Annual Cloud Seeding Report

Northern Utah Program

2021-2022 Winter Season

Prepared For:

Bear River Water Conservancy District

Box Elder County

Cache County

State of Utah, Division of Water Resources

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EXECUTIVE SUMMARY

In past winter seasons beginning in 1989, cloud seeding has been conducted in portions of northern Utah. This includes the northern Wasatch Range of eastern Box Elder and Cache Counties above approximately 6,000 feet MSL, and separate ranges in northwestern Box Elder County above the same elevation. The Northern Utah Seeding Program utilizes over 30 ground-based, manually-operated Cloud Nuclei Generator (CNG) sites, containing a 2% silver iodide solution. The goal of the seeding program is to augment wintertime snowpack/precipitation over the seeded watersheds. Cost sharing for the seeding program is provided by the Utah Division of Water Resources.

Precipitation and snowfall were below normal again during the 2021-2022 winter season. A total of 1,469.75 CNG hours were conducted during 12 storm periods for the core program this season. There were no seeding suspensions during the 2021-2022 season.

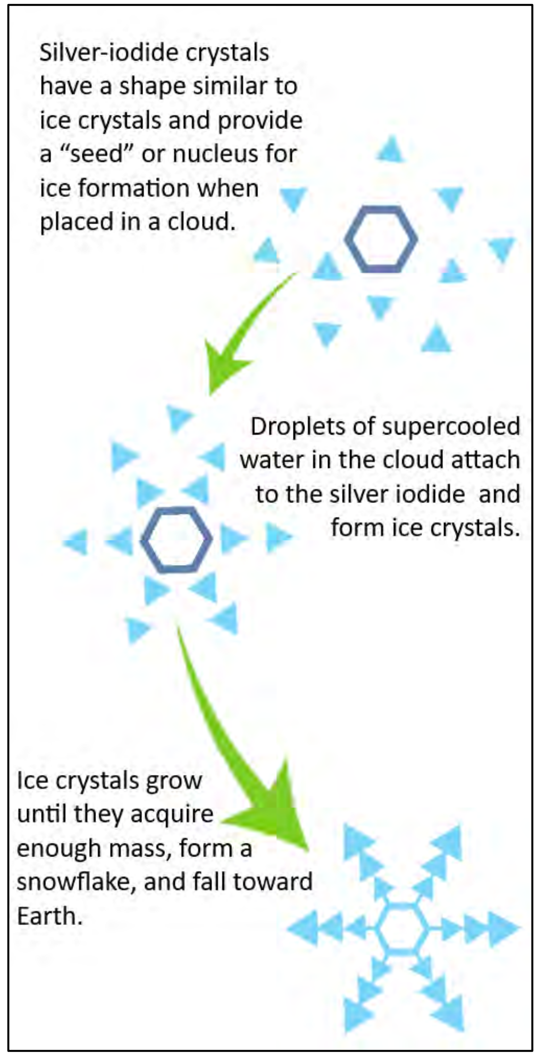
Evaluations of the effectiveness of the cloud seeding program have been made for both the past winter season and for the combination of all seeded seasons. These evaluations utilize SNOTEL records collected by the Natural Resources Conservation Service (NRCS) at selected sites within and surrounding the seeded target areas. Analyses of the effects of seeding on target area precipitation and snow water content have been conducted for this seeding program, utilizing target/control comparison techniques. Evaluation of December – March precipitation data have suggested long-term average seasonal increases averaging 5-6% for the eastern Box Elder and Cache County portions of the program (where long-term precipitation records are available). This is equivalent to roughly an additional inch of precipitation seasonally. Similar regressions with April 1 snow water content data have suggested increases anywhere from 6-13%, implying increases between about 1.4-2.5 inches of water content. While it is not clear which of these results are the most accurate, they fall within the generally observed range of 5-15% increases for winter cloud seeding programs, and thus provide reasonable estimates. A 2012 study estimated a total (average) seasonal increase of approximately 56,000 acre-feet from the seeding program.

THE SCIENCE BEHIND CLOUD SEEDING

The Science

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

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

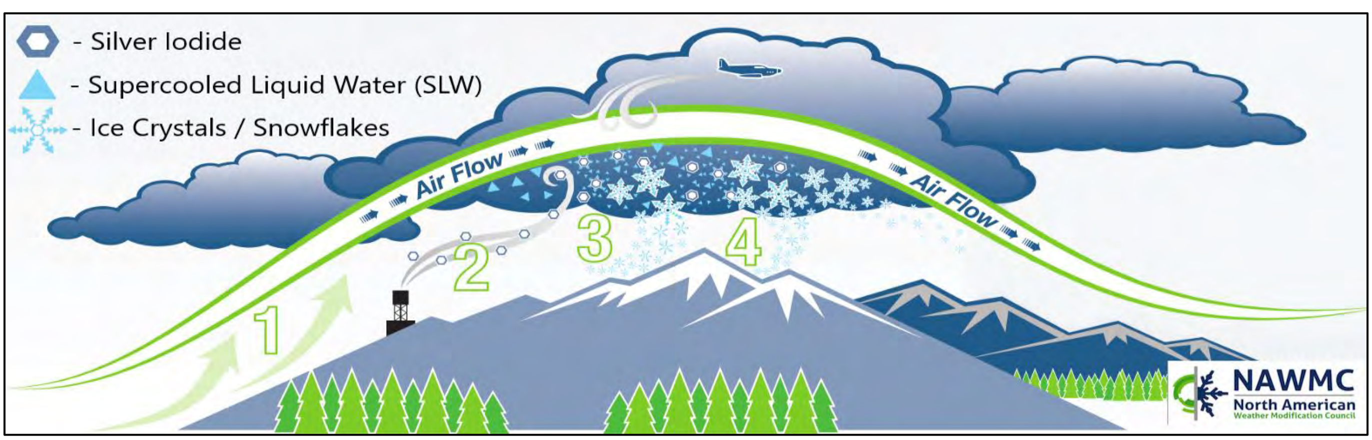


Safety

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

Effectiveness

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



STATE OF THE CLIMATE

Every ten years, the National Oceanic and Atmospheric Association (NOAA) releases a summary of various U.S. weather conditions for the past three decades to determines average values for a variety of conditions, including, temperature and precipitation. These 30-year normal values can help to determine a departure from historic norms and identify current weather trends.

Images in Figure 1 and 2 show how each 30-year average for the past 120 years compares to the composite 20th century average for temperature and precipitation. For the western U.S., the 1990-2020 average show much warmer than average temperatures, 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.

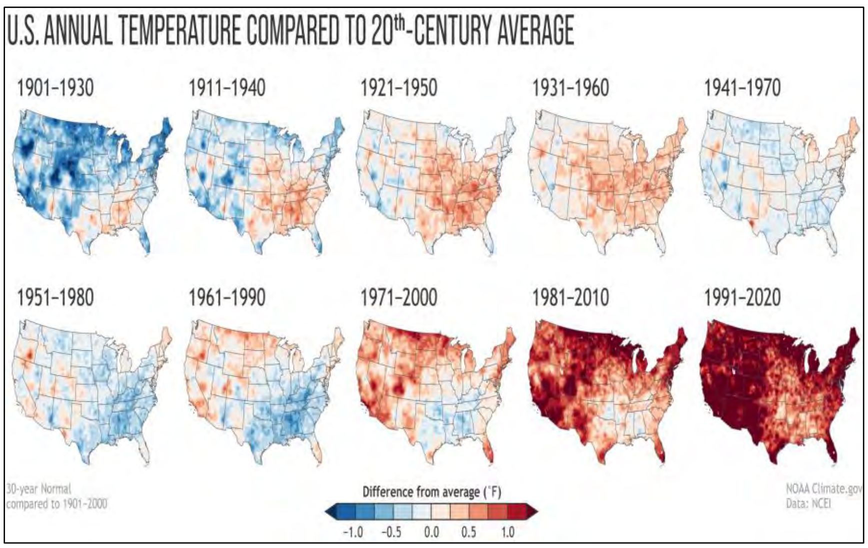


Figure 1 **U.S. Annual Temperature compared to 20th-Century Average**

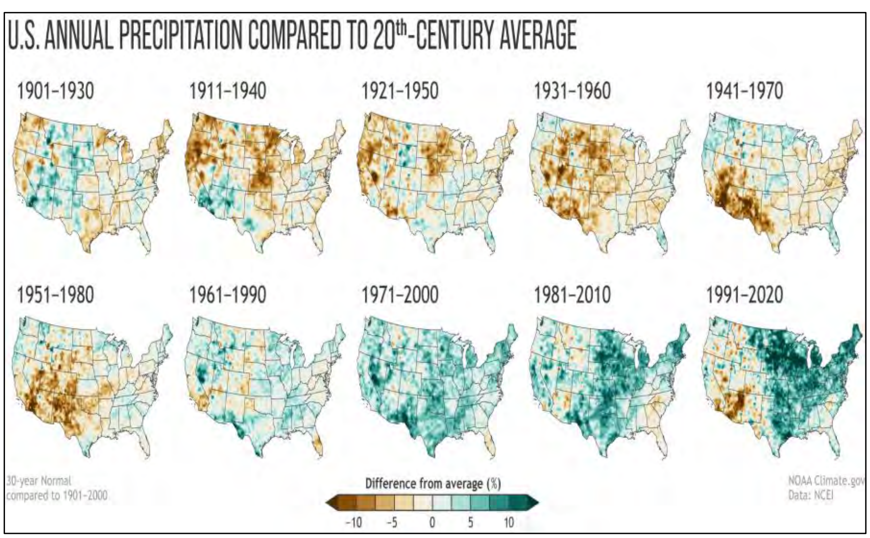


Figure 2 **U.S. Annual Precipitation compared to 20th-Century Average**

1. INTRODUCTION

Cache County and Box Elder County have, for many years, sponsored a winter cloud seeding program over portions of the high-elevation watersheds within each county. The program continued this past winter with the goal of augmenting the natural precipitation in mountainous areas of each county. Statistical analysis of cloud seeding effectiveness in past years has generally indicated an estimated 5-15% increase in winter precipitation and snowpack in the project target areas.

Box Elder and Cache Counties again contracted with North American Weather Consultants, Inc. (NAWC) for the operational cloud seeding services for their mountain watersheds during the 2021-2022 winter season. NAWC has been active in cloud seeding since 1950, with operational programs in Utah since the mid-1970s, and is the longest standing private weather modification company in the world. The State of Utah, through its Division of Water Resources (UDWR) regulates cloud seeding activities within Utah and provides cost sharing funds to project sponsors.

The target area of the program consists of the mountainous portions of Cache and Box Elder Counties above approximately 6,000 feet MSL. These areas represent significant snowpack accumulation zones, which provide substantial spring and summer streamflow. Figure 1.1 shows the average annual precipitation for the State of Utah, delineating these higher-yield areas.

Utah law requires both a license and a project-specific permit be issued to the organization conducting the cloud seeding. The law also requires that a notice of the intent be made available to the public prior to the start of a cloud seeding project. NAWC complied with these requirements in the conduct of the program.

This report covers the operational cloud seeding conducted over the project watersheds during the 2021-2022 winter season. Section 2 contains a brief background on cloud seeding technology and the design of the seeding program. 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 this past season. Section 5 details statistical evaluations of the effects of the cloud seeding program. A summary and recommendations for future seasons are given in Section 6.

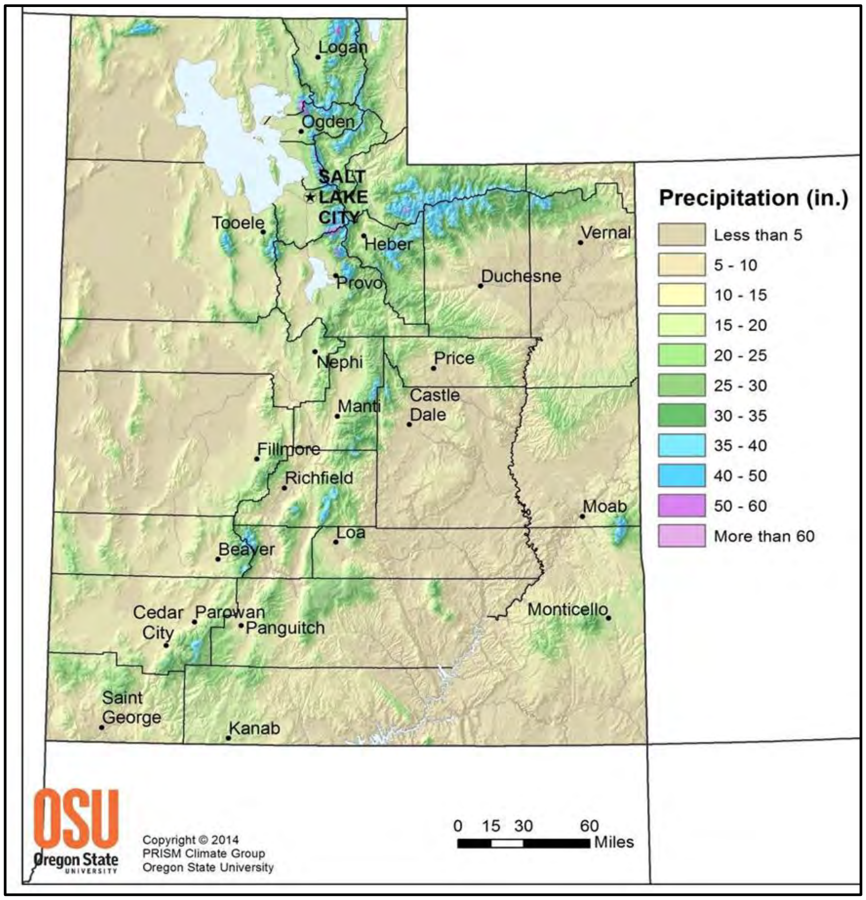


Figure 1.1 **Average annual precipitation for Utah, 1981-2010**

2. PROJECT DESIGN

2.1 Background

The operational procedures used in this cloud seeding project have been found to be effective during many years of wintertime cloud seeding in the mountainous regions of Utah. The results from this particular operational seeding program in northern Utah have consistently indicated increases in wintertime precipitation and snowpack water content during the periods in which cloud seeding was conducted.

2.2 Seeding Criteria

It is necessary that the silver iodide crystals become active upwind of the crest of a mountain barrier (i.e., the crest within the target area or defining its downwind boundary) so that the available supercooled liquid water (SLW) in the precipitation formation zone can be effectively converted to ice crystals, with enough time for the crystals to grow to snowflake size and precipitate within the intended target area. If the AgI crystals take too long to become active, or if the temperature upwind of the crest is too warm, the silver iodide crystals will pass from the generator through the precipitation formation zone and over the mountain crest without freezing additional water cloud droplets. Thus, an important task for the project meteorologists is to identify the seedable portions of the cloud systems which traverse the project area.

Operations have utilized a selective seeding approach, which has proven to be the most efficient and cost-effective method, providing the most beneficial results. Selective seeding means that seeding is conducted only during specific time periods, and in specific locations, where it is likely to be effective. This decision is based on several criteria which determine the seedability of the storms affecting the region. These criteria deal with the nature of the atmosphere (temperature, stability, wind flow, and moisture content) both in and below the clouds, and are summarized in the following list.

Winter Orographic Ground Based Seeding Criteria

- Cloud bases are near or 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).

Use of this focused seeding methodology has yielded consistently favorable results at very attractive benefit/cost ratios.

2.3 Equipment and Project Set-Up

In November 2021, NAWC installed ground-based cloud seeding equipment at locations which are typically upwind (generally on the west sides) of the mountain ranges in Cache County, and in easternmost and northwestern Box Elder County. These mountain ranges generally have crest elevations between 7,000 and 8,000 feet, although some peaks exceed 9,000 feet. The locations of the mountain ranges in northern Utah are shown in Figure 2.1. The intended target area of the cloud seeding program includes the areas that exceed 6,000 feet in elevation. The locations of the cloud nuclei generator (CNG) sites are also shown in Figure 2.1.

The cloud seeding equipment consists of ground-based cloud nuclei generator units, each connected to a propane gas supply. Each unit contains an eight-gallon tank for the seeding solution, an attached flow regulator, a burner head, and a windscreen. The propane gas supply is connected to the CNG by copper tubing. NAWC's CNGs are a field-proven standardized design. NAWC uses a fast-acting seeding solution, in order to provide maximum benefit for the target areas. The seeding solution consists of two percent (by weight) silver iodide (AgI), complexed with very small amounts of sodium iodide and para-dichlorobenzene in solution with acetone. During operation, the propane gas pressurizes the solution in the tank and also provides a heat source to vaporize the seeding solution. After propane flowing through the burner head is manually ignited, a metering valve is opened and adjusted, spraying the seeding solution into the propane gas flame where the silver iodide is vaporized. When the vapor comes into contact with cold air, it crystallizes to form microscopic silver iodide particles. The seeding units are manually operated and, when properly regulated, consume 0.12 gallons of solution per hour. Microscopic silver iodide crystals are emitted from each CNG at a rate of approximately 8 grams per hour via combustion of the 2% solution. These crystals closely resemble natural ice crystals in structure. Their activity as ice forming nuclei is temperature sensitive, occurring at temperatures < -5°C (23°F). The number of ice crystals activated per gram will vary as a function of temperature, with more nuclei becoming active at colder temperatures. The activity of these nuclei is converting supercooled liquid water droplets within the clouds to ice particles, which, given the right conditions, can grow to precipitation sized particles.

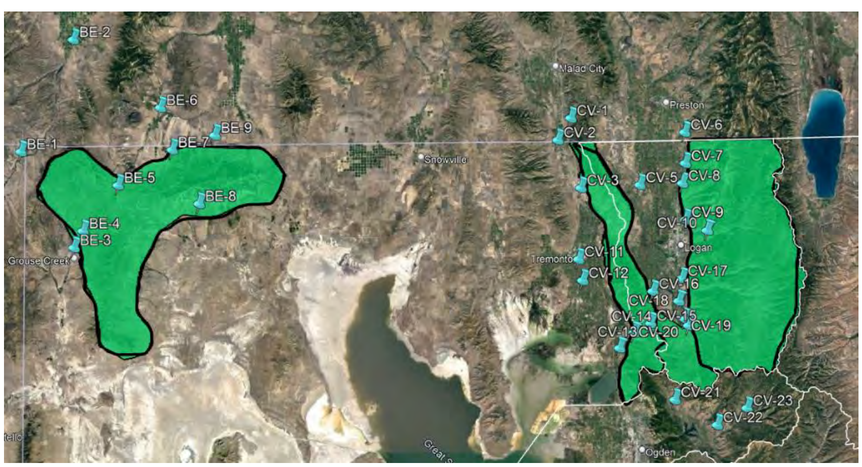


Figure 2.1 CNG sites and seeding target areas for the 2021-2022 Northern Utah Program

There were 31 available sites with cloud nuclei generators, located in Cache County, Box Elder County, and Weber County for seeding the target areas. Threee CNGs were located on the Idaho side of the state line, two for seeding northwestern Box Elder County and one to target the more eastern portions of the program. Figure 2.1 shows the CNG site locations and target area for the project. These are essentially the same site locations that were utilized during the previous seasons. Pertinent site information is listed in Table 2-1.

The process of choosing seeding sites involves studying topographical maps and identifying general areas most suitable, considering the typical wind flows and terrain effects during storm periods. Most sites are restricted to populated areas, since the cloud nuclei generators are manually operated.

Most winter storms that affect the northern Utah mountains are associated with synoptic weather systems which move into Utah from the southwest, west, or northwest. They often consist of a frontal system and/or an upper trough, with south or southwesterly winds ahead of these features. In meteorology, wind directions are reported as the direction the wind is blowing from, in advance of the system. As the front and/or trough moves through the area, the wind flow typically becomes more northwesterly as time passes. Clouds and precipitation may precede, as well as follow, the front/trough passage, and thus seeding sites are situated to enable seeding operations in southwesterly, westerly, or northwesterly flow situations.

Table 2-1
Cloud Seeding Nuclei Generator Sites

ID	Site Name	Elevation (ft)	Lat (N)	Long (W)
BE-1	Trout Creek	5070	41° 57.00'	114° 04.00'
BE-2	Oakley	4570	42° 14.04'	113° 53.55'
BE-3	Grouse Greek	5334	41° 42.54'	113° 52.94'
BE-4	Grouse Creek N	5484	41° 45.08'	113° 51.07'
BE-5	Lynn	5930	41° 52.00'	113° 44.00'
BE-6	Almo	5340	42.10.00’	113.35.20’
BE-7	Yost	5986	41° 57.40'	113° 33.01'
BE-8	Rosette	5640	41° 49.29'	113° 27.49'
BE-9	Standrod	5811	41° 59.61'	113° 24.34'
CV-1	Malad South	4450	42° 02.00’	112° 12.00’
CV-2	Portage	4500	41° 58.71'	112° 14.68'
CV-3	Plymouth	4417	41° 51.45'	112° 10.09'
CV-5	Newton	4662	41° 51.78'	111° 58.12'
CV-6	Cove	4577	41° 59.65'	111° 48.81'
CV-7	Richmond	4600	41° 54.96'	111° 48.84'
CV-8	Smithfield	4694	41° 51.96'	111° 49.50'
CV-9	Logan	4580	41° 46.41’	111° 48.94’
CV-10	Logan Canyon	4971	41° 44.77'	111° 44.72'
CV-11	Tremonton	4295	41° 40.69'	112° 10.75'
CV-12	Bear River City	4265	41° 37.49'	112° 09.96'
CV-13	Perry	4404	41° 27.21'	112° 02.67'
CV-14	Brigham City	4690	41° 29.54'	111° 59.77'
CV-15	Mantua	5200	41° 30.89'	111° 56.34'
CV-16	Wellsville	4884	41° 35.72'	111° 55.80'
CV-17	Hyrum	4816	41° 37.58'	111° 49.92'
CV-18	Paradise	4875	41° 34.19'	111° 50.62'
CV-19	Avon	5059	41° 31.45'	111° 49.39'
CV-20	Avon South	5079	41° 30.47'	111° 48.70'
CV-21	Liberty	5107	41° 19.31'	111° 51.70'
CV-22	Huntsville	5066	41° 15.37'	111° 43.21'
CV-23	Red Rock Ranch	5473	41° 17.86'	111° 37.17'

2.4 Suspension Criteria

NAWC 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 can be found 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. No suspensions were enacted for the Northern Utah seeding program during the 2020-2021 operational season.

3. WEATHER DATA AND MODELS USED IN SEEDING OPERATIONS

NAWC maintains a fully equipped operations center at its Sandy, Utah headquarters. Meteorological information is acquired online from a wide variety of sources, including some subscriber services. This information includes weather forecast model data, surface observations, rawinsonde (weather balloon) upper-air observations, satellite images, radar information and weather cameras. NAWC's meteorologists have access to all meteorological products from their homes, allowing continued monitoring and conduct of seeding operations outside of regular business hours. This wide variety of available products and information helps NAWC meteorologists to determine when conditions are appropriate for cloud seeding.

Figures 3.1 – 3.4 show examples of some of the available weather information that was used in this decision-making process during the 2021-2022 winter season. One relatively new display shown here is the vertically integrated liquid (Figure 3.3). This is beneficial during seeding operations as it depicts the amount of liquid water in the clouds, a variable that is critical for seeding to be effective. Figure 3.5 illustrates the predictions of ground-based seeding plume dispersion using the National Oceanic and Atmospheric Administration's HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model. This model provides forecasts of 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 regional NAM (North American Model) forecast model is shown in Figure 3.6.

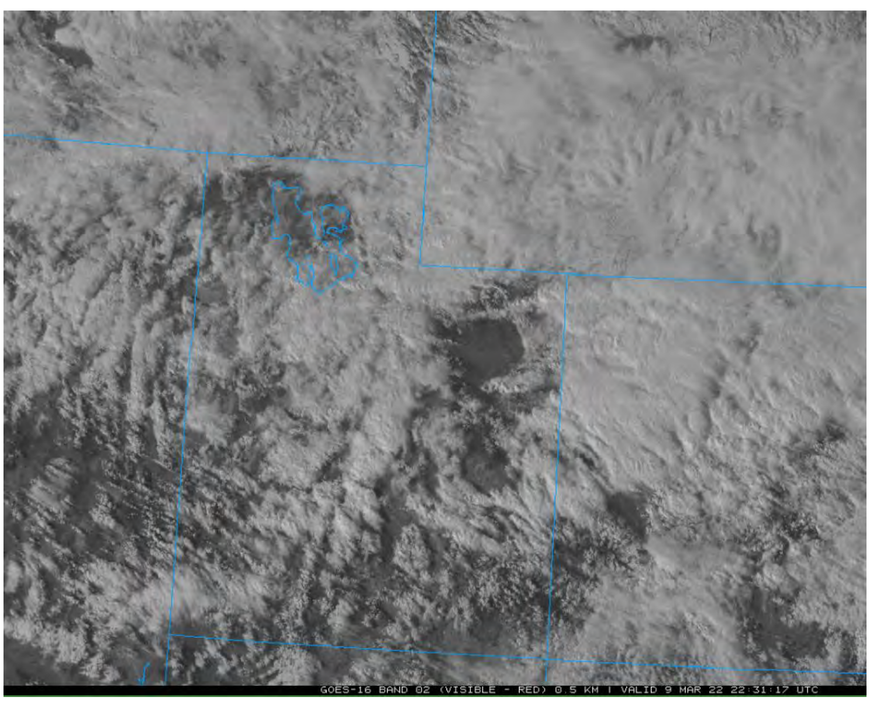


Figure 3.1 Visible spectrum satellite image during a storm event over northern Utah on March 9, 2022

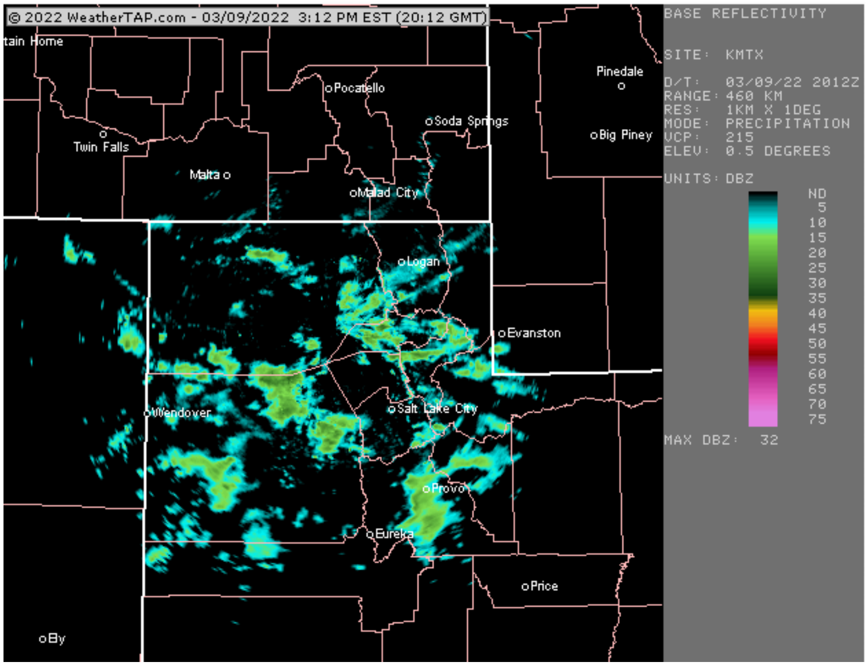


Figure 3.2 **Northern Utah weather radar image on the afternoon of March 9, 2022**

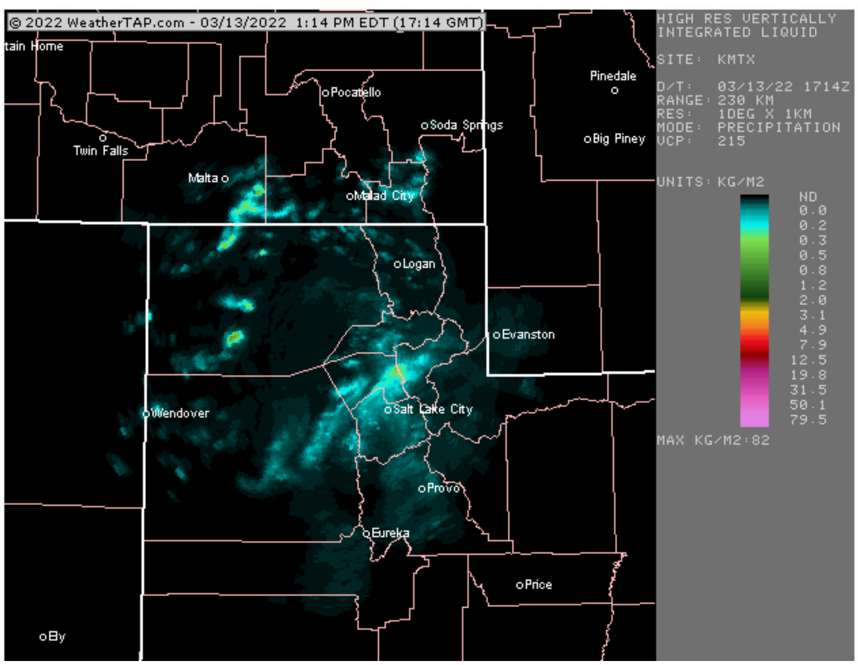


Figure 3.3 **Vertically integrated liquid water from the Salt Lake City radar, around midday on March 13**

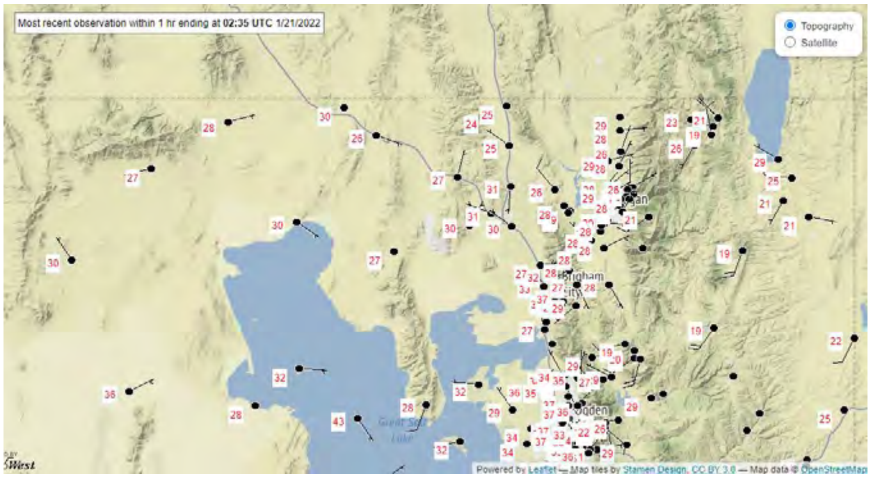


Figure 3.4 **Mesowest surface data map on January 20, 2022. Surface observations are important for diagnosing low-level wind patterns and mixing.**

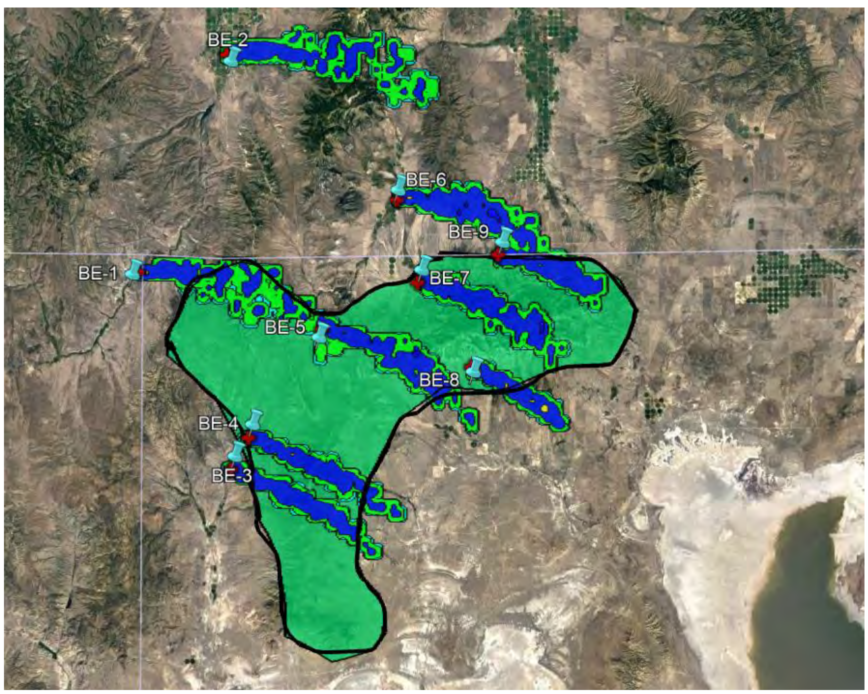


Figure 3.5 **HYSPLIT plume dispersion forecast for a storm event on the morning of March 8, 2022, for all potential seeding locations that can be used to target northwestern Box Elder County (target shaded in green). Only some of these sites were utilized in this event.**

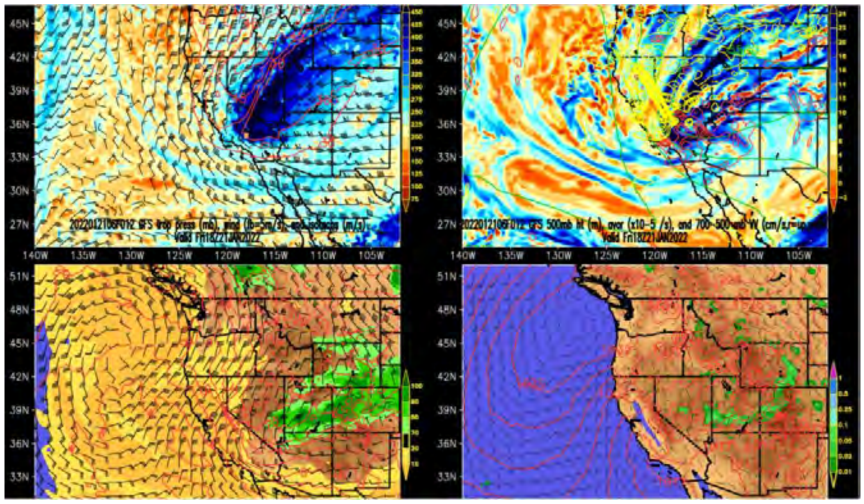


Figure 3.6 GFS (Global Forecast Systems) forecast data plot for a storm event on January 21, 2022.

4. OPERATIONS

The 2021-2022 seeding program in Box Elder and Cache Counties began on December 1, 2021 and was contractually scheduled to end on March 31, 2022. During the 2020-2021 season, there were 12 seeded storm periods conducted on portions of 18 days. Five storm events were seeded in December, three in January, none in February, and four in March. A cumulative 1,469.75 operational hours were conducted from all generator sites during the season. Table 4-1 shows the dates and seeding generator usage for the storm events, and Appendix B shows seeding times for individual generator sites. Figure 4.1 is a graph of seeding operations (CNG usage) this season.

Precipitation was below average in northern Utah during the 2021-2022 winter season. Snowpack in the Bear River Basin on April 1, 2022 averaged 68% of normal (median) with about 92% of the normal (median) water year precipitation to date. The much higher value for water year precipitation was due primarily to a very wet month of October, before seasonal snow accumulation began. Figures 4.2 to 4.4 show snow water content and precipitation this season, compared to various historical measures, at the Tony Grove Lake, Bug Lake, and Monte Cristo SNOTEL sites.

Table 4-1
Storm Dates and Number of Generators Used,
2021-2022 Season

	Date(s)	No. of Generators Used	No. of Hours
1	December 8-9	12	153.5
2	December 14-15	20	217.5
3	December 16-17	5	92.25
4	December 24-25	3	44
5	December 30-31	9	157
6	January 4	10	59
7	January 7-8	7	73.5
8	January 20-21	5	55
9	March 8-9	21	410
10	March 13	14	94.5
11	March 20	6	51.25
12	March 29	8	62.25
Season Total	---	---	1,469.75

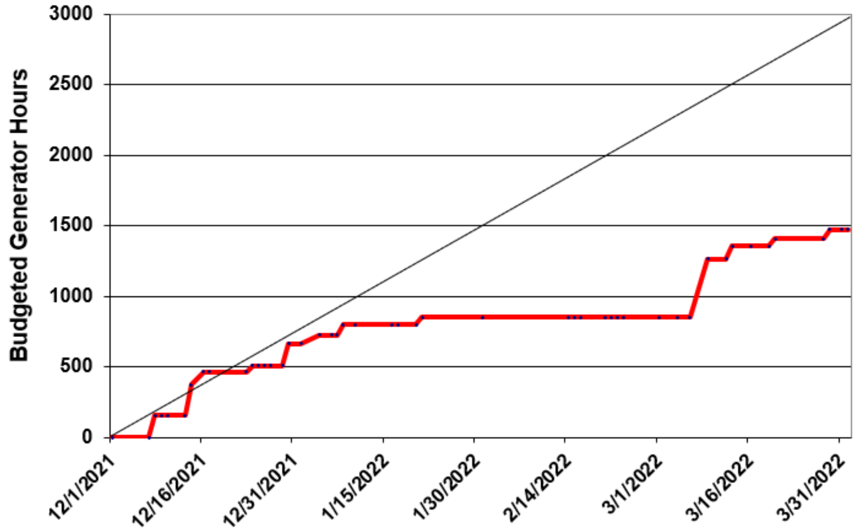


Figure 4.1 Seeding operations during the 2021-2022 season (red), compared with a linear usage of total budgeted hours (diagonal black line).

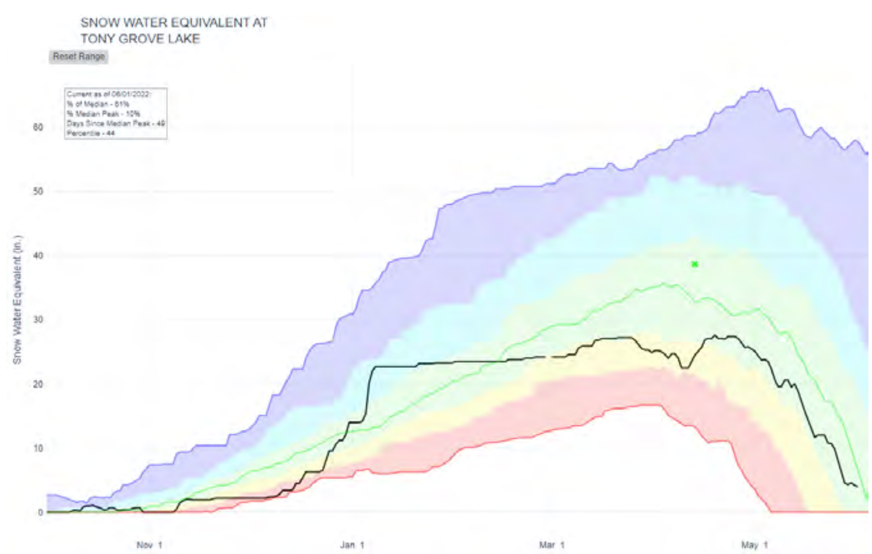


Figure 4.2 SNOTEL snow and precipitation plot for October 2021 through May 2022 for Tony Grove Lake, UT. Black line is the current water year, and green represents the median values. Purple and red lines represent maximum and minimum historical values, respectively.

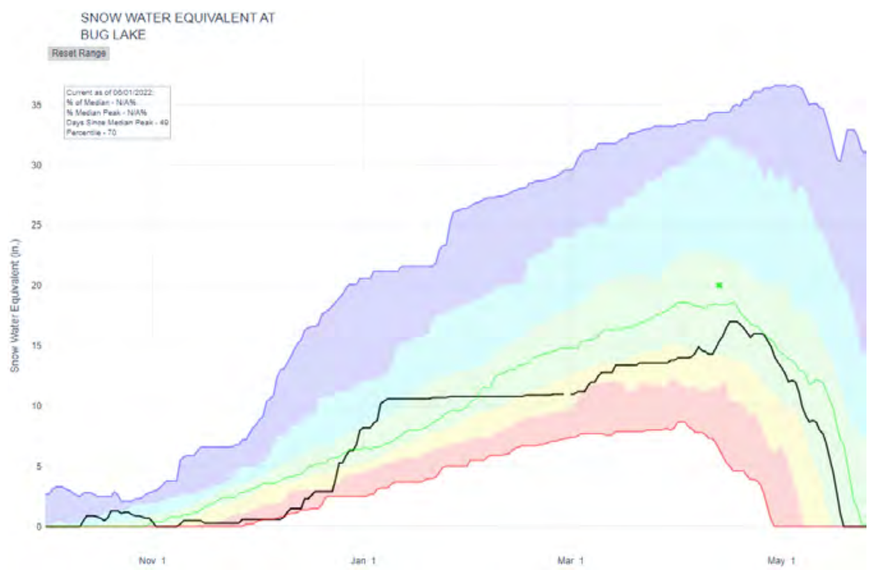


Figure 4.3 **SNOTEL snow and precipitation plot for October 2021 through May 2022 for Bug Lake Lake, UT. Black line is the current water year, and green represents the median values. Purple and red lines represent maximum and minimum historical values, respectively.**

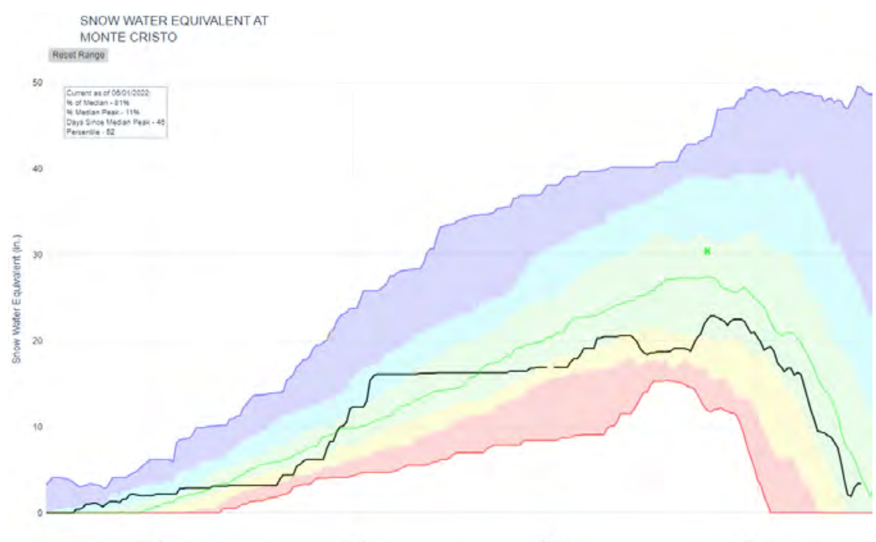


Figure 4.4 **SNOTEL snow and precipitation plot for October 2021 through May 2022 for Monte Cristo, UT. Black line is the current water year, and green represents the median values. Purple and red lines represent maximum and minimum historical values, respectively.**

4.1 Operational Procedures

During the operational period, the project meteorologist monitored each approaching storm with the aid of continually updated online weather information. If the storm parameters met the seedability criteria presented in Section 2 and if no seeding curtailments or suspensions were in effect, an appropriate array of seeding generators were 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.

4.2 Operational Summary

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

December 2021

Although the first week of December was essentially dry, the pattern changed dramatically after that with frequent storm events the remainder of the month. The final week of December was particularly stormy, with a large and deep trough over the Pacific Northwest driving a series of storms across Utah in west-southwesterly flow. Only some of these systems presented seeding opportunities while others were outside of the proper temperature range or lacked significant liquid water. However, there were a total of five seeded events in December.

A cold front moved across southern Idaho and far northern Utah on the evening of December 8. 700 mb temperatures fell to near -6 C overnight with some mostly orographic, showery type precipitation activity over the Cache Valley portion of the target area. The cold front was not reflected well at the surface with winds favoring a SW direction and good mixing, as valley surface temperatures remained in the 40s F this evening. Some orographic type echoes developed with at least a little liquid water evident on radar at 1900 MST in westerly flow, up to about 0.2 – 0.3 g/m^2 observed in a few showers. Seeding was conducted for eastern portions of the target area overnight. Light snowfall continued on the morning of the 9th from mainly a high deck. Very limited liquid was evident with only some broken lower clouds. Ended seeding operations by late morning as snowfall has generally ended and no LW clouds were evident. Most operators reported about an inch of snowfall. The 700 mb temperature fell to around -8 C by late morning with very light flow at that level. Precipitation totals ranged from about 0.2 – 0.7” in the target area with this event.

A strong cold front moved into the area on the evening of December 14, with widespread precipitation and the 700 mb temperature dropping from about -3 to -12 C with its passage. Seeding began in northwest Box Elder County early in the afternoon and eastern areas during the evening hours as the front arrived. Atmospheric mixing was good within the frontal zone, although there was a lot of snowfall being produced in higher cloud layers and a good deal of natural seeding of the storm taking place. Seeding continued in eastern areas overnight, ending early on December 15. Temperatures were quite cold at that point, near -15 C at 700 mb with snowfall having ended. Snowfall totals of 6-12” were widespread even across valley areas with this system, and most SNOTEL sites in the target areas received between 0.7 – 1.5” of water equivalent.

Another system began to produce light snowfall on December 16, although there was warming aloft and cold air in the lower levels initially which was not favorable for seeding operations. Conditions improved a little in the afternoon and evening and seeding was initiated at a few sites, although conditions remained marginal with lower level stability keeping effective seeding options at a minimum. Some orographic type snowfall developed which had potential for seeding impacts where it could be targeted. Good orographic type precipitation continued on the night of December 16-17 with a 700 mb temperature near -12 C and west-northwesterly winds at that level. Orographic streamer type features were evident on radar downwind of mountainous areas, a favorable indication. Seeding conditions continued to improve through midday on December 17 with better mixing at the surface and snow showers ongoing until about mid-afternoon. Snow shower activity and seeding basically ended by late afternoon. Precipitation totals during the period ranged from about 0.4 to as much as 1.4 inches of water.

A deep trough over the Pacific Northwest brought a series of systems across northern Utah beginning around December 23. Clouds were high initially and lacking in liquid water, but by December 24 conditions had become quite good with decent liquid water clouds and even some significant convective activity in southwesterly flow. Clouds were based near 9,000 feet elevation or lower and low-level mixing was good. Seeding began during the daytime hours and continued overnight (Dec 24-25) with significant storm and snowfall activity over the area. The 700 mb temperature was generally around -7 C during this time period. By the morning of December 25, snowfall tapered off and seeding operations ended. Precipitation totals during this storm period ranged from about 0.7 – 1.5" of water equivalent.

More storm activity continued during the December 26-29 period with intermittent snowfall, although temperatures were quite cold during most of this period and the storms lacked liquid water content that would be favorable for seeding. However, a significant storm period near the end of the month brought warmer temperatures (up to near -10 C at 700 mb) and more significant liquid water clouds that were favorable for a period of seeding from late morning on the 30th and continuing through the overnight period. Seeding ended on the morning of December 31 with colder temperatures again and only some icy looking clouds and snow showers on that day. Precipitation totals during this final seeding event of December were generally in the 0.6 – 1.4" range.

Figure 4.5 shows December precipitation across the area as a percentage of normal (median) values. The northern Utah target areas received anywhere from about 110 – 200% of the normal December precipitation.

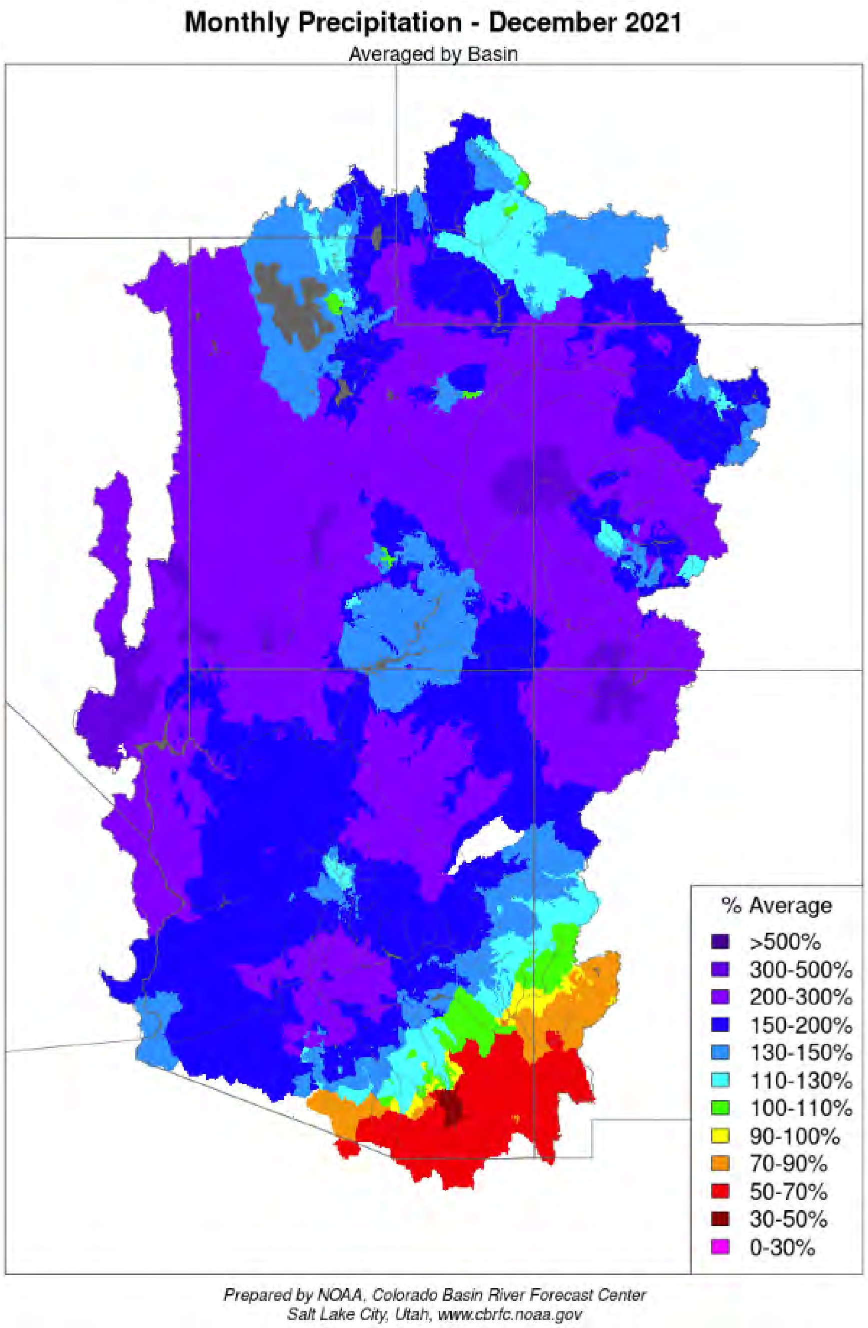


Figure 4.5 December 2021 precipitation, percent of normal

January 2022

January was essentially the inverse of December in terms of precipitation patterns, with a very wet first week of the month in far northern Utah as a series of moist storms affected the area. The remained of the month was quite dry. There were two seeding opportunities during the wet period in early January and one other seeded period later in the month.

A zonal (west to east) jet stream pattern with strong winds provided a limited seeding opportunity on January 4. Some relatively cold and dry air in the lower levels mixed out by late morning, and seeding began with a 700 mb temperature near -8 C and winds westerly at 50 knots or stronger at that level. Moisture continued to increase during the day, although temperatures gradually warmed as well. Seeding began during the late morning of for eastern portions of the target area and continued until after sunset, at which point temperatures had become marginally too warm and a stable layer was evident below the -5 C level. Winds were too strong to effectively target the more limited ranges in northwestern Box Elder County. The warming temperatures, along with some stable layers and very strong winds at and above the -5 C level precluded any further ground-based seeding during the next couple of days, although orographic effects remained strong with fairly abundant moisture aloft, and some portions of the northern Wasatch Range received as much as several inches of water equivalent during this time period.

Later during this storm period, there was additional seeding opportunity beginning on the evening of January 7 with cooling temperature aloft and a decrease in mid-level winds. This also improved mixing in the lower levels and seeding was conducted again for eastern target areas on the night of January 7-8 with snow shower activity over the area, ending early on the 8th as skies began to clear. Precipitation was fairly light compared to earlier periods, with an additional 0.1 – 0.3" observed during the January 7-8 event.

A weak system moved into the area from the northwest on the evening of January 20. Widespread temperature inversions had developed during much of January and lower level stability remained an issue, as well as very limited moisture in this system. The 700 mb temperature did drop to around -10 C in northerly flow by the morning of the 21st which helped to improve low level mixing. Seeding was conducted from several of the more favorable sites, mainly targeting northwestern Box Elder County in this event. Seeding operations began on the evening of the 20th and ended early on the 21st, with precipitation amounts ranging from 0.1 – 0.4" at target area SNOTEL sites.

Figure 4.6 shows January precipitation as a percentage of the median. The vast majority of the northern Utah totals were received during the early January stormy period, but were still well below average for the month as a whole.

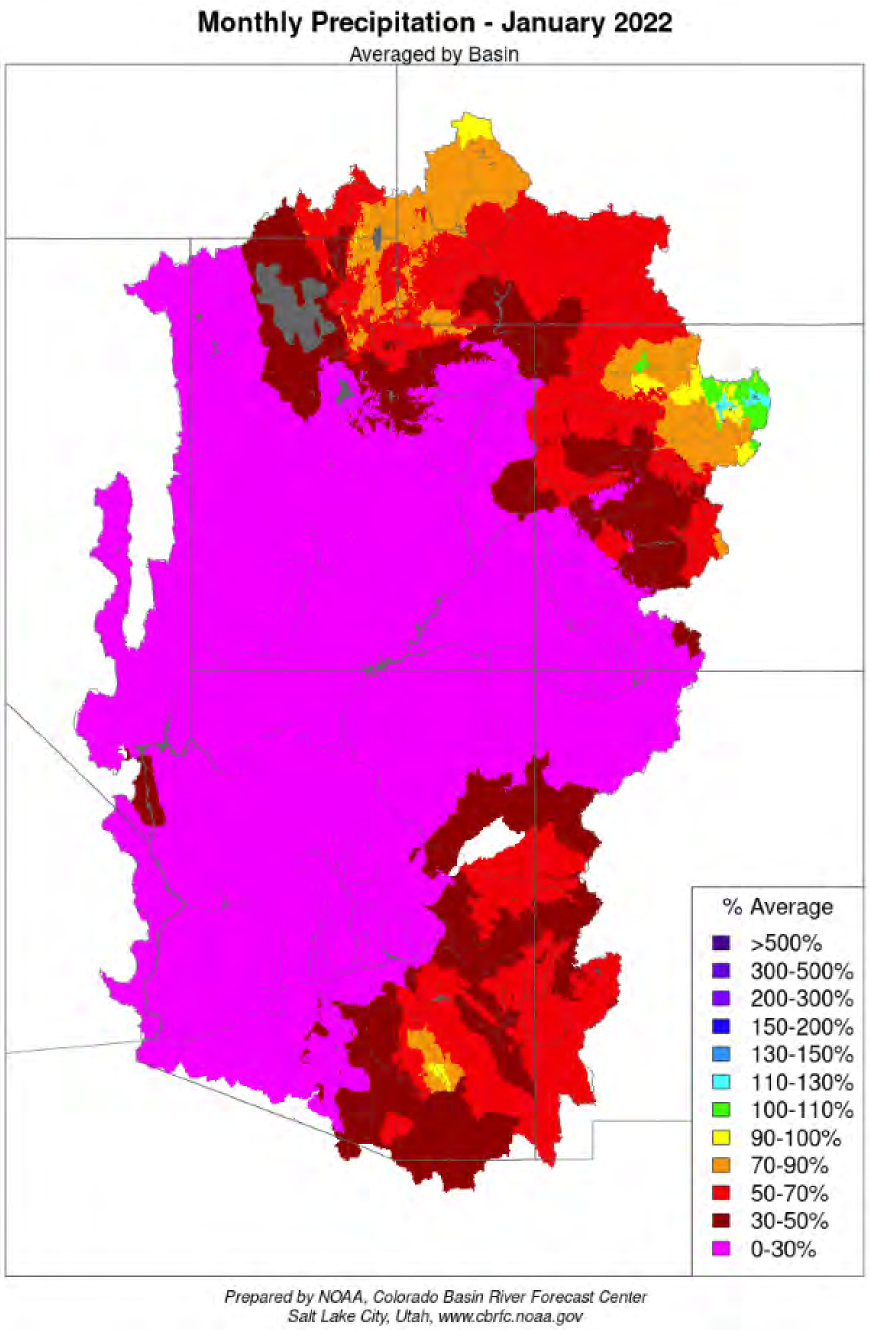


Figure 4.6 January 2022 precipitation, percent of normal

February 2022

February was a very dry month, particularly in far northern Utah with only a few weak systems that produced very limited snowfall amounts. Temperature inversions remained strong and widespread with cold air at the surface in snow-covered areas, and systems that did affect the area lacked any significant liquid water. Due to this persistent pattern, there were no seeding opportunities in February. Figure 4.7 shows February precipitation patterns as a percentage of the median.

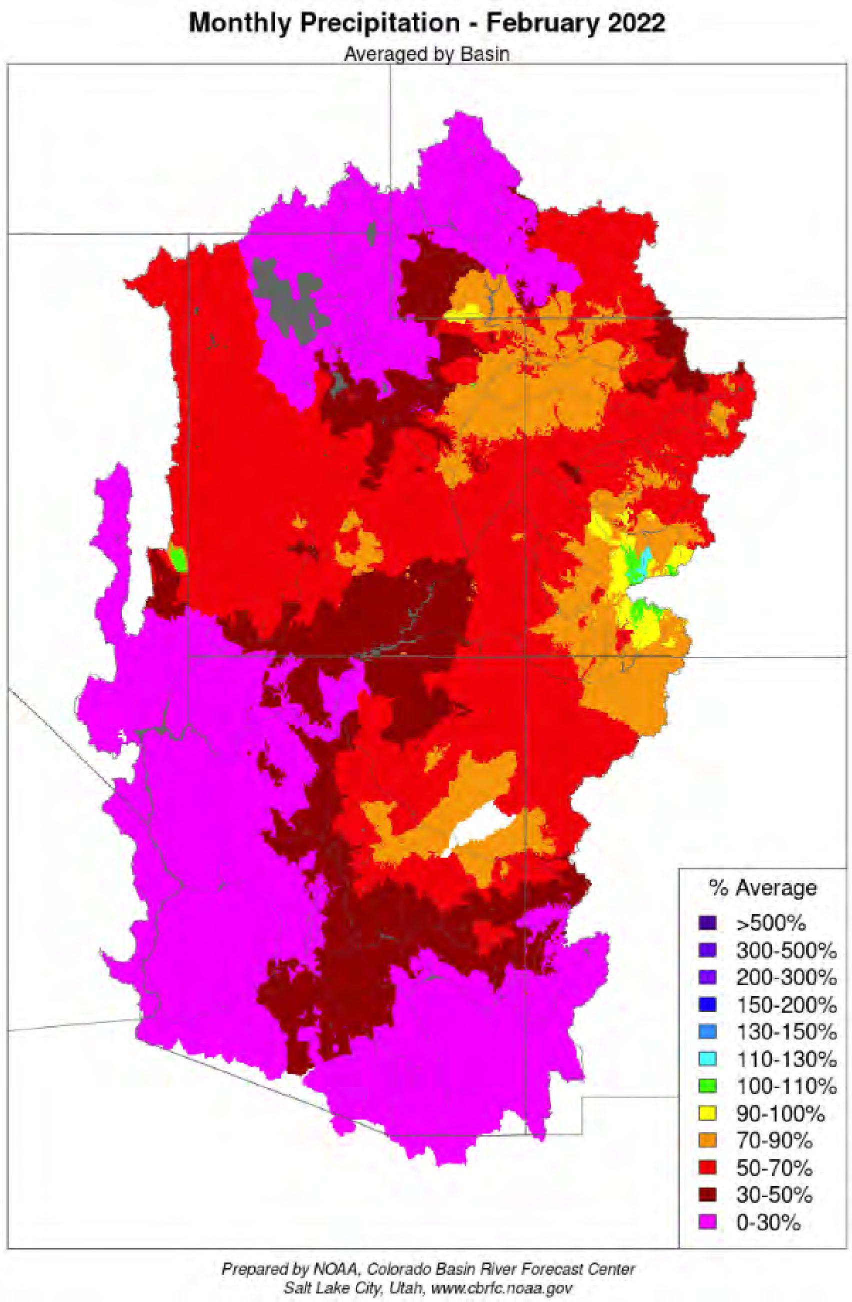


Figure 4.7 February 2022 precipitation, percent of normal

March 2022

March was a somewhat more active month with frontal systems affecting the area on a fairly regular basis, resulting in a total of four seeding opportunities. Despite this, most of the systems that did affect the area were lacking in lower-level moisture and for this reason many were somewhat marginal for seeding. This lack of moisture also resulted in low precipitation totals for March, which were quite variable but generally under about 75% of the monthly median in the northern Utah target areas (and much less than this in many areas).

Despite some storm activity over much of the state during the first week of March, northern Utah was basically left out of this, being only on the margins of some of this at times. Due to a combination of factors, seedable conditions did not develop with some of these initial storm events. However, a moist westerly flow on March 8, combined with favorable temperatures (around -10 C at 700 mb) and good apparent orographic precipitation resulted in a fairly widespread seeding opportunity beginning midday and increasing through the afternoon and evening hours. This continued overnight, with winds becoming northerly by early on March 9. An arctic boundary moved southward through the area on the morning of the 9th, with temperatures becoming quite cold and a lack of any significant liquid clouds north of the boundary. This resulted in an end to seeding operations by mid to late morning. Precipitation totals for this seeded storm period were generally in the 0.4 – 0.8" range across the northern Utah target areas.

A fast-moving cold front on March 13 brought convective showers during the afternoon and evening hours in a west-northwesterly wind pattern, with the 700 mb temperature near -8 to -10 C. Seeding was conducted from both the western and eastern portions of the target areas during the afternoon and evening hours, ending late evening as activity subsided. Precipitation totals ranged from about 0.3 to 0.8" at SNOTEL sites.

A cold frontal passage on March 20 resulted in temperatures falling to around -10 to -12 C in northwesterly flow during the daytime hours. There was a mix of different cloud types observed at various levels, with snow shower activity mainly in eastern portions where seeding was conducted from late morning through the evening hours. Activity generally decreased after sunset and all seeding ended by late evening. Precipitation amounts averaged around a quarter inch at SNOTEL sites.

A large trough was in place over the western U.S. on March 29, along with a good low level moisture field over northern Utah. Although temperatures were relatively mild, around -3 to -4 C at the 700 mb level, daytime heating resulted in the development of fairly deep convective showers and scattered thundershowers across the area in a northwesterly wind pattern. Convective showers developed mainly along the northern Wasatch range where winds were favorable for strong orographic lift as well. Seeding was conducted from midday until the early evening hours to target these convective showers. Precipitation totals in northern Utah target areas were fairly limited, mostly in the 0.1 – 0.3" range, although much greater totals occurred in some nearby areas such as the Uintas and adjacent parts of the Wasatch Range.

Figure 4.8 shows March 2022 precipitation as a percentage of the historical median values.

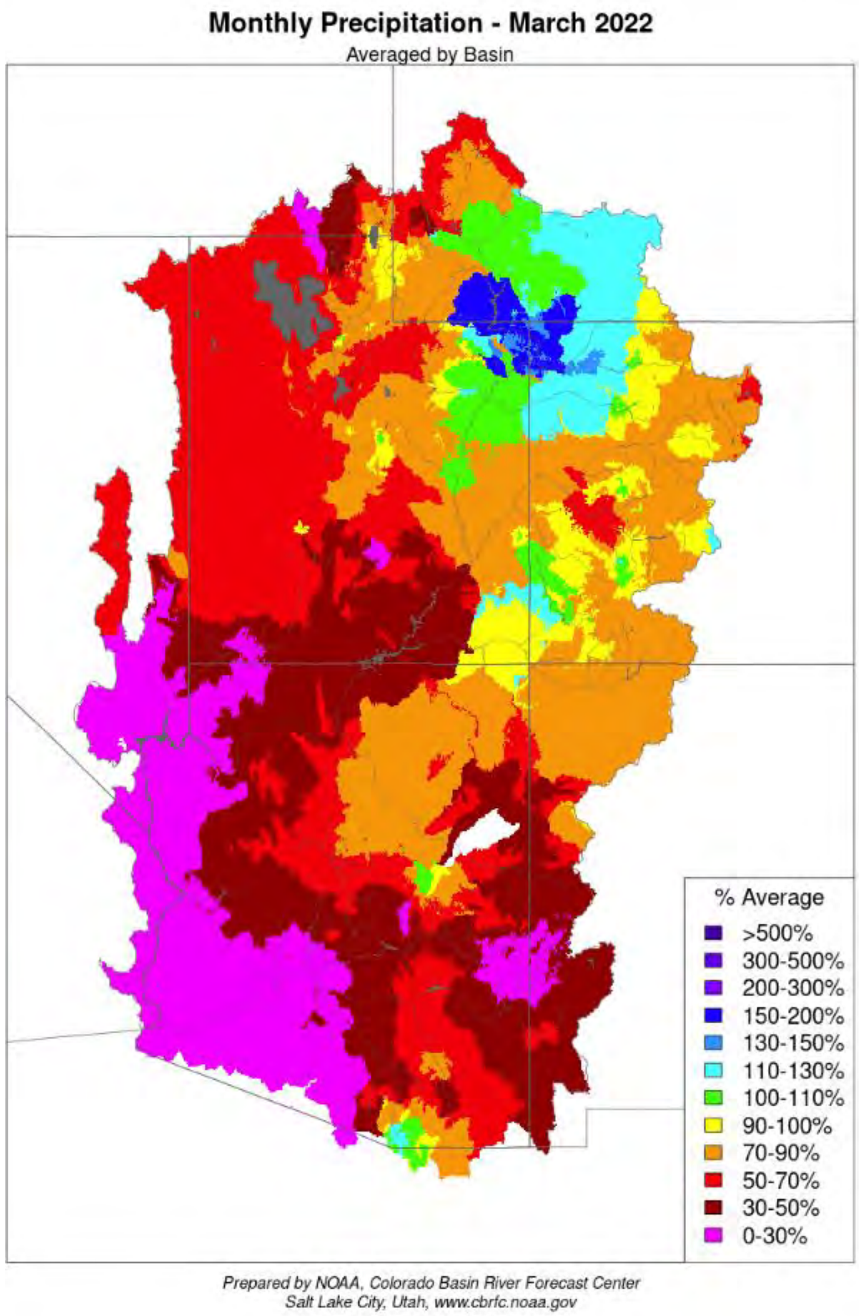


Figure 4.8 March 2022 precipitation, percent of normal

5. ASSESSMENT OF SEEDING EFFECTS

5.1 Background

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, especially when considering single-season results. The primary reason for this difficulty stems from the large natural variability in the amounts of precipitation that occur in a given region. The ability to detect seeding effects is a function of the size of the seeding increase relative to the natural variability in the precipitation pattern. Larger seeding effects can be detected more readily and with a smaller number of seeded cases than are required to detect smaller increases.

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

NAWC has utilized a commonly employed evaluation technique, referred to as a target and control evaluation. This method evaluates the effects of seeding on a variable that would be affected by seeding, such as precipitation or snow. Records of the variable to be evaluated are acquired for an historical (unseeded) period of sufficient duration, 20 years or more if possible. These records are partitioned into those that lie within the designated seeded target area of the project and those in a nearby control area. Ideally the control area consists of sites well-correlated with the target area sites, but which would be unaffected by the seeding. All the historical data, for example, precipitation in both the target and control areas are taken from a period that has not been subject to cloud seeding activities, since past seeding could affect the development of a relationship between the target and control areas. These two sets of data are analyzed mathematically to develop a regression equation which estimates the most likely amount of natural target area precipitation, based on the amount of precipitation observed in the control area. This equation is then used during the seeded period to estimate what the target area precipitation should have been in the absence of cloud seeding. A comparison can then be made between the estimated natural target area precipitation and that which actually occurred.

This target and control technique works well where a good statistical correlation can be found between the target and control area variables. Generally, the closer the control sites are to the seeding target area, the higher the correlation will be. Control sites which are too close to the target area, however, can be subject to the effects of the seeding activities at times. This can result in an underestimate of the seeding effect when using such control sites. For precipitation and snowpack assessments, correlations of 0.90 or better are considered excellent and correlations around 0.85 are good. A correlation of 0.90 indicates that over 80 percent of the variance (random variability) in the historical data set is explained by the regression equation. Correlations less than about 0.80 can still be acceptable, but it would likely take much longer (many more years of comparison for both historical data and seeded periods) to attach any statistical significance to the apparent seeding results.

5.2 General Considerations in the Development of Target/Control Evaluations

With the establishment of the Natural Resources Conservation Service's (NRCS) Snow Telemetry (SNOTEL) automated data acquisition system in the late 1970's, access to precipitation and snow water equivalent data in mountainous locations became routine. Before the automated system was developed, these data had to be acquired by having NRCS personnel visit the site to make measurements, which is still done at some sites. Precipitation and snowpack data used in the analysis were obtained from the NRCS website.

The current season NRCS data are considered provisional and subject to quality control analysis. Figure 5.1 is a photo of a SNOTEL site with the major components labeled.

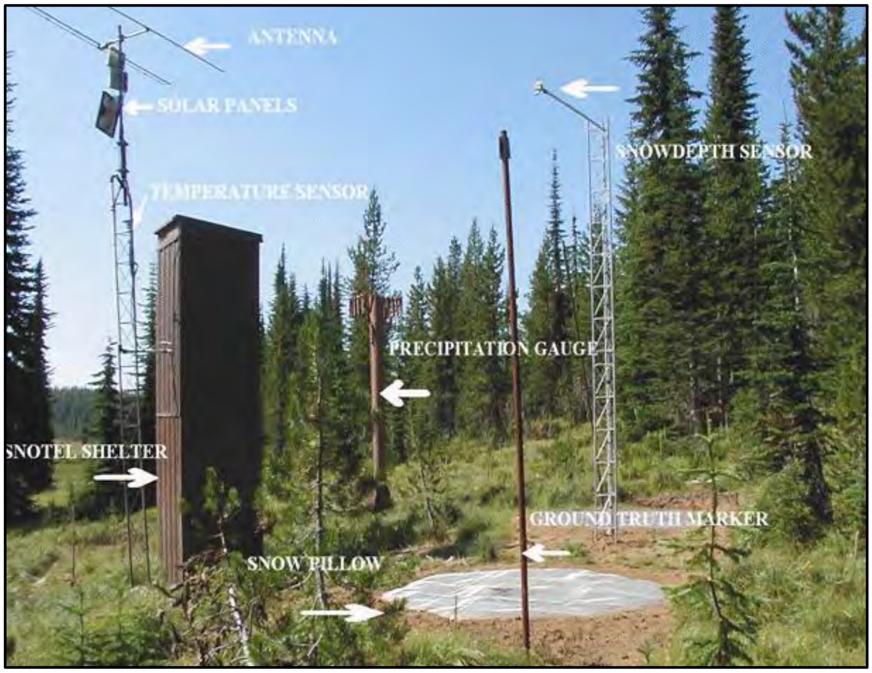


Figure 5.1 SNOTEL site photo

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

Our normal approach in selecting control sites for a new project includes looking for sites that will geographically bracket the intended target area. The reason for this approach is that some winter seasons are dominated by a particular upper airflow (jet stream) pattern while other seasons are dominated by other flow patterns. These different upper airflow patterns and resultant storm tracks often result in heavier precipitation in one area versus the other. For example, a strong El Nino associated weather pattern may favor the production of heavy winter precipitation in some areas, while the opposite phase, La Nina, will tend to favor other areas. Having control sites either side of the target area relative to the generalized flow pattern can improve the estimation of natural target area precipitation under these variable upper airflow pattern situations.

Another consideration in the selection of control sites for the development of an historical target/control relationship is one of data quality. A potential control site may be rejected due to poor data quality, which usually manifests itself in terms of missing data. A site would be excluded if it has significant amounts of missing data. If a significant measurement site move is indicated in the station records, for example more than a mile or a change in elevation of a least a few hundred feet, this may also be a factor. The double-mass plot, an engineering tool, will indicate any systematic changes in relationships between the two stations. If changes shown as inflections in the slope of the line connecting the points are significant, a site(s) may be excluded from further consideration.

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

5.3 Evaluation of Precipitation and Snowpack in the Target Areas

Precipitation data used in these analyses were obtained from the NRCS and/or from the National Climatic Data Center and represent the official published records of those organizations. Similar snow water equivalent records used in the snowpack analysis were also obtained from the NRCS. The current season NRCS data are considered provisional at the time this report is being prepared.

Precipitation Analysis

Precipitation measurements are available from several locations within the mountain watersheds of the Eastern Box Elder and Cache County portions of the target area. In northwestern Box Elder County, precipitation sites with sufficient historical records are not available, so no precipitation analysis has been conducted for that area. However, snowpack analyses from snowcourse and SNOTEL sites in the northwestern Box Elder target are included in the analyses.

Target Area Gauge Sites

The selected target sites extend southward from near the Idaho/Utah border (west of Bear Lake), along the crest of the Wasatch mountains between Cache and Rich Counties, to the southeast corner of Cache County, near Monte Cristo R.S.). The precipitation sites extend westward along the mountains between Weber and Cache Counties to the Ben Lomond Peak area. The latter is in the Weber/Ogden watershed, but is very likely affected by the seeding generators in southeastern Box Elder County and should represent seeding affecting the Little Bear River and Davenport Creek drainages. The seven precipitation gauge sites that constitute the target area are shown in Figure 5.2. These sites range in elevation from 6,000 to 8,960 feet above mean sea level (MSL). The average elevation of the target sites is 7,744 feet above MSL. The names, locations, and elevations of the sites are listed in Table 5-1.

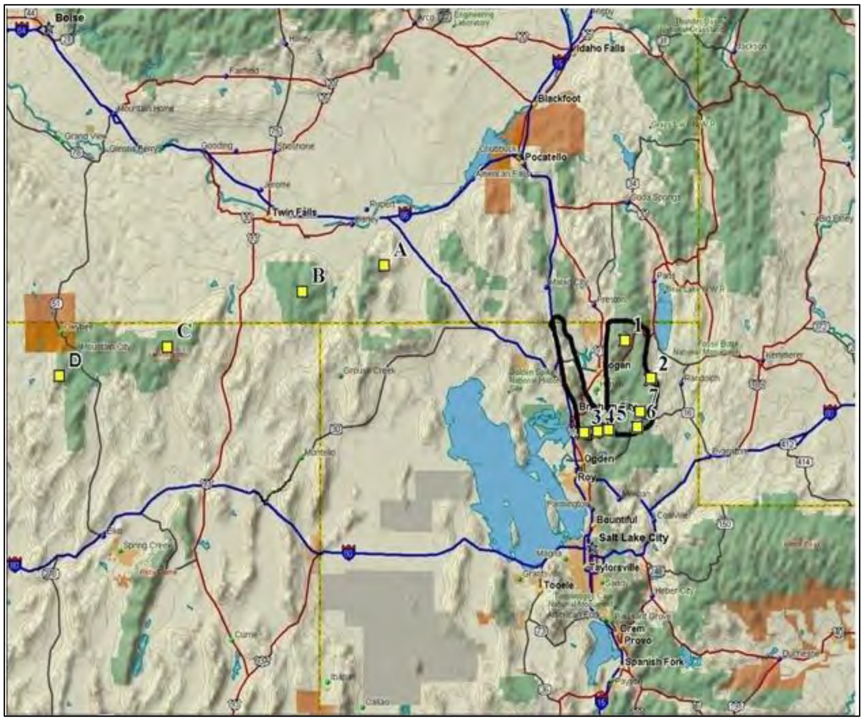


Figure 5.2 **Precipitation gauge sites used in evaluation, eastern Box Elder and Cache Counties, with site data in Table 4-1. The target area is outlined in black. The target sites are numbered; the control sites have letter ID's.**

Table 5-1
Target and Control Precipitation Gauge Locations

ID	Site Name	Site No.	Elev. (Ft)	Lat. (N)	Long. (W)
Control Sites					
A	Howell Canyon, ID	I13G01	7,980	42° 19'	113° 32'
B	Bostetter RS, ID	I14G01	7,500	42° 10'	114° 11'
C	Pole Creek RS, NV	N15H14	8,330	41° 52'	115° 15'
D	Fawn Creek #2, NV	N16H10	7,050	41° 49'	116° 06'
Target Sites					
1	Tony Grove Lake	U11H36	8,400	41° 54'	111° 38'
2	Bug Lake	U11H37	7,950	41° 41'	111° 25'
3	Ben Lomond Peak	U11H08	8,000	41° 22'	111° 57'
4	Ben Lomond Trail	U11H30	6,000	41° 23'	111° 55'
5	Little Bear Upper	U11H25	6,550	41° 24'	111° 49'
6	Dry Bread Pond	U11H55	8,350	41° 25'	111° 32'
7	Monte Cristo	U11H57	8,960	41° 28'	111° 30'

Control Area Gauge Sites

Widespread seeding activity in Utah has compromised, if not eliminated, most of the nearby high-elevation sites along the Wasatch Mountains as possible control sites. To further complicate the matter, the number of established storage gauge/snow course sites has been reduced, with some eliminated as SNOTEL sites were developed to replace them. In addition, the cooperative observer sites, which are managed by the National Weather Service, have also had reductions. All target/control sites used in last year's analyses remain active and were used again this season.

The program in northern Utah has been conducted for the period of December – March for most of its history. For this reason, the December – March period is used in the precipitation target/control analyses. The sites used for these analyses are the same as those used previously. The average elevation for the four control area precipitation gauges is 7,715 feet MSL. They are shown in Figure 5.2, with their locations and elevations provided in Table 5-1.

The database utilized for the mountain target area sites in the evaluations was developed from NRCS SNOTEL and snow course data. Some estimation of monthly precipitation totals was necessary before about 1988, since after this time NRCS began replacing storage gauge sites (which required a manual reading) with automated SNOTEL sites. Since then, reliable monthly readings have been available from all the SNOTEL sites.

Regression Equation Development

Monthly precipitation values were totaled at each gauge in the control and target areas for the December-March period in each of the historical, non-seeded water years of 1970 through 1988 (19 seasons), and averages for each group were obtained. The predictor equation was developed from these data for the December - March period:

$$Y_C = 0.33 + 1.27(X_0) \qquad (1)$$

where Y_C is the calculated average target precipitation (inches) and X_0 is the 4-station Nevada/Utah control average observed precipitation (inches) for the December-March period.

The four-site control has a fairly strong correlation with the target area gauge sites for the 19 historical years (1970-88 water years) with a correlation coefficient of 0.91. This correlation coefficient provided a variance (r^2) of approximately 0.82, indicating that 82 percent of the variance in the historical data set could be explained by the regression equation used to predict the precipitation in the seeded years.

A multiple linear regression analysis is also included among the analyses. This technique has also been used in the evaluation of some of the other cloud seeding programs in Utah and is similar to the linear regression technique, with the same data sets used in both. The multiple linear technique relates each control site individually (or, in some cases, groups of control sites) to the average target area precipitation whereas the simple linear regression technique relates the average of the control sites to the average of the target sites. The multiple linear regression method was considered since it typically provides a higher correlation between the control and target areas. That was the case in Northern Utah where an r value of 0.94 was obtained using the four available control sites. The resulting equation is:

$$Y_C = 1.24 + 0.57(X_1) - 0.21(X_2) + 0.13(X_3) + 0.75(X_4) \quad (2)$$

where Y_C is the calculated average target precipitation (inches), X_1 is Howell Canyon SNOTEL (ID), X_2 is Bostetter R.S. (ID), X_3 is Fawn Creek #2 (NV), and X_4 is Pole Creek (NV).

Linear Regression Evaluation Results

When the observed average control precipitation of 12.00 inches for the December 2021 through March 2022 period was inserted in equation (1), the most probable average target area natural precipitation was calculated to be 15.54 inches using the linear regression technique. The average observed precipitation for the seven gauges in the target group was 13.97 inches.

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

$$SE = R = Y_0 / Y_C \quad (3)$$

where Y_0 is the target area average observed precipitation (inches) and Y_C is the target area average calculated (predicted) precipitation (in inches).

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

$$SE = [(Y_0 - Y_C) / Y_C] * 100 \quad (4)$$

From equation (3), the ratio of the average observed precipitation to the average calculated precipitation in the target area during the December – March period was 0.90, which is less than that predicted using the regression equation. As previously noted, individual year ratios in the target/control analysis are not very meaningful, because they can be greatly affected by variations in weather patterns affecting the target and control sites. It is important to note that the season-to-season variability in the weather primarily affects the mathematical results obtained in the target/control analysis, to a much greater degree than the actual effectiveness of the cloud seeding which theoretically should be somewhat consistent on a percentage effect basis from year to year.

When the data, using the four-site control group, are combined for the 33 seeded December-March periods (1989-2021 water years, excluding water year 2017 due to seeding suspensions and anomalous precipitation patterns as described in the 2017 report), **the indicated average increase in the eastern Box Elder/Cache County target area is 5%. The seasonal (December-March) difference between the observed and calculated precipitation is an area-wide average of over 0.80 inches more than predicted during the seeded periods.** Appendix C shows additional information for all the historical and seeded years in the regression analyses.

There are several types of plots that can be used to illustrate the mathematical difference between the seeded and non-seeded years. Figure 5.3 is a plot of the ranked ratios of observed to calculated precipitation in the Eastern Box Elder/Cache County target area for all the water years (December - March period) used in the evaluation. This consists of a total of 52 water years, with the 19 water years from 1970 through 1988 representing the historical (unseeded) years and the remaining 33 years (1989 – 2022, excluding 2017) being the seeded years. The reader should remember that in developing the regression equation the mean of the ratio of all the historical years is 1.0, and therefore (by definition) approximately one-half of the historical years (denoted by the white bars) will be below 1.0. The ratios are plotted in ranked ascending order from left to right in the figure. It is evident that the highest ratios generally occur in the seeded years (black bars), which dominate the right side of the plot. Figure 5.4 is a scatterplot comparing the seeded and non-seeded seasons, with the regression lines shown for both the seeded and non-seeded years' data. This illustrates the mathematical differences between the seeded and non-seeded data sets, as well as the amount of spread for individual seasons.

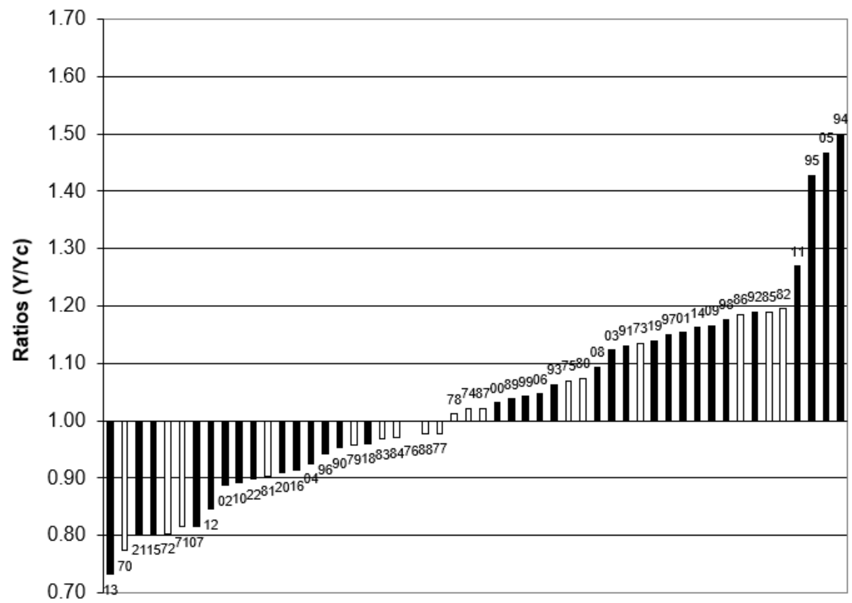


Figure 5.3 **Calculated ratios for 1970-2022 December – March precipitation, using the linear regression technique; White bars represent the historical, unseeded years and black bars the seeded years.**

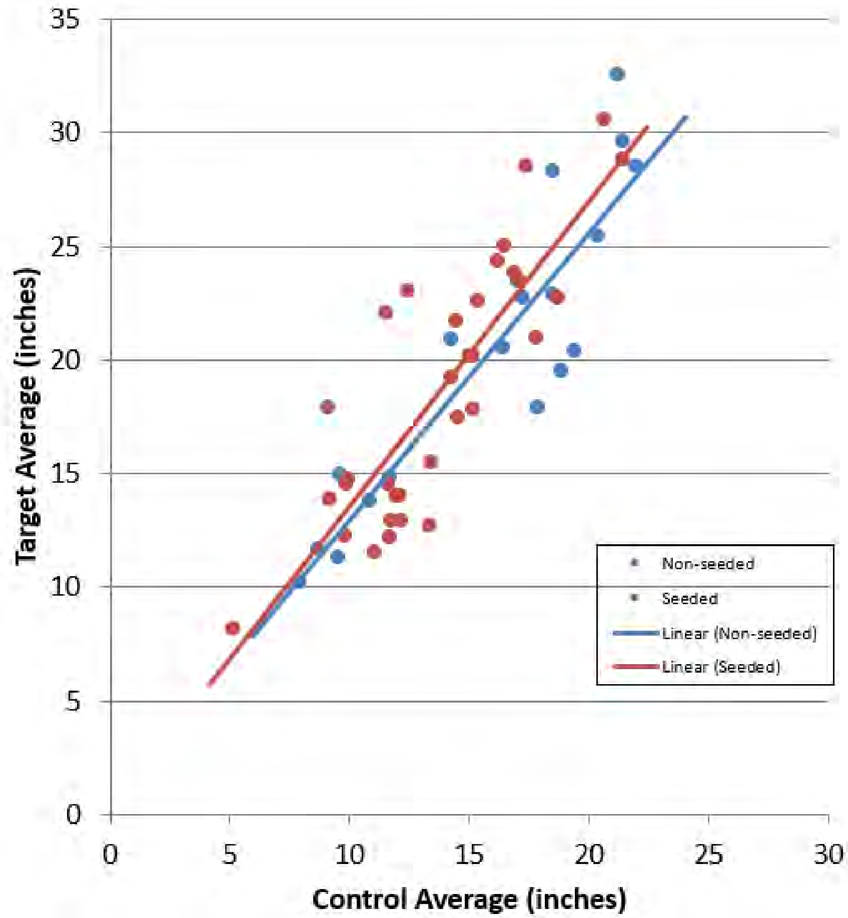


Figure 5.4 Scatterplot with seeded data (red), non-seeded (blue), and regression lines for eastern Box Elder and Cache County precipitation linear regression

Figure 5.5 is a double mass plot, an engineering tool designed to display data in a visual format in which it can readily be seen if there has been a change in the relationship between two measurements or variables. NAWC has applied this technique to the northern Utah cloud seeding program. As noted earlier in this report, the northwestern Box Elder County target area has only a snowpack data regression analysis. Target and control area-average seasonal values for both the historical (not-seeded) and the seeded periods are plotted on the figures. The plotted values are cumulative, meaning that each new season is added to the sum of all of the previous seasons. In each figure, a line has been drawn through the points during the not-seeded base period. The plots show stable linear relationships prior to the beginning of cloud seeding. For comparison with the seeded period, the line describing the not-seeded period is extended at a constant slope through the seeded period.

The double-mass plot (Figure 5.5) shows a distinct change in the relationship between the target and control areas (a sustained change in the slope of the line representing the seeded seasons) that begins at approximately the same time as the start of the cloud seeding program in 1989. **Beginning at/near this time the plots in each case show greater precipitation and more April 1 snowpack water content in the target area compared to the control area. NAWC believes that this is evidence of a consistent, positive seeding effect.** A separate line could be drawn through the data points since about 1989. Such a line would have a rather constant slope, departing from the slope of the line describing the non-seeded base period.

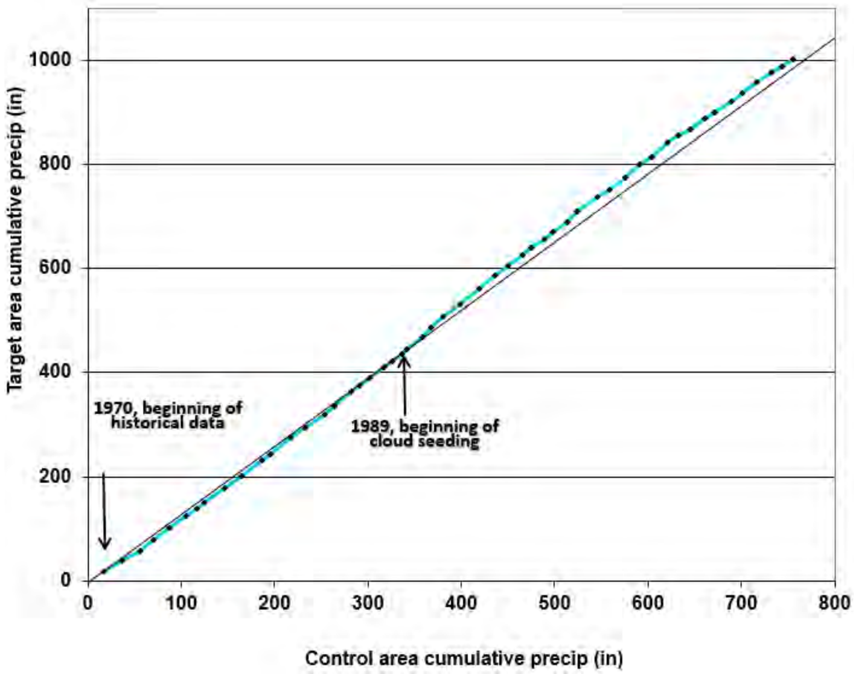


Figure 5.5 **Double mass plot showing cumulative Dec-Mar precipitation for eastern Box Elder and Cache County target and control areas, water years 1970-2022.**

Multiple Linear Regression Evaluation Results

The results of the precipitation multiple linear regression, as a whole, are similar to those for the linear regression. The resulting multiple linear regression ratio for this season is 0.86 with a ratio of 1.06 for the 33 seeded seasons of data, suggesting an average of 1.0 inches of increased water per season (fairly similar to that of the linear regression). Additional details are contained in Appendix B.

Snowpack Analysis

The water content within the snowpack or snow water equivalent (SWE) is important since, after consideration of antecedent soil moisture conditions, it ultimately determines how much water will be available to replenish the water supply when the snowmelt occurs. Hydrologists routinely use snow water content to generate forecasts of streamflow during the spring and early summer months.

As with the precipitation storage gauge and SNOTEL precipitation gauge networks, the State of Utah also has an excellent snow course and SNOTEL snow pillow reporting system. Many of the same stations are available for snow water measurements as those for precipitation measurements. Consequently, snow water measurements were utilized to conduct an additional evaluation of potential seeding effects.

There are some potential pitfalls with SWE data that must be recognized when using snow water content to evaluate seeding effectiveness. One potential problem is that not all winter storms are cold, and sometimes rain falls in the mountains. This can lead to a disparity between precipitation totals, which include all precipitation that falls, and snowpack water content, which measures only the water contained in the snowpack at the time of measurement. Also, warm periods can occur between snowstorms. If a significant warm period occurs, some of the precipitation that fell as snow may melt. Thus, snowpack water content may be reduced, and may not reflect the total snowfall for the season. This can also lead to a disparity between snow water content at higher elevations (where less snow will melt in warm weather) and that at lower elevations.

Another variable that can affect the results of the snowpack evaluation, in the context of manual snow course sites, is the date on which the snowpack measurement was made. Any manual snow course measurements are usually made near the end of a month and, since the vast majority of the snowpack sites are automated SNOTEL sites with daily data, timing is generally not a major issue. 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 can be made as much as several days before or after the end of the month. This variability can complicate the relationship between the sites in the control and target groups.

Most of the snowpack data used in this analysis are from sites that were originally snow course sites, but were converted to SNOTEL sites after approximately 1980 (some much later than others). The data set that was utilized in some prior season evaluations contained both snow course and SNOTEL data for these sites. However, it was recognized that this could present a problem because of potential differences between the snow course and SNOTEL measurement techniques. The NRCS recognized this potential problem, and obtained concurrent data at the newly established SNOTEL sites using both (collocated) measurement techniques for an overlap period of approximately 10 years in duration. The NRCS then developed mathematical relations that converted the previous monthly snow course measurements to estimated values, as if the SNOTEL measurements had been available at these sites. The resulting estimated data at some sites were very similar to the original snow course data while there were differences of 10-15% at a number of the sites. Some sites today continue as manually observed snow course sites. The use of data from these sites continues without any changes to the data type.

Target Area Snowpack Sites

The eastern Box Elder/Cache County target group consists of seven sites. These sites are the same sites used in previous evaluations. The sites are shown in Figure 5.6, and names and locations are listed in Table 5-2. The average elevation of the target area sites is 7,760 feet MSL. A snowpack evaluation was also conducted for northwestern Box Elder County, using two available snow course/SNOTEL sites. Figure 5.6 depicts these site locations as well, and Table 5-2 lists pertinent site data.

Control Area Snowpack Sites

Figure 5.6 shows the locations of the eastern Box Elder/Cache County control area snowpack sites. The site names and locations of the five control sites are listed in Table 5-2. The average elevation of these sites is 7,298 feet MSL. The same control set used for eastern Box Elder and Cache counties is also used to evaluate the northwestern Box Elder County portion of the program.

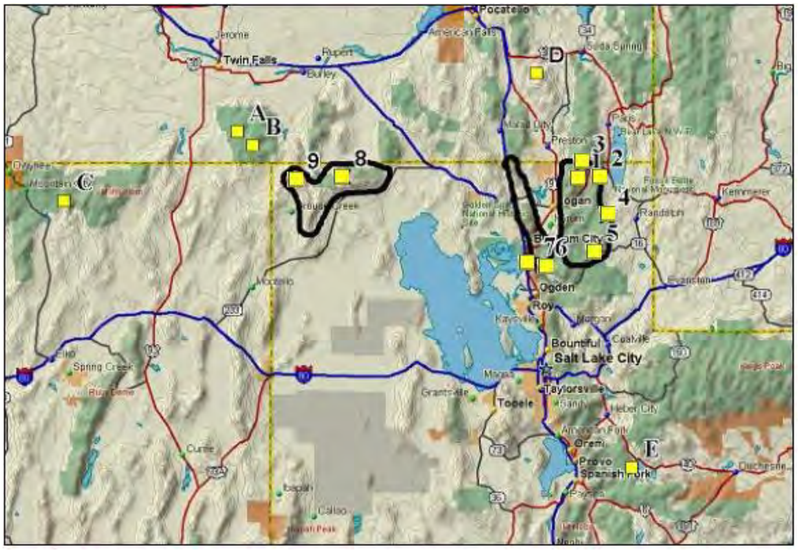


Figure 5.6 **Target and control sites used in eastern Box Elder/Cache County snowpack evaluation, with site data shown in Table 4-2. The target areas are outlined in black. The target sites are numbered; the control sites have letter ID's.**

Table 5-2
Snowpack Control and Target Measurement Sites

ID	Site Name	Site Number	Elevation (Ft)	Latitude	Longitude (W)
Control (for both areas)					
A	Magic Mountain, ID	14G02S	6,880	42° 11'	114° 18'
B	Badger Gulch, ID	14G03S	6,660	42° 06'	114° 11'
C	Big Bend, NV	15H04S	6,700	41° 46'	115° 41'
D	Sedgwick Peak, ID	11G30S	7,850	42° 32'	111° 58'
E	Strawberry Divide, UT	11J08S	8,400	40° 11'	111° 13'
Eastern Box Elder/Cache County Target					
1	Tony Grove Lake, UT	11H36	8,400	41° 54'	111° 38'
2	Garden City Summit, UT	11H07	7,600	41° 55'	111° 28'
3	Klondike Narrows, UT	11H01	7,400	41° 58'	111° 36'
4	Bug Lake, UT	11H37	7,950	41° 41'	111° 25'
5	Monte Cristo, UT	11H57	8,960	41° 28'	111° 30'
6	Ben Lomond Trail, UT	11H30	6,000	41° 23'	111° 55'
7	Ben Lomond Pk., UT	11H08	8,000	41° 23'	111° 57'
Northwestern Box Elder County Target					
8	George Creek, UT	13H05	8,840'	41°54'	113°29'
9	Vipont, UT	13H03	7,670'	41°54'	113°51'

Regression Equation Development

The procedure was essentially the same as was done for the precipitation evaluation, i.e., control and target area stations were selected and average values for each were determined from the historical snowpack data. The same 19-year historical period (1970-88 water years) that was used in the precipitation evaluation was also used for the snowpack evaluation. The snowpack simple linear regression equation developed for Eastern Box Elder/Cache Counties, using historical SNOTEL and estimated SNOTEL April 1st snow water content data, was:

$$Y_C = 1.47 + 1.44(X_O) \quad (5)$$

where Y_C is the calculated average target area snowpack based on X_O (the observed average control area snowpack). The correlation coefficient r was 0.91, with an r^2 value of 0.83.

For northwestern Box Elder County, the equation is:

$$Y_C = 2.15 + 0.95(X_O) \quad (6)$$

The correlation coefficient (r) was 0.91, with an r^2 value of 0.83.

As in the precipitation evaluation, multiple linear regression analyses were also performed on the snowpack data. In some cases, it has been found that averaging groups of control sites for use in the multiple linear regression analysis can yield a mathematically superior prediction of target area precipitation compared to using each control site individually. This is typically the case when there are more than about 4 or 5 control sites, and/or when some of the control sites are in close proximity to each other. The result of such grouping of control sites can be observed mathematically in the form of decreased year-to-year variability in the observed/predicted target area ratios which are obtained. The objective is to minimize the level of background "noise" (e.g., seasonal variations in natural precipitation patterns between control and target areas) to provide as accurate a prediction as possible of the "natural" (non-seeded) precipitation in the target area during each seeded season. The April 1 snowpack multiple regression equation that was developed for Eastern Box Elder/Cache Counties (using each control site individually) is:

$$Y_C = -5.24 + 0.06(X_1) + 0.39(X_2) - 0.56(X_3) + 0.62(X_4) + 0.80(X_5) \quad (7a)$$

where $X_1 \ldots X_5$ are Magic Mountain (ID), Badger Gulch (ID), Big Bend (NV), Sedgewick Peak (ID), and Strawberry Divide (UT), respectively. The r value obtained with this analysis was 0.97, as compared to 0.91 from the linear regression equation.

When two groups of control sites were averaged for use with the multiple regression technique, the number of independent control variables was reduced from five to two. In this case, an average of the three Idaho sites (Magic Mountain, Badger Gulch, and Sedgewick Peak) constitutes a northern group, and the remaining two (Big Bend, NV and Strawberry Divide, UT) a southern group. The resulting equation is

$$Y_C = 1.78 + 0.78(X_1) + 0.67(X_2) \quad (7b)$$

where X_1 is an average of the Idaho sites and X_2 an average of the two Nevada/Utah control sites. The R-value for equation 7b is 0.91, very similar to that for the linear regression equation.

The multiple linear regression equation that was developed for Northwestern Box Elder County (using each control site individually) is:

$$Y_C = 2.09 + 0.36(X_1) + 0.43(X_2) - 0.18(X_3) + 0.13(X_4) + 0.33(X_5) \quad (8a)$$

where X_1....X_5 are Magic Mountain (ID), Badger Gulch (ID), Big Bend (NV), Sedgewick Peak (ID), and Strawberry Divide (UT), respectively. The r value obtained with this analysis was 0.94 as compared to 0.91 from the linear regression equation.

$$Y_C = 2.78 + 0.72(X_1) + 0.25(X_2) \qquad (8b)$$

where X_1 is an average of the Idaho sites and X_2 an average of the two Nevada/Utah control sites. The r value obtained with this analysis was 0.91, again very similar to that of the linear regression equation. However (and this is particularly true of the Box Elder County snowpack evaluation), the multiple regression equations with two groups of control sites (e.g. 7b and 8b) yield less year to year variability of the observed/predicted ratios than do the original forms of the multiple regression (7a and 8a). This implies greater mathematical stability and likely more accurate indications of true seeding effects.

Results of Linear Regression Snowpack Evaluation

The April 1, 2022 snow water content averaged 9.20 inches for the eastern Box Elder/Cache County control sites. When this value was inserted into equation (4), the predicted target area snow water content was 14.83 inches. The measured average target area water content was 14.74 inches, which yields an observed/predicted ratio of 0.99 for the eastern Box Elder/Cache County portion of the target. The average increase for the 33 seeded seasons (excluding 2017 as previously noted) is about 6%. The corresponding average estimated increase in snow water content (which could be attributed to seeding) is approximately 1.4 inches. Figure 5.7 provides a graphical plot of the ratios of observed to calculated snowpack for the eastern Box Elder/Cache County portion of the target. The snowpack normally begins accumulating in October. As a consequence, snow water content measurements on April 1 include snow that fell during some non-seeded periods. This would typically result in a lower indicated percentage increase in April 1 snow water content when compared to December – March precipitation totals. Figure 5.8 is a scatterplot of the seeded and non-seeded seasons' data and corresponding linear regressions for each sample, and Figure 5.9 is a corresponding double mass plot as described previously (Section 4.3.1.4).

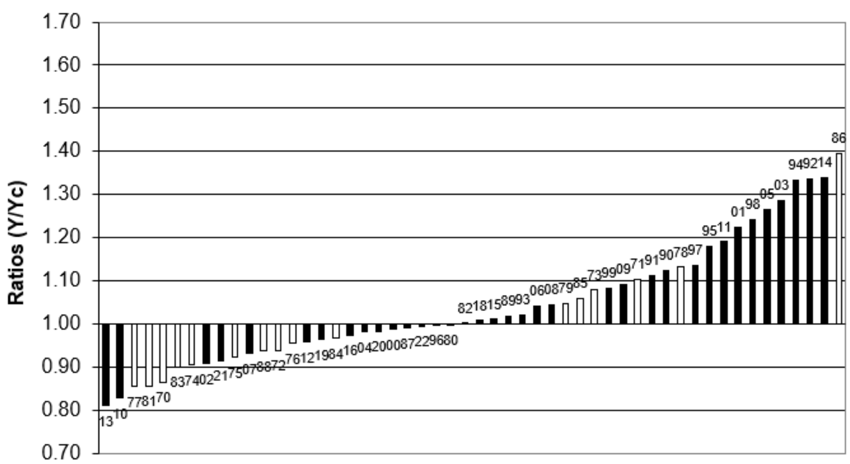


Figure 5.7 Observed/predicted ratios for 1970-2022 April 1st snow water content, using the linear regression technique, <u>Eastern Box Elder/Cache Counties</u>. White bars = historical (unseeded) seasons; black bars = seeded seasons

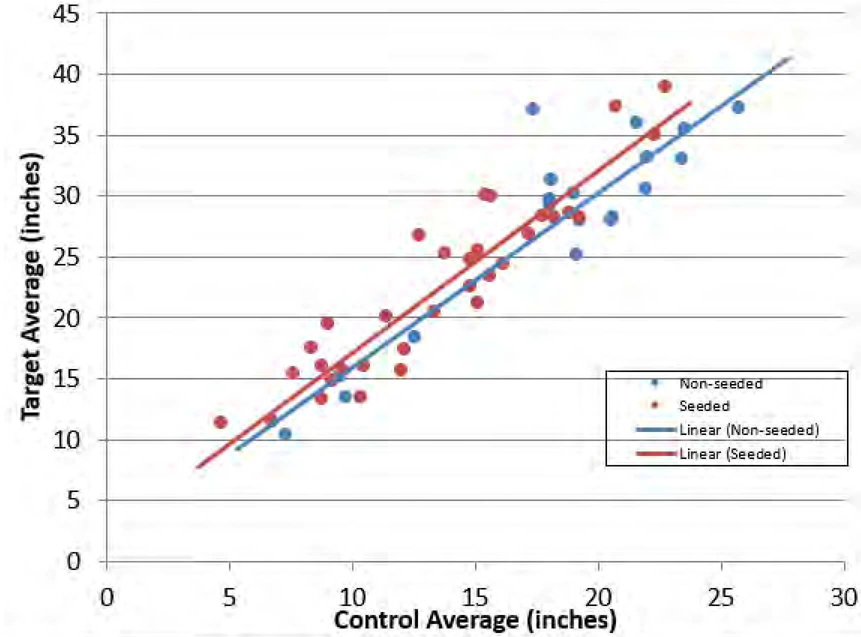


Figure 5.8 **Scatterplot with seeded data (red), non-seeded (blue), and regression lines for eastern Box Elder and Cache County snowpack linear regression.**

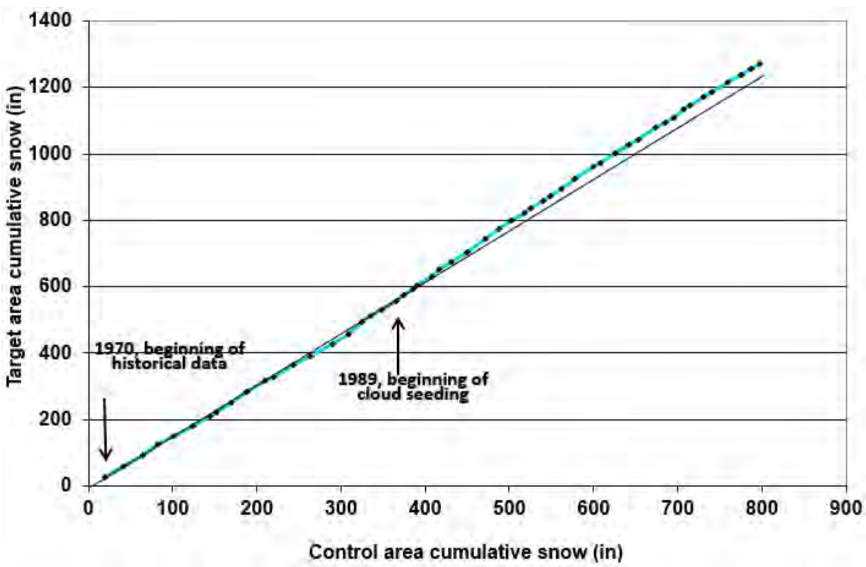


Figure 5.9 **Double mass plot showing cumulative April 1 <u>snow water content</u> amounts for eastern Box Elder and Cache County target and control areas, water years 1970-2022.**

In the northwestern Box Elder County portion of the target, the April 1, 2022 observed water content was 12.71 inches, with a predicted value of 10.87 inches. This yields an observed/predicted ratio of 1.17 for the northwestern Box Elder County portion of the target for this season. The average increase for the 29 seeded seasons (through 2022) is 13%, and the average estimated increase in snow water content is approximately 1.9 inches. Figure 5.10 is a bar chart showing the observed/predicted ratios for seeded and non-seeded seasons. Figure 5.11 is a corresponding scatterplot, and Figure 5.12 a double-mass plot as described previously.

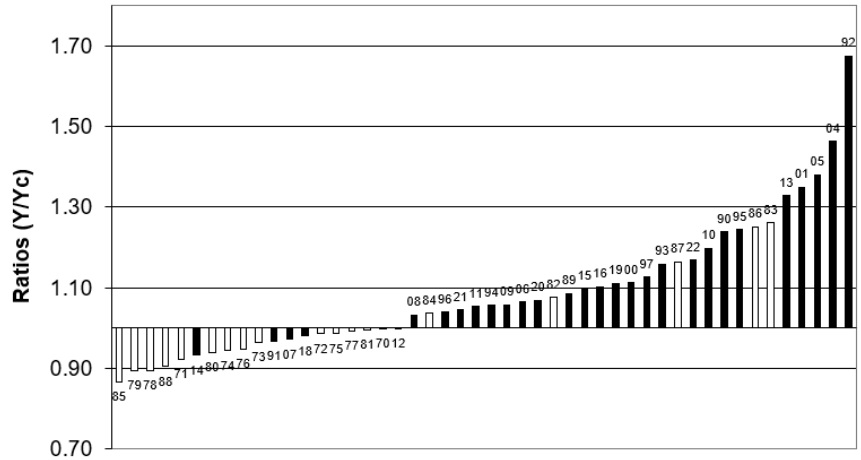


Figure 5.10 Observed/predicted ratios for 1970-2022 April 1st snow water content, using the linear regression technique, Northwest Box Elder County. White bars are historical (unseeded) seasons; black bars = seeded seasons; 1998, 1999, 2002, and 2003, are not shown because of no seeding in those years. 2017 was also excluded.

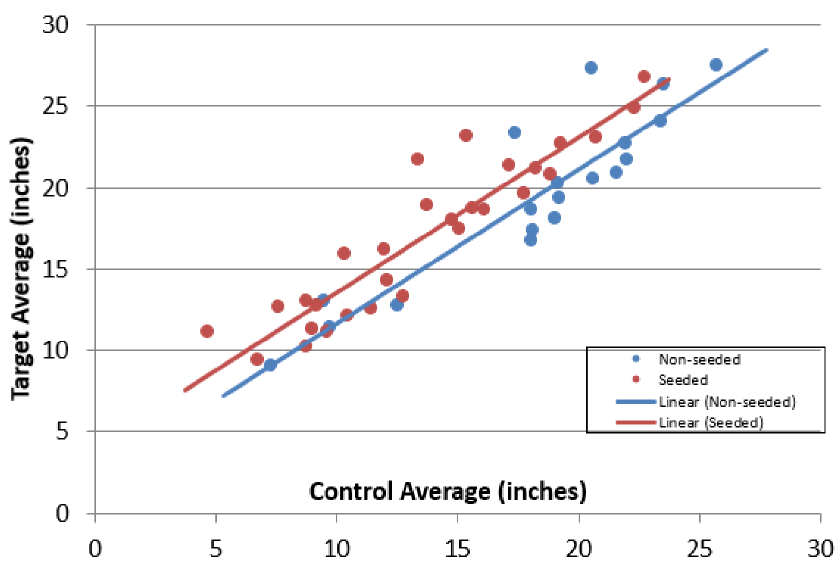


Figure 5.11 Scatterplot with seeded data (red), non-seeded (blue), and regression lines for Northwest Box Elder County snowpack linear regression

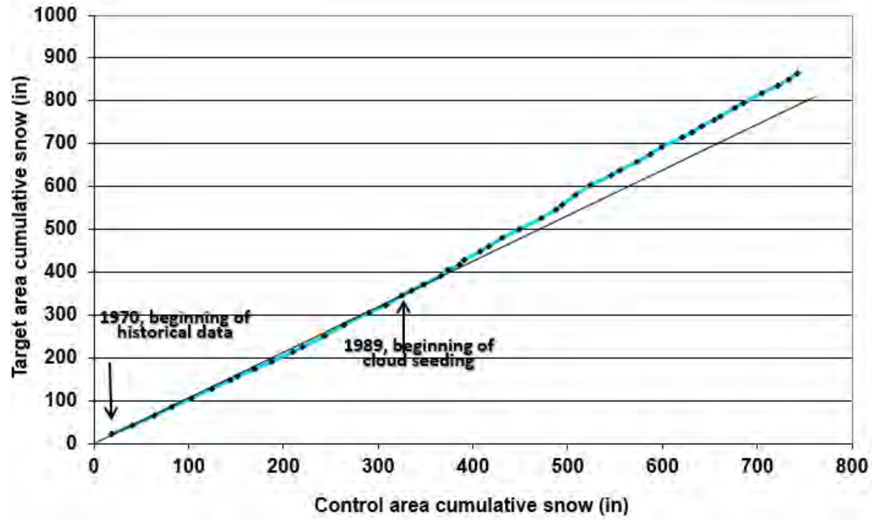


Figure 5.12 Double mass plot showing cumulative April 1 snow water content amounts for Northwest Box Elder County target and control areas for water years 1970-2022 (plot excludes the water years 1998, 1999, 2002, and 2003, when no seeding was conducted, as well as water year 2017).

Results of Multiple Linear Regression Snowpack Evaluation

The multiple regression evaluation resulted in ratios of 1.14 and 1.03 this season for the Eastern Box Elder/Cache County area and the Northwestern Box Elder County area, respectively. The long-term indications of these multiple regression for snowpack (through 2022) include a 13% increase, or about 2.5 inches of additional snow water content, based on the multiple linear regression for the Eastern Box Elder/Cache County area over 33 seasons of seeding. These results are higher than the linear regression equations results for this data set, for largely unknown reasons. For northwestern Box Elder County, the long-term analysis shows a 9% increase (about 1.4 inches of additional snow water) based on the multiple linear equation for 29 seasons of seeding. These and other evaluation results are shown in detail in Appendix B.

5.4 Discussion of Evaluation Results

Results of the single-season target/control precipitation and snowpack evaluations presented in this section vary considerably from year to year. This inherent variability is due largely to differences in weather patterns from season to season. This is why individual year results, while potentially providing some insight, are not particularly accurate in reflecting the true magnitude of seeding effects and thus should be viewed with appropriate caution. **The strength in this type of evaluation lies in the long-term average of these results for many seeded seasons. These long-term averages show that winter season seeding programs such as this can increase seasonal precipitation on average in the range of about 5 to 15 percent over mountainous regions of the western U.S.**

This year's evaluation results for the eastern Box Elder and Cache County portion of the target area (December – March precipitation, and April 1 snowpack), and for Northwestern Box Elder County (April 1 snowpack) were quite variable, as is sometimes the case. Some unusual storm track characteristics were noted again this season. In particular, storms affecting Utah arrived mostly from the north, with moist southwesterly flow situations (which in many seasons contribute to a large portion of mountain snowfall) very lacking this season. This resulted in some abnormal regional patterns of precipitation and snow accumulation that affected the target and control sites in various ways. Table 5-3 summarizes the cumulative results of the various target/control evaluations conducted for this program.

The long-term results for 33 seeded seasons in the Eastern Box Elder/Cache County portion of the target indicate 6-13% increases in April 1 snowpack (an average of 1.4-2.5 inches of additional water) and a 5-6% increase in December through March precipitation (a little under 1.0 inch of additional water). These cumulative results likely constitute reasonable estimates of the true seeding effects for this program, although the reasons for a difference in results between precipitation and snowpack is not really known. The natural seasonal variability which occurs in weather patterns and precipitation between target and control areas is expected to cause much more variation in the results of the single season mathematical target/control evaluation results, than for the actual effects of the seeding from one season to another which should be relatively consistent.

Table 5-3
Comparison of Results of Linear and Multiple Linear Analyses, for the Combination of all Seeded Seasons.

Area	Ratio (Observed/Predicted)		Excess Water (inches)	
	Linear	Multiple Linear	Linear	Multiple Linear
Cache/E. Box Elder Dec-Mar Precipitation (33 years)	1.05	1.06	+0.8	+1.0
Cache/E. Box Elder April 1 Snowpack (33 years)	1.06	1.13	+1.4	+2.5
NW Box Elder April 1 Snowpack (29 years)	1.13	1.09	+1.9	+1.4

Snowpack evaluations for the Northwestern Box Elder County portion of the target area this season produced long-term results indicating average increases for the 29 seeded seasons of +13% (linear) and +9% (multiple linear), which is equivalent to about 1.4 – 1.9 inches of additional snow water content. The evaluation results for Northwest Box Elder County are based on the two available target sites, George Creek and Vipont.

Appendix C contains the complete listing of historical and seeded season data and the regression equation information.

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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	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	29.80	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. 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. There are a number of SNOTEL stations in the various basins of central and southern Utah on which these criteria are based. These include Castle Valley, Harris Flat, and Farnsworth Lake in the Sevier Basin; Midway Valley, Kolob, Harris Flat, Webster Flat, and Long Flat in southwestern Utah; and Rocky Basin Settlement and Mining Fork in eastern Tooele County.

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 which 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.

SEEDING OPERATIONS TABLE

Table B-1
Generator Hours – Northern Utah, 2021-2022, Storms 1-8

Storm	1	2	3	4	5	6	7	8
Dates	Dec 8-9	Dec 14-15	Dec 16-17	Dec 24-25	Dec 30-31	Jan 4	Jan 7-8	Jan 20-21
SITE								
BE-1		6.75						12
BE-2								
BE-3		5			16			12
BE-4		5						
BE-5								12.25
BE-6								
BE-7		5						7.5
BE-8								
BE-9								
CV-1		12.5			13.5	1		
CV-2	15.75	13				6.5	12	
CV-3		13					12	
CV-5	17.5	13				2	12	
CV-6					20		12.25	
CV-7	16.25				19.5	1	12	
CV-8	1							
CV-9	16	14.5	15.5		19.25	5		
CV-10								
CV-11	16.25	13			13.25	9.25	11.25	11.25
CV-12	16.5	14.5	22.5	5.5	13	11.5	2	
CV-13	16.25	14.5	22			5		
CV-14						9		
CV-15		14.5			23			
CV-16	2	14.5						
CV-17	16.5	14.25	23.25					
CV-18		14.25	9	21.5		8.75		
CV-19	4.75							
CV-20	14.75	14.25						
CV-21		5		17				
CV-22		5.5			19.5			
CV-23		5.5						
Storm	**153.5**	**217.5**	**92.25**	**44**	**157**	**59**	**73.5**	**55**

Table B-2
Generator Hours – Northern Utah, 2021-2022, Storms 9-12

Storm	9	10	11	12	Site Totals
Dates	Mar 8-9	Mar 13	Mar 20	Mar 29	
SITE					
BE-1	24.5	6			49.25
BE-2					0
BE-3	24				57
BE-4	24				29
BE-5					12.25
BE-6	17.25				17.25
BE-7		6.5			19
BE-8					0
BE-9					0
CV-1	14.75	6.75	7.25		55.75
CV-2	13.75	6.75	6		73.75
CV-3			7.25		32.25
CV-5	21.75	8.25	9.5	7.75	91.75
CV-6	14.75	9	10.75	8.25	75
CV-7	21.5	6.5	10.5	8.25	95.5
CV-8	15				16
CV-9	22			7	99.25
CV-10	22				22
CV-11	22	4			100.25
CV-12	21.75	6.5			113.75
CV-13	21	6			84.75
CV-14	13.5				22.5
CV-15	25	7.75		7.75	78
CV-16	20				36.5
CV-17	22.5	7.5		8.25	92.25
CV-18	22	6.5		8	90
CV-19				7	11.75
CV-20	7	6.5			42.5
CV-21					22
CV-22					25
CV-23					
Storm	410	94.5	51.25	62.25	

APPENDIX C SEEDING EVALUATION TABLES

Eastern Box Elder and Cache County Dec-Mar Precipitation – Linear Regression

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
Regression (non-seeded) period:					
1970	17.93	17.85	23.05	0.77	-5.21
1971	19.45	20.37	24.99	0.82	-4.62
1972	18.88	19.50	24.26	0.80	-4.76
1973	14.28	20.90	18.43	1.13	2.47
1974	17.25	22.69	22.20	1.02	0.49
1975	17.05	23.46	21.94	1.07	1.52
1976	11.73	14.79	15.19	0.97	-0.40
1977	7.93	10.15	10.38	0.98	-0.23
1978	21.98	28.52	28.19	1.01	0.33
1979	18.55	22.85	23.85	0.96	-1.00
1980	21.45	29.57	27.52	1.07	2.05
1981	9.55	11.24	12.44	0.90	-1.19
1982	21.23	32.54	27.24	1.19	5.31
1983	16.45	20.51	21.18	0.97	-0.67
1984	20.43	25.44	26.22	0.97	-0.78
1985	9.63	14.91	12.53	1.19	2.38
1986	18.55	28.24	23.85	1.18	4.40
1987	8.73	11.64	11.39	1.02	0.25
1988	10.88	13.79	14.12	0.98	-0.33
Mean	15.89	20.47	20.47	1.00	0.00
Seeded period:					
YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1989	15.03	20.11	19.38	1.04	0.74
1990	9.85	12.21	12.82	0.95	-0.60
1991	10.00	14.71	13.01	1.13	1.71
1992	5.15	8.16	6.86	1.19	1.30
1993	17.13	23.44	22.04	1.06	1.40
1994	9.15	17.89	11.93	1.50	5.96
1995	12.45	23.00	16.11	1.43	6.89
1996	18.73	22.67	24.07	0.94	-1.40
1997	20.68	30.53	26.54	1.15	3.99
1998	16.48	24.97	21.22	1.18	3.76

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1999	14.28	19.20	18.43	1.04	0.77
2000	15.15	20.14	19.54	1.03	0.61
2001	9.23	13.87	12.03	1.15	1.85
2002	13.45	15.43	17.38	0.89	-1.95
2003	9.93	14.50	12.91	1.12	1.59
2004	14.58	17.40	18.81	0.93	-1.41
2005	11.60	22.06	15.04	1.47	7.02
2006	21.43	28.77	27.49	1.05	1.28
2007	12.23	12.91	15.83	0.82	-2.91
2008	16.93	23.81	21.79	1.09	2.03
2009	16.20	24.33	20.87	1.17	3.46
2010	12.13	14.00	15.70	0.89	-1.70
2011	17.43	28.46	22.42	1.27	6.04
2012	11.78	12.91	15.26	0.85	-2.34
2013	13.35	12.64	17.25	0.73	-4.61
2014	14.48	21.71	18.68	1.16	3.03
2015	11.08	11.53	14.37	0.80	-2.84
2016	17.80	20.93	22.90	0.91	-1.97
2017*	21.30	38.04	27.33	1.39	10.71
2018	11.63	14.47	15.07	0.96	-0.60
2019	15.38	22.57	19.82	1.14	2.75
2020	15.20	17.77	19.60	0.91	-1.83
2021	11.73	12.19	15.19	0.80	-3.01
2022	12.00	13.97	15.54	0.90	-1.57
Seeded Mean	13.74	18.58	17.75	**1.05**	**0.83**
* 2017 not included in mean					
SUMMARY OUTPUT					
Regression Statistics					
Multiple R	0.905497				
R Square	0.819925				
Adjusted R Square	0.809333				
Standard Error	2.880614				
Observations	19				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
Intercept	0.330681	2.382764	0.13878	0.891255	
X Variable 1	1.267686	0.144088	8.798025	9.77E-08	

Eastern Box Elder and Cache County Dec-Mar Precipitation – Multiple Linear Regression

YEAR	Howell Canyon Tel	Bostetter R.S. Tel	Fawn Creek #2 Tel	Pole Creek Tel	YOBS	YCALC	RATIO	EXCESS
Regression (non-seeded) period:								
1970	20.40	15.60	26.20	9.50	17.85	19.84	0.90	-1.99
1971	20.50	15.90	29.60	11.80	20.37	21.99	0.93	-1.62
1972	21.60	16.20	23.20	14.50	19.50	23.78	0.82	-4.28
1973	16.90	12.20	18.00	10.00	20.90	17.94	1.16	2.95
1974	18.20	13.60	20.70	16.50	22.69	23.61	0.96	-0.93
1975	14.90	11.20	29.00	13.10	23.46	20.75	1.13	2.71
1976	11.60	9.20	16.70	9.40	14.79	14.98	0.99	-0.19
1977	10.70	6.80	9.80	4.40	10.15	10.36	0.98	-0.21
1978	30.90	17.30	25.40	14.30	28.52	28.92	0.99	-0.41
1979	24.00	14.50	23.00	12.70	22.85	24.12	0.95	-1.27
1980	26.50	14.60	29.40	15.30	29.57	28.28	1.05	1.29
1981	10.70	11.00	11.10	5.40	11.24	10.37	1.08	0.88
1982	30.50	16.50	23.10	14.80	32.54	28.96	1.12	3.59
1983	26.10	11.00	18.80	9.90	20.51	23.43	0.88	-2.92
1984	24.20	16.60	26.00	14.90	25.44	25.81	0.99	-0.37
1985	11.70	9.20	11.30	6.30	14.91	12.03	1.24	2.89
1986	27.40	15.20	19.90	11.70	28.24	24.75	1.14	3.50
1987	11.30	6.60	10.20	6.80	11.64	12.60	0.92	-0.96
1988	17.40	8.20	10.10	7.80	13.79	16.44	0.84	-2.66
Mean	19.76	12.71	20.08	11.01	20.47	20.47	1.00	0.00
Seeded period:								
YEAR	Howell Canyon Tel	Bostetter R.S. Tel	Fawn Creek #2 Tel	Pole Creek Tel	YOBS	YCALC	RATIO	EXCESS
1989	19.10	10.80	20.60	9.60	20.11	19.52	1.03	0.60
1990	11.10	8.20	13.00	7.10	12.21	12.72	0.96	-0.51
1991	11.90	8.00	13.80	6.30	14.71	12.71	1.16	2.00
1992	6.90	3.80	5.80	4.10	8.16	8.14	1.00	0.02

1993	24.20	15.10	18.90	10.30	23.44	21.78	1.08	1.66
1994	12.60	7.50	11.10	5.40	17.89	12.20	1.47	5.69
1995	16.30	11.00	14.80	7.70	23.00	15.73	1.46	7.27
1996	27.30	16.40	19.30	11.90	22.67	24.51	0.93	-1.83
1997	32.20	18.40	21.40	10.70	30.53	26.20	1.17	4.33
1998	28.00	13.30	16.70	7.90	24.97	22.23	1.12	2.74
1999	21.30	13.30	15.30	7.20	19.20	17.74	1.08	1.46
2000	22.30	13.10	17.60	7.60	20.14	18.94	1.06	1.20
YEAR	Howell Canyon Tel	Bostetter R.S. Tel	Fawn Creek #2 Tel	Pole Creek Tel	YOBS	YCALC	RATIO	EXCESS
2001	11.20	8.20	11.90	5.60	13.87	11.51	1.21	2.36
2002	18.80	13.10	14.20	7.70	15.43	16.61	0.93	-1.18
2003	12.90	8.60	12.50	5.70	14.50	12.53	1.16	1.97
2004	19.40	13.60	17.30	8.00	17.40	17.46	1.00	-0.06
2005	14.90	11.70	12.10	7.70	22.06	14.45	1.53	7.61
2006	32.20	19.80	22.40	11.30	28.77	26.47	1.09	2.30
2007	18.20	9.90	13.40	7.40	12.91	16.64	0.78	-3.73
2008	28.00	14.80	15.80	9.10	23.81	22.70	1.05	1.12
2009	24.00	14.10	17.10	9.60	24.33	21.13	1.15	3.20
2010	17.80	10.70	12.90	7.10	14.00	15.95	0.88	-1.95
2011	24.40	15.50	18.90	10.90	28.46	22.26	1.28	6.20
2012	19.40	14.10	6.80	6.80	12.91	15.12	0.85	-2.21
2013	18.70	13.00	14.20	7.50	12.64	16.43	0.77	-3.78
2014	22.40	14.20	14.20	7.10	21.71	17.95	1.21	3.76
2015	16.60	10.80	11.20	5.70	11.53	13.98	0.82	-2.45
2016	26.80	16.90	16.60	10.90	20.93	23.02	0.91	-2.09
2017*	31.80	19.70	21.40	12.30	38.04	26.90	1.41	11.14
2018	16.30	10.60	11.90	7.70	14.47	15.45	0.94	-0.98
2019	20.30	15.20	15.00	11.00	22.57	19.59	1.15	2.98
2020	20.00	15.90	14.70	10.20	17.77	18.63	0.95	-0.86
2021	15.50	11.70	11.70	8.00	12.19	14.96	0.81	-2.78
2022	18.40	12.30	9.20	8.10	13.97	16.23	0.86	-2.26
Seeded Mean	19.68	12.53	14.61	8.15	18.58	17.62	**1.055**	**0.96**
* 2017 not included in mean								

SUMMARY OUTPUT				

Regression Statistics				
Multiple R	0.93659			
R Square	0.87719			
Standard Error	2.62139			
Observations	19			
	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	1.24114	2.3293	0.5328	0.602
X Variable 1	0.56527	0.15918	3.5512	0.003
X Variable 2	-0.21731	0.39505	0.5501	0.590
X Variable 3	0.12575	0.17583	0.7151	0.486
X Variable 4	0.75375	0.32639	2.3093	0.036

Eastern Box Elder and Cache County April 1 Snow – Linear Regression

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS	
Regression (non-seeded) period:						
1970	19.14	25.11	28.96	0.87	-3.84	
1971	21.62	35.99	32.52	1.11	3.47	
1972	23.42	33.01	35.10	0.94	-2.09	
1973	18.06	29.64	27.41	1.08	2.24	
1974	20.64	28.23	31.11	0.91	-2.88	
1975	21.96	30.53	33.01	0.92	-2.48	
1976	19.26	27.90	29.13	0.96	-1.23	
1977	7.30	10.34	11.95	0.87	-1.61	
1978	18.12	31.21	27.49	1.14	3.72	
1979	19.02	30.21	28.78	1.05	1.43	
1980	22.04	33.14	33.12	1.00	0.02	
1981	9.76	13.37	15.48	0.86	-2.11	
1982	23.54	35.40	35.28	1.00	0.12	
1983	20.58	27.99	31.02	0.90	-3.04	
1984	25.74	37.19	38.44	0.97	-1.25	
1985	18.08	29.16	27.43	1.06	1.72	
1986	17.38	37.01	26.43	1.40	10.59	
1987	9.52	15.13	15.14	1.00	-0.01	
1988	12.54	18.37	19.48	0.94	-1.11	
Mean	18.30	27.84	27.75	1.00	0.09	
Seeded period:						
YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS	
1989	18.24	28.23	27.66	1.02	0.56	
1990	8.80	16.01	14.11	1.14	1.91	
1991	11.42	20.01	17.87	1.12	2.15	
1992	4.72	11.26	8.24	1.37	3.01	
1993	17.18	26.79	26.14	1.02	0.64	

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS	
1994	9.02	19.41	14.42	1.35	4.99	
1995	13.76	25.17	21.23	1.19	3.94	
1996	18.84	28.56	28.53	1.00	0.03	
1997	22.74	38.84	34.13	1.14	4.72	
1998	15.68	29.94	23.99	1.25	5.96	
1999	14.82	24.76	22.75	1.09	2.01	
2000	14.80	22.53	22.72	0.99	-0.19	
2001	7.62	15.39	12.41	1.24	2.98	
2002	15.16	21.20	23.24	0.91	-2.04	
2003	8.36	17.51	13.47	1.30	4.04	
2004	13.38	20.41	20.68	0.99	-0.27	
2005	15.42	30.01	23.61	1.27	6.40	
2006	22.32	34.96	33.52	1.04	1.43	
2007	8.80	13.29	14.11	0.94	-0.82	
2008	17.76	28.29	26.97	1.05	1.31	
2009	15.10	25.41	23.15	1.10	2.26	
2010	12.00	15.60	18.70	0.83	-3.10	
2011	20.76	37.31	31.28	1.19	6.03	
2012	10.50	15.97	16.55	0.97	-0.58	
2013	10.36	13.37	16.35	0.82	-2.97	
2014	12.78	26.70	19.82	1.35	6.88	
2015	6.78	11.49	11.37	1.01	0.12	
2016	15.62	23.39	24.01	0.97	-0.62	
2017*	18.96	33.59	28.78	1.17	4.80	
2018	9.64	15.57	15.46	1.01	0.12	
2019	19.30	28.19	29.27	0.96	-1.08	
2020	16.14	24.34	24.75	0.98	-0.41	
2021	12.12	17.40	19.00	0.92	-1.60	
2022	9.20	14.74	14.83	0.99	-0.08	
Seeded Mean	13.61	22.49	21.13	**1.06**	1.35	
* 2017 not included in mean values						
SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.911075					
R Square	0.830058					
Adjusted R Square	0.820062					
Standard Error	3.395702					
Observations	19					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	957.452	957.452	83.03436	5.94E-08	
Residual	17	196.0235	11.53079			
Total	18	1153.475				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	1.465645	2.997273	0.488993	0.631096	-4.85806	7.789347

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS	
X Variable 1	1.436298	0.157622	9.112319	5.94E-08	1.103745	1.768851

Eastern Box Elder and Cache County April 1 Snow – Multiple Linear Regression

YEAR	Magic Mtn Pil	Badger Gulch Sc	Big Bend Pil	Sedgewick Pk Pil	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS
Regression (non-seeded) period:									
1970	23.30	15.30	10.80	28.10	18.20	25.11	28.04	0.90	-2.93
1971	24.80	14.10	12.70	35.20	21.30	35.99	33.48	1.07	2.51
1972	33.40	20.40	10.90	34.40	18.00	33.01	34.33	0.96	-1.31
1973	21.60	14.40	8.90	25.60	19.80	29.64	28.37	1.04	1.27
1974	25.20	20.00	11.90	28.10	18.00	28.23	29.22	0.97	-0.99
1975	24.40	18.70	15.70	29.80	21.20	30.53	30.15	1.01	0.38
1976	22.00	15.50	12.70	30.20	15.90	27.90	26.45	1.05	1.45
1977	8.40	6.00	3.10	11.30	7.70	10.34	9.02	1.15	1.32
1978	19.20	12.40	9.20	24.90	24.90	31.21	30.91	1.01	0.31
1979	19.60	14.60	10.10	27.50	23.30	30.21	31.64	0.96	-1.42
1980	21.50	15.70	13.70	31.30	28.00	33.14	36.27	0.91	-3.13
1981	12.00	7.20	2.00	13.50	14.10	13.37	16.79	0.80	-3.41
1982	28.10	18.20	13.70	31.60	26.10	35.40	36.30	0.98	-0.90
1983	24.60	14.60	15.70	23.70	24.30	27.99	27.22	1.03	0.77
1984	32.00	19.50	18.00	29.80	29.40	37.19	36.14	1.03	1.04
1985	20.80	14.70	9.10	25.50	20.30	29.16	28.67	1.02	0.49
1986	19.10	16.10	4.40	24.30	23.00	37.01	33.16	1.12	3.86
1987	10.60	8.80	2.30	14.10	11.80	15.13	15.71	0.96	-0.58
1988	16.10	9.00	6.80	16.40	14.40	18.37	17.08	1.08	1.29
Mean	21.41	14.48	10.09	25.54	19.98	27.84	27.84	1.00	0.00
Seeded period:									
YEAR	Magic Mtn Pil	Badger Gulch Sc	Big Bend Pil	Sedgewick Pk Pil	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS
1989	23.60	16.20	10.50	23.10	17.80	28.23	25.15	1.12	3.08
1990	10.20	7.70	0.00	13.30	12.80	16.01	16.84	0.95	-0.82
1991	14.70	7.50	2.40	16.60	15.90	20.01	20.20	0.99	-0.18
1992	3.60	3.00	0.00	10.10	6.90	11.26	7.92	1.42	3.34
1993	18.10	14.60	8.40	23.50	21.30	26.79	28.42	0.94	-1.63
1994	11.60	8.40	0.40	14.60	10.10	19.41	15.63	1.24	3.79
1995	15.70	10.40	3.90	21.90	16.90	25.17	24.65	1.02	0.52
1996	21.20	14.70	10.20	25.70	22.40	28.56	29.87	0.96	-1.32
1997	26.90	18.60	8.40	32.50	27.30	38.84	40.87	0.95	-2.03

YEAR	Magic Mtn Pil	Badger Gulch Sc	Big Bend Pil	Sedgewick Pk Pil	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS
1998	18.20	11.50	7.20	22.90	18.60	29.94	25.35	1.18	4.59
1999	20.00	13.80	8.00	20.80	11.50	24.76	18.95	1.31	5.81
2000	18.50	11.90	8.80	17.60	17.20	22.53	20.22	1.11	2.31
2001	11.40	6.10	2.00	10.10	8.50	15.39	9.74	1.58	5.64
2002	20.90	15.80	10.40	15.80	12.90	21.20	16.45	1.29	4.75
2003	10.60	4.20	2.00	14.70	10.30	17.51	13.24	1.32	4.27
2004	20.20	13.00	3.60	19.60	10.50	20.41	19.57	1.04	0.85
2005	16.70	9.80	7.70	20.70	22.20	30.01	25.82	1.16	4.20
2006	28.20	18.20	14.50	27.00	23.70	34.96	31.09	1.12	3.87
2007	14.00	5.20	1.80	14.40	8.60	13.29	12.40	1.07	0.88
2008	20.00	16.80	11.60	21.40	19.00	28.29	24.46	1.16	3.82
2009	20.40	10.20	10.10	20.70	14.10	25.41	18.39	1.38	7.02
2010	15.70	11.20	8.40	14.70	10.00	15.60	12.47	1.25	3.13
2011	21.80	15.40	13.80	28.10	24.70	37.31	31.49	1.18	5.82
2012	17.20	10.90	2.80	15.70	5.90	15.97	12.93	1.24	3.05
2013	15.20	9.60	2.00	15.50	9.50	13.37	15.49	0.86	-2.12
2014	17.70	11.40	2.20	18.30	14.30	26.70	21.80	1.22	4.90
2015	13.00	5.40	0.00	10.60	4.90	11.49	8.12	1.41	3.37
2016	22.40	14.70	9.50	19.20	12.30	23.39	18.24	1.28	5.14
2017*	19.80	15.10	10.10	26.60	23.20	33.59	31.20	1.08	2.38
2018	12.70	6.90	2.70	18.30	7.60	15.57	14.12	1.10	1.45
2019	21.20	17.70	10.40	23.30	23.90	28.19	30.65	0.92	-2.46
2020	21.40	15.60	8.40	19.80	15.50	24.34	22.08	1.10	2.26
2021	16.60	12.40	6.70	14.90	10.00	17.40	14.07	1.24	3.33
2022	14.90	7.00	2.00	11.20	10.90	14.74	12.89	1.14	1.85
Seeded Mean	17.41	11.39	6.08	18.68	14.48	22.49	19.99	**1.13**	**2.50**
SUMMARY OUTPUT									
Regression Statistics									
Multiple R	0.9708								
R Square	0.9425								
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*	*Upper 95.0%*
Intercept	-5.2440	2.43758	-2.1513	0.0508	-10.51	0.022	-10.51	0.02203	8.29924
X Var 1	0.0570	0.2439	0.2337	0.8188	-0.47	0.5841	-0.47	58409	0.63945
X Var 2	0.3935	0.3366	1.1691	0.2633	-0.3337	1.1208	0.3337	1.1208	1.91336
X Var 3	0.5596	0.2273	-2.4613	0.0286	-1.0509	-0.0684	1.0509	-0.0684	0.403

YEAR	Magic Mtn Pil	Badger Gulch Sc	Big Bend Pil	Sedgewick Pk Pil	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS
X Var 4	0.6219	0.1739	3.5747	0.0034	0.2461	0.9978	0.2461	0.9977	1.65304
X Var 5	0.7967	0.1405	5.6698	8E-05	0.4932	1.1004	0.4932	1.1003	

Northwest Box Elder County – April 1 Snow Water Content Linear Regression

Regression (non-seeded) period:					
YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1970	19.14	20.25	20.29	1.00	-0.04
1971	21.62	20.90	22.65	0.92	-1.75
1972	23.42	24.00	24.35	0.99	-0.35
1973	18.06	18.60	19.27	0.97	-0.67
1974	20.64	20.50	21.72	0.94	-1.22
1975	21.96	22.65	22.97	0.99	-0.32
1976	19.26	19.35	20.41	0.95	-1.06
1977	7.30	9.00	9.07	0.99	-0.07
1978	18.12	17.30	19.33	0.90	-2.03
1979	19.02	18.05	20.18	0.89	-2.13
1980	22.04	21.65	23.04	0.94	-1.39
1981	9.76	11.35	11.40	1.00	-0.05
1982	23.54	26.30	24.47	1.07	1.83
1983	20.58	27.30	21.66	1.26	5.64
1984	25.74	27.50	26.55	1.04	0.95
1985	18.08	16.70	19.29	0.87	-2.59
1986	17.38	23.30	18.63	1.25	4.67
1987	9.52	13.00	11.17	1.16	1.83
1988	12.54	12.70	14.04	0.90	-1.34
Mean	18.30	19.49	19.50	1.00	0.00
Seeded Period:					
YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1989	18.24	21.10	19.44	1.09	1.66
1990	8.80	13.00	10.49	1.24	2.51
1991	11.42	12.55	12.98	0.97	-0.43
1992	4.72	11.10	6.62	1.68	4.48
1993	17.18	21.35	18.44	1.16	2.91
1994	9.02	11.30	10.70	1.06	0.60
1995	13.76	18.90	15.19	1.24	3.71
1996	18.84	20.80	20.01	1.04	0.79
1997	22.74	26.70	23.71	1.13	2.99
1998*	15.68	19.40	17.01	1.14	2.39
1999*	14.82	16.10	16.20	0.99	-0.10
2000	14.80	18.00	16.18	1.11	1.82

2001	7.62	12.65	9.37	1.35	3.28
YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
2002*	15.16	18.90	16.52	1.14	2.38
2003*	8.36	9.80	10.08	0.97	-0.28
2004	13.38	21.70	14.83	1.46	6.87
2005	15.42	23.15	16.77	1.38	6.38
2006	22.32	24.80	23.31	1.06	1.49
2007	8.80	10.20	10.49	0.97	-0.29
2008	17.76	19.60	18.99	1.03	0.61
2009	15.10	17.40	16.46	1.06	0.94
2010	12.00	16.20	13.53	1.20	2.67
2011	20.76	23.00	21.83	1.05	1.17
2012	10.50	12.10	12.10	1.00	0.00
2013	10.36	15.90	11.97	1.33	3.93
2014	12.78	13.30	14.27	0.93	-0.97
2015	6.78	9.40	8.58	1.10	0.82
2016	15.62	18.70	16.96	1.10	1.74
2017**	18.96	20.30	20.12	1.01	0.18
2018	9.64	11.10	11.29	0.98	-0.19
2019	19.30	22.70	20.45	1.11	2.25
2020	16.14	18.64	17.45	1.07	1.18
2021	12.12	14.25	13.64	1.04	0.61
2022	9.20	12.71	10.87	1.17	1.84
Seeded Mean	13.62	16.98	15.07	**1.13**	**1.91**

* No seeding in these seasons, not included in mean

** 2017 not included in mean values due to suspensions

Regression Statistics						
Multiple R	0.910073					
R Square	0.828234					
Adjusted R Square	0.81813					
Standard Error	2.258002					
Observations	19					
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.152556	1.984266	1.084812	0.29315	-2.03388	6.338997
X Variable 1	0.947606	0.104664	9.053822	6.51E-08	0.726784	1.168427

Northwest Box Elder County – April 1 Snow Water Content Multiple Regression

YEAR	Magic Mtn Pil	Badger Gulch SC	Sedgewick Pk Pil	Big Bend Pil	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS
Regression (non-seeded) period:									
1970	23.3	15.3	28.1	10.8	18.2	20.3	19.57	1.03	0.68
1971	24.8	14.1	35.2	12.7	21.3	20.9	19.64	1.06	1.26
1972	33.4	20.4	34.4	10.9	18.0	24.0	24.21	0.99	-0.21
1973	21.6	14.4	25.6	8.9	19.8	18.6	19.30	0.96	-0.70
1974	25.2	20	28.1	11.9	18.0	20.5	22.35	0.92	-1.85
1975	24.4	18.7	29.8	15.7	21.2	22.7	22.78	0.99	-0.13
1976	22	15.5	30.2	12.7	15.9	19.4	18.31	1.06	1.04
1977	8.4	6	11.3	3.1	7.7	9.0	8.67	1.04	0.33
1978	19.2	12.4	24.9	9.2	24.9	17.3	19.45	0.89	-2.15
1979	19.6	14.6	27.5	10.1	23.3	18.1	19.66	0.92	-1.61
1980	21.5	15.7	31.3	13.7	28.0	21.7	22.20	0.98	-0.55
1981	12	7.2	13.5	2.0	14.1	11.4	12.07	0.94	-0.72
1982	28.1	18.2	31.6	13.7	26.1	26.3	24.94	1.05	1.36
1983	24.6	14.6	23.7	15.7	24.3	27.3	23.21	1.18	4.09
1984	32	19.5	29.8	18.0	29.4	27.5	28.89	0.95	-1.39
1985	20.8	14.7	25.5	9.1	20.3	16.7	19.35	0.86	-2.65
1986	19.1	16.1	24.3	4.4	23.0	23.3	19.83	1.18	3.47
1987	10.6	8.8	14.1	2.3	11.8	13.0	11.43	1.14	1.57
1988	16.1	9	16.4	6.8	14.4	12.7	14.55	0.87	-1.85
Mean	21.41	14.48	25.54	10.1	19.98	19.49	19.49	1.00	0.00
YEAR	Magic Mtn Pil	Badger Gulch SC	Sedgewick Pk Pil	Big Bend	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS
Seeded Period:									
1989	23.6	16.2	23.1	10.5	17.8	21.1	20.77	1.02	0.33
1990	10.2	7.7	13.3	0.0	12.8	13.0	10.98	1.18	2.02
1991	14.7	7.5	16.6	2.4	15.9	12.6	13.28	0.95	-0.73
1992	3.6	3	10.1	0.0	6.9	11.1	5.19	2.14	5.91
1993	18.1	14.6	23.5	8.4	21.3	21.4	18.93	1.13	2.42
1994	11.6	8.4	14.6	0.4	10.1	11.3	10.70	1.06	0.60
1995	15.7	10.4	21.9	3.9	16.9	18.9	14.48	1.31	4.42
1996	21.2	14.7	25.7	10.2	22.4	20.8	20.31	1.02	0.49
1997	26.9	18.6	32.5	8.4	27.3	26.7	24.22	1.10	2.48

YEAR	Magic Mtn Pil	Badger Gulch SC	Sedgewick Pk Pil	Big Bend Pil	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS
1998*	18.2	11.5	22.9	7.2	18.6	19.4	16.68	1.16	2.72
1999*	20.0	13.8	20.8	8.0	11.5	16.1	16.42	0.98	-0.32
2000	18.5	11.9	17.6	8.8	17.2	18.0	17.64	1.02	0.36
2001	11.4	6.1	10.1	2.0	8.5	12.7	10.11	1.25	2.54
2002*	20.9	15.8	15.8	10.4	12.9	18.9	19.26	0.98	-0.36
2003*	10.6	4.2	14.7	2.0	10.3	9.8	8.81	1.11	0.99
2004	20.2	13.0	19.6	3.6	10.5	21.7	15.43	1.41	6.27
2005	16.7	9.8	20.7	7.7	22.2	23.2	17.07	1.36	6.08
2006	28.2	18.2	27.0	14.5	23.7	24.8	25.09	0.99	-0.29
2007	14.0	5.2	14.4	1.8	8.6	10.2	9.91	1.03	0.29
2008	20.0	16.8	21.4	11.6	19.0	19.6	20.59	0.95	-0.99
2009	20.4	10.2	20.7	10.1	14.1	17.4	16.18	1.08	1.22
2010	15.7	11.2	14.7	8.4	10.0	16.2	14.39	1.13	1.81
2011	21.8	15.4	28.1	13.8	24.7	23.0	21.65	1.06	1.35
2012	17.2	10.9	15.7	2.8	5.9	12.1	12.50	0.97	-0.40
2013	15.2	9.6	15.5	2.0	9.5	15.9	12.36	1.29	3.54
2014	17.7	11.4	18.3	2.2	14.3	13.3	15.16	0.88	-1.86
2015	13.0	5.4	10.6	0.0	4.9	9.4	8.83	1.07	0.57
2016	22.4	14.7	19.2	9.5	12.3	18.7	18.41	1.02	0.29
2017**	19.8	15.1	26.6	10.1	23.2	20.3	20.08	1.01	0.22
2018	12.7	6.9	18.3	2.7	7.6	11.1	9.27	1.20	1.83
2019	21.2	17.7	23.3	10.4	23.9	22.7	22.54	1.01	0.16
2020	21.4	15.6	19.8	8.4	15.5	18.6	19.26	0.97	-0.62
2021	16.6	12.4	14.9	6.7	10.0	14.3	14.96	0.95	-0.71
2022	14.9	7.0	11.2	2.0	10.9	12.7	12.36	1.03	0.35
Seeded Mean	17.4	11.4	18.7	6.0	14.6	17.0	15.6	**1.09**	**1.37**

* No seeding in these seasons, not included in mean

** 2017 not included in mean values due to suspensions

SUMMARY OUTPUT

Regression Statistics						
Multiple R	0.93784					
R Square	0.879544					
Standard Error	2.162331					
Observations	19					
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.088813	2.333923	0.894979 6	0.38706 9	-2.9533192	7.13094 6

YEAR	Magic Mtn Pil	Badger Gulch SC	Sedgewick Pk Pil	Big Bend Pil	Strawberry Div Pil	YOBS	YCALC	RATIO	EXCESS

X Variable 1	0.357386	0.233593	1.5299493	0.149993	-0.1472617	0.862034
X Variable 2	0.428867	0.322314	1.3305894	0.206193	-0.2674492	1.125184
X Variable 3	-0.17568	0.166582	1.0546019	0.310814	-0.535557	0.184201
X Variable 4	0.134263	0.217714	0.6166958	0.548084	-0.3360791	0.604606
X Variable 5	0.3341	0.134553	2.4830346	0.027453	0.0434157	0.624784

APPENDIX D

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 increases 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 were 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