WINTER PARK CLOUD SEEDING PROGRAM
WATER YEAR 2021
FINAL REPORT

Final Report

Cloud Seeding Project for Winter Park for WY2021

Submitted to

Mr. Andrew Rickert
Colorado Water Conservation Board
1313 Sherman St, Suite 721
Denver, CO 80203
and
Mr. Doug Laraby
Planning Director
Winter Park Resort

By

Frank McDonough, Project Manager
Division of Atmospheric Sciences
Desert Research Institute

August 21, 2021

Cloud Seeding Project for Winter Park for Water Year 2021: Final Report

Summary

The Winter Park Cloud Seeding Program for Water Year 2021 was highly successful. Conservatively 3,625 acre-feet of snow water equivalent (SWE) was added to the local snowpack and 17.2” of additional fresh powder was added to the resort’s slopes.

The cloud seeding generators ran well over the winter and were mostly available for use when needed. There were 35 cloud seeding periods over the winter and a total of 178 generator-hours were accumulated. All of the available cloud seeding events were seeded by at least one generator and the identification of the seeding events by the forecast team was excellent, leading to a seeding efficiency of more than 97%.

The Target Control validation used 32 years of SWE data from the Berthoud SNOTEL and the Rabbit Ears SNOTEL site. The findings showed that the observed SWE in the Berthoud target area was 29% above the expected unseeded value.

Introduction

A cloud seeding program primarily targeting the Winter Park Ski Area and operated by the Desert Research Institute (DRI) has been conducted since Water Year 2010. The goals of the Water Year 2021 DRI cloud seeding efforts in the Winter Park/Upper Frasier Basin remain essentially the same from previous years: to enhance snowfall at the Winter Park Resort and to increase the snowpack and subsequent runoff in the Upper Frasier Basin through the application of wintertime cloud seeding technology. This report constitutes the summary of the project for Water Year 2021 (WY2021).

This project is funded by the Winter Park Ski Area and the Colorado Water Conservation Board (CWCB). Seeding is conducted from two ground-based high output cloud seeding generators (CSGs) positioned a few miles upwind (northwest) of the Ski Area (Fig. 1). The generators are placed at the highest altitudes possible and positioned to take advantage of the generally west-northwesterly to nearly north wind directions in winter storms in the northern Colorado Continental Divide area. The generators are remotely activated by DRI staff when the proper weather and cloud conditions for seeding were verified. Forecasting for potential cloud seeding events during (WY2021) began on November 1, 2020. Due to the previous year's droughts and low reservoir levels, seeding forecasting and operations were extended from the usual ending period of April 15 until April 30, 2021.

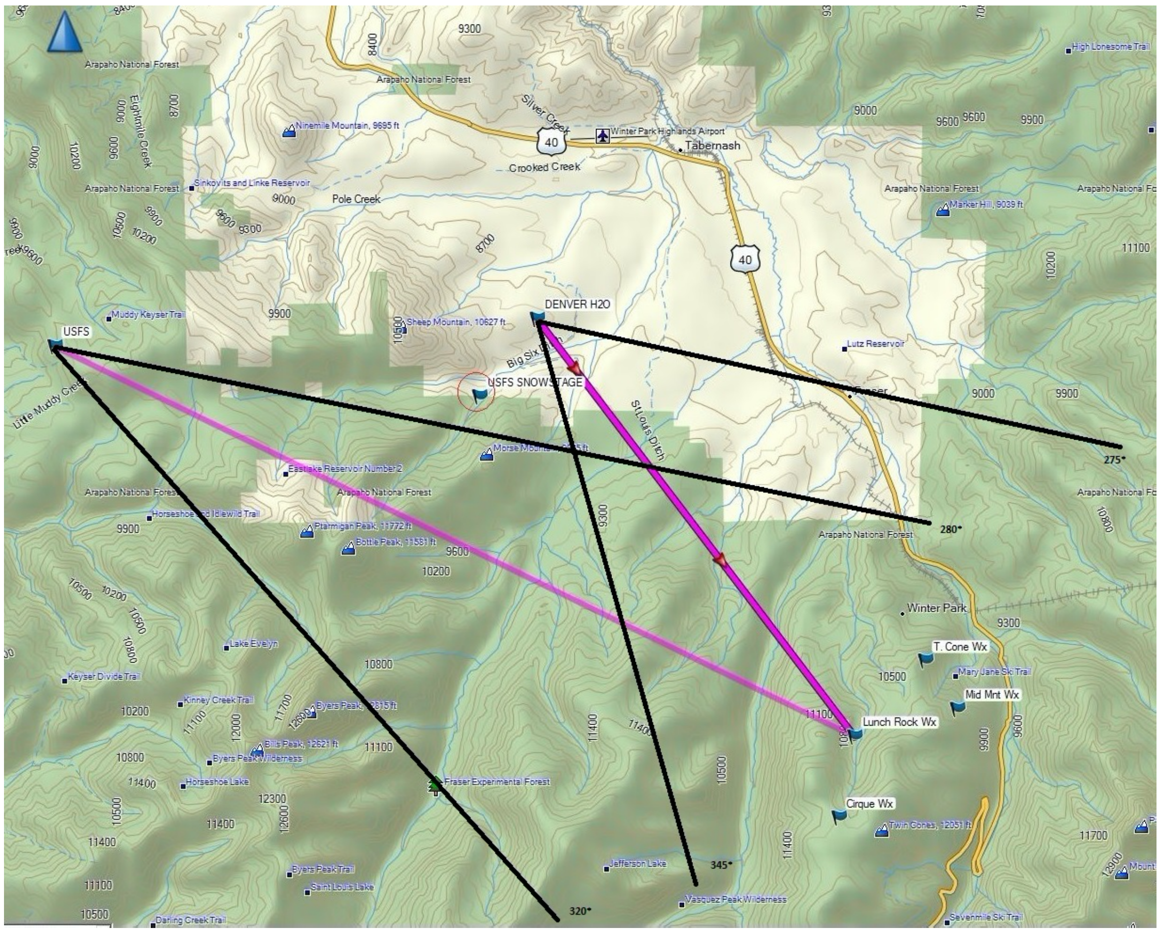

Figure 1. Map of Winter Park Target area, generator locations. The Denver Water (DenverH2O) and Blue Ridge (USFS) generator sites are shown along with the purple line extending to Winter Park (Lunch Rock). Black lines show the approximate range of wind directions to target the ski area.

The project is broken into three phases. Phase 1 included the work associated with the generators and other field equipment. Maintenance and installation of equipment was conducted in the preseason (before November 1) with weekly monitoring and continuing maintenance as needed during winter operations. A final late spring trip is required to transport one of the generators from USFS land into summer storage as required by the USFS land use permit. The Phase 2 work includes the 24/7 weather monitoring and forecasting, and generator operations for the WY2021 season. Phase 3 activities occur after the season has ended. These include a review and analysis of the winter weather and operations, estimation of the cloud seeding precipitation augmentation, validation of the seeding efforts and reporting on the results.

Phase 1

The same two permitted generator sites (Blue Ridge and Denver Water) were utilized as last year WY2020. The October 2020 Troublesome Fire delayed the installation of Blue Ridge generator, as the Arapahoe National Forest was closed and could not be accessed. Into late October. The generator was finally installed during the first storm of the winter in late October, but no propane deliveries were possible. The DRI technicians installed 2 100 gallons propane tanks to use for the winter. Both generators were filled with seeding solution and fully operational by October 31, 2020 (Fig. 2 and Fig. 3). Hardware and software upgrades were again installed to make the generators and remote operations more efficient and reliable. The in-house developed stepper motor flow metering and adjustment system installed in both generators have significantly improved performance and maintain the optimal flow rate. This system constantly monitors the flow rate of the solution to the burner and adjusts it if necessary due to fluctuations in tank pressure or temperature. This ensures the maximum production of ice nuclei from the generators. Another new feature implemented a couple of seasons ago was a stainless steel thermocouple sleeve that eliminated any corrosive/ heat wear and tear on the sensor, thus eliminating the ill-timed outages and required fieldtrips to replace them during the season. There were no sensor failures this year.

The generators were calibrated for flow rate at the nozzle and satellite communications were reinstalled at Blue Ridge and cellular at the Denver Water site. A new modem reboot system was installed to allow the satellite modem to reboot if the signal was lost. These communications systems worked reasonably well during the winter season, but there were a few periods with satellite communications problems at the Blue Ridge but these were resolved remotely and through the modem reset program.

The weather stations at the Blue Ridge and Denver Water generator sites were also tested and found to be operating properly. These observational platforms aid in real-time storm monitoring and also provide a unique data set for reporting and validation of the seeding effect. Software for the datalogger program was further updated to process the season's data and provide information for field technicians to use for maintenance and repairs. This data is available in realtime for reporting and validation.

Fig 2. Installation of Blue Ridge generator.

Fig 3. The Denver Water generator in October.

Phase 2

Cloud Seeding Operations and Assessing Associated Meteorological Conditions

Identification of winter clouds suitable for seeding requires a review and careful analysis of numerous, sometimes conflicting, data sources to determine when the meteorological parameters for successful cloud seeding are present. In general, for the meteorological parameters to be met, low-level clouds must be present across the area. Next the atmospheric stability profile must be favorable so that the seeding plume produced from the generators is able to mix vertically and reach the clouds. The cloud temperatures that the cloud seeding plume interacts with must be colder than -5^{o}C, and the clouds must also contain subfreezing liquid water drops. The final requirement is the winds must be favorable to deliver the cloud seeding plume and increased snowfall into the Winter Park resort.

The detection of clouds is through the use of satellite imagery, surface observations, or web cams. The temperatures and atmospheric stability is obtained though the relationship between observations from the generator weather stations and Winter Park weather stations at the mid, and upper mountain (Fig. 4). The cloud winds and temperature at the mountain top level is provided Winter Park weather stations. Output from the numerical weather prediction models can be useful as well.

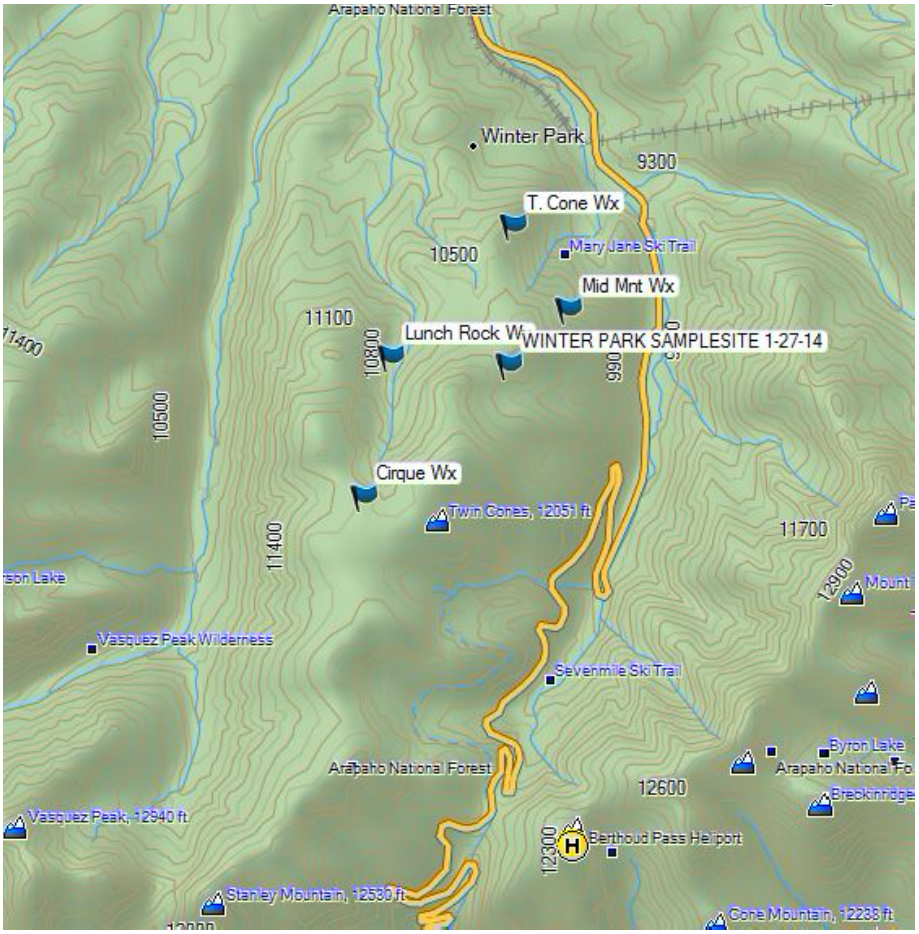

Fig 4. Winter Park Ski Area weather stations. The Cirque Wx and T. Cones Wx are primarily used to represent the weather in the seeding target area. Berthoud SNOTEL is along highway at bottom center of map.

The most challenging and critical prediction is the identification of the presence of subfreezing water drops (icing conditions). Cloud seeding cannot be effective in the absence of these cloud drops. Figure 5 shows an example of icing conditions. During WY21 a radiometer was installed at Winter Park and was very useful as a nowcast tool. The icing detector was installed at Eagle Wind and this data is still under QC review and was not used as a forecast tool.

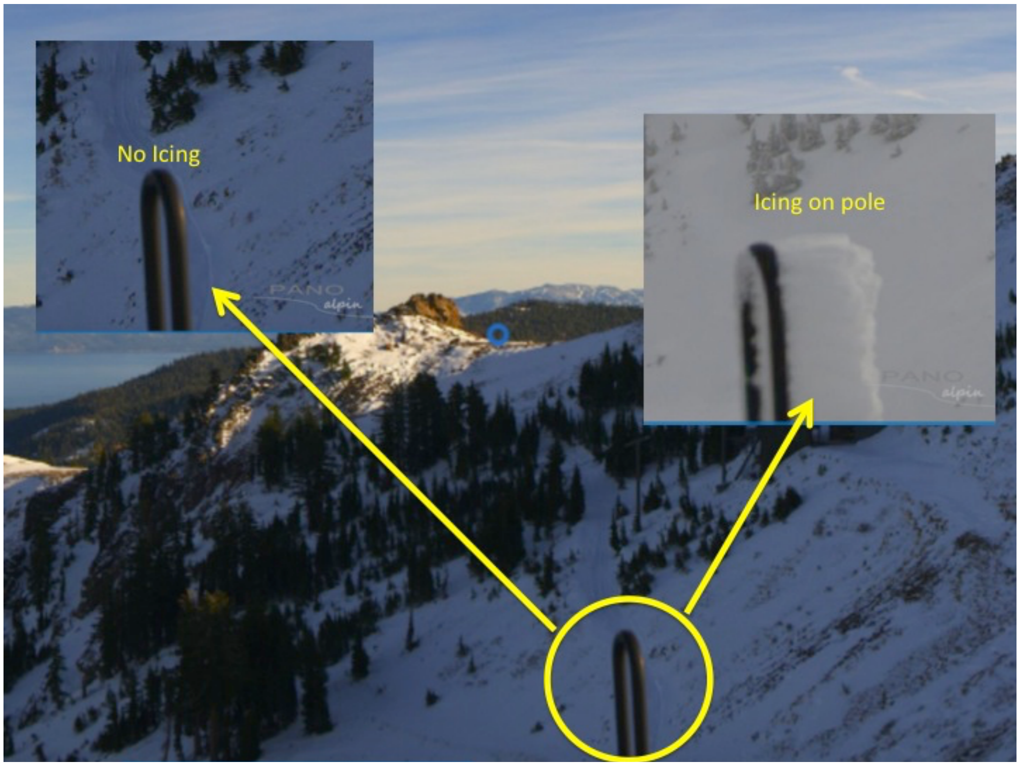

Figure 5. Example of mountain top icing conditions. The yellow circle shows the icing pole. The inset image on left shows the no icing conditions and the inset image on the right shows the results when icing (cloud seeding conditions) are present.

Summary

There were 35 cloud seeding operations with a total of 178 generator-hours (one generator-hour is one generator operating for one hour) (Fig. 6). Seeding events were spread across all the winter months, with March 2021 and December 2020. Having the greatest number of seeding opportunities. There were a few periods with satellite communications problems at the Blue Ridge site but the generator was frequently used (Fig 7).

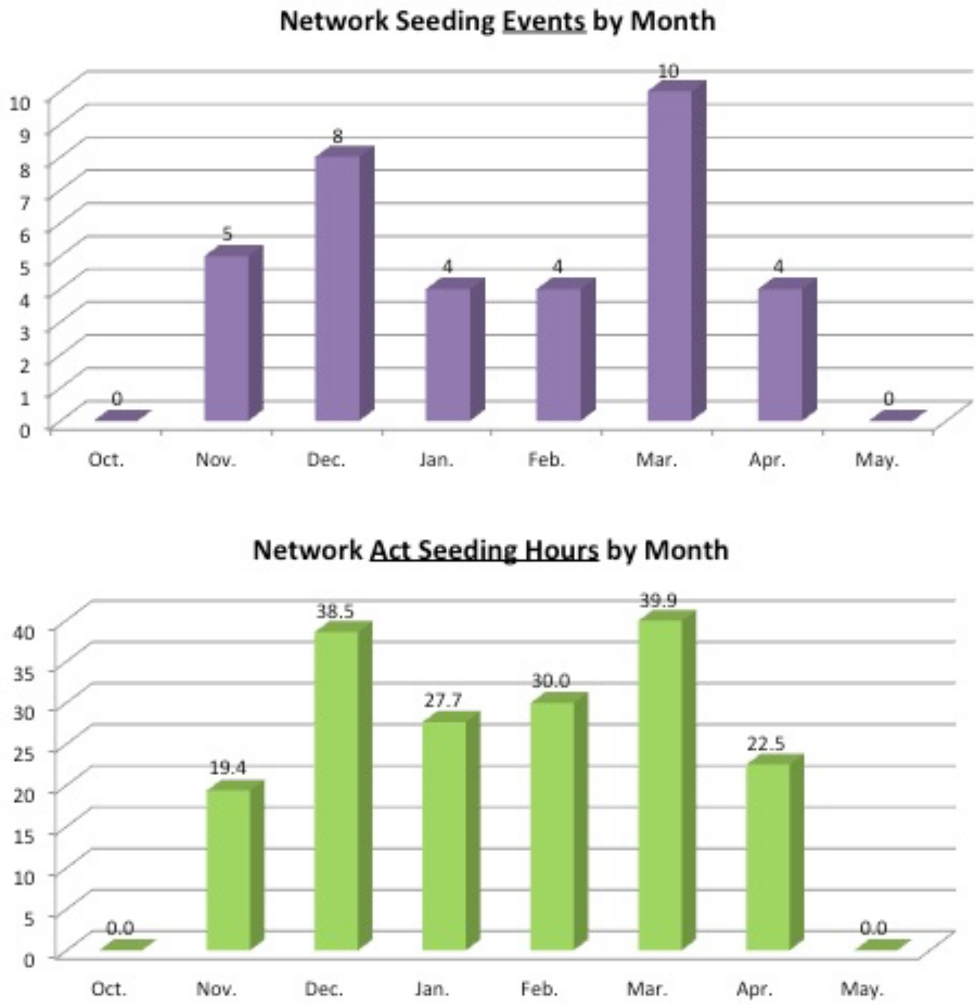

Figure 6. The number of cloud seeding events for WY2021. Events per month presented in the upper panel and the operational generators-hours per month lower panel

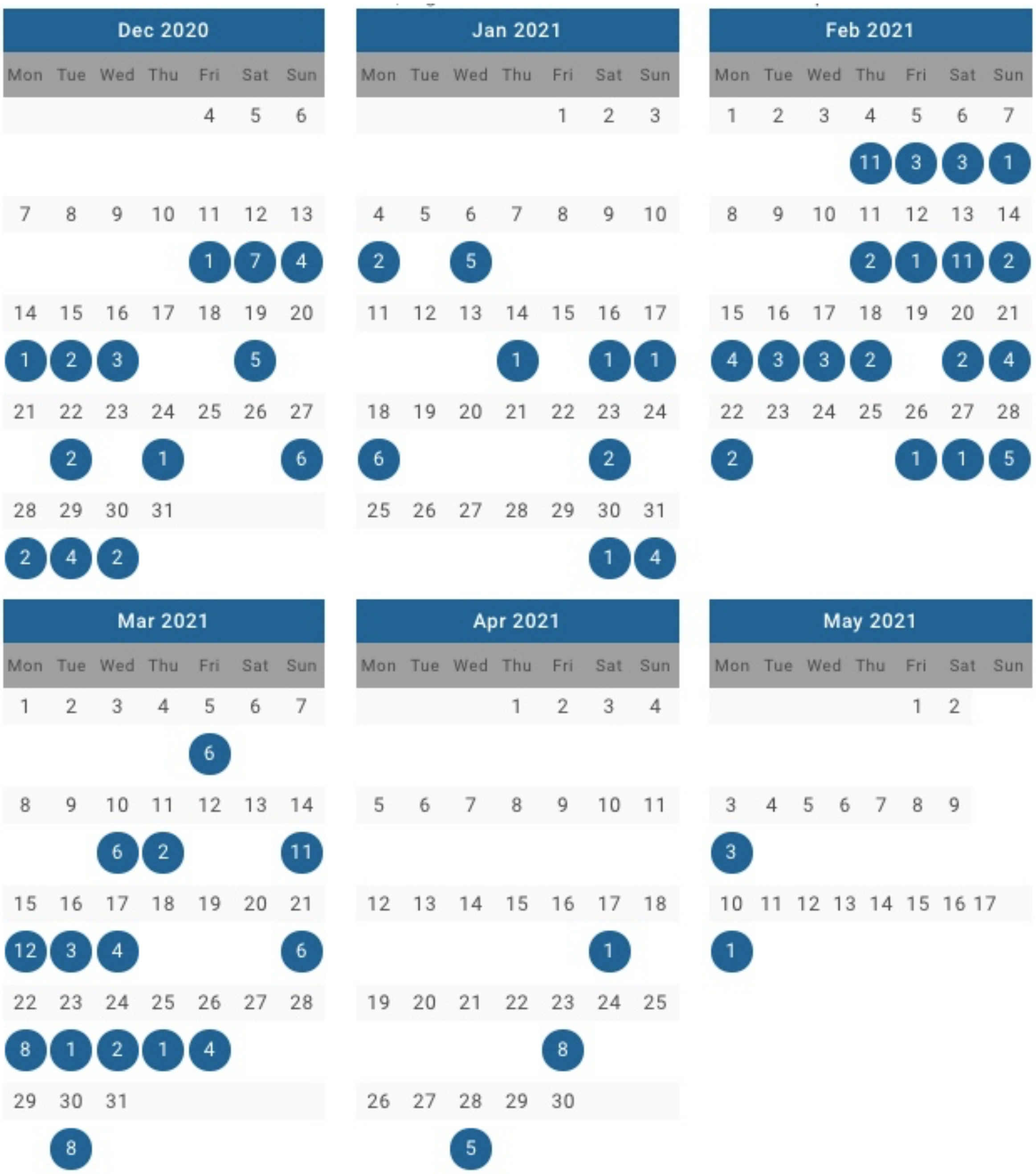

Fig 7. Summary of the daily 5 AM Winter Park 24-hour snow report by day for WY2021. Snow accumulations shown occurred over the previous 24-hours. Reports started on December 4, 2020.

November 2020

A strong cold front in late October dumped a foot of snow on the Troublesome fire, mostly putting an end to it.

Figure 8 shows the November 2020 time series of hourly weather observations at the Winter Park weather stations T. Cones (Cirque is also used) (see Fig. 4 for locations). Temperatures and winds are shown in the top two panels and the snow water equivalent (SWE) from the Berthoud Pass SNOTEL (at 11,300' MSL; see Fig 16 for location) is shown in the bottom panel. The gray bars are the time periods with active cloud seeding. The blue shading denotes favorable cloud seeding temperatures and wind directions in Figure 8.

During November 2.9" of SWE and 15" of snow was added to the snowpack at the Berthoud Pass NRCS SNOTEL site.

The cloud seeding season started on November 1, 2020 with the first significant storm moving in on November 8-10, 2020. The first half of the storm had unfavorable winds but the winds shifted as the cold front moved across on Nov 9 with 0.7" of SWE added to the Berthoud SNOTEL site. This portion of the storm was successfully seeded.

Very cold air was in place for the next storm on Nov 12, which added 0.3" of SWE at Berthoud. There were a couple of time periods during this weak storm where temperatures warmed enough for several hours of seeding.

On Nov 14 a fast moving cold front crossed the area adding 0.7" of SWE at the Berthoud SNOTEL. This storm had favorable winds and temperatures for seeding and the generators were operated.

After a ten-day dry period the final storm of the month arrived on Nov 24. This storm added 1.0" of SWE. The leading edge of the cold front was too warm to seed but the second half of the storm was seeded.

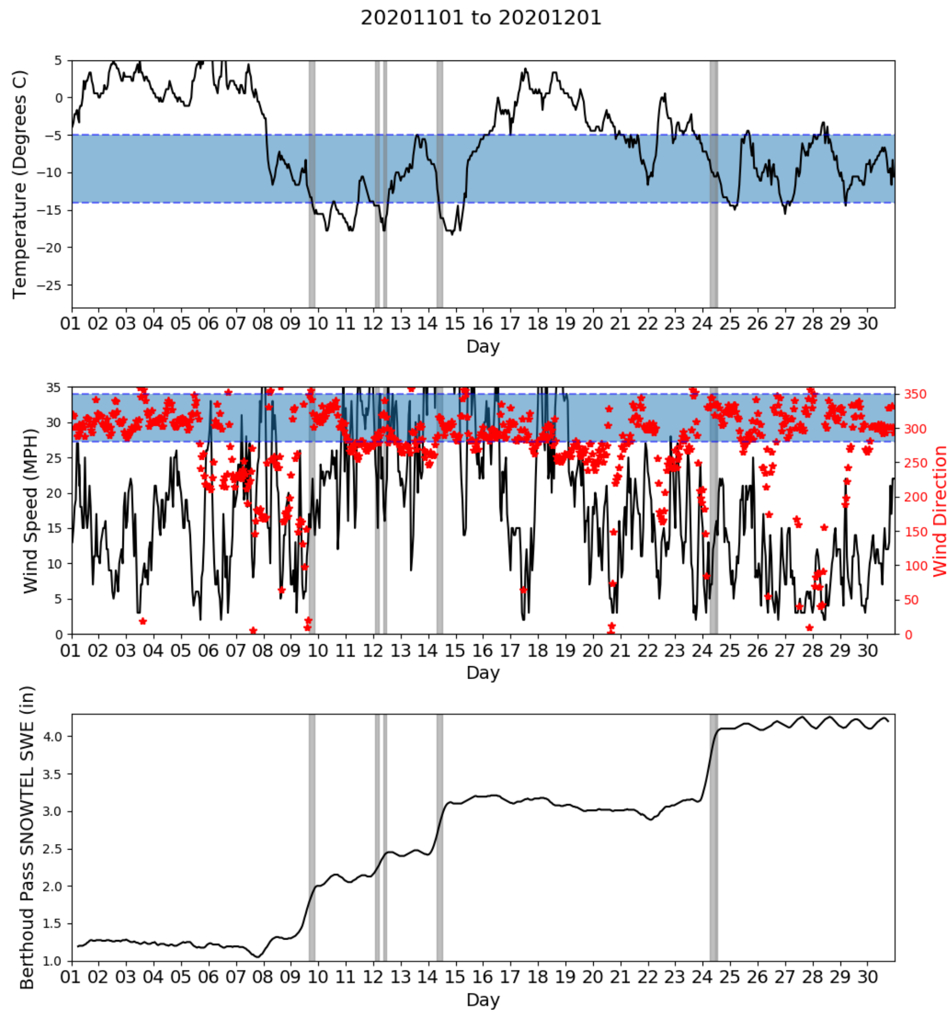

Figure 8. Monthly time series plot of weather conditions at Winter Park for November 2020. Upper panel shows temperatures at Winter Park T. Cones weather station (blue shading shows favorable seeding temperatures). Middle panel wind speed (black line) and direction (red dots) from T. Cones weather station (blue shading shows favorable wind direction band). Lower panel shows the smoothed hourly snow water equivalent (SWE) at the Berthoud SNOTEL. Gray vertical bars show cloud seeding periods.

December 2020

Daily (24 hour) snowfall data became available from the ski area starting on December 4 and are included in the below discussion.

December started with a fast-moving cold front moving through the area (Fig. 9). The portion of the storm with temperatures warmer than -15^{o}C was seeded as 0.2" of SWE was added to the snowpack.

After a dry 10-day period the next storm of the winter moved in on December 11. This weak storm added 0.3" of SWE and was seeded.

Over the next week Dec 12 – Dec 18 a series of fast-moving waves crossed from the northern Pacific across the region, adding 1.2” of SWE at Berthoud SNOTEL and 22” of snow at Winter Park. The weather conditions were monitored and the generators operated when weather conditions conducive to cloud seeding crossed the area.

Mostly dry weather was present between Dec 19 – Dec 22, with a weak fast-moving storm and associated cold front arriving late on Dec 22. This storm was seeded adding 0.4” of SWE at Berthoud and 2” of snow at the resort.

Another plume of increased moisture and associated cold front moved across the area under northwesterly winds on Dec 27. The event was seeded with 0.4” of SWE and 8” of snow at the resort.

The final storm of the month occurred overnight on Dec 28-29, winds remained unfavorable (southerly) for seeding this event.

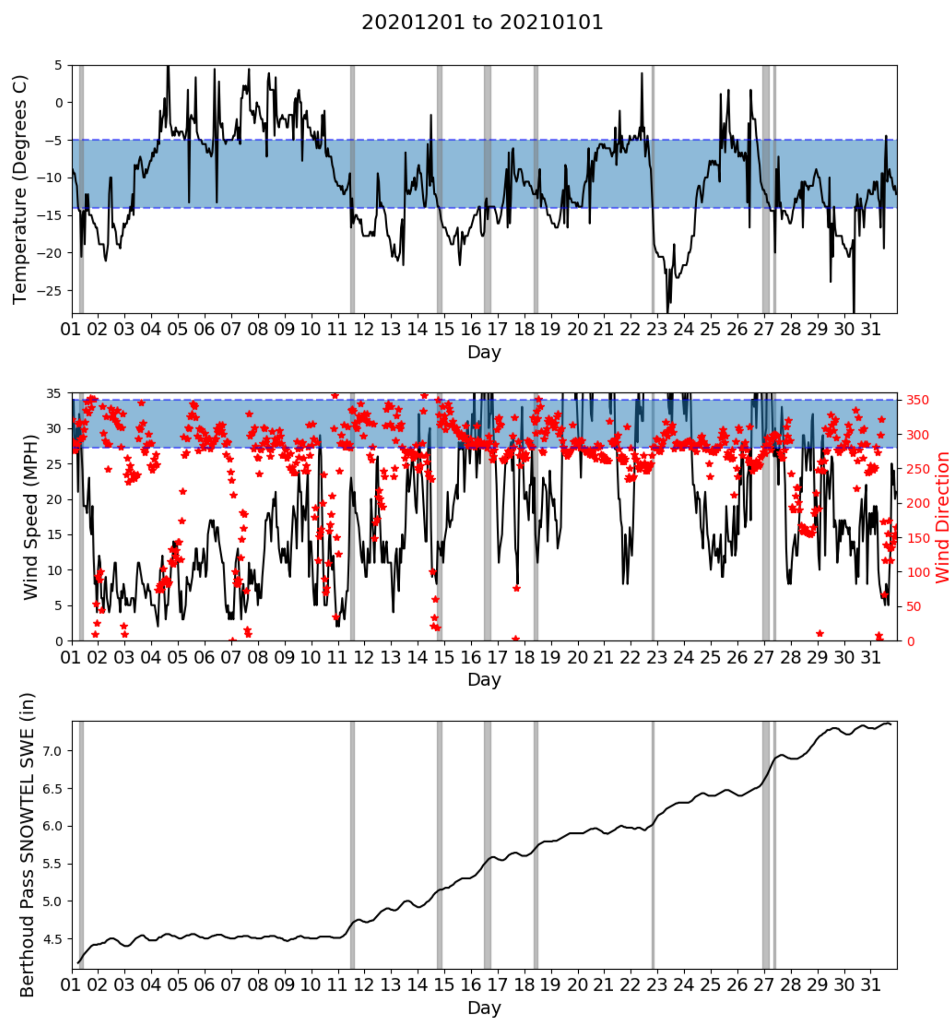

Figure 9. As in Figure 6 except Cirque weather observations for December 2020.

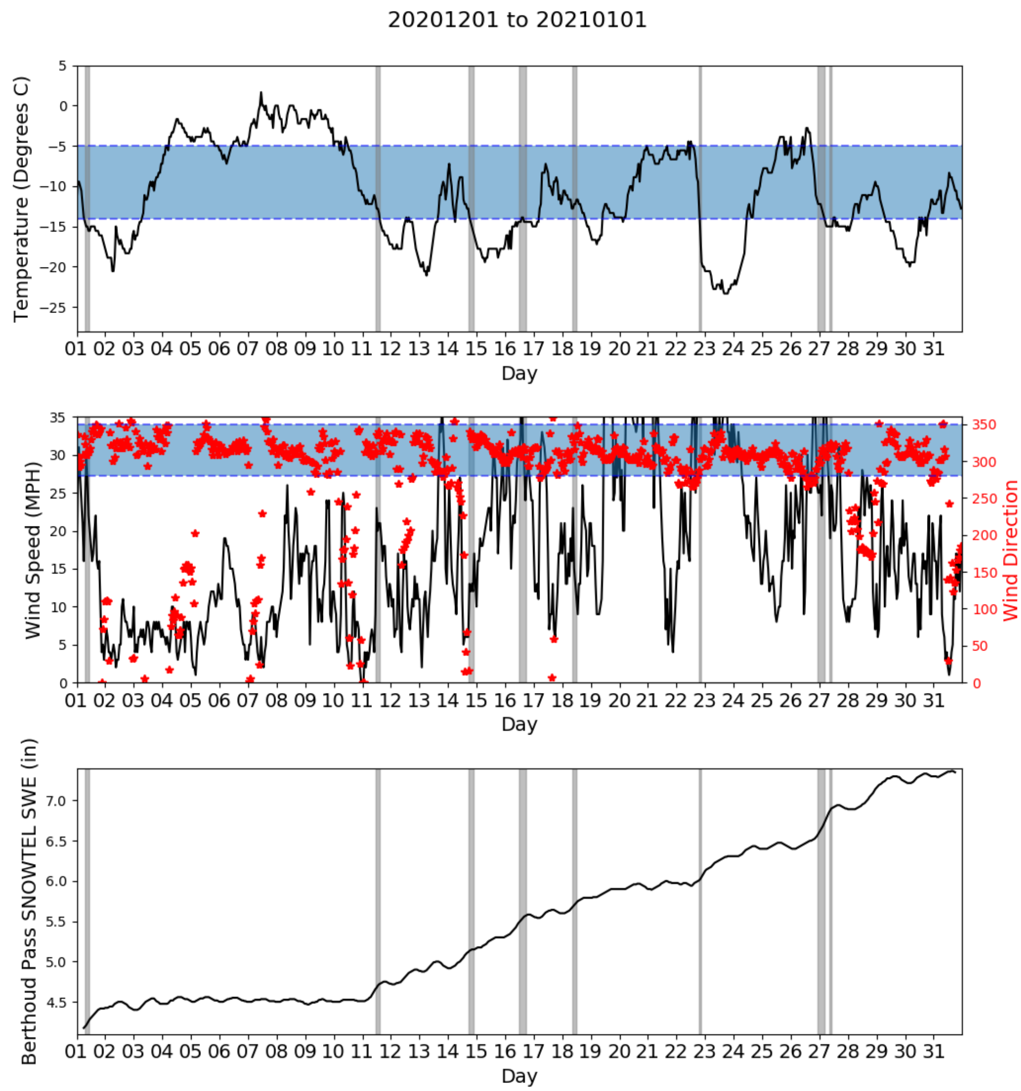

Figure 10. As in Figure 6 except December 2020, T. Cone weather station.

January 2021

January 2021 featured several storms with 4 seeded events (Fig. 11). The Winter Park Ski Area reported new snow on 9 days with 23" of fresh powder (see Fig 7). The Berthoud Pass SNOTEL added 1.8" of SWE.

On January 3 a weak cold storm moved across the area. Temperatures were marginally too cold for seeding and the amount of supercooled liquid water appeared to be limited so this event was not seeded.

A second cold front crossed the area on Jan 5, adding 5" of snow to the ski area and 0.3" of SWE at Berthoud SNOTEL. The event had favorable clouds, temperatures and winds and was successfully seeded.

Dry conditions with some melting were present until mid-January when the next storm moved into the area. Seeding was conducted on Jan 16 and late on Jan 17, with 0.8” of SWE at Berthoud SNOTEL and 8” of snow at Winter Park.

The ten-day period between January 19 and Jan 29 was mostly dry but had some light snow, 2” at Winter Park and 0.3” of SWE at Berthoud.

The last storm of the month occurred on Jan 30 as a low crossed southern CO. Winter Park reported 5” of snow with this storm and Berthoud SNOTEL reporting 0.3” of SWE.

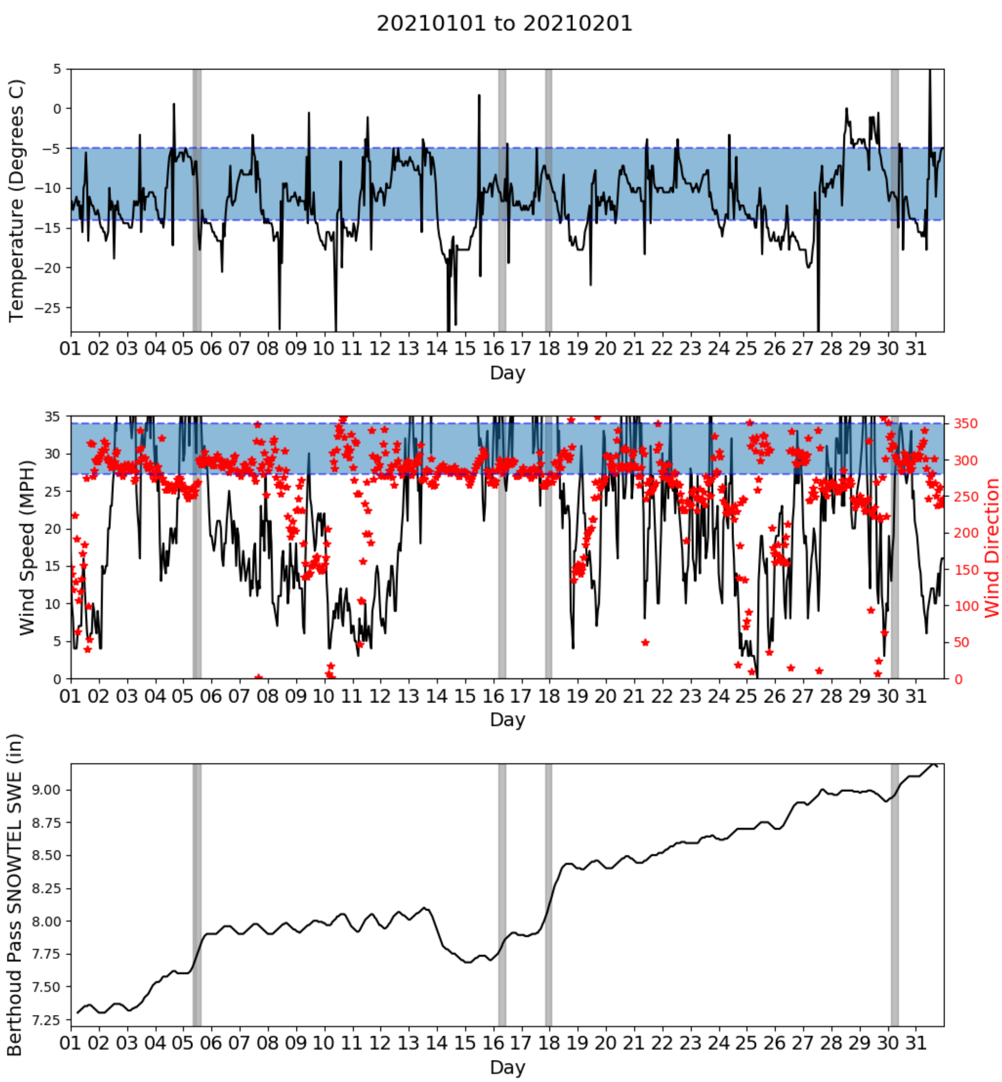

Figure 11. Cirque weather station as in Figure 5 except for January 2021.

February 2021

February had several storms and a long-lived period of cold and light snow (Fig. 12). Over the month, Winter Park added 61” of snow and 3.5” of SWE was added to the snowpack at the Berthoud SNOTEL.

The first seeded storm came through as a very strong cold front starting in the late morning of February 3 and lasted into the early morning of February 4. Winds started from the west but then became northwest and temperatures cooled from +4C to colder than -20C. SWE at Berthoud SNOTEL increased by 0.9 inches during this event. Snowfall accumulation was significant at Winter Park with 11 inches being reported during that time period.

The following several days featured new snowfall accumulations from fully glaciated clouds at temperatures well below the favorable cold seeding range.

The second seedable storm came through in the afternoon of February 12 and lasted through the morning of February 13. SWE at Berthoud SNOTEL increased by 0.5” with this system. Total snowfall accumulation with this system at Winter Park was 1 foot. Temperatures were between -7C and -12C, and winds from the west and northwest. Seeding was conducted during the storm periods with the winds from the northwest.

Following the Feb 13 storm a cold airmass, temperatures colder that -15C (5F), covered the resort and Berthoud Pass area. In addition, a 30MPH northwesterly wind was present much of the time. Light orographic snow was observed on 5 consecutive days and 1.0” of SWE was added at Berthoud SNOTEL.

On the afternoon of Feb 20 temperatures warmed as a new moderate storm moved towards the area under westerly winds. The cold front arrived in the evening, bringing winds back to northwesterly and sending temperatures from -5C to -20C. Much of this period was seeded. The ski area added 6” of snow and 0.2” of SWE at Berthoud.

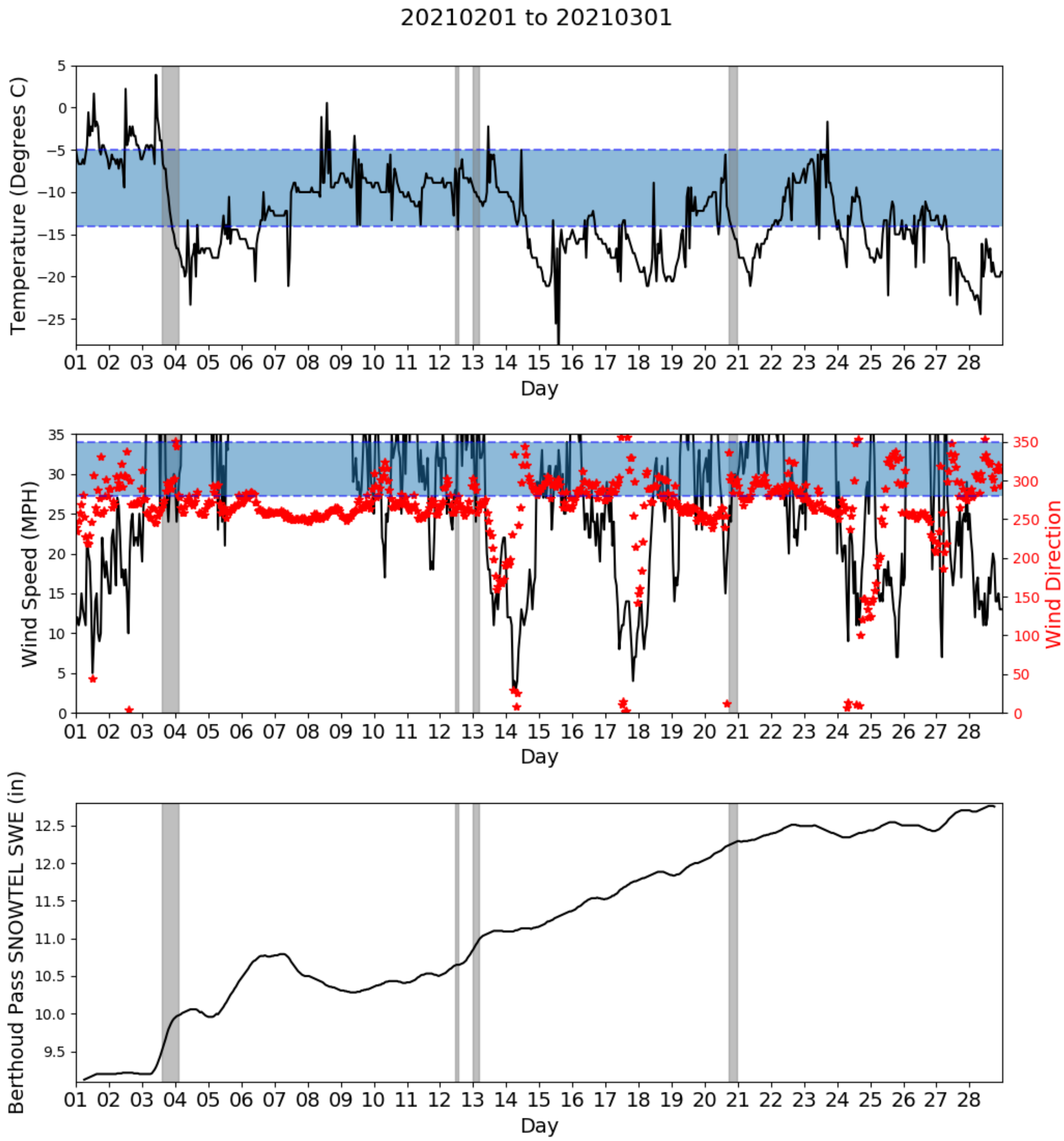

Figure 12. Cirque weather observations, as in Figure 5 except for February 2021.

March 2021

During the month of March 72” of snow was reported at the Winter Park Resort and 5.9” of SWE was added to the snow pack (Fig. 13).

The first storm came through on March 4 and added 6” of snow at the resort and 0.5” of SWE at Berthoud. The temperatures, winds, and cloud bases were ideal for seeding and the generators were operated.

Dry and warm conditions beneath a strong ridge were over the area from March 5 – March 8.

A cold front crossed the area under a mostly westerly winds on Mar 9. This was not seeded due to the generally unfavorable wind direction.

A moist Front Range cyclonic 'upslope' storm on Mar 13-15 delivered abundant moisture to the area. Southeast and easterly winds accompanied the clouds associated with the storm. Late in the storm the winds swung around to from the northwest and a brief seeding operation was conducted. The ski area added 23" of new snow and 1.8" of SWE was added at Berthoud SNOTEL.

A second 'upslope' storm crossed the are on Mar 16-17 with unfavorable winds. A brief seeding operation was conducted after the winds swung around to from the northwest late in the storm period. Berthoud reported 0.5" of SWE and 7" of new snow to Winter Park.

Between Mar 21 and Mar 27 a trio of slow moving closed low pressure systems moved from the Pacific, across southern and central Colorado. These systems had favorable temperatures for cloud seeding but only some periods of the storms had favorable winds. These periods were seeded. Winter Park reported snow on 6 consecutive days with 22" total, while Berthoud SNOTEL added 1.9" of SWE.

On the evening March 29 a strong cold front crossed the area. Temperatures started out too warm (+4C) for cloud seeding but they quickly cooled into the ideal range prior cooling below -15C. The heart of the storm was seeded with Winter Park reporting 8" of new snow and Berthoud SNOTEL adding 0.7" of SWE.

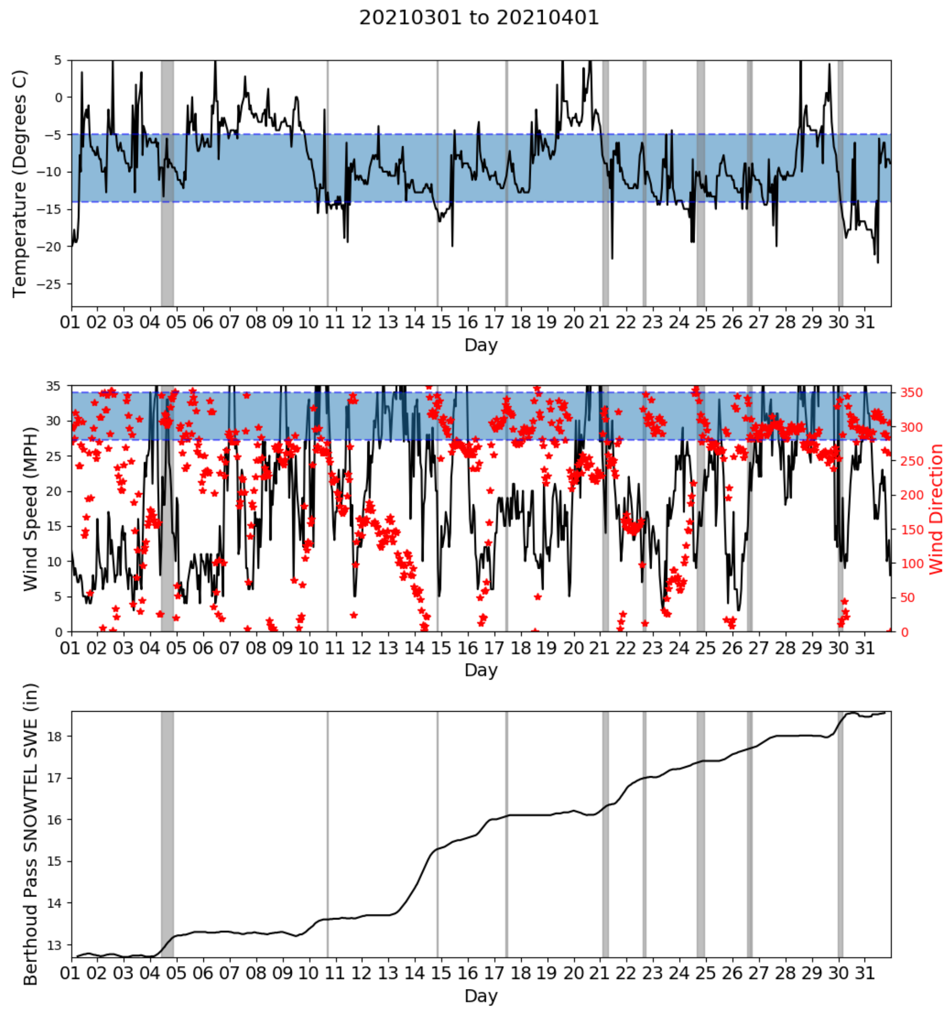

Figure 13. Cirque weather observations, As in Figure 5 except for March 2021.

April 2021

The April 1 Berthoud SNOTEL had 18.6" of SWE on the ground. With the 30-year median also at 18.6", put **the official WY2021 Berthoud snowpack at 100% of normal**.

The month of April started out slowly with a dry period between April 1 and April 15.

On the afternoon of April15 a cold front associated with a closed upper-level low moved into the area. Seeding was conducted once the low moved east of the Divide and winds became northwesterly. Only 1" of new snow was observed at Winter Park and 0.4" of SWE at Berthoud.

An Arctic cold front moved south over the Rockies on April 20 leading to low clouds and northwesterly winds. Winter Park reported no snow but Berthoud SNOTEL observed 0.3" of SWE and 2" of snow.

The final seeded storm of the season occurred on the afternoon of April 22 as a weak open wave trough cross the area from northwest to southeast. Temperatures were warm but the steep lapse rates associated with this spring storm would likely mix the seeding plume well below the -6C cloud level. Winter Park reported 8" of fresh snow with Berthoud observing 0.4" of SWE.

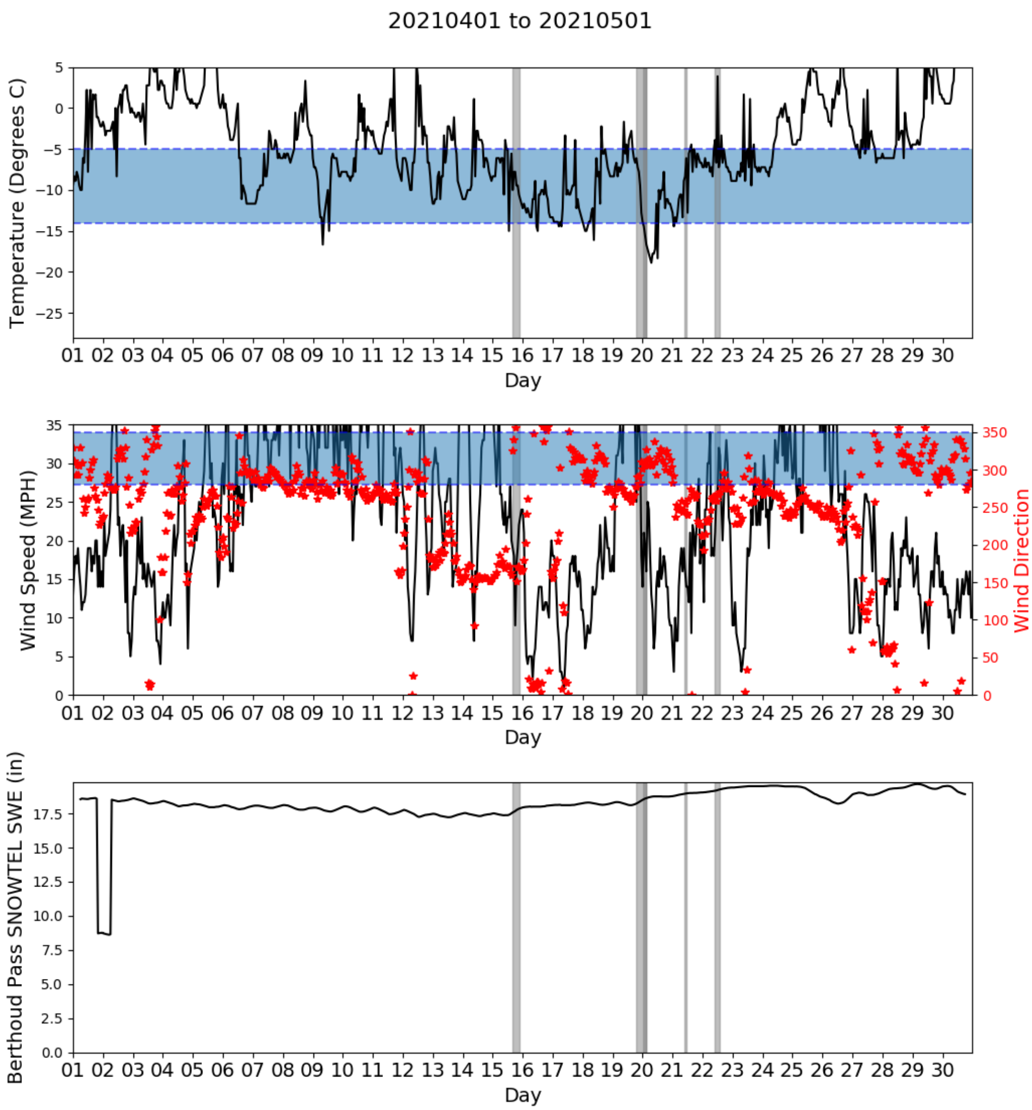

Figure 14. Cirque weather observations, as in Figure 5 except for April 2021..

Phase 3

Water Resource Augmentation

The Phase 3 work begins after the winter season has ended and includes an estimate of the snow augmentation from the cloud seeding activities. As mentioned in the Phase 2 discussion, there are several cloud seeding meteorological condition requirements that need to be present for successful operations. These include the presence of supercooled liquid water (icing). Since icing conditions often cannot be directly measured the icing conditions are inferred using the methods outlined in Bernstein et. al 2007. In-cloud temperatures colder than -5^{o}C (23^{o}F) and warmer than -15^{o}C (5^{o}F) are required, wind directions and speeds within the prescribed thresholds, and atmospheric stability profiles that would allow the seeding plume to reach the cloud bases and will deliver newly created ice crystals and snowfall into the Winter Park Ski Area. An evaluation of these conditions in Phase 2 showed that of the 35 cases 33 had all the required conditions. This leads to an excellent seeding efficiency of 97% while the generators were operating.

The seeding effect can be computed through the following derived equation (Huggins 2009). The precipitation increase in the seeding area during the operational periods over the Rockies is very conservatively estimated at 0.01" of SWE or 0.1" of increased snow per hour. The snow density is assumed at a 10:1 snow to liquid ratio. Past studies of cloud seeding plume dispersal over mountainous target areas, and documentation of the fallout area of seeded snow within a seeding plume from one generator is approximately 40 square miles. This area of effect will vary as cloud conditions and wind speed vary, and can also change as the dimension of the mountain barrier along the wind direction changes. Since all the parameters cannot be precisely evaluated, this analysis will use the 40 mi^2 value as a constant.

The estimate of the amount of SWE produced by seeding (W_s) is provided by multiplying the total time of generator operation (T_s = 178 hours) by the liquid equivalent precipitation rate increase (P_s = 0.25 mm (0.01) per hour). This product is then multiplied by the area of effect (A_s = 40 sq. miles), and then by seeding efficiency for the season (0.97). To obtain the estimate in units of acre-feet the following conversions are also needed:

0.25 mm = 0.00328 ft.
1 sq. mile = 640 acres.

So, for the 2020-21 winter season the estimated snow water increase from seeding is:

W_s = 178 h x 0.25 mm/h x 0.00328 ft/mm x 40 sq mi x 640 acres/sq mi x 0.97

W_s ≈ 3,625 acre-feet or 1.18 billion gallons of fresh clean water

If all of the 2.25 billion gallons of additional water from the cloud seeding operations were to run off, it would be enough water for 7,250 households (an average metered household uses 163,000 gallons (0.5 acre-ft) per year).

Snowfall Augmentation

The snowfall at the resort can be estimated in two different ways. The first uses the estimate of 0.10" of snow per seeded hour for 178 hours at 97% efficiency.

Total Seeded Snow = 178 hr x 0.10 inches/hr x 0.97 =
Total Seeded Snowfall = 17.2" of extra snow at the resort.

The lower number of seedable hours compared to WY20 was due to the 2 'upslope' storms that delivered heavy snow to the resort under southeasterly and northeasterly winds.

Target and Control Validation

The majority of storms that impact Winter Park occur under northwesterly flow aloft. Figure 15 shows a typical large-scale weather pattern (500 mb) that produces the majority of snowfall over the northern CO Rockies, including at Winter Park. This weather pattern also is the primary storm pattern that produces snow over the Steamboat/Rabbit Ears Pass area.

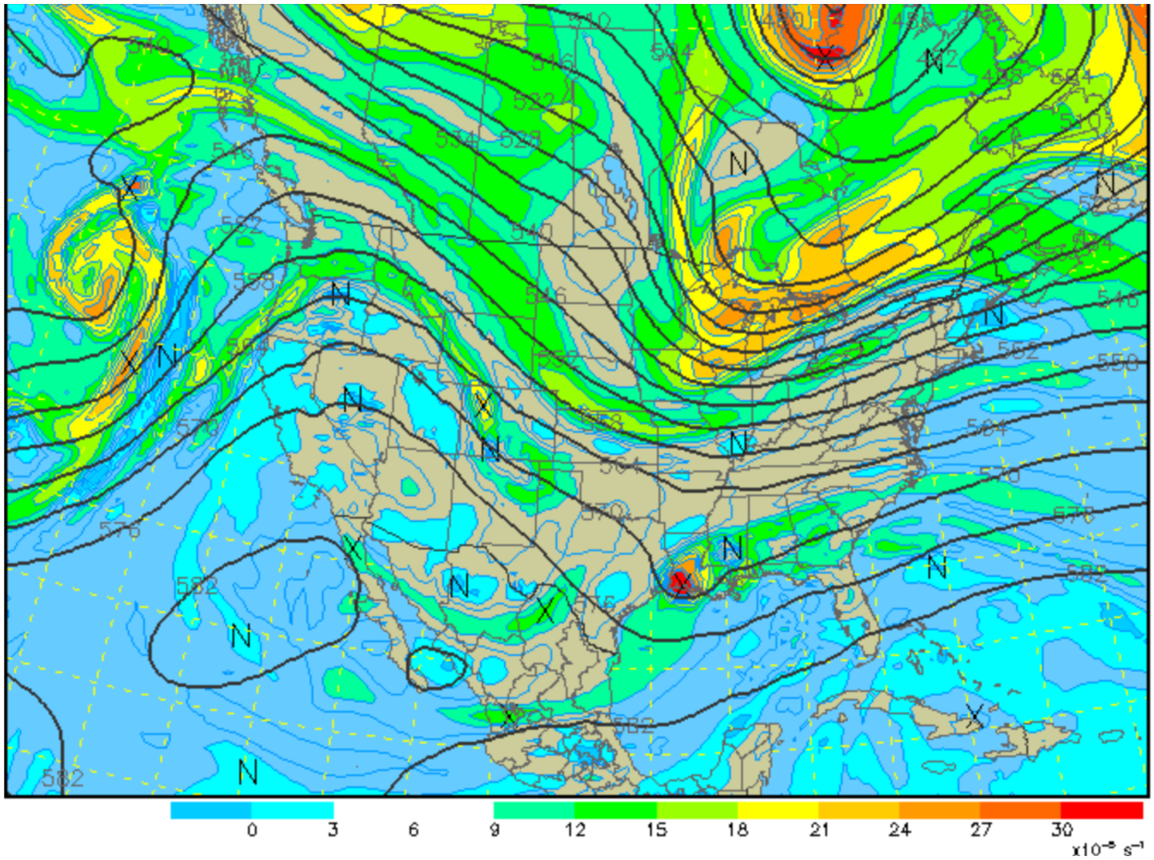

Figure 15. A typical large-scale (500 mb) weather pattern that brings snowfall to the northern CO Rockies.

For the target and control assessment Berthoud SNOTEL (11,300' MSL) was chosen as the target and the Rabbit Ears SNOTEL (9,400' MSL) was chosen as the control (Fig. 16). Both of these sites typically receive snowfall from the same storms with northwesterly flow aloft, have 30+ years of SWE observations, and the annual SWE values are well correlated (R^2 = 0.742). The Winter Park resort sometimes will receive snow when Berthoud gets missed, especially when the atmospheric stability profile is more stable, but in general they get hit with the same storms and this is the best site to serve as the target area due to the availability of long-term SWE observations.

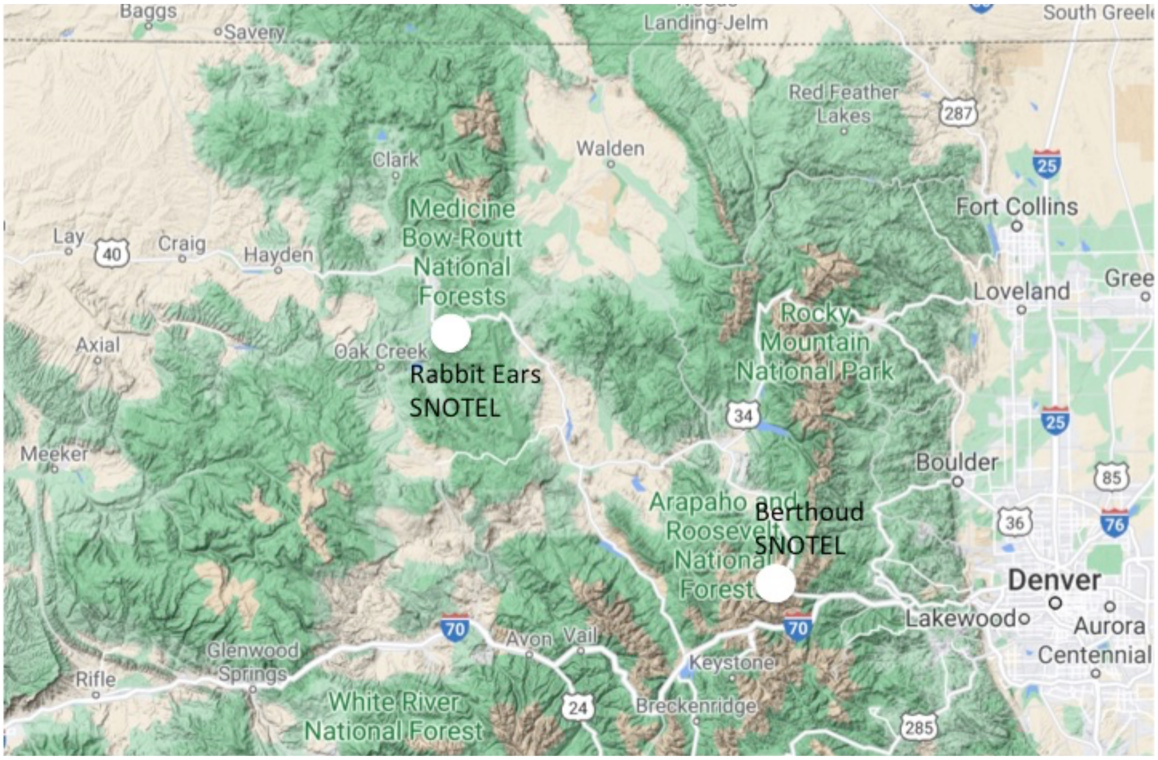

Figure 16. Map of the northern CO Rockies. The white dots show the target (Berthoud SNOTEL) and the control (Rabbit Ears SNOTEL).

The Winter Park Cloud Seeding Program has been active for the past 12 winters, since the winter of 2009-2010. For the target-control analysis 21 unseeded winters (1989-2009) at both Berthoud and Rabbit Ears were compared to the 12 seeded winters, in which Berthoud SNOTEL was seeded and Rabbit Ears was not.

The May 1 SWE values at both locations for the 31 winters are plotted in Figure 17. The unseeded winters are represented by the blue squares and the seeded years are represented by the red squares. The blue line shows the unseeded best-fit line for the unseeded winters. Positive seeding effect is above and to the left of the blue line.

Over the entire project period the results show a positive seeding effect, with Berthoud receiving additional snow over the expected values during the seeded years. Over all of the unseeded winters, Berthoud received 77.7% of the yearly SWE that was observed at Rabbit Ears. During the seeded winters Berthoud received 89.2% of the Rabbit Ears SWE, an increase of 11.5%. This suggests a strong seeding effect.

During WY2021 the unseeded expected value of SWE at Berthoud would be 13.4” for the Rabbit Ears observed value of 11.4” (blue line). Berthoud SNOTEL observed 19.1” of SWE on May 1, 2020, providing evidence of a potential 29% increase in SWE potentially from cloud seeding. If we remove the 2 'upslope' storms from the study (2.3" of SWE) there is still a 26% increase over the expected unseeded SWE value.

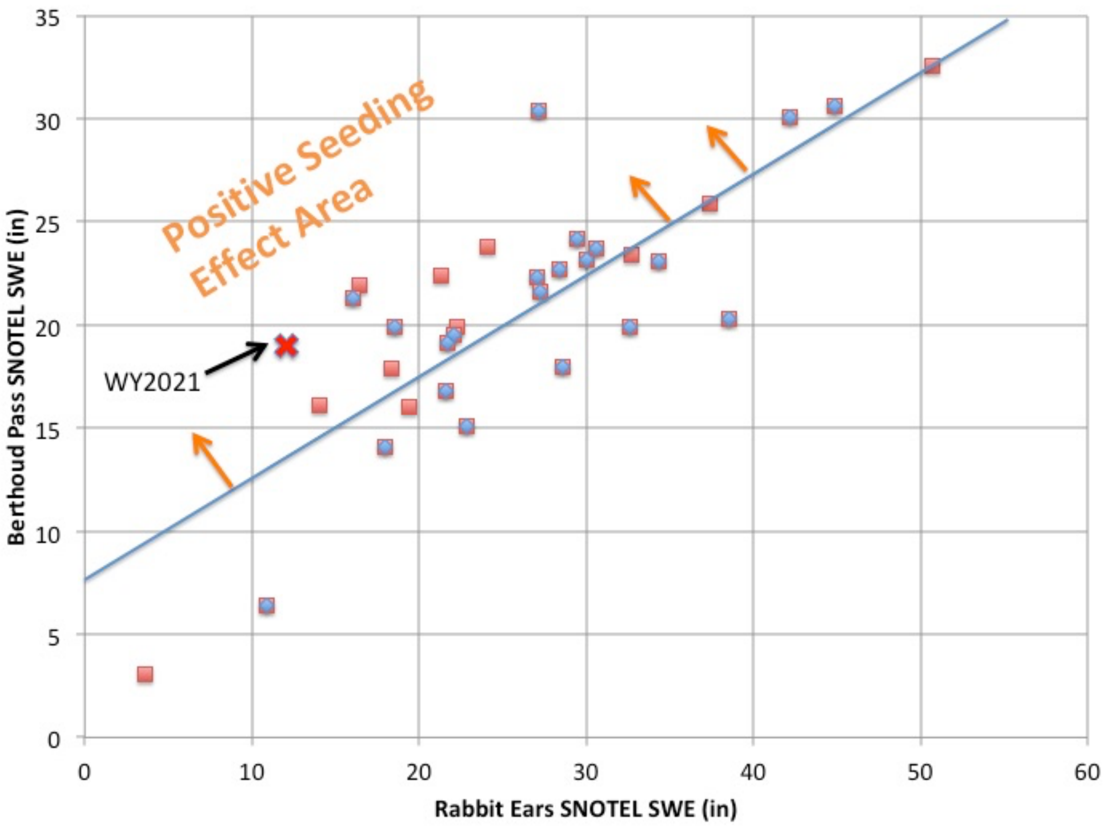

Figure 17. The target-control analysis from 32 years of May 1 SWE. The Rabbit Ears control site is along the x-axis and the Berthoud Pass target sites is along the y-axis. The blue boxes are for both sites unseeded years and the orange boxes are the seeded years at Berthoud. The blue line is the best fit line for unseeded winters.

References

Bernstein, B.C, F. McDonough, M.K. Politovich, B.G. Brown, T.P. Ravatsky, D.R. Miller, C.A. Wolff and G. Cunning (2005): Current Icing Potential Algorithm Description and Comparison with Aircraft Observations. Jour. Appl. Meteor. https://doi.org/10.1175/JAM2246.1

Huggins, A.W. (2009): Summary of Studies that Document the Effectiveness of Cloud Seeding for Snowfall Augmentation. The Journal of Weather Modification, April 2009. v. 41.