Annual Cloud Seeding Report

Book Cliffs/Tavaputs Cloud Seeding Program

2022-2023 Winter Season

Prepared For:

Range Valley Ranch

Prepared By:

Todd Flanagan

Garrett Cammans

North American Weather Consultants, Inc.

8180 S. Highland Dr., Suite B-2

Sandy, Utah 84093

August 2023

Table of Contents

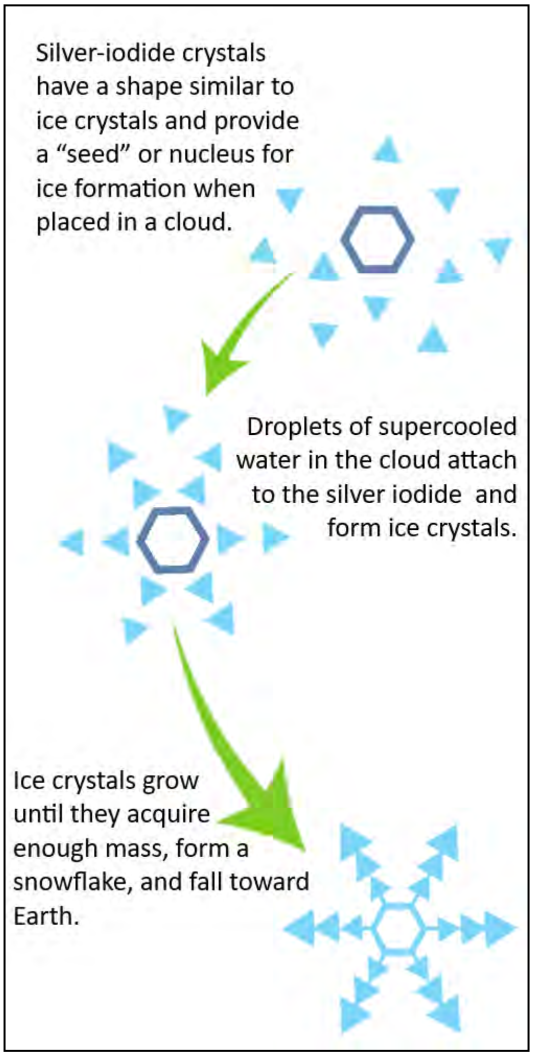
WEATHER MODIFICATION

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. This is known as the U.S Climate normal, with a 30-year average, representing the "new normal" for our climate. These 30-year normal values can help to determine a departure from historic norms and identify current weather trends.

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

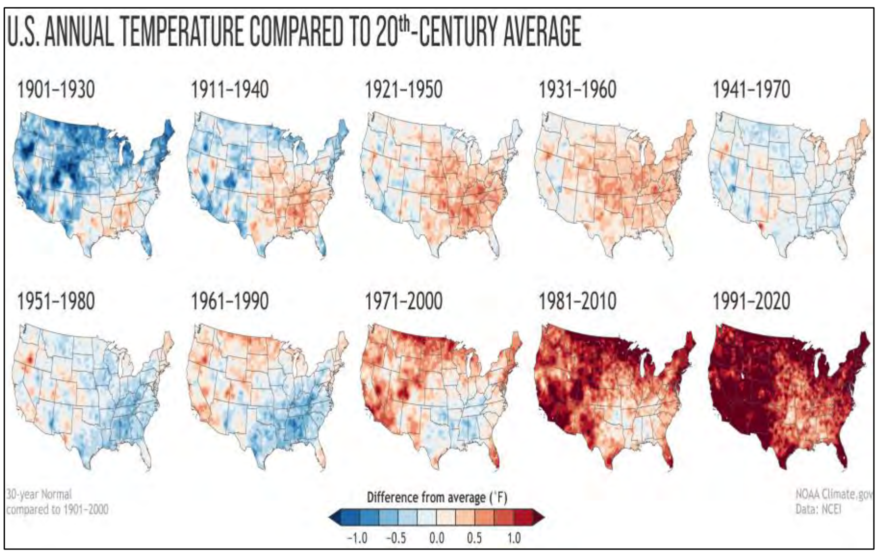


Figure 1. U.S. Annual Temperature compared to 20th-Century Average

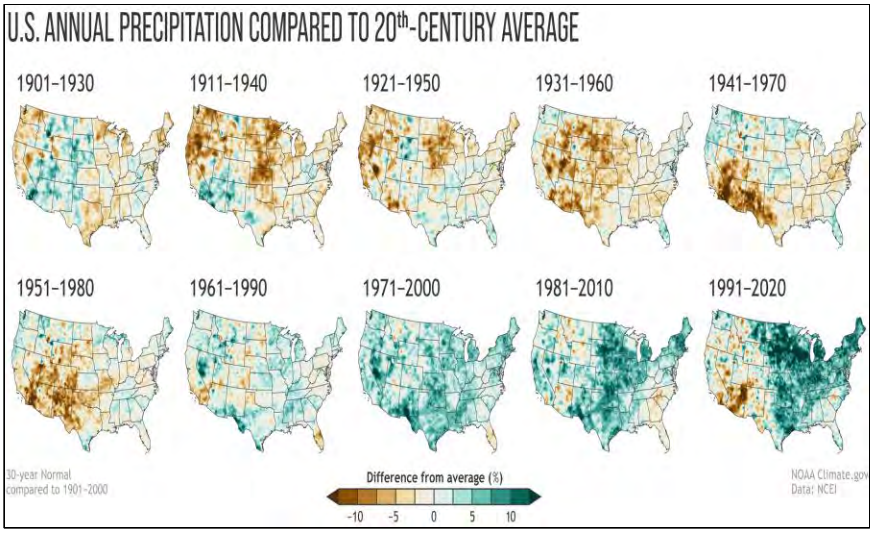


Figure 2. **U.S. Annual Precipitation compared to 20th-Century Average**

1.0 INTRODUCTION

North American Weather Consultants (NAWC) has been involved in cloud seeding operations since the 1950s, beginning in California and in more recent decades, various other states and countries. Due to high natural precipitation variability and the increased demand for water, cloud seeding has been conducted over large areas of Utah for over 40 years. Cloud seeding in Utah is regulated and cost shared by the Utah Department of Natural Resources through the Division of Water Resources.

Most cloud seeding programs in Utah are conducted for relatively high-yield areas of the Wasatch Range and Plateau, areas from the northern to southern borders of the state, as well as the Uinta Range in northeastern Utah. These programs are normally conducted from November to April in order to target winter storms.

In 2020, NAWC was contacted by Daniel Campbell from the Range Valley Ranch requesting information regarding the potential for cloud seeding operations over the Tavaputs Plateau with the intent of increasing snowfall. Upon further discussion, it was determined that there were multiple entities with a vested interest in augmenting the precipitation that occurs in portions of the Rocky Mountains around the Tavaputs Plateau. In order to determine the feasibility of a program in this area of Utah, NAWC performed preliminary research to estimate the potential increase in precipitation and runoff in the area.

Due to the remote nature of this portion of the Rocky Mountains, snow gauges and stream flow gauges are limited, as are historic records. Fortunately, NAWC's experience in other portions of the state, particularly those portions of the state with similar geographical and climatological patterns, assisted in the development of the estimates we present in this report.

1.1 Seasonal Precipitation

To determine the potential efficacy of a program and the value of such a program, NAWC first evaluates historical precipitation data for the intended target area. Two measures are of particular importance when determining the value of a cloud seeding program. The first is the total precipitation that occurs during portions of the calendar year when storms are typically seeable. This is typically measured in inches of total precipitation. The second, which is only applicable to higher elevation cloud seeding programs, is a measure of the amount of water stored in snowpack throughout the cold season. This is measured in terms of snow water equivalent (SWE) and represents the depth of water in inches that would result if the current snowpack were melted. Both of these measurements are representative of the amounts of liquid water, the first being a representation of the total amount of water that has fallen in the form of rain or snow, the second representing the amount of water stored in the existing snowpack.

To determine the values for these key metrics, NAWC utilizes data from Snow Telemetry (SNOTEL) sites, administered by the United States Department of Agriculture (USDA). Higher areas of the Tavaputs

Plateau (east of Price) have two available SNOTEL sites: the Timberline site at 8,736 feet elevation (established during the 2007-08 season) and Corral site at 8,207 feet (established during the 2013-14 season). These two sites, as well as another site near the western edge of the target area (Indian Canyon) at the summit along Highway 191, are designated in Figure 1.1 as blue circles. The Indian Canyon site is over 9,000 feet in elevation and does have a long-term record, although is less representative of the core area of this seeding program.

Although having too short of a period of record to establish a reliable long-term normal value, the available record suggests that SWE values peak in March with median values near 8 inches of liquid water equivalence at Timberline and near 6 inches at Corral. Typical total precipitation observed during the cold season (roughly November – April) is generally near 10 inches in these areas, with dry years receiving as little as half this amount of precipitation and the wettest years receiving nearly double this amount.

Annual precipitation in this area, in contrast to some other ranges in Utah, exhibits an overall maximum from late July to early/mid-October, associated with a seasonal monsoonal pattern. The driest months tend to be during late fall to early winter (November/December), with the November - April season representing roughly half (or slightly less) of the annual total precipitation of 20-25 inches on average.

1.2 Climate Overview

Climate analysis for the Book Cliffs / western Tavaputs Plateau area was conducted by NAWC based on two SNOTEL sites (Timberline and Corral) located near the center of the target area. The analyses showed that the winter climate is somewhat drier in this area than that of most areas with winter seeding programs. These sites receive roughly 8-10 inches of precipitation / snow water content during the November – April period on average, although there is a high year to year variability. In some wet years, these sites can receive as much as 15-20 inches during the winter season period, and in dry years can receive less than 6 inches. A large portion of precipitation that falls in these areas occurs during the summer monsoon period from roughly late July to early October. This warm season precipitation is not considered seedable from ground-based sites due to temperature parameters, as well as its minor contribution to runoff and water storage. Seeding during the winter season can add additional moisture to the snowpack which contributes substantially to runoff and water storage. One key attribute of the eastern Utah basins and mountains is that the highest producing winter season precipitation periods are associated with south to southwesterly winds, with westerly to northerly wind patterns generally associated with drier conditions. These and other attributes have impacted the program design that was recommended and implemented for the Book Cliffs program. Figure 1.2 shows the average annual precipitation across the state of Utah.

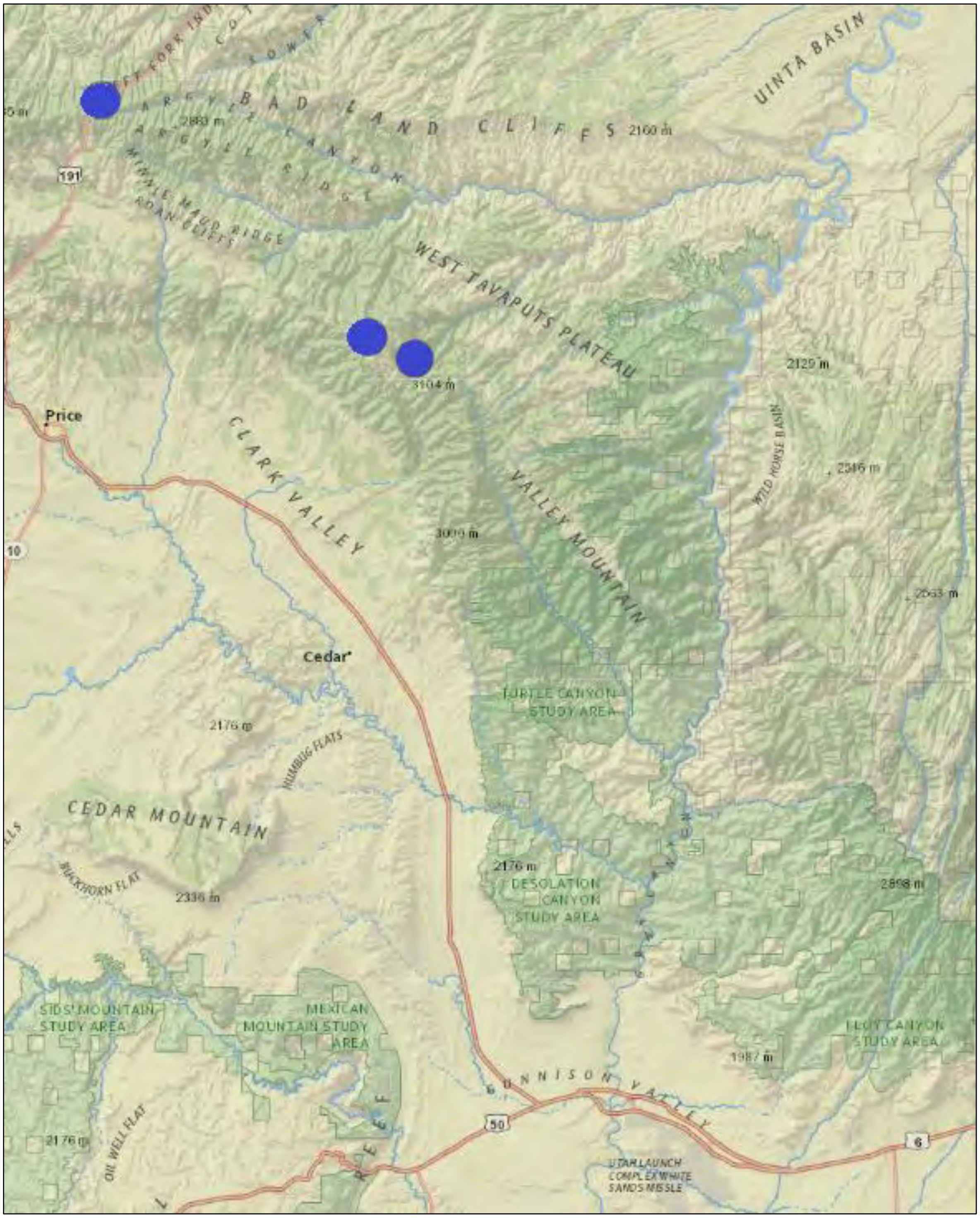


Figure 1.1. Location of SNOTEL sites in the Book Cliffs area.

Figure 1.2. **Mean annual precipitation for the state of Utah based on 30-year period from 1991-2020.**

There are two potential concerns as far as targeting this area with cloud seeding operations. The first, is that winter storms (or portions of storm) that come from the south do tend to be somewhat warmer than precipitation periods with northwesterly winds. Cloud seeding agents are generally most active at temperatures between -5° and -15°C. Due to the warmer nature of these southerly storms, the -5°C level inside the cloud deck may be found at elevations higher than the mountain barrier. This is often the case with NAWC's California programs, and it does not always negate cloud seeding efforts but can render a program less effective. The second concern is that low-level thermodynamic stability (inversion) can affect the dispersion of seeding material from ground-based sites. Though the prevalence of stability is not as notorious in this region as it is in the Uinta Basin, this is something operational meteorologists will be aware of in regards to program design and seeding increase projections.

1.3 Increase Projections

Based on all of the considerations, it was estimated that this area could be reasonably targeted by an array of four or more ground-based sites, ideally located above the valley floor (above the 6,000-foot elevation level) to maximize material dispersion.

Long term historic records and extensive mathematical modeling using these records have produced seasonal seeding increase estimates of 3 to 15% in precipitation for well executed weather modification programs, in the Utah and Colorado Rockies. The program most topographically and climatologically similar to this proposed program is the weather modification program comprising the eastern two thirds of the Uinta Mountain Range. Data for the Uintas program suggests an increase in seasonal precipitation that is on the lower end of the overall range shown above, or roughly 3-5% resulting from cloud seeding endeavors. We therefore predict an estimated seasonal increase of a similar 3-5% for the November – April period for the Book Cliffs program given its climatological and topographical similarities. This would equate to roughly 0.3 to 0.5 inches of additional precipitation (liquid water equivalent) or roughly 3-5 inches of additional seasonal snowfall. Based on the size of the target area (outlined in Figure 1.3), NAWC expects that this increase would amount to between 10,000 and 20,000 acre-feet (AF) of additional snowmelt runoff, depending on the nature of seasonal weather patterns. In drier climates where ground water absorption rates are high, the increases in stream flow can substantially exceed the seasonal precipitation increase **on a percentage basis**. This is the result of runoff being more efficient when precipitation is higher, as well as a reduction in the percentage of ground water absorption when snow melt rates are higher.

1.4 Program Design

In order to maximize the program coverage and contribution to spring runoff, operational seeding sites were distributed from the Helper area, southeast to Green River, with the primary target area being those areas of the Tavaputs Range that exceed 6,000 to 7,000 ft in elevation. Desirable generator locations as well as NAWC's proposed target area are represented in Figure 1.3. It should be noted that a fifth site near Price was planned to be operational but several complications arose that resulted in the site never becoming active during the season.

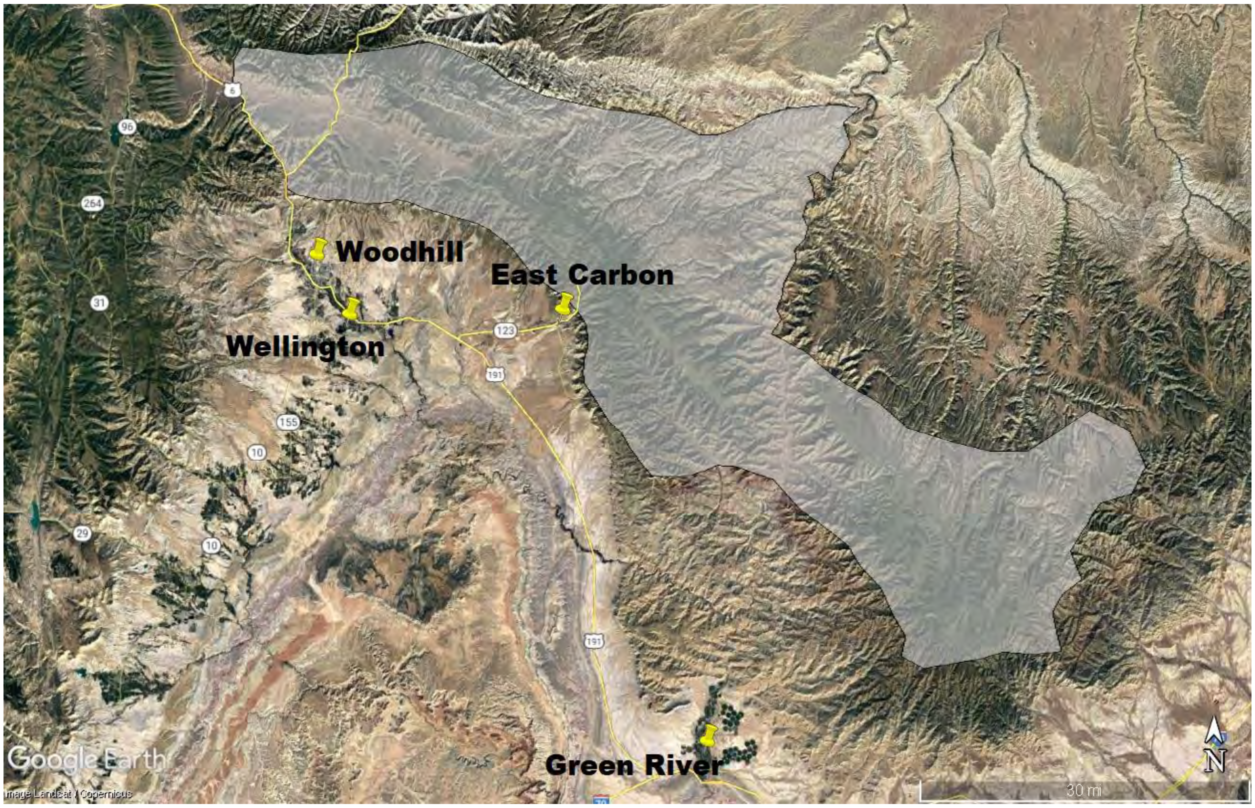


Figure 1.3. Book Cliffs seeding sites and target area

Estimates of potential cloud seeding benefits in the Book Cliffs area were based on those made for seeding in the Uinta Range, given the general proximity and similarities of climate and barrier orientation. While many winter programs in Utah are estimated to produce increases of 5-10% or locally more to the winter snowpack, estimates for the Uinta Range are lower, on the order of 3-5% and these estimates were used as the basis for the Book Cliffs program. A 4% increase, applied to total winter season precipitation in the Book Cliffs, results in an estimate of roughly a 0.4 inch potential increase for seeding in the Book Cliffs.

This report summarizes operations conducted for the Book Cliffs program during the 2022-2023 season, as well as development of target/control precipitation and snowpack equations, which could become useful for the estimation of seeding benefits if the program continues.

2.0 WEATHER DATA AND MODELS USED IN SEEDING OPERATIONS

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 2.1 – 2.4 show examples of some of the available weather information that was used in this decision-making process during the 2022-23 winter season. These include weather radar images, satellite images, surface wind and temperature maps, rawinsonde/weather balloon soundings and aviation hazards. 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 is shown from the Global Forecast System **(GFS)** model (Figure 2.5). Other models used on a daily basis during the program include but are not limited to the European Center for Medium-Range Weather Forecast **(ECMWF)** model, High-Resolution Rapid Refresh **(HRRR)** model, and North American Model **(NAM)**.

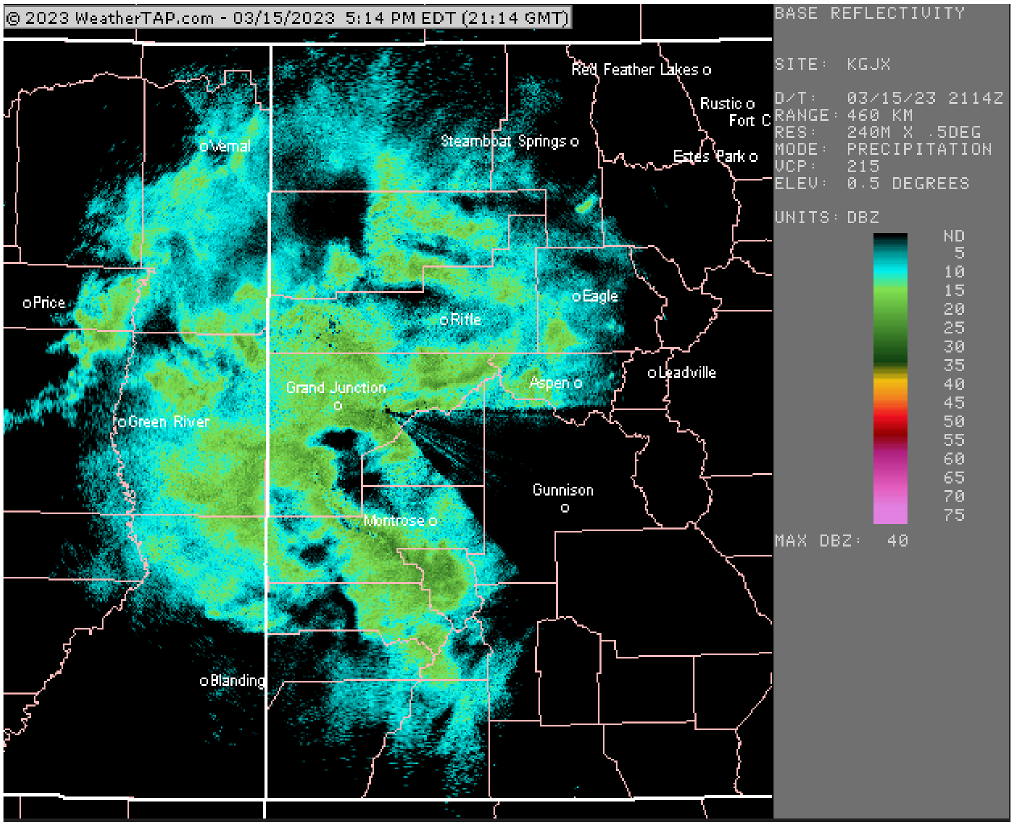


Figure 2.1. **Weather radar image from Grand Junction, CO during a storm event over eastern Utah on March 15, 2023.**

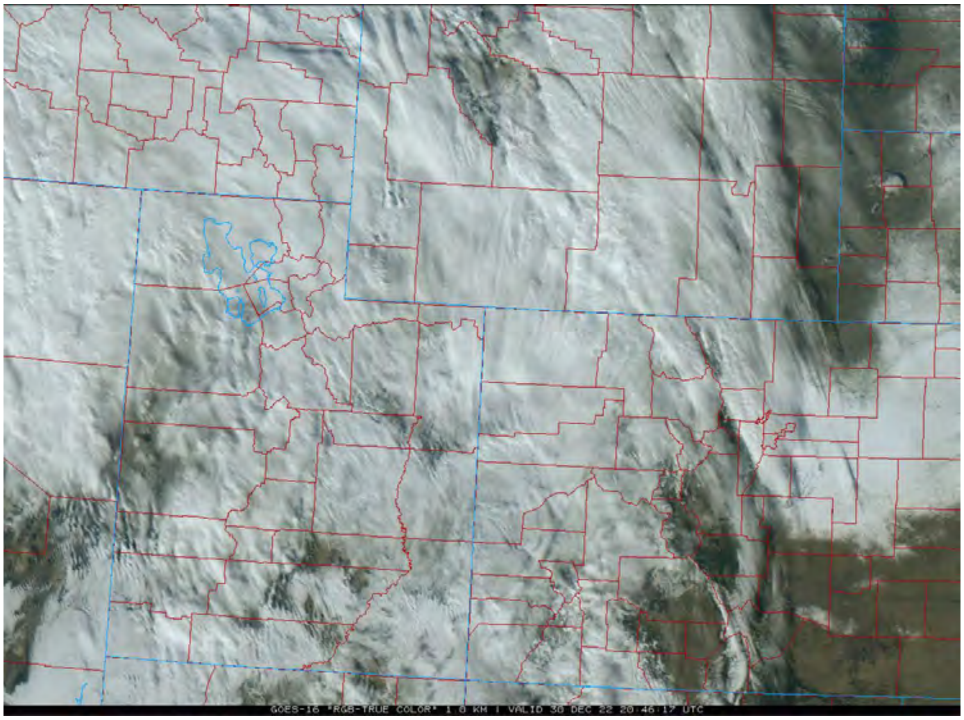


Figure 2.2. **Visible spectrum satellite image on December 30, 2022.**

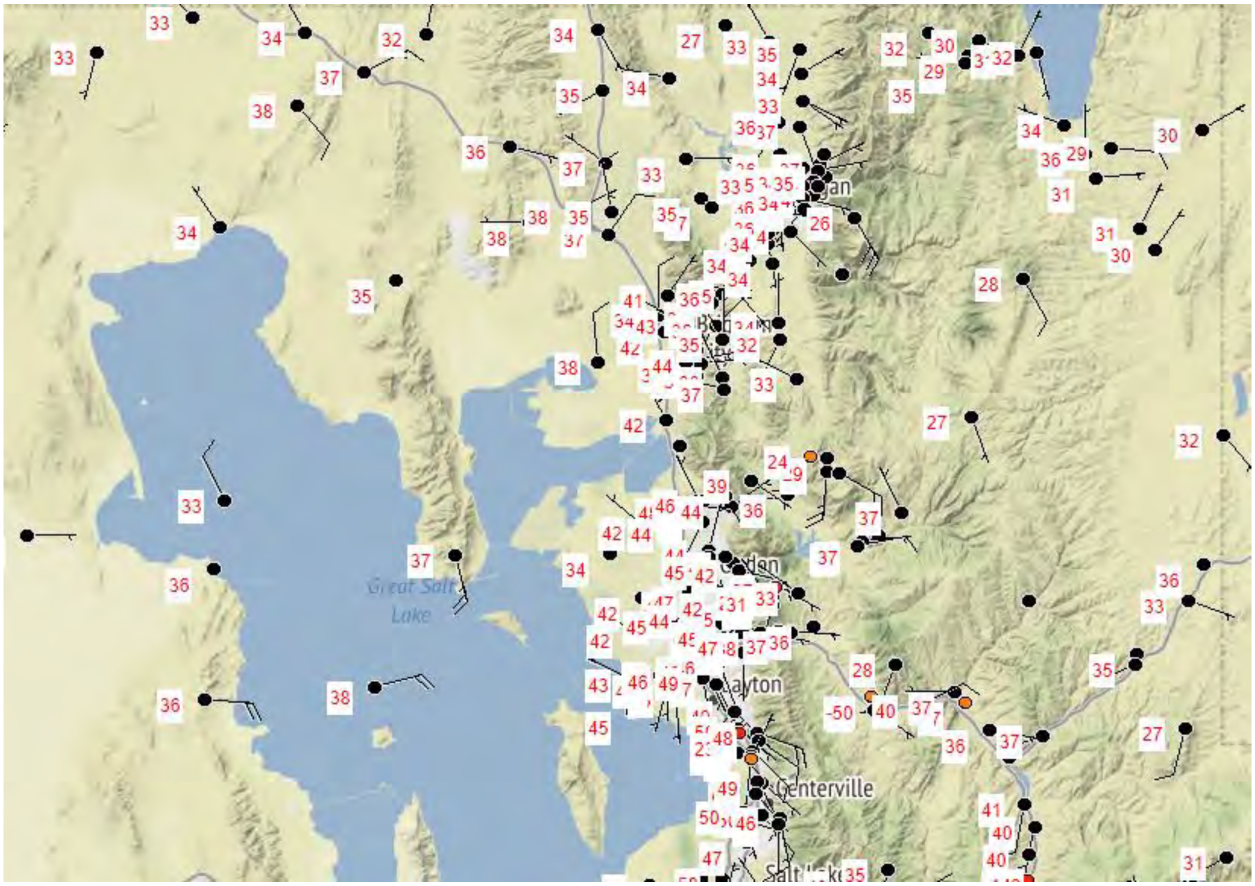


Figure 2.3. **MesoWest surface data map on January 10, 2023. Surface observations are important for diagnosing low level wind patterns and mixing.**

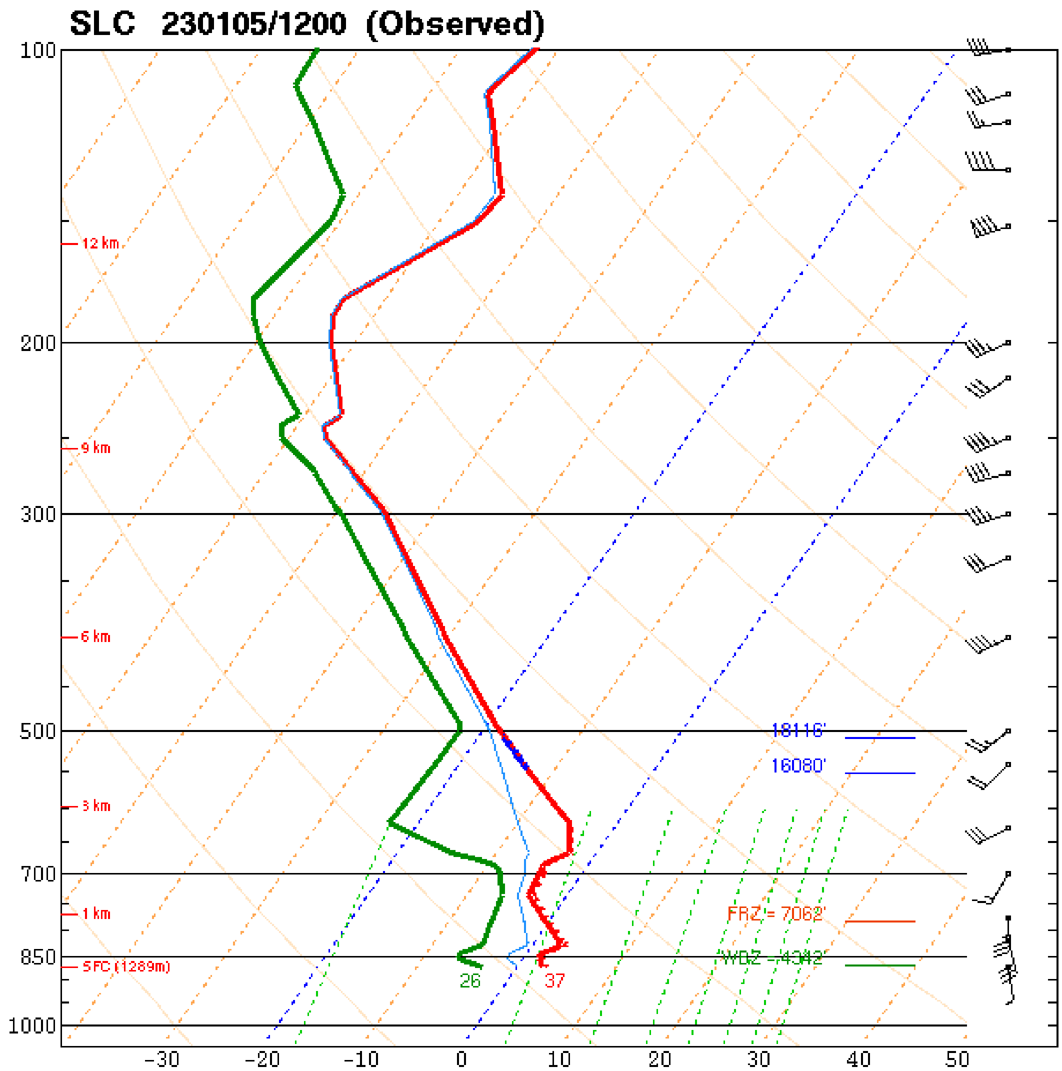


Figure 2.4. **Weather balloon/rawinsonde sounding from Salt Lake City, valid at 12Z/0500 MST on January 5, 2023 showing temperature (red line), dewpoint (green line) and wind speed/direction (right side barbs) from the surface to 100 mb (approximately 52,000 feet MSL).**

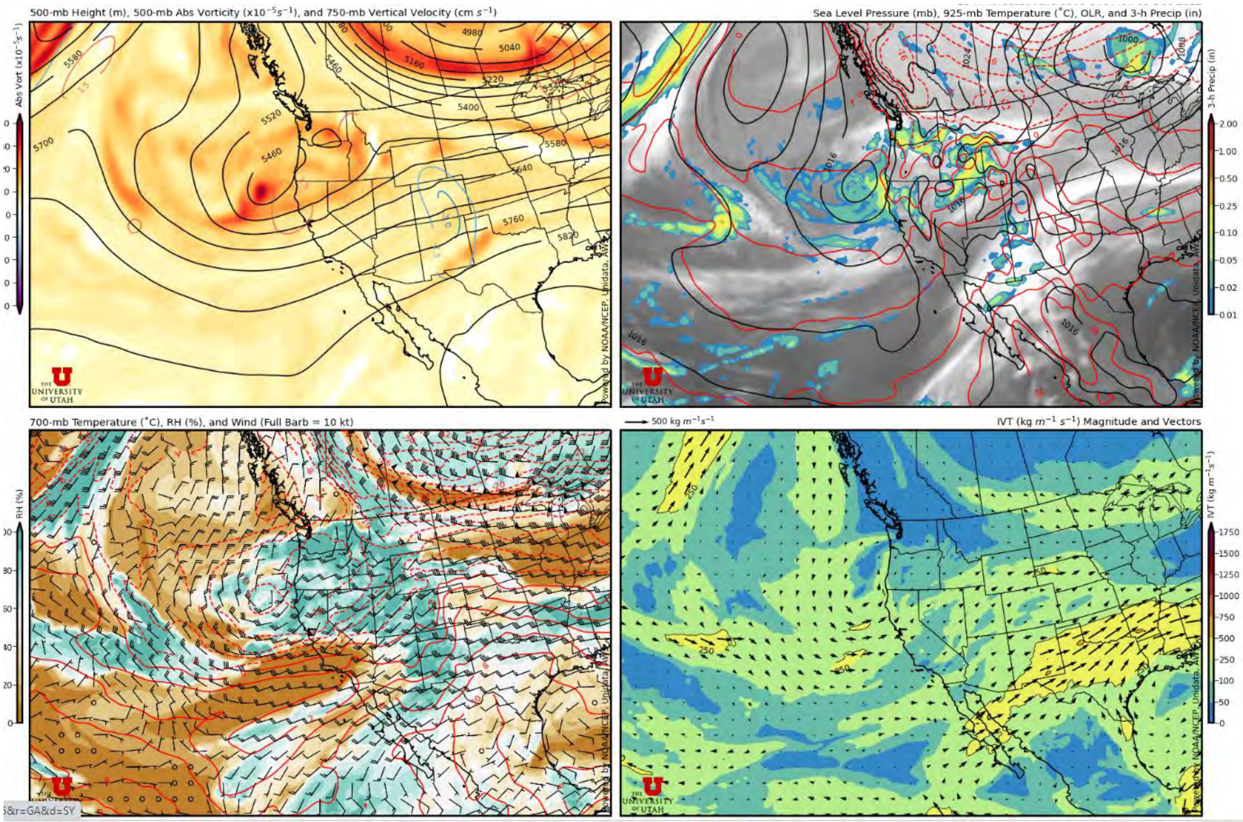


Figure 2.5. GFS (Global Forecast Systems) model forecast (4-panel plot) during a storm event on December 4, 2022.

3.0 OPERATIONS DURING THE 2022-2023 SEASON

The 2022-2023 season was well above normal region wide in terms of storm activity and snowpack. Snow water equivalent (SWE) values peaked in early April in higher portions of the Book Cliffs seeding target area, where two SNOTEL sites are located. SWE values of 20.8 inches at Corral and 25.5 inches at Timberline were observed on April 1, which is well above average for the (short) existing periods of record at these sites. In general, the snowpack here, similar to much of the state, appeared to peak at 200-300 % of the average values this season. Figure 3.1 shows the percent of median values of April 1 snow water equivalent (SWE) for the state of Utah on April 1, 2023.

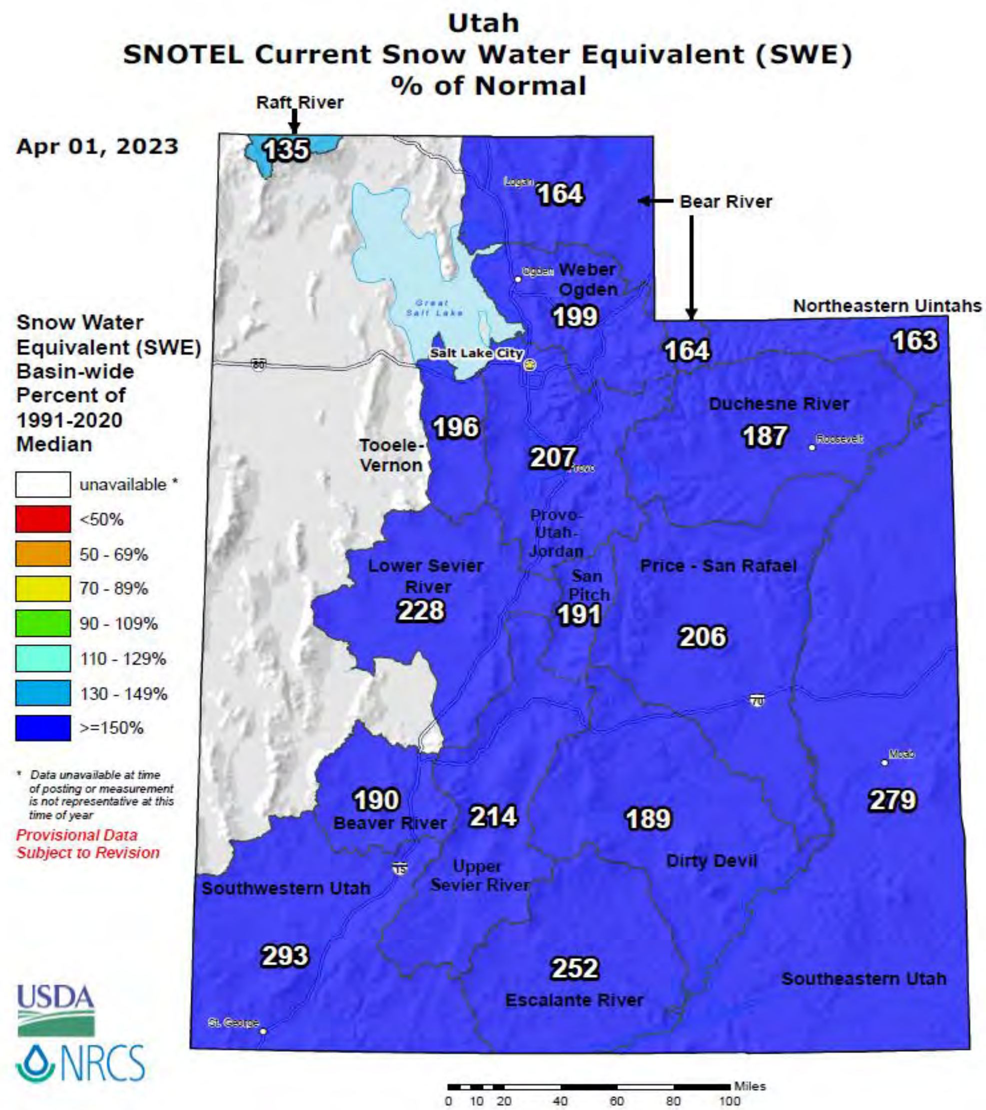


Figure 3.1. **Snow water content in Utah on April 1st, 2023 (percent of median)**

Figure 3.2 is a graph of snow water equivalent (SWE) and Figure 3.3 is cumulative water year precipitation, both for the Timberline site from October 2022 through May 2023. Figures 3.4 and 3.5 are similar plots for the nearby Corral site. Aside from a few brief periods, both precipitation and SWE were above to well above the mean at both locations. As seen in these graphs, snowpack began to quickly melt at these sites after mid-April. Water year precipitation to date (as of May 1) ranged between 19 – 25 inches at these sites, or about 150-160% of the mean for that date.

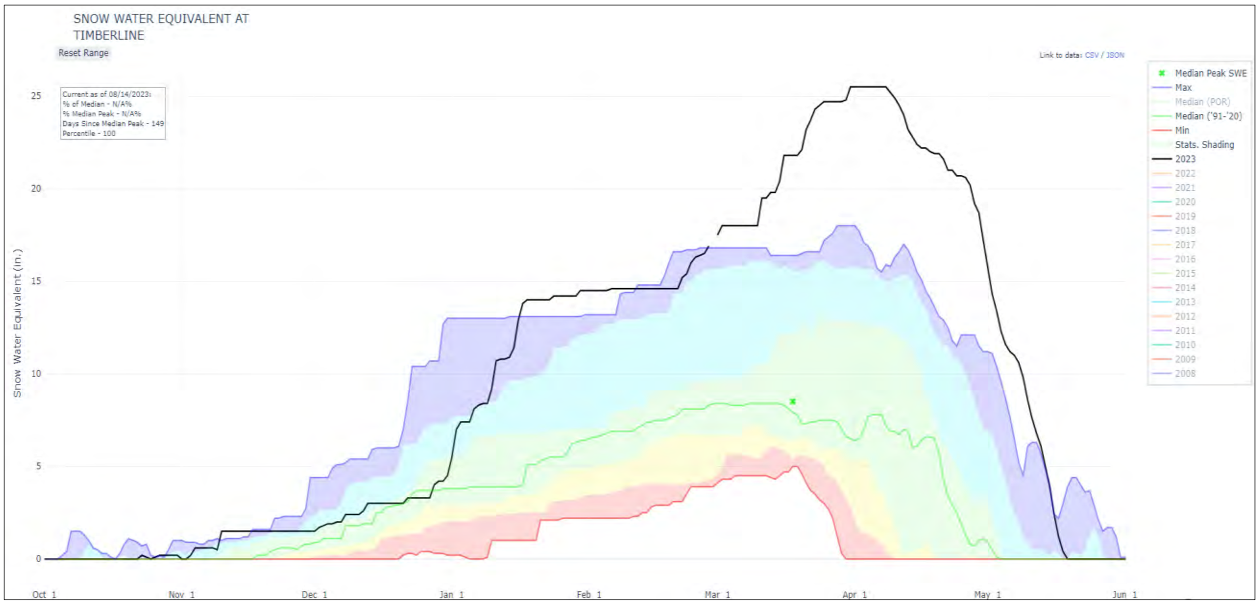


Figure 3.2. **Snow Water Equivalent (SWE) graph for Timberline site, October 2022-May 2023.**

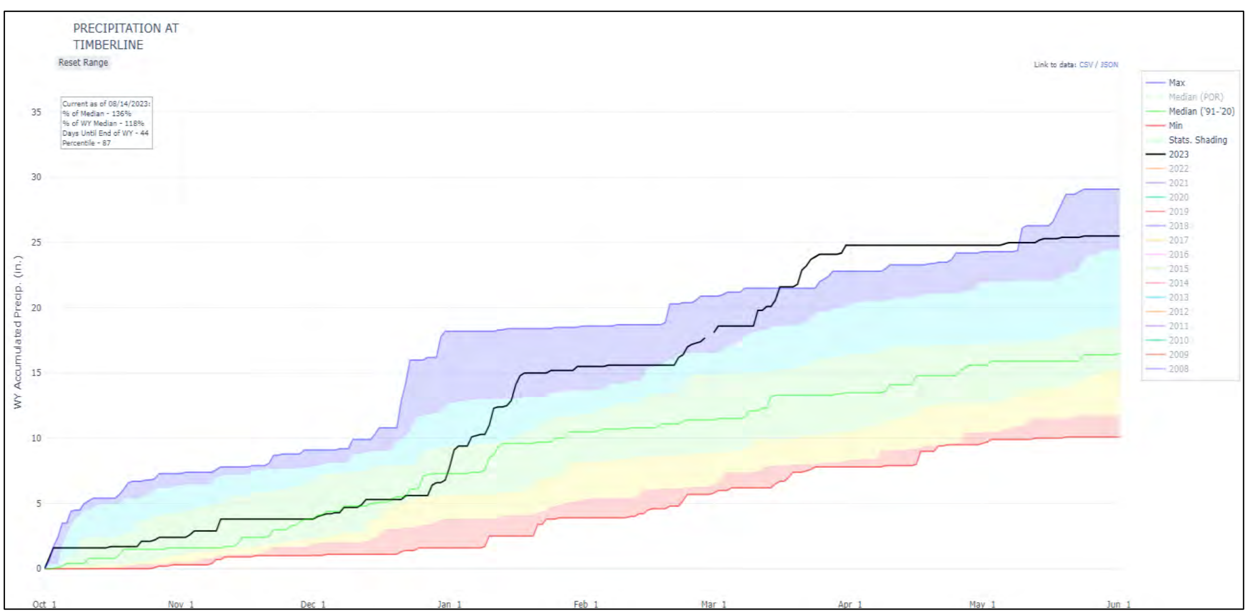


Figure 3.3. **Cumulative Precipitation graph for Timberline site, October 2022-May 2023.**

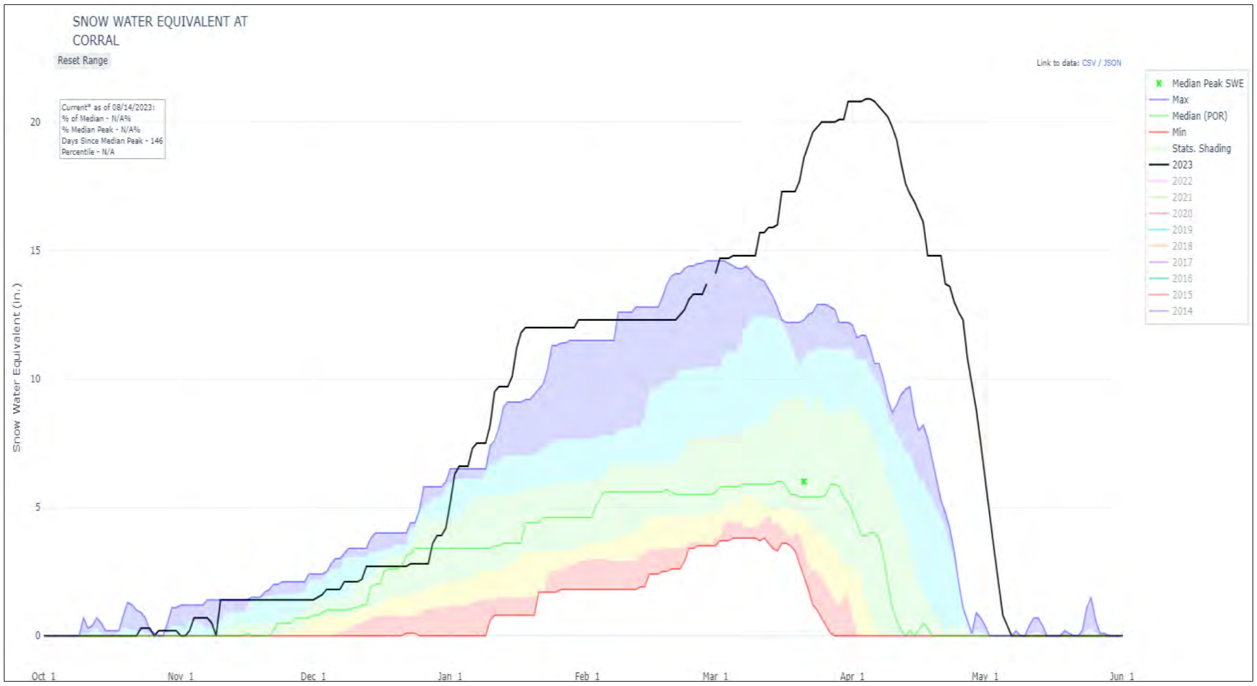


Figure 3.4. **Snow Water Equivalent (SWE) graph for Corral site, October 2022-May 2023.**

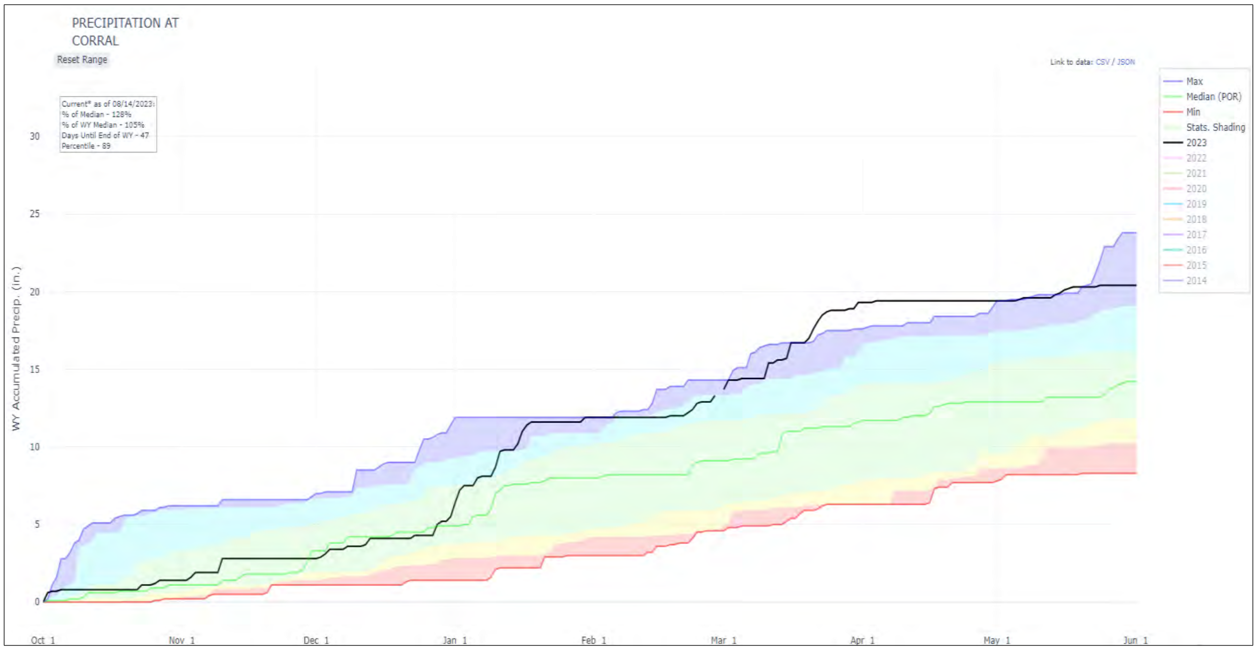


Figure 3.5. **Cumulative Precipitation graph for Corral site, October 2022-May 2023.**

A total of 13 seeded storm events occurred for the Book Cliffs program during the 2022-2023 season. Seeding activity during each of these events is shown in Tables 3-1a, b. A total of 414.25 generator hours were utilized during the season.

Table 3-1a
Summary of seeding operations during the season, storms 1-8

Storm #	1	2	3	4	5	6	7	8
	Nov 28-29	**Dec 2**	**Dec 11-12**	**Dec 28**	**Jan 5-6**	**Jan 10-11**	**Jan 14-15**	**Feb 5**
Woodhill		3.00	17.25	6.75	19.75	11.25	9.75	
Wellington	13.50			8.50	19.25	11.50	10	
East Carbon	13.25	3.00	18.00		20.50	11.50		4.00
Green River								
Storm Total	**26.75**	**6.00**	**35.25**	**15.25**	**59.50**	**34.25**	**19.75**	**4.00**

Table 3-1b
Summary of seeding operations during the season, storms 9-13

Storm #	9	10	11	12	13	Site Total
	Feb 21-22	**Feb 27-28**	**Mar 1**	**Mar 15**	**Mar 21-22**	
Woodhill	20.25	11.75	11.75		17.25	**128.75**
Wellington	24.75	13.00	9.50	9.25	18.25	**137.50**
East Carbon	20.25	12.25		9.50	19.25	**131.50**
Green River					16.50	**16.50**
Storm Total	**65.25**	**37.00**	**21.25**	**18.75**	**71.25**	**414.25**

3.1 Storm Summary

The first seeded event of the season took place on November 28; a large, deep trough of low pressure moved into Utah from the northwest. A cold front associated with the trough pushed into northern Utah during the morning hours, with a moist, unsettled northwest flow pattern translating in behind the front. A couple of sites were activated in the evening. Convective snow showers continued into the overnight hours, ending by the morning of the 29th, at which time all sites were shut off. SWE totals of 0.1-0.5” were recorded. 700 mb temperatures had fallen sharply and were around -15°C by the time the generators were shut off.

Late on December 1/early on December 2, a trough of low pressure pushed into Utah while weakening and lifting northward. Strong winds associated with the trough were mixing down to the surface in some areas, primarily across west-central Utah. A cold front accompanying the trough swept across the state with a band of heavy snow along and behind the front, lasting a couple of hours. Two sites were activated for the event. Observations indicated more ice in the clouds compared to supercooled liquid water (SLW). SWE amounts were generally less than a half inch.

On December 11, an upper level trough was located over the West Coast states and was slowly pushing eastward. Strong winds ahead of the trough were spreading across Utah, with 700 mb (approx. 10,000 feet MSL) southwesterly winds of 45-55 knots mixing down to the surface. A diffluent region ahead of the trough axis spread across Utah during the day, promoting large scale lift and subsequent precipitation development. Precipitation arrived in the Book Cliffs that evening, with a brief lull overnight into the morning of December 12, when a second burst of snow developed and affected the area through early afternoon. Given the prevailing wind direction, two sites were activated in the evening of the 11th and continued into the early afternoon of the 12th. SWE amounts of 0.5-1.0 inch were reported across the Book Cliffs.

A trough of low pressure approached the area on December 27th, with warm mid-level temperatures at or just below freezing. Moisture availability was good, with precipitable water (PWAT) values of 0.6-0.8 inches observed across Utah. Initially stratiform rain and snow was observed, but once the cold front and trough axis moved through, colder air aloft pushed in making for better seeding conditions. Sites were activated, running from late morning into the early evening as convective snow showers moved across the area. Overall, new SWE totals under a half inch were reported.

On January 5, a trough of low pressure was located over California accompanied by an atmospheric river of moisture. These features were moving towards Utah, with the atmospheric river feed weakening as it approached. Broad upper level diffluence on the forward/east side of the trough was spreading across the state which was increasing large scale lift resulting in the development of areas of precipitation. Low level stability was an issue during the first part of the storm event across many of the valleys in the state, including Castle Country, and as such seeding operations initially were held off until evening when it appears temperatures aloft were beginning to finally cool. Three sites were activated during the evening and continued to run overnight into the morning hours of January 6. Additional convective development by late morning into the afternoon hours allowed for seeding operations to continue. Activity began to wane by late afternoon and sites were shut off. SWE totals of a half inch to inch were reported in the Book Cliffs target area.

A trough of low pressure moved across Utah on January 9 bringing rain and gusty south and southwest winds within a warm advection regime, unfavorable for seeding as it increased stability across the area. A second disturbance in its wake moved into Utah on January 10 accompanied by a cold front and band of convection. The front and associated convective band crossed the state during the afternoon and evening hours of the 10^{th}, with west to northwest flow developing in the wake of the front which promoted additional convective development (snow showers) that affected the Book Cliffs target area. Three sites were activated on the evening of the 10^{th} and continued to run overnight as snow showers continued to move across the area, ending early in the morning of the 11^{th}. SWE totals for this event were in the 0.5-1.5 inch range.

On January 14, an upper level trough over the West Coast was moving east toward the Intermountain West, accompanied by a strong upper level jet (150+ kt) and upper level diffluent flow. Precipitation entered southwest Utah during the afternoon, spreading north and east into the Book Cliffs region by evening. Early on in the event, area observations and the nearby sounding from Grand Junction indicated a stable layer at low elevations that was expected to remain through the night before eroding in the morning on the 15^{th}. With snow shower development occurring over the Book Cliffs, the Woodhill and Wellington sites were activated and ran through the day as snow shower activity continue to move across the target area. Sites were deactivated by evening as precipitation came to an end. SWE totals for this event were in the 0.5-1.0 inch range. Beyond this event there were a few more storm systems to affect the area in January, but a combination of poor wind direction and unfavorable temperatures did not provide any additional seedable events for the remainder of the month.

On February 5, a trough of low pressure over the West Coast was forecast to move east/southeast towards Utah. Moisture quality with this storm was not great, with PWAT values of 0.25-0.40 inches tied to the cold front. Once the cold front crossed the area during the afternoon, a period of moist, unstable westerly flow resulted in scattered snow showers across parts of the Book Cliffs target area, and one site was activated for a period of time from late afternoon through mid-evening. SWE totals for this event were on the low side, around 0.1-0.3 inches.

A cold trough of low pressure was digging southward across the western United States on February 21 accompanied by a cold front. Ahead of the front, strong southwest winds were in place across western and southern Utah with sustained winds of 30-40 mph with gusts to 70 mph. Somewhat lighter winds were in place across Castle Country but were still elevated. The front was located from around Vernal to near Price to Cove Fort by early evening, with snow beginning across the area. Sites were activated around this time and continued to run through the night as snow showers continued across the area. Convective activity continued in the morning of February 22, with clouds becoming more icy by midday as much colder temperatures aloft began to filter in. 700 mb temperatures dropped to -15°C by the afternoon, at which time sites were deactivated. SWE totals for this event were in the 0.5-1.5 inch range.

On February 27, an upper level longwave trough was digging southeast through the Pacific Northwest into the Great Basin, with a few embedded shortwave disturbances moving through the trough. An initial shortwave moved into Utah during the morning and early afternoon with snow across western, southern and northern Utah. A second shortwave approached in the evening, with additional snow over the Book Cliffs region; three sites were activated in the evening and ran overnight as snow continued, with a band of heavier snow towards the morning of February 28 as a cold front associated with the second shortwave disturbance began to cross the target area. Sites were shut off by mid-morning as snow came to an end. SWE totals for this event ranged from 0.5-1.0 inches.

On March 1, a trough of low pressure over California/Nevada was forecast to dive southeast while evolving into a closed low over the Desert Southwest near Las Vegas by evening. Southwesterly flow/diffluent flow aloft was in place over Utah, and this was contributing to lift and resultant areas of snow, one of which was over Castle Country and adjacent Book Cliffs. Surface winds were light west to northwesterly. Wellington and Woodhill sites were activated that morning and ran through the afternoon, shutting down by evening as precipitation came to an end. SWE totals for this event were around 0.5 inches.

On March 14, subtropical moisture was being drawn into the southern and eastern sides of an upper level trough over the West Coast. This moisture and associated warmer air began to move into Utah just behind a warm front that crossed the state bringing rain to a good portion of the mid and lower elevations of Utah. Mid-level temperatures were mild, ranging from 0°C to -3°C, a little too warm for seeding operations. The axis of the trough and associated cold front approached Utah on the morning of the 15th and crossed the state, bringing colder temperatures and a moist, unstable northwest flow. Seeding operations actually commenced during the warmer part of the storm on the morning of the 15^{th} as the operators were going to be out of the area for several hours, but before midday conditions became better for seeding operations. Seeding continued into the afternoon hours as temperatures aloft began to cool and precipitation became more convective. By late afternoon precipitation began to taper off, and seeding operations ceased. SWE totals for this event were in the 0.5-1.0 inch range.

The final seeding event of the season began on March 21. A large, cold upper low located off the central California coast was pushing slowly east and southeast. Widespread light rain and snow located within an area of good upper level diffluent flow was moving into southern and western Utah, spreading north and east throughout the day. Weakly stable conditions in some of the valleys, including Castle Country were in place in the morning, but modest heating helped to remove this by midday. Precipitation did not arrive in the Book Cliffs area until early evening, and this is when generator sites were activated. Precipitation continued through the night and into the following day, March 22 as south to southwesterly flow continued across the state. By early afternoon, precipitation was tapering off as moisture and lift were beginning to exit the area, and all active generators were shut off. SWE for this event ranged from 0.5-2.0 inches.

Monthly precipitation across Utah during the seeding season are shown in Figures 3.6-3.11.

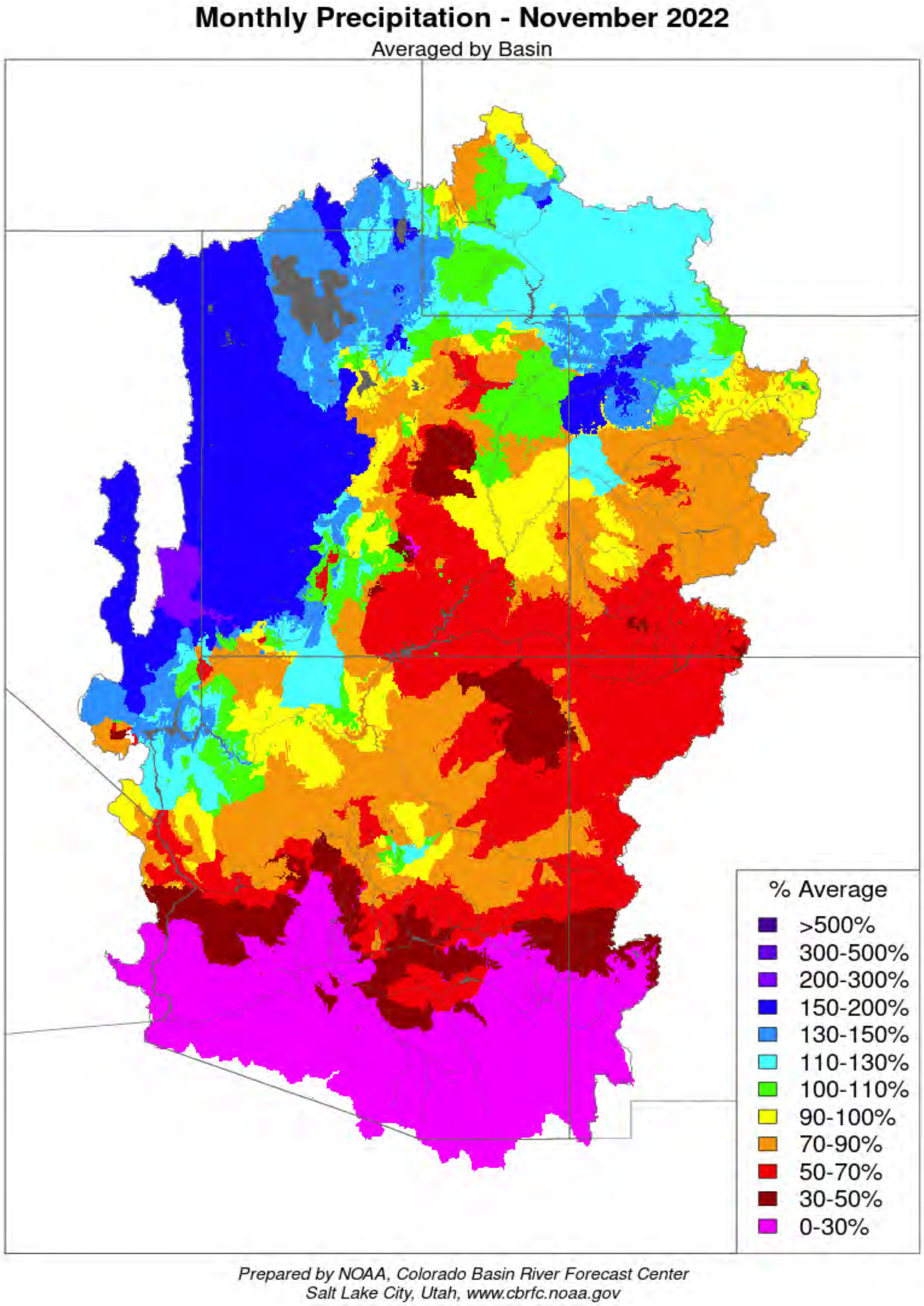


Figure 3.6. November 2022 precipitation, percent of normal.

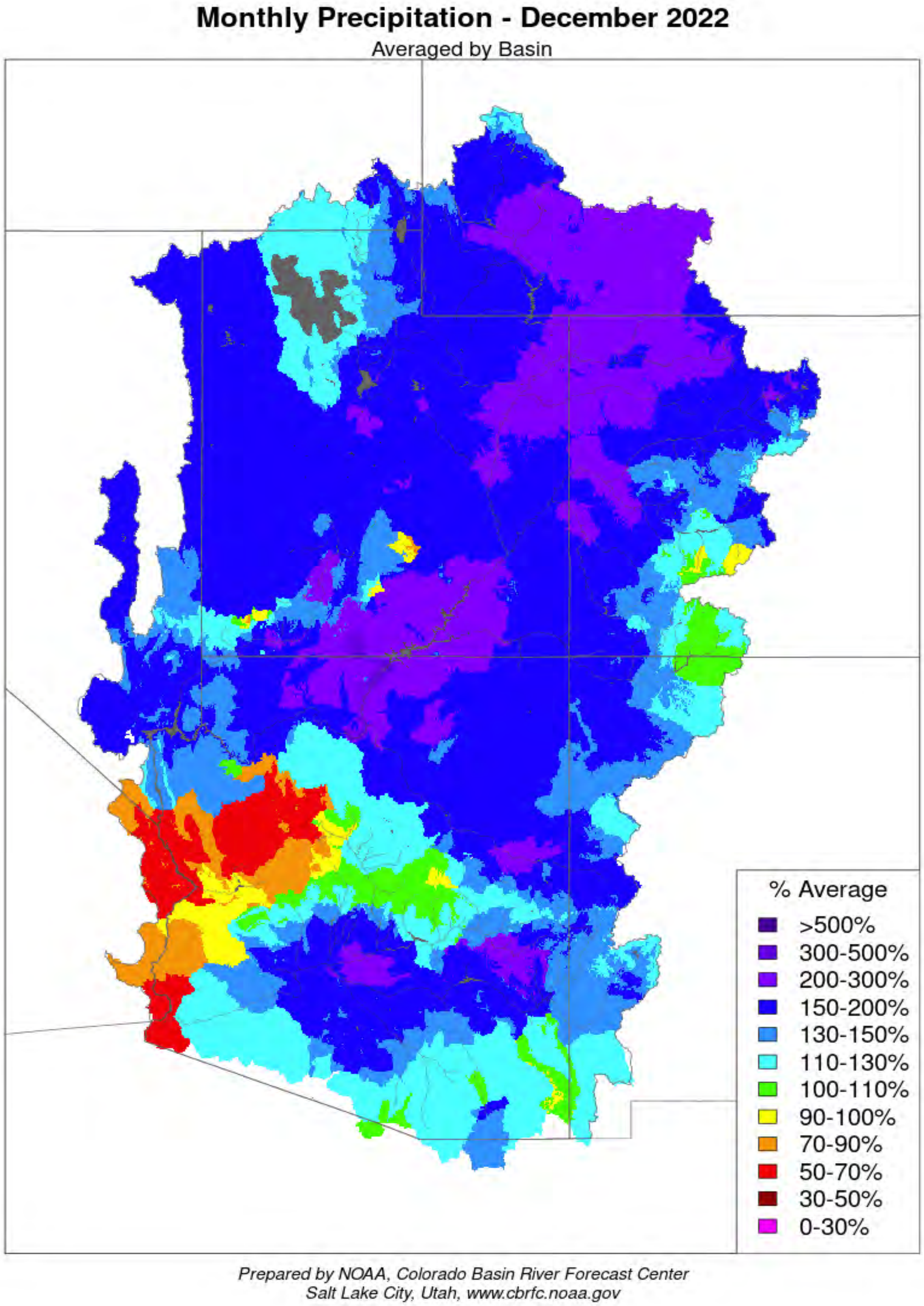


Figure 3.7. December 2022 precipitation, percent of normal.

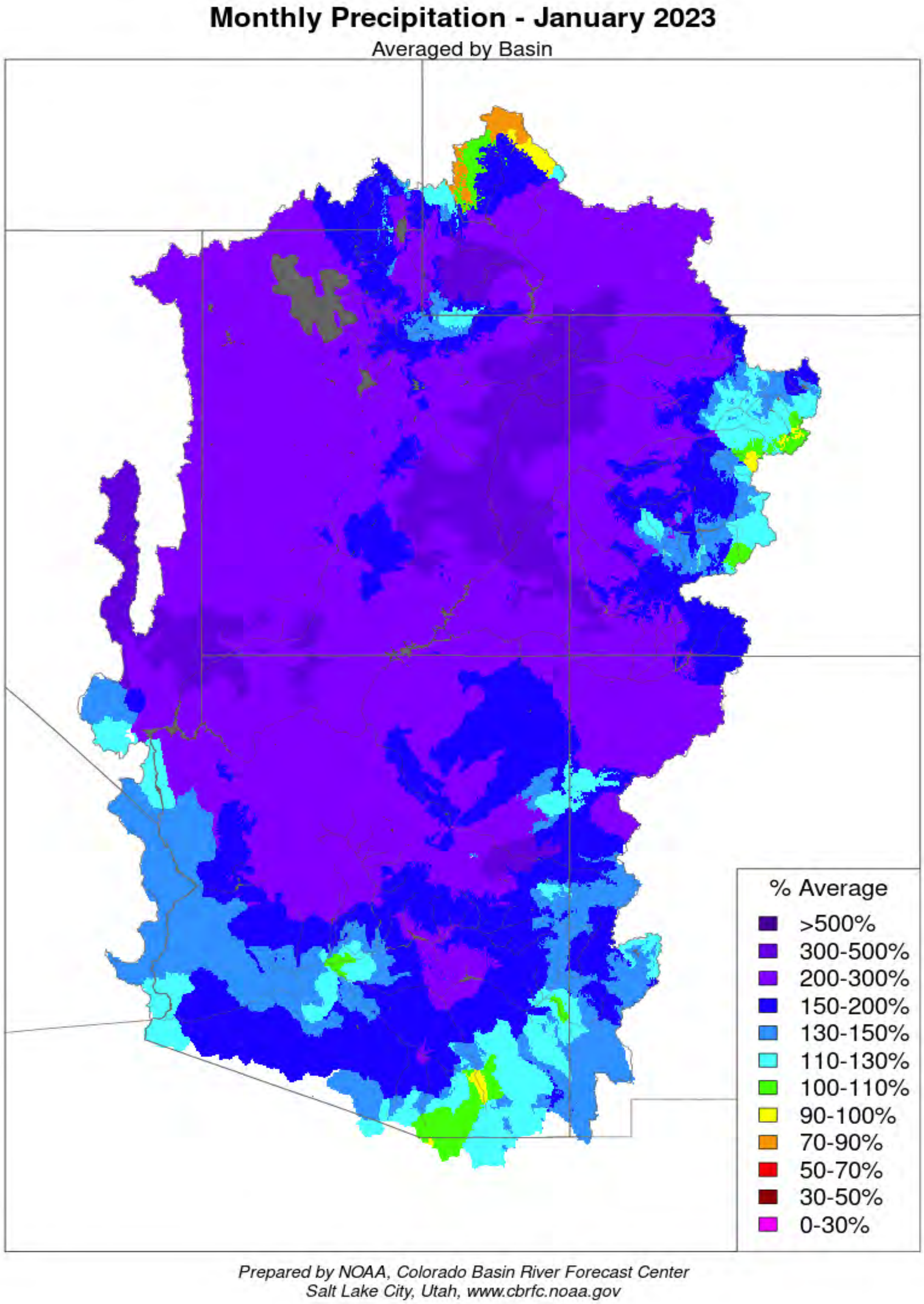


Figure 3.8. January 2023 precipitation, percent of normal.

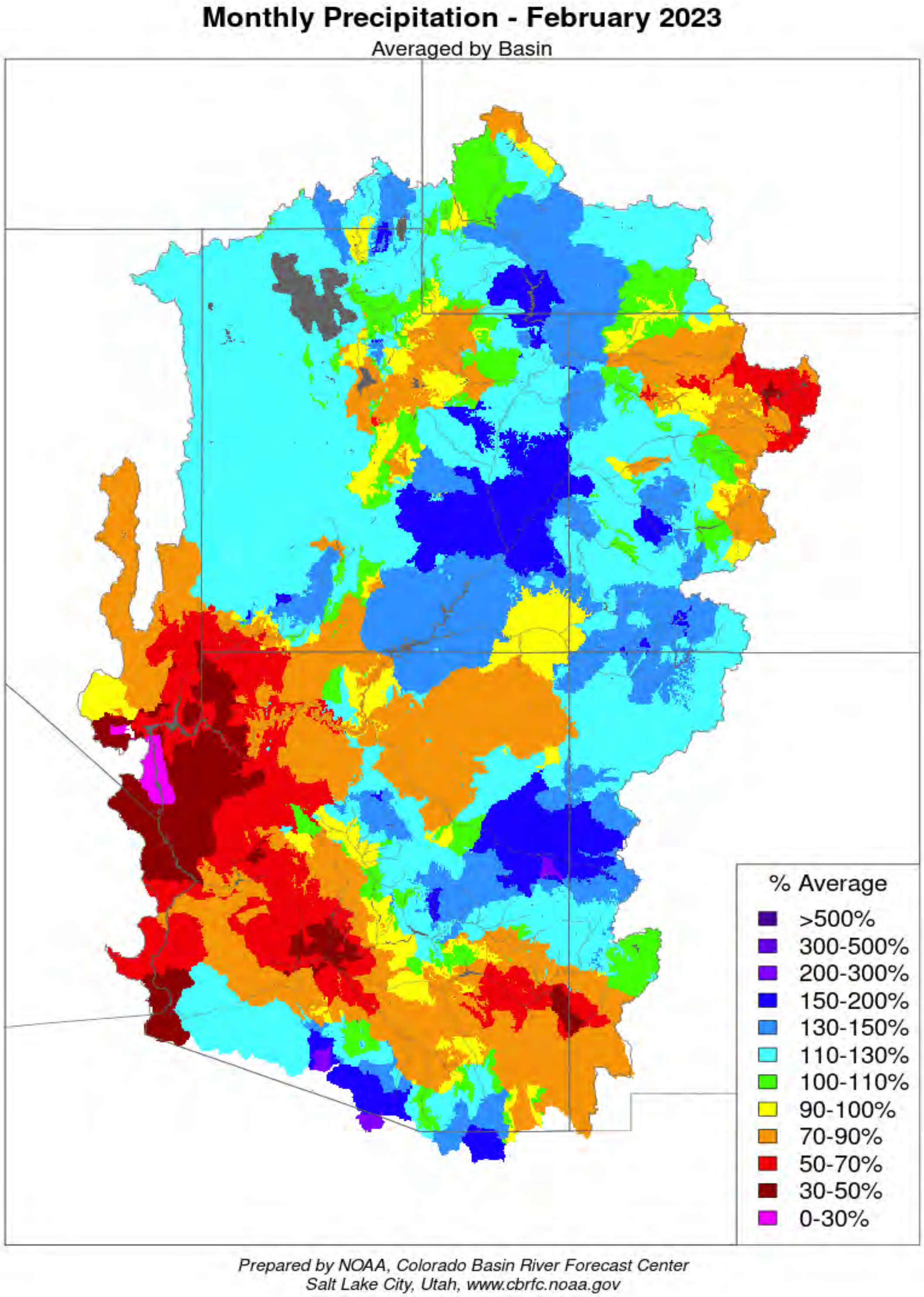


Figure 3.9. February 2023 precipitation, percent of normal.

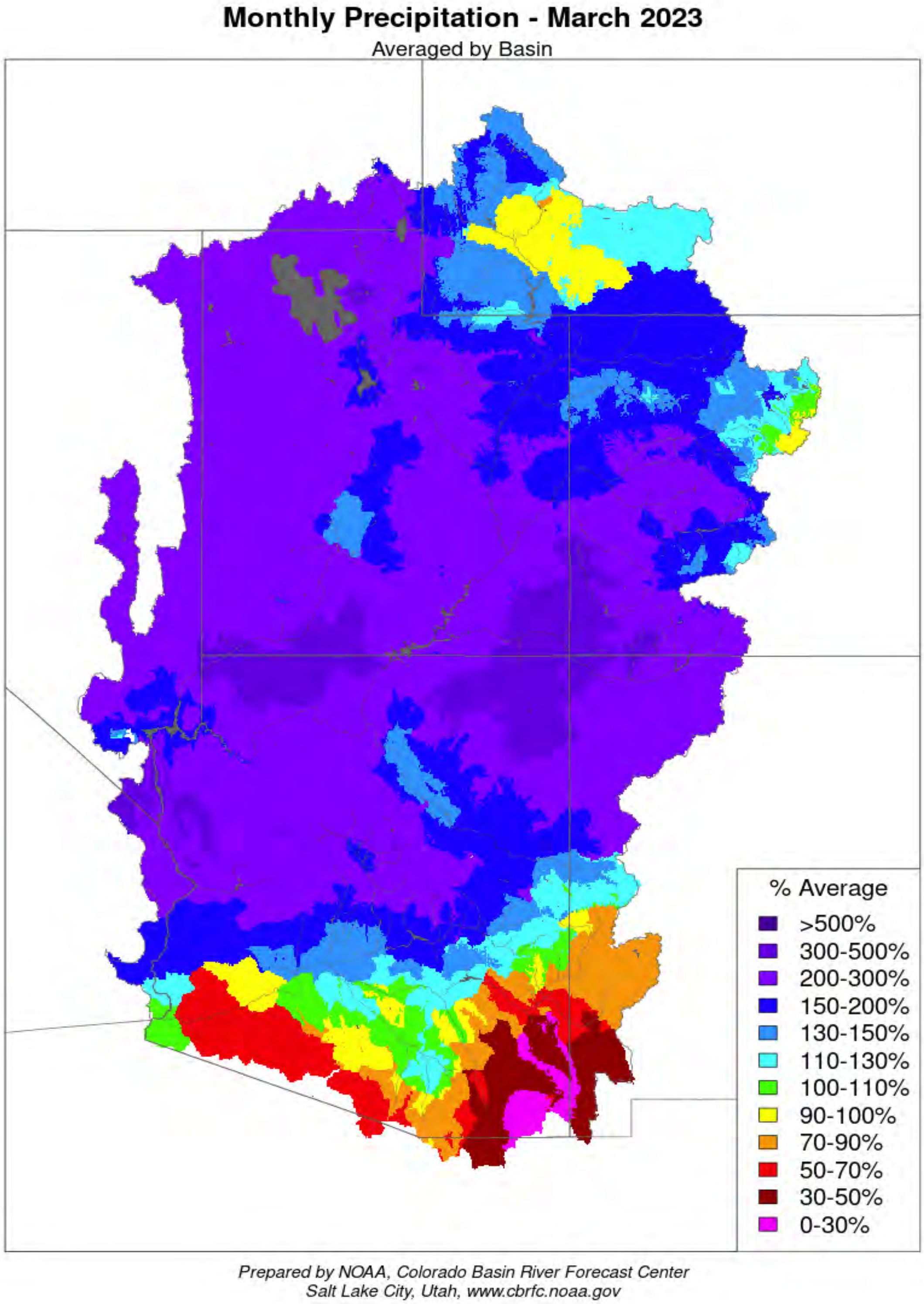


Figure 3.10. March 2023 precipitation, percent of normal.

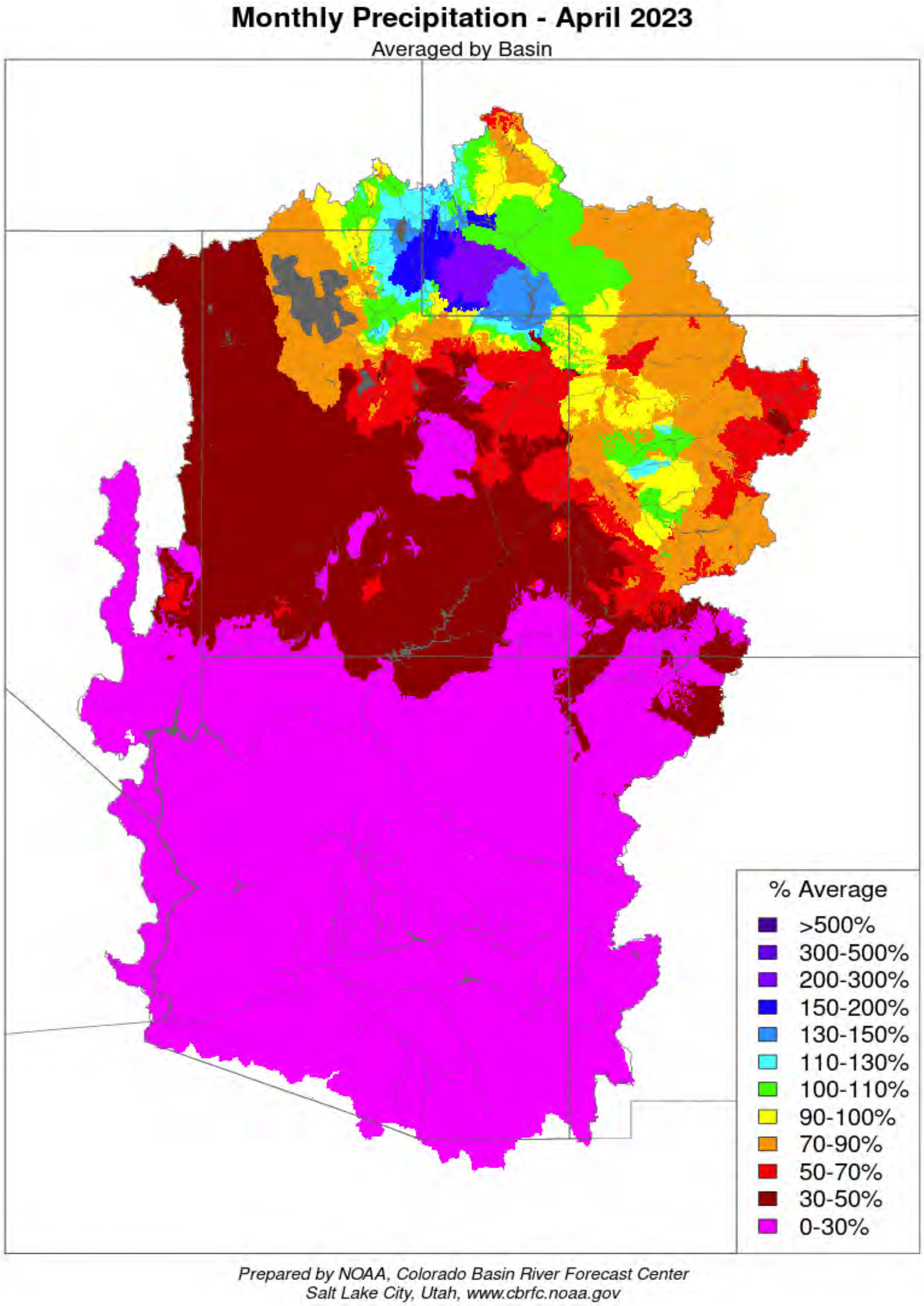


Figure 3.11. April 2023 precipitation, percent of normal.

4.0 TARGET/CONTROL EVALUATIONS

NAWC normally attempts target/control evaluations of its operational cloud seeding programs, utilizing SNOTEL data in and surrounding seeding target areas. This type of evaluation establishes an equation between one or more control sites versus target sites for a historical base period, which is a period of record before the start of a seeding program. This equation is then utilized to produce predicted natural values, in the absence of seeding, which can then be compared to observed values from the seeded periods. SNOTEL sites measure both accumulation water year precipitation from October 1 of each season, and snow water equivalent (SWE) values which normally peaks around March to early April in this area.

In a target/control evaluation, the control sites are those which would not be affected by seeding operations, at least not from those of the program being evaluated. Some of these sites may be affected by seeding from other programs in the state, in which case careful consideration must be given as to whether those effects would be consistent over time and allow a site to be used as a control. The target sites are those within the seeding target area, which may include one or more sites that are expected to be affected by seeding operations.

For the Book Cliffs target area, three potential target SNOTEL sites were considered (see Figure 1.1 in Section 1.0). Corral, at 8,207 feet elevation, has data only since water year 2014. The nearby Timberline site, at 8,736 feet, has data beginning in the 2008 water year. These two sites are near the geographic center of the seeding program target area. Another site, Indian Canyon, is located at the summit along Highway 191, near the Emma Park Road seeding site. This site is at 9,171 feet elevation and is one of the earliest SNOTEL sites with data beginning in the 1979 water year. However, it is located essentially along the edge of where seeding effects may occur with this program, and so it is not very suitable for either a target or a control site, as it may sometimes (but only occasionally) be affected by seeding.

For the Timberline (target) site, best-correlated control sites were selected that should result in reasonable target/control evaluations using a base (pre-seeding) period that includes water years 2008-2020, a total of 13 seasons. By far the best correlated control site appears to be Mosby Mountain, at 9,553 feet, on the southern flank of the Uinta Range. Although this site is within a seeding program, it has been included in this program consistently during this entire period and continues to be, such that it may still be a suitable control site given the long-term nature of the seeding program there. Another well correlated site is East Willow Creek, located further east on the Tavaputs Plateau. This site is at 8,302 feet, roughly 10 miles east of the Green River, and has data beginning in the 1987 water year. It would likely be largely unaffected by the Book Cliffs seeding program. A third site that was included is Camp Jackson, at 8,858 feet in the Abajo Range of southeastern Utah with data beginning in the 1986 water year. Figure 4.1 shows the target and control sites selected for this analysis.

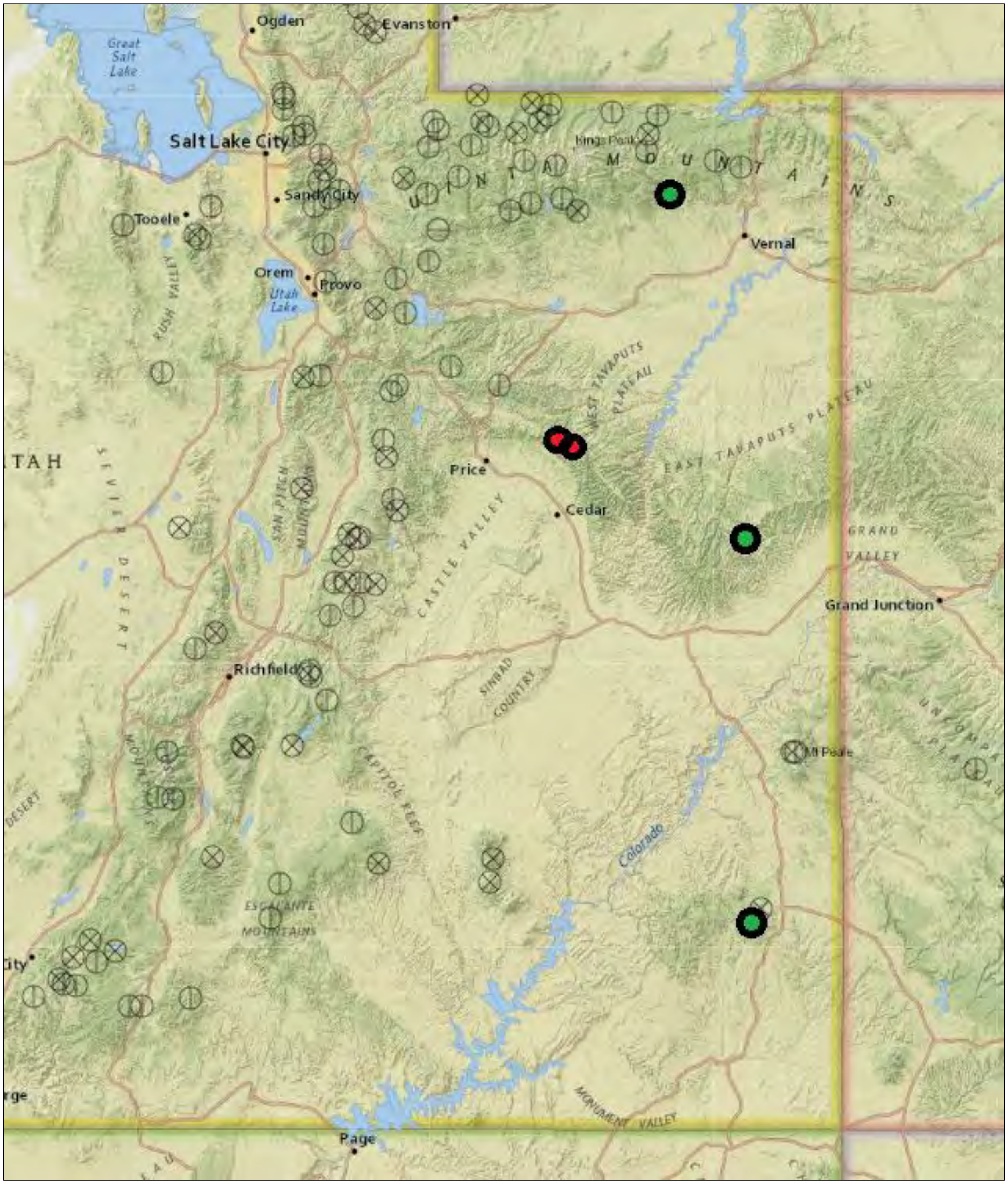


Figure 3.1. **SNOTEL map of central/eastern Utah with the Book Cliffs evaluation target sites (red) and control sites (green).**

For these data sets, both linear and multiple linear equations were developed. The linear regression compares two variables, in this case an average of the data from three control sites to the target site. The multiple linear regression uses a separate coefficient for each control site, allowing a more complex equation to be developed. For precipitation, the associated R values were high, 0.86 for the linear and 0.95 for the multiple linear. For snow (using SWE), April 1 data is typically used, but some years have a large amount of snow melt prior to this that can essentially invalidate the April 1 SWE for the purposes of this type of evaluation. For this reason, both April 1 and March 1 snowpack were examined. Using the same selection of target and control sites, correlations were good for both with R values of 0.92 and 0.98 (linear/multiple linear) for April 1 SWE and 0.95/0.97 respectively for (linear/multiple linear) evaluations of March 1 SWE.

These sets of equations were then applied to the 2022-2023 seeded season, the third season of seeding. For this type of analysis, single-season results do not have much mathematical significance, with the evaluation method becoming more meaningful for long standing programs (ideally, 10-20 years or more). Combined season results of this type typically show seeding program increases in the 5-10% range (based on seasonal precipitation or SWE) for most seeded mountain ranges in Utah. For the Book Cliffs program, the initial estimates made by NAWC were lower (3-5%) which is more similar to estimates for seeding in the Uinta Range. Application of the newly developed equations for the Book Cliffs program showed mixed results for the 2022-2023 single season. This suggests, as already expected, that there are not enough seeded data available at this point to produce any conclusive results for the Book Cliffs program. At the very least, it will likely be five seeding seasons before any initial statistics regarding the efficacy of the Book Cliffs program will be published in the yearly report.

5.0 CONCLUSIONS AND RECOMMENDATIONS

A total of 13 storm events were seeded in the Book Cliffs during the 2022-2023 season, the THIRD season for the seeding program in this area. There were a total of 414.25 seeding generator hours utilized. Precipitation was well above average this season, and several good seeding opportunities were realized for this program.

Given that the program has been active for only three seasons, and with a limited number of available seeding site locations, there are not enough data available at this point to provide any realistic estimates of the seeding effects achieved. The target/control evaluations unfortunately require a number of seeded seasons in order to make an estimate that has a reasonable confidence level.

The program sponsors may wish to continue this program on a regular basis, and not only during drought conditions. Drought periods usually offer less opportunities for seeding, and continuing seeding during wetter season can contribute substantially to surface and ground water resources and storage. The November – April period is considered to be the seasonal window for potential operations, although some portions of this period (particularly March – April) are likely to provide the best seeding opportunities for this area in a typical season.

Seeding sites should be located in areas which are ideal for targeting, based on prevailing wind patterns, and ideally should be above the valley floor to avoid shallow surface-based temperature inversions. It is also important to have site operators who are usually available, in order to effectively utilize the equipment. Land use issues and lack of residents in some areas of Utah can make this a challenge. Maintaining an adequate network of sites and operators should be a priority if the program continues to be active during the 2023-2024 winter season.

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:

- Excess snowpack accumulation
- Rain-induced winter flooding
- Severe weather

Excess Snowpack Accumulation

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

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

Snowpack-related suspension considerations will be assessed on a geographical division or sub-division basis. The NRCS has divided the State of Utah into 13 such divisions as follows: Bear River, Weber-Ogden Rivers, Provo River-Utah Lake-Jordan River, Tooele Valley-Vernon Creek, Green River, Duchesne River, Price-San Rafael, Dirty Devil, Southeastern 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.
- **Severe Thunderstorm Warning** – This is issued by the NWS when thunderstorms producing winds of 58 mph or higher and/or 1” or larger hail.

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 and Severe Thunderstorm Warnings are usually issued when intense convective activity causing heavy rainfall/strong winds/hail 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 April. The type of storm that may cause problems is one that has the potential of producing 1-2 inches (or greater) of rainfall in approximately a 24-hour period, combined with high freezing levels (e.g., > 8,000 feet MSL). Seeding operations will be suspended for the duration of the warning period in the affected areas.

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

APPENDIX B GLOSSARY OF RELEVANT METEOROLOGICAL TERMS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Precipitable Water, or PWAT: The total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending between the surface and top of the atmosphere, expressed in terms of the depth to which that water substance would be if completely condensed and collected in a vessel of the same unit cross-section.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

UTC (or GMT, or Z) time: Greenwich Mean Time, universal time zone corresponding to the time at Greenwich, England. Mountain Standard Time (MST) = GMT – 7 hours; Mountain Daylight Time (MDT) = GMT – 6 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