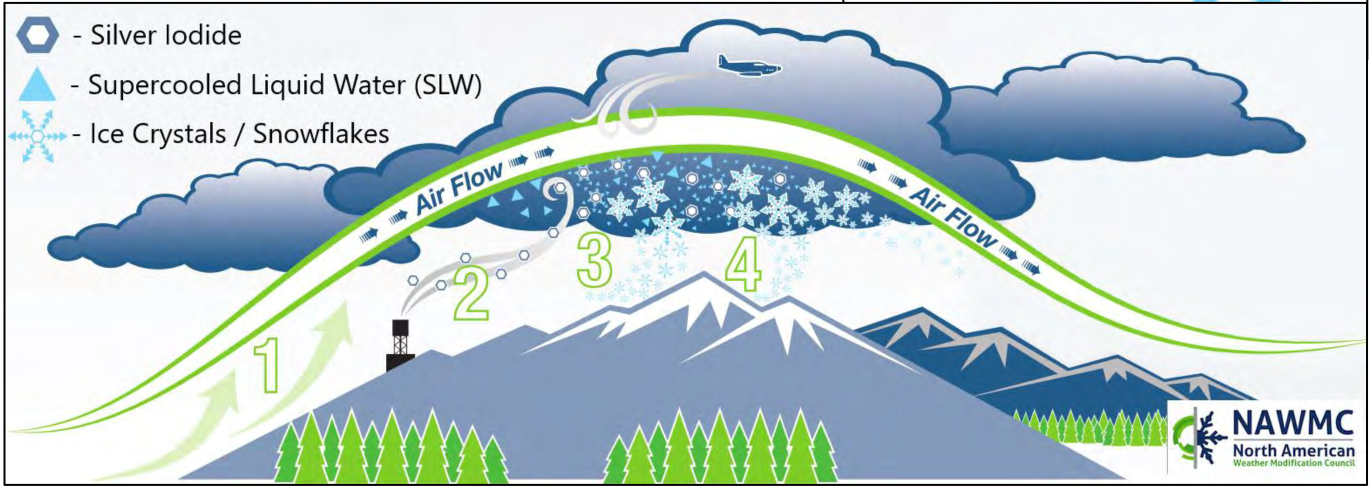
Numerous studies performed by universities, professional research organizations, private utility companies and weather modification providers have conclusively demonstrated the ability for Silver Iodide to augment precipitation under the proper atmospheric conditions.



Silver-iodide crystals have a shape similar to ice crystals and provide a “seed” or nucleus for ice formation when placed in a cloud.

Droplets of supercooled water in the cloud attach to the silver iodide and form ice crystals.

Ice crystals grow until they acquire enough mass, form a snowflake, and fall toward Earth.



CLIMATE TRENDS

Every ten years, the National Oceanic and Atmospheric Association (NOAA) releases a summary of various U.S. weather conditions for the past three decades to determine average values for a variety of conditions, including, temperature and precipitation. This is known as the U.S Climate normal, with a 30-year average. These 30-year normal values can help to determine a departure from historic norms and identify current weather trends. The current 30-year average is based on the period of 1990 – 2020. Images in Figures 1 and 2 show how each 30-year average for the past 120 years compares to the composite 20th century average for temperature and precipitation. For the western U.S., the 1990-2020 average show much warmer than average temperatures, in comparison to the 100-year 20th century average. When comparing precipitation for the past 30 years to both the previous 30-year average and the 1901-2000 average, the American Southwest (including portions of Utah, Arizona, California and Nevada) has seen as much as a 10% decrease in average annual precipitation.

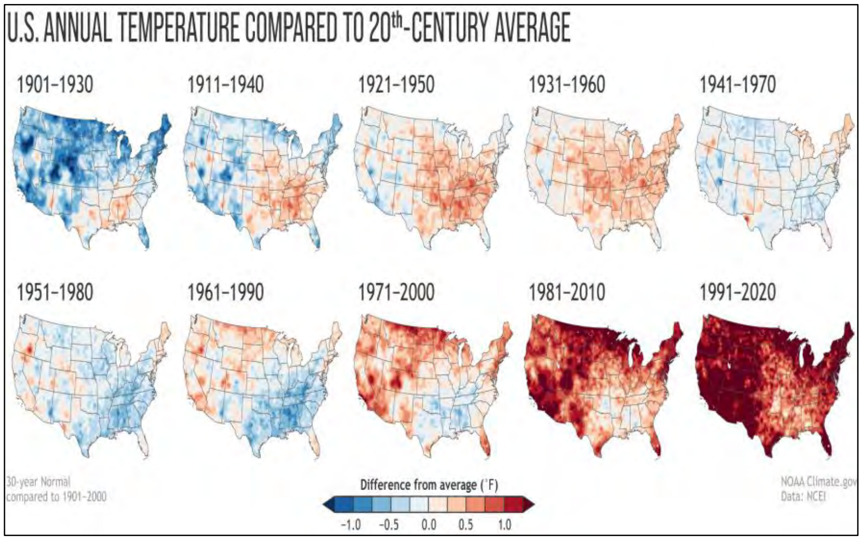


Figure 1 **U.S. Annual Temperature compared to 20th-Century Average**

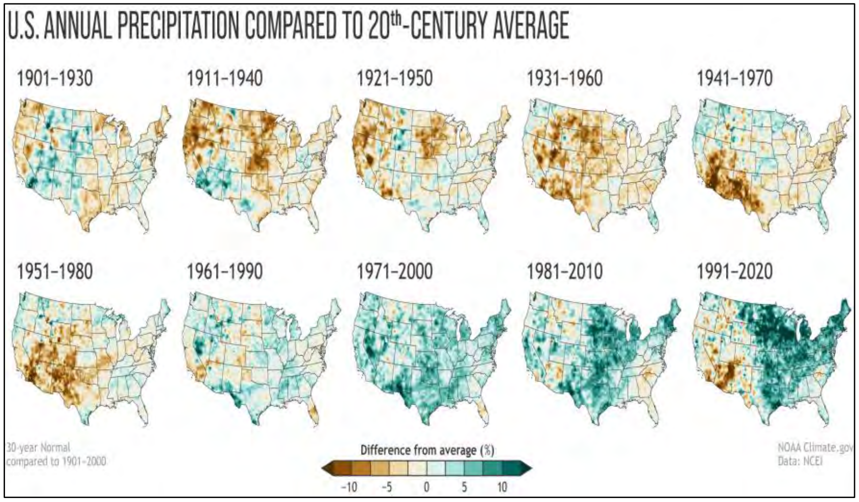


Figure 2 **U.S. Annual Precipitation compared to 20th-Century Average**

EXECUTIVE SUMMARY

Program History

A total of 27 winter seasons of cloud seeding have been conducted in portions of the Western Uinta Range in Utah. The Western Uintas program utilizes 11 ground-based, manually operated (Cloud Nuclei Generator, or CNG) sites, containing a 2% silver iodide solution. The goal of the seeding program is to augment wintertime snowpack/precipitation over the seeded watersheds. The areas targeted for seeding have included the upper portions of both the Weber River and the Provo River drainages in most years.

Precipitation and snowfall were again above normal during the 2023-2024 winter season, with snow water equivalent for the Weber-Ogden River Basin averaging about 133% of the median value on April 1st. The water year precipitation through April 1st averaged 123% of the normal median value across the basin. The Provo River basin had corresponding April 1st averages of 135% of median snowpack and 126% of median precipitation.

A total of 1592.25 seeding hours were conducted during 31 storm periods this season, out of a maximum budgeted 2250 hours. Although the seeding program has normally been conducted during the months of December – March, additional program sponsorship by the Jordan Valley Water Conservancy District this season resulted in an extension of the Western Uintas program through the month of April, with additional budgeted seeding hours compared to the original 1500.

Results

To evaluate the increase in snowpack and precipitation resulting from cloud seeding, long term target/control evaluations have been performed for the Western Uintas program. These studies use linear and multiple linear regressions to compare seasonal performance in seeded areas vs non-seeded areas. **The results of these evaluations, for the past 24 years, point to an average increase of 3% to 6% in April 1st snowpack (as measured by liquid water equivalence) resulting from cloud seeding. This equates to an average increase in runoff of roughly 25,000 acre-feet in the target areas.** 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 5% increase in snowpack (a rough average result taken from the target/control evaluations). Resulting streamflow increases ranging from about 6-10% were indicated by these evaluations. Section 5.5 of the report contains further discussion of these mathematical analyses.

Recommendations

It is recommended that the winter seeding program for the Western Uintas target area be continued. Routine application of weather modification technology each year can help stabilize and bolster water supplies (both surface and underground storage). Commitment to conduct a program each winter provides stability and acceptance by funding agencies and the general public. The program is designed so that it can be temporarily suspended or terminated during a given winter season.

1. INTRODUCTION

Due to high natural precipitation variability and the increasing demand for water, cloud seeding has been conducted in some parts of Utah for over 45 years, helping to augment water supplies. 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 Western Uintas program watersheds. A cloud seeding program has continued over recent winter seasons up to the present time for the Upper Weber and Provo River Basins. Cloud seeding programs have been conducted in this area by North American Weather Consultants dating back to 1989. These programs have often been jointly sponsored by two agencies: the Provo River Water Users Association and the Weber Basin Water Conservancy District.

The Weber Basin Water Conservancy District's participation has been continuous since the project's inception while the Provo River Water Users Association opted out during water years 2006 to 2012. The Provo River Water Users Association rejoined the program for the 2012-13 season through the present. Eleven ground-based silver iodide cloud nuclei generators (CNGs) were installed for the 2022-2023 season's program. The Western Uintas program became operational on December 1, 2023 and ended on April 30, 2024. The program was originally contracted to end on March 31, 2024. However, additional program sponsorship by the Jordan Valley Water Conservancy District resulted in an extension of the Western Uintas program through the month of April, with additional budgeted seeding hours that raised the total to a maximum of 2,250. This report provides information about the operational cloud seeding and results of statistical analyses toward estimations of cloud seeding effects. Section 2 describes the seeding project design and provides maps of the seeded target areas, as well as the locations of the CNGs with which the seeding was conducted. Section 3 discusses the types of real-time and forecast meteorological data that are used for conduct of the seeding programs. Section 4 summarizes the seeding operations conducted during this past season. Section 5 details statistical evaluations of the effects of the cloud seeding program.

2. PROGRAM DESIGN

2.1 Background

The operational procedures utilized for this cloud seeding project are essentially the same as those that have been proven to be effective for over 45 years of wintertime cloud seeding in the mountainous regions of Utah. The results from these operational seeding efforts have consistently indicated long-term average increases in wintertime precipitation and snow water content during the periods in which cloud seeding was conducted. These estimated increases have generally ranged from 5 to 10 percent (for the majority of seeded areas) in excess of what would have been expected without seeding, as predicted by historical linear regression target/control analyses.

2.2 Seeding Criteria

Project operations have utilized a selective seeding approach, which has proven to be the most efficient and cost-effective method, and has provided the most beneficial results. Selective seeding, or seeding only of storms or portions of storms 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 key characteristics of the air mass (temperature, thermodynamic stability, wind flow and moisture content), both in and below the precipitating clouds. The following list includes some of the key meteorological conditions that generally qualify an event for cloud seeding.

- Cloud bases are 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).

2.3 Equipment and Project Set Up

In the fall of 2023 NAWC reinstalled ground-based cloud seeding equipment for the winter seeding program. The equipment is placed at carefully selected sites, to provide seeding plumes that would be effective in enhancing snowfall over the project target area. Climatological winter storm behavior and prevailing wind direction are major factors in the placement of these sites. Eleven seeding sites were installed for this year's seeding program, whose locations are shown in Figure 2.1. Occasionally, seeding sites installed for other seeding programs in the region (such as the nearby High Uintas program) are used to target the Western Uintas program during less commonly occurring wind flow situations. Also, there are a number of automated sites that have been install as part of a state-sponsored seeding program.

While these are budgeted separately, they can provide an added benefit to the program in certain situations.

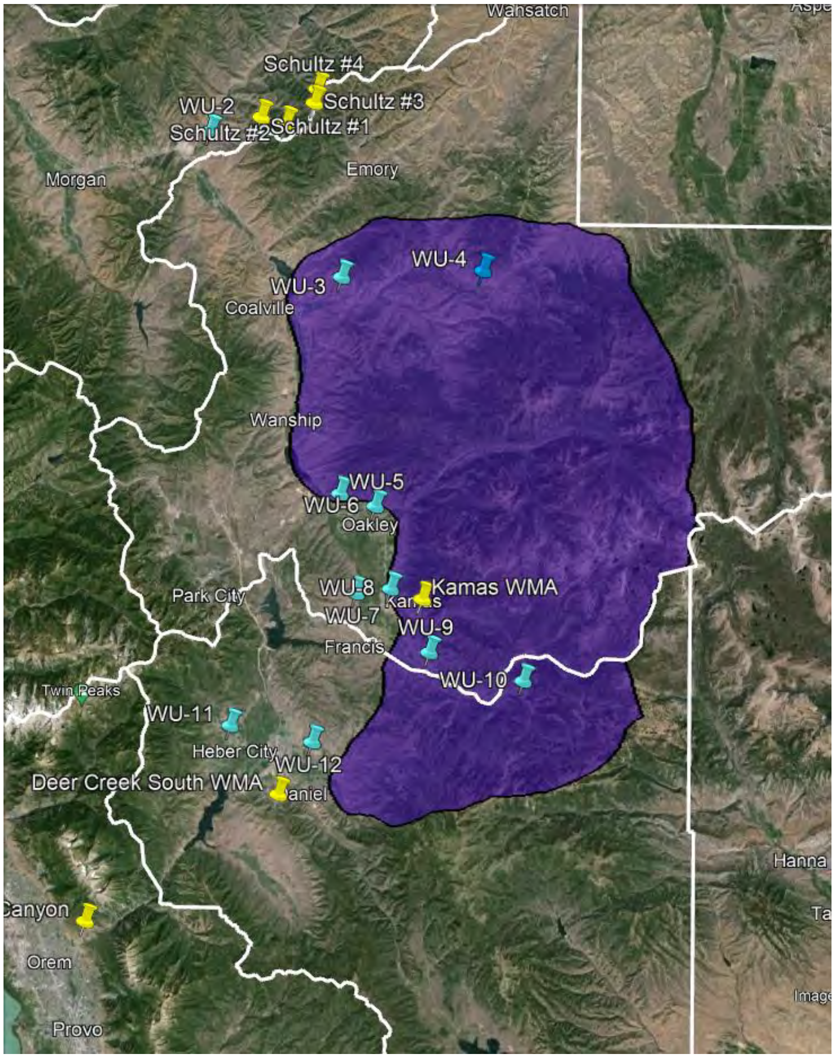


Figure 2.1 **Western Uintas target area (purple) and ground-based cloud seeding site locations (blue pins). Yellow pins are automated sites that can potentially seed the Western Uintas.**

Ground-Based Manual Seeding Sites

The cloud seeding equipment at each site consists of a cloud nuclei generator (CNG) unit and a propane gas supply (Figure 2.2). The seeding solution, emitted via combustion, consists of two percent by weight silver iodide (AgI), complexed with small portions of sodium iodide and para-dichlorobenzene in solution with acetone.

The CNG is manually operated by igniting the propane flame (at the flame head in a burn chamber) and adjusting the flow of seeding solution through a flow rate meter. The propane gas also pressurizes the solution tank, which allows the solution to be sprayed into the CNG's burn chamber at a regulated rate, where microscopic (sub-micron)-sized silver iodide crystals are formed. The crystals, which closely resemble natural ice crystals in structure, are released at a rate of 8 grams per hour per generator when using the 2% solution. These crystals become active as artificial ice nuclei in-cloud at temperatures between -5°C (23°F) and -10°C (14°F).

It is necessary that the AgI crystals become active in the formation zone (the region in the cloud which contains supercooled liquid water) upwind of, or over the project area mountain crest. This allows the available supercooled liquid water to be effectively converted to ice crystals which grow to snowflake size and precipitate onto the mountain barrier within the intended area of effect. If the AgI crystals take too long to become active, or if the temperature upwind of the crest is too warm, the seeding plume will pass from the generator through the precipitation formation zone and over the mountain crest without producing any additional snowfall at the surface. It is the meteorologist's task to identify storm situations in which the seeding treatment can be effective.

Figure 2.2 **Manually operated cloud seeding equipment**

Manual cloud seeding equipment was sited at 11 locations (mostly in the valleys), ranging from the southwest to northwest sides of the target area, as shown in Figure 2.1. Pertinent CNG site information is provided in Table 2-1. Most of the winter storms that affect the northern Utah Mountains are associated with synoptic weather systems that move into Utah from the northwest, west or southwest. Usually, they consist of a frontal system and/or an upper trough with the winds preceding the front or trough blowing from the south or southwest. As each system passes through the area, the wind flow changes to the west, northwest, or north. Clouds and precipitation may precede as well as follow the front/trough passage, or they may occur primarily after the passage along the boundary of the colder air mass that moves into the region. For the region comprising the project target area, the most abundant precipitation and low-mid level moisture usually occurs in west to northwest flow patterns. This is when the best seeding opportunities typically occur. Southwesterly flow is generally associated with somewhat warmer conditions that are sometimes less seedable.

Table 2-1
Manually Operated Cloud Seeding Sites

Site ID	Site Name	Elev (Ft)	Lat (N)	Long (W)
WU-2	Croyden	5371	41° 04.12'	111° 30.83'
WU-3	Coalville	5587	40° 55.95'	111° 20.72'
WU-4	Pineview	6407	40° 56.39'	111° 10.18'
WU-5	Peoa	6148	40° 43.75'	111° 20.61'
WU-6	Oakley	6472	40° 43.07'	111° 18.00'
WU-7	Kamas West	6872	40° 38.16'	111° 19.33'
WU-8	Kamas	6489	40° 38.43'	111° 16.77'
WU-9	Woodland	6706	40° 34.89'	111° 13.81'
WU-10	Woodland East	7305	40° 33.35'	111° 06.80'
WU-11	Midway	5570	40° 30.59'	111° 28.64'
WU-12	Heber City	5810	40° 29.73'	111° 22.52'

2.4 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 seeding suspensions during the 2023-24 season.

3. WEATHER DATA AND MODELS

NAWC meteorologists acquire weather information online from a wide variety of freely available 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 displays predictions of ground-based seeding plume dispersion for a discrete storm period in the Western Uintas Program from the 2023-2024 season 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 based on wind fields contained in the weather forecast models.

Global and regional forecast models are the basis of most modern weather forecasts, and important tools 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 GFS forecast model for a storm event during the 2023-2024 season is shown in Figure 3.5.

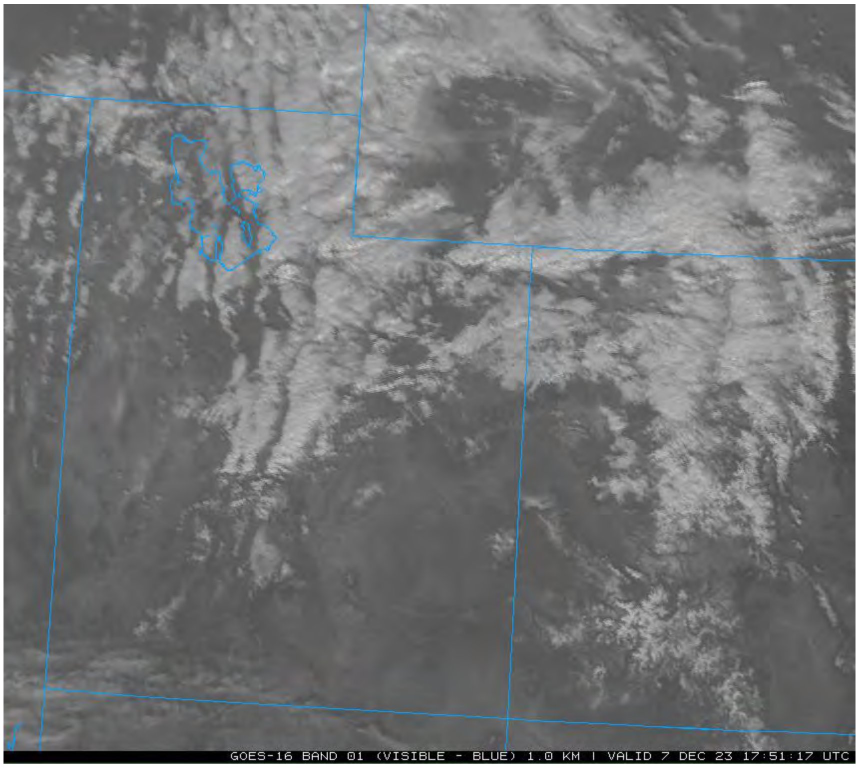


Figure 3.1 Visible spectrum satellite image of Utah during the afternoon of December 7, 2023 during a seeded event.

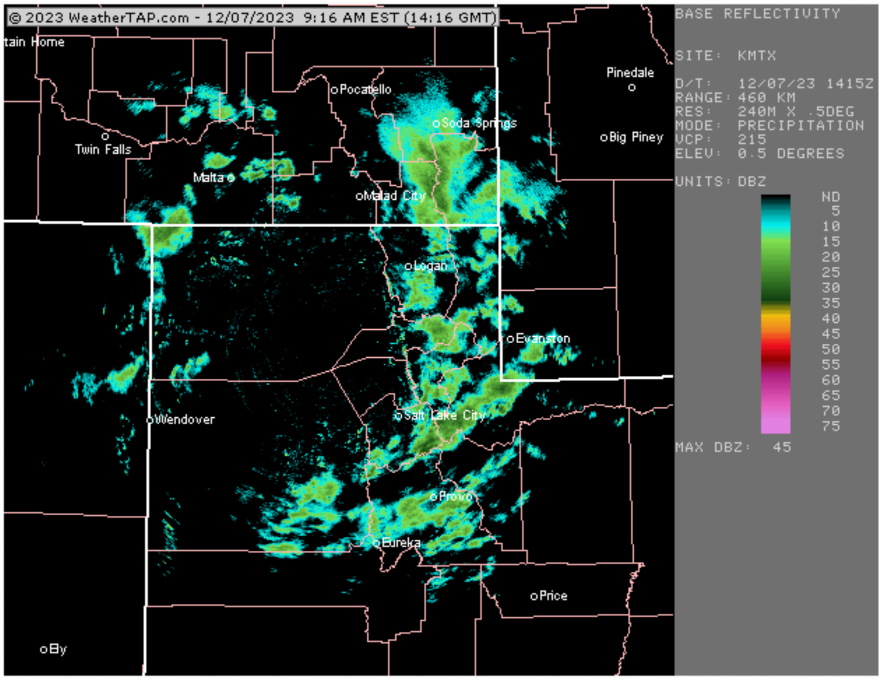


Figure 3.2 Weather radar image over northern Utah on the morning of December 7, 2023.

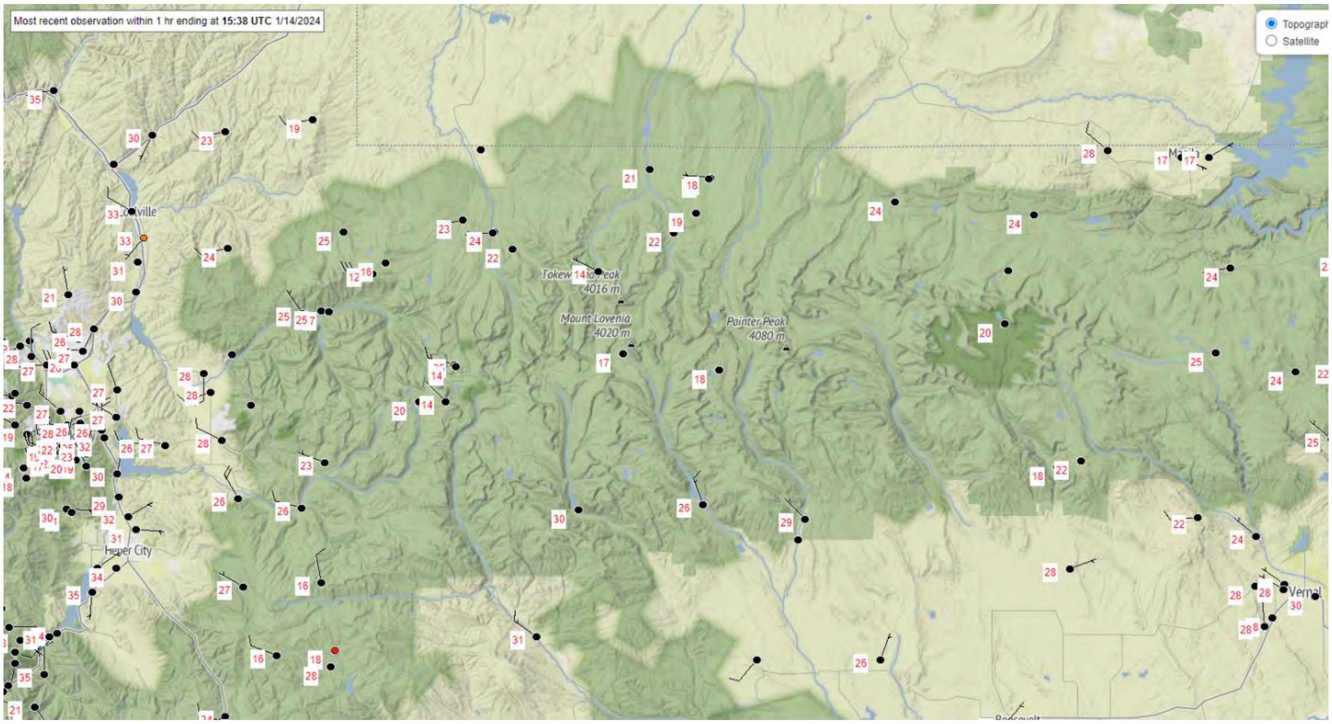


Figure 3.3 Map of surface temperatures and wind on the morning of January 14, 2024

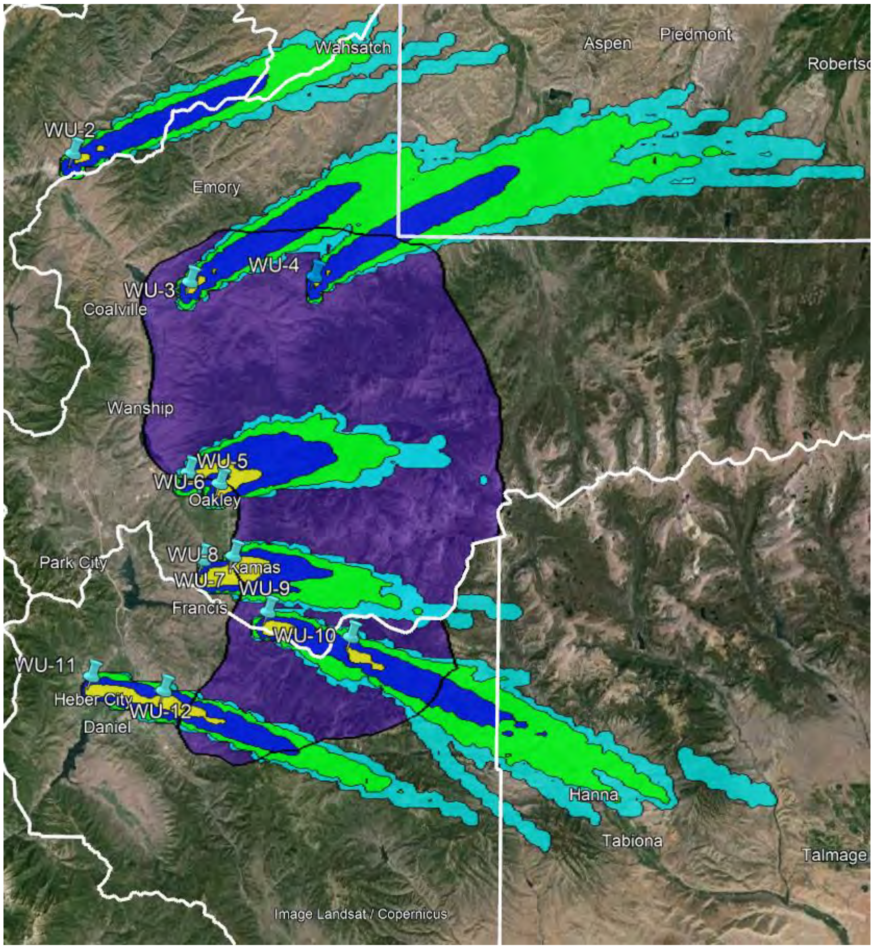
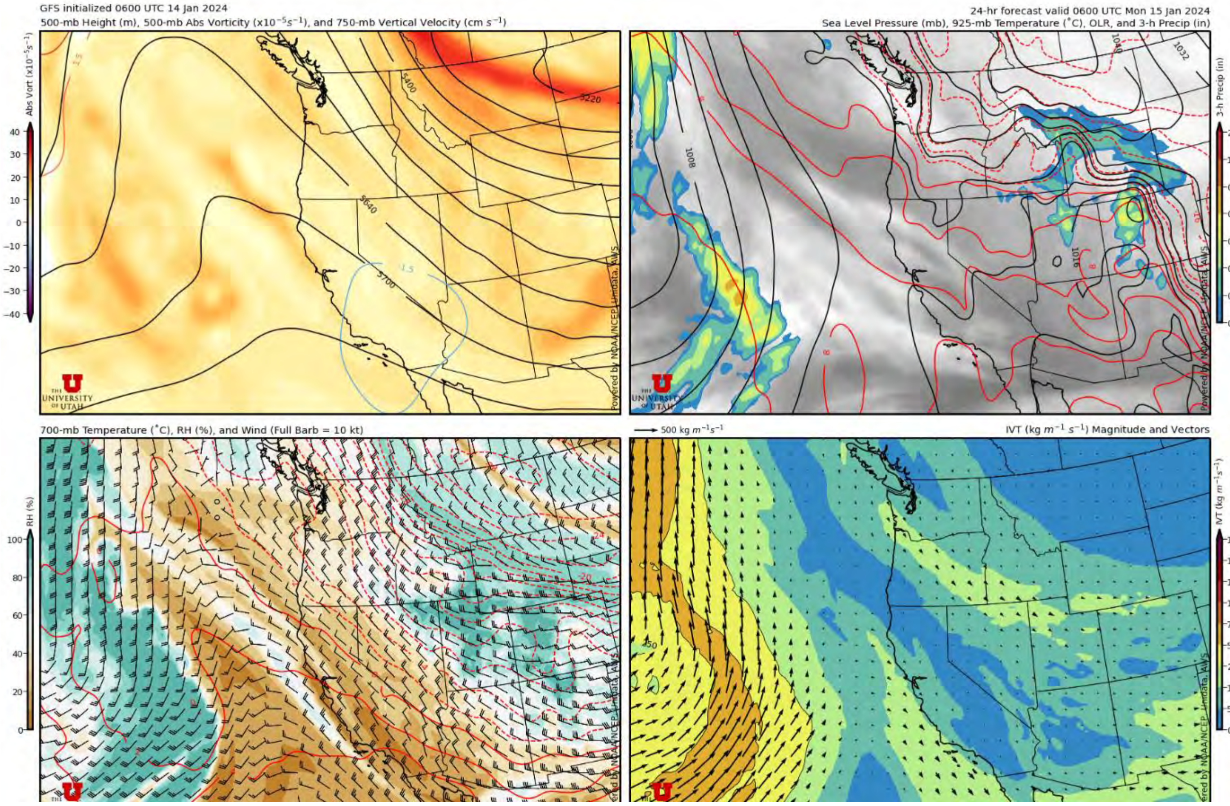


Figure 3.4 HYSPLIT plume dispersion forecast for potential seeding site locations on the evening of December 7, 2023



Figures 3.5 GFS (Global Forecast Systems) 4-Panel model plot during storm event on the night of January 14, 2024

4. OPERATIONS

The 2023-2024 Western Uintas cloud seeding program for the Weber and Provo River basins began on December 1, 2023, and ended April 30, 2024 (extended through April with sponsorship from the Jordan Valley Water Conservancy District). The program was originally contracted to end on March 30 prior to the additional sponsorship. A total of 31 storm periods were seeded during all or portions of 41 days. Four storms were seeded in December, seven in January, eight in February, eight in March and four in April. A total of 1592.25 seeding generator hours were conducted this season. Table 4-1 shows the dates and ground generator usage for the storm events, and Appendix B contains more detailed site usage data. Figure 4.1 shows the usage of generator hours during the season.

Precipitation and snowfall were again above normal during the 2023-2024 winter season, with snow water equivalent for the Weber-Ogden River basin averaging about 133% of the median value on April 1. The water year precipitation through April 1 averaged 123% of the normal (medium value) across the basin. The Provo River basin had corresponding April 1 averages of 135% of median snowpack and 126% of medium precipitation. Figures 4.2 to 4.4 are seasonal graphs for some SNOTEL sites in the target area.

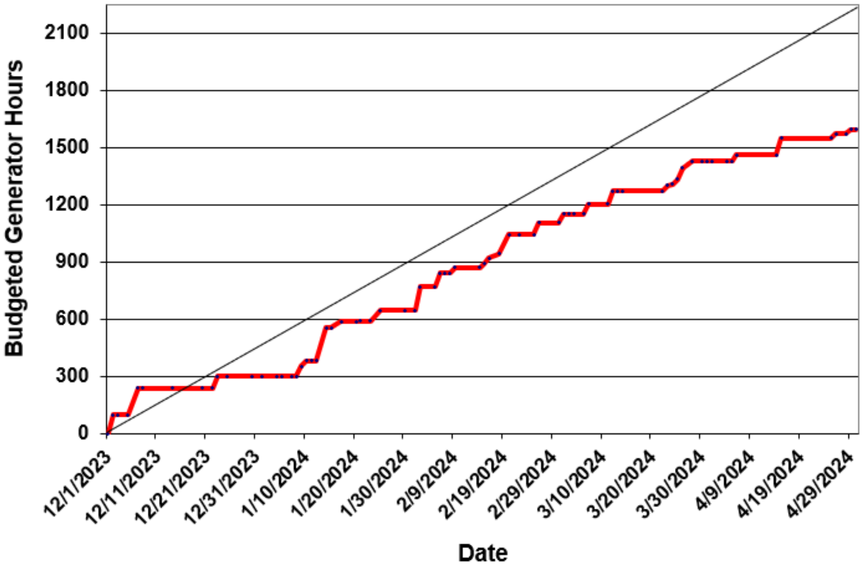


Figure 4.1 **Seeding during the 2023-2024 season (red), in comparison to a linear usage of total budgeted hours through the season (diagonal line).**

Table 4-1

Storm dates and number of sites/hours used, 2023-2024 season.

Storm No.	Date(s)	# Sites Used	# Hours
1	December 2-3	5	95.5
2	December 7	2	13
3	December 7-8	9	127.5
4	December 23	9	62
5	January 9-10	4	53.5
6	January 10	8	29
7	January 13-15	8	172
8	January 17	2	10.25
9	January 17-18	2	22.25
10	January 21	1	4
11	January 25	6	55.25
12	February 2-3	8	123.25
13	February 6-7	7	73.25
14	February 9	4	28.5
15	February 15	4	20.75
16	February 16	6	27.25
17	February 18	6	25
18	February 20-21	7	99.25
19	February 26-27	4	63
20	March 2	9	45.25
21	March 7	7	52.75
22	March 12-13	10	68
23	March 23	7	28.25
24	March 24	2	8.75
25	March 25	4	23.75
26	March 26	7	60
27	March 28	8	35.5
28	April 6	4	31
29	April 15-16	6	90.75
30	April 26-27	1	20
31	April 29	5	23.75
Season Total	---	---	1592.25

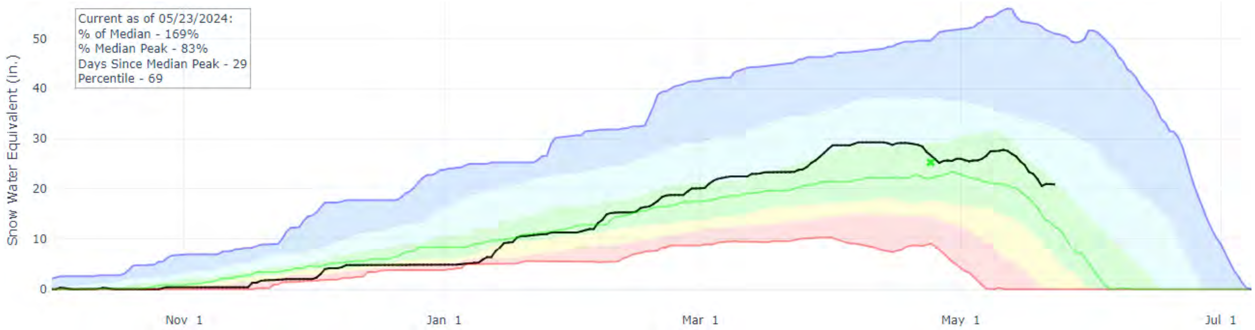


Figure 4.2 NRCS SNOTEL snow water content plot for October 1, 2023 through May 23, 2024 for the Trial Lake, UT SNOTEL Site. Black line is the 2023-24 season data. Green represents the median, while purple and red are the historical max and min values respectively.

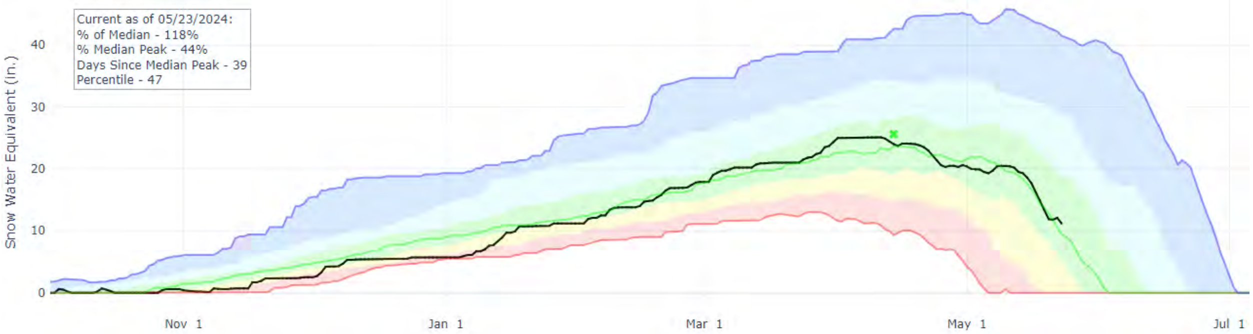


Figure 4.3 NRCS SNOTEL snow water content plot for October 1, 2023 through May 23, 2024 for Chalk Creek #1, UT SNOTEL site. Black line is the 2023-24 season data. Green represents the median, while purple and red are the historical max and min values respectively.

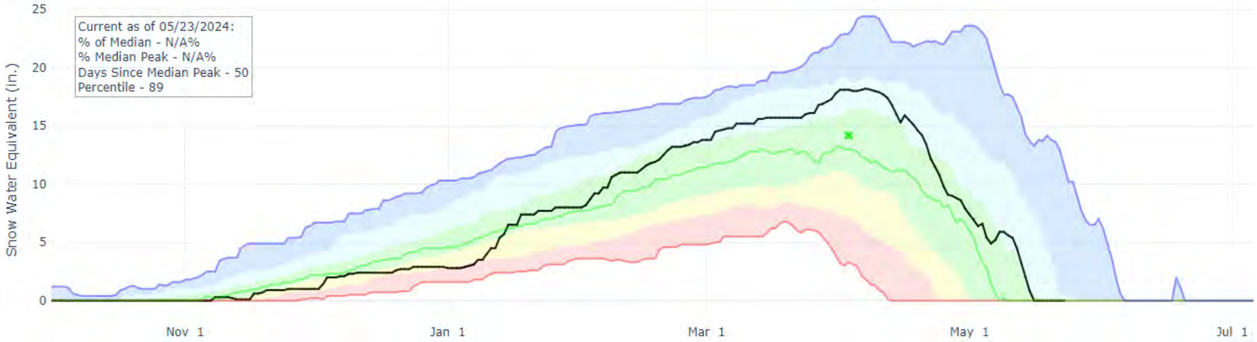


Figure 4.4 NRCS SNOTEL snow water content plot for October 1, 2023 through May 30, 2024 for the Smith and Morehouse, UT SNOTEL site. Black line is the 2023-24 season data. Green represents the median, while purple and red are the historical max and min values respectively.

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 Table 2-1, 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.

4.1 Operational Summary

A brief synopsis of seeded (or otherwise significant) storm events during the operational seeding period is provided below. All times are local (MST/MDT) unless otherwise noted. References to wind direction in meteorology correspond to the direction that the wind is coming from (the upwind direction). The 700 mb level (~9,500 feet above sea level during the winter) temperature in the atmosphere is often referenced, given that the temperature near mountain crest height is an important consideration for cloud seeding.

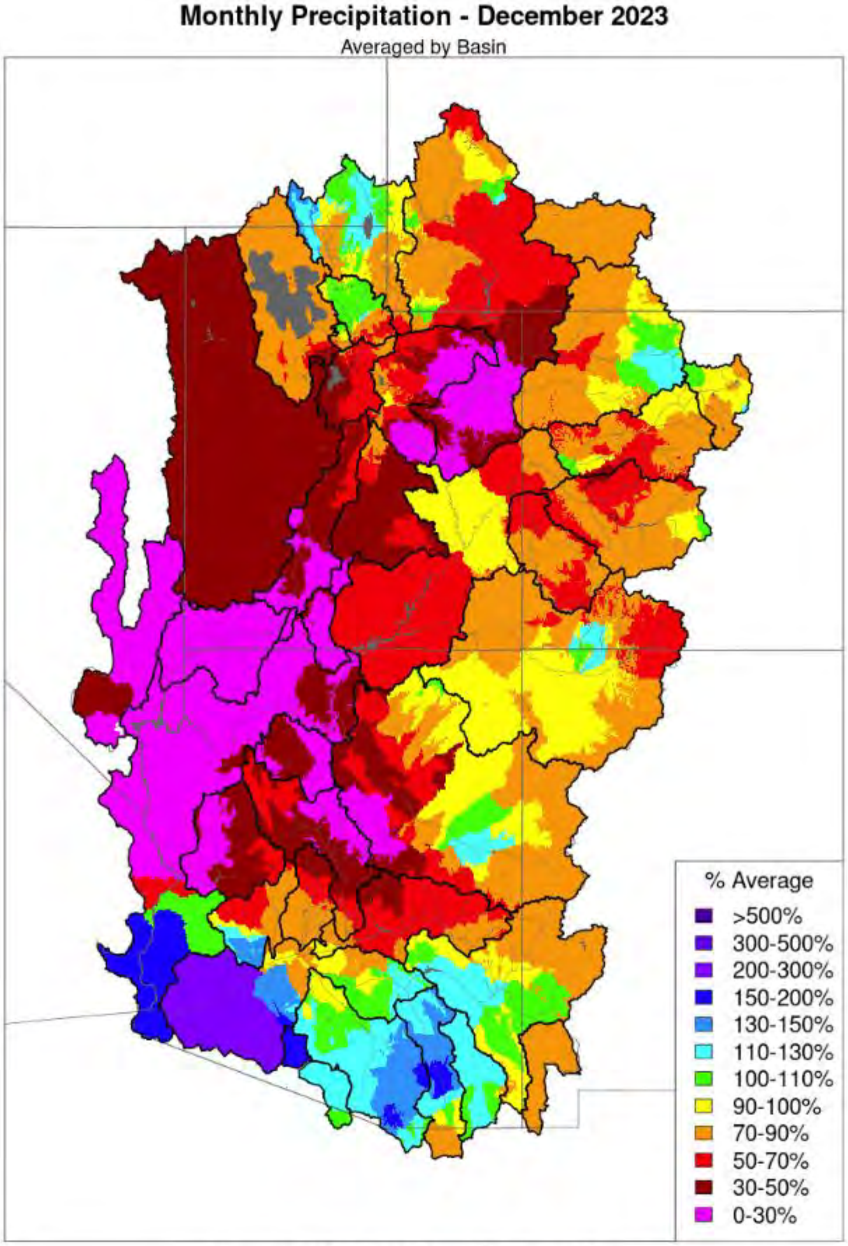
December 2023

December produced below normal precipitaiton and snowpack across the area (Figure 4.5), 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. There were four seeding opportunities for the Western 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 higher elevation 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 first with a 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. 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 northern portion of the target area, but amounts were light (near 0.1 inch) over southern portions.

After a period of dry weather with some valley temperature inversions, a frontal snow band moved into northern Utah on December 23. Seeding was initiated 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 WU target area, with about 0.1 – 0.2 inches of water content.



Prepared by NOAA, Colorado Basin River Forecast Center
Salt Lake City, Utah, www.cbrfc.noaa.gov

Figure 4.5 December 2023 precipitation, percent of normal

January 2024

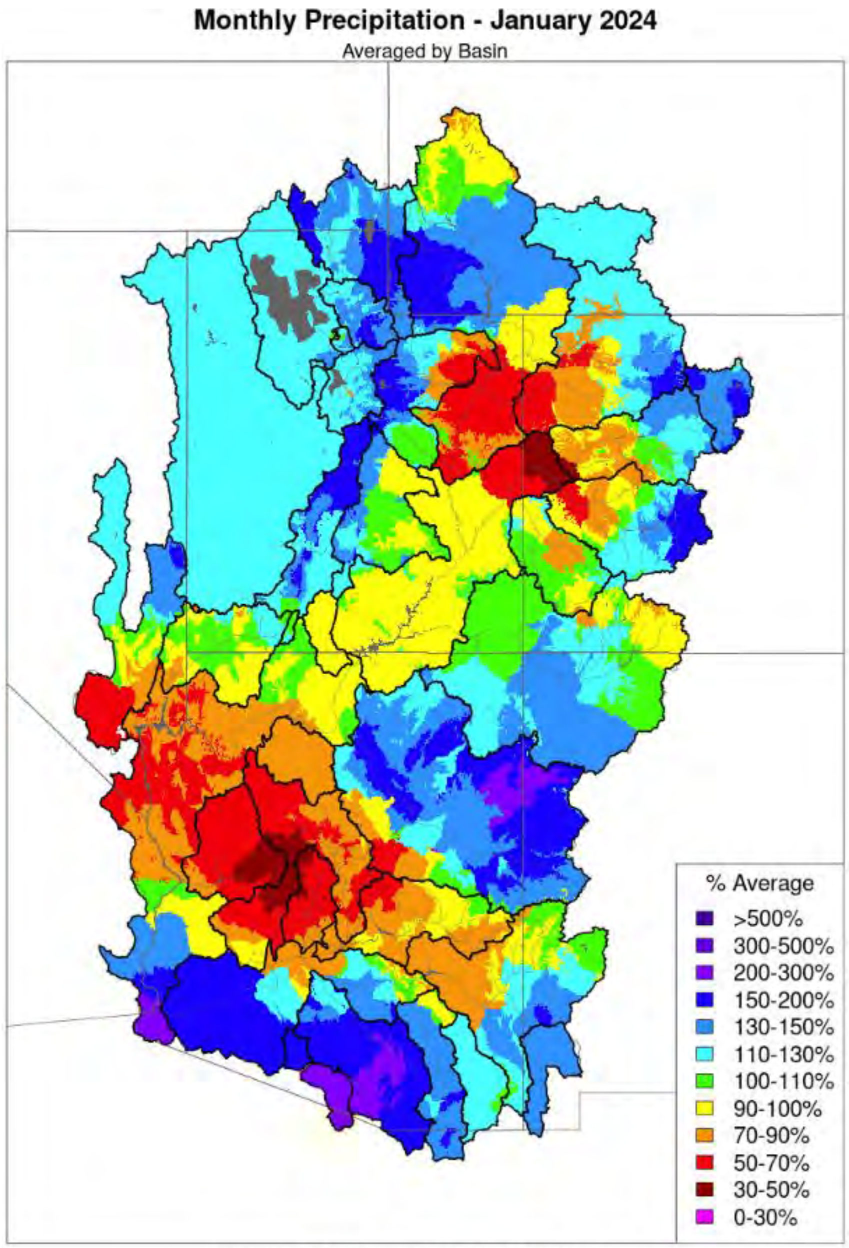
After a very dry start to the season, with weather pattern changed in January and brought much more frequent storm events to the region. Precipitation and snowfall ended up being substantially above average in January (Figure 4.6), which began a recovery from the low early season snowpack. The Western Uintas had 7 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 area just after sunset. Seeding began during the early evening, and continued overnight at some sites with additional snow shower activity. Precipitation totals with this frontal passage amounted to about 0.5 – 0.8 inches of water content in the WU 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 fall 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. Precipitation totals amount 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 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, 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 couple of weak systems brought some snowfall on January 17-18, with seeding initially conducted during a frontal snowfall band during the late morning to early afternoon of the 17th. 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. Seeding was again conducted at a few sites in a westerly wind pattern. Precipitation amounts during this period in general were between about 0.5 – 1.0 inches of water content, with the majority of this during the initial snowfall period midday on the 17th.



Prepared by NOAA, Colorado Basin River Forecast Center
Salt Lake City, Utah, www.cbrfc.noaa.gov

Figure 4.6 January 2024 precipitation, percent of normal

A weak system provided a very limited seeding opportunity during the late afternoon to early evening of January 21, with some light showers occurring and a 700 mb temperature near -5 C. Precipitation totals were around 0.1 – 0.2 inches of water content.

A trough extended from Oregon into the northern Great Basin on January 25, and brought some increasing moisture and snow shower activity. Seeding was conducted in the afternoon to early evening with the 700 mb temperature dropping to around -8 C. Precipitation amounts of 0.2 – 0.5 inches of water content were observed at target area SNOTEL sites.

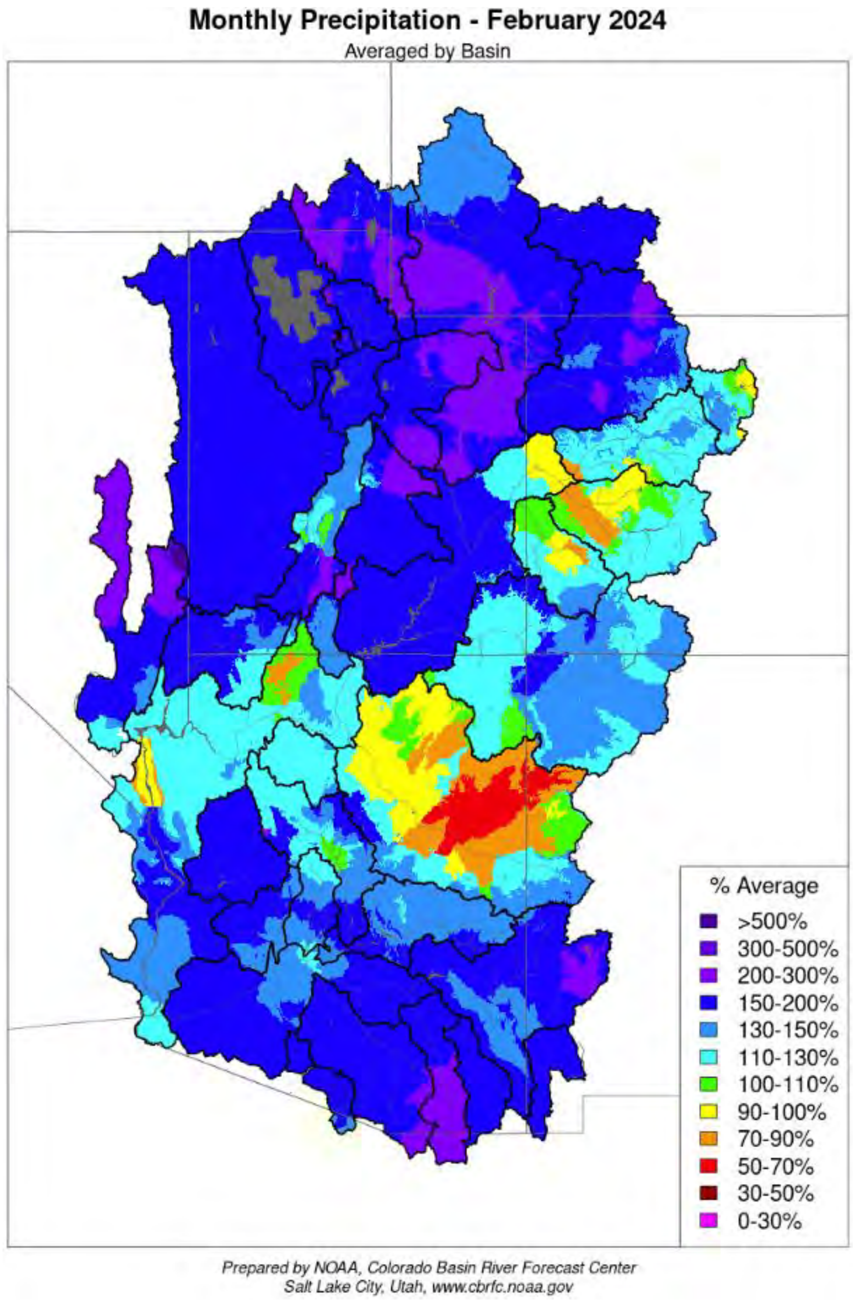
February 2024

February was an active weather month that brought up to twice the normal monthly snowfall to portions of the Uintas (Figure 4.7), and a consistently active weather pattern through the month. Snowpack values improved into the normal seasonal range from their low beginning, and there were 8 seeded storm periods in February.

Widespread, light precipitation on February 2 was associated with a fairly warm air mass and precipitation from a higher cloud deck initially. The passage of the trough axis through the area resulted in northwesterly winds by night of February 2-3 and cooling, with the 700 mb temperature falling to around -8 C. Snow and seeding ended on the morning of February 3, with precipitation totals from the storm period in general between about 0.5 – 1.0 inches of water content in the WU target area.

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 moved had moved inland and was crossing Utah and Arizona. Temperatures cooled somewhat (near -6 C at 700 mb) with better mixing and widespread precipitaiton at times, although seeding was mainly targeted to the higher (southern) half of the WU area. 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 WU target area.

A fairly weak trough moved across the area on February 15, although temperatures and winds were generally suitable for seeding operations. A band of precipitation in the morning was followed by a few convective snow showers in the afternoon. Precipitation totals were somewhat variable, ranging from about 0.2 – 0.7 inches at target area SNOTEL sites.


Monthly Precipitation - February 2024

Averaged by Basin

Prepared by NOAA, Colorado Basin River Forecast Center
Salt Lake City, Utah, www.cbrfc.noaa.gov

Figure 4.7 February 2024 precipitation, percent of normal

With a trough over the Pacific Northwest, a frontal boundary approached from the north on February 16 with moisture mostly along and south of it, and some arctic air to the north and east of Utah. Some snow squalls during the afternoon and evening were seeded, ending on the night of the 16th with the 700 mb temperature dropping to around -10 C as activity waned. Precipitation totals were relatively light, around 0.2 – 0.4 inches of water content.

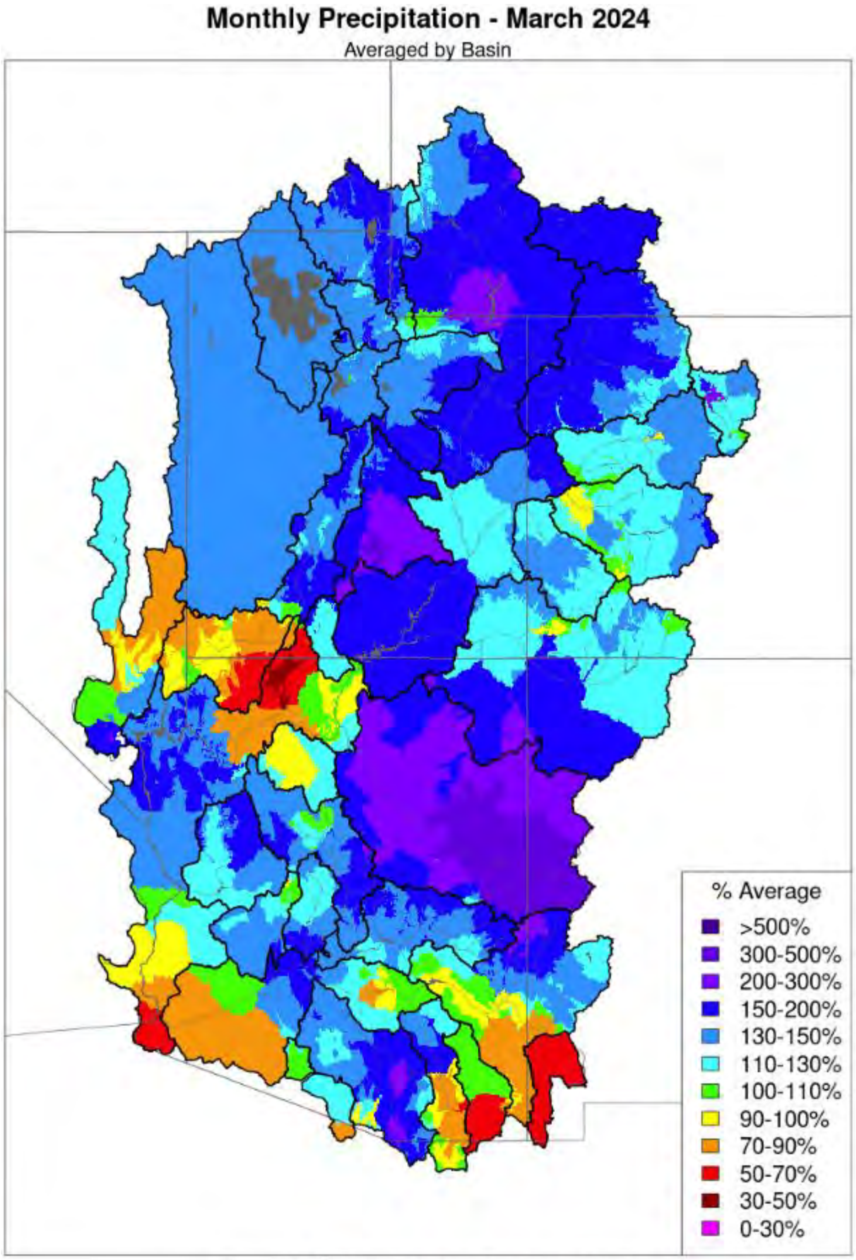
A weak trough crossed Idaho on far northern Utah on February 18, although the air mass over Utah was relatively moist and generated a good deal of snow shower activity during the daytime hours. Winds shifted from the southwest to northwest with a frontal passage, with fairly low cloud bases and a 700 mb temperature from about -5 to -7 C. Seeding was conducted from midday through the afternoon hours, and precipitation totals ranged from about 0.2 – 0.5 inches of water content.

A band of rain and snow set up across the area on the night of February 20-21 along a weak frontal boundary, with a 700 mb temperature near -5 C. Lower levels winds remained very light, making targeting somewhat of a challenge. Snow showers continued in light southwesterly flow through much of the 21st, with a 700 mb temperature near -6 C being favorable for seeding to continue through the afternoon hours. Seeding ended on the evening of the 21st as conditions began to dry out. Due to the fairly long residence of the precipitation band over the area, substantial totals were realized over portions of the WU target with totals ranging between about 0.7 – 2.3 inches of water equivalent at SNOTEL sites.

A large, cold trough moved into the northwestern U.S. on February 26. A large cold front crossed northern Utah on the evening and night of the 26th, bringing temperatures down near -4 C to the -16 to -18 C range behind it on the 27th. The overnight frontal snow band was seeded from several sites, with seeding continuing through midday on the 27th as some convective snow showers developed. However, these were generally lacking in liquid water content due to cold temperatures and seeding ended shortly after midday. Precipitation totals at target area SNOTEL sites ranged from 0.3 – 0.8 inches with this storm event.

March 2024

The month of March was an active weather month with significantly above normal precipitation over most of the region, although totals were quite variable around the Uintas (Figure 4.8). There were eight seeded storm periods for the WU program in March.



Prepared by NOAA, Colorado Basin River Forecast Center
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Figure 4.8 March 2024 precipitation, percent of normal

A large and very cold trough moved onshore into the northwestern U.S. on March 2-3, bringing a strong cold front across northern portions of Utah on the afternoon to early evening of March 2. Winds were very strong along and ahead of the front, and temperatures dropped from about -4 C at 700 mb ahead of the front to -13 C behind it. Seeding was conducted for several hours during the late afternoon and early evening with the frontal passage, ending later in the evening as conditions dried out behind it. There was some additional snow shower activity on March 3-4 with the trough over the region, but the air mass was cold and lacking in liquid water so no additional seeding was conducted with this system. SNOTEL data indicated water content amounts in the 0.5 – 0.9 inch range with the seeded frontal passage on March 2.

A disorganized trough included a closed low centered near far southern Nevada on the morning of March 7. Some convective precipitation developed over portions of Utah including the Western Uintas beginning early in the day. Cloud bases were fairly low at times, ranging from about 6,000 to 8,000 feet and the atmosphere was suitably cold with a 700 mb temperature near -7 C. Winds were west – northwesterly and snow showers continued during the daytime hours. Seeding was conducted from nearly all site, ending around sunset. Precipitation totals were around 0.2 – 0.3 inches of water content.

A cold trough moved onshore in the Pacific Northwest on March 12, with a cold front and associated snowfall band moving into the WU area during the evening hours. Seeding began in the early evening and continued overnight at some sites, with the 700 mb temperature falling between about -5 to -10 C during the frontal passage and overnight. Snow showers lingered during much of the day on March 13 in northwesterly flow and seeding continued at some sites, ending before sunset. Precipitation totals ranged from about 0.4 – 0.8 inches of water content from this system.

A large trough centered near Oregon pushed a cold front boundary into the Great Basin on March 23, reaching the Uintas area during the evening hours. The 700 mb temperature dropped to below -5 C with the front, and there was embedded convection as well. The event was short-lived, however, with seeding for only several hours ending late in the evening. Precipitation amounts ranged from about 0.4 – 0.8 inches of water content at SNOTEL sites in the target area.

A large trough remained over much of the western U.S. during the March 24-26 period, with a cold, moist northwesterly wind pattern over Utah and mostly diurnally driven convective showers each day. A few thundershowers also developed at times, and many of the showers contained graupel which is indicative of good liquid water content. The 700 mb temperature ranged from about -8 to -10 C during this time period. Seeding was conducted during the daytime hours on each of these three days. Precipitation totals were somewhat light and scattered, with about 0.1 – 0.2” recorded at SNOTEL sites in the WU target each day on March 24 and 25 and somewhat higher totals (0.2 – 0.5 inches) on March 26.

Yet another large and cold trough brought a frontal passage to the area on the afternoon/evening of March 28, with seeding conducted for several hours from mid afternoon into the evening. The 700 mb temperature dropped to around – 7 C with the frontal passage, and there was some embedded convection as well. Snowfall and seeding operations ended later in the evening, and precipitation ranged from about 0.3 – 0.8 inches of water content at SNOTEL sites.

April 2024

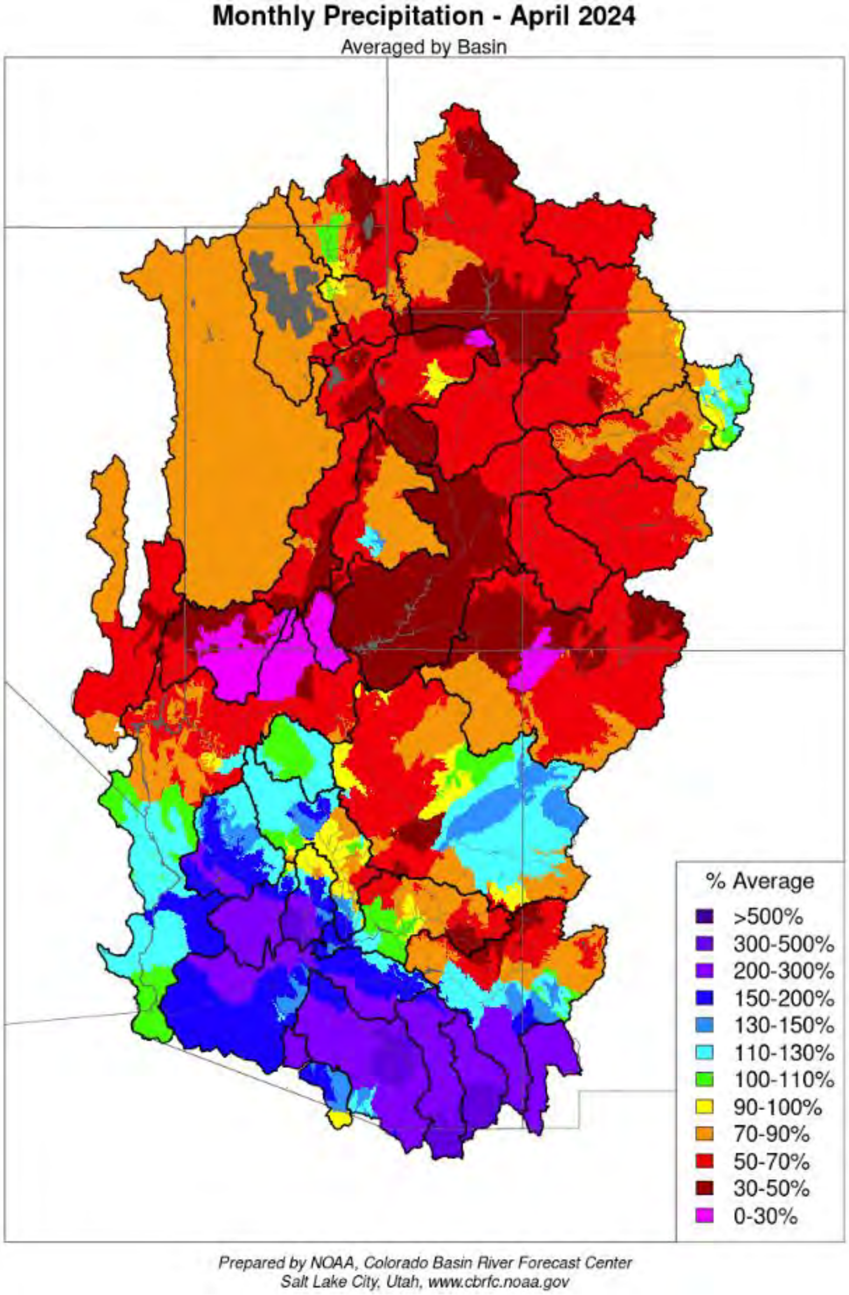
Thanks to additional sponsorship of the seeding program by the Jordan Valley Water Conservancy District this season, extending the program through the month of April. Although April was a drier than average month (Figure 4.9), this extension allowed the seeding of four storm periods in April.

A large trough moved from California into Nevada on April 5, with snowfall over the western Uintas beginning on the evening and night of the 5th. While cloud types and wind patterns were not conducive to seeding initially, the trough core moved across the region on April 6 with convective snow showers and cold temperature. The 700 mb temperature was near -11 C on April 6 with northwesterly winds, and seeding was conducted from late morning until about sunset. Precipitation total during this period were around 0.2 – 0.4 inches of water content.

After a period of warm and dry weather, a trough affected Utah beginning on April 15 with convective showers developing in northwesterly flow. These showers occurrred mainly during the afternoon and evening hours but persisted into the night, with a 700 mb temperature near -5 C. Seeding began midday to the afternoon hours with more sites added in the evening as winds become north-northwesterly. Seeding operations ended early on April 16. Precipitation totals with this system were in the 0.5 – 0.8 inch range at target area SNOTEL sites.

A large trough moved across the area on April 26-27, bringing areas of precipitation and a limited seeding opportunity. Temperatures were on the warm side during much of the event and winds mostly unfavorable, being quite variable with easterly component flow during much of the event. One available site within the seeding target area was used in this event, from midday on the 26th until the morning of the 27th. Precipitation totals for the event as a whole ranged from about 0.5 – 1.0 inches of water content.

The final seeded event of the season occurred on April 29, with a cold front bringing a band of snowfall and embedded thundershower activity across the area during the late afternoon and evening hours. Seeding was conducted during the late afternoon and evening hours and the 700 mb temperature cooled to near or below -5 C with the frontal passage. There was fairly rapid drying behind the frontal passage and seeding operations ended late in the evening. SNOTEL data showed water content ranging from about 0.2 – 0.5 inches in the target area with this event.


Monthly Precipitation - April 2024

Averaged by Basin

Prepared by NOAA, Colorado Basin River Forecast Center
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Figure 4.9 **April 2024 precipitation, percent of normal**

5. ASSESSMENT OF SEEDING EFFECTS

5.1 Background

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

Historically, among all cloud seeding project types, the most consistent results have been observed in wintertime seeding programs in mountainous areas, with results indicating 5-15 percent increases in seasonal precipitation. Establishing an accurate approximation of the effects of seeding within a single operational season can be challenging. To provide our clients with greater decision making power, NAWC had historically used a “target and control” regression to evaluate seeding impacts. This involves comparison of a variable that is affected by seeding (precipitation or snowpack) between a “target” area (where seeding occurred for the season being assessed) and a “control” area (where no seeding occurred for the season being assessed).

After identifying appropriate control sites, data for the selected variable (e.g., precipitation) is analyzed for both the “target” area and the “control” area **for years where no seeding was performed in either area**. A mathematical model (regression) is developed to determine the relationship between precipitation in the “target” area and precipitation in the “control” area under natural circumstances. This mathematical model is then used to analyze the selected variable in years where seeding **did not** occur in the “control” area but **did** occur in the “target” area. Using this model with data for the control sites, a reasonable prediction can be made of what would have transpired in the target area had no seeding occurred, then compare this to what actually happened in the target area. Consistent differences between the predicted and observed target area data 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 good mathematical correlation can be found between target and control area precipitation. Generally, the closer the two areas are geographically, and the more similar they are in terms of elevation and topography, the higher the correlation and the more certain the results. Areas selected that are too close together, however, can be subject to contamination of the control sites by 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, and correlations around 0.85 would be very good. A correlation coefficient of 0.90

would indicate that over 80 percent of the variance (r^2) in the historical data set is explained by the regression equation used to estimate the subject variable (expected precipitation or snowpack) in the seeded years. Correlations less than about 0.80 are still acceptable, but it would likely take much longer to attach any statistical significance to the apparent results of seeding.

5.2 Considerations in the Development of Target/Control Evaluations

With the advent of the Natural Resources Conservation Service's (NRCS) SNOTEL automated data acquisition system in the late 1970's, access to precipitation and snowpack (water equivalent) data in mountainous locations became routine. Before the automated system was developed, these data had to be acquired by having NRCS personnel visit the site to take necessary measurements. This is still done at some sites although most have been automated. Historically, Utah has had snowpack measurements taken at (usually) monthly intervals. Precipitation and snowpack data used in the analysis were obtained from the NRCS and/or from the National Climatic Data Center.

Control sites are typically selected (from areas not affected by seeding) with some geographic diversity, to help offset seasonal variations in weather patterns that may greatly affect specific locations. Another consideration in the selection of control sites for the development of an historical target/control relationship is one of data quality. A potential control site may be rejected due to poor data quality if the data significantly diverges over time from other sites in the area. SNOTEL sites, the type used in the evaluation of the Western Uintas program, typically have reliable long-term records with external variables (such as terrain aspect and surrounding vegetation) carefully selected or maintained.

5.3 Evaluation of Snow Water Content

Historically, the Soil Conservation Service (SCS) routinely measured the mountain snowpack at snow courses once or twice per month, usually starting in January and continuing until May or June. Measurements were made by visiting the snow course (commonly a group of ten measurement points) and taking core samples of the snow to determine the water content and depth of the snow at each designated location along the course. Though this manual method is still being used at a few sites, beginning in the 1980s, most of these sites (now known as SNOTEL) were automated. With the use of a snow pillow, the water equivalent of the snowpack can be determined remotely by reading the weight of the snow on the snow pillow. 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 as runoff when the snow melt occurs. Hydrologists routinely use snow water content to make forecasts of 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 configured with collocated precipitation and snowpack measurements. Consequently, it was judged important to evaluate the effects of seeding on snowpack as well.

There are some potential pitfalls with snowpack measurements that must be recognized when using snow water content to evaluate seeding effectiveness. One problem that can occur is that not all winter storms are cold, and sometimes rain as well as snow falls in the mountains. This can lead to a disparity between precipitation totals (which measure everything that falls) and snowpack water content (which measures only the water held in the snowpack at a particular time). Also, warm periods can occur between snowstorms particularly in the spring season. If a significant warm period occurs, some of the precipitation that fell as snow may melt or sublimate by the time the next snow course measurement is made. This can also lead to a greater disparity between snow water content and precipitation at lower elevations (where more snow will melt in warm weather) than at higher elevations.

April 1st snowpack readings are widely used for runoff forecasting since they usually closely represent 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 three to four months of seeding are generally represented in the April 1st snowpack measurements, April 1st was selected as the date for snowpack analyses.

Target/Control Sites and Regression Equation Development

The procedure was essentially the same as what was done for the precipitation evaluation, e.g., control and target area sites were selected, and average values for each were determined. Seven target area snow measurement sites were utilized for the Western Uintas Program, as shown in Figure 5.1. Table 5-1 provides the target area site names, elevations, and locations of these sites. The average elevation of the target sites is 8,637 feet MSL.

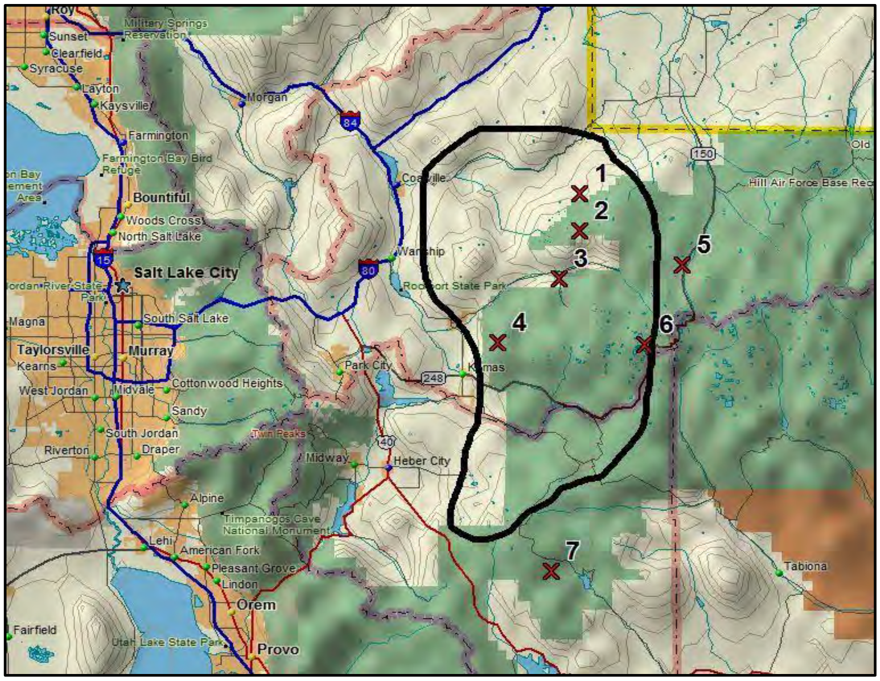


Figure 5.1 **Western Uintas target area and snowpack target sites**

Table 5-1
Target area snowpack sites

Map Label	Site Name	Elev. (Ft)	Lat. (N)	Long. (W)
1	Chalk Creek #2	8,200	40° 54'	111° 04'
2	Chalk Creek #1	9,100	40° 51'	111° 04'
3	Smith & Morehouse	7,600	40° 47'	111° 06'
4	Redden Mine, Lower	8,500	40° 41'	111° 13'
5	Hayden Fork	9,100	40° 48'	110° 53'
6	Trial Lake	9,960	40° 41'	110° 57'
7	Currant Creek	8,000	40° 21’	111° 05’

The five control sites are located in southern Idaho, northeastern Nevada and central Utah as shown in Figure 5.2. Control area site names, elevations and locations are provided in Table 5-2. The elevations of the control area sites average 6,887 feet (MSL). The non-seeded seasons were 1970-1988 and 1997-2000 (a total of 23 seasons). **Many more historical seasons were available for the snow water content analyses than for precipitation data, 23 versus 11 seasons. As a consequence, the snow water content analyses results are likely to be much more reliable than the precipitation analyses for this particular seeding program.**

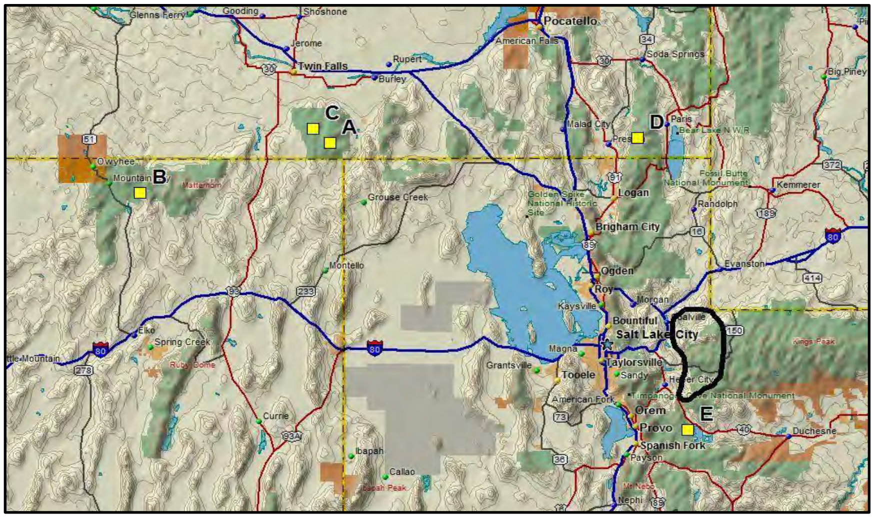


Figure 5.2 **Western Uintas target area and snow control sites (squares)**

Table 5-2
Control area snowpack sites

Map Label	Site Name	Site ID	Elev. (Ft)	Lat. (N)	Long. (W)
A	Badger Gulch SC, ID	14G03	6,660	42°06'	114°10'
B	Big Bend, NV	15H04S	6,700	41°46'	115°43'
C	Magic Mountain, ID	14G02S	6,880	42°11'	114°18'
D	Willow Flat SC, ID	11G04	6,070	42°08'	111°38'
E	Strawberry Divide, UT	11J08S	8,123	40°11'	111°13'

The linear regression equation developed from the historical relationship between the average control snowpack data and the average target snowpack data for April 1st was the following:

$Y_C = 0.741 (X_O) + 6.36$ (4)

where Y_C is the calculated average snow water content (inches) for the seven-station target and X_O is the five-station control average observed snow water content for April 1st.

Linear Regression Snowpack Analysis

The combined (26-year) snow water linear regression evaluation for April 1st, for the Western Uintas target sites, yields a ratio of 1.03. This long-term mean excludes water years 2004 and 2015 during which abnormal early snowmelt occurred, and thus includes 26 seeded seasons. The implied 3% increase based on the snowpack evaluation is equivalent to an average of about 0.53 inches more water over the watersheds than might have occurred without the cloud seeding.

Multiple Linear Regression Snowpack Analysis

A multiple linear regression analysis has been conducted for snowpack, and exhibits much lower seasonal variability in the indicated observed/predicted ratios than does the corresponding linear regression. The r value is also much better than for the standard linear regression (0.90 vs. 0.79). This implies less background noise in this equation, and thus likely more reliable estimates of the true seeding effects. The results of the multiple regression snowpack analyses suggest about a 6% increase over the long term. In the case of the Western Uintas evaluations, the multiple linear snowpack analysis is by far the strongest mathematically and is likely the most reliable for evaluation of this program.

A double ratio analysis using snowpack data (similar to that for precipitation) resulted in a ratio of 1.13, implying a 13% increase in the target area (relative to the control) during the seeded seasons. However, this result is a high outlier in these evaluations and may not be representative of the actual seeding effects. NAWC's best estimate of seeding effects for the Western Uintas program is about a 6% increase, as obtained in the multiple linear regression snowpack analysis.

5.4 Summary of Snow and Precipitation Evaluation Results

The April 1st **snowpack** analyses for 26 seeded seasons (2004 and 2015 were excluded) yield observed/predicted ratios of 1.03 (linear) and 1.06 (multiple linear). The results using April 1st snowpack imply average increases of roughly 3%-6%, which seems reasonable for this program, particularly in comparison to results of similar programs in the western U.S. and nearby programs in Utah. The April 1st snowpack evaluations are considered much more representative than the December-March precipitation evaluation (previously included in this section) due to a much longer historical period being available for the snow water versus precipitation evaluation of 23 versus 11 seasons, and a stronger statistical correlation (i.e., r value of 0.90). Also, of interest in the case of the snowpack evaluations is the much lower year-to-year variability observed in the results of the snowpack multiple linear evaluation, suggesting that this particular equation is likely the best predictor of the “expected” natural target area precipitation based on the available control site snowpack data. **This suggests a likely long-term average seeding effect of 3-6% for this program, with the better correlated evaluations leaning toward the upper side of this range.**

NAWC considers the Western Uintas evaluations to be conservative estimates of the effects of seeding for a variety of reasons. For example, some months that were included in the “seeded” period actually were not seeded during all seasons. Also, one of the control sites (Strawberry Divide) is located in an area that has been seeded for another program during some winter seasons. The snowpack evaluations are conservative because they are based upon April 1st data. These data contain periods in the fall and early winter in which snowpack accumulated in the target area without any effects of seeding. This would dilute the indicated effects of seeding over the long term. Another potential confounding issue in evaluating the effects of cloud seeding in the Western Uintas target area is that the historical target/control evaluations seem to be impacted by urban air pollution, based upon an analysis performed and published by NAWC (Griffith et al., 2005). A copy of the paper on this topic was provided in the 2005 report and is also available on NAWC’s website (www.nawcinc.com/nawcpapers.html). That analysis documented an approximate 16% decline in the November through March precipitation at Trial Lake during the period from 1956 to 2004. In other words, cloud seeding may potentially be offsetting the negative effects of air pollution on precipitation.

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 the seasonal evaluations are now in areas targeted by seeding operations. This includes the Strawberry Divide SNOTEL, which was an important control site historically for evaluating the Western Uintas program. For this reason, rather than updating the same target/control results on an annual basis, a different approach was used this season as detailed in the following section.

5.5 Results – Impact of Cloud Seeding on Runoff

Given that cloud seeding operations have been expanding in Utah due to additional state sponsorship and deployment of remotely operated sites, there are now very few non-seeded control sites that are well correlated to the target areas. For example, one of the control sites (Strawberry Divide) for the Western Uintas snowpack analysis is now subject to seeding effects, and elimination of this imporatant control site reduces correlation to the target area significantly. While re-creating the target/control regression equations with less control sites could be a reasonable option if larger sets of seeded and historical (non-seeded) data were available, for the current analysis another approach was taken. NAWC examined the correlation of streamflow gauges for runoff originating in the WU target area to SNOTEL snow and seasonal precipitation data. This allows previously obtained (long-term program average) seeding increase estimates to snowpack and precipitation, on the order of ~5% from the majority of the previous analysis, to be calibrated to streamflow increases for the program. While not a new technique, this is an expansion of this analysis to additional areas where it has not been examined before.

Stream gauges located for such an analysis, which appear essentially unregulated (e.g. represent the natural runoff) and correlate well to SNOTEL sites in their respective draining basins, include the Weber River near Oakley (USGS site #10128500) and Chalk Creek near Coalville (USGS site #10131000). For these comparisons, a seasonal (March – July) streamflow total was used to best represent seasonal runoff, with regression again SNOTEL April 1 SWE and seasonal (November – April) precipitation. It is recognized that this seasonal precipitation period is somewhat longer than the Western Uintas seeding program alone which has run from December – March in most seasons, although there is frequently seeding outside of this time period for the nearby High Uintas program. In any case, if a somewhat conservative 5% seasonal increase in precipitation/snowpack in the target area due to cloud seeding is assumed, corresponding estimates in streamflow increases from regression using these stream gauge data.

For the Weber River gauge, application of a 5% increase in snowpack and precipitation to the regression equations showed corresponding streamflow increases of 6-7%. This larger increase (in terms of percentage) to streamflow may seem counterintuitive, but is actually an expected result due to the negative offset term in the equations. This is related to the fact that there is some inefficiency in conversion of watershed precipitation and snowpack to streamflow, as some of the water evaporates or is taken up by the soil and used by vegetation during the growing season, etc. Thus, increasing the total precipitation/snowpack by a given percentage over a seasonal period would yield a somewhat larger percentage increase to streamflow. These 6-7% suggested increases in streamflow at this Weber River gauge site, when applied to a long-term seasonal March – July average of over 115,000 acre-feet (AF), would yield increases of roughly 7,200 to 8,200 AF for this location in the Weber River near the town of Oakley in an average season. Note that the relationship between streamflow and snowpack/precipitation is itself independent of seeding operations, allowing both seeded and non-seeded seasons to be used in the analysis, although the results would be applicable to seeded seasons in terms of an increase estimate to streamflow from the seeding program.

For the Chalk Creek gauge, regression equations (also best correlated with the Chalk Creek #1 SNOTEL) showed somewhat poorer correlation than for the Weber River. This could be due to water diversions upstream of the gauge site, for example, or to higher natural variability related to larger inefficiencies in conversion to streamflow in this northern portion of the Western Uintas target area. This is frequently the case in areas of somewhat lower, semi-arid terrain. The Chalk Creek streamflow regression equations suggested that a 5% increase in SWE and seasonal precipitation would lead to a 10% or more increase in streamflow at this gauge site. When applied to an average long-term seasonal (March – July) streamflow of over 40,000 AF at this gauge, seeding increase estimates yielded about 4200 to 4800 additional AF seasonally, considered representative of an average year.

5.6 Results - Impact of Cloud Seeding on Runoff

The likely seasonal streamflow percentage increase due to seeding is in the 6-10% range based on these regression equations, perhaps closer to the lower end of this range if weighted by volume. This is higher than the assumed (likely conservative) 5% increase to snowpack or seasonal precipitation which was input to these regressions. The greater **percentage** increase to runoff (as compared to precipitation or snowpack) is an expected result of these analyses, due the fact that only some of the natural precipitation/snowpack is converted to streamflow and any increase from seeding thus increases the efficiency of conversion. Such an increase (6-10%) applied to a total runoff value for the watershed in an average season would yield an estimated range of streamflow increase per season. This would be at least the sum of the independent estimates from these two gauge sites, e.g. likely over 12,000 AF in an average season, which is a lower end number that excludes runoff not measured by these gauges. Previous estimates using the total volume of a 5% increase to snowpack, scaled to the geographical size of the target area, resulted in an estimate on the order of 25,000 AF increase in total water volume due to seeding in an average season. This is likely a reasonable estimate based on the most recent analyses, considering that only a portion of the runoff is accounted for by stream gauges measuring the natural (unregulated) flow that are suitable for these analyses.

APPENDIX A SUSPENSION CRITERIA

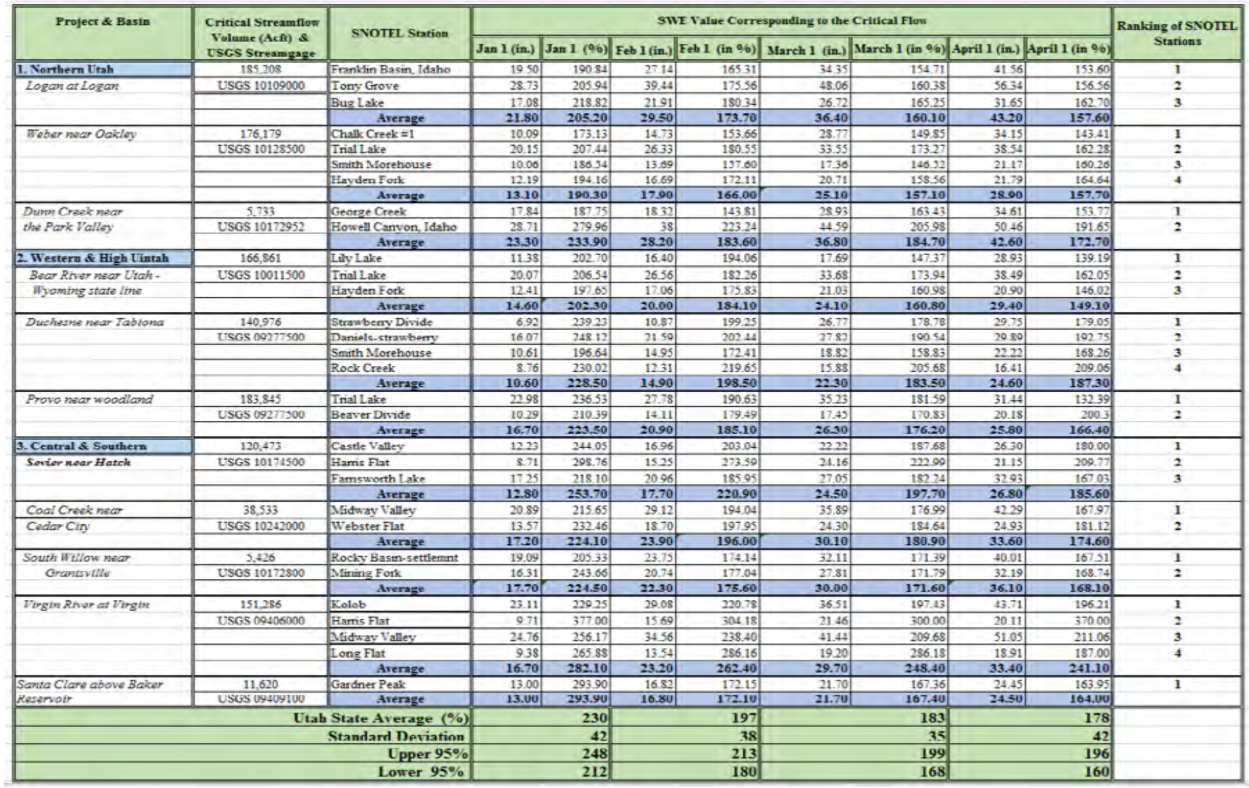
Certain situations require temporary or longer-term suspension of cloud seeding activities, with reference to well-considered criteria for consideration of possible suspensions, to minimize either an actual or apparent contribution of seeding to a potentially hazardous situation. The ability to forecast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

1. Excess Snowpack Accumulation

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



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	157.60	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 the Park Valley	5,733	George Creek	17.84	187.75	18.32	143.81	28.93	163.43	34.61	153.77	1
	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 - Wyoming state line	USGS 10011500	Trial Lake	20.07	206.54	26.56	182.26	33.68	173.94	38.49	162.05	2
		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 Cedar City	38,533	Midway Valley	20.89	215.65	29.12	194.04	35.89	176.99	42.29	167.97	1
	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 Grantsville	5,426	Rocky Basin-settlemnt	19.09	205.33	23.75	174.14	32.11	171.39	40.01	167.51	1
	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 Reservoir	11,620	Gardner Peak	13.00	293.90	16.82	172.15	21.70	167.36	24.45	163.95	1
	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 Western Uintas, four SNOTEL sites (Chalk Creek #1, Trial Lake, Smith and Morehouse, 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.

2. Rain-induced Winter Floods

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

3. Severe Weather

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

- **Winter Storm Warning** - This is issued by the NWS when it expects heavy snow warning criteria to be met, along with strong winds/wind chill or freezing precipitation.
- **Flash Flood Warnings** - This is issued by the NWS when flash flooding is imminent or in progress. In the Intermountain West, these warnings are generally issued relative to, but are not limited to, fall or spring convective systems.

Seeding operations may be suspended whenever the NWS issues a weather warning for or adjacent to any target area. Since the objective of the cloud seeding program is to increase winter snowfall in the mountainous areas of the state, operations will typically not be suspended when Winter Storm Warnings are issued, unless there are special considerations (e.g., a heavy storm that impacts Christmas Eve travel).

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

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

APPENDIX B SEEDING OPERATIONS TABLES

Table B-1
Seeding Hours – Western Uintas, 2023-2024
Storms 1-11 (rounded to quarter hour) Note: These tables exclude hours credited to the High Uintas program during these events

Storm	1	2	3	4	5	6	7	8	9	10	11
Date	**Dec 2-3**	**Dec 7**	**Dec 7-8**	**Dec 23**	**Jan 9-10**	**Jan 10**	**Jan 13-15**	**Jan 17**	**Jan 17-18**	**Jan 21**	**Jan 25**
SITE											
WU-2											
WU-3			17.25	6	13.5	4	22.75				10
WU-4			16	6.5			22.5				8.5
WU-5				5.5	13.5	2.75	20.5		10.25		9.5
WU-6	7		17	7.75	13.5	4	23				10.75
WU-7		6.5	17.25	7.75		2.75	23.25				9
WU-8	23.75	6.5	17.25	7.75		4.25	35.5				7.5
WU-9	23		17.25	7		4.25	35.25	4.5			
WU-10	22.5		9	7.25			34.75			4	
WU-11			7.5		13	3.25					
WU-12	19.25		9	6.5		3.75		5.75	12		
Storm Total	**95.5**	**13**	**127.5**	**62**	**53.5**	**29**	**172**	**10.25**	**22.25**	**4**	**55.25**

Table B-2
Seeding Hours – Western Uintas, 2023-2024
Storms 12-22 (rounded to quarter hour)

Storm	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Date	**Feb 2-3**	**Feb 6-7**	**Feb 9**	**Feb 15**	**Feb 16**	**Feb 18**	**Feb 20-21**	**Feb 26-27**	**Mar 2**	**Mar 7**	**Mar 12-13**
SITE											
WU-2					4					7.25	
WU-3	16.25			2.5	5.25	3		18	4	8.25	2.75
WU-4	12								4	9.75	21
WU-5	14.5				3		12.25	10.5			4.75
WU-6	16	10.5							4.5	7	6.25
WU-7	13	2		5	5.5	3	6		5.25	5.25	5.25
WU-8	16.25	11	6.5		5.5	3	20		5	8.75	5.5
WU-9	17.5	10.75	7	7	4	5	23	18.25	6	6.5	5
WU-10	17.75	24	8.5			5.5	10		6		6
WU-11		4	6.5				6	16.25	4.75		5.25
WU-12		11		6.25		5.5	22		5.75		6.25
Storm Total	**123.25**	**73.25**	**28.5**	**20.75**	**27.25**	**25**	**99.25**	**63**	**45.25**	**52.75**	**68**

Table B-3
Seeding Hours – Western Uintas, 2023-2024
Storms 23-31 (rounded to quarter hour)

Storm	23	24	25	26	27	28	29	30	31	Site Totals
Date	Mar 23	Mar 24	Mar 25	Mar 26	Mar 28	Apr 6	Apr 15-16	Apr 26-27	Apr 29	
SITE										
WU-2		4.75	5.5	10		9.5				41
WU-3				4.5	5.75	9.5	11			164.25
WU-4							19.5			119.75
WU-5	4.25			5.25	2.75	2	11		4.5	136.75
WU-6	4.5	4	5.75	10.5	4.5	10	16.25		5.25	188
WU-7	4		6.25	9.5	5					141.5
WU-8	3.5		6.25	10.5	5.5		16			225.75
WU-9	3.5			9.75			17		4	235.5
WU-10	4				3			20		182.25
WU-11					5.5				4.5	76.5
WU-12	4.5				3.5				5.5	126.5
Storm Total	28.25	8.75	23.75	60	35.5	31	90.75	20	23.75	

APPENDIX C GLOSSARY

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Pressure Heights:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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