Model Simulations for 6 Storms that Produced Seedable Clouds over the San Juan Mountains

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High-resolution WRF simulations for 6 storms that produced seedable clouds and precipitation over the western San Juan Mountain

Project Report

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Executive Summary

The San Juan Mountains are a significant range along the Continental Divide in southwestern Colorado. Rivers that drain the northern, western, and southern flanks of the mountains, all contribute to the Colorado River. Runoff from snowfall in this area contributes a significant fraction of the water in the river. This water, used for domestic, irrigation, wildlife, and recreational purposes, is apportioned to users along the specific rivers of the San Juan Mountains and the Lower Basin of the Colorado River. Cloud seeding, conducted to enhance this snowpack, is conducted in several drainages of the mountain range. Cloud seeding winter storms has been found to add 5% to 15% more snow to nearby mountain ranges (Breed et. al. 2011).

In the state of Colorado, there are currently seven permitted wintertime weather modification (cloud seeding) programs that involve over 100 manual generators and several remote-controlled generators. The focus of this study is to use high-resolution modeling to study winter storms, clouds, and the cloud seeding potential over the Colorado River side of the San Juan Mountains. The primary purpose of this work will be to determine the frequency and locations of favorable cloud seeding over the region and to examine the effectiveness of silver iodide (AgI) cloud seeding from different ground based locations. These locations including lower-elevation valley floor, and different altitudes within the mountain range. Accordingly, the seeding effectiveness of the San Juan Mountains Program and three of its watersheds' have been evaluated over six winter case studies of differing weather conditions during the winters of 2015-2016 and 2016-2017.

Successful cloud seeding requires all the components the 'chain of events' be present. The 'chain of events' for successful cloud seeding require: clouds with low bases be present across the area, the atmospheric stability profile must be favorable so that the seeding plume produced from cloud seeding generators is able to reach the clouds, the cloud temperatures that the cloud seeding plume interacts with must be at or colder than -6^{o}C, and the clouds must also contain subfreezing liquid water drops (icing conditions). The final requirement is the winds must be favorable to deliver the cloud seeding plume and increased snowfall into the target watershed.

During the case selection, cloudy periods were identified through the use of satellite imagery. The temperatures, winds, and atmospheric stabilities were obtained through the numerical weather prediction model, SNOTEL temperature observations, as well as the closest National Weather Service weather balloon data. The most challenging and critical parameter in the case selection was identification of the presence of subfreezing (supercooled) cloud liquid water drops. Cloud seeding cannot be effective in the absence of these cloud liquid water drops. There are no operational instruments in the San Juan Mountains to directly measure this atmospheric property, although radiometers have been operated for research purposes. The DRI team designed an ice detection surrogate using icing pilot reports. When aircraft in flight encounter clouds containing subfreezing water drops the drops will freeze on contact with the airframe. The pilots of the iced aircraft will often call in a pilot report of icing, providing a direct observation of the presence of cloud seeding conditions. Although this is not a perfect surrogate for a radiometer or icing detector, it greatly increases confidence that the clouds within the storm contained supercooled liquid water drops.

After a detailed analysis, six significant winter storms that occurred over the San Juan Mountains during the winters of 2015-2016 and 2016-2017 were selected for analysis. These storms combined produced 204 inches of snow at the Silverton Ski Resort and more than 8 inches of snow water equivalent (SWE) at the Lizard Head Pass National Resources Conservation Service (NRCS) Snow Telemetry (SNOTEL) site along the San Miguel/Dolores Divide (Fig. E.1 and Table E.1). The storms all were found to have periods with clouds containing subfreezing liquid water, which are required for successful cloud seeding. Due to the close time proximity cases 3 and 4 were combined to simplify the presentation of the results.

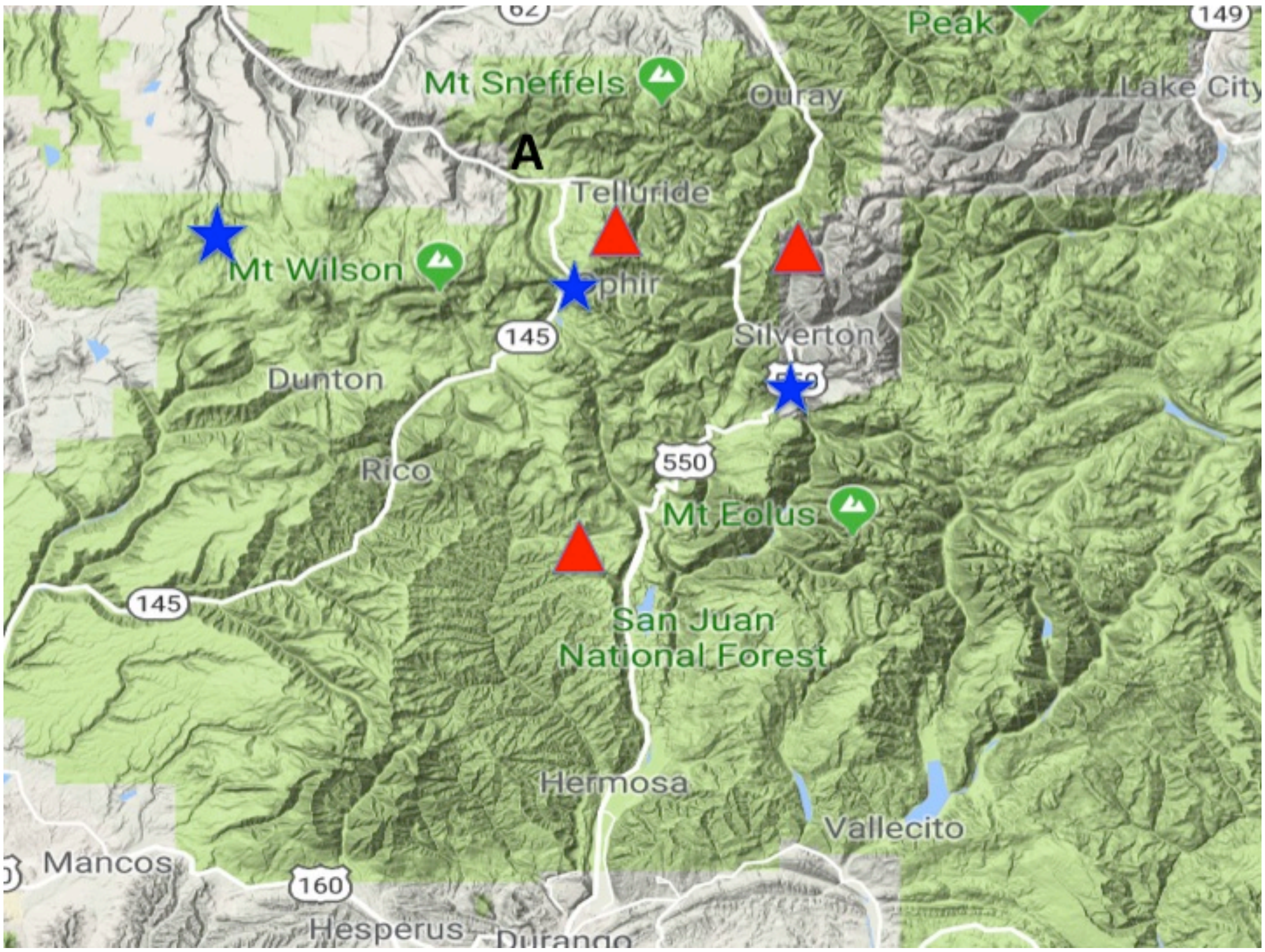


Figure E.1. *Cloud seeding target area. Red triangles indicate ski resort locations (Telluride, Silverton, Purgatory, clockwise from upper left), blue starts indicate available SNOTEL sites in the San Miguel, Dolores, and Animas River Basins (Lone Cone, Lizard Head Pass, and Molas Lake, left to right). Bold A indicates the Telluride airport (KTEX) location.*

Table E.1. *The case list and observed storm characteristics. SWE values from Lizard Head Pass (10,200' MSL) and snowfall data from the Silverton Mountain Resort.*

Case	Start Date	End Date	Icing Present	SWE (in)	Snowfall (in)
1	01/21/2017 1800 UTC	01/24/2017 1200 UTC	Yes	1.5	41

2	12/15/2016 18:00 UTC	12/17/2016 12:00 UTC	Yes	2.2	12
3*	12/22/2016 00:00 UTC	12/23/2016 18:00 UTC	Yes	0.8	41
4*	12/24/2016 21:00 UTC	12/26/2016 00:00 UTC	Yes	0.8	18
5	01/30/2016 18:00 UTC	02/02/2016 18:00 UTC	Yes	2.1	48
6	03/23/2017 0000 UTC	03/24/2016 1800 UTC	Yes	0.6	36
Totals			All	8.0	196

* *Cases 3 and 4 were combined due to the close time proximity*

Methodology

Once the cases were selected and analyzed, the Weather Research and Forecasting (WRF; Skamarock and Klemp, 2008; Skamarock et al. 2008) numerical weather model was run on each case. The model domains consist of 9 km, 3 km, and 1 km nested domains with the 3 km grid size domain covering the San Juan Mountains and the 4-Corners area, and the 1 km domain centered over the San Juan Mountains (Fig. E.2). All model results shown in this report were for the 1 km grid size domain unless otherwise noted. Once the numerical model runs were competed, a Lagrangian Stochastic Particle Dispersion Model (LSPDM), which uses a combination of modeled winds and turbulence to simulate transport of plume/passive constituents (e.g., cloud seeding ice forming nuclei (AgI)), was run from each generator within the region. By studying the particle trajectories, the Lagrangian method is able to calculate the particle concentrations at a receptor site (Fig. E.3 shows different application of the LSPDM).

The LSPDM is reversible in the sense that it can be used to identify the dispersed cloud seeding plumes from existing cloud seeding generators and also run backwards from the cloud seeding target areas to optimize cloud seeding generator locations. The locations of the existing San Juan ground cloud seeding generator network is presented in Figure E.4.

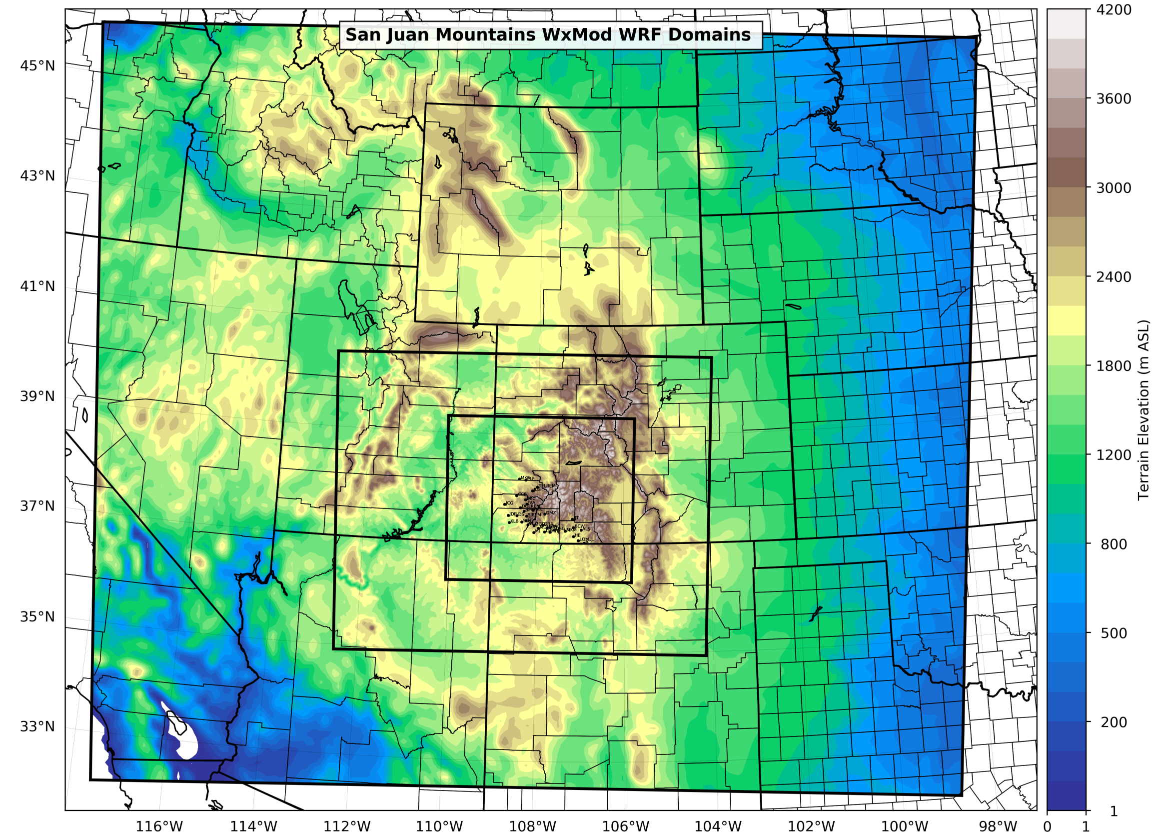


Figure E.2. *DRI model nested domains using D01=9km, D02=3km, and D03=1km grid sizes (black boxes). Shaded contours correspond to the terrain elevation using the each simulated domain resolution.*

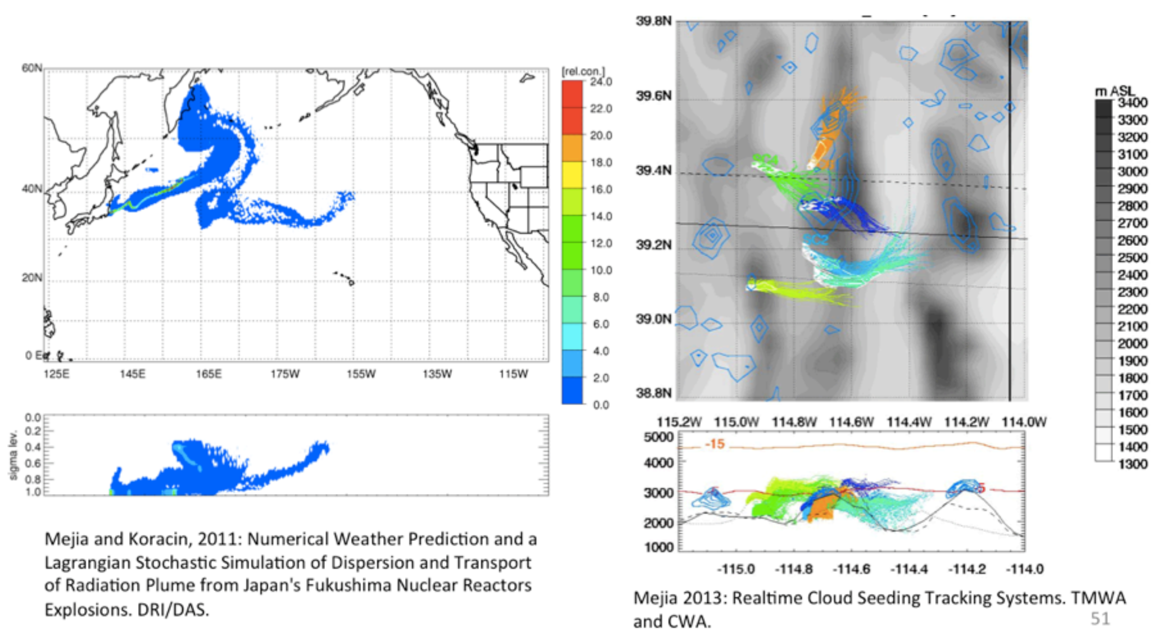


Figure E.3. *Examples of LSPDM model estimate for long-range radiation plume dispersion from Japan's Fukushima Nuclear Reactors Explosions (left panels) and cloud seeding dispersion from various generators over eastern Nevada for hindcast and realtime forecast applications (right panels).*

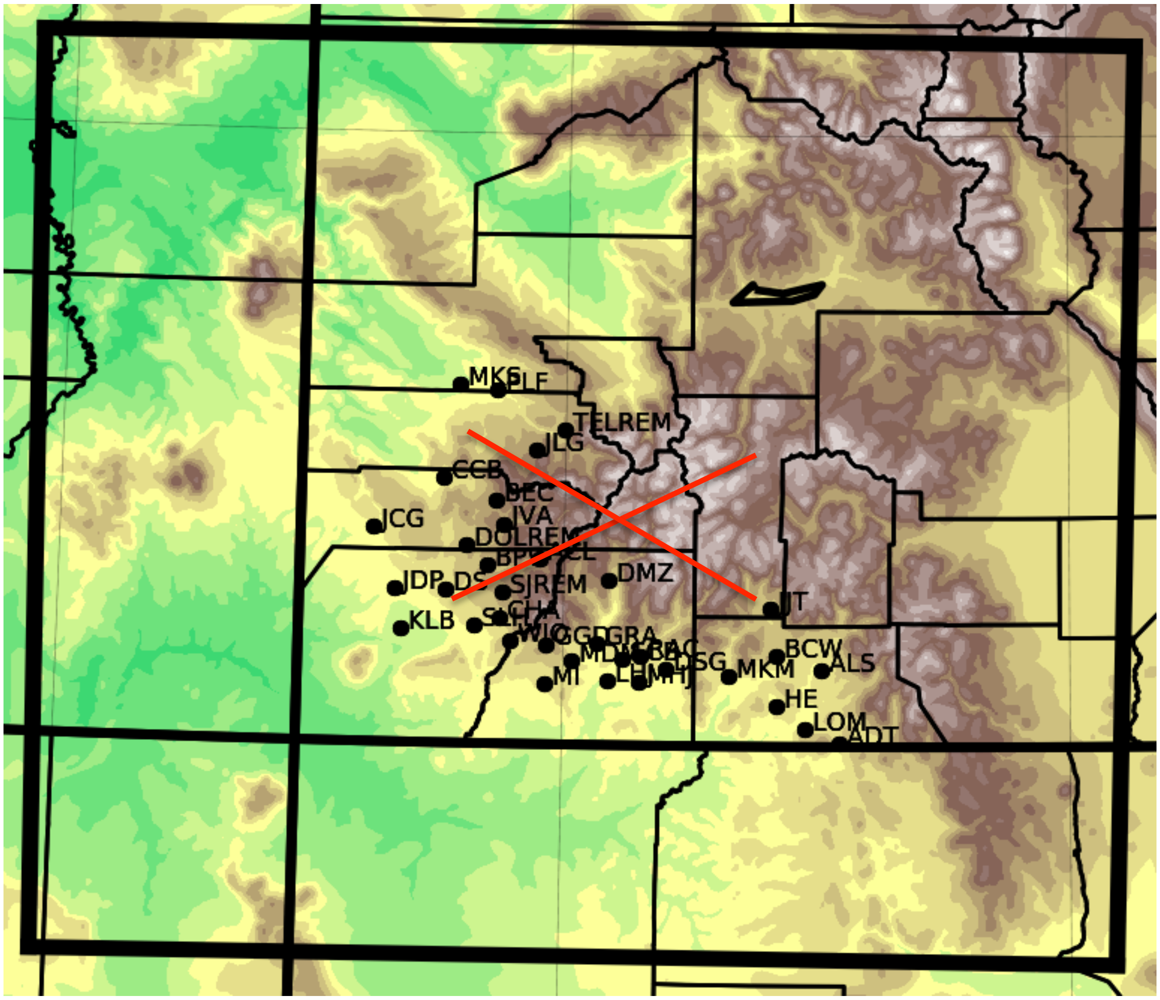


Figure E.4. *Cloud seeding generator sites for the San Juan Mountains network (Black dots). Red lines denotes cross-section locations.*

In order to determine the times when modeled cloud seeding opportunities were present during the cases, we defined the Cloud Seeding Potential (CSP) or “seedability” from the WRF model output. This was done using a simple approach that estimates the frequency of finding subfreezing liquid water clouds (model predicted cloud water, rain water, or both liquid types) over the cloud seeding target areas. The approach is to define a cloud seeding opportunity following seedability criteria for silver iodide (AgI):

$$\text{If } -6°\text{C} < T(t, x, y, p) < -18°\text{C and } Q_{liquid} \geq 0.001\text{g/kg}$$
$$\text{then: } CSP(t, x, y, p) = 1$$
$$\text{else: } CSP(t, x, y, p) = 0,$$

where t is the model output time increments (30 min), T is the temperature field in the three-dimensional space (x: east-west direction, y: north-south, p: pressure as the vertical coordinate), and Q_{liquid} is liquid water defined as $Q_{liquid} = Q_{cloud} + Q_{rain}$. (see Fig. E.5)

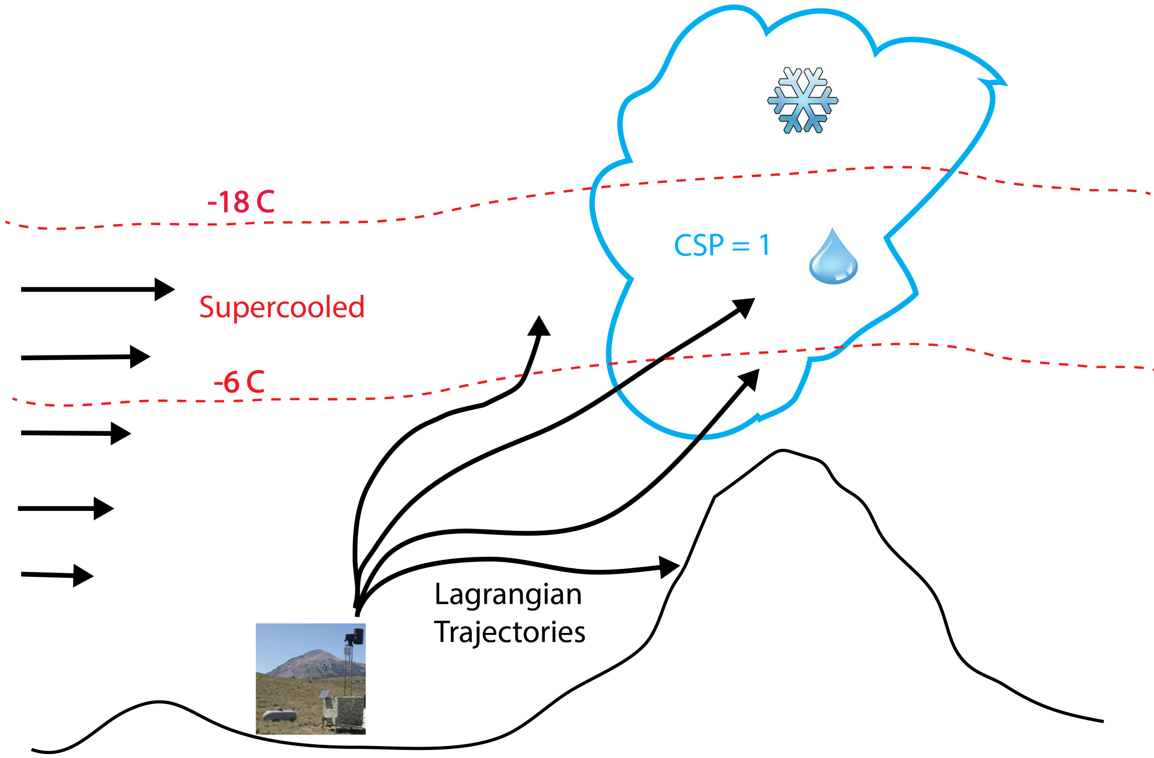
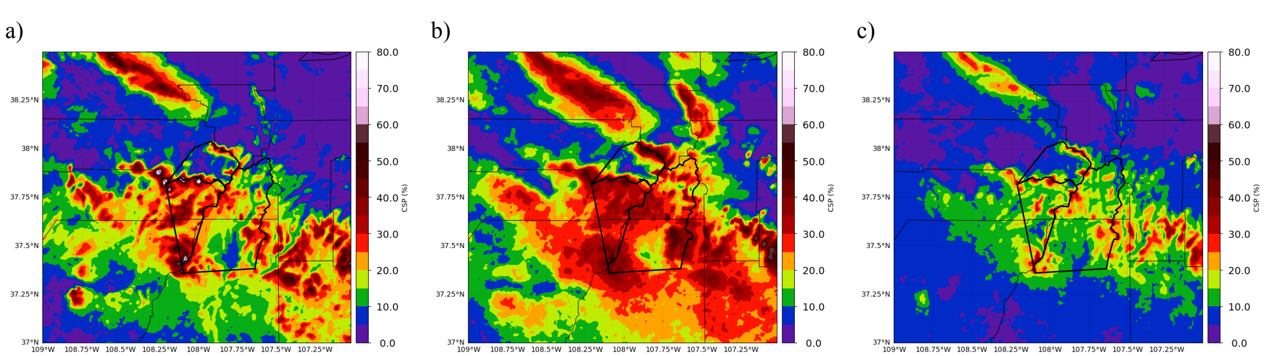


Figure E.5. *Cloud Seeding Potential schematic diagram. CSP is equal to one cloud seeding conditions are present. Cloud seeding is successful when a particle reaches favorable CSP conditions.*

Results

Detailed discussions of the weather and evolution of the cases and the results are presented in the Case Study section, here the results are summarized. Figure E.6 (a-e) shows the horizontal projection of maximum Cloud Seeding Potential (CSP) frequencies for each of the case study time periods. There were significant cloud seeding opportunities over the San Juan Mountains for all of the storms. Vertical cross sections show that the most significant seeding opportunities are over the highest terrain on the upslope side of the terrain. (Fig. E.7 (a-e); southwest-northeast cross-section and Fig. E.8 (a-e): northwest-southeast cross-section). The CSP storm percentages over the San Juan Mountain ridges are quite high for the cases (50% - 90% of the storm period).



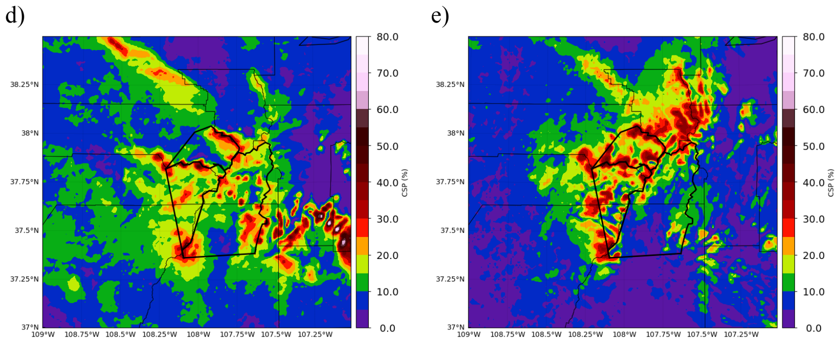


Figure E.6. *Maximum horizontal AgI Cloud Seeding Potential (CSP; % of total simulation period) estimated over the San Juan Mountains for (a-e) the events. Contours indicate the maximum values of the three-dimensional field projected into the horizontal plane. The bold black lines denoted the Animas, Dolores, and San Miguel Headwaters region.*

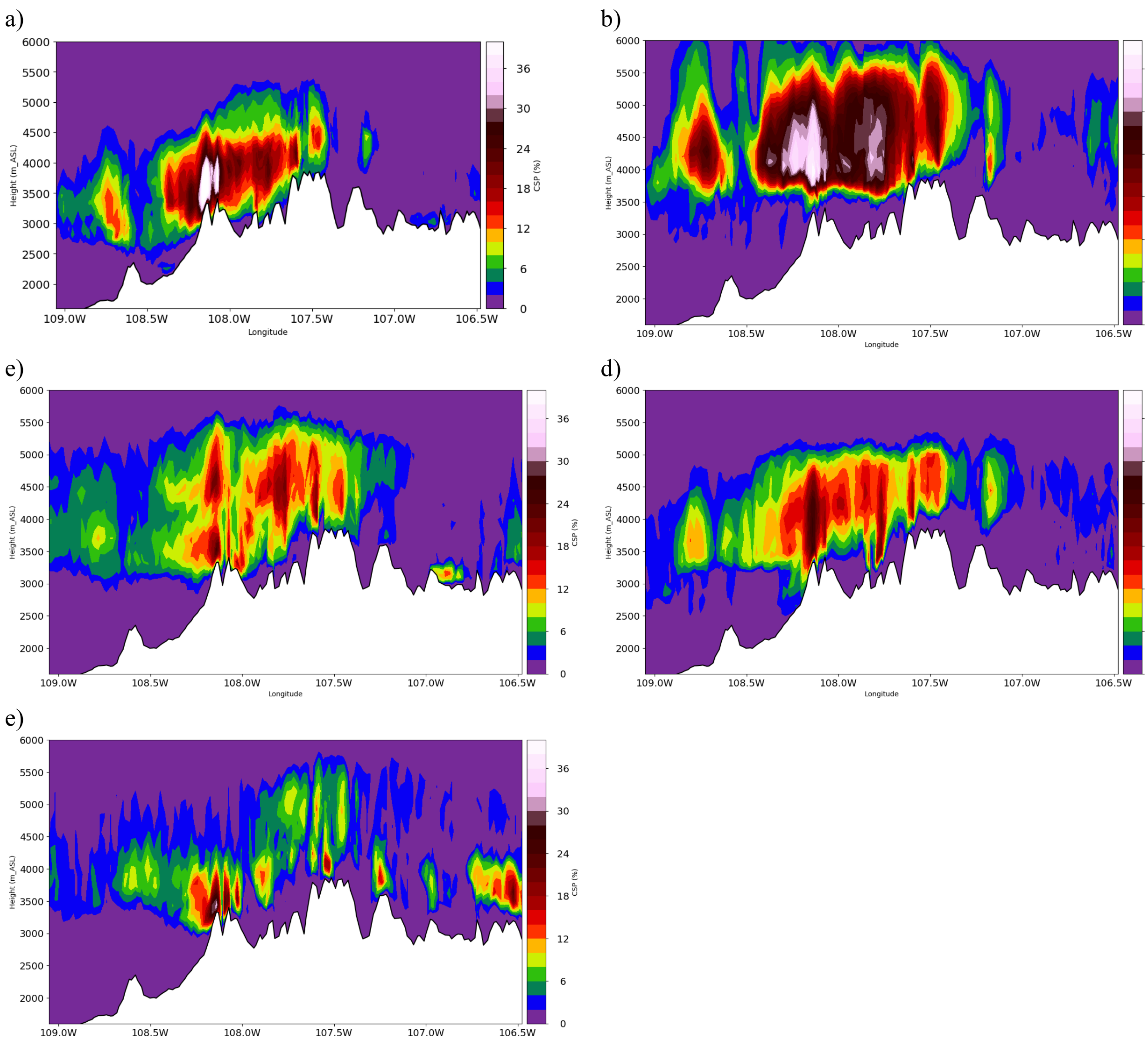


Figure E.7. *Southwest to northeast vertical cross-section of Cloud Seeding Potential (CSP; % of total simulation period) across line indicated Fig. E.4 (for (a-e) the storm events. White shaded area indicates the terrain elevation along the same cross section.*

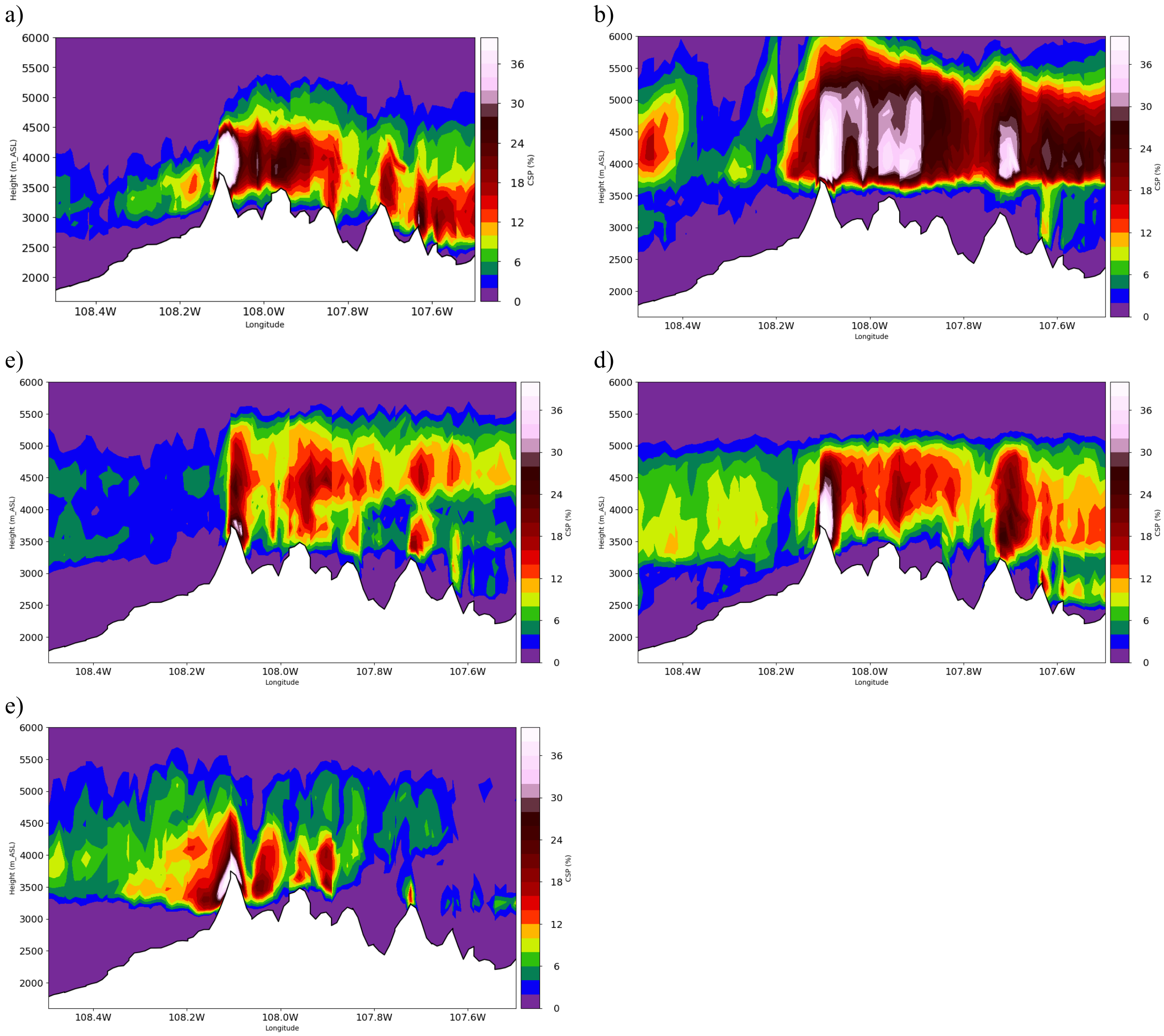


Figure E.8. *Northwest to southeast vertical cross-section of Cloud Seeding Potential (CSP; % of total simulation period) across line indicated Fig. E.4 (for (a-e) the storm events. White shaded area indicates the terrain elevation along the same cross section.*

Figure E.9 (a-e) shows the total amount precipitation produced by the model simulations for each case. As expected, the heaviest precipitation occurs over the highest terrain. The storm precipitation amounts were relatively close to the observed precipitation amounts (more details on these comparison are presented in the individual case studies).

The ratio of time when precipitation is present and when cloud seeding conditions were also present compared to the total storm precipitation time are presented in Figure E.10 (a-e). For the majority of the cases 70% to 80% of the periods when precipitation was occurring over the higher terrain cloud seeding conditions were also present. This suggests that mixed phase clouds (ice and subfreezing liquid) are often present over the San Juan Mountains and cloud effective cloud seeding can potentially add ~7% to 8% more snow to the total storm precipitation amounts (assuming a 10% increase from cloud seeding). For example cloud seeding could add more than 1” more of SWE across the region for the combined 4 days of Cases 3 and 4 (Fig E.9 c). In addition, it suggests that cloud seeding operations should often occur when precipitation is falling over the higher terrain.

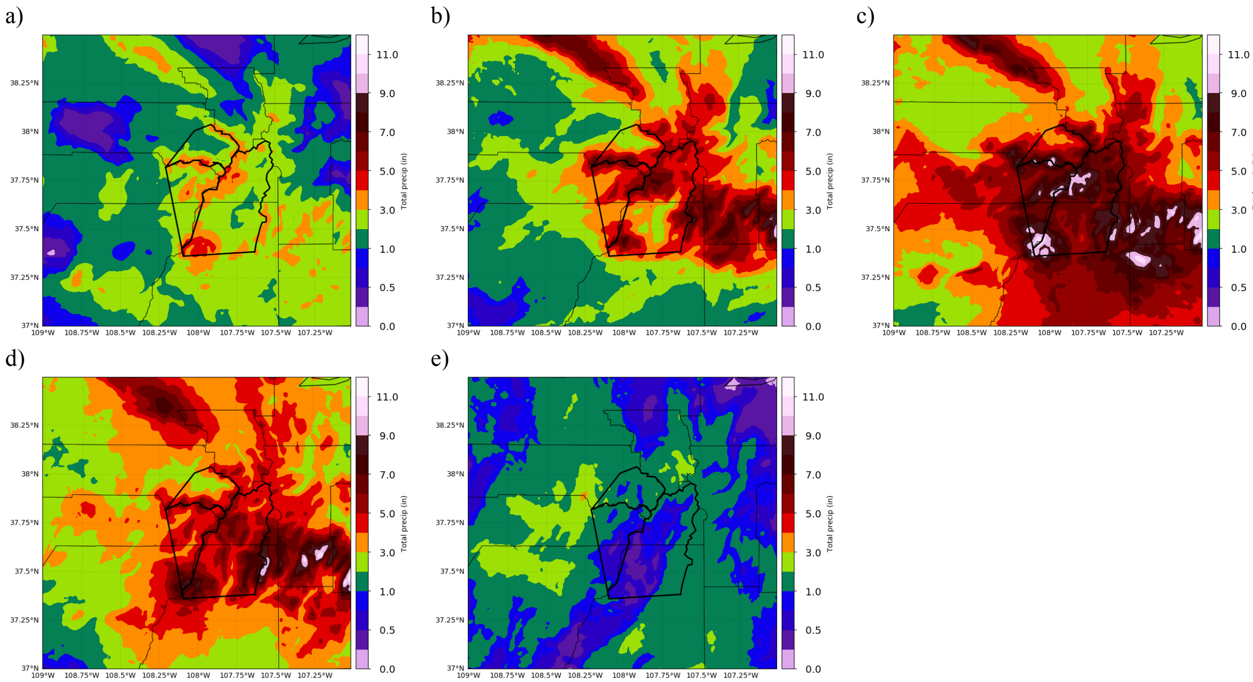


Figure E.9. *Precipitation amounts (in) over the San Juan Mountain (a-e) for the storm events. The bold black lines denoted the Animas, Dolores, and San Miguel Headwaters region.*

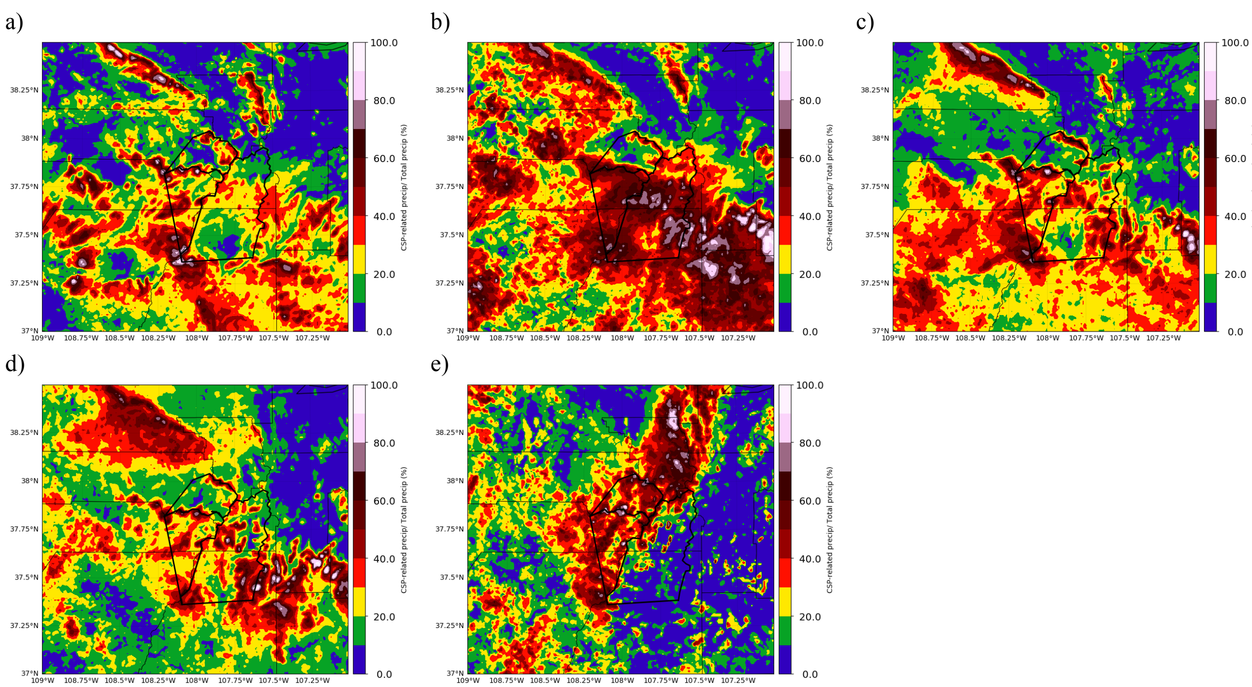


__Figure E.10.__ Percent of precipitation periods in which cloud seeding conditions were present over the San Juan Mountain for the storm events (a-e). The bold black lines denoted the Animas, Dolores, and San Miguel Headwaters region.

The predominant airflow for each of the storm's cloud seeding periods over the San Juan Mountains are presented in Fig E.11 (a-e). Case 1 (Fig. E. 11 a) had a west-southwest flow and the Dolores and eastern San Juan has significant seeding opportunities. Case 2 (Fig. E.11 b) had a strong west-southerly flow, while Case 3 and 4 have a more predominately southwesterly flow (Fig. E.11 c). Case 5 had a westerly flow (Fig. E.11 d), while Case 6 had a light northwesterly flow over the San Miguel and a southwesterly flow over the southwestern San Juan Mountains (Fig. E.11 e).

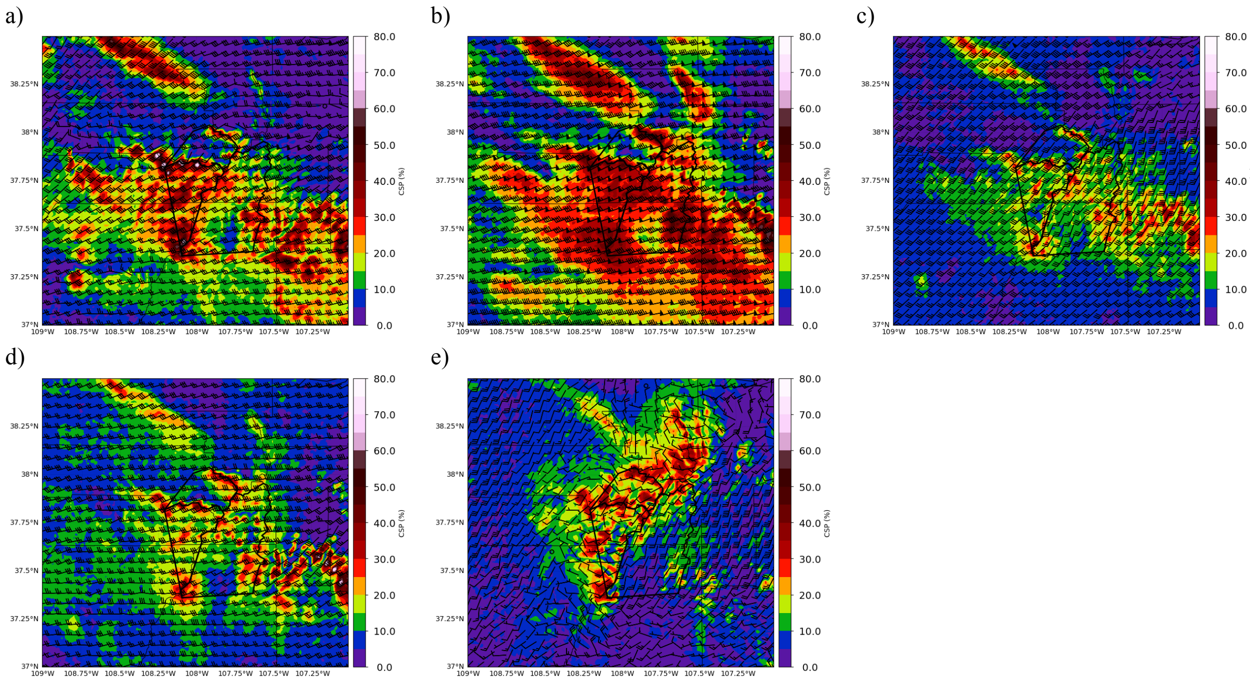


__Figure E.11.__ Percent of precipitation periods in which cloud seeding conditions were present over the San Juan Mountain for the storm events (a-e). The bold black lines denoted the Animas, Dolores, and San Miguel Headwaters region.

The LSPDM was implemented by releasing particles from all San Juan Basin generators during the model simulation periods. Figure E.12 shows two snapshots of the three-dimensional particle distributions projected into the horizontal plane during one of the simulated storms. Note the turbulent diffusion nature of the cloud seeding plumes. Figure E.13 shows the generator efficiency for plume releases shown in Figure E.15 for all the cloud seeding generators in the San Juan Basin. The plot (Fig E.16) shows a snapshot of the efficiency of each of the generators (see Fig E.4 for locations) to reach subfreezing temperatures (supercooled; red), supercooled liquid water clouds (blue) over the San Juan Mountains target area.

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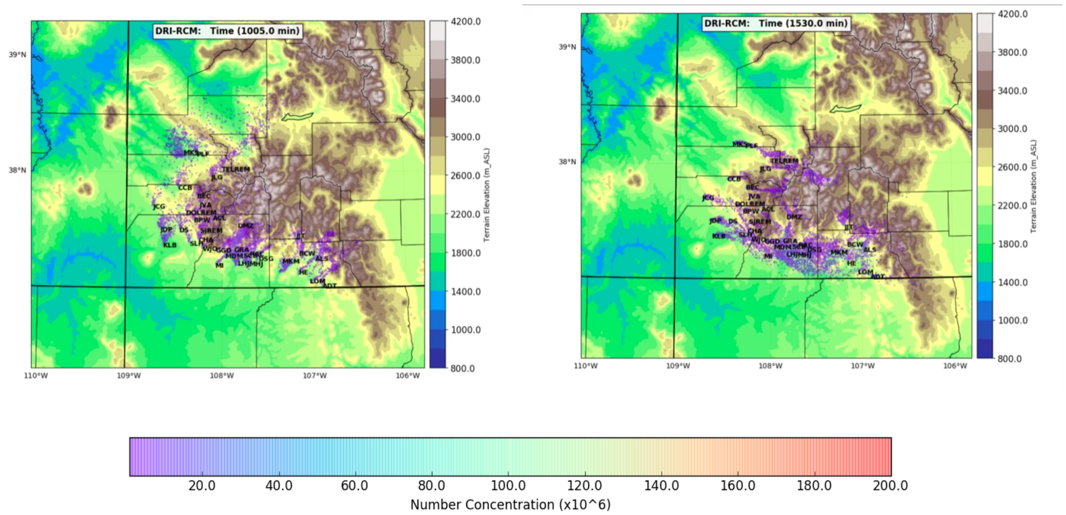


Figure E.12. *LSPDM number concentration of the cloud seeding plumes for storm #6 during two different time snapshots. The plume dispersal during the southwesterly flow part of the storm (left), and the plume dispersal during the northwesterly flow part of the storm. The model digital elevation model (m_MSL) is used as background.*

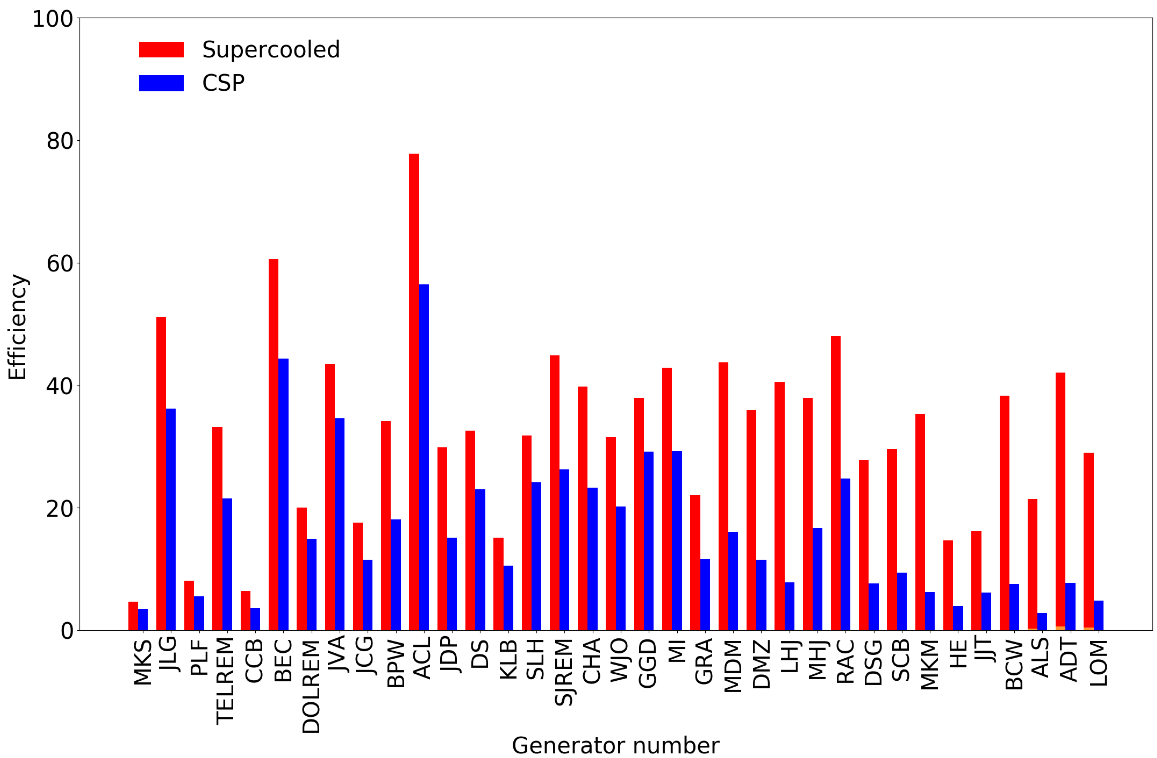
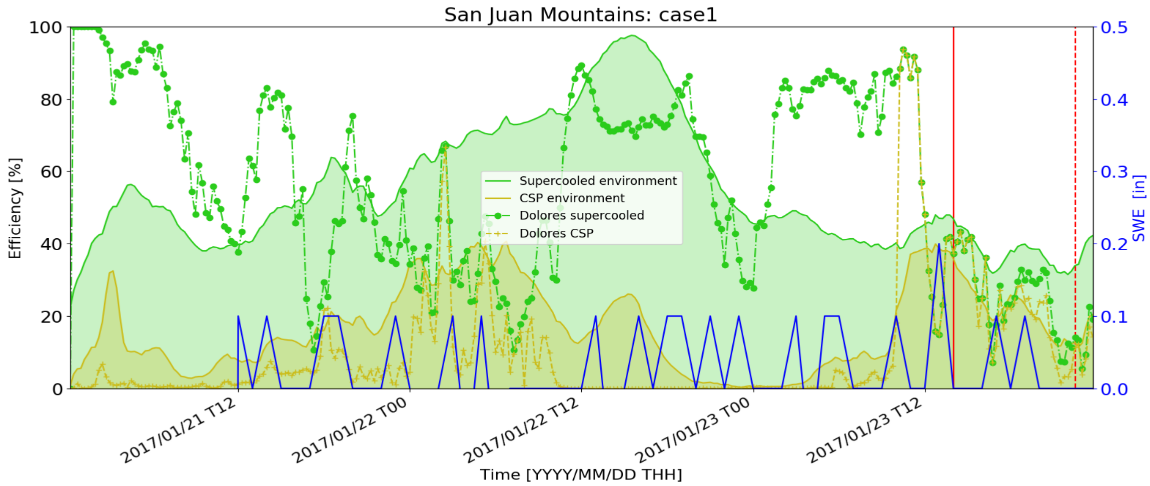


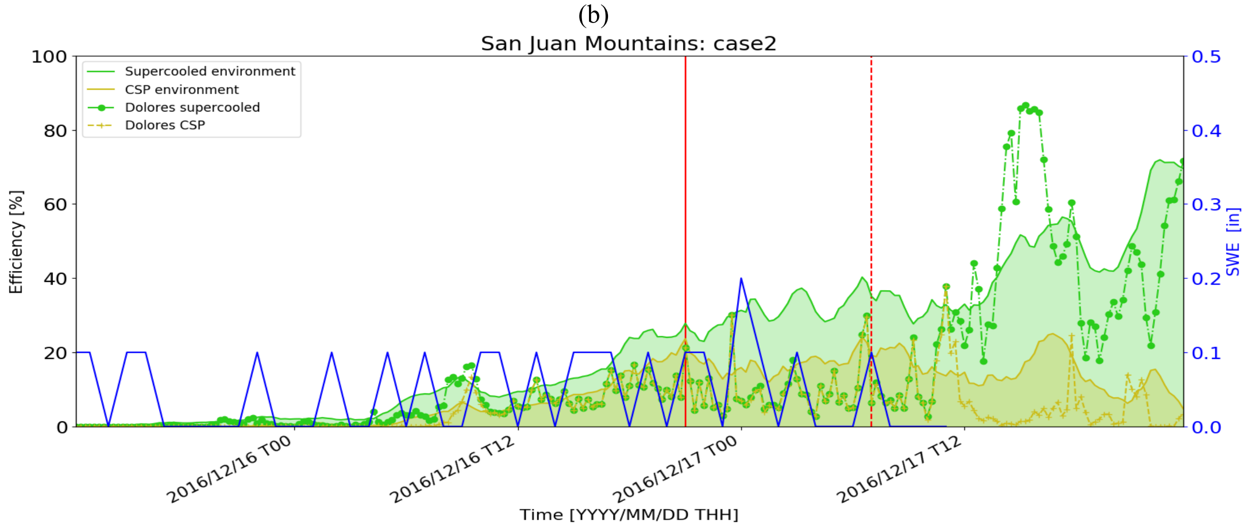
Figure E.13. *Generator efficiency [%] for individual generators defined as the percentage of released particles reaching the following environments: (red bars) supercooled over the greater San Juan target area, (blue bars), CSP over the greater San Juan target area.*

Another way to look at the generator efficiency is through a time series plot (Fig E.14 a-f). These figures show the overall efficiency of the cloud seeding network, the percent of released particles that reach supercooled temperatures (green shading) and clouds which contain seeding conditions (CSP: orange shading) as a function of time. The shaded areas show the efficiency over entire domain (both the western and eastern San Juan Mountains). Three of the watersheds were also plotted and are discussed in more detail in the Case Studies. The Dolores watershed (generators and target) results are shown in the plots in the Executive Summary, while the Animas and San Miguel watersheds are presented in the individual case studies.

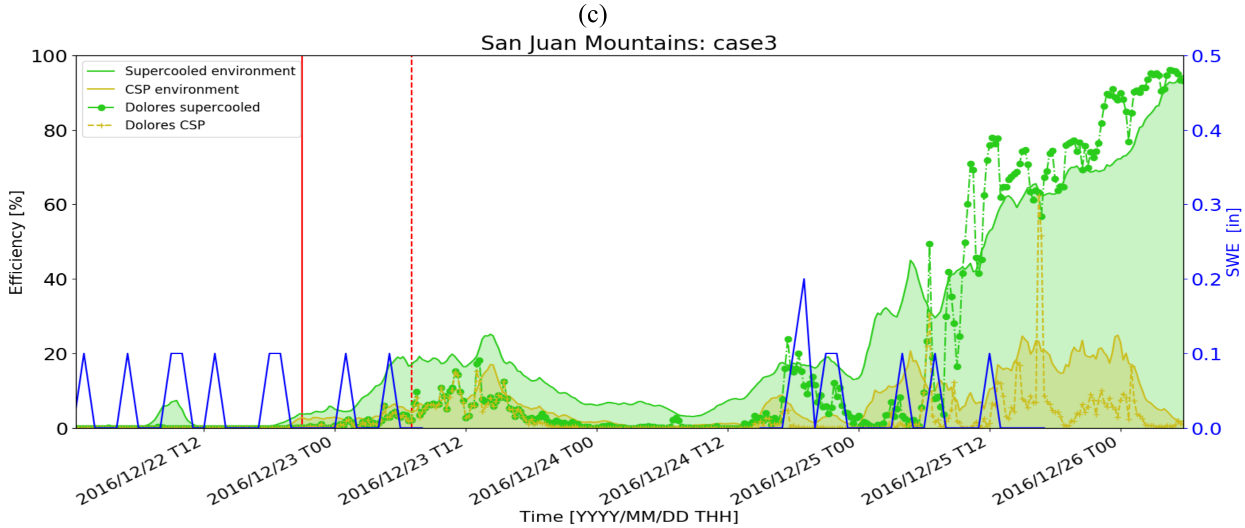
(a)



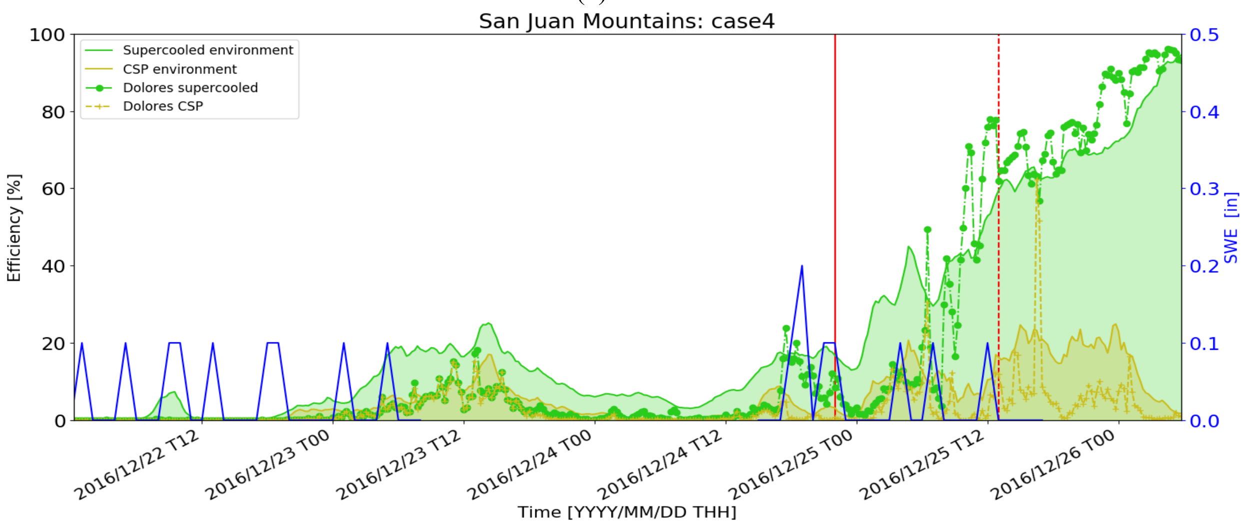
(b)



(c)



(d)


San Juan Mountains: case4
Supercooled environment
CSP environment
Dolores supercooled
Dolores CSP
Efficiency [%]
SWE [in]
2016/12/22 T12
2016/12/23 T00
2016/12/23 T12
2016/12/24 T00
2016/12/24 T12
2016/12/25 T00
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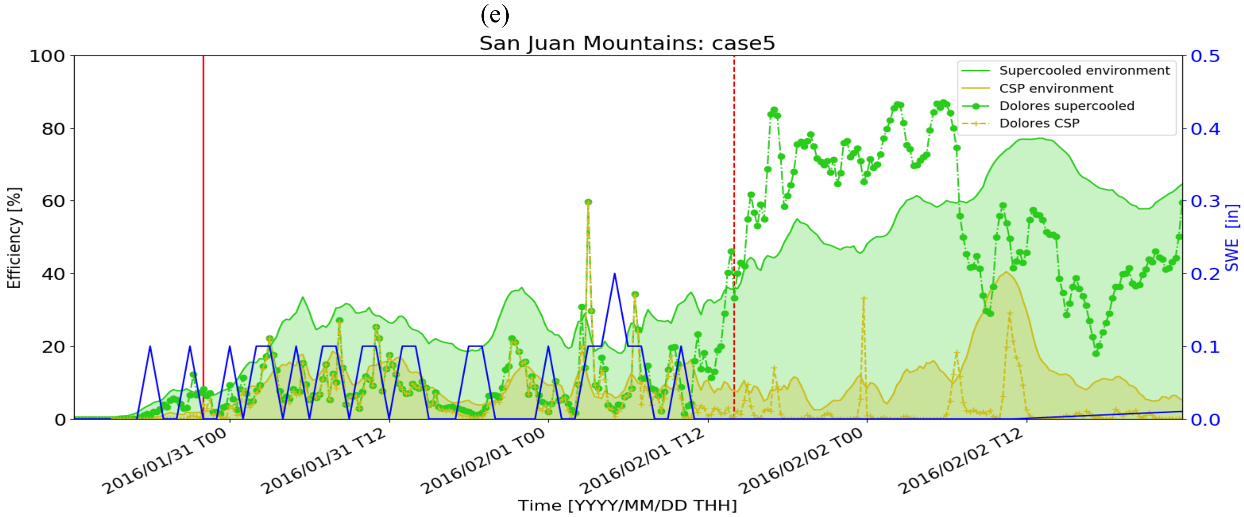
Time [YYYY/MM/DD THH]

(e)


San Juan Mountains: case5
Supercooled environment
CSP environment
Dolores supercooled
Dolores CSP
Efficiency [%]
SWE [in]
2016/01/31 T00
2016/01/31 T12
2016/02/01 T00
2016/02/01 T12
2016/02/02 T00
2016/02/02 T12
Time [YYYY/MM/DD THH]

(f)

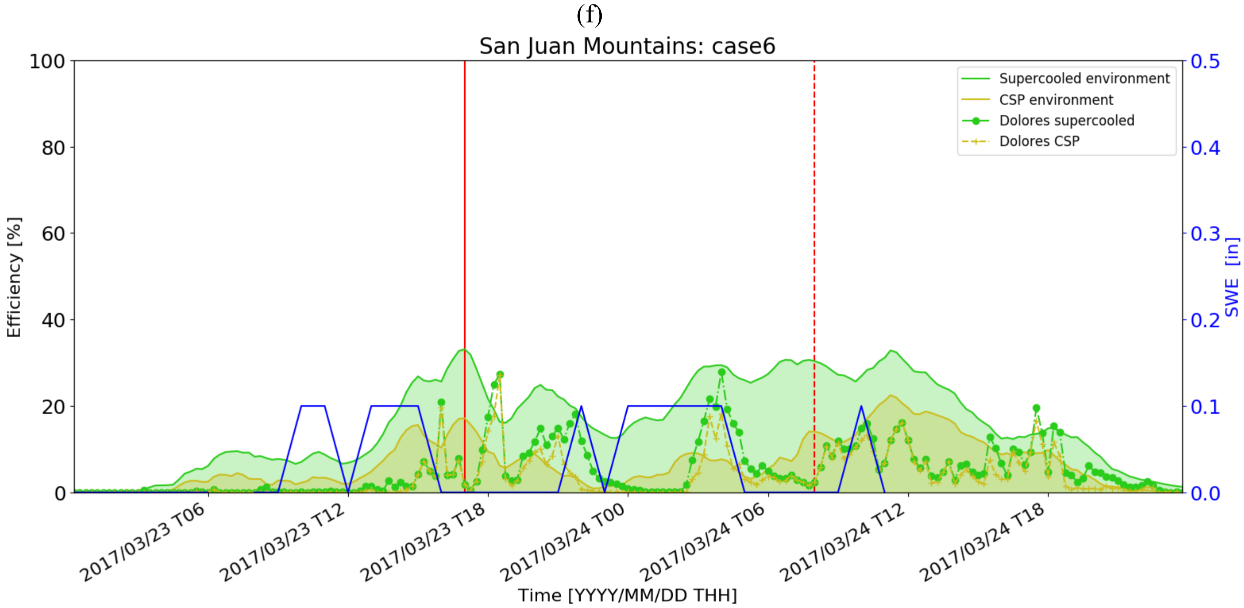

San Juan Mountains: case6
Supercooled environment
CSP environment
Dolores supercooled
Dolores CSP
Efficiency [%]
SWE [in]
2017/03/23 T06
2017/03/23 T12
2017/03/23 T18
2017/03/24 T00
2017/03/24 T06
2017/03/24 T12
2017/03/24 T18
Time [YYYY/MM/DD THH]

Figure E. 18. *Generator efficiency plots for all generators across the San Juan Mountains (green shading percent of all released particles reaching temperatures colder than -5^{o}C), (orange shading percent of particles reaching seedable clouds), red lines show start and end times of the operational cloud seeding conducted during this storm. (a) Dolores Watershed (green dashed line percent of particles reaching temperatures colder than -5^{o}C), (orange dashed line percent of particles reaching seedable clouds), blue line shows hourly precipitation rate in the Dolores Watershed.*

Case 1 Analysis

The results for the greater San Juan Mountains for Case 1 show that generators could have potentially delivered ice nuclei to seedable clouds from the start of the case study through 2100 UTC on 22 January 2017. The plume model suggests that between 10% and 40% of the particles released from the existing generator network would have reached seedable clouds over the western and eastern San Juan Mountains. Another period of successful seeding (up to 40% efficient) was possible after 0600 UTC 23 January 2017 through the end of case study (Fig E. 18 a).

Analysis of the actual period when operational cloud seeding was conducted (times between red and red-dashed lines) suggests that 30% of the silver iodide (AgI) particles (cloud seeding plumes) reached seedable clouds over the target area. The results also suggest that the early portions of the storm could have been seeded and the seeding operations during the final period of the case study should have been initiated several hours earlier.

Case 2 Analysis

The results for the greater San Juan Mountains for Case 2 show that generators could have potentially delivered ice nuclei to seedable clouds for the final third of case study period. The first portion of the storm was too warm for the network to reach temperatures that were cold enough. During the later portions of the storm the plume model suggests that between 10% and 20% of the particles released from the network would have reached seedable clouds during this period (Fig E. 18 b).

Analysis of the actual period when operational cloud seeding was conducted (between red and red-dashed lines) suggests that the cloud seeding plumes did reach seedable clouds over the greater San Juan target area and also the Dolores, Animas and San Miguel. The results also suggest that the seeding operations during the final period of the case should have been extended for several hours.

Case 3 and 4 Analysis

The results for the greater San Juan Mountains show that generators could have potentially delivered ice nuclei to seedable clouds from 0600 UTC to 1800 UTC on 23 December 2016 and after 0000 UTC on 25 December 2016. The plume model suggests that 5% to 15% of the particles released would have reached seedable clouds.

Analysis of the actual period when cloud seeding was conducted (between red and red-dashed lines in Fig E.18 c) suggests that the cloud seeding plume did not reach seedable clouds over the target area during the seeding period of 22 and 23 December 2016. The results also suggest that the second operational seeding period (red lines in Fig. E.18 d) was successful but should have been started a few hours later and extended beyond 0000 UTC 26 December 2016. Up to 20% of the particles would have reached the target area at this later time period.

Case 5 Analysis

The results for the greater San Juan Mountains show that generators could have potentially delivered ice nuclei to seedable clouds after 0000 UTC on 31 January 2017 (Fig. E.18 e). The plume model suggests that only 5% to 15% of the particles released would have reached seedable clouds, with a notable spike at about 1200 UTC on 2 February 2017.

Analysis of the actual period when cloud seeding was conducted (between red and red-dashed lines in Fig. E.18 e) suggests that the cloud seeding plume reached seedable clouds over the target areas during the seeding period of 0000 UTC 31 January 2017 through 1400 UTC 1 February 2017. The results also suggest that the cloud seeding operations could have been extended beyond 1400 UTC 1 February 2017.

Case 6 Analysis

The results for the greater San Juan Mountains show that generator network would have delivered about 10% of the released ice nuclei into the target area. This was the case for the greater San Juan Mountains as well as the individual watersheds (Fig E.18 f).

Analysis of the actual period when operational cloud seeding was conducted (between red and red-dashed lines) suggests that the cloud seeding plume reached seedable clouds over the target area at about 10% efficiency. The results also suggest that the generator operations were initiated at the correct time but should have been continued overnight and until about or just after 1800 UTC 24 March 2017

Summary

- Six storms that impacted the San Juan Mountains during winter 2015-2016 and 2016-2017 were hand analyzed and it was determined that cloud seeding cloud structures were present.
- The storms were simulated at 1-km horizontal resolution using the Weather Forecasting and Research (WRF) model.
- The storms contained long-lived periods of supercooled liquid water (cloud seeding periods).
- WRF cloud seeding conditions were detected in clouds over the area for up to 90% of the storm times.
- Most of the WRF cloud seeding periods also included modeled precipitation.
- A cloud seeding plume dispersion model was added to the WRF runs.
- Low-level inversions were largely absent during the storm periods, especially under northwesterly flow.
- The WRF cloud seeding periods also included modeled precipitation although cloud seeding opportunities were sometimes present when precipitation was absent.

- A cloud seeding plume dispersion model was added to the WRF runs and shows that 5% to 40% of the released particles from the generators reach the western and eastern target area.
- The operational cloud seeding program delivered cloud seeding material to seedable clouds over the target areas.
- Assessments of three specific watersheds were also computed.

Recommendations

- The lower percentages of particles reaching the target area suggest that having the generators closer to the target area may increase the seeding efficiencies.
- Using remote higher output generators which can be operated at all times of day or night by seeding meteorologists and can deliver 3 to 4 time more particles to the target area and potentially increase the seeding effectiveness.
- The generators more frequently during storms.
- The operators could use realtime high-resolution modeling plots such as presented in Figure E.18 to conduct operational cloud seeding.
- When new seeding equipment becomes available these cases studies should be used to study back trajectories to help site the new equipment,

1 Case Studies

Case 1. 21 January 2017 0000 UTC – 24 January 2017 1200 UTC

An active pattern was in place across the San Juan Mountains the third week of January 2017. Between 0000 UTC 21 January 2017 and 1200 UTC 24 January 2017 two waves crossed the San Juan Mountains from the west. The sequence of events related to these waves are described below. The watershed snow data is represented by 3 NRCS SNOTEL precipitation gauges (Lone Cone (San Miguel (SM)), Lizard Head (Dolores D), Molas Lake (Animas (A)).

By 1800 UTC on 2017 January 21 a moist open wave trough and cold front was crossing San Juan Mountains. Winds at 700mb (~10,000 ft MSL) at that time were from the west-southwest at 25 MPH and with temperatures at that level at -6C.

By 2100 UTC 2017 January 21 the winds have become more west-northwesterly and increased to 45 MPH, temperatures had dropped to -7C (Fig. 1). Precipitation was falling in the headwaters of all the watersheds. An icing report was received that confirmed supercooled liquid was present during this period (Fig. 2). The stability profile suggested that the layer was unstable (moist adiabatic) from the surface to cloud top at -55^{o}C and 335 mb (Fig. 3).

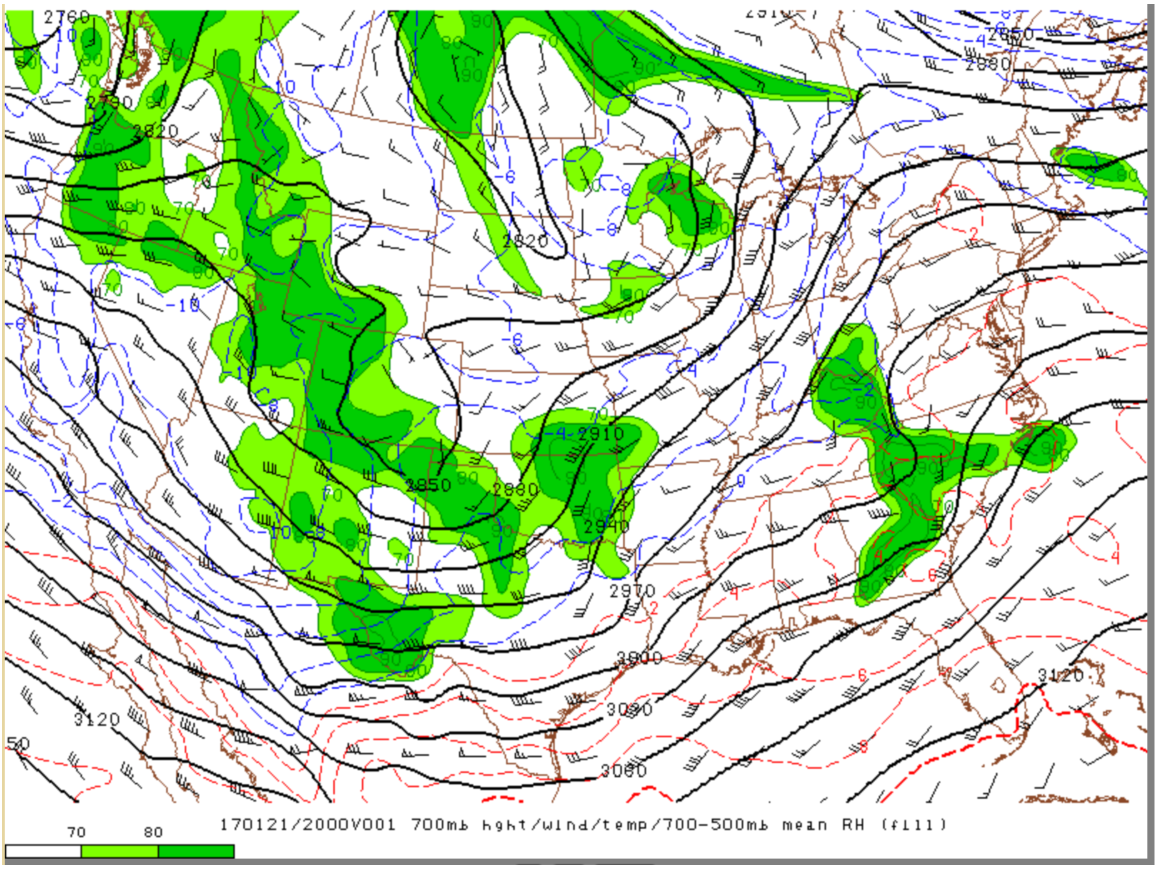


Fig 1. *700mb Rapid Refresh analysis field valid at 2017 January 21 2000 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (^oC)*, green shading relative humidity (%), wind barbs (kts).

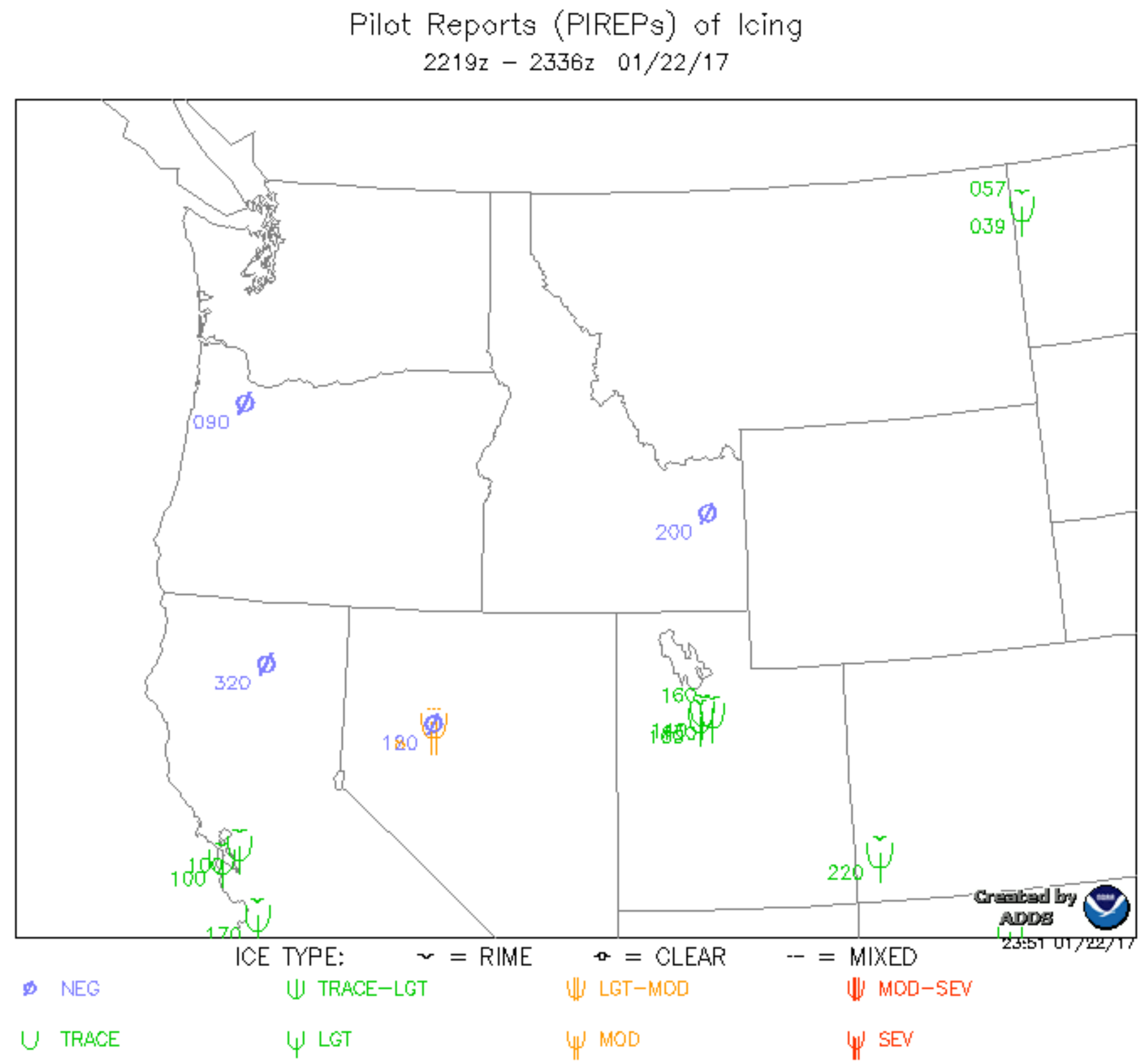


Figure 2. *Aircraft icing reports between 2219 UTC and 2336 UTC on 22 January 2017. Colors and symbols indicate icing severity and ice type.*

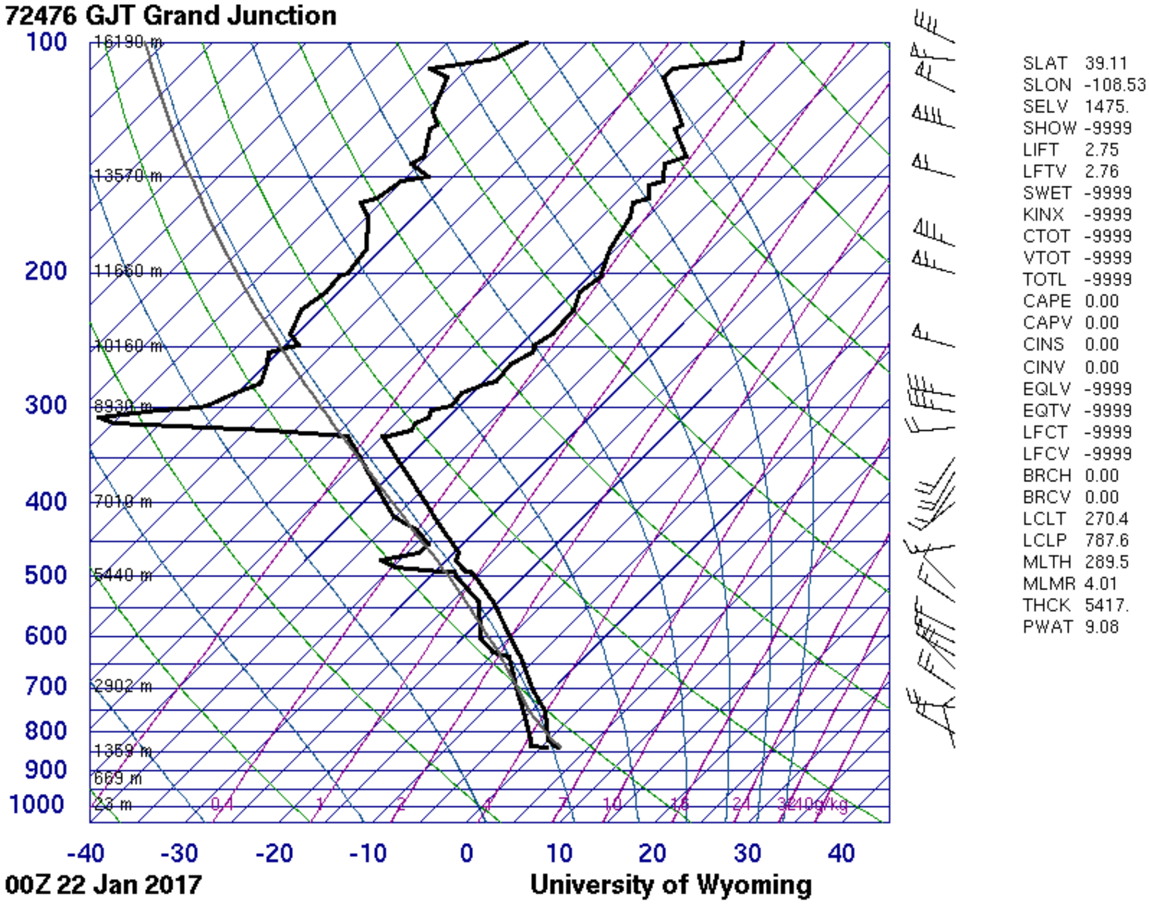


Figure 3. *Balloon sounding from the National Weather Service Grand Junction, CO, 0000 UTC 22 January 2017**.***

By 0300UTC 2017 January 22 the precipitation had ended at the Molas Lake (A) and Lone Cone (SM) SNOTEL sites, with 0.3" and 0.5" of SWE reported between 21 January 2017 1800 UTC and 22 January 2017 0300 UTC.

Precipitation continued overnight at the Lizard Head (D) SNOTEL (0.4") as the winds became northwesterly and decreased to 20 MPH. The moist northwesterly flow continued overnight with the Telluride Ski Resort reporting an impressive 18" 24 hour snowfall by 22 January 2017 1200 UTC. Skies cleared over mountains at dawn on 22 January 2017 as a shortwave ridge moved into the area with the 700mb temperatures dipping to -10C (Fig. 4).

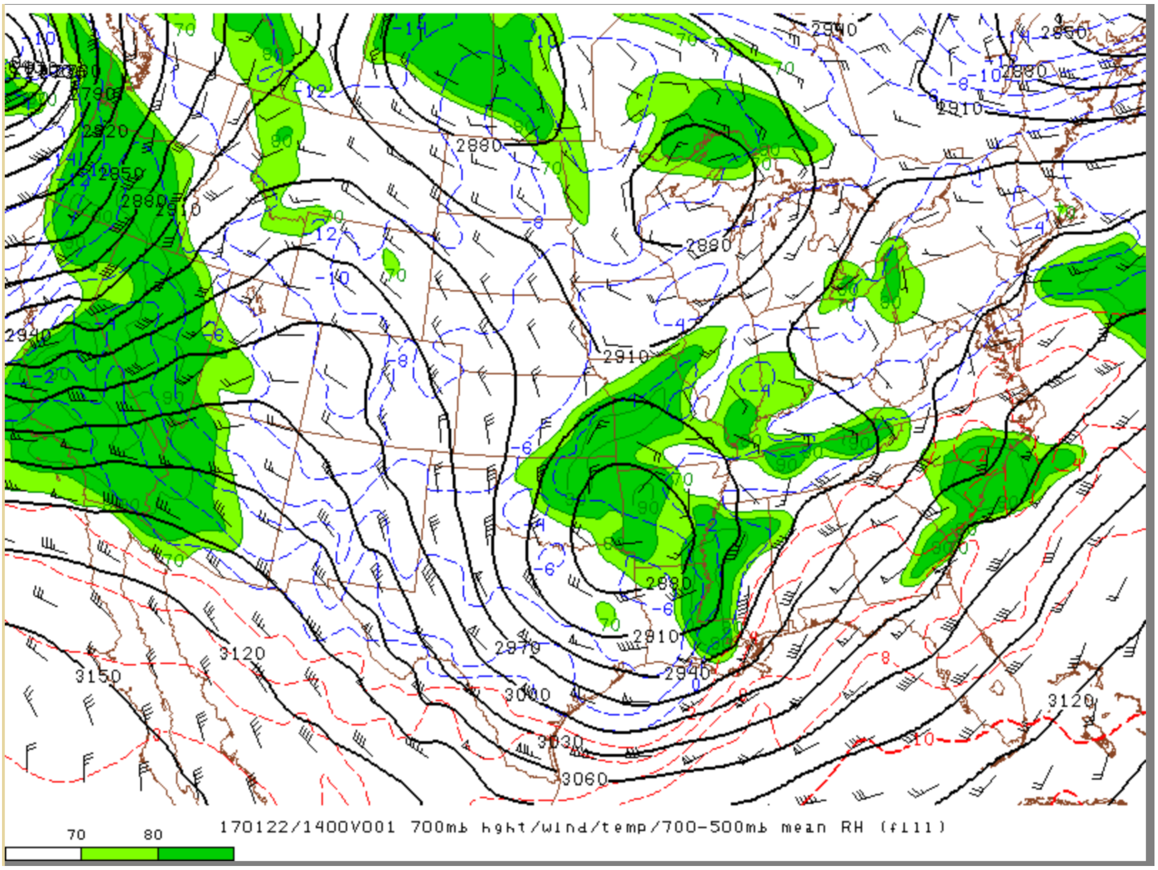


Fig 4. *700mb Rapid Refresh analysis field valid at 2017 January 22 1400 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (^{o}C)*, green shading relative humidity (%), wind barbs (kts).

Moisture associated with the next wave to the west moved across the area by 2200 UTC on 22 January 2017. Winds veered back to southwesterly. This moist warm air advection southwesterly flow continued trough 0900 UTC 23 January 2017 with 700mb temperatures warming to -2C and wind speeds reaching 50 MPH (Fig. 5). Another 0.5" of SWE was reported at both Molas Lake (A) and Lizard Head (D) SNOTEL sites and the Lone Cone (SM) remained dry through the period. The upstream sounding from Flagstaff, AZ suggests that a multilayer cloud was likely present over the San Juan Mountains with a very moist and unstable low-level boundary layer cloud that would have been orographicly lifted over the south and west faces of the San Juan Mountains (Fig. 6).

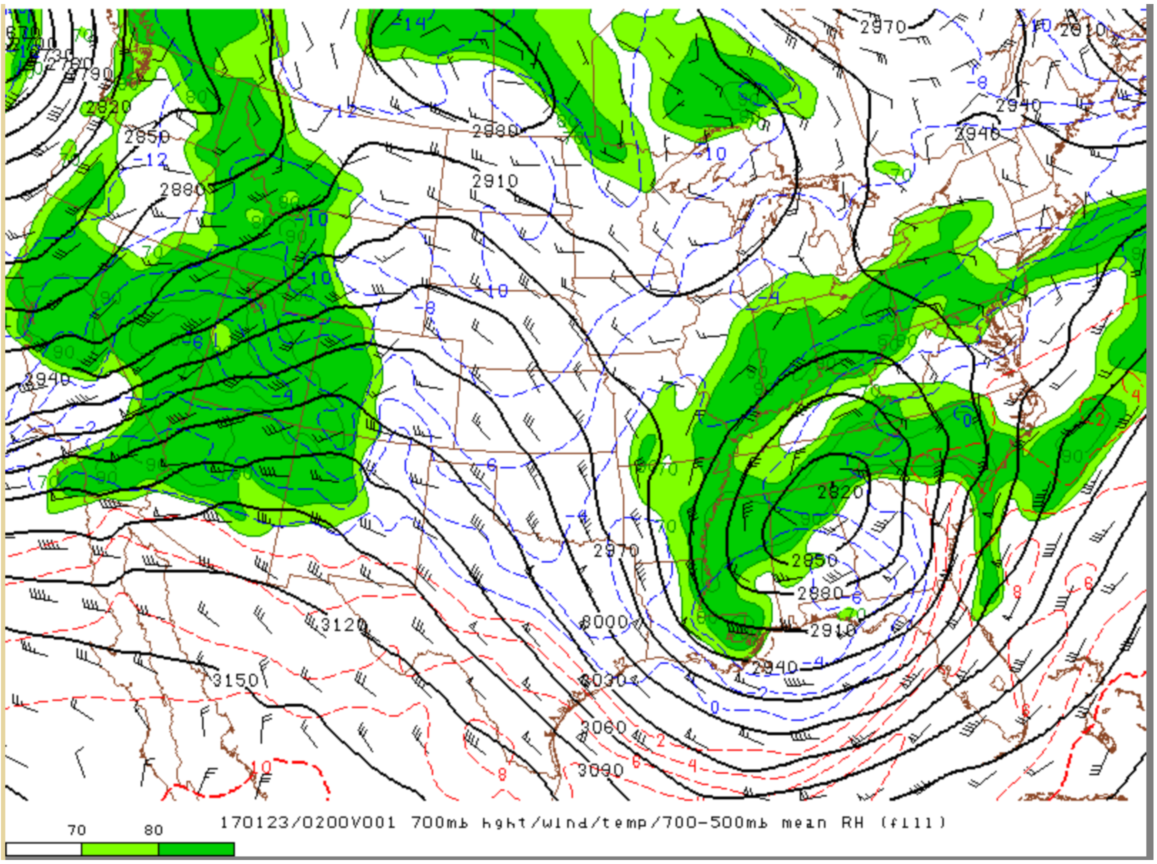


Fig 5. *700mb Rapid Refresh analysis field valid at 2017 January 23 0200 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (^{o}C)*, green shading relative humidity (%), wind barbs (kts).

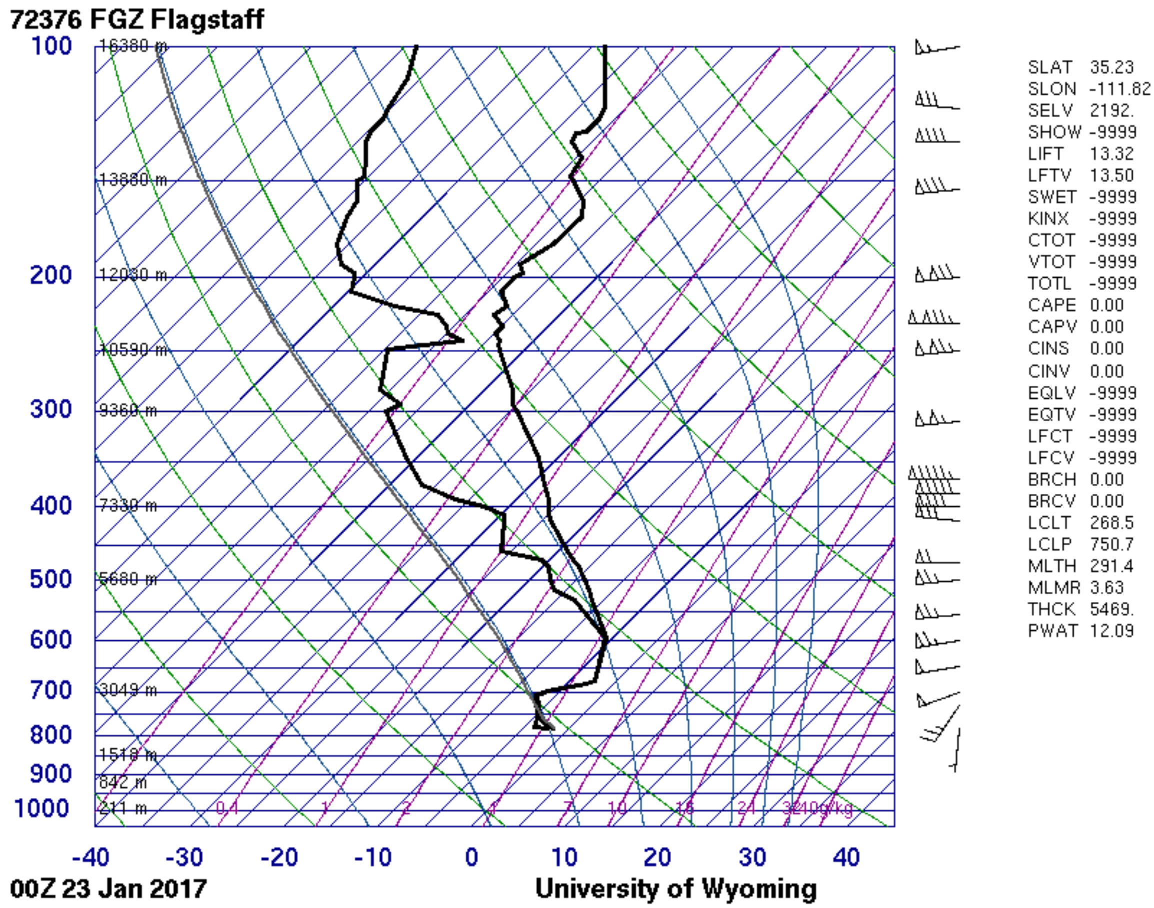


Figure 6. *Balloon sounding from the National Weather Service Flagstaff, CO, 0000 UTC 23 January 2017***.**

Conditions remained dry after 0900 UTC 23 January 2017 as temperatures at 700mb dipped to -5°C, the best moisture moved north of the area, as southwesterly flow ahead of the main low continued (Fig. 7). The Telluride and Purgatory resorts both reported a 24-hour totals of 4” of new snow through 1200 UTC 23 January 2017.

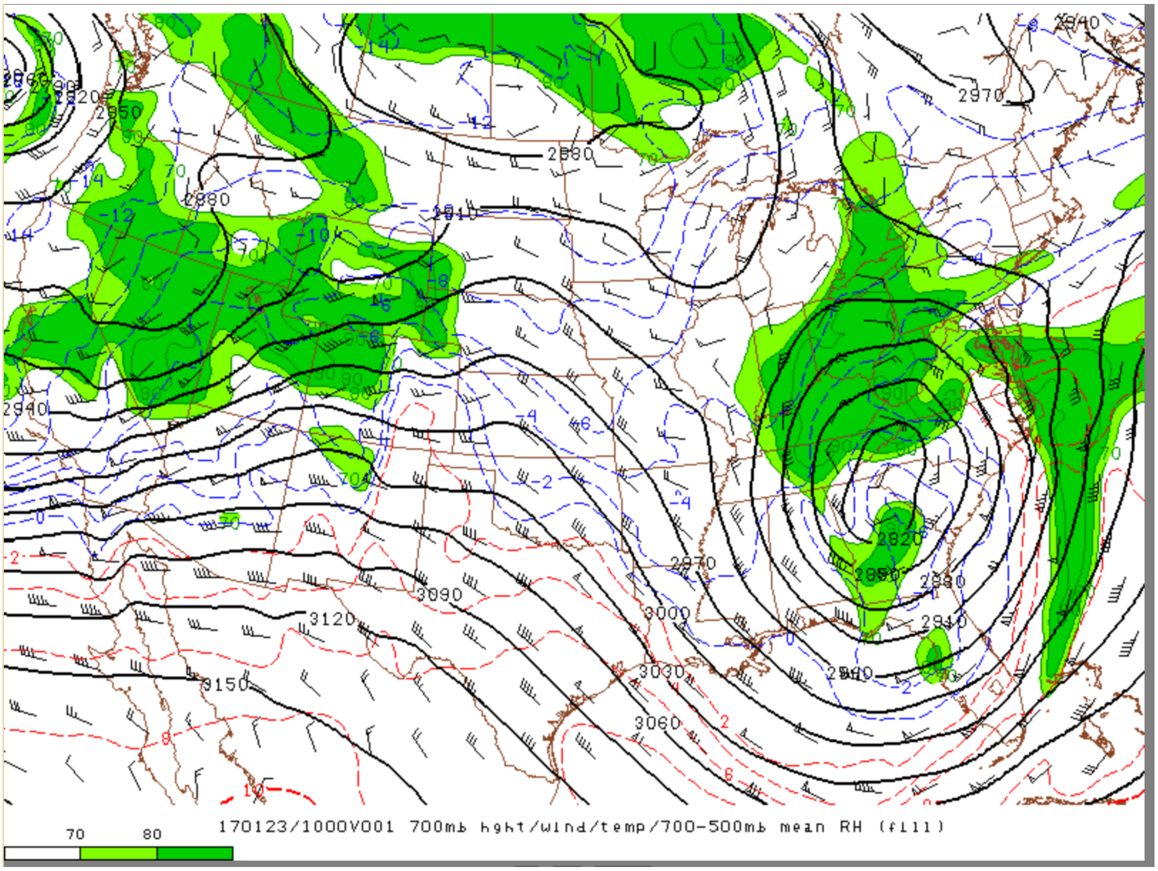


Fig 7. *700mb Rapid Refresh analysis field valid at 2017 January 23 1000 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (^oC)*, green shading relative humidity (%), wind barbs (kts).

After 1400 UTC 2017 January 23 the trough/upper level low started to move into the eastern Great Basin and closer to the area. The southwesterly flow continued through 0000 UTC 24 January 2017 and the clouds and moisture again increased (Fig. 8). Through this period Molas Lake SNOTEL in the Animas Basin reported 1.1” of SWE and 7” of new snow, Lizard Head near the Dolores/San Miguel Divide reported 0.4” of SWE and Lone Cone, on the north slopes of El Diente in the San Miguel Basin only received 0.1” of SWE. Supercooled liquid water was observed near the area, as reported by aircraft flying the vicinity of the Durango and Grand Junction Airports. (Fig. 9 and Fig. 10). Mid level layer cooled and the cloud layer appeared to be well-mixed from the surface to the 500mb (-30^{o}C) cloud top level by 0000 UTC 24 January 2017 (Fig. 11).

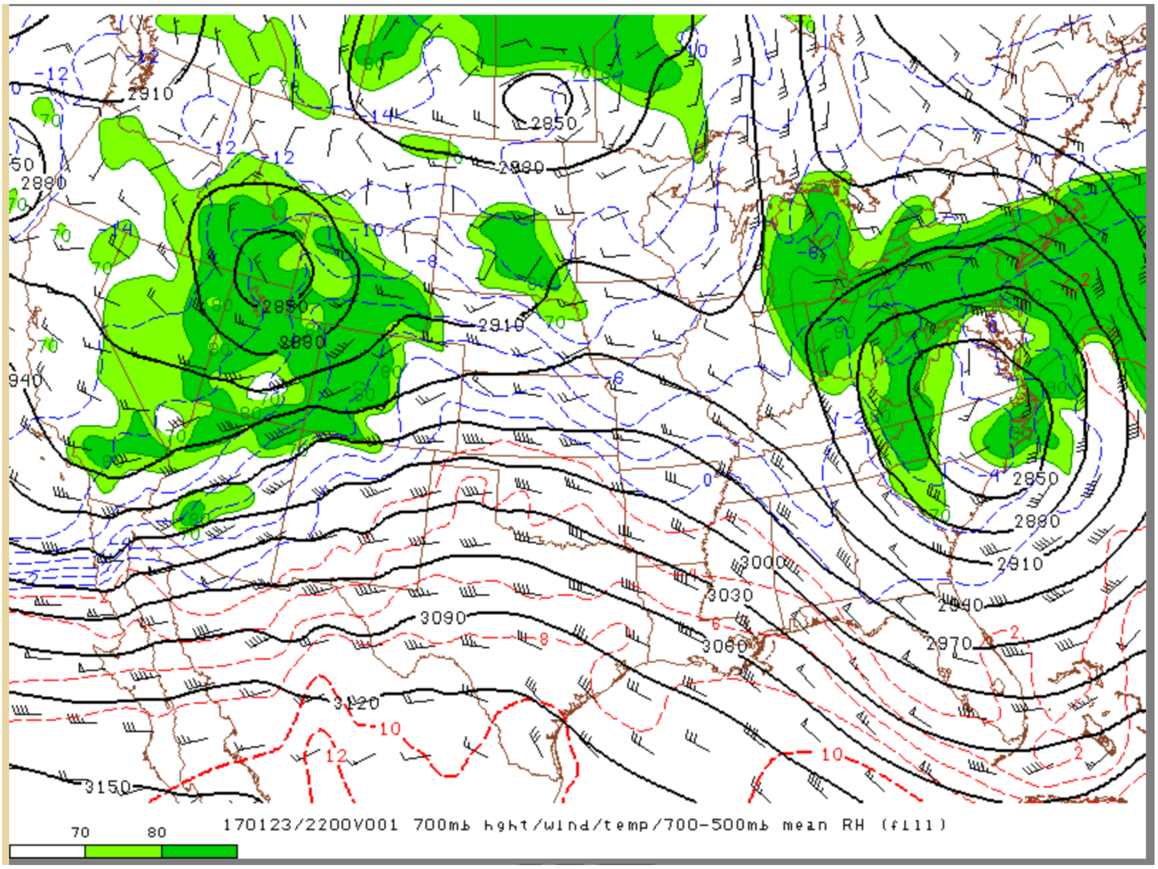


Fig 8. *700mb Rapid Refresh analysis field valid at 2017 January 23 2200 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (^oC)*, green shading relative humidity (%), wind barbs (kts).

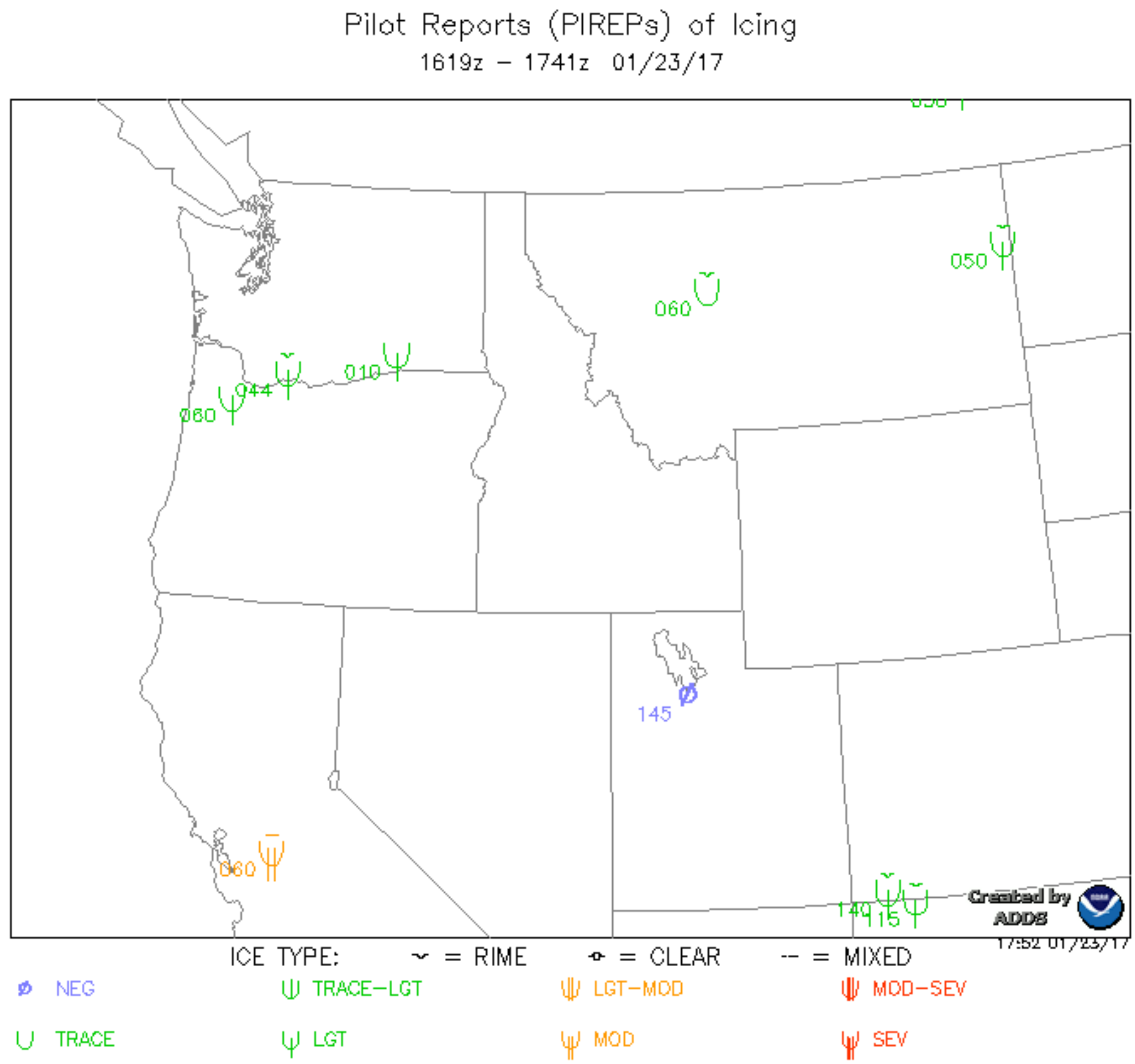


Figure 9. *Aircraft icing reports between 1619 UTC and 1741 UTC on 23 January 2017. Colors and symbols indicate icing severity and ice type.*

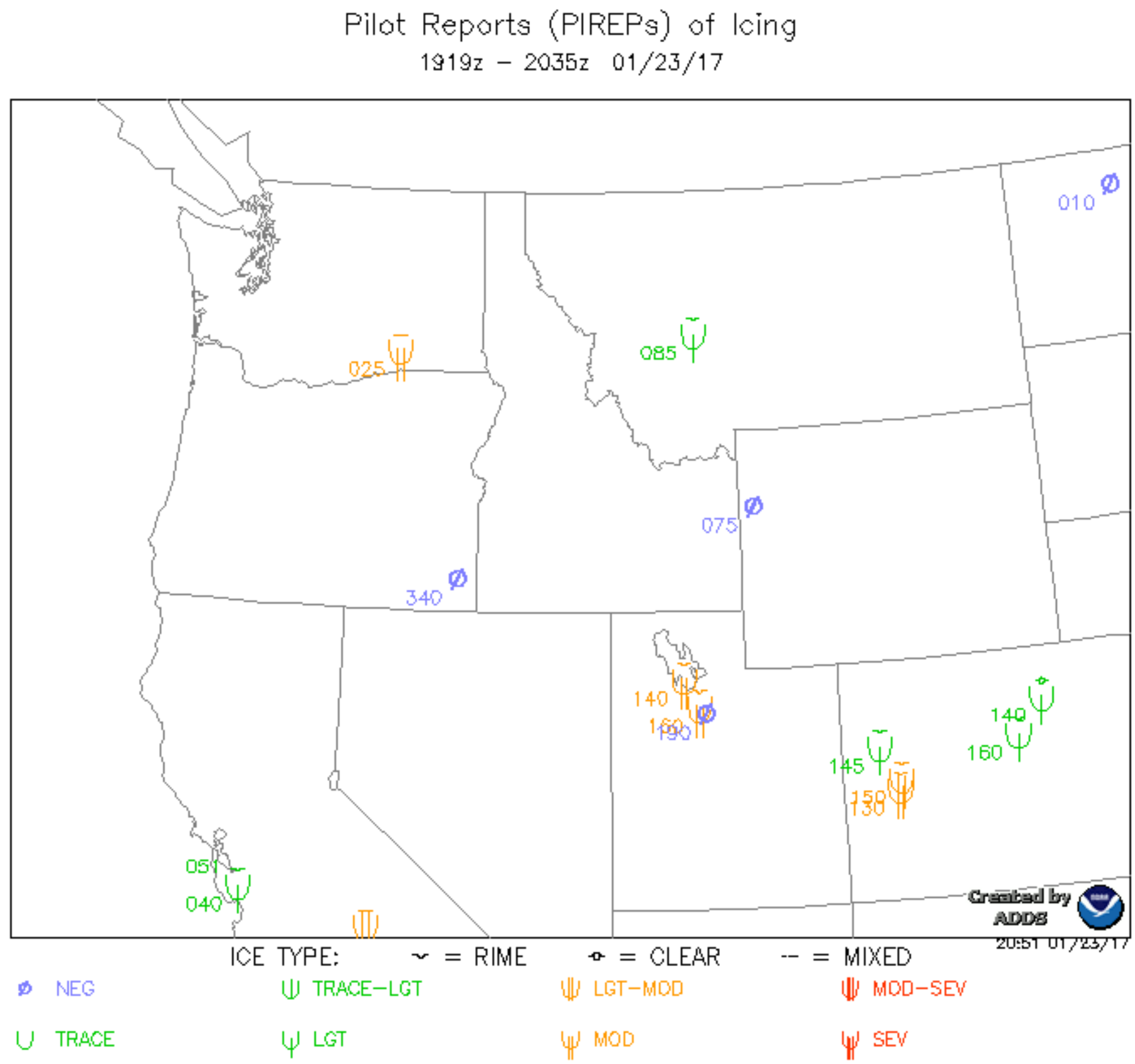


Figure 10. *Aircraft icing reports between 1919 UTC and 2035 UTC on 23 January 2017. Colors and symbols indicate icing severity and ice type.*

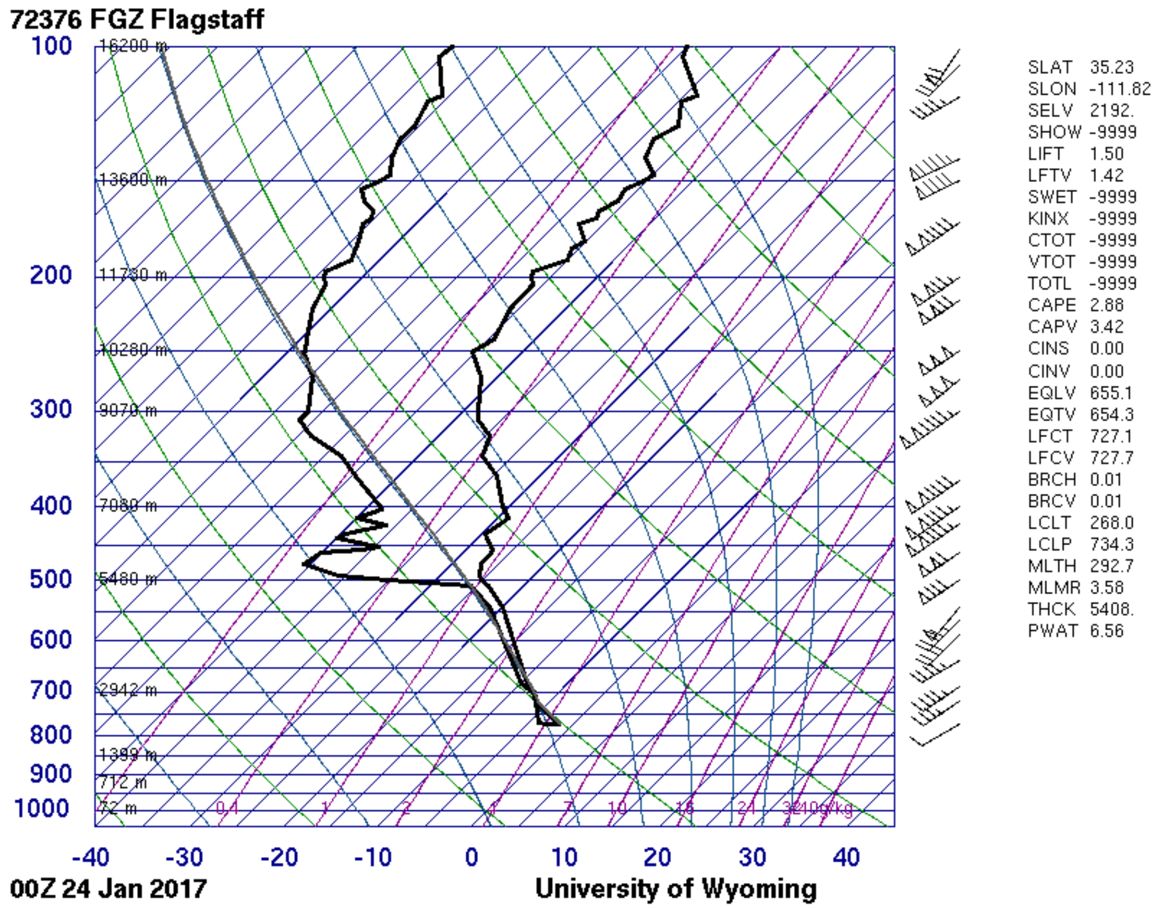


Figure 11. *Balloon sounding from the National Weather Service Flagstaff, AZ, 0000 UTC 24 January 2017****.***

After 0000 UTC on 24 January 2017, the cold front at 700mb moved across the area with 700mb temperatures cooling to -9^{o}C by 0800 UTC 24 January 2017. Winds become west to west-northwesterly through this period (Fig. 12). Lone Cone (SM) reported 0.4” of SWE and 4” of snow through this period, with Lizard Head (D) reporting 0.2” of SWE and 3” of snow, while Molas Lake (A) reported no precipitation through this period with the west-northwesterly flow.

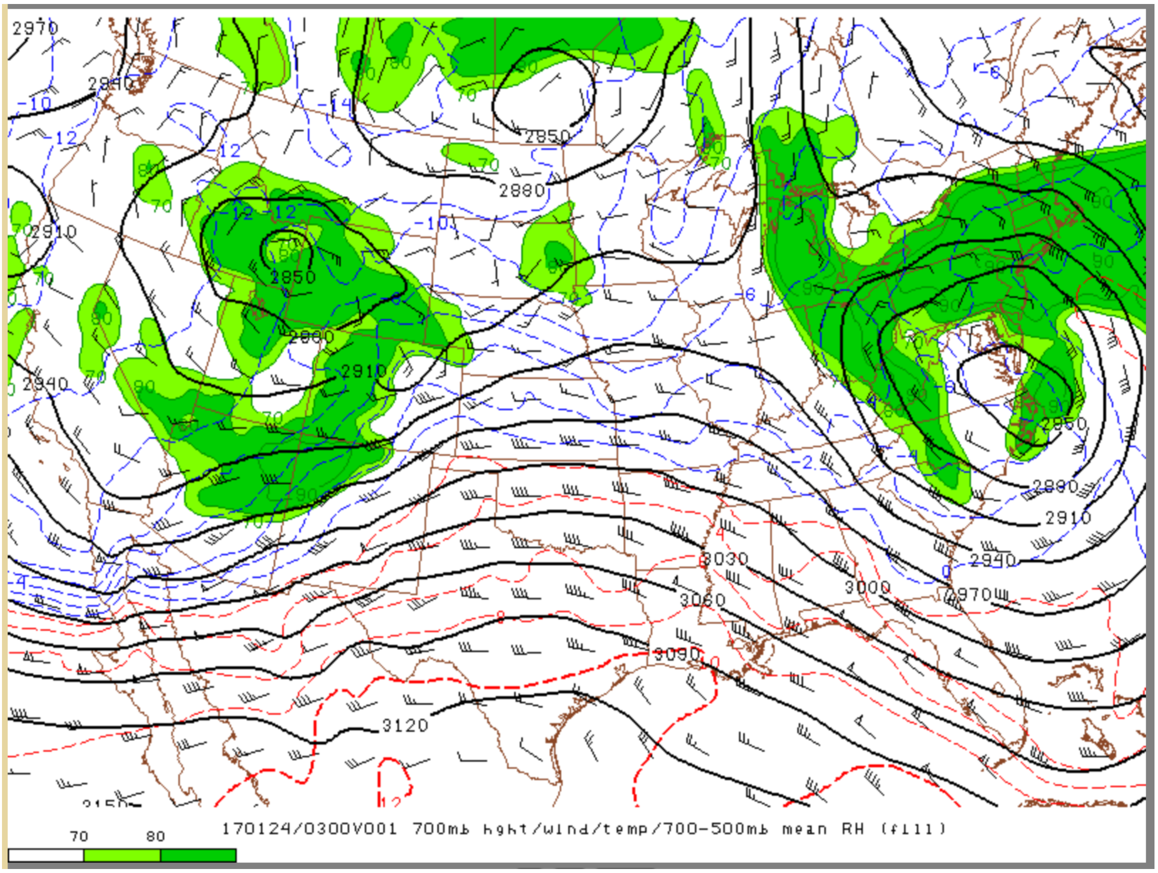


Fig 12. *700mb Rapid Refresh analysis field valid at 2017 January 24 0300 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (^oC)*, green shading relative humidity (%), wind barbs (kts).

From 0700 UTC 24 January 2017 through 1200 UTC 24 January 2017 conditions again dried with no precipitation reported at any of the SNOTEL sites. At 1200 UTC 24 January 2017 Telluride reported 8” of snow with Purgatory reporting 6” in the previous 24 hours.

Analysis: Case 1

Precipitation validation

The modeled total precipitation is presented in Figure 13. Over the higher terrain between 3” and 5” of liquid equivalent precipitation was produced by the model. These totals closely match the observed SNOTEL and Ski Resort values (Table 1), giving confidence that model was accurately simulating the storm period.

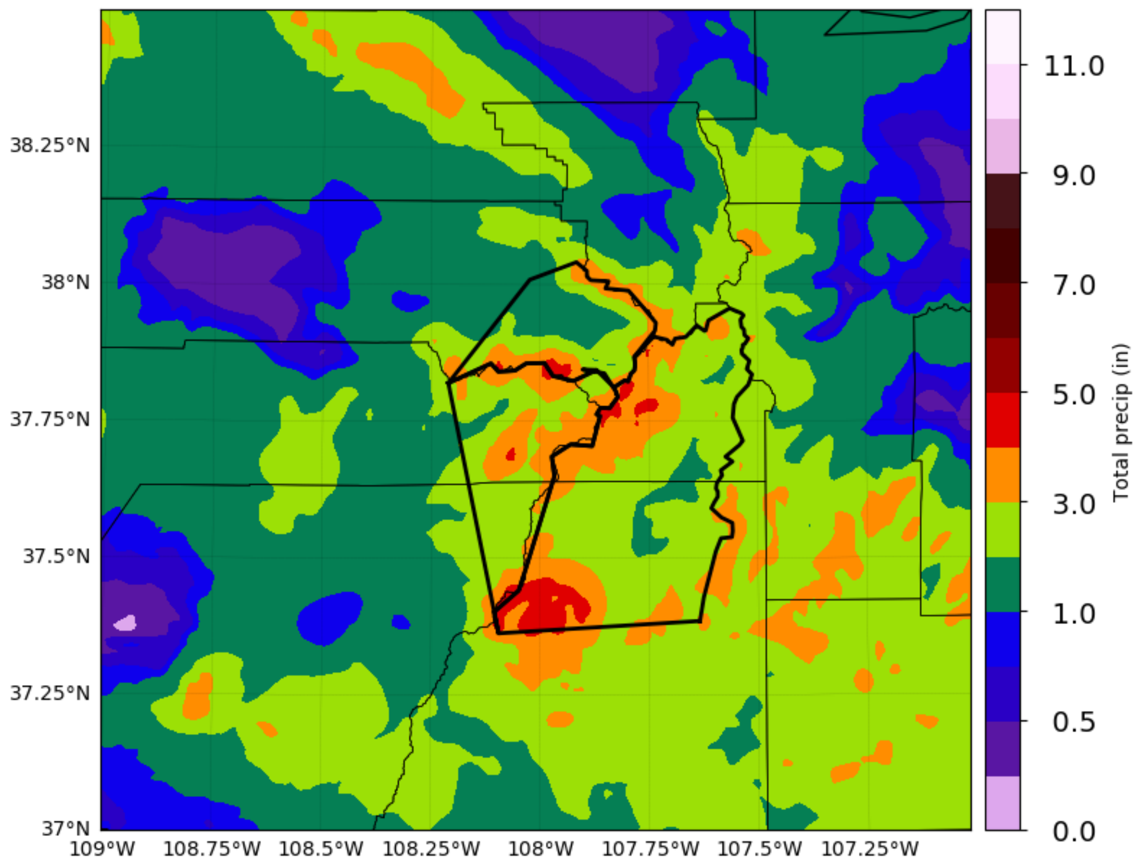


Figure 13. *Total liquid equivalent precipitation for the model run between 0600 UTC 21 January and 1200 UTC 24 January 2017, The heavy black lines indicate the approximate headwaters of the Dolores, Animas, and San Miguel Watersheds.*

Table 1. *Total precipitation at the ski resorts and NRCS SNOTEL sites during the model precipitation period. Snowfall data period from 1200 UTC 20 January and 1200 UTC 24 January 2017. Snow Water Equivalent data period from 0600 UTC 21 January and 1200 UTC 24 January 2017.*

Ski Resort	**Storm Period Snowfall (in)**
Silverton	41
Telluride	24
Purgatory	31
NRCS SNOTEL	**Snow Water Equivalent (in)**
Lizard Head	2.4
Lone Cone	2.5
Molas Lake	2.9

Cloud Seeding Potential

The results of the numerical model simulation show that cloud seeding opportunities were present over the San Juan Mountains for much of the storm period. Cloud seeding opportunities were present for more than 70% of the storm period over the highest terrain of the

San Miguel and Dolores headwaters and the highest terrain of the La Plata Mountains. A second seeding potential maxima is indicated over the eastern San Juan Mountains (Fig. 14).

The southwest to northeast (SW-NE) and northwest to southeast (NW-SE) (see Fig. E.4 for locations) vertical cross-sections show that the most favorable cloud seeding locations are tied to the higher terrain of the Dolores Watershed, on the upslope faces of the highest terrain Fig. 15 a and b. In addition, most of the potential cloud seeding periods occurred while precipitation was falling (Fig. 16).

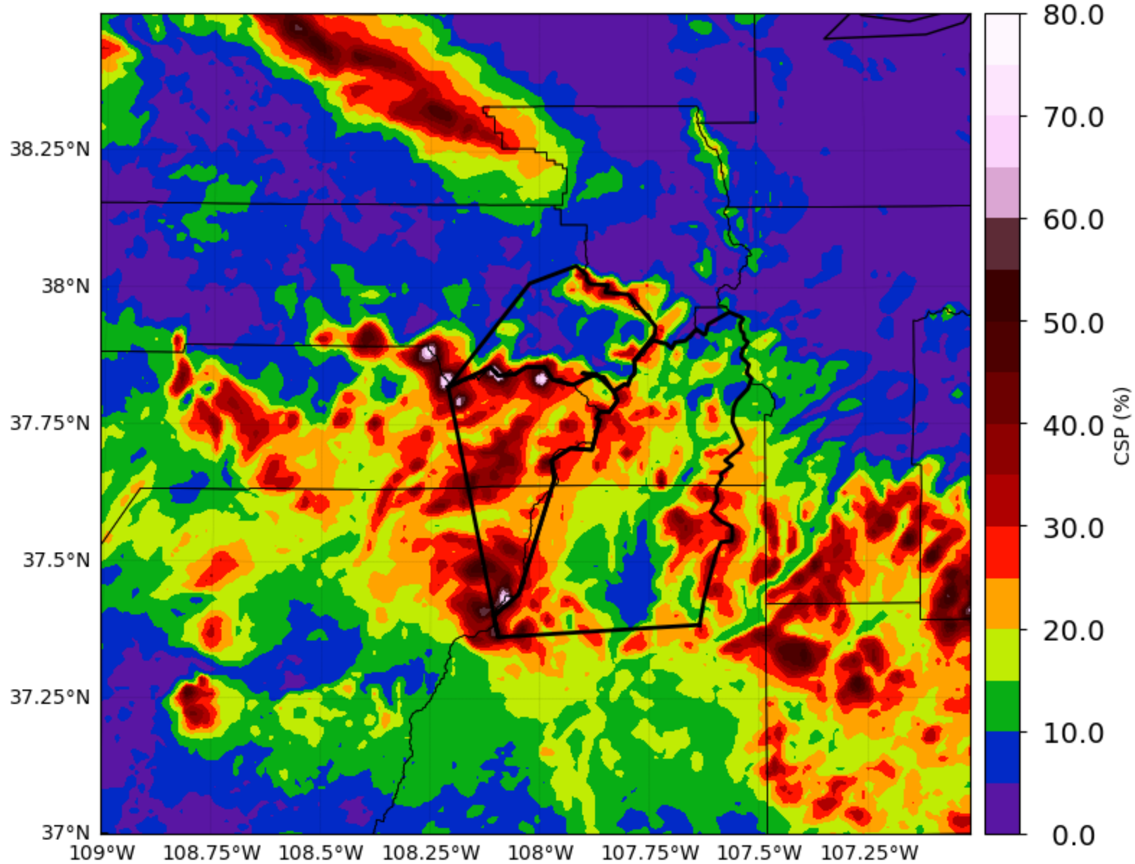


Figure 14*. Horizontal view of the percent of time cloud seeding conditions were present across the region from 0600 UTC 21 January and 1200 UTC 24 January 2017.*

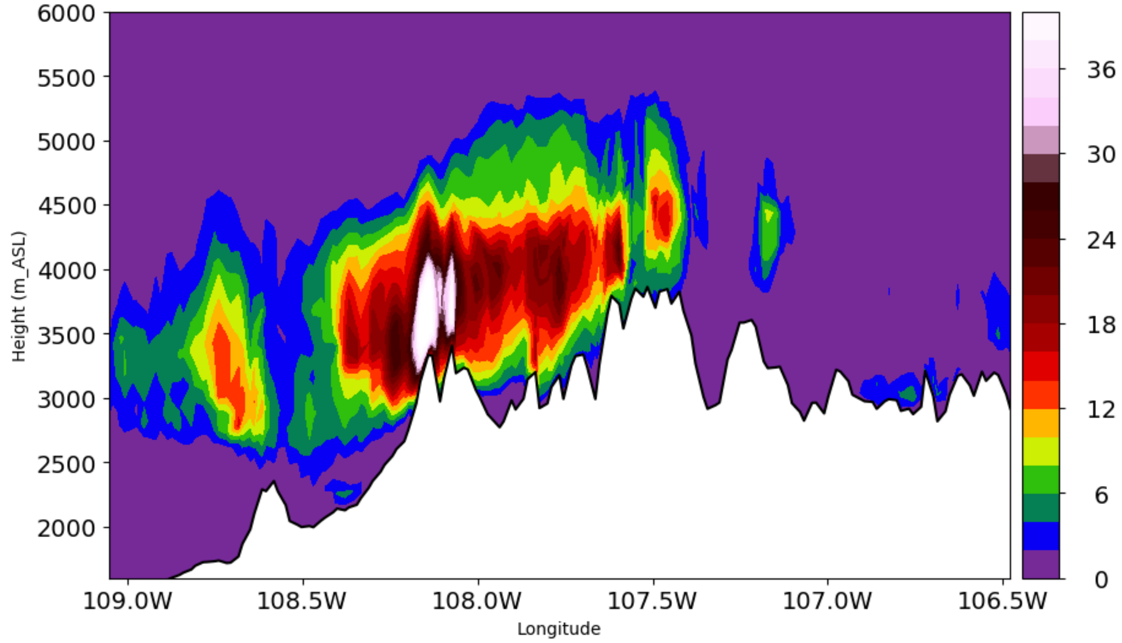


Figure 15 (a). *Southwest to northeast vertical cross-section of the percent of time cloud seeding conditions were present from 0600 UTC 21 January and 1200 UTC 24 January 2017. See Fig E.4 for cross section location*

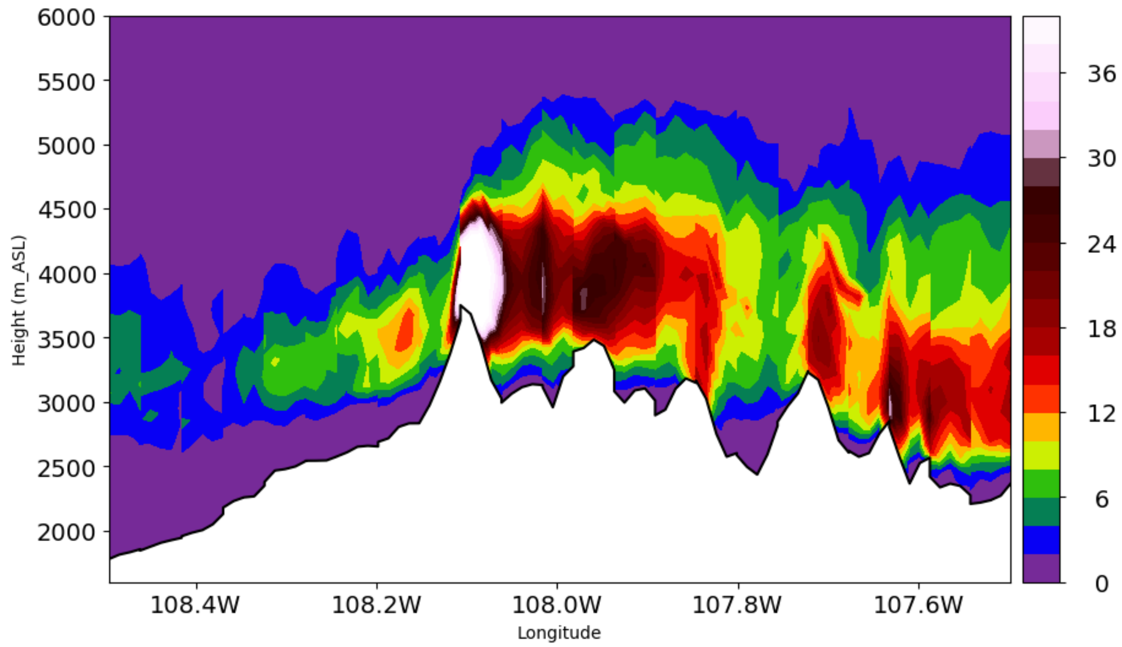


Figure 15 b. *Northwest to southeast vertical cross-section of the percent of time cloud seeding conditions were present from 0600 UTC 21 January and 1200 UTC 24 January 2017. See Fig E.4 for cross section location. The high point near 108.1 W Longitude is Mt Wilson along the Dolores/San Miguel Divide.*

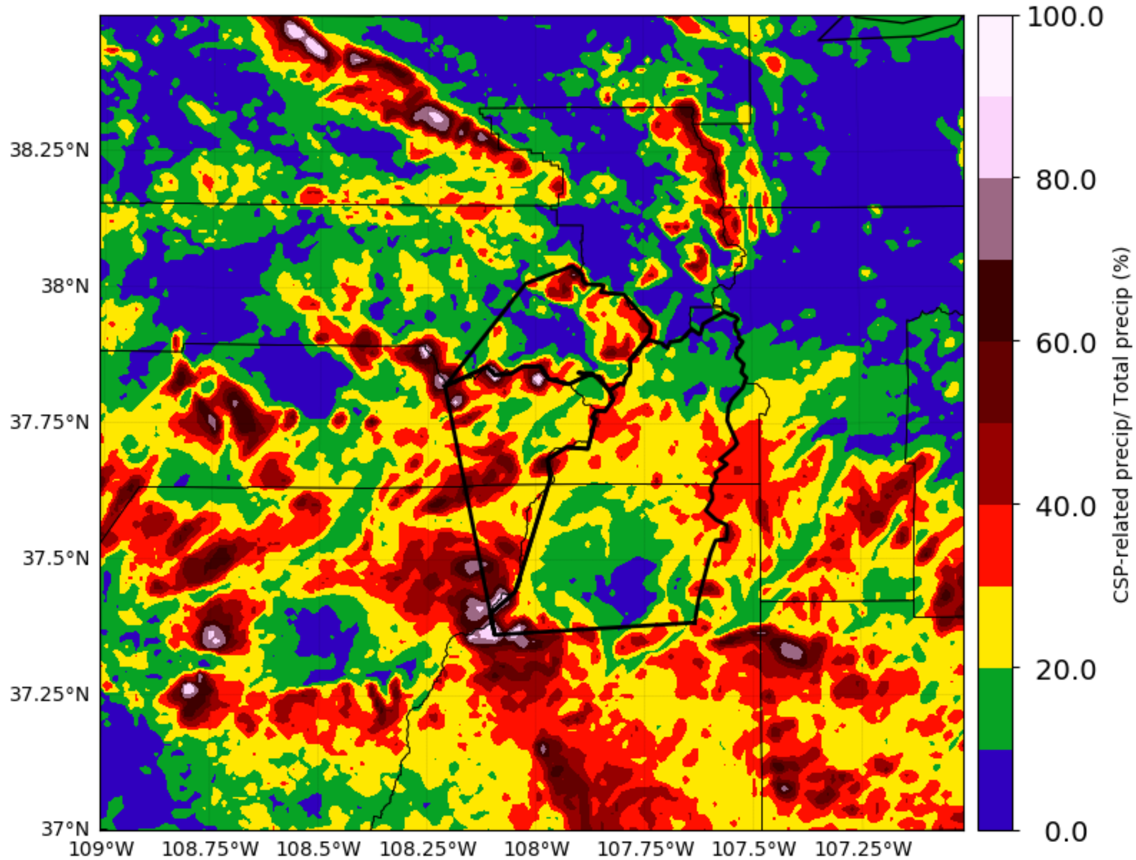


Figure 16. *The percent of time when modeled cloud seeding conditions were present and precipitation is also falling. High values suggest mixed phase clouds (ice and liquid water).*

Results from plume model

Particles were released from all of the San Juan generators during the entire storm period. The particles were tracked as they moved with the winds away from the generator for their interactions with supercooled temperatures (T colder than -5^{o}C) and seedable clouds (CSP: T < -5^{o}C and liquid water). Figure 17 shows an example of each of the San Juan network generator's efficiency at 1800 UTC 23 January 2017.

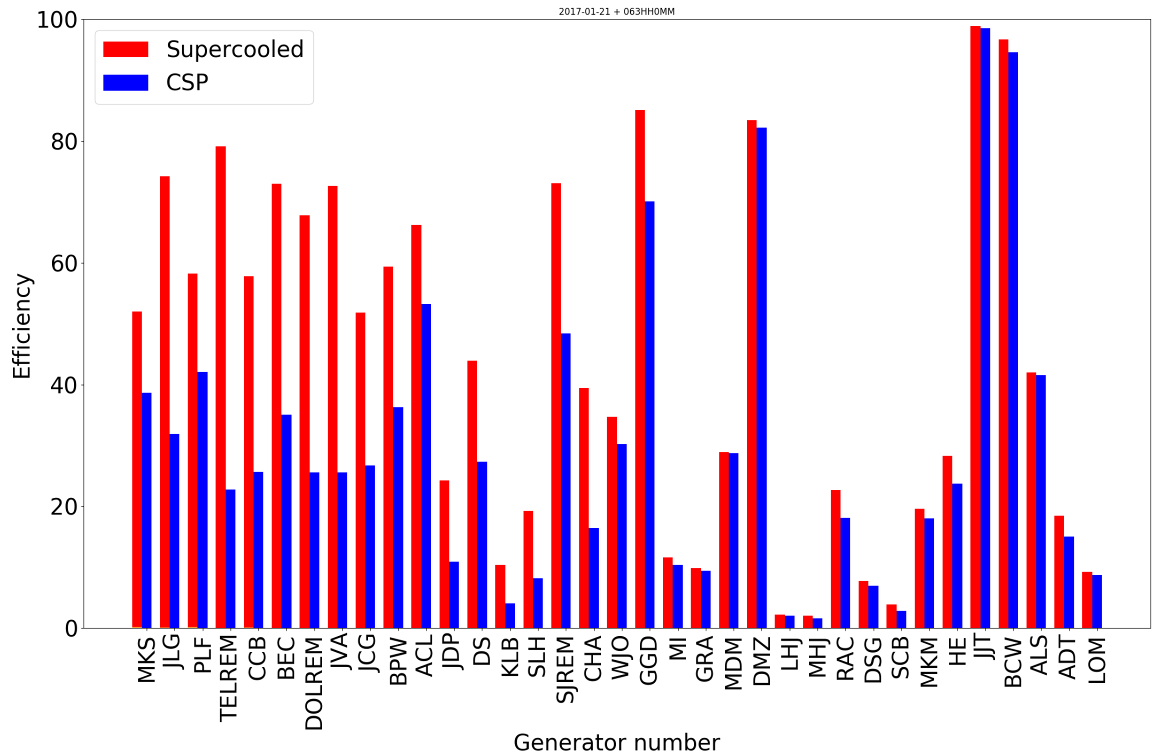


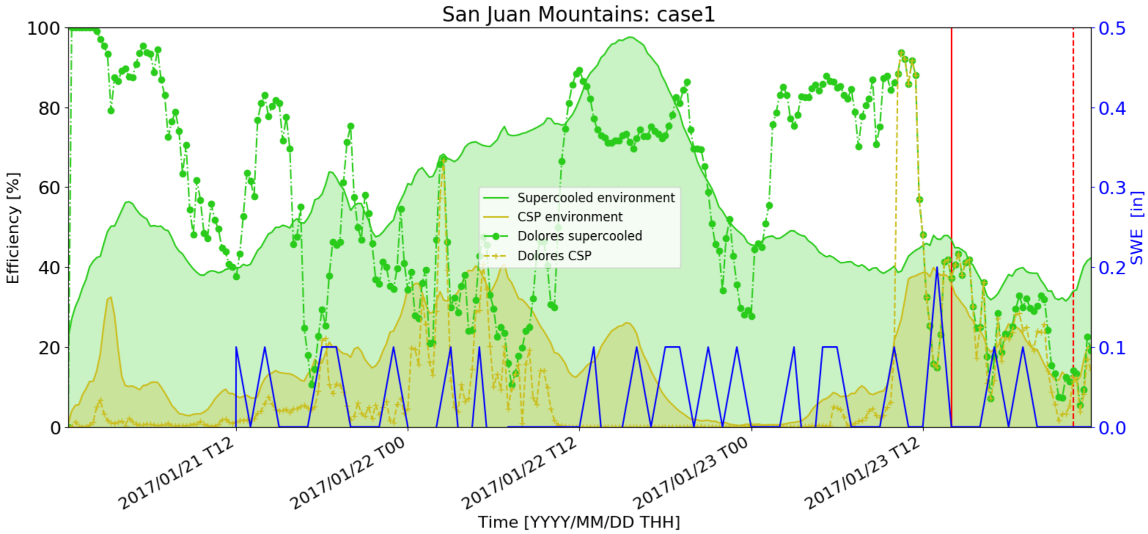
Figure 17*. Individual generator plume efficiencies for cloud seeding particles reaching model temperatures between -6C and -18C (red) and model clouds with supercooled liquid water and temperatures between -6C and -18C (blue). See Fig E.4 for generator locations.*

The analysis of the generator plumes with all the storm times produced the percent of particles released from all of the generator plumes which interacted with seedable clouds over the greater San Juan Mountains during the Case 1 storm period (Fig. 18 a, b, c). The seeding efficiency for the Dolores (Fig. 18 a), Animas (Fig. 18 b), and San Miguel (Fig. 18 c) headwaters region were also computed.

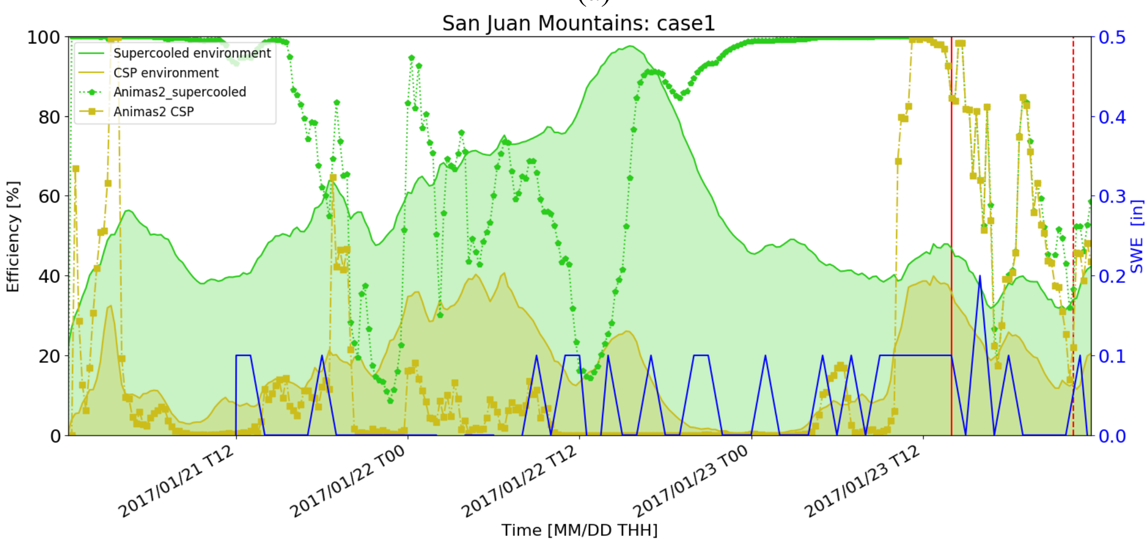
The results for the greater San Juan Mountains for Case 1 show that generators could have potentially delivered ice nuclei to seedable clouds from the start of the case study through 2100 UTC on 22 January 2017. The plume model suggests that between 10% and 40% of the particles released from the existing generator network would have reached seedable clouds. Another period of successful seeding (up to 40% efficient) was possible after 0600 UTC 23 January 2017 through the end of case study.

Reviewing the successful targeting results for the Dolores, Animas and San Miguel watersheds show that the generator network would produce several periods of successful cloud seeding through much of the case study period.

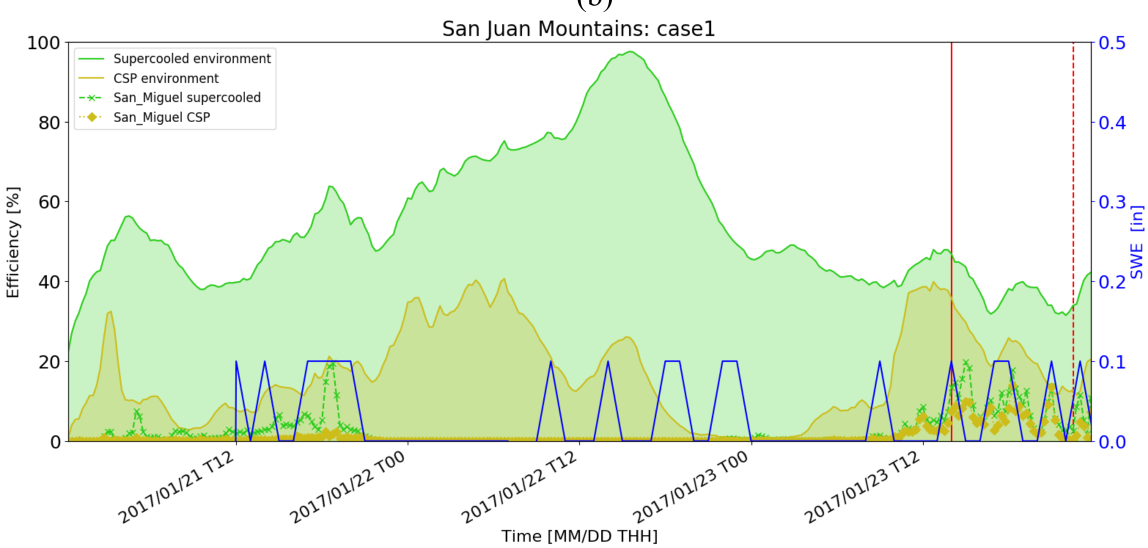
Analysis of the actual period when operational cloud seeding was conducted (times between red and red-dashed lines) suggests that 30% of the silver iodide (AgI) particles (cloud seeding plumes) reached seedable clouds over the target area. The results also suggest that the early portions of the storm could have been seeded and the seeding operations during the final period of the case study should have been initiated several hours earlier.


San Juan Mountains: case1
Efficiency [%]
SWE [in]
Time [YYYY/MM/DD THH]
2017/01/21 T12
2017/01/22 T00
2017/01/22 T12
2017/01/23 T00
2017/01/23 T12
Supercooled environment
CSP environment
Dolores supercooled
Dolores CSP

(a)


San Juan Mountains: case1
Efficiency [%]
SWE [in]
Time [MM/DD THH]
2017/01/21 T12
2017/01/22 T00
2017/01/22 T12
2017/01/23 T00
2017/01/23 T12
Supercooled environment
CSP environment
Animas2_supercooled
Animas2 CSP

(b)


San Juan Mountains: case1
Efficiency [%]
SWE [in]
Time [MM/DD THH]
2017/01/21 T12
2017/01/22 T00
2017/01/22 T12
2017/01/23 T00
2017/01/23 T12
Supercooled environment
CSP environment
San_Miguel supercooled
San_Miguel CSP

(c)

Figure 18. *Generator efficiency plots for all generators across the San Juan Mountains (green shading percent of particles reaching temperatures colder than -5^{o}C), (orange shading percent of particles reaching seedable clouds), red lines show start and end times of the operational cloud seeding conducted during this storm. (a) Dolores Watershed (green dashed line percent of particles reaching temperatures colder than -5^{o}C), (orange dashed line percent of particles reaching seedable clouds), blue line shows hourly precipitation rate in the Dolores Watershed. (b) same as (a) except for Animas watershed, (c) same as (a) except for San Miguel Watershed.*

Case 2: 15 December 2016 1800 UTC – 17 December 2016 1800 UTC

At 1800 UTC on 15 December 2016 a large-scale upper level trough was over northern CA. Some mid-level moisture was moving across the San Juan Mountains, with 700mb temperatures at a warm +3C.

By 0000 UTC on 2016 December 16 a strong west-southwesterly flow was over San Juan Mountains (Fig. 19). A lead shortwave embedded in the westerly flow was also moving across the area. Further west, off the central CA Coast a stronger short-wave was present and moving towards the southeast. Moisture associated the lead shortwave moved across the area between 1900 UTC 15 December 2016 and 0400 UTC 16 December 2016 as 700mb temperatures cooled to -2C. This led to precipitation over the area Table 2.

Table 2. *Snow Water Equivalent Precipitation totals at three representative NRCS SNOTEL sites over the Dolores, Animas, and San Miguel Watersheds.*

SNOTEL (watershed)	Start Date Time (UTC)	End Date Time (UTC)	Snow Water Equivalent (SWE)
Lizard Head (D)	15 December 1900	16 December 0400	0.3
Molas Lake (A)	15 December 1900	16 December 0400	0.4
Lone Cone (SM)	15 December 1900	16 December 0400	0.2

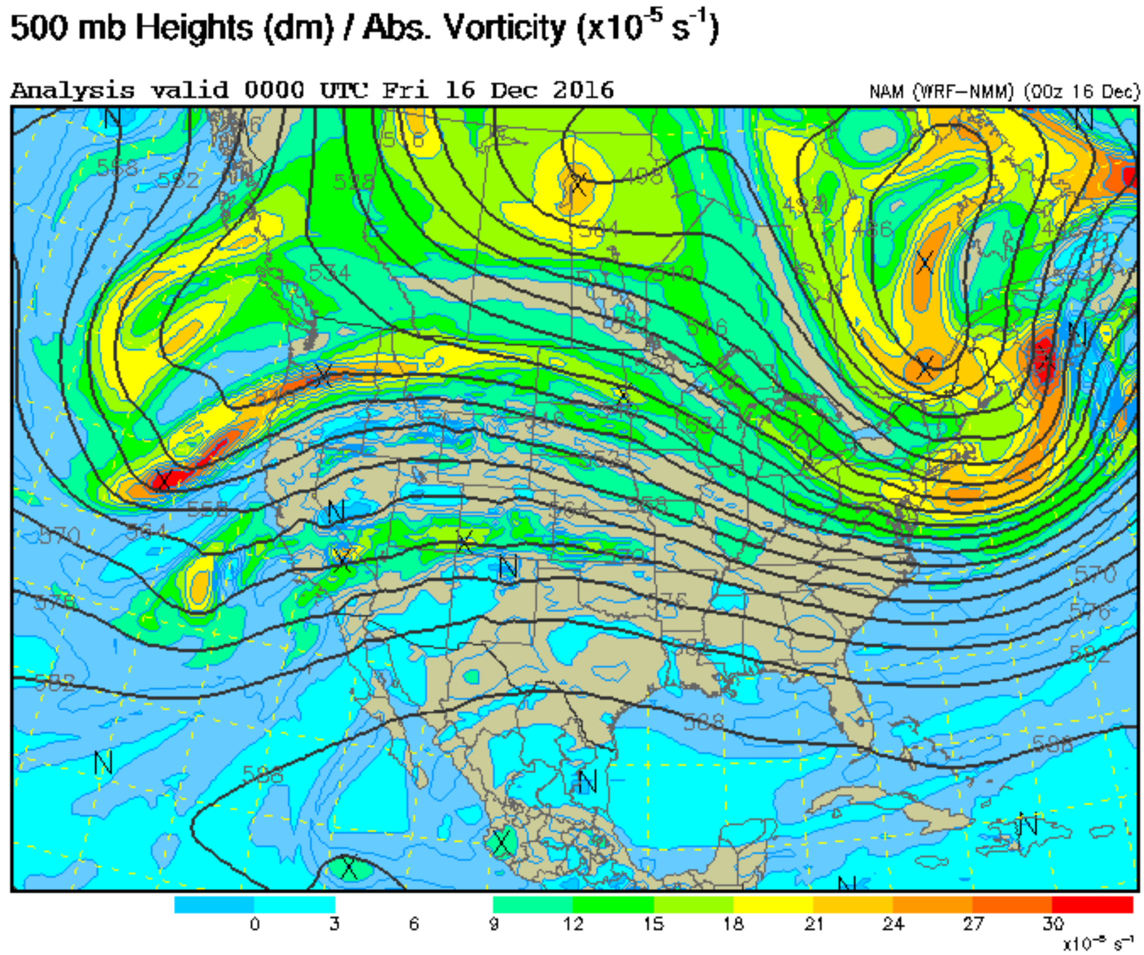


Figure 19. *500mb NAM analysis field valid at 2016 December 16 0000 UTC. Heavy black lines: geopotential height (m), dashed lines:* shading indicated vorticity(x10^5 s^{-1}).

Between 0600 UTC and 1200 UTC 16 December 2016 additional precipitation was observed (Table 3). The 24-hour snowfall reported at 1200 UTC at the Purgatory Resort was 4" of new, Telluride reported 7" (Silverton Mountain Resort did not report on the morning of 16 December 2016).

Table 3*. Snow Water Equivalent Precipitation totals at three representative NRCS SNOTEL sites over the Dolores, Animas, and San Miguel Watersheds.*

SNOTEL (watershed)	Start Date Time (UTC)	End Date Time (UTC)	Snow Water Equivalent (SWE)
Lizard Head (D)	16 December 0600	16 December 1200	0.3
Molas Lake (A)	16 December 0600	16 December 1200	0.2
Lone Cone (SM)	16 December 0600	16 December 1200	0.2

In the morning of 16 December (1600 UTC) the moisture increased as the warm sector ahead of the cold front moved into the area. Moisture was present but the stability profile was stable below 12,000 ft MSL (Fig. 20) with a moist unstable layer with a cloud top at 500mb

(18,000’ MSL) and -17°C above 12,000 ft MSL. Several icing pilot reports were received just north and southwest of the San Juan Mountains adding confidence that supercooled liquid water clouds were indeed present within the storm structure (Fig. 21). At 700mb winds remained from the west-southwest and temperatures were -1C, with the cold front still to the northwest of the area (Fig. 22). In addition to supercooled liquid water, these clouds produced more precipitation across the area (Table 4).

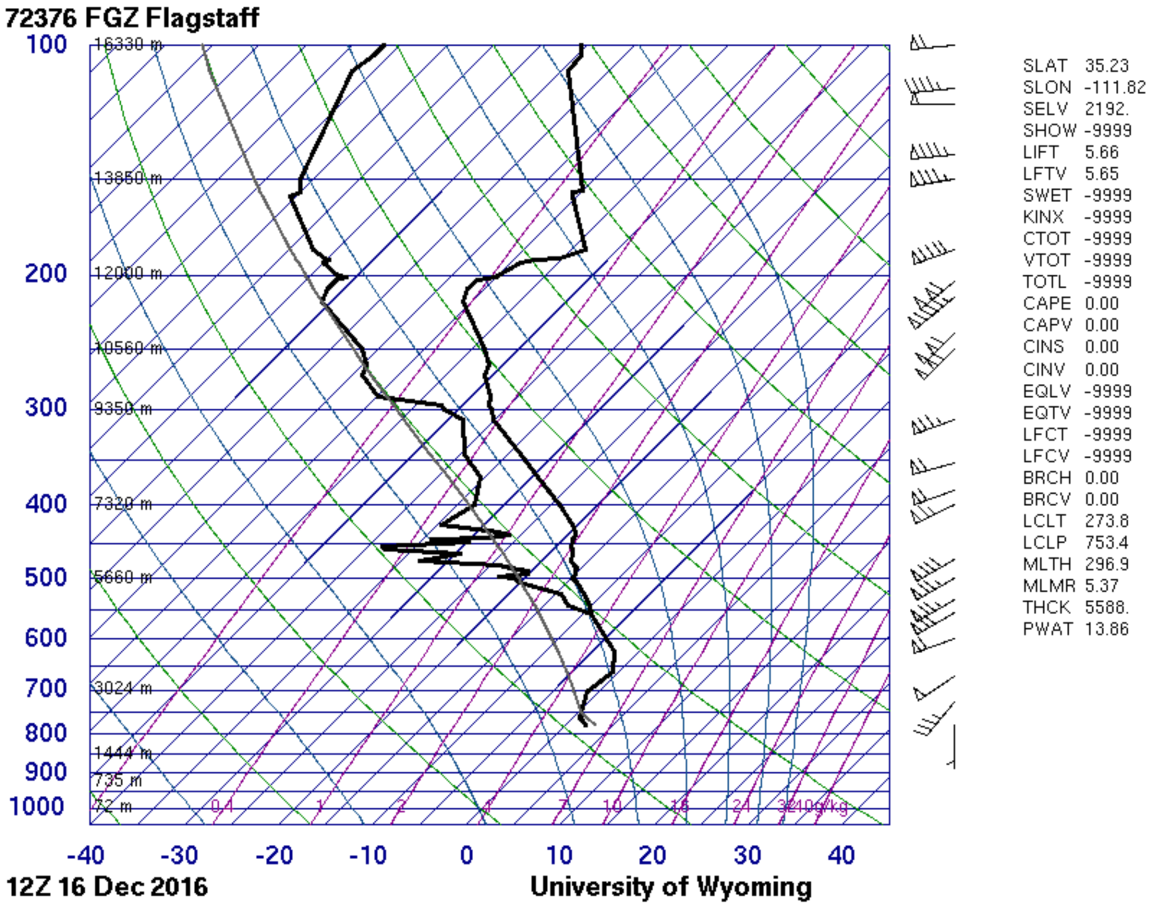


Figure 20. *Balloon sounding from the National Weather Service Flagstaff, AZ, 1200 UTC 16 December 2016.*

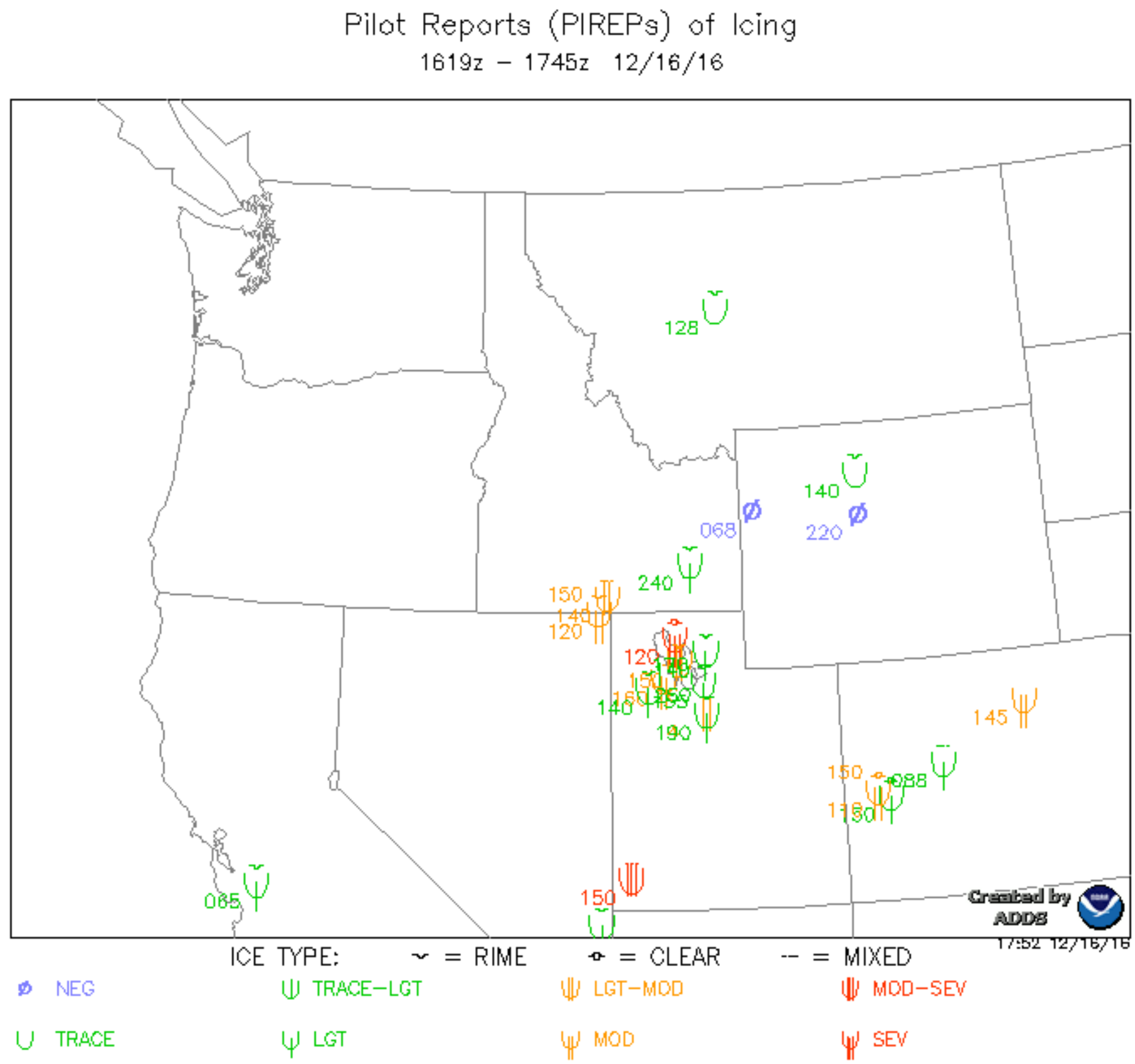


Figure 21. *Aircraft icing reports between 1619 UTC and 1745 UTC on 16 December 2016. Colors and symbols indicate icing severity and ice type.*

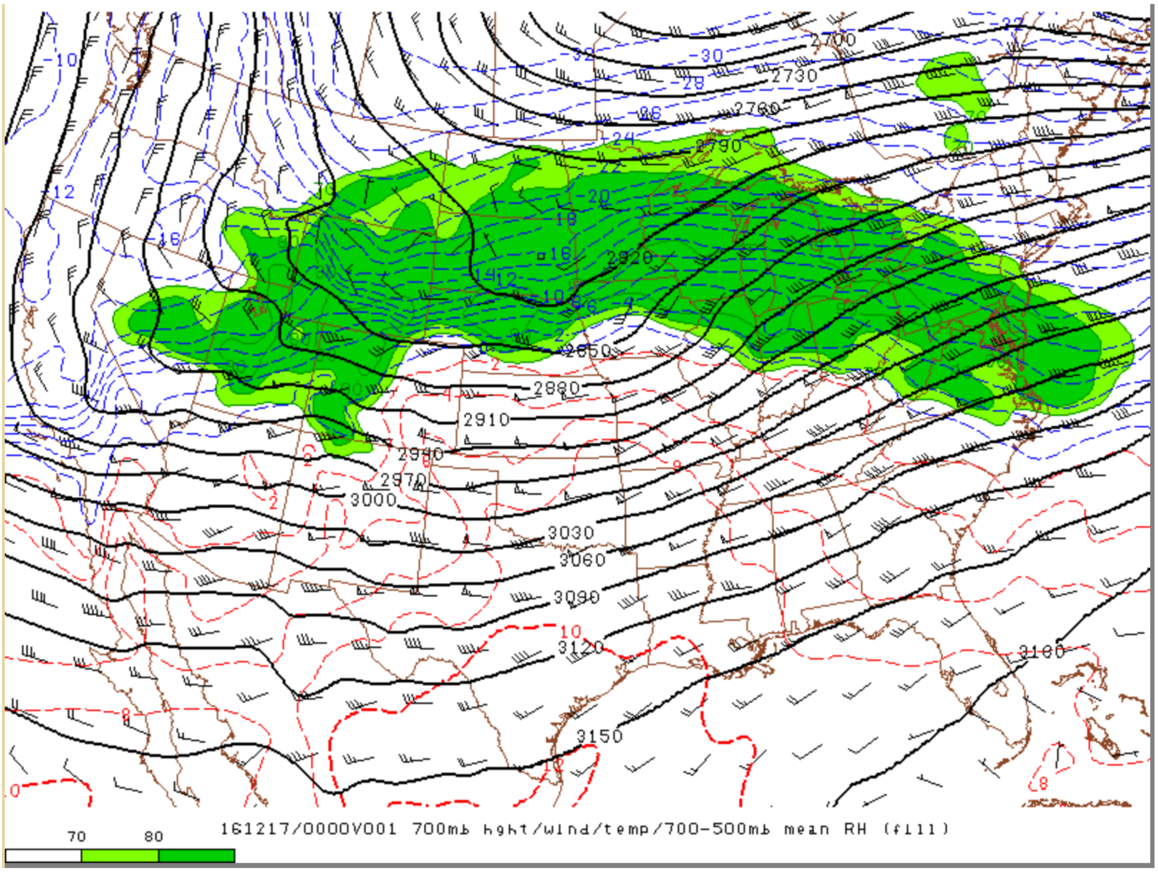


Figure 22. *700mb Rapid Refresh analysis field valid at 2016 December 17 0000 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (^{o}C)*, green shading relative humidity (%), wind barbs (kts).

Table 4. *Snow Water Equivalent Precipitation totals at three representative NRCS SNOTEL sites over the Dolores, Animas, and San Miguel Watersheds.*

SNOTEL (watershed)	Start Date Time (UTC)	End Date Time (UTC)	Snow Water Equivalent (SWE)
Lizard Head (D)	16 December 1200	17 December 0000	0.7
Molas Lake (A)	16 December 1200	17 December 0000	1.0
Lone Cone (SM)	16 December 1200	17 December 0000	0.7

Between 0000 UTC and 0700 UTC 17 December 2016 the cold front moved southeast and was just west the San Juan Mountains. Temperatures cooled to -4C and a deep layer of moisture under southwesterly flow continued across the Mountains. Additional significant precipitation was observed (Table 5) and icing was reported during this period (Fig. 23).

Table 5. *Snow Water Equivalent Precipitation totals at three representative NRCS SNOTEL sites over the Dolores, Animas, and San Miguel Watersheds.*

SNOTEL (watershed)	Start Date Time (UTC)	End Date Time (UTC)	Snow Water Equivalent (SWE)
Lizard Head (D)	17 December 0000	17 December 0700	0.8
Molas Lake (A)	17 December 0000	17 December 0700	1.0

Lone Cone (SM)	17 December 0000	17 December 0700	1.0

The cold front moved through after 0800 UTC December 17 with the 700mb winds shifting to northwesterly and temperatures cooling to -8C. The 24 hour snowfall reported at Purgatory and Telluride 14”, and at Silverton it 29”. Snow under the north-northwesterly flow at 700mb continued through 1800 UTC December 17 with 0.2” of SWE at Molas Lake (A) and Lizard Head Pass (D) to 0.4” at Lone Cone with temperature cooling to -10C.

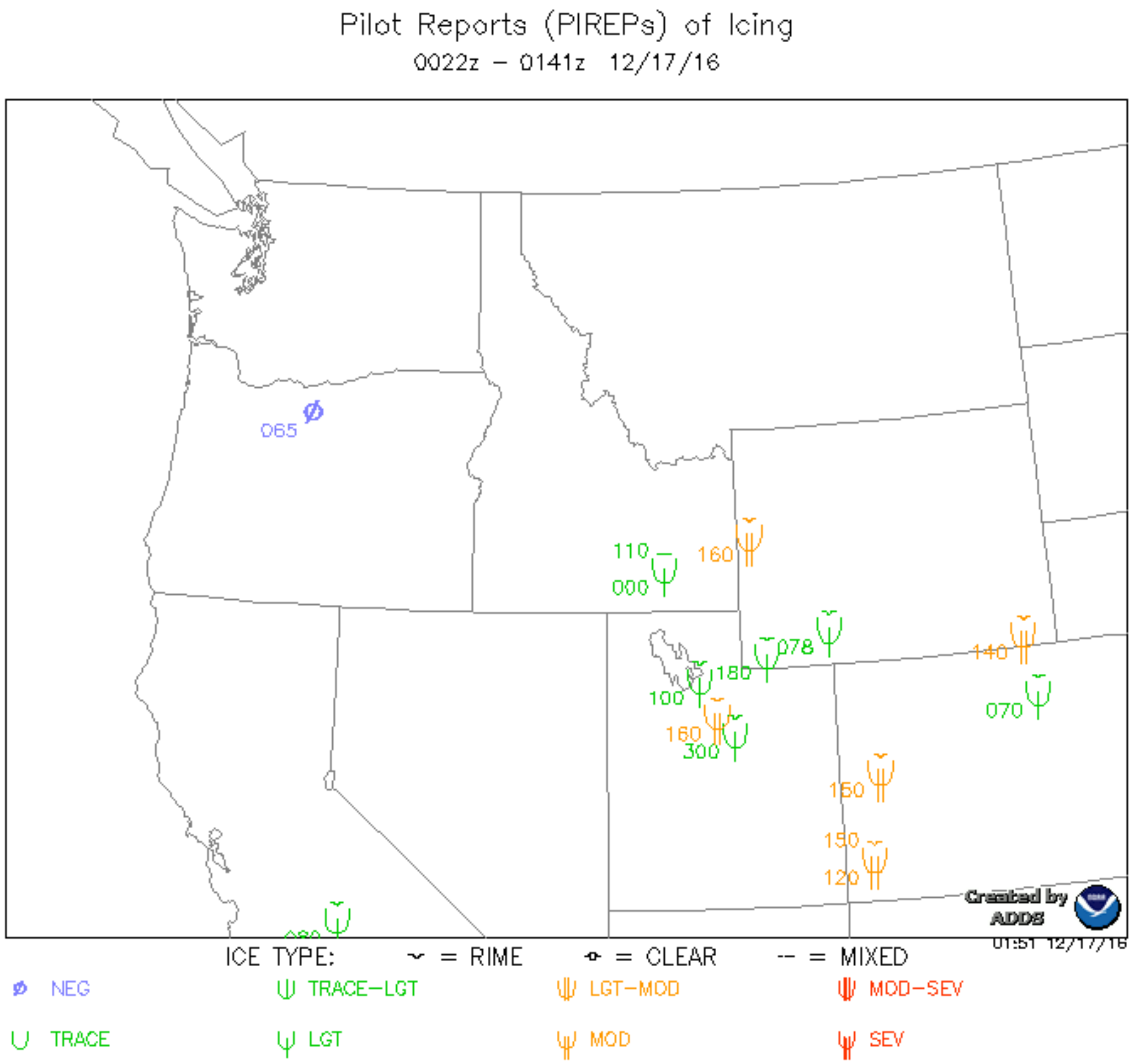


Figure 23. *Aircraft icing reports between 0022 UTC and 0141 UTC on 17 December 2016. Colors and symbols indicate icing severity and ice type.*

Analysis: Case 2

Precipitation validation

The modeled total precipitation is presented in Fig. 24. Over the highest terrain between 5” and 6” of liquid equivalent precipitation was produced by the model. These totals are higher than those observed by SNOTEL but more inline with the most favorable locations for high amounts of precipitations, the ski resorts (Table 6). The warm nature of this storm likely reduced the typical 10:1 snow to liquid ratio suggesting that Telluride and Silverton certainly received over 4” and perhaps 5” of SWE.

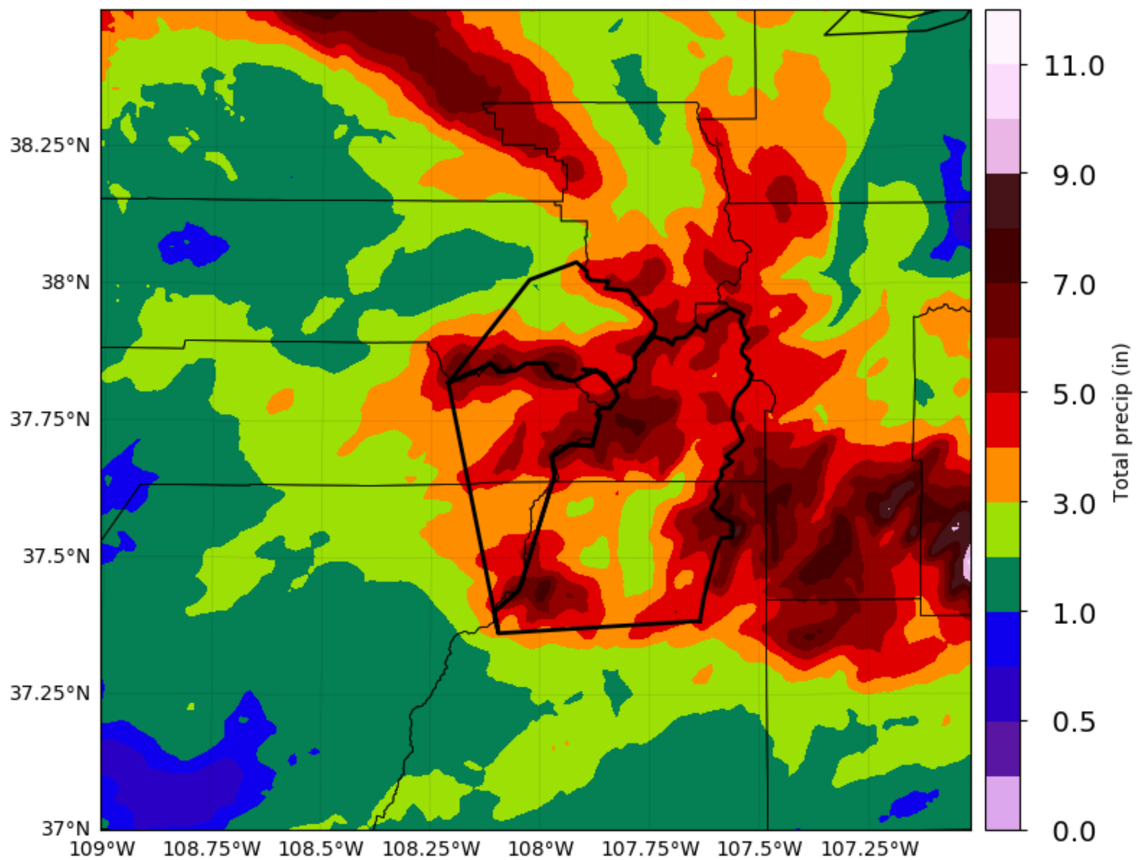


Figure 24. *Total liquid equivalent precipitation for the model run between 15 December 2016 1800 UTC – 17 December 2016 1800 UTC, The heavy black lines indicate the approximate headwaters of the Dolores, Animas, and San Miguel Watersheds.*

Table 6. *Total precipitation at the ski resorts and NRCS SNOTEL sites during the model precipitation period. Snowfall data period from 1200 UTC 15 December and 1200 UTC 18 December 2016. Snow Water Equivalent data period from 15 December 2016 1800 UTC – 17 December 2016 1800 UTC.*

Ski Resort	**Storm Period Snowfall (in)**
Silverton	29
Telluride	31
Purgatory	19
NRCS SNOTEL	**Snow Water Equivalent (in)**
Lizard Head	2.0
Lone Cone	2.3
Molas Lake	2.6

Cloud Seeding Potential

The results of the numerical model simulation show that cloud seeding opportunities were present over the San Juan Mountains for much of the storm period. Cloud seeding opportunities were present for more than 50% of the storm period over the highest terrain of the San Miguel and Dolores watersheds and the highest terrain of the La Plata Mountains. A second significant maxima is indicated over the eastern Animas Watershed and the eastern San Juan Mountains (Fig. 25).

The SW-NE vertical cross-section shows the warmer nature of this storm and that the higher levels (above 12,000' MSL) had the seedable cloud. The most favorable cloud seeding locations are again tied to the higher terrain of the Dolores Watershed, on the upslope faces of the highest terrain (Fig. 26 a and b). In addition most of the cloud seeding periods occurred while precipitation was falling, especially over the eastern San Juan Mountains (Fig. 27).

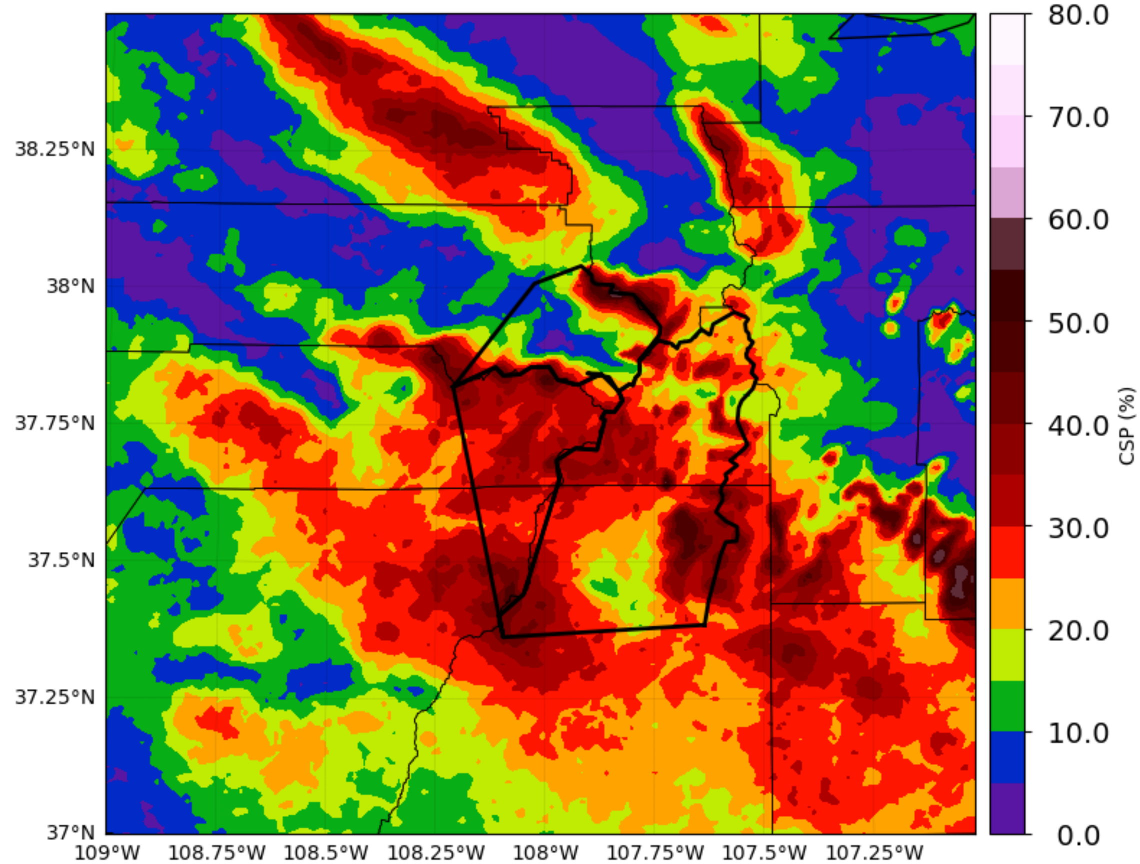


Figure 25. *Horizontal view of the percent of time cloud seeding conditions were present across the region from 15 December 2016 1800 UTC – 17 December 2016 1800 UTC.*

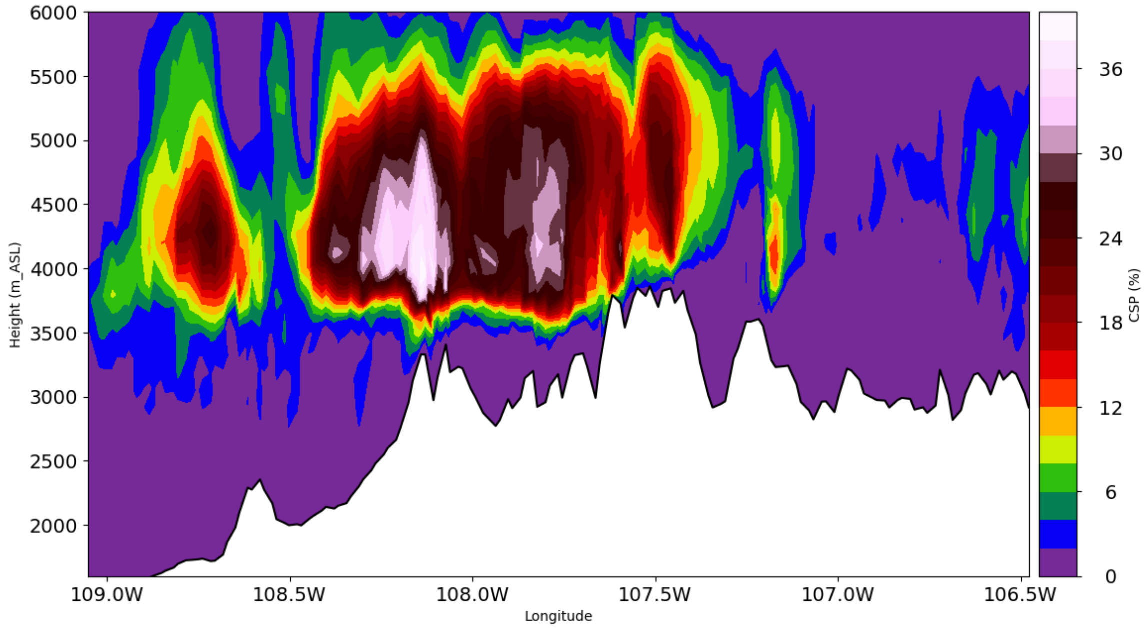


Figure 26 (a). *Southwest to northeast vertical cross-section of the percent of time cloud seeding conditions were present from 15 December 2016 1800 UTC – 17 December 2016 1800 UTC. See Fig E.4 for cross section location.*

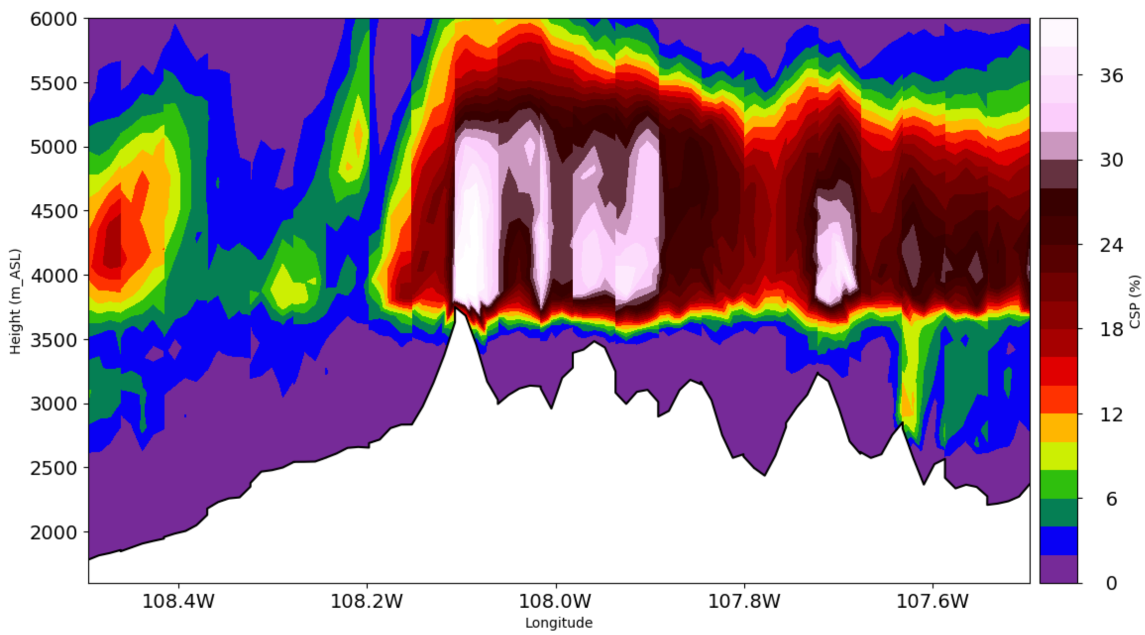


Figure 26 b. *Northwest to southeast vertical cross-section of the percent of time cloud seeding conditions were present from 15 December 2016 1800 UTC – 17 December 2016 1800 UTC. See Fig E.4 for cross section location. The high point near 108.1 W Longitude is Mt Wilson along the Dolores/San Miguel Divide.*

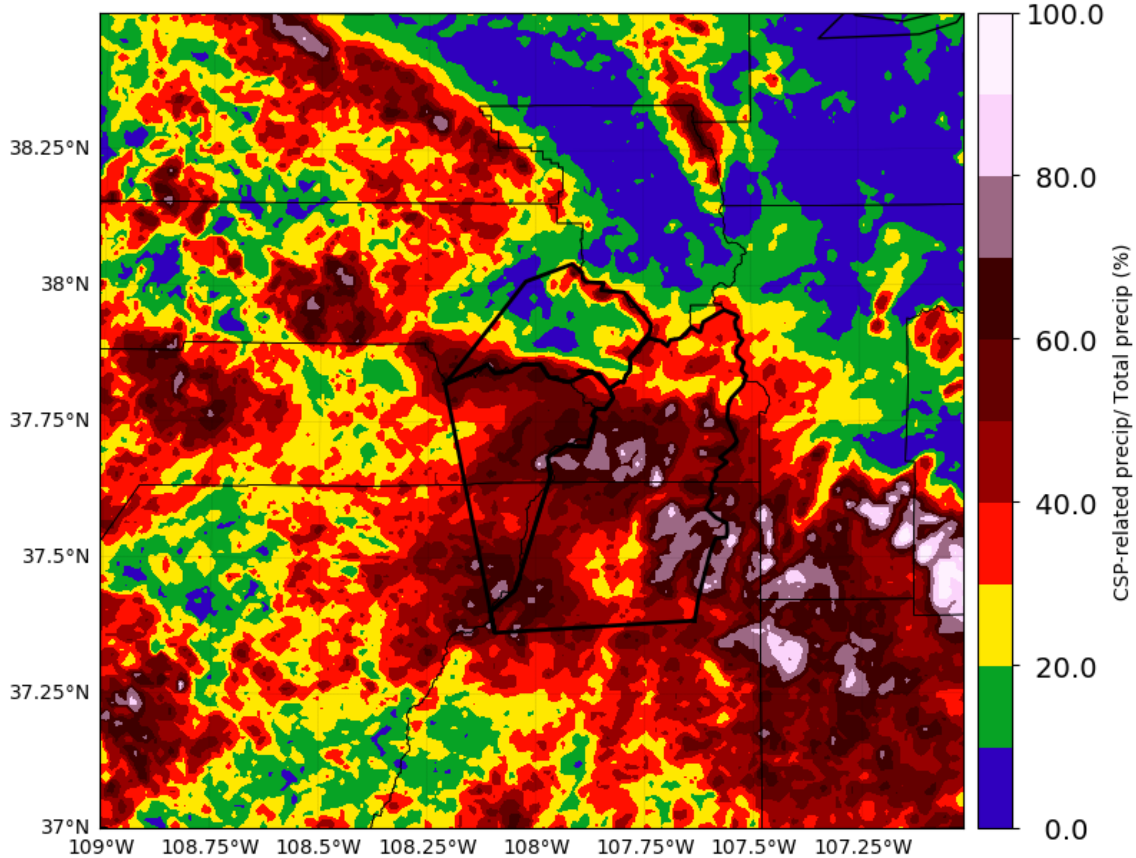


Figure 27. *The percent of time when modeled cloud seeding conditions were present and precipitation is also falling. High values suggest mixed phase clouds (ice and liquid water).*

Results from plume model

Particles were released from all of the San Juan generators during the entire storm period. The particles were tracked as they moved with the winds away from the generator for their interactions with supercooled temperatures (T colder than -5^{o}C) and seedable clouds (T < -5^{o}C and liquid water). Figure 28 shows an example of each of the San Juan network generator's efficiency at 2000 UTC 16 December 2016.

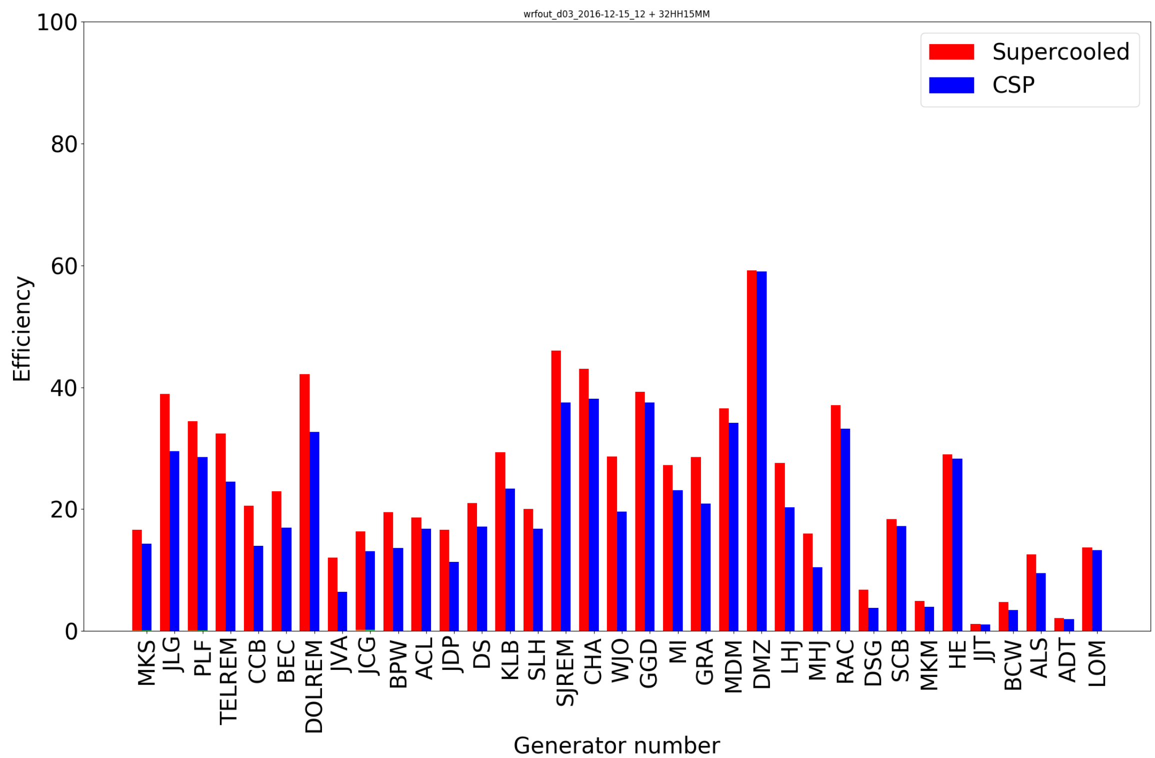


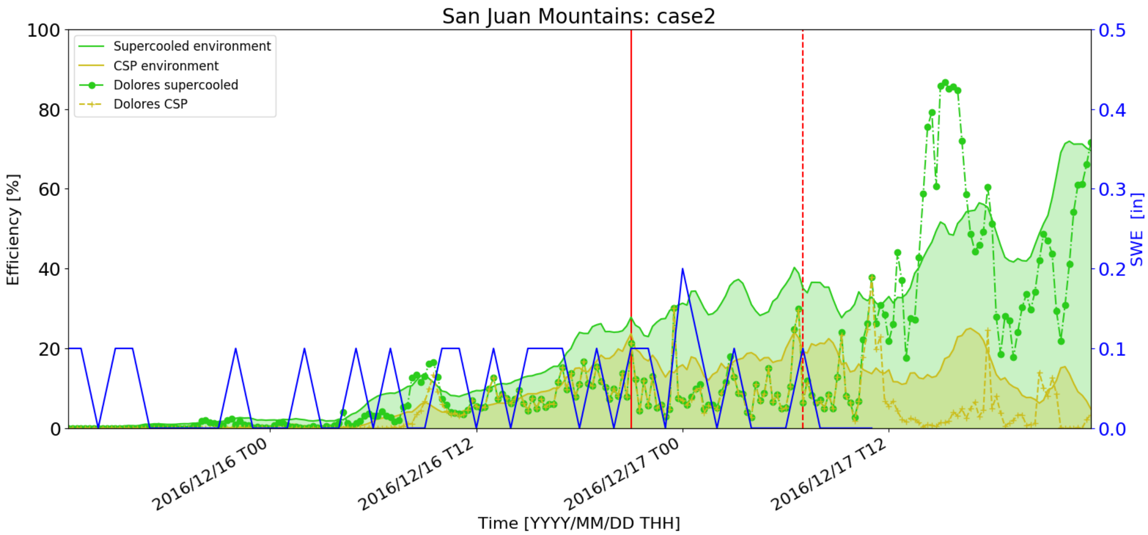
Figure 28. *Individual generator plume efficiencies for cloud seeding particles reaching model temperatures between -6C and -18C (red) and model clouds with supercooled liquid water and temperatures between -6C and -18C (blue). See Fig E.4 for generator locations.*

The analysis of the generator plumes with all the storm times produced the percent of particles released from all of the generator plumes which interacted with seedable clouds over the greater San Juan Mountains during the Case 1 storm period (Fig. 29 a, b, c). The seeding efficiency for the Dolores (Fig. 29 a), Animas (Fig. 29 b), and San Miguel (Fig. 29 c) headwaters region were also computed.

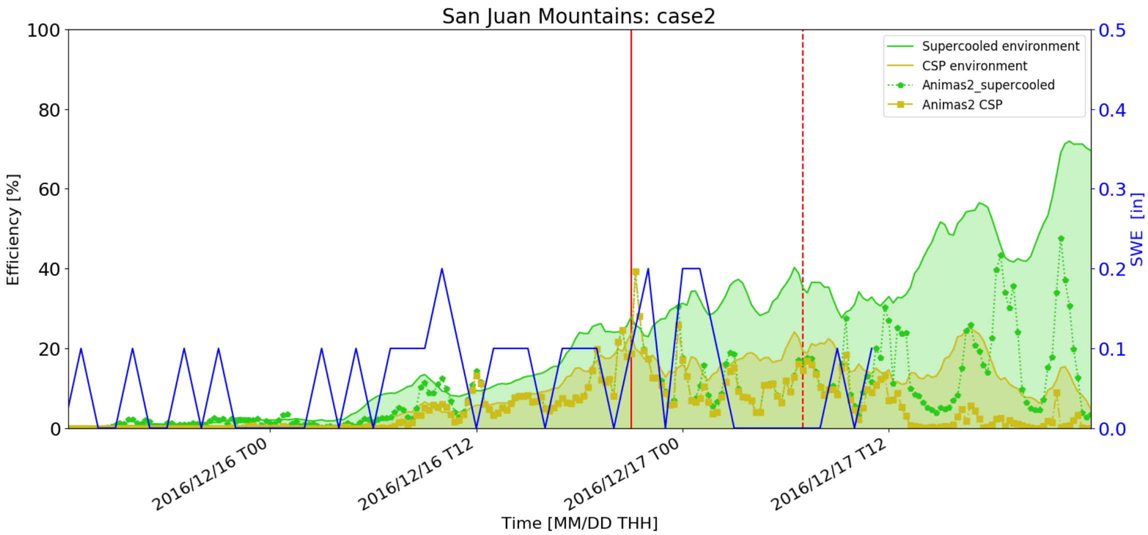
The results for the greater San Juan Mountains show that generators could have potentially delivered ice nuclei to seedable clouds for the final third of case study. The first portion of the storm was too warm for the network to reach temperatures that were cold enough. During the later portions of the storm the plume model suggests that between 10% and 20% of the particles released from the network would have reached seedable clouds during this period.

Reviewing the targeting results for the Dolores, Animas and San Miguel watershed show that several periods of low efficiency but successful cloud seeding were possible though the later part case study period (Fig. 29 (a), (b), (c)).

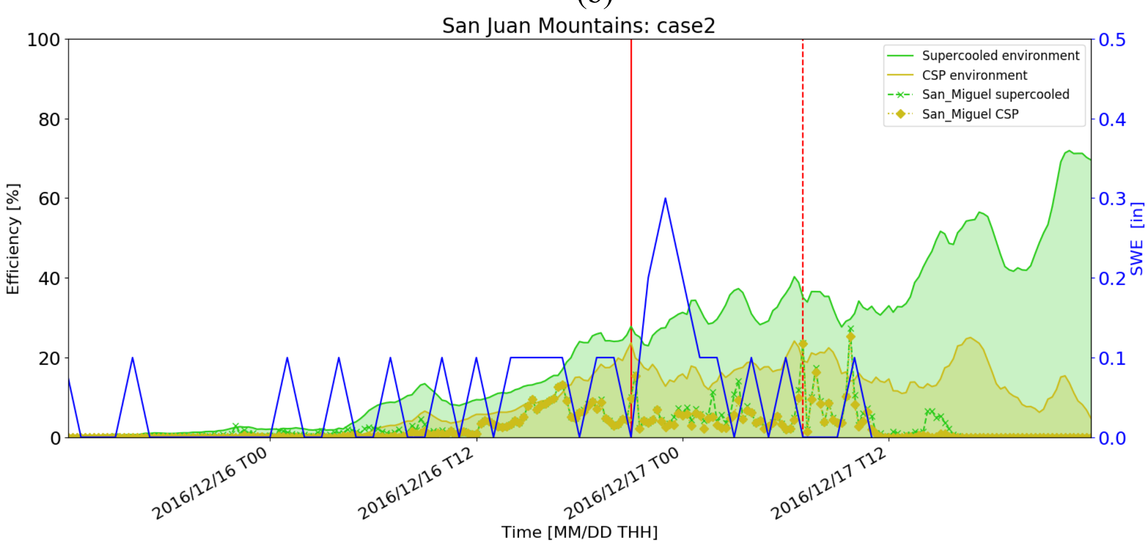
Analysis of the actual period when operational cloud seeding was conducted (between red and red-dashed lines) suggests that the cloud seeding plumes did reach seedable clouds over the greater San Juan target area and also the Dolores, Animas and San Miguel. The results also suggest that the seeding operations during the final period of the case should have been extended for several hours.


San Juan Mountains: case2
Supercooled environment
CSP environment
Dolores supercooled
Dolores CSP
Efficiency [%]
SWE [in]
Time [YYYY/MM/DD THH]
2016/12/16 T00
2016/12/16 T12
2016/12/17 T00
2016/12/17 T12

(a)


San Juan Mountains: case2
Supercooled environment
CSP environment
Animas2_supercooled
Animas2 CSP
Efficiency [%]
SWE [in]
Time [MM/DD THH]
2016/12/16 T00
2016/12/16 T12
2016/12/17 T00
2016/12/17 T12

(b)


San Juan Mountains: case2
Supercooled environment
CSP environment
San_Miguel supercooled
San_Miguel CSP
Efficiency [%]
SWE [in]
Time [MM/DD THH]
2016/12/16 T00
2016/12/16 T12
2016/12/17 T00
2016/12/17 T12

(c)

Figure 29. *Generator efficiency plots for all generators across the San Juan Mountains (green shading percent of particles reaching temperatures colder than -5°C), (orange shading percent of particles reaching seedable clouds), red lines show start and end times of the operational cloud seeding conducted during this storm. (a) Dolores Watershed (green dashed line percent of particles reaching temperatures colder than -5°C), (orange dashed line percent of particles reaching seedable clouds), blue line shows hourly precipitation rate in the Dolores Watershed. (b) same as (a) except for Animas watershed, (c) same as (a) except for San Miguel Watershed.*

Case 3: 22 December 2016 0000 UTC – 23 December 2016 1500 UTC

At 500mb 0000 UTC on 22 December 2016 a trough was over the West Coast and a closed low was off the CA/Mexico Coast (Fig. 30). At 700mb at that time, light westerly winds were observed across the San Juan Mountain clouds and clouds and moisture were to the southwest of the San Juan Mountains and temperatures were -1C.

At 0800 UTC the closed low moved onshore. Over the San Juan Mountains, a deep layer of moisture moved towards the area (Fig. 31). as winds became south-southwesterly at 700mb and temperatures cooled to -3C. Precipitation began falling over the south and southwest facing terrain. By 1200 UTC 22 December 2016, relatively light SWE increases were observed across the area (Table X). Light 24-hour snowfalls were reported on 22 December 2016 (1200 UTC). Purgatory Ski Resort and the Telluride Ski Area reported 2” of new snow, with 5” of new snow reported at Silverton Mountain.

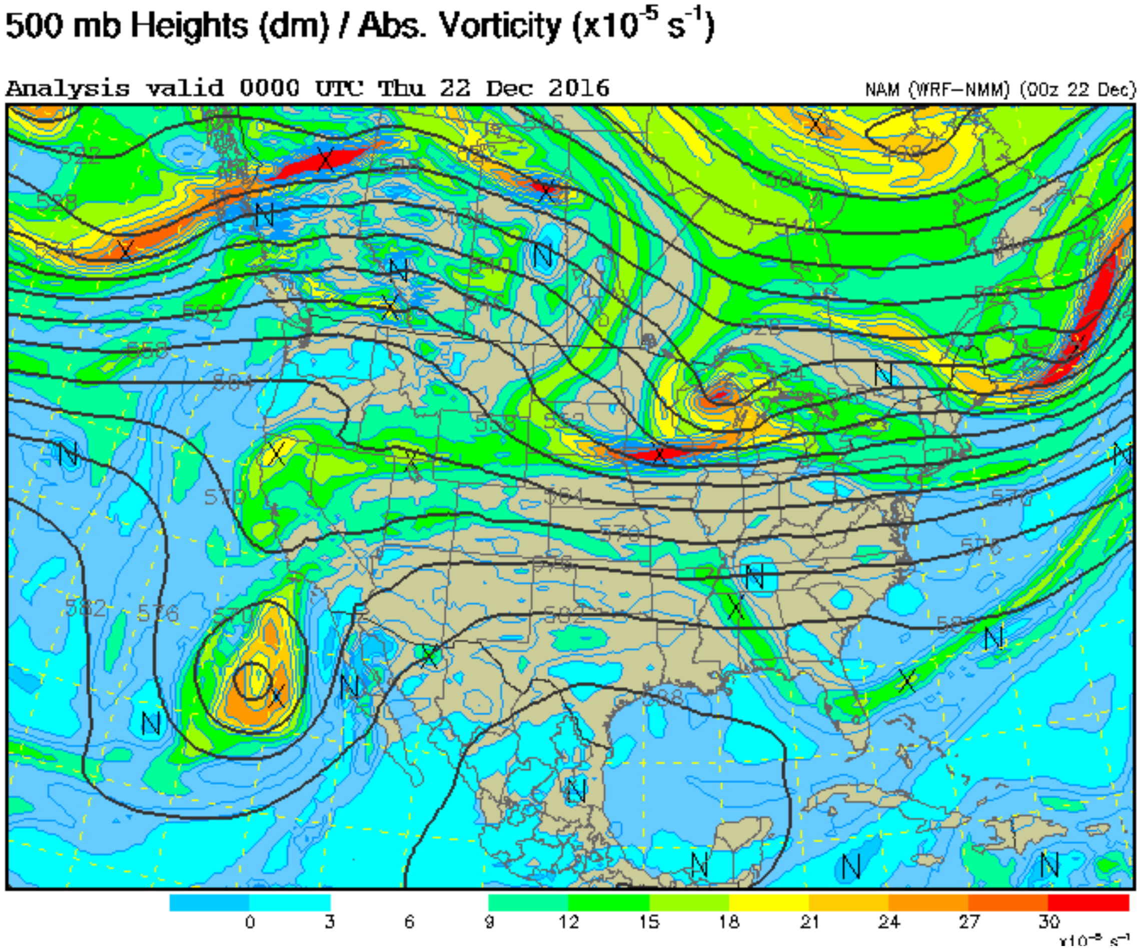


Figure 30. *500mb NAM analysis field valid at 2016 December 22 0000 UTC. Heavy black lines: geopotential height (m), dashed lines:* shading indicated vorticity (x10^{5} s^{-1}).

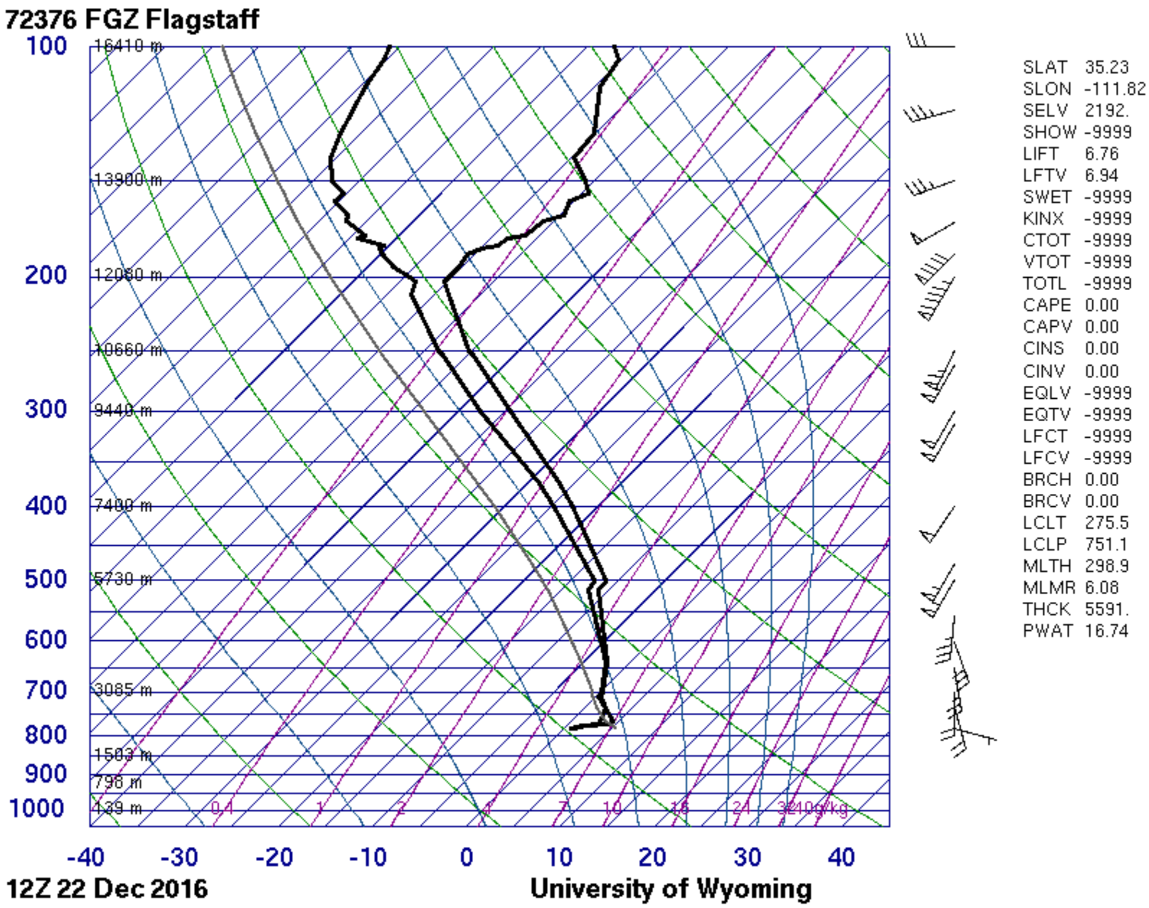


Figure 31. *Balloon sounding from the National Weather Service Flagstaff, AZ, 1200 UTC 22 December 2016.*

***Table** 7. Snow Water Equivalent Precipitation totals at three representative NRCS SNOTEL sites over the Dolores, Animas, and San Miguel Watersheds.*

SNOTEL (watershed)	Start Date Time (UTC)	End Date Time (UTC)	Snow Water Equivalent (SWE)
Lizard Head (D)	22 December 0000	22 December 1200	0.1
Molas Lake (A)	22 December 0000	22 December 1200	0.2
Lone Cone (SM)	22 December 0000	22 December 1200	0.0

After sunrise (1300 UTC) on 22 December 2016 the southwesterly flow continued at both 500mb and 700mb, as the low opened up and moved across southern CA (Fig. 32). To the east of the trough the moist southerly flow continued across the San Juan Mountains. Aircraft icing, confirming the presence of supercooled liquid water, was reported through day in the vicinity of the project areas (Fig. 33). The 12-hour precipitation totals between 1200 UTC 22 December 2016 and 0000 UTC 23 December 2016 are presented in Table 8. These results show the favorable moist flow into the Animas Watershed.

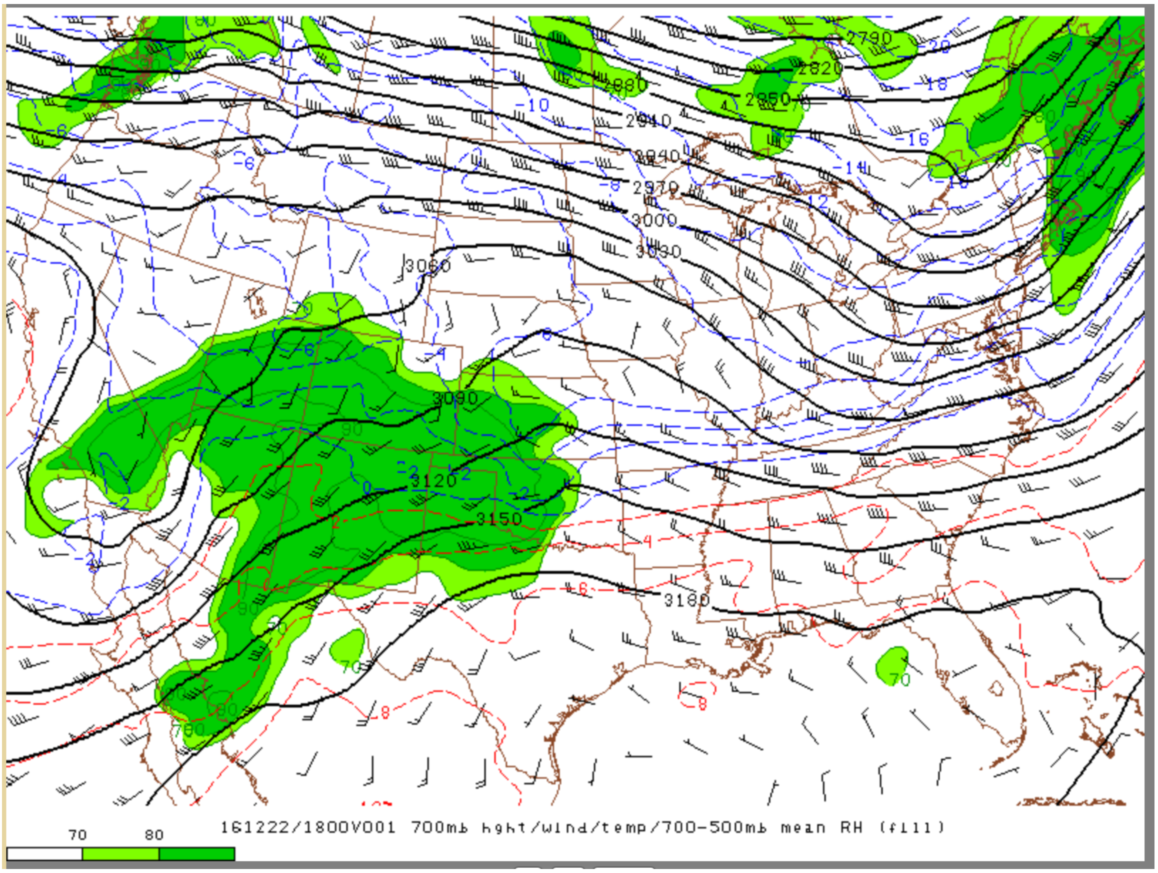


Figure 32. *700mb Rapid Refresh analysis field valid at 2016 December 22 1800 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (^oC)*, green shading relative humidity (%), wind barbs (kts).

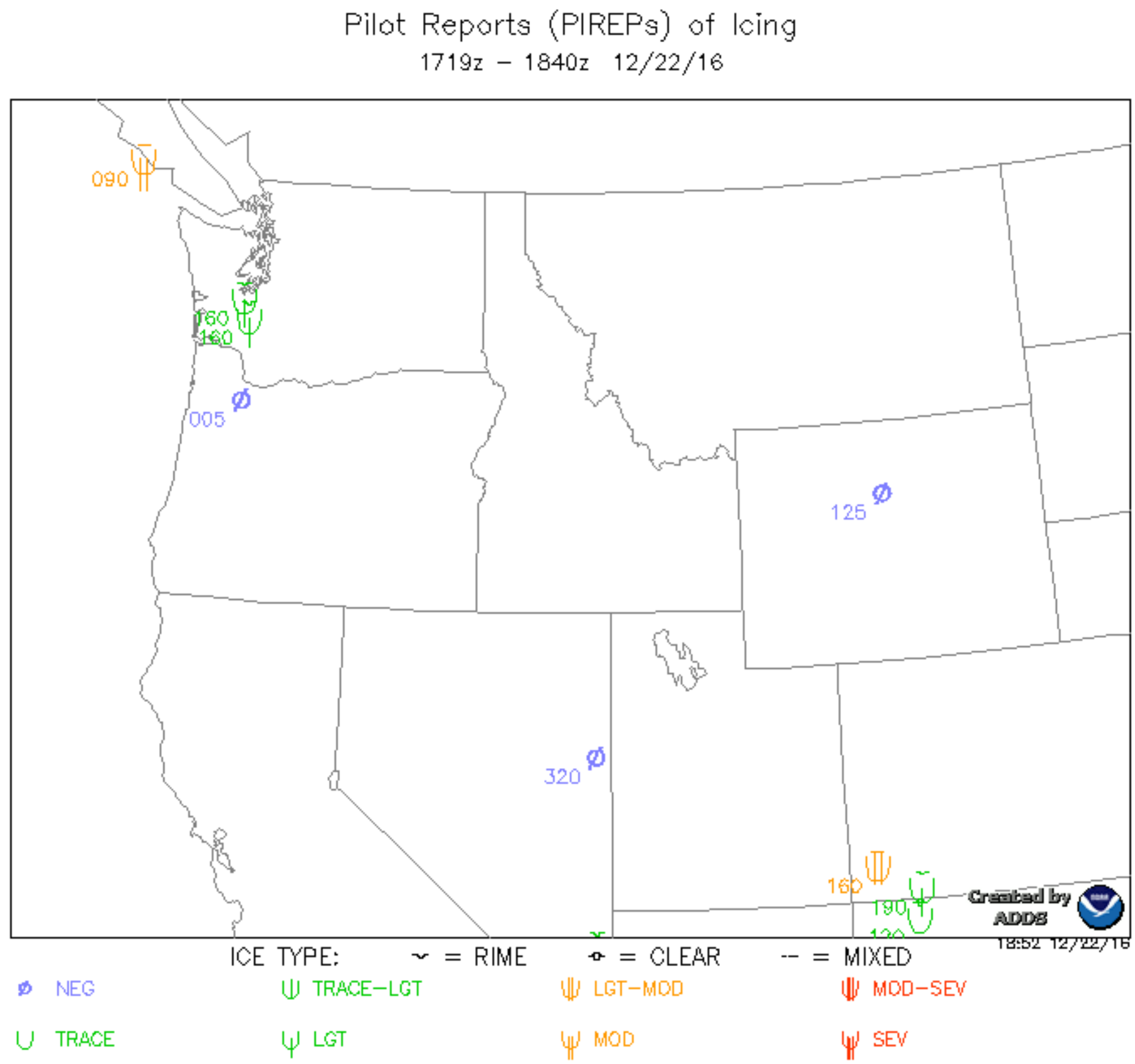


Figure 33. *Aircraft icing reports between 1719 UTC and 1840 UTC on 22 December 2016. Colors and symbols indicate icing severity and ice type.*

Table 8*. Snow Water Equivalent Precipitation totals at three representative NRCS SNOTEL sites over the Dolores, Animas, and San Miguel Watersheds.*

SNOTEL (watershed)	Start Date Time (UTC)	End Date Time (UTC)	Snow Water Equivalent (SWE)
Lizard Head (D)	22 December 1200	23 December 0000	0.3
Molas Lake (A)	22 December 1200	23 December 0000	0.6
Lone Cone (SM)	22 December 1200	23 December 0000	0.2

Late in the day the upper level wave and colder air began to accelerate towards the area. The trough/cold front crossed the San Juan Mountains at 0600 UTC 23 December 2016 with the 700mb temperatures cooling to -5C and winds becoming more westerly (Fig. 34). The upper level moisture decreased but a moist cloudy mid and low-level air mass continued to move into the San Juan Mountains (Fig. 35). Cooling at the mountain top level (600mb) was also observed leading to an unstable airmass. The 12-hour precipitation totals showed increases across all watersheds (Table 9) and 24-hour snowfall increases reported at 5AM (local time) on the morning of 23 December were 5” at Telluride, 12” at Purgatory, with the Silverton report missing.

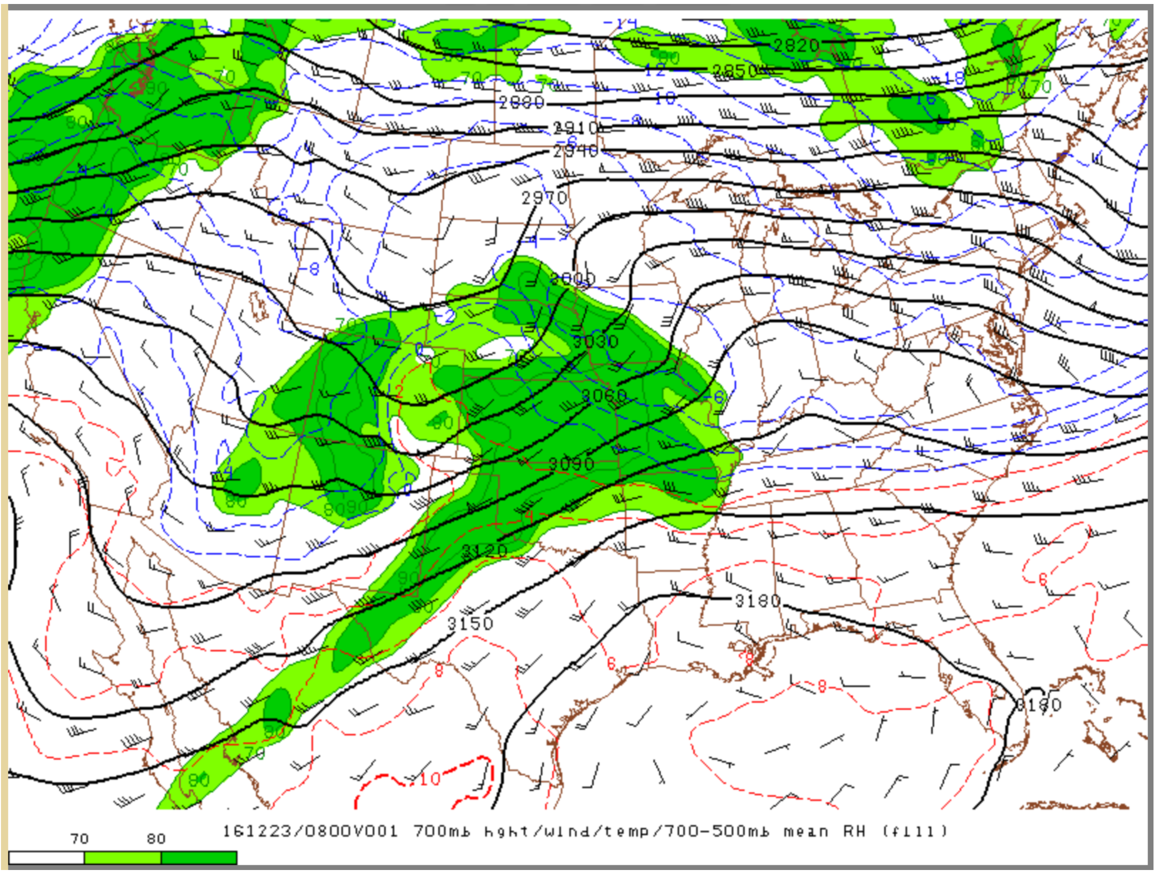


Figure 34. *700mb Rapid Refresh analysis field valid at 2016 December 23 0800 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (^oC)*, green shading relative humidity (%), wind barbs (kts).

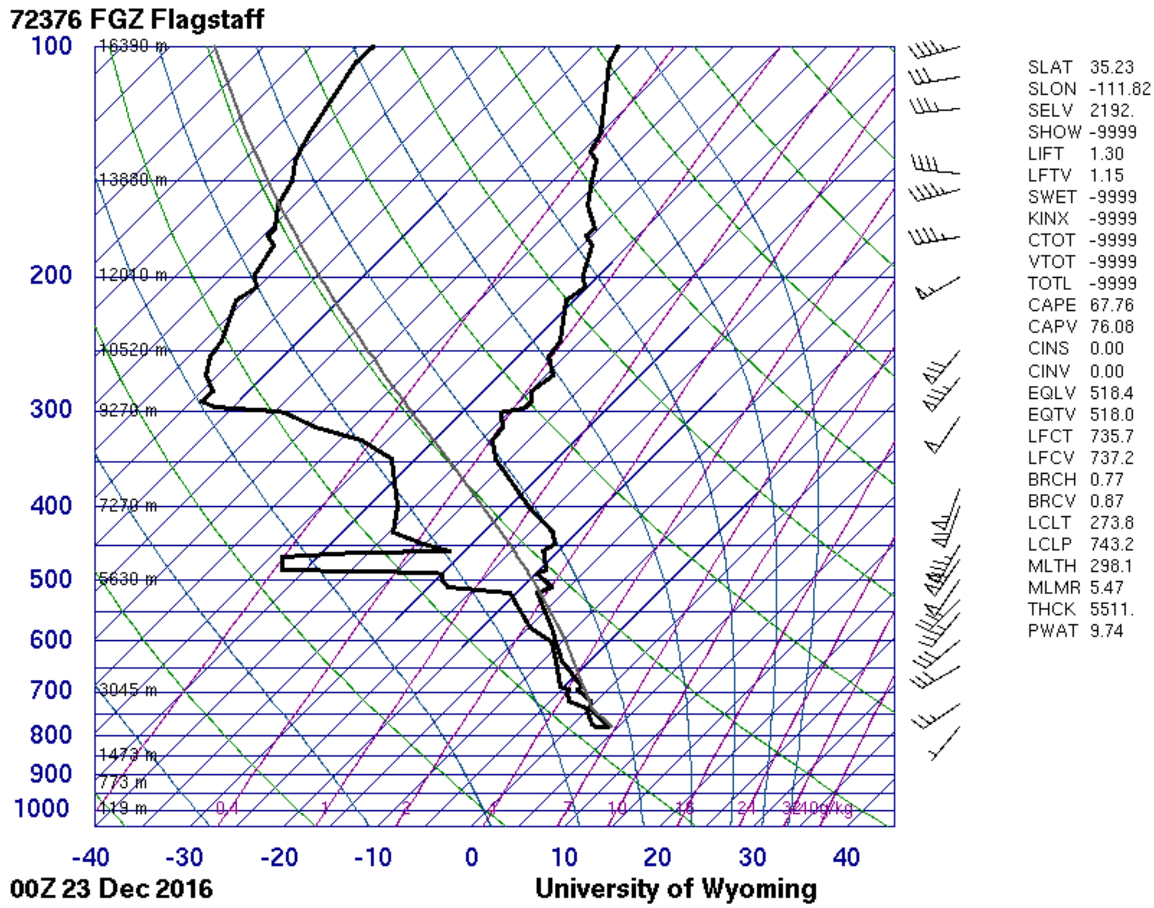


Figure 35. *Balloon sounding from the National Weather Service Flagstaff, AZ, 0000 UTC 23 December 2016***.**

Table 9*. Snow Water Equivalent Precipitation totals at three representative NRCS SNOTEL sites over the Dolores, Animas, and San Miguel Watersheds.*

SNOTEL (watershed)	Start Date Time (UTC)	End Date Time (UTC)	Snow Water Equivalent (SWE)
Lizard Head (D)	23 December 0000	23 December 1200	0.4
Molas Lake (A)	23 December 0000	23 December 1200	0.5
Lone Cone (SM)	23 December 0000	23 December 1200	0.6

Case 4: 24 December 2016 2100 UTC – 26 December 2016 0000 UTC

At 2100 UTC on 24 December 2016 a deep narrow trough was over the Great Basin and Desert Southwest. A southerly flow was over the area with clouds and moisture just west of the area. By 0000 UTC 25 December the deep moisture had moved into the area under a southerly low-level flow (Fig. 36). A strong cold front was present just west of the area.

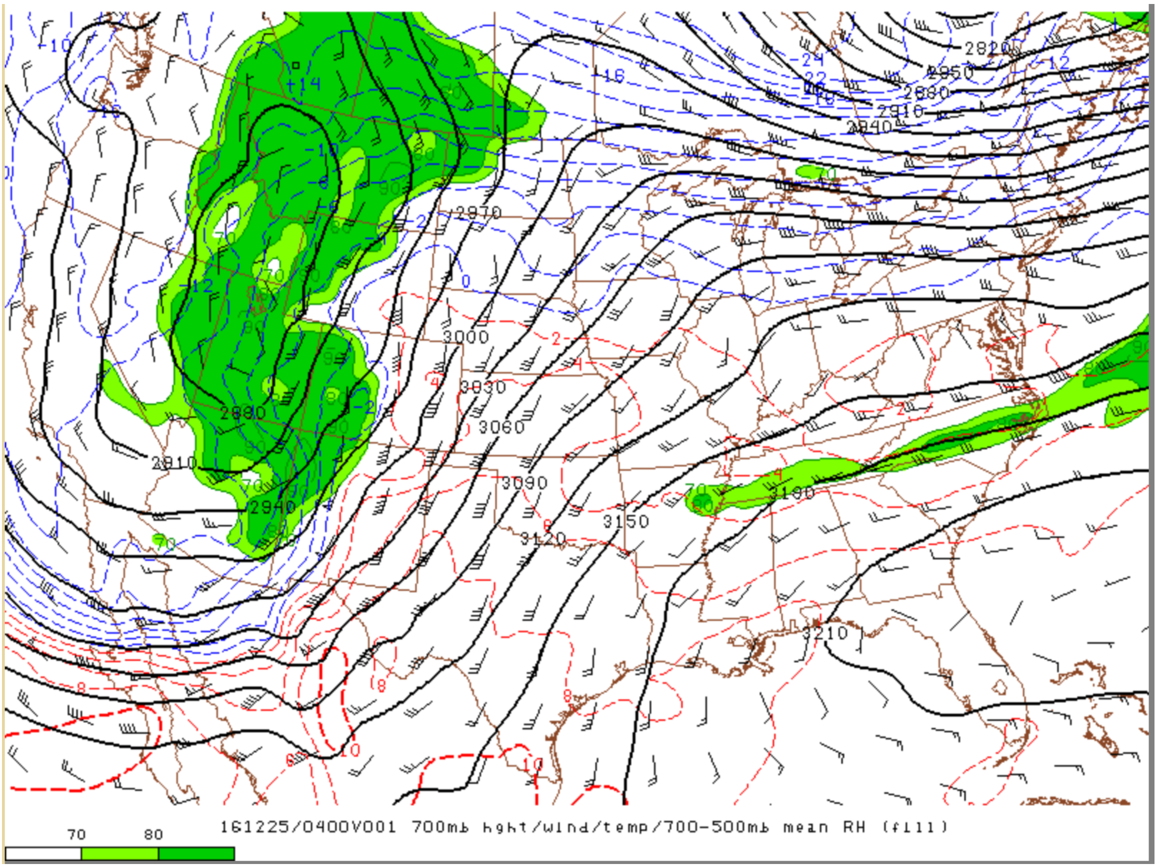


Figure 36. *700mb Rapid Refresh analysis field valid at 2016 December 25 0400 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (°C)*, green shading relative humidity (%), wind barbs (kts).

Between 0000 UTC 25 December 2016 and 1200 UTC 25 December 2016 the strong cold front crossed the area as temperatures cooled below -11C and winds remained strong and transitioned for southerly to west-southwesterly (Fig. 37). Although air traffic in the are was likely very light during the stormy Christmas Eve evening, severe icing was report over the 4-Corners (Fig. 38). During this 12-hour period at all three representative SNOTEL sites 0.6" of SWE was reported (Table 10). Twenty-four hour snowfall totals reported at 1200 UTC at Silverton Mountain Resort were 11", Purgatory reported 10", and Telluride reported 11".

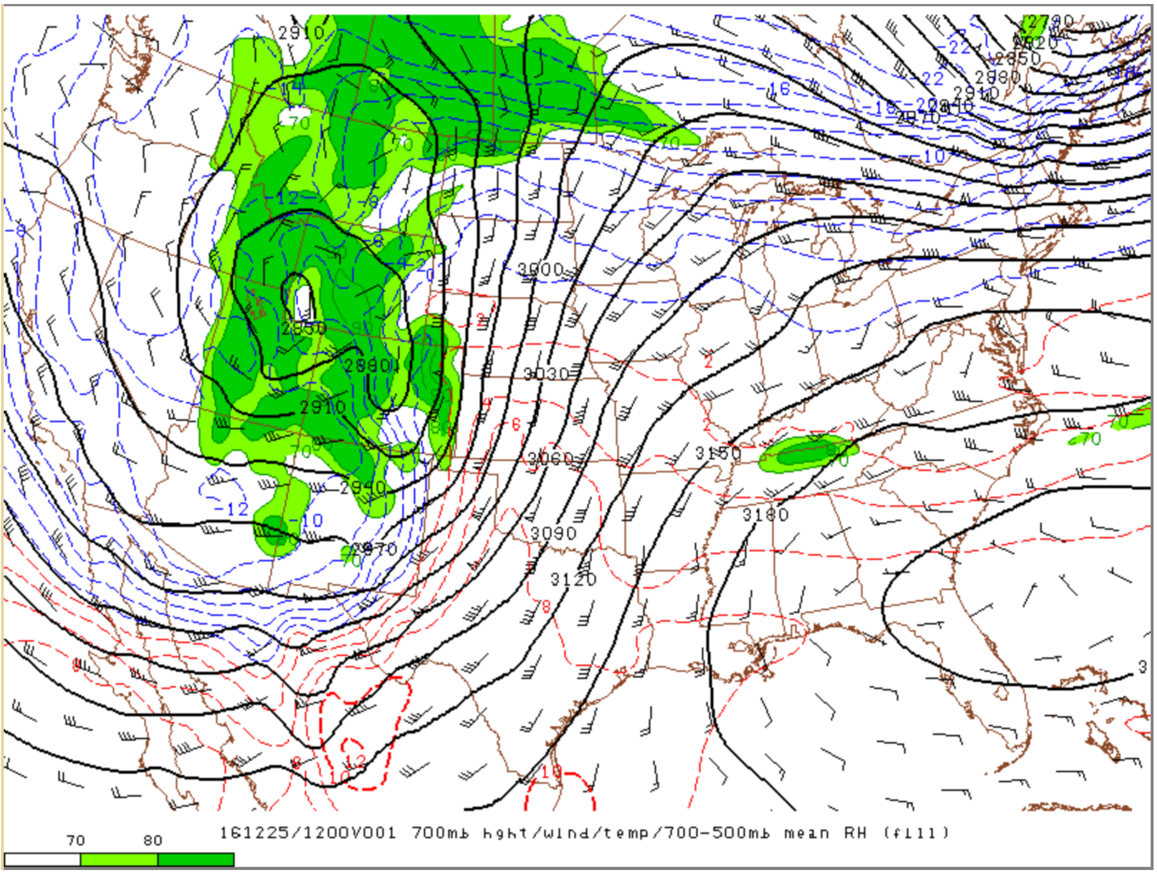


Figure 37. *700mb Rapid Refresh analysis field valid at 2016 December 25 1200 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (^{o}C)*, green shading relative humidity (%), wind barbs (kts).

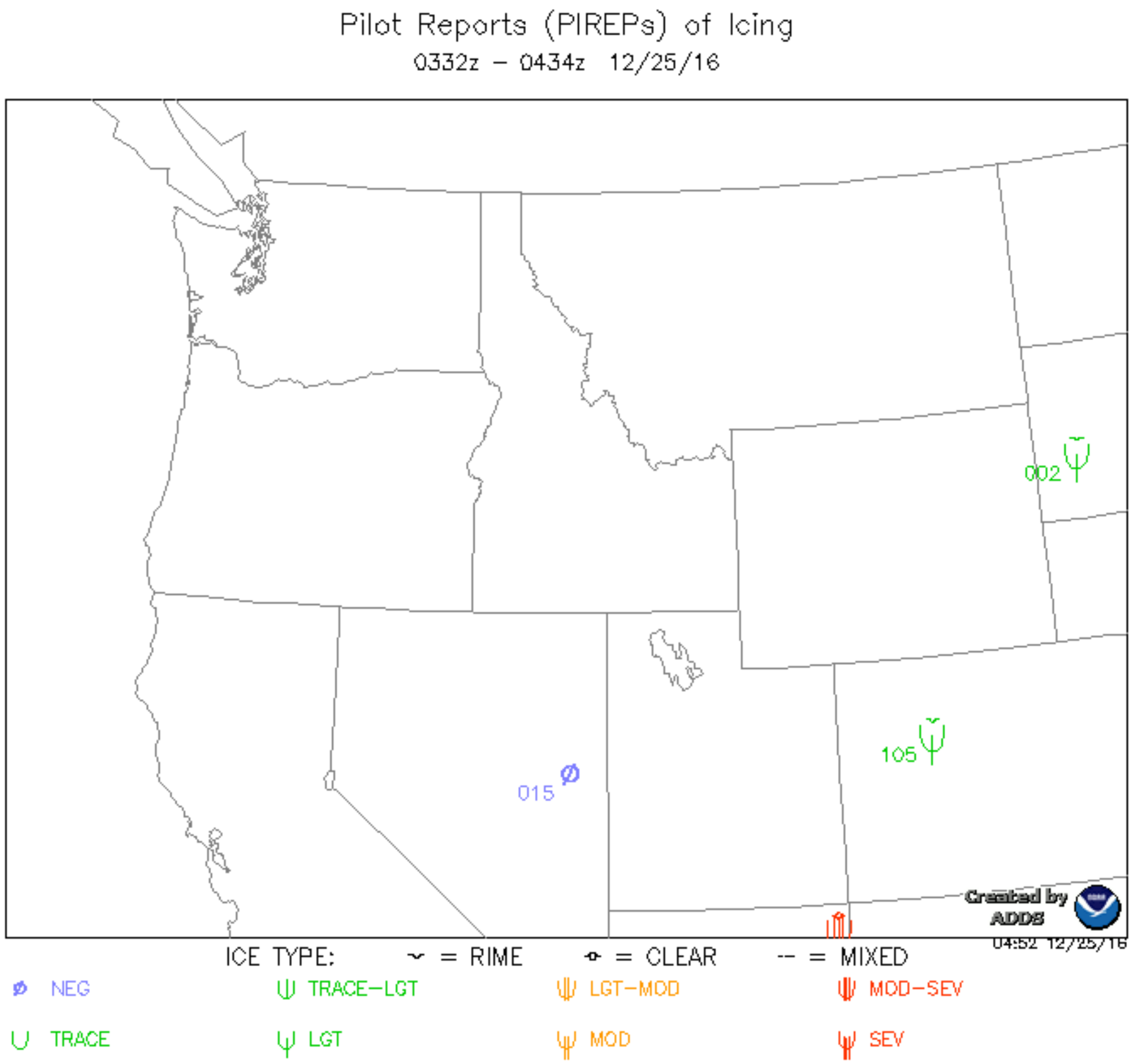


Figure 38. *Aircraft icing reports between 0332 UTC and 0434 UTC on 25 December 2016. Colors and symbols indicate icing severity and ice type.*

Table 10*. Snow Water Equivalent Precipitation totals at three representative NRCS SNOTEL sites over the Dolores, Animas, and San Miguel Watersheds.*

SNOTEL (watershed)	Start Date Time (UTC)	End Date Time (UTC)	Snow Water Equivalent (SWE)
Lizard Head (D)	25 December 0000	25 December 1200	0.6
Molas Lake (A)	25 December 0000	25 December 1200	0.6
Lone Cone (SM)	25 December 0000	25 December 1200	0.6

During the daytime hours of 25 December 2016 (1200 UTC – 0000 UTC) a cold moist unstable airmass remained over the area (Fig. 39), as the low moved northeast of the region. Winds became westerly as 700mb temperatures dipped below -12C (Fig. 40). By 0000 UTC 26

December the moisture had moved to the northeast and the storm came to an end. Precipitation was observed over area with the 12-hour precipitation totals for this period presented in Table 11.

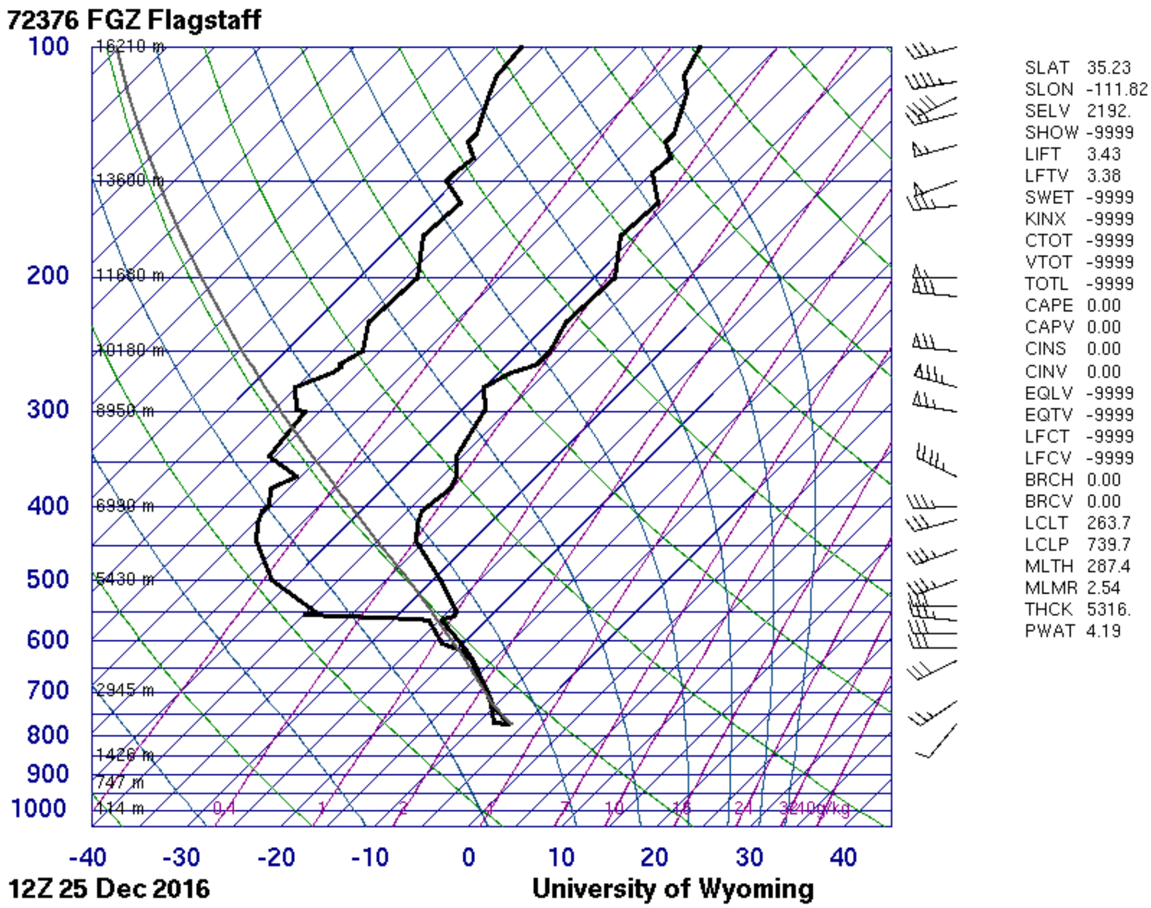


Figure 39. *Balloon sounding from the National Weather Service Flagstaff, AZ, 1200 UTC 25 December 2016**.***

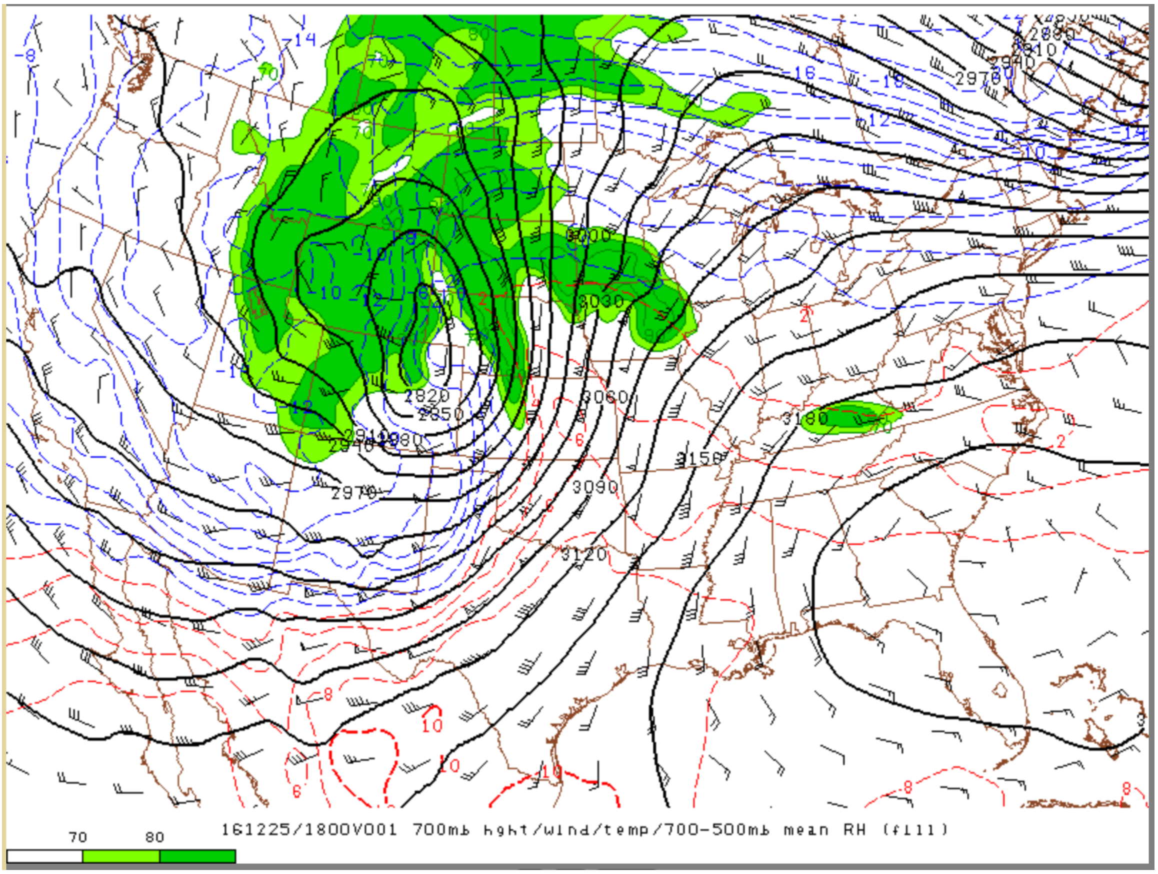


Figure 40. *700mb Rapid Refresh analysis field valid at 2016 December 25 1800 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (^{o}C)*, green shading relative humidity (%), wind barbs (kts).

Table 11. *Snow Water Equivalent Precipitation totals at three representative NRCS SNOTEL sites over the Dolores, Animas, and San Miguel Watersheds.*

SNOTEL (watershed)	Start Date Time (UTC)	End Date Time (UTC)	Snow Water Equivalent (SWE)
Lizard Head (D)	25 December 1200	26 December 0000	0.2
Molas Lake (A)	25 December 1200	26 December 0000	0.3
Lone Cone (SM)	25 December 1200	26 December 0000	0.3

Analysis: Case 3 and 4

Precipitation validation

The modeled total precipitation is presented in Figure 41. Over the higher terrain over 7” (some local area had over 9”) of liquid equivalent precipitation was produced by the model over the entire model simulation. These precipitation totals are higher than the observed values (Table 13), suggesting that for these storm the model is too efficient at converting supercooled liquid water to ice phase and resulting precipitation. This result would likely be underestimating the cloud seeding potential during the storm period. Even with the over forecast of precipitation, the model simulations are suitable to analyze the case.

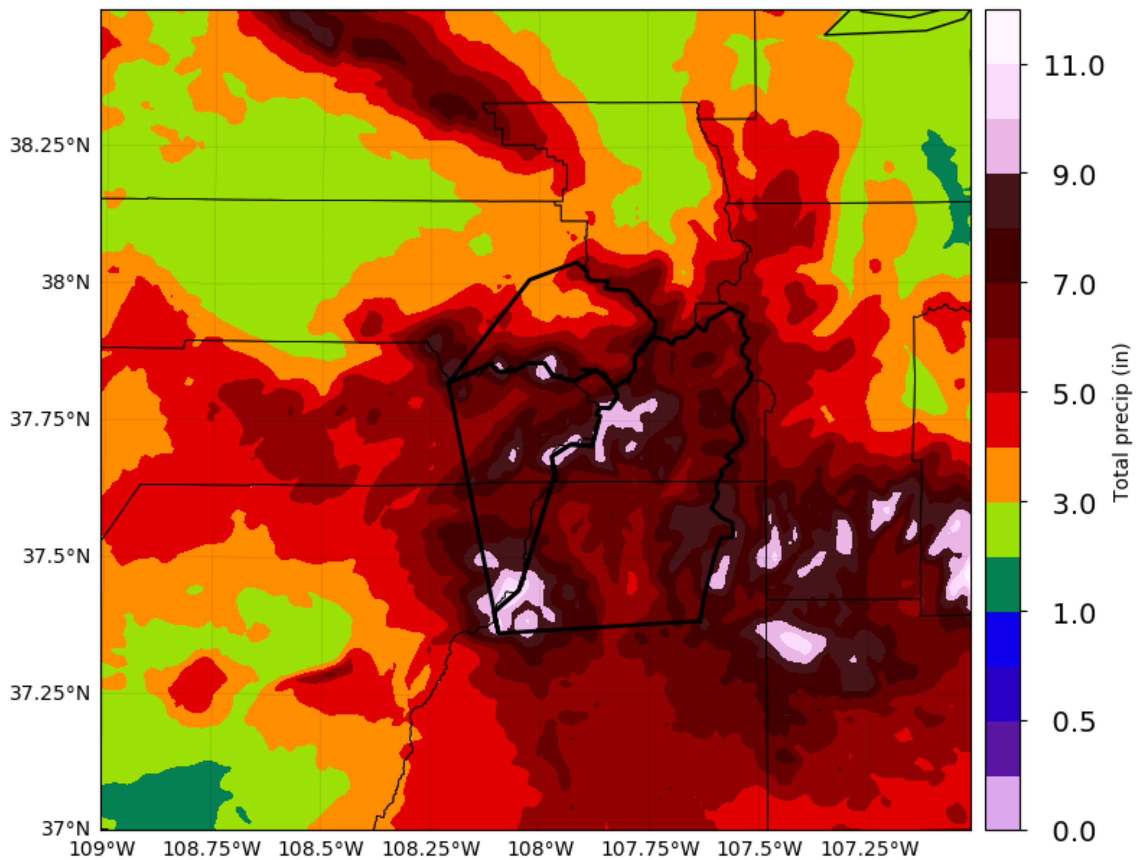


Figure 41. *Total liquid equivalent precipitation for the model run between* 22 December 2016 0000 UTC – 26 December 2016 0000 UTC, *The heavy black lines indicate the approximate headwaters of the Dolores, Animas, and San Miguel Watersheds.*

Table 13. *Total precipitation at the ski resorts and NRCS SNOTEL sites during the model precipitation period. Snowfall data period from 1200 UTC 21 December and 1200 UTC 26 December 2016. Snow Water Equivalent data period from 22 December 2016 0000 UTC – 26 December 2016 0000 UTC.*

Ski Resort	**Storm Period Snowfall (in)**
Silverton	M
Telluride	19
Purgatory	27
NRCS SNOTEL	**Snow Water Equivalent (in)**
Lizard Head	2.3
Lone Cone	2.1
Molas Lake	2.3

Cloud Seeding Potential

The results of the numerical model simulation show that cloud seeding opportunities were present over the San Juan Mountains for much of the storm periods of Case 3 and Case 4. Cloud seeding opportunities were present for more than 50% (likely an underestimate) of the combined storm periods over pockets of the highest terrain of the San Miguel and Dolores watersheds and the highest terrain of the La Plata Mountains. A second maxima is again indicated over the eastern San Juan Mountains (Fig. 42). The SW-NE and NW-SE vertical cross-section shows that the most favorable cloud seeding locations are tied to the higher terrain of the Dolores Watershed, on the upslope faces of the higher terrain (Fig. 43 a and b). The San Miguel watershed had minimal seeding opportunities for these cases. In addition, the majority of the modeled analyzed cloud seeding periods over the highest terrain occurred while model precipitation was falling (Fig. 44). The most favored locations over the Mountains had cloud seeding opportunities for most to the period precipitation was present.

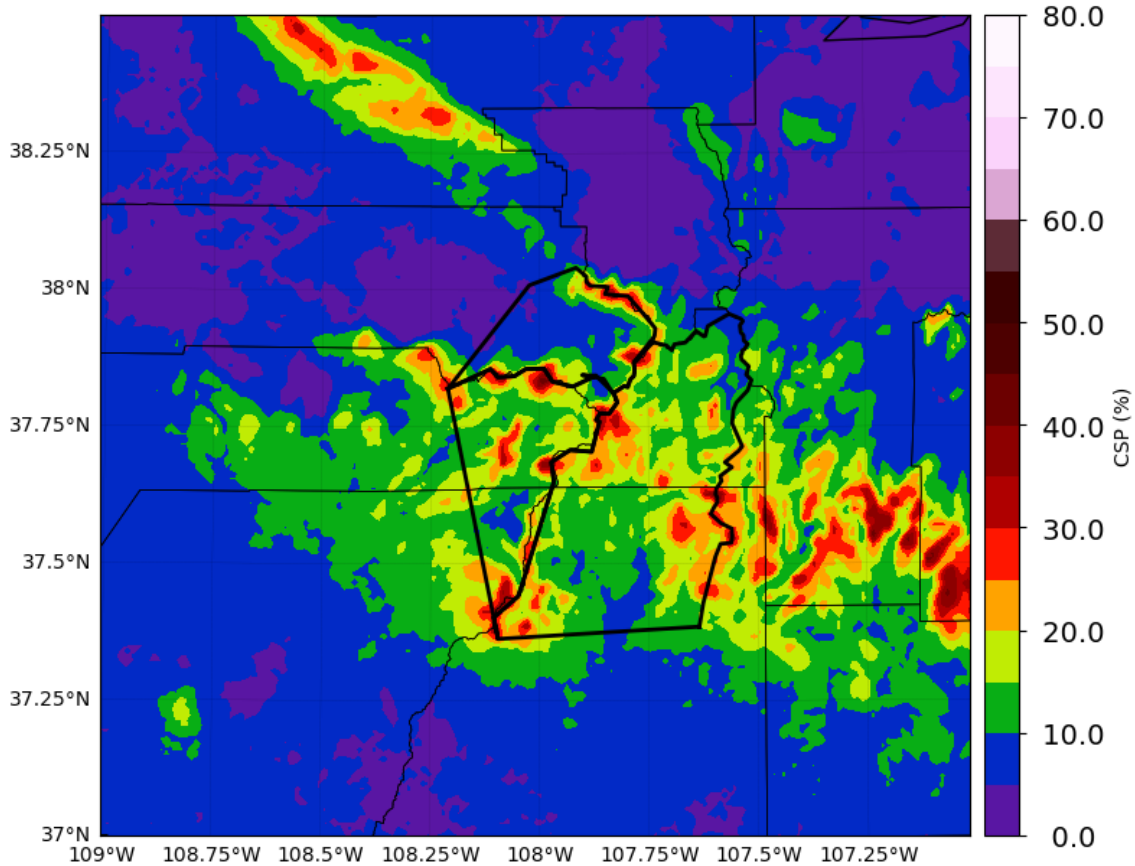


Figure 42. *Horizontal view of the percent of time cloud seeding conditions were present across the region from 22 December 2016 0000 UTC – 26 December 2016 0000 UTC.*

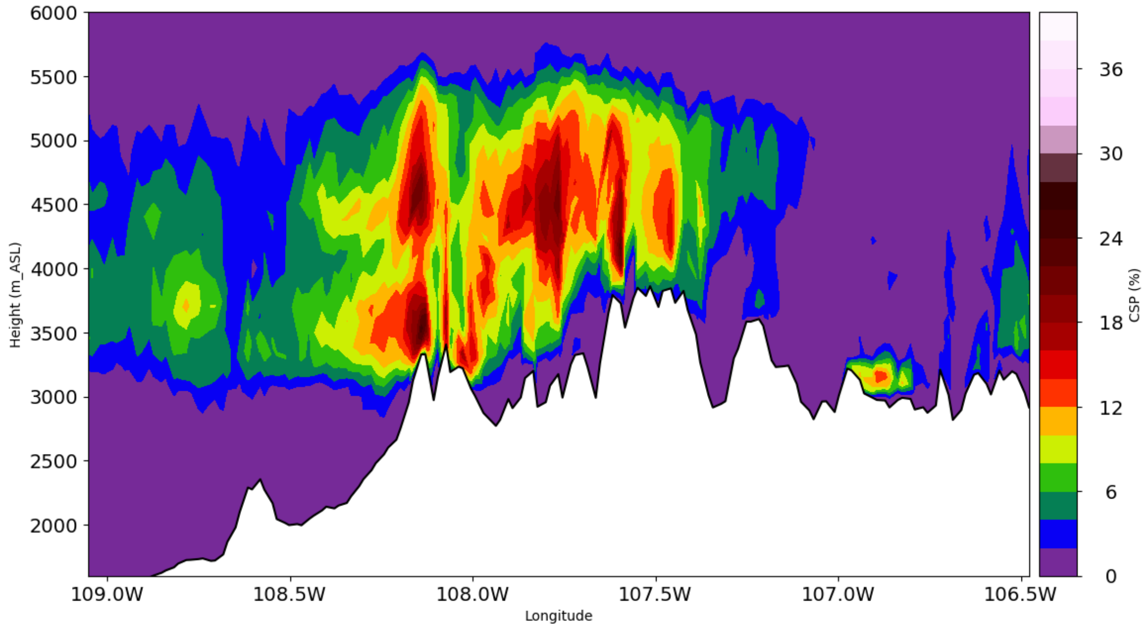


Figure 43 (a). *Southwest to northeast vertical cross-section of the percent of time cloud seeding conditions were present from 22 December 2016 0000 UTC – 26 December 2016 0000 UTC. See Fig E.4 for cross section location.*

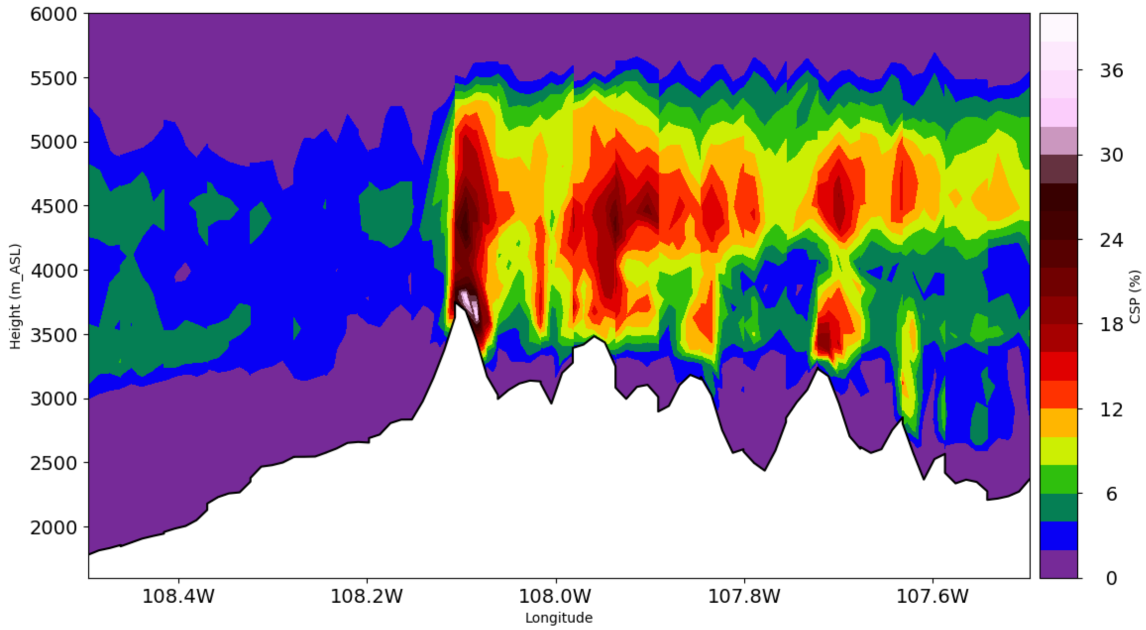


Figure 43 (b). *Northwest to southeast vertical cross-section of the percent of time cloud seeding conditions were present from 22 December 2016 0000 UTC – 26 December 2016 0000 UTC. See Fig. E.4 for cross section location. The high point near 108.1 W Longitude is Mt Wilson along the Dolores/San Miguel Divide.*

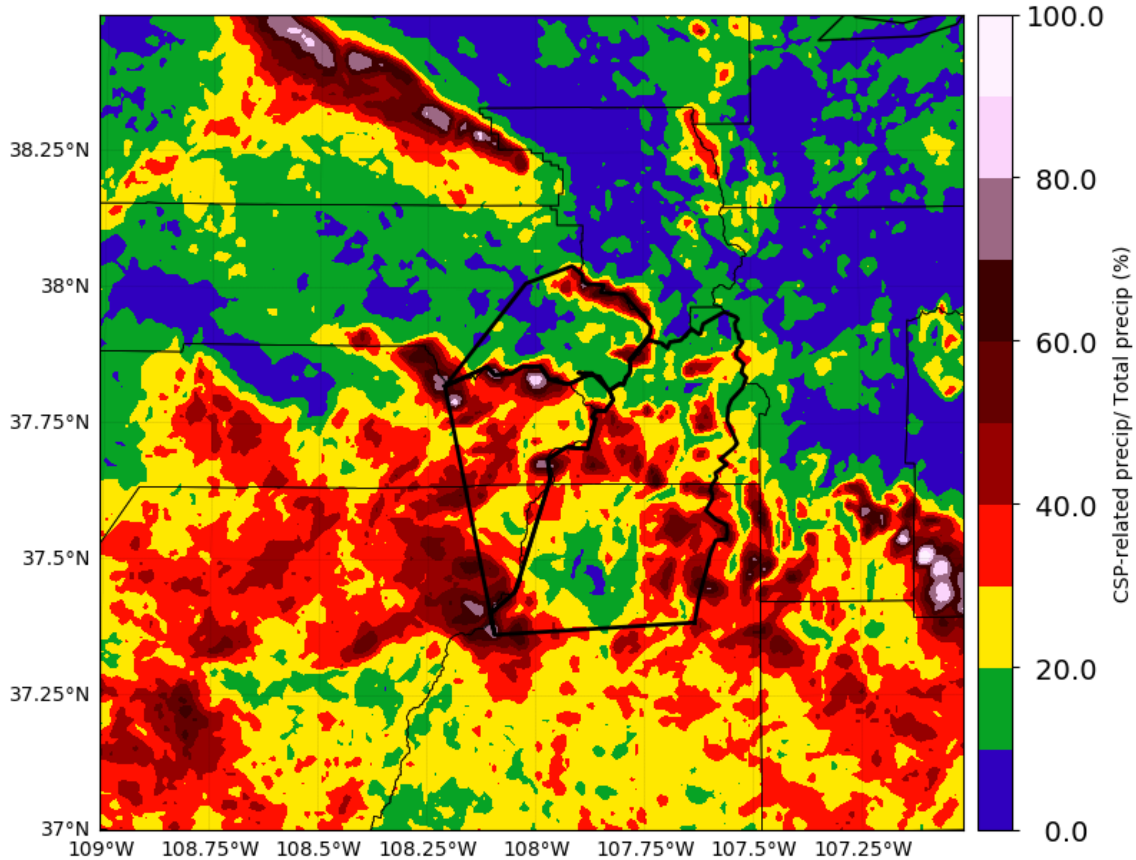


Figure 44. *The percent of time when modeled cloud seeding conditions were present and precipitation is also falling. High values suggest mixed phase clouds (ice and liquid water).*

Results from plume model

Particles were released from all of the San Juan generators during the entire storm period. The particles were tracked as they moved with the winds away from the generator for their interactions with supercooled temperatures (T) colder than -5°C and seedable clouds (T < -5°C and liquid water). Figure 45 shows an example of each of the San Juan network generator's efficiency near the end of the simulation at 0900 UTC 26 December 2016.

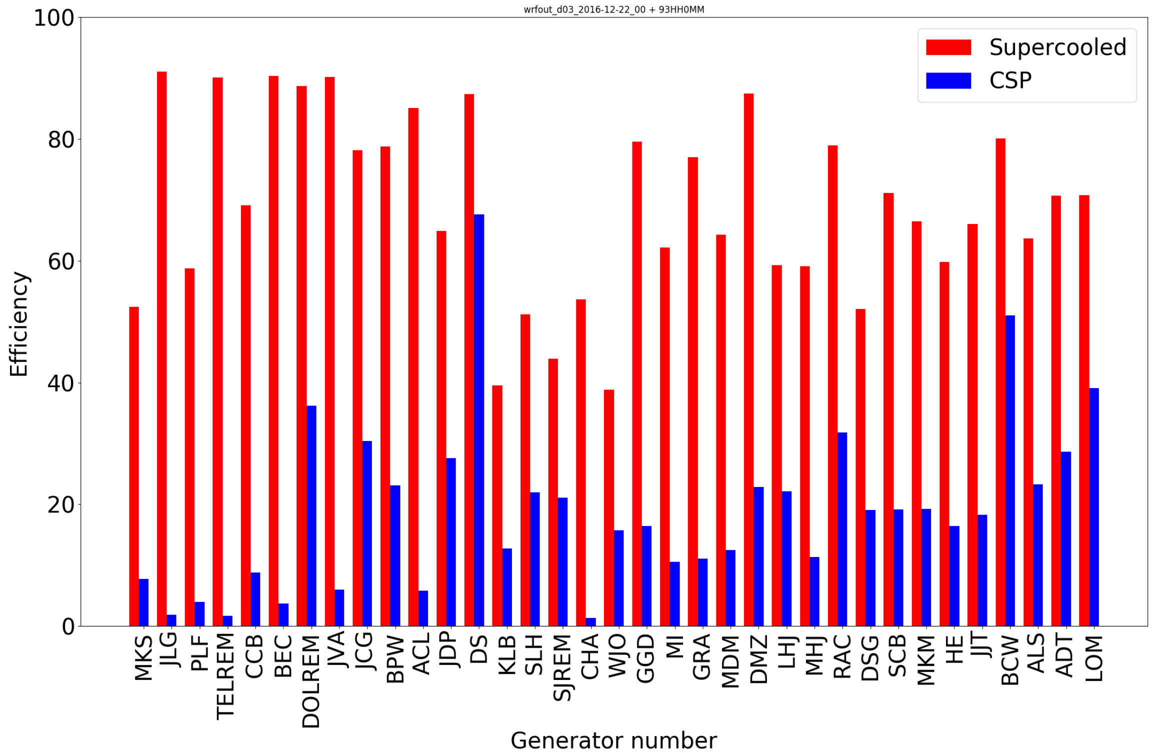


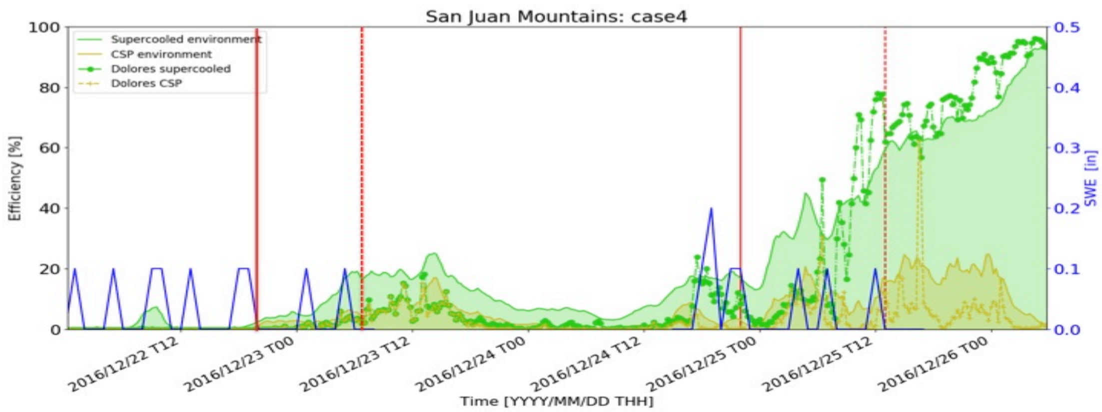
Figure 45. *Individual generator plume efficiencies for cloud seeding particles reaching temperatures between -6C and -18C (red) and model clouds with supercooled liquid water and temperatures between -6C and -18C (blue). See Fig E.4 for generator locations.*

The analysis of the generator plumes with all the storm times produced the percent of particles released from all of the generator plumes which interacted with seedable clouds over the greater San Juan Mountains during the Case 1 storm period (Fig. 46 a, b, c). The seeding efficiency for the Dolores (Fig. 46 a), Animas (Fig. 46 b), and San Miguel (Fig. 46 c) headwaters region were also computed.

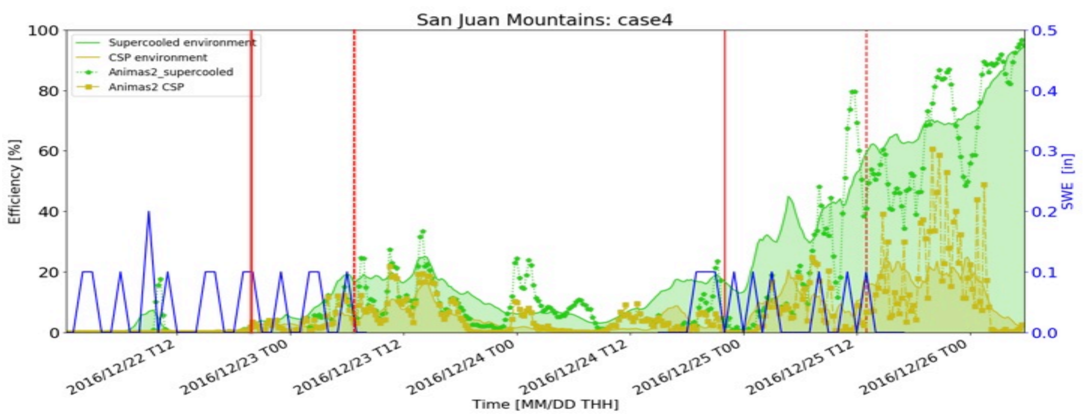
The results for the greater San Juan Mountains show that generators could have potentially delivered ice nuclei to seedable clouds from 0600 UTC to 1800 UTC on 23 December 2016 and after 0000 UTC on 25 December 2016. The plume model suggests that only 5% to 15% of the particles released would have reached seedable clouds.

Reviewing the successful targeting results for the Dolores, Animas and San Miguel watershed show that the later period of the storm had seeding success over the Animas and to a lesser extent the Dolores.

Analysis of the actual period when cloud seeding was conducted (between red and red-dashed lines) suggests that the cloud seeding plume did not reach seedable clouds over the target area during the seeding period of 22 and 23 December 2016. The results also suggest that the second operational seeding period (red lines in Fig. 46) should have been started a few hours later and extended beyond 0000 UTC 26 December 2016. Up to 20% of the particles would have reached the target area at this time.


San Juan Mountains: case4
Supercooled environment
CSP environment
Dolores supercooled
Dolores CSP
Efficiency [%]
SWE [in]
Time [YYYY/MM/DD THH]
2016/12/22 T12
2016/12/23 T00
2016/12/23 T12
2016/12/24 T00
2016/12/24 T12
2016/12/25 T00
2016/12/25 T12
2016/12/26 T00

(a)


San Juan Mountains: case4
Supercooled environment
CSP environment
Animas2_supercooled
Animas2 CSP
Efficiency [%]
SWE [in]
Time [MM/DD THH]
2016/12/22 T12
2016/12/23 T00
2016/12/23 T12
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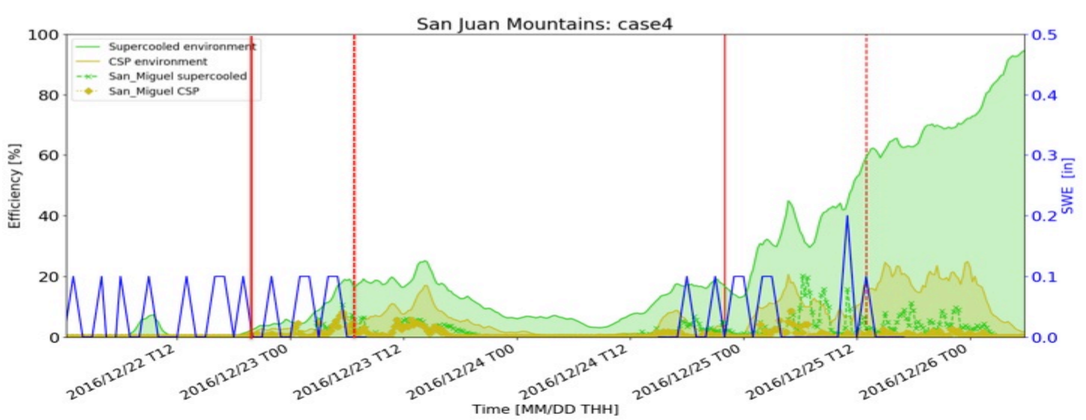
2016/12/24 T12
2016/12/25 T00
2016/12/25 T12
2016/12/26 T00

(b)


San Juan Mountains: case4
Supercooled environment
CSP environment
San_Miguel supercooled
San_Miguel CSP
Efficiency [%]
SWE [in]
Time [MM/DD THH]
2016/12/22 T12
2016/12/23 T00
2016/12/23 T12
2016/12/24 T00
2016/12/24 T12
2016/12/25 T00
2016/12/25 T12
2016/12/26 T00

(c)

Figure 46. *Generator efficiency plots for all generators across the San Juan Mountains (green shading percent of particles reaching temperatures colder than -5°C), (orange shading percent of particles reaching seedable clouds), red lines show start and end times of the operational cloud seeding conducted during this storm. (a) Dolores Watershed (green dashed line percent of particles reaching temperatures colder than -5°C), (orange dashed line percent of particles reaching seedable clouds), blue line shows hourly precipitation rate in the Dolores Watershed. (b) same as (a) except for Animas watershed, (c) same as (a) except for San Miguel Watershed.*

Case 5: 30 January 2016 1800 UTC – 2 February 2016 1800 UTC

Summary:

At 1800 UTC 30 January 2016 a west-east oriented cold front was over the western US and north of the San Juan Mountains (Fig. 47). Precipitation moved into the Mountains by 0400 UTC 31 January 2016 as the cold front and deeper moisture slowly sagged south towards the area. By 0600 UTC the 700mb temperatures cooled to -4C with winds from the west (Fig. 48).

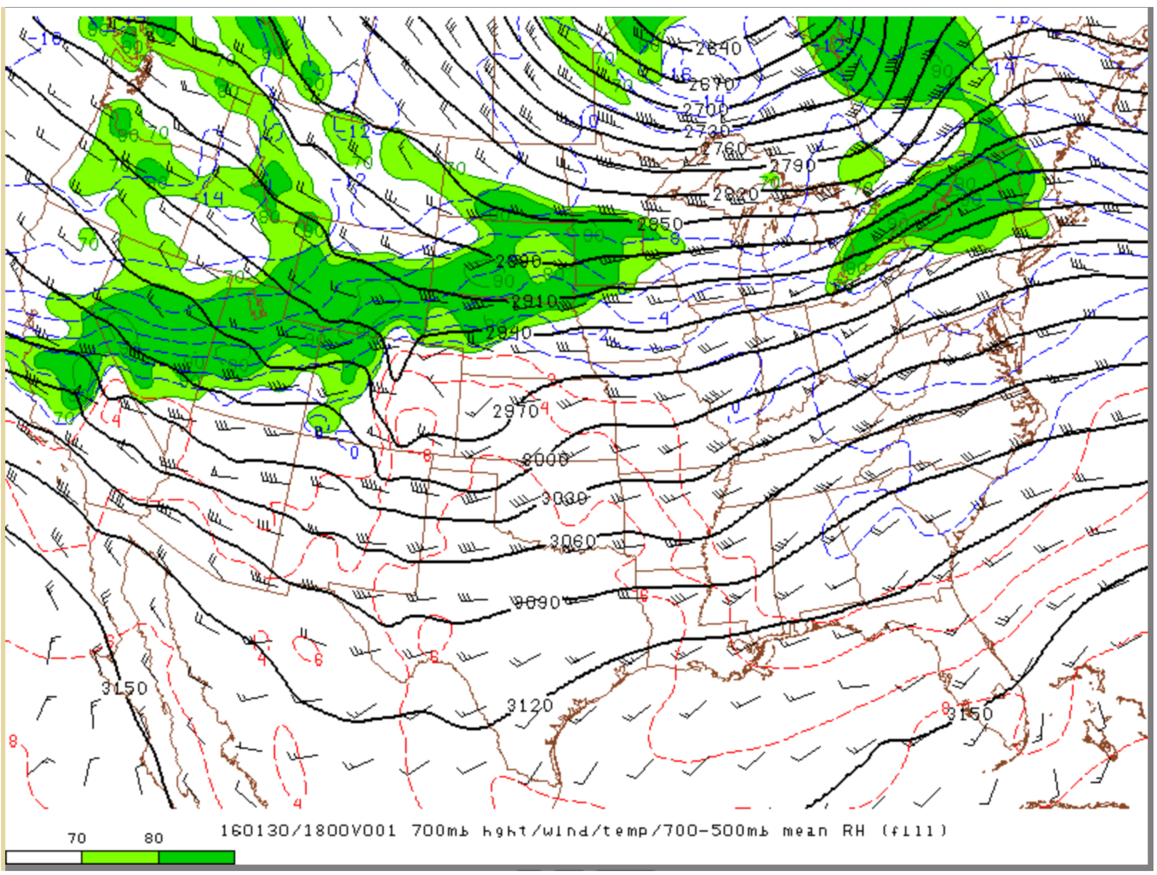


Figure 47. *700mb Rapid Refresh analysis field valid at 2016 January 30 1800 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (°C*), green shading relative humidity (%), wind barbs (kts).

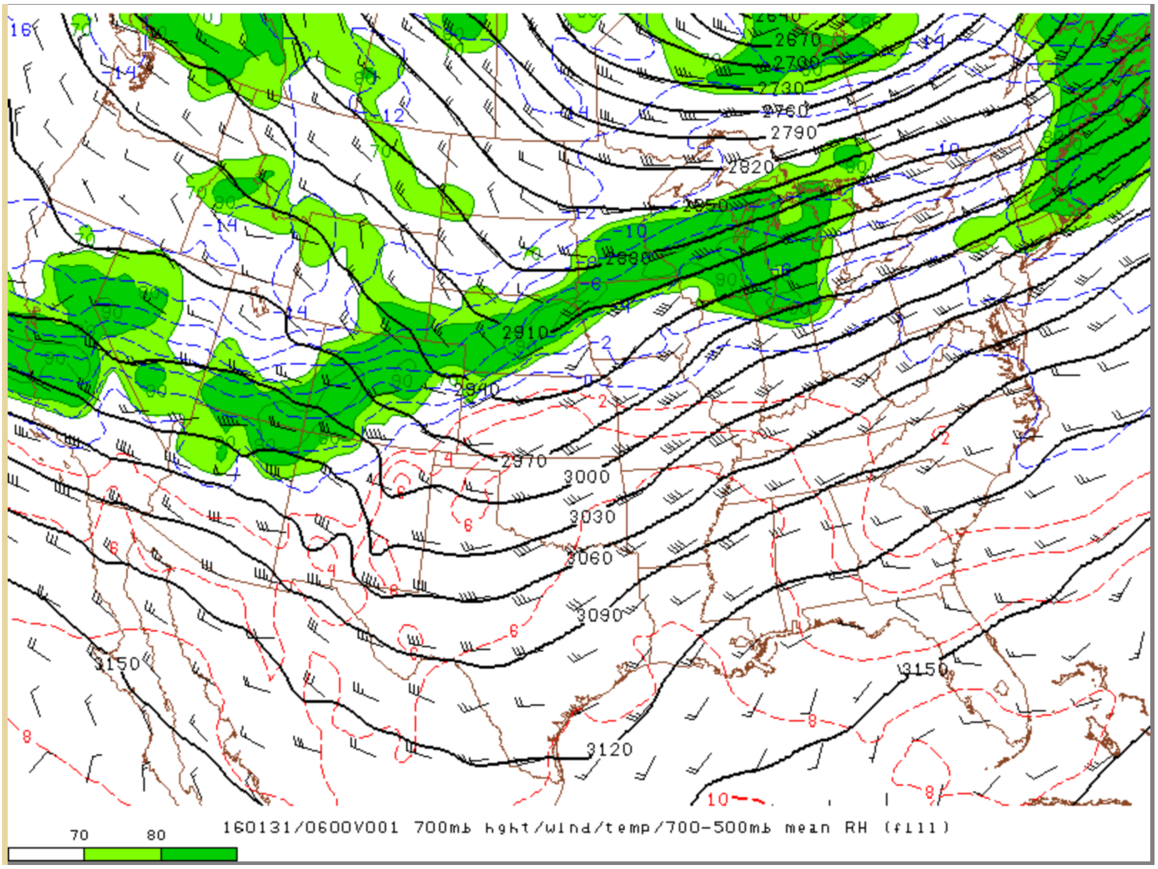


Figure 48. *700mb Rapid Refresh analysis field valid at 2016 January 31 0600 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (${}^{o}C$)*, green shading relative humidity (%), wind barbs (kts).

By 1200 UTC 31 January 2016 the progression of the cold front had slowed as a short wave moved south just west of the California Coast (Fig. 49). By this time temperatures at 700mb had cooled to -5C and winds continued from the west-southwest at 25 MPH. Between 0400 UTC and 1200 UTC 0.7" of SWE had been observed at Molas Lake (A), with 0.5" at Lizard Head Pass (D), and 0.3" at Lone Cone (SM). At Telluride 4" of new snow was observed, at Silverton Mountain 8" of snow was reported and at Purgatory 5" of new snow was reported.

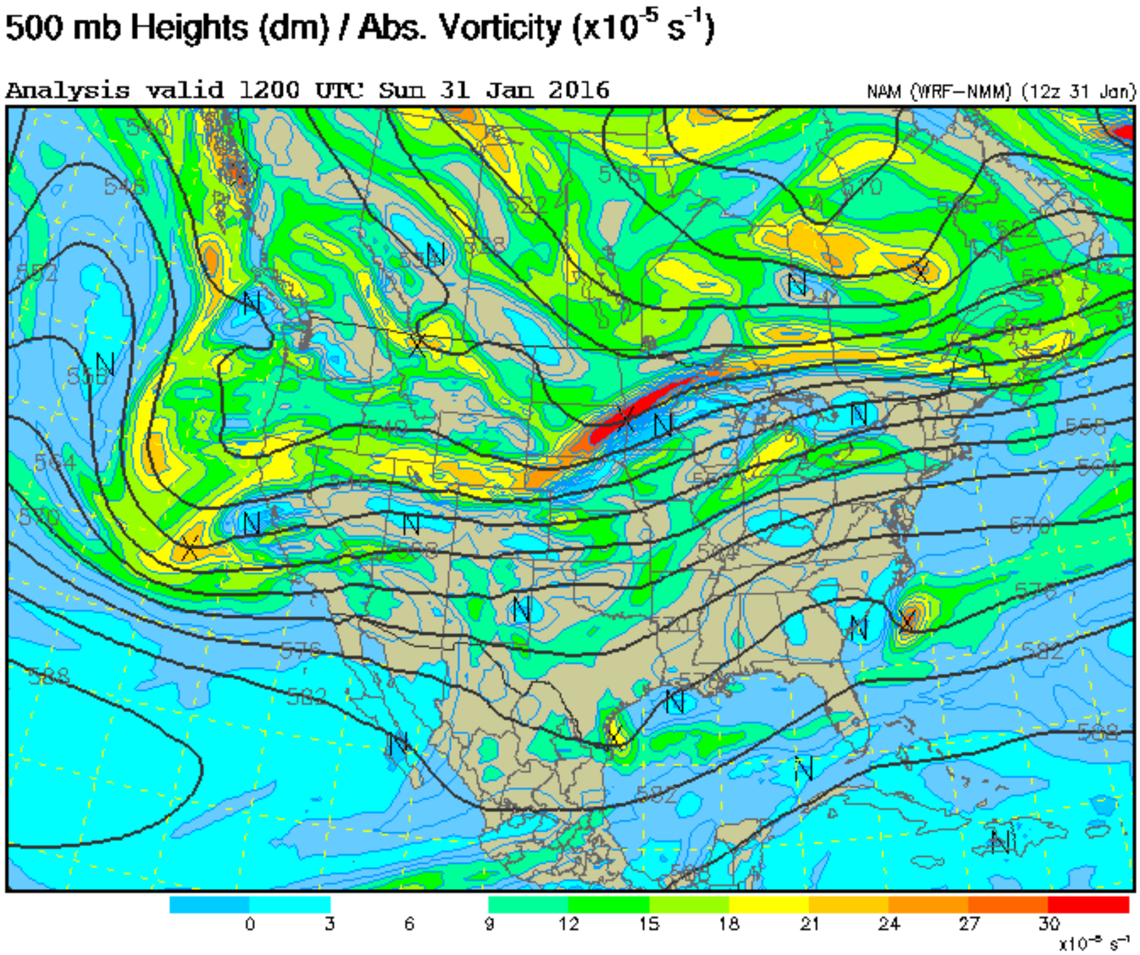


Figure 49. *500mb NAM analysis field valid at 2016 January 31 1200 UTC. Heavy black lines: geopotential height (m), dashed lines:* shading indicated vorticity ($x10^5$ s^{-1}).

As the upper level wave continued to dig south (Fig. 50), the moist westerly flow continued through the daytime hours of January 31 and by 0000 UTC 1 February 2016 (5PM local time). A deep low was over the CA/NV border, over the San Juan Mountains, the 700mb temperatures remained at about -4C with wind speeds decreasing to 15 MPH and starting to transition from the west to southwest (Fig. 51).

The vertical structure of the clouds, represented by 0000 UTC 1 February Grand Junction sounding, showed deep cloud layers, with an elevated cloud layer at the mountain top level with a strong southwesterly flow (Fig. 52). The low-level cloud was colder and had a weaker southeasterly flow. During this 12 hour period another 0.7” of SWE was observed at Lone Cone (SM), 0.6” at Lizard Head Pass (D) and at Molas Lake 0.8”. Aircraft icing was reported during the day as well.

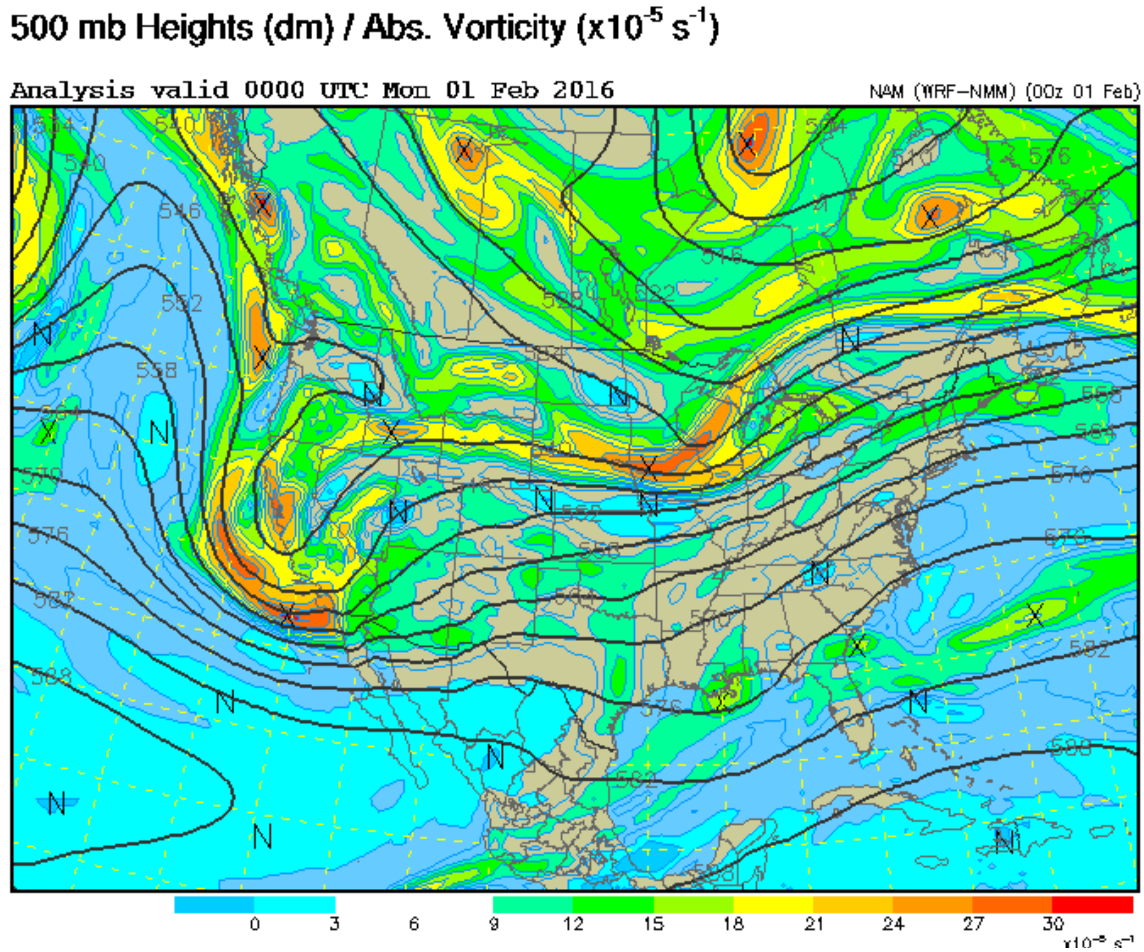


Figure 50. *500mb NAM analysis field valid at 2016 February 01 1200 UTC. Heavy black lines: geopotential height (m), dashed lines:* shading indicated vorticity ($x10^5$ s^{-1}).

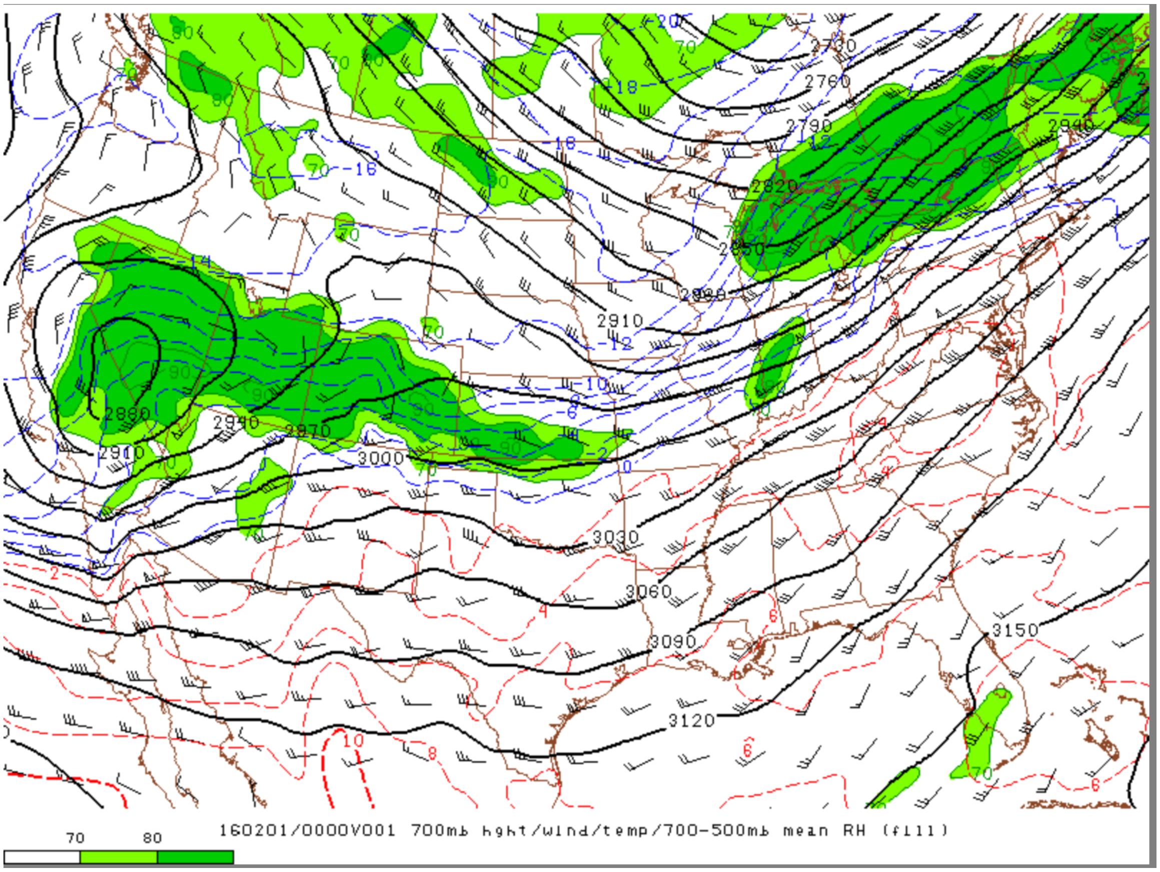


Figure 51. *700mb Rapid Refresh analysis field valid at 2016 February 01 0000 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (^oC)*, green shading relative humidity (%), wind barbs (kts).

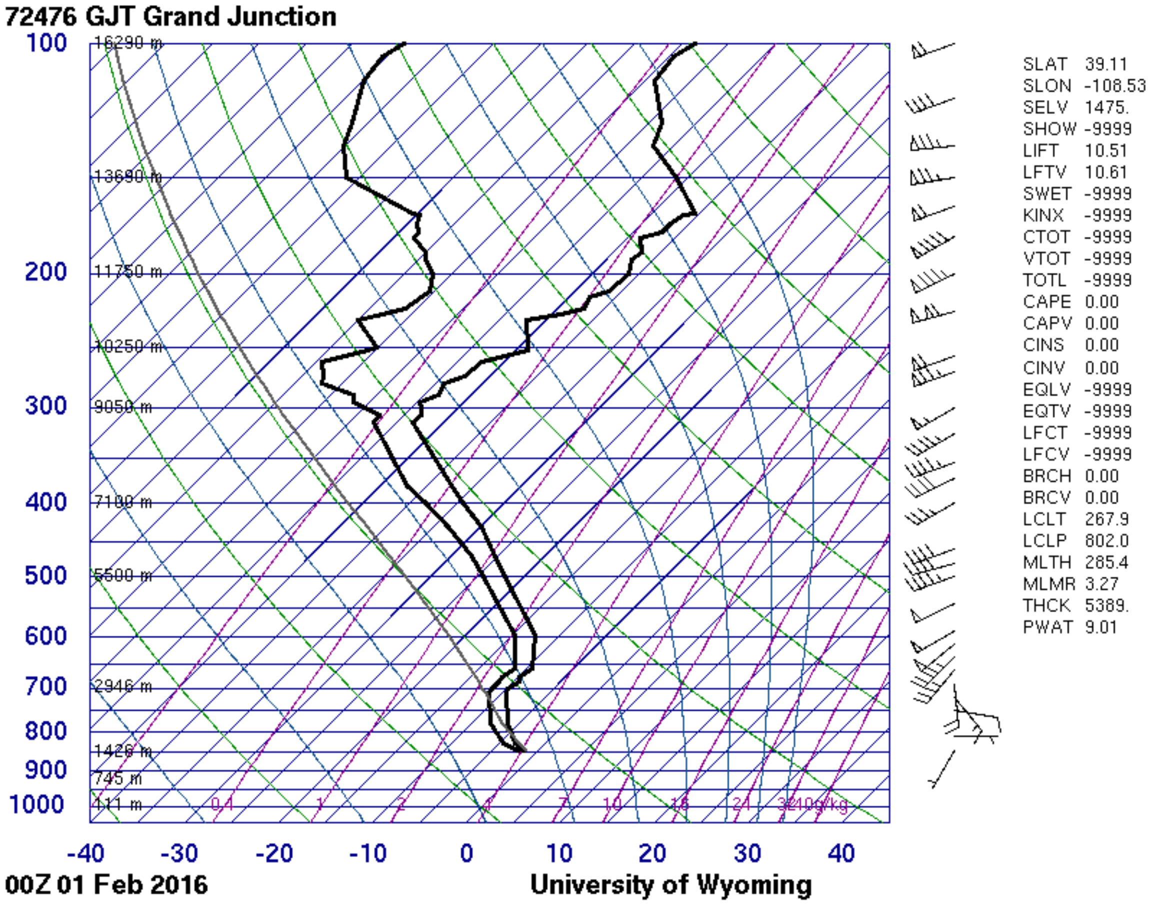


Figure 52. *Balloon sounding from the National Weather Service Grand Junction, CO, 1000 UTC 01 February 2016***.**

Overnight, between 0000 UTC February 01 and 1200 UTC February 01 the low continued to move closer the San Juan Mountains. A very moist airmass continued to move into the region under an increasingly strong southerly flow at 700mb (Fig. 53). Temperatures at that level remained at -4C. Another 1.0" of SWE was observed at Molas Lake (A), 0.8" at Lone Cone (SM) and 0.7" at Lizard Head Pass (D). The 24-hour snowfall at Purgatory was 18", with 19" at Telluride and no report was received from Silverton Mountain. There were some scattered reports of aircraft icing in the storm clouds.

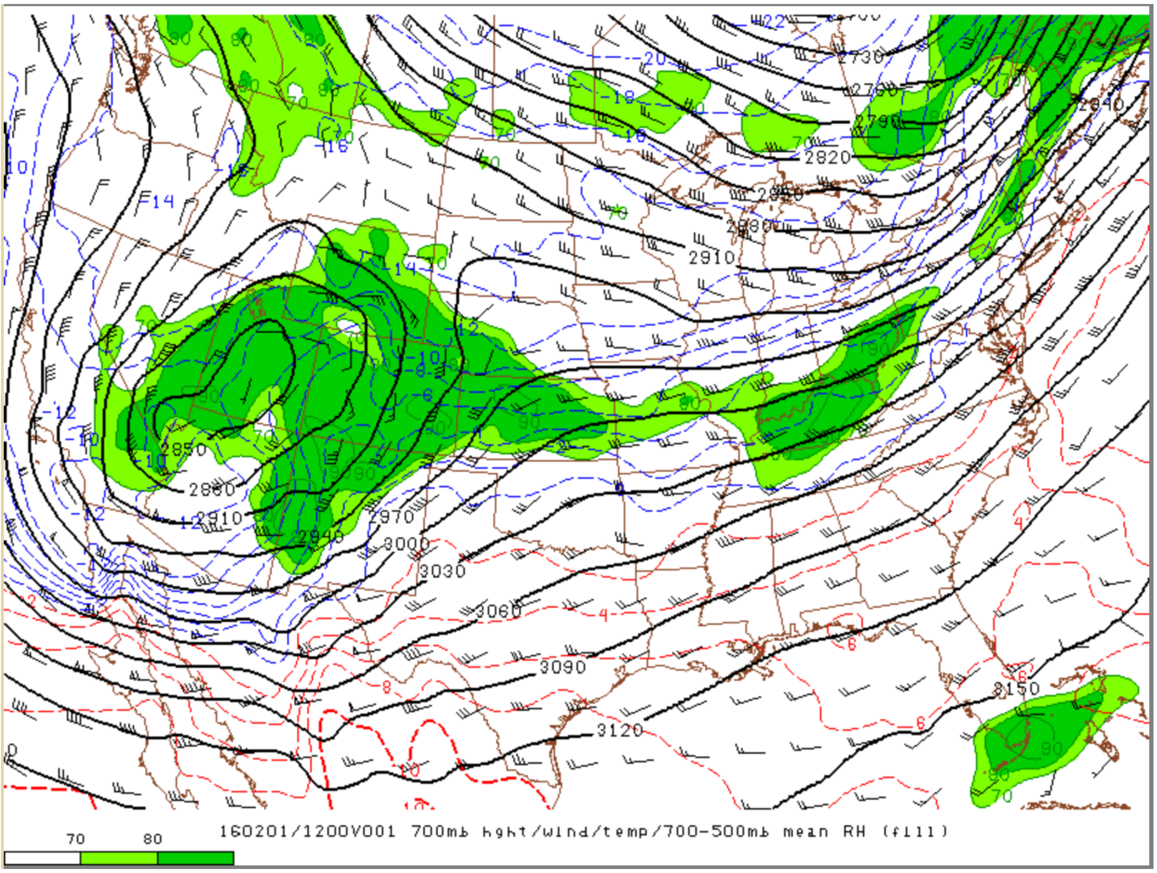


Figure 53. *700mb Rapid Refresh analysis field valid at 2016 February 01 1200 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (^{o}C)*, green shading relative humidity (%), wind barbs (kts).

After 1200 UTC on February the cold front moved through the area as the low tracked just north of the region (Fig. 54). Temperature at 700bm cooled to -9C and winds became more westerly (Fig. 55). Precipitation came to an end at the SNOTEL sites by 1800 UTC 01 February 2016 although clouds remained over the area through the day. The passage of the cold front reduced the moisture but increased the instability.

Clouds persisted over night (0000 UTC 02 February 2016 to 1200 UTC 02 February 2016). On the morning of 02 February 2016 Telluride reported another 7” of snow, Purgatory reported another 12” and Silverton Mountain Resort reported at two-day total of 40”. Later that morning skies started to clear.

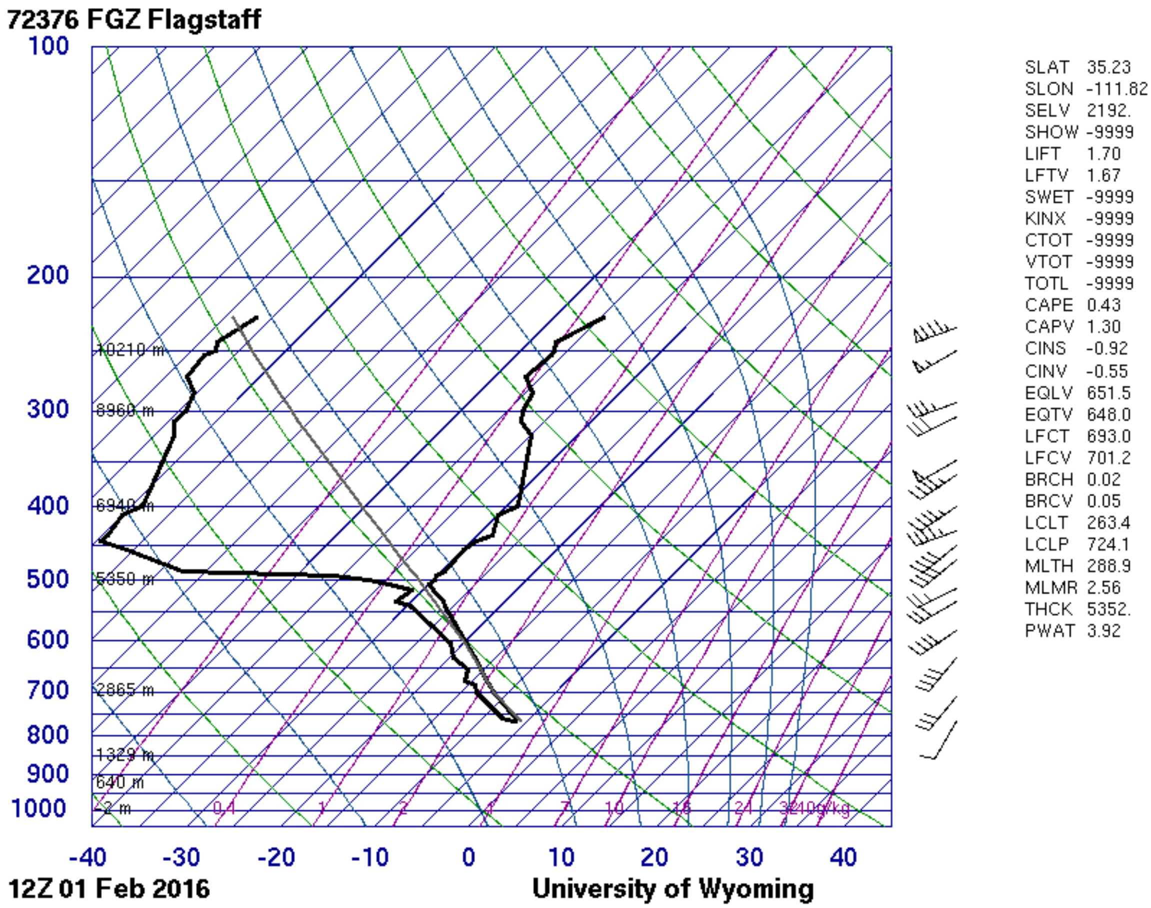


Figure 54. *Balloon sounding from the National Weather Service Flagstaff, AZ, 1200 UTC 01 February 2016.*

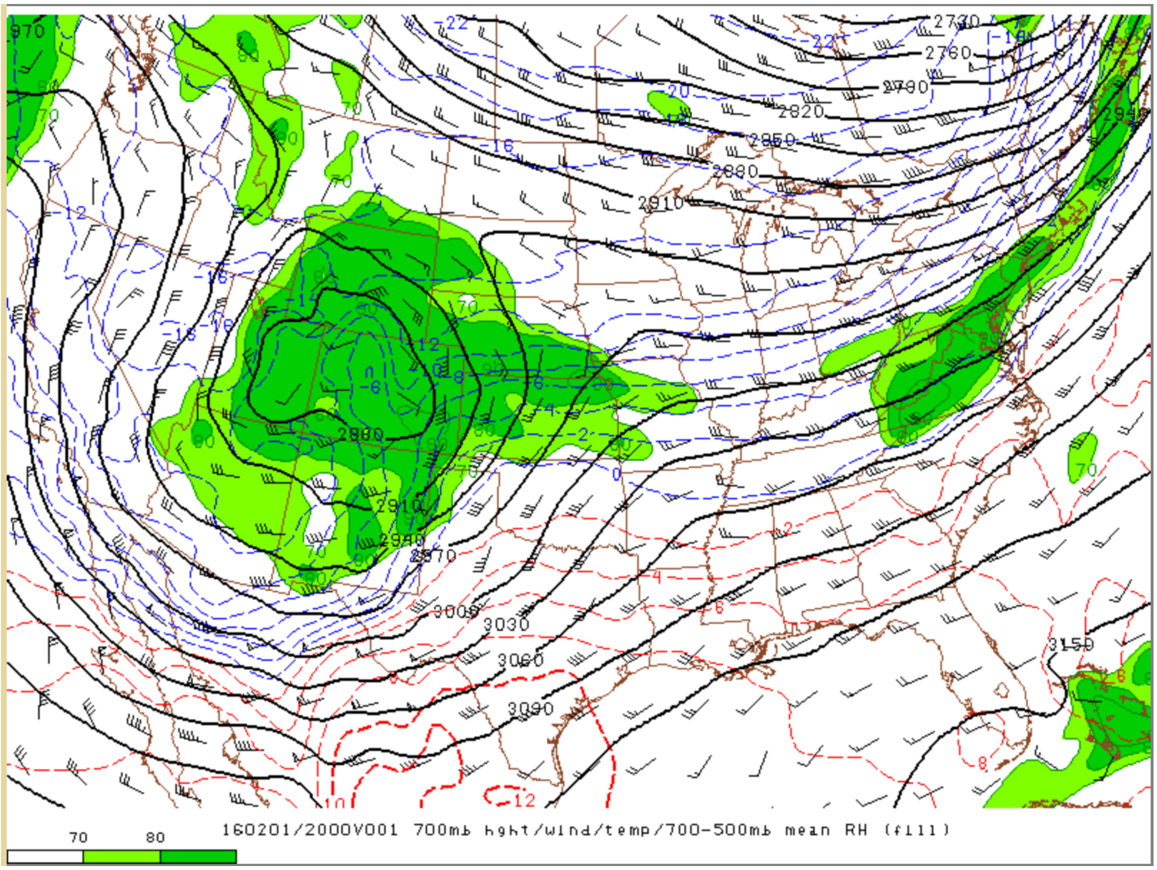


Figure 55. *700mb Rapid Refresh analysis field valid at 2016 February 01 2000 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (^oC)*, green shading relative humidity (%), wind barbs (kts).

Analysis: Case 5

Precipitation validation

The modeled total precipitation is presented in Figure 56. Over the higher terrain over 4” to 6” of liquid equivalent precipitation was produced by the model over the western San Juan Mountains with some local areas over the eastern higher terrain indicating over 9” of SWE. These precipitation totals are again slightly higher than the observed values at the SNOTEL sites but reasonable compared to the Silverton snowfall (Table 14), suggesting that the model may be too efficient at converting supercooled liquid water to ice phase and resulting precipitation. As mentioned in Case 3 and 4, this result would likely be underestimating the cloud seeding potential during the storm period. Even with the over forecasted of precipitation, the model simulations are favorable to analyze the case.

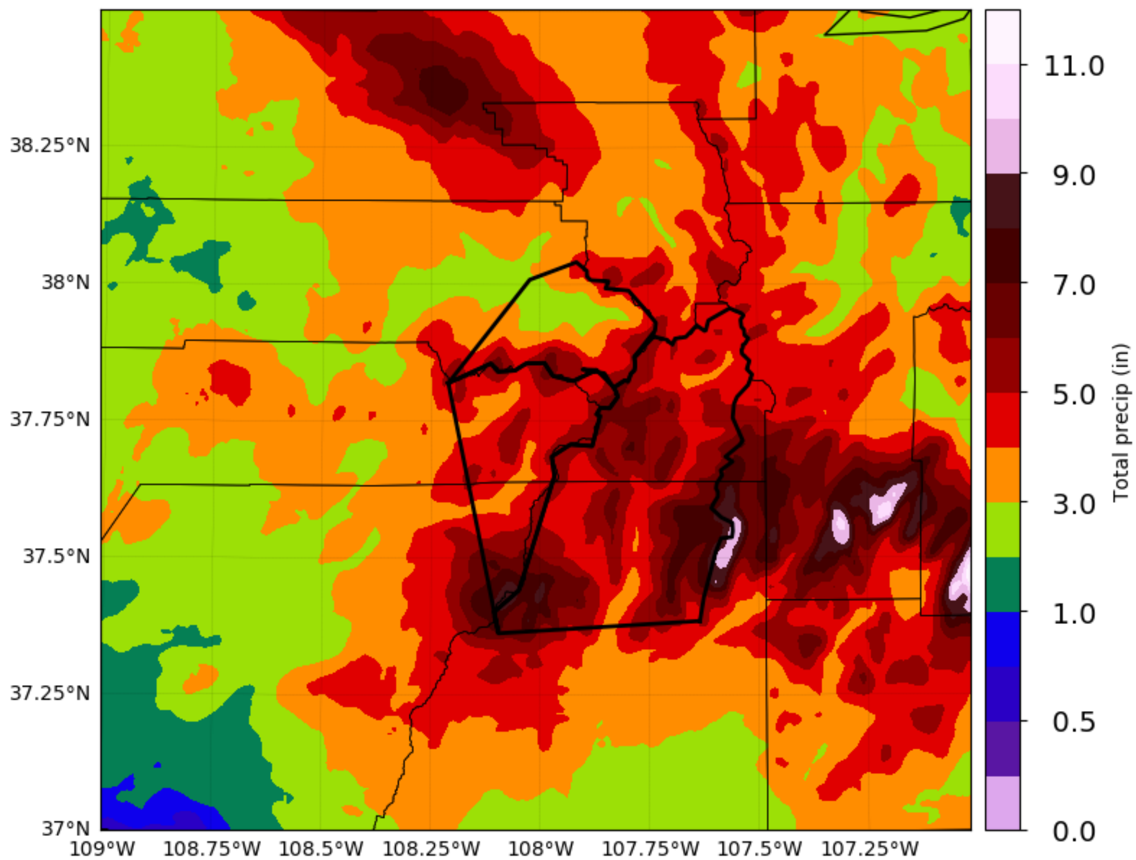


Figure 56. *Total liquid equivalent precipitation for the model run between 30 January 2016 1800 UTC – 2 February 2016 1800 UTC, The heavy black lines indicate the approximate headwaters of the Dolores, Animas, and San Miguel Watersheds.*

Table 14. *Total precipitation at the ski resorts and NRCS SNOTEL sites during the model precipitation period. Snowfall data period from 1200 UTC 30 January and 1200 UTC 2 February 2016. Snow Water Equivalent data period from 30 January 2016 1800 UTC – 02 February 2016 1800 UTC.*

Ski Resort	**Storm Period Snowfall (in)**
Silverton	48
Telluride	30
Purgatory	35
NRCS SNOTEL	**Snow Water Equivalent (in)**
Lizard Head	2.1
Lone Cone	2.7
Molas Lake	1.9

Cloud Seeding Potential

The results of the numerical model simulation show that cloud seeding opportunities were present over the western San Juan Mountains for about half storm period of Case 5, with 60% to 70% of the period having seeding conditions over the high peaks along the Continental Divide over the eastern San Juan (Fig. 57).

The SW-NE and NW-SE vertical cross-section shows that the most favorable cloud seeding locations are again tied to the higher terrain of the Dolores Watershed, on the upslope faces of the higher terrain (Fig. 58 a and b). The San Miguel watershed had more seeding opportunities for this case. In addition, a significant fraction of the modeled analyzed cloud seeding periods over the highest terrain occurred while model precipitation was falling (Fig. 59).

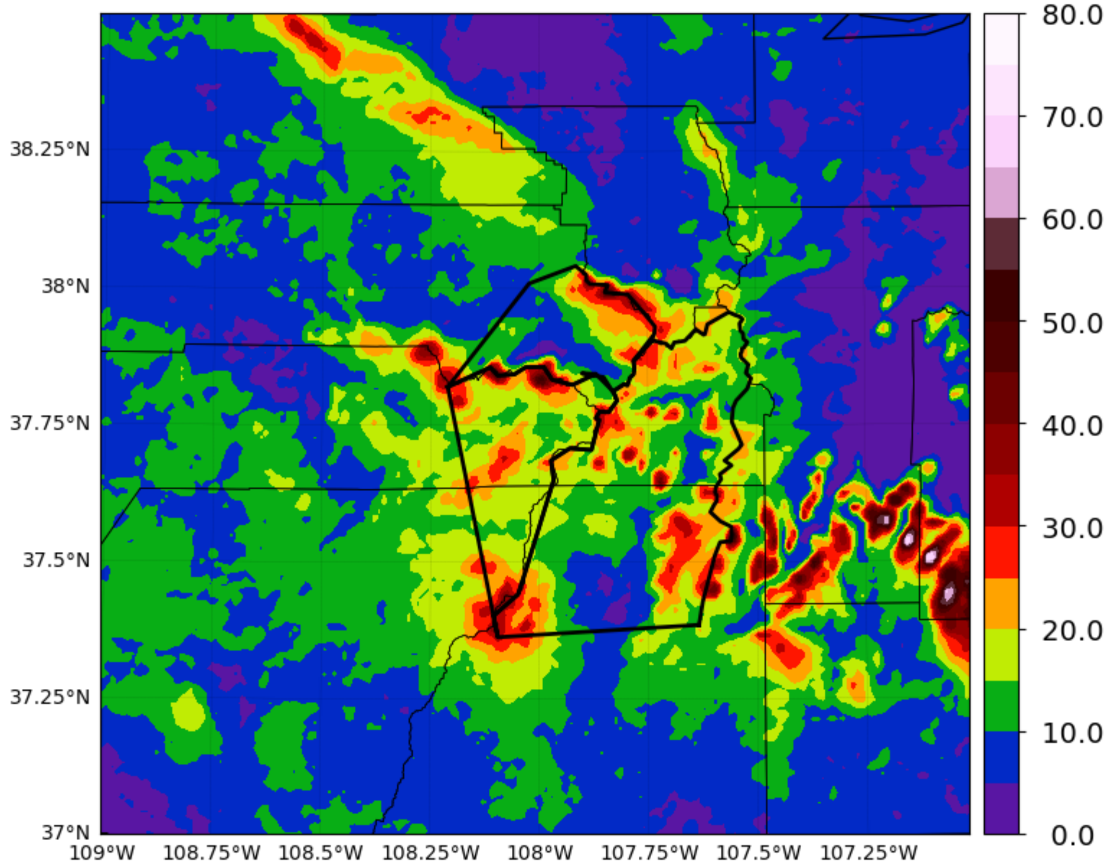


Figure 57. *Horizontal view of the percent of time cloud seeding conditions were present across the region from 30 January 2016 1800 UTC – 02 February 2016 1800 UTC.*

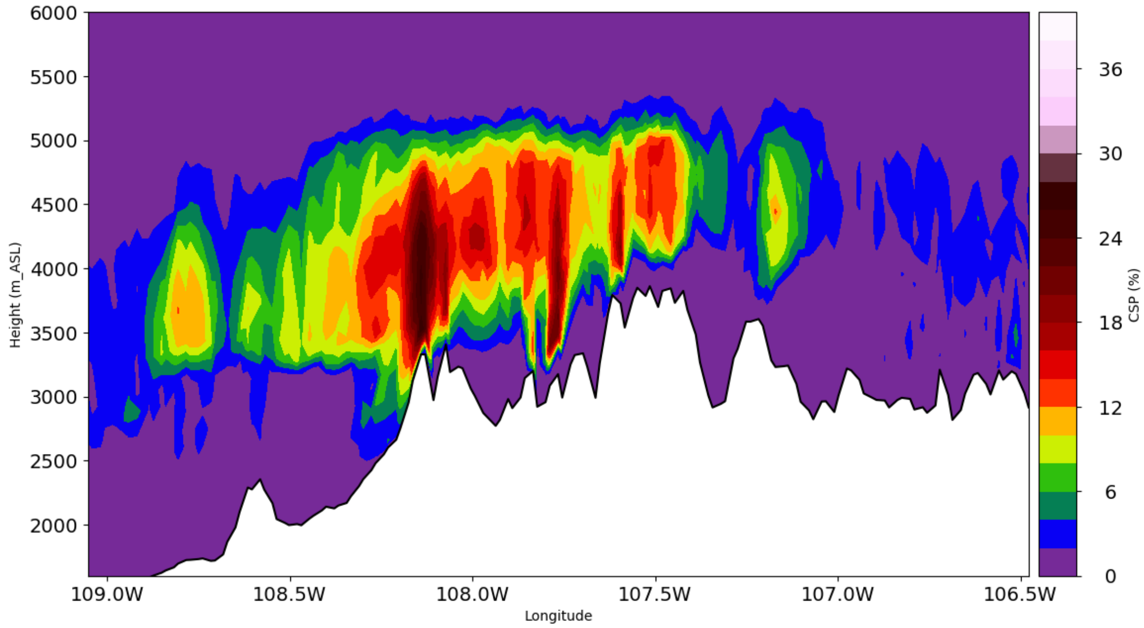


Figure 58 (a). *Southwest to northeast vertical cross-section of the percent of time cloud seeding conditions were present from 30 January 2016 1800 UTC – 02 February 2016 1800 UTC. See Fig E.4 for cross section location.*

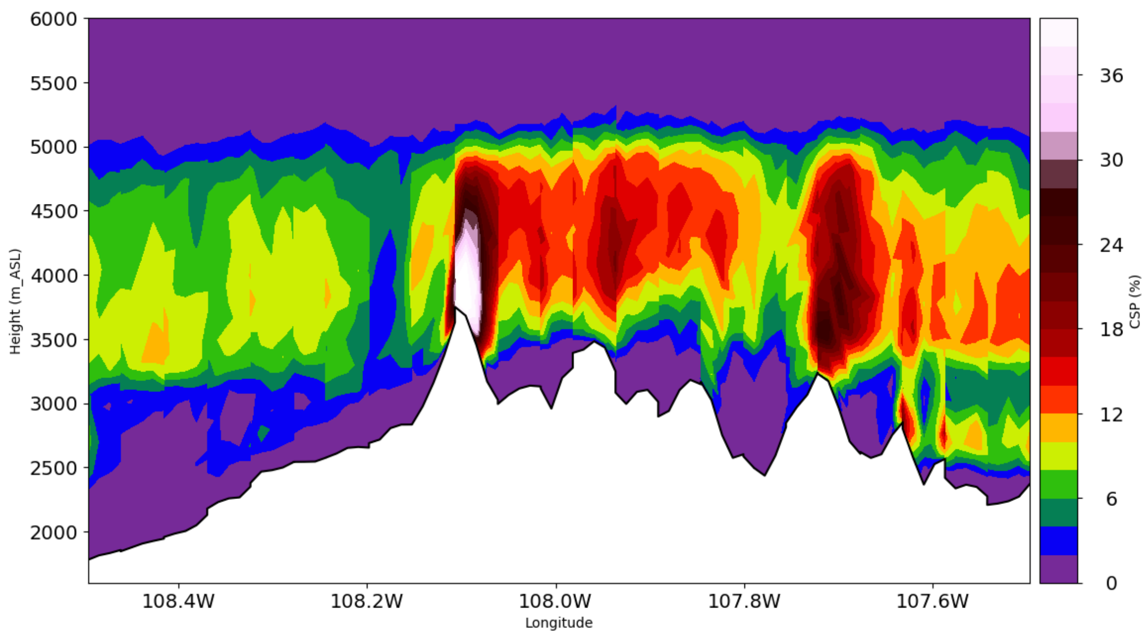


Figure 58 (b). *Northwest to southeast vertical cross-section of the percent of time cloud seeding conditions were present from 30 January 2016 1800 UTC – 02 February 2016 1800. See Fig E.4 for cross section location. The high point near 108.1 W Longitude is Mt Wilson along the Dolores/San Miguel Divide.*

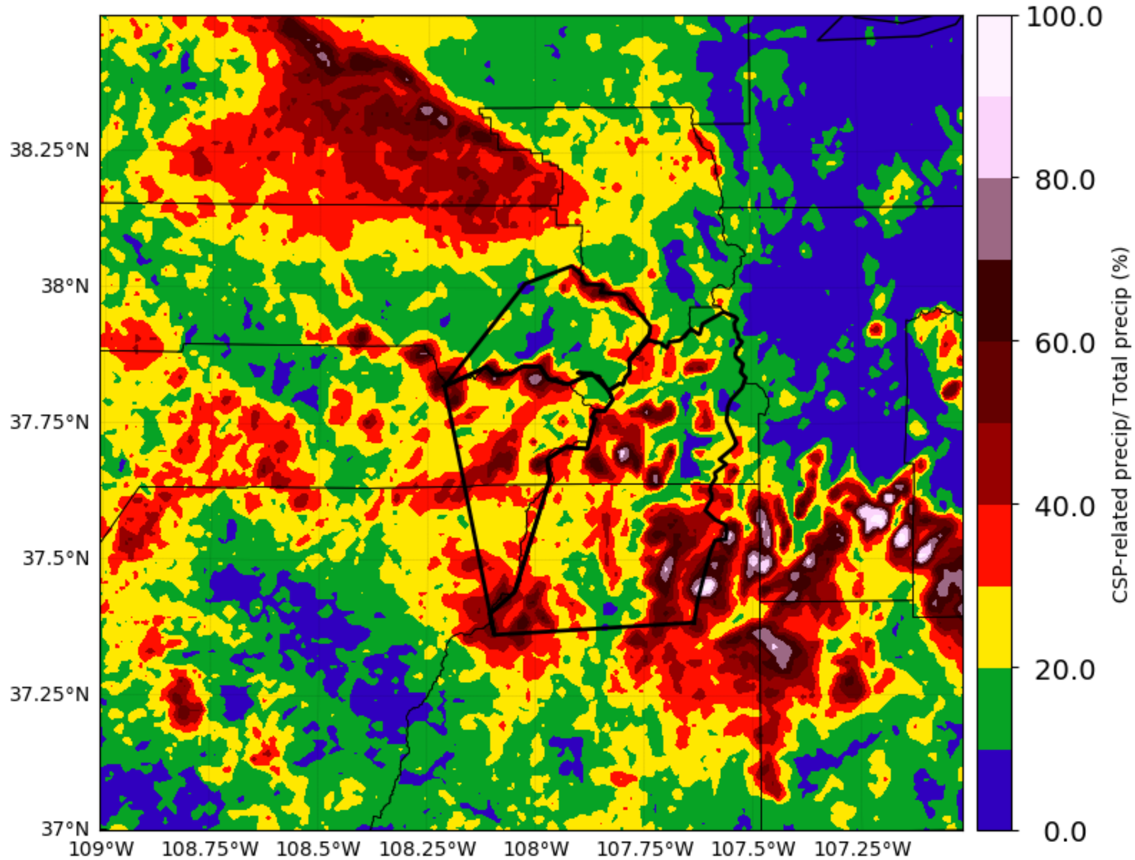


Figure 59. *The percent of time when modeled cloud seeding conditions were present and precipitation is also falling. High values suggest mixed phase clouds (ice and liquid water).*

Results from plume model

Particles were released from all of the San Juan generators during the entire storm period. The particles were tracked as they moved with the winds away from the generator for their interactions with supercooled temperatures (T) colder than -5°C and seedable clouds (T < -5°C and liquid water). Figure 60 shows an example of each of the San Juan network generator's efficiency at 2300 UTC 01 February 2017.

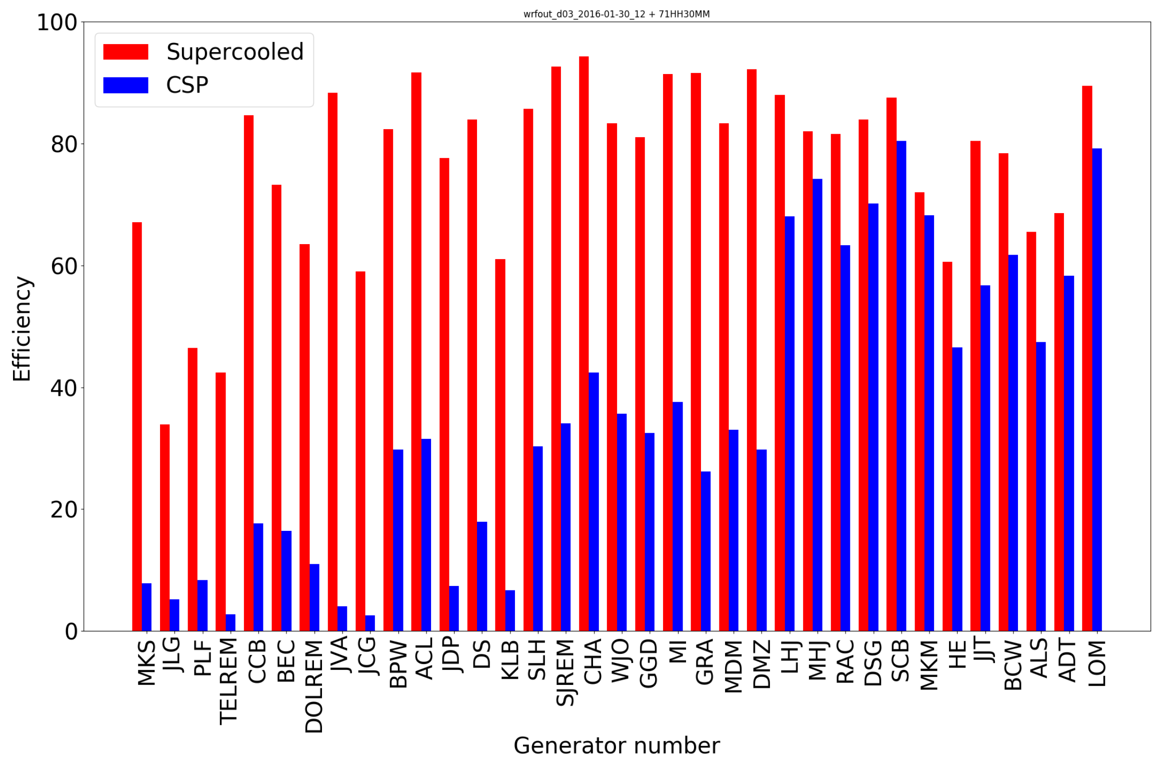


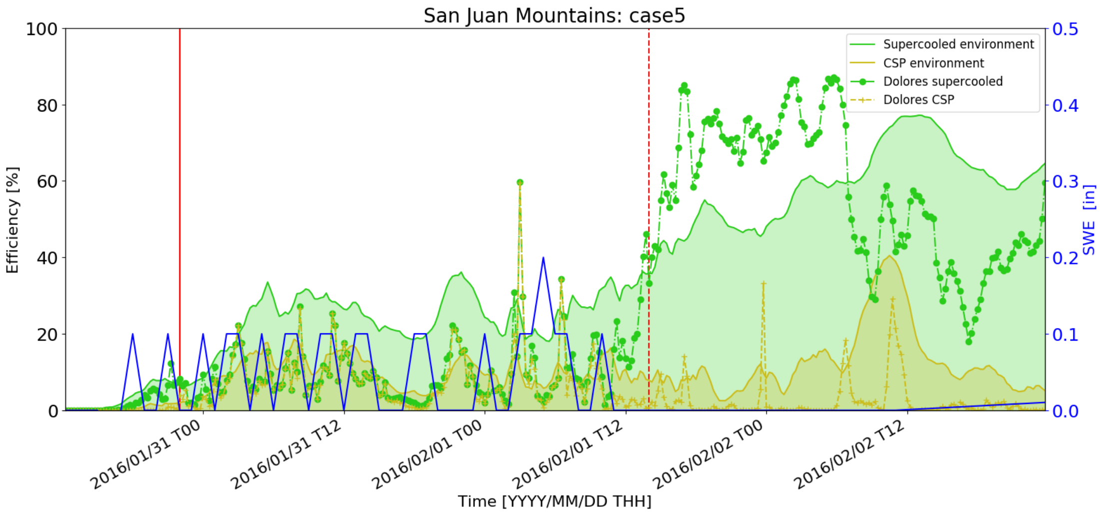
Figure 60. *Individual generator plume efficiencies for cloud seeding particles reaching temperatures between -5C and -18C (red) and model clouds with supercooled liquid water and temperatures between -5C and -18C (blue). See Fig E.4 for generator locations.*

The analysis of the generator plumes with all the storm times produced the percent of particles released from all of the generator plumes which interacted with seedable clouds over the greater San Juan Mountains during the Case 1 storm period (Fig. 61 a, b, c). The seeding efficiency for the Dolores (Fig. 61 a), Animas (Fig. 61 b), and San Miguel (Fig. 61 c) headwaters region were also computed.

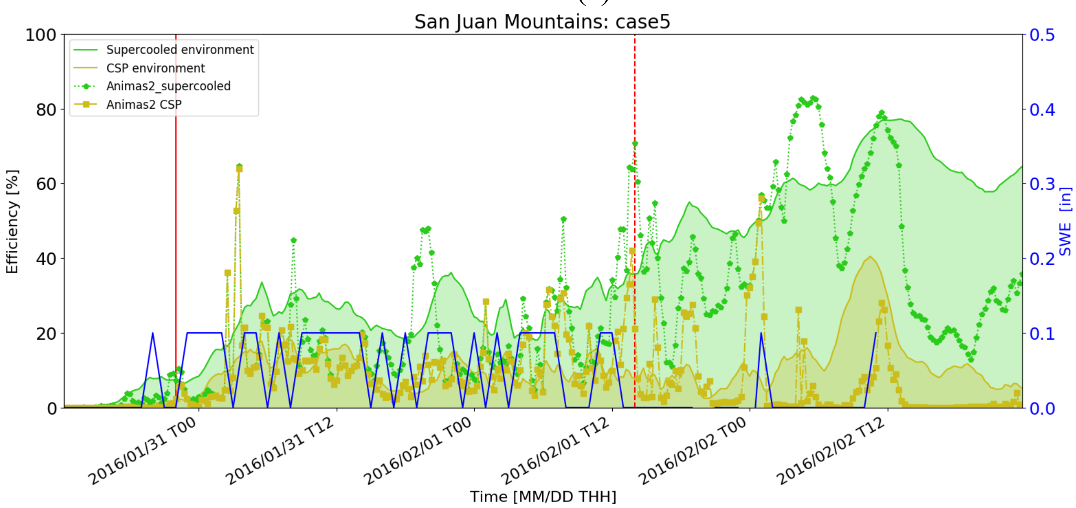
The results for the greater San Juan Mountains show that generators could have potentially delivered ice nuclei to seedable clouds after 0000 UTC on 31 January 2017 (Fig. 61). The plume model suggests that only 5% to 15% of the particles released would have reached seedable clouds, with a notable spike at about 1200 UTC on 2 February 2017.

Reviewing the successful targeting results for the Dolores, Animas and San Miguel watershed show that periods of the storm had some seeding success (10% - 15% efficiency) over the Animas and Dolores, and to a much lesser extent the San Miguel.

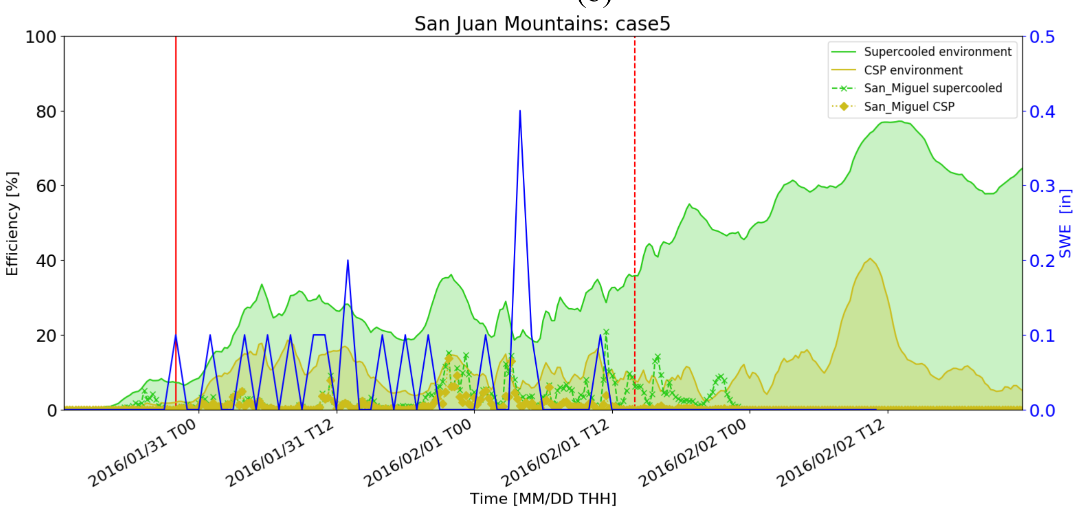
Analysis of the actual period when cloud seeding was conducted (between red and red-dashed lines) suggests that the cloud seeding plume reached seedable clouds over the target areas during the seeding period of 0000 UTC 31 January 2017 through 1400 UTC 1 February 2017. The results also suggest that the cloud seeding operations could have been extended beyond 1400 UTC 1 February 2017.



(a)



(b)



(c)

Figure 61. *Generator efficiency plots for all generators across the San Juan Mountains (green shading percent of particles reaching temperatures colder than -5°C), (orange shading percent of particles reaching seedable clouds), red lines show start and end times of the operational*

cloud seeding conducted during this storm. (a) Dolores Watershed (green dashed line percent of particles reaching temperatures colder than -5°C), (orange dashed line percent of particles reaching seedable clouds), blue line shows hourly precipitation rate in the Dolores Watershed. (b) same as (a) except for Animas watershed, (c) same as (a) except for San Miguel Watershed.

Case 6: 23 March 2017 0000 UTC – 24 March 2017 1500 UTC

Summary.

A trough and associated cold front crossed the area between 23 March 2017 0000 UTC and 24 March 2017 1500 UTC. The precipitation came in two distinct waves one on during the day on 23 March 2017 and the second overnight on 23-24 March 2017. Winds remained from the southwest trough 2200 UTC on March 23 then became northwesterly until the end of the case study. Supercooled liquid water was observed during both precipitation periods.

At 0000 UTC on 23 March 2017 an open wave trough was approaching the CA/Mexico Coast (Fig. 62). At this time a diffluent southwest flow aloft was over the San Juan Mountains. High cirrus clouds were over the area at this time with temperatures at 700mb at a warm +5C.

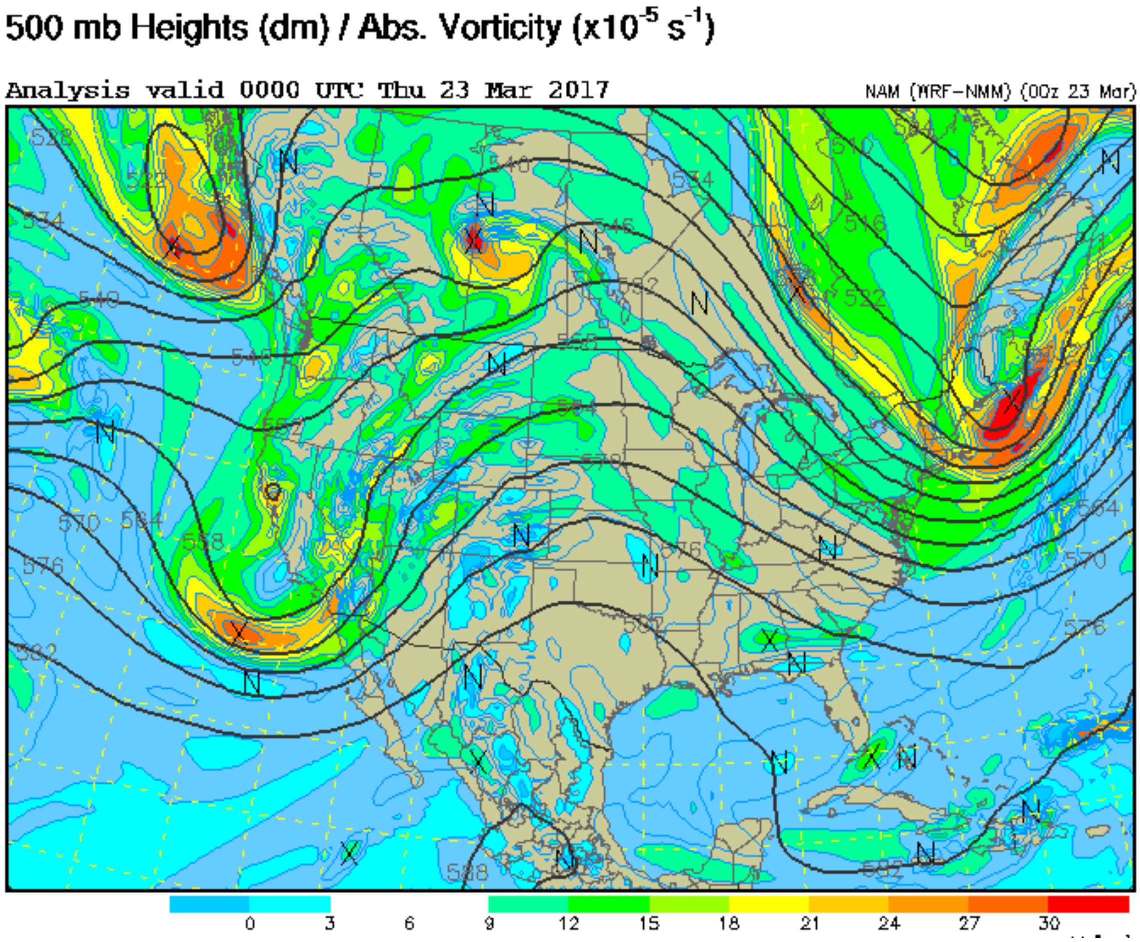


Figure 62. *500mb NAM analysis field valid at 2017 March 23 1200 UTC. Heavy black lines: geopotential height (m), dashed lines:* shading indicated vorticity (x10^5 s^{-1}).

By 1200 UTC 23 March 2017 mid level clouds with bases as low as 12,000' MSL moved into the area, but precipitation was absent over night at all the representative SNOTELs and the ski resorts (Telluride, Purgatory, and Silverton). By at least dawn (1400 UTC 23 March 2017) these clouds likely contained supercooled liquid water. We can infer this due to the lack of precipitation forming in the clouds, the observed mid-level clouds and icing pilot reports.

Between 1700 UTC – and 2200 UTC on 23 March with the 700mb cold front continuing to cross the area and the trough axis over Utah, precipitation was initiated at both Lizard Head and Molas Lake. As much as 0.5" of SWE was reported at both Lizard Head and Molas Lake by 2200 UTC with no new snow at Lone Cone. 700mb winds remained from the southwest. Icing was reported as low as 13,000' MSL and as high as 24,000' MSL over the greater San Juan Mountain region at this time (Fig. 63). The temperatures at 700mb had cooled by 8C to -3C and winds remained from the south-southwest (Fig. 64). The cooling aloft, as shown in the upstream sounding from Flagstaff, AZ (Fig. 65) destabilized the atmosphere leading to lighting observed across the area.

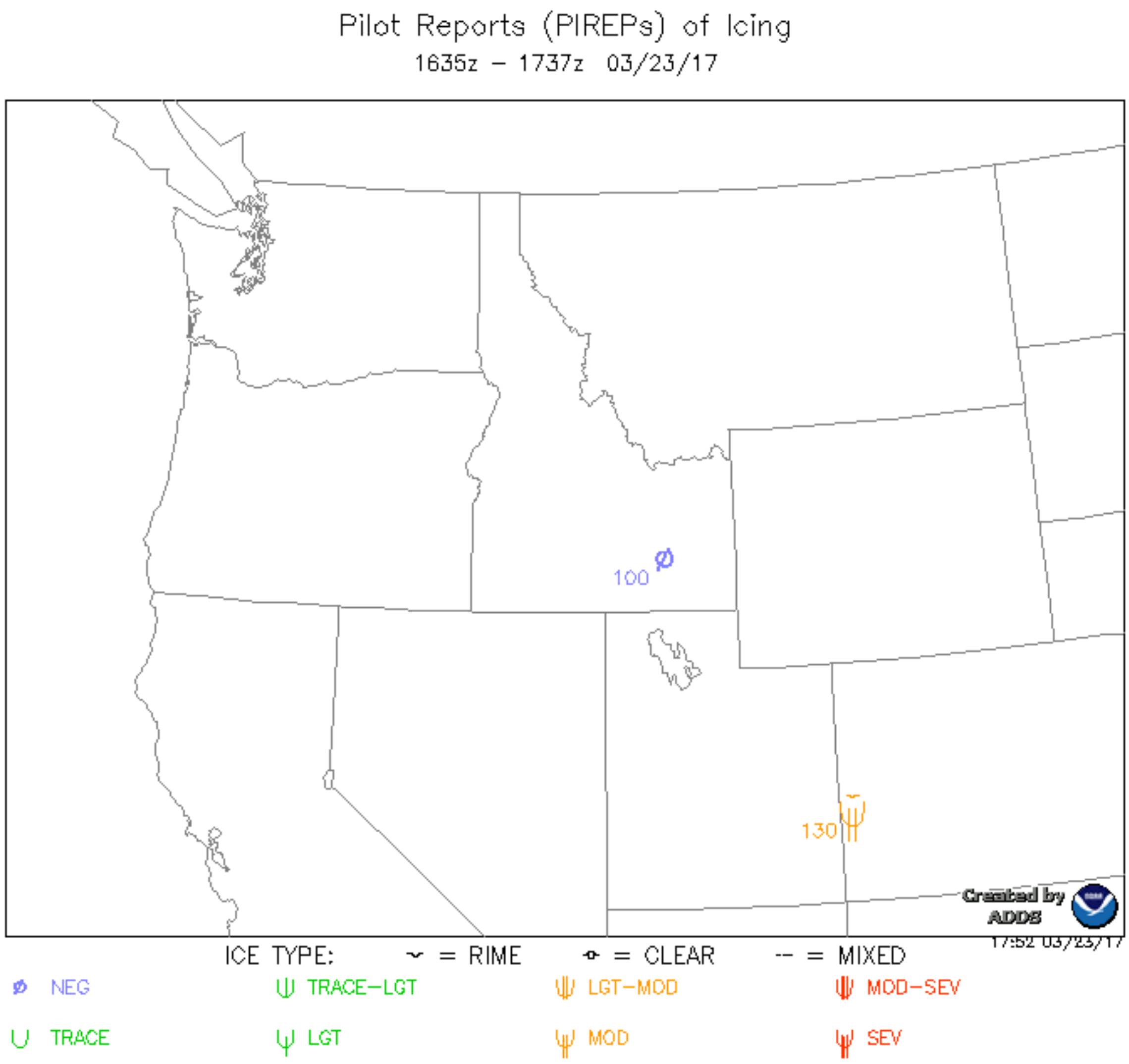


Figure 63. *Aircraft icing reports between 1635 UTC and 1737 UTC on 23 March 2017. Colors and symbols indicate icing severity and ice type.*

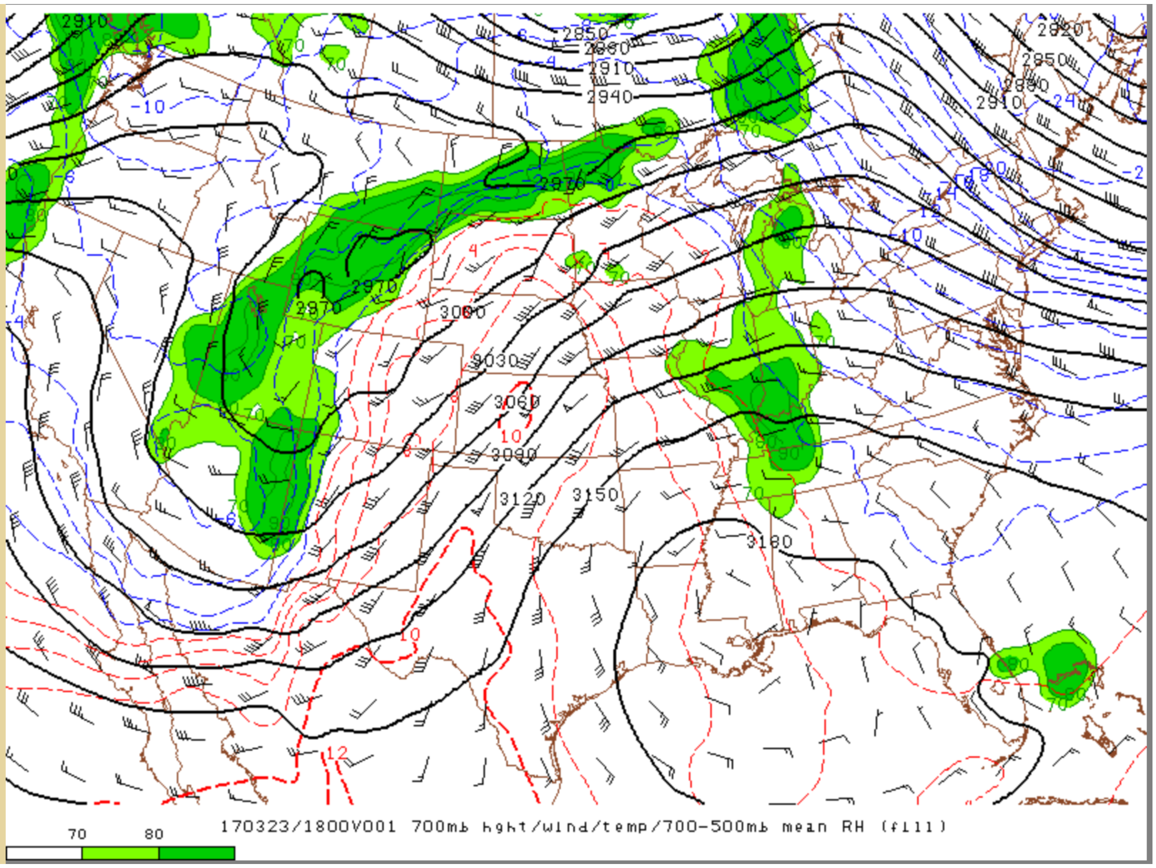


Figure 64. *700mb Rapid Refresh analysis field valid at 2017 March 23 1800 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (^oC)*, green shading relative humidity (%), wind barbs (kts).

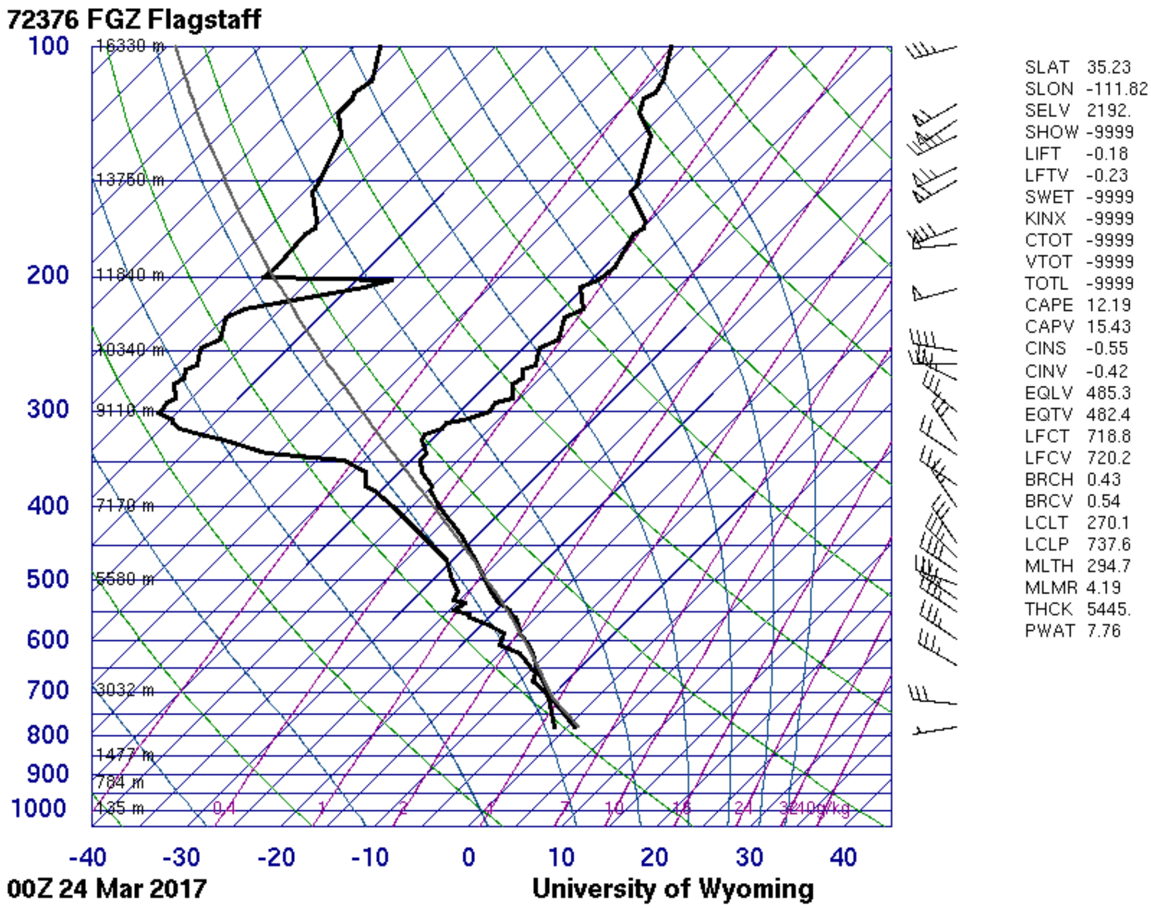


Figure 65. *Balloon sounding from the National Weather Service Flagstaff, AZ, 0000 UTC 24 March 2017****.***

The precipitation ended after 2200 UTC 23 March at both Lizard Head (D) and Molas Lake (A) as the winds became light from the west-northwest as the trough axis crossed the area (Fig. 66). With the wind shift, snow started to fall at both Lone Cone and the Telluride Airport.

By 0700 UTC 24 March, the 700mb trough had closed off into a deep low east of the San Juan Mountains (Fig. 67). This strengthened the moist unstable northwesterly flow at 700mb as temperatures remained at -3C and aircraft icing was reported over the area. An additional 0.6” of SWE was observed at Lizard Head (D) between 0500 UTC and 0900 UTC 24 March 2017, at Molas Lake 0.3” of SWE was observed, and at Lone Cone 0.8” of SWE was observed. The Lone Cone precipitation started as the wind shifted to west-northwesterly at 22 UTC 23 March 2017. By 1200 UTC the Silverton Resort had received a 24-hour of 28”, at Telluride 19” of new snow was reported, while only 6” was reported at Purgatory Ski Area.

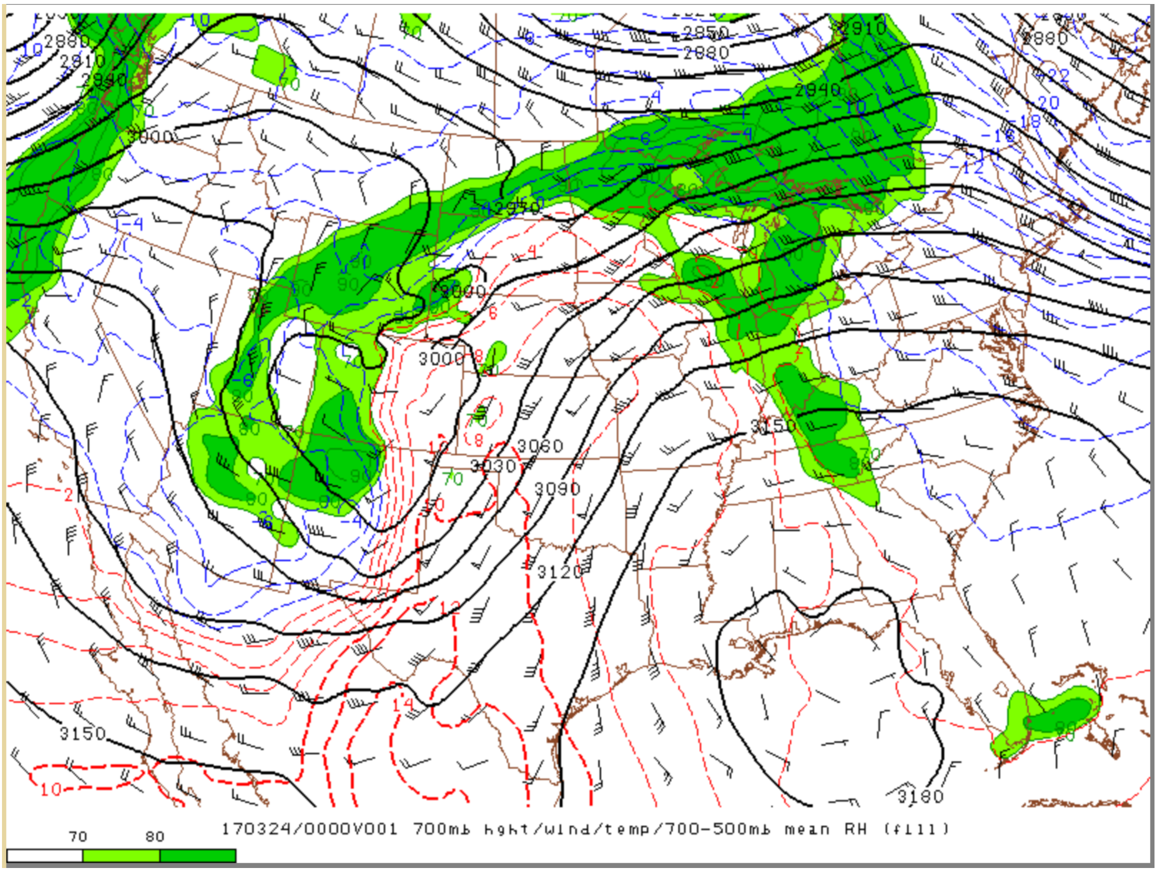


Figure 66. *700mb Rapid Refresh analysis field valid at 2017 March 24 0000 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (^{o}C)*, green shading relative humidity (%), wind barbs (kts).

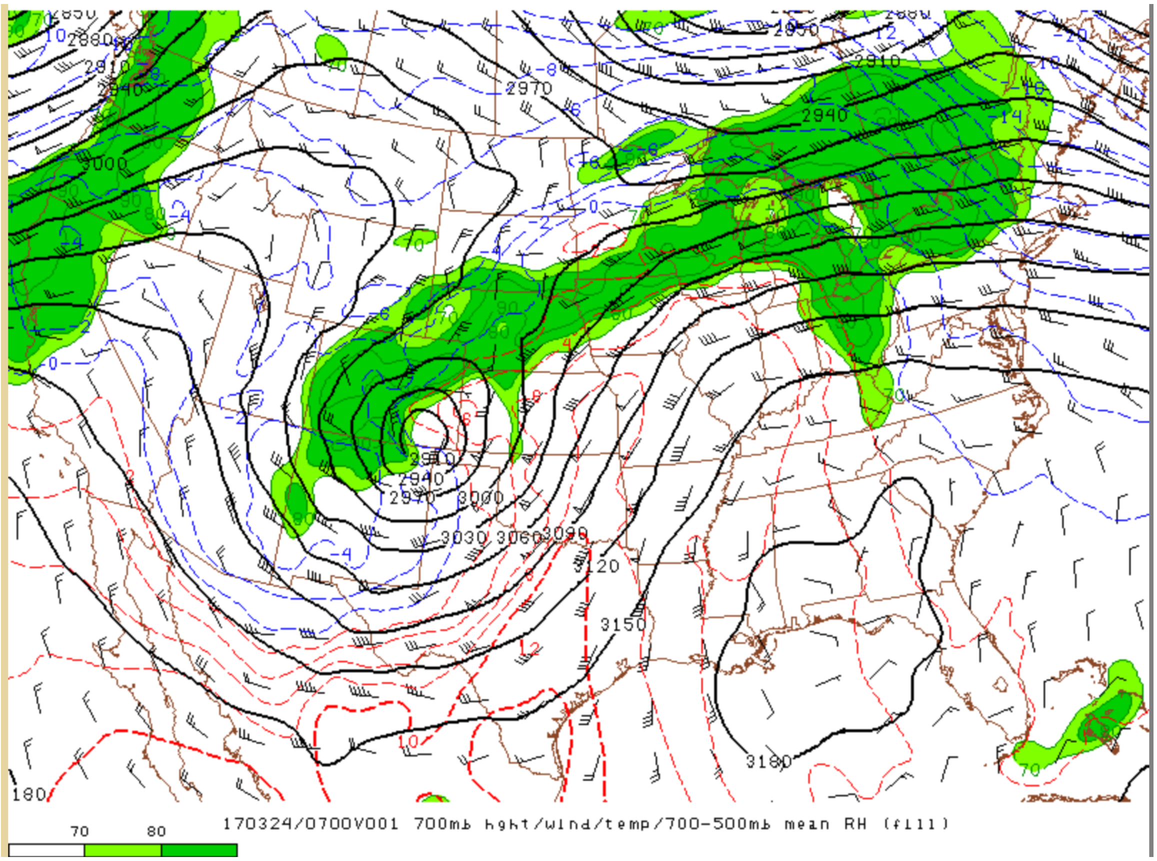


Figure 67. *700mb Rapid Refresh analysis field valid at 2017 March 24 0700 UTC. Heavy black lines: geopotential height (m), dashed lines: temperatures (°C)*, green shading relative humidity (%), wind barbs (kts).

Analysis: Case 6

Precipitation validation

The modeled total precipitation is presented in Figure 68. Over the higher terrain between 0.5” and 2” of liquid equivalent precipitation was produced by the model over the target areas. These totals reasonably match the SWE and ski resort observed values (Table 15), giving confidence that model was closely simulating the storm period.

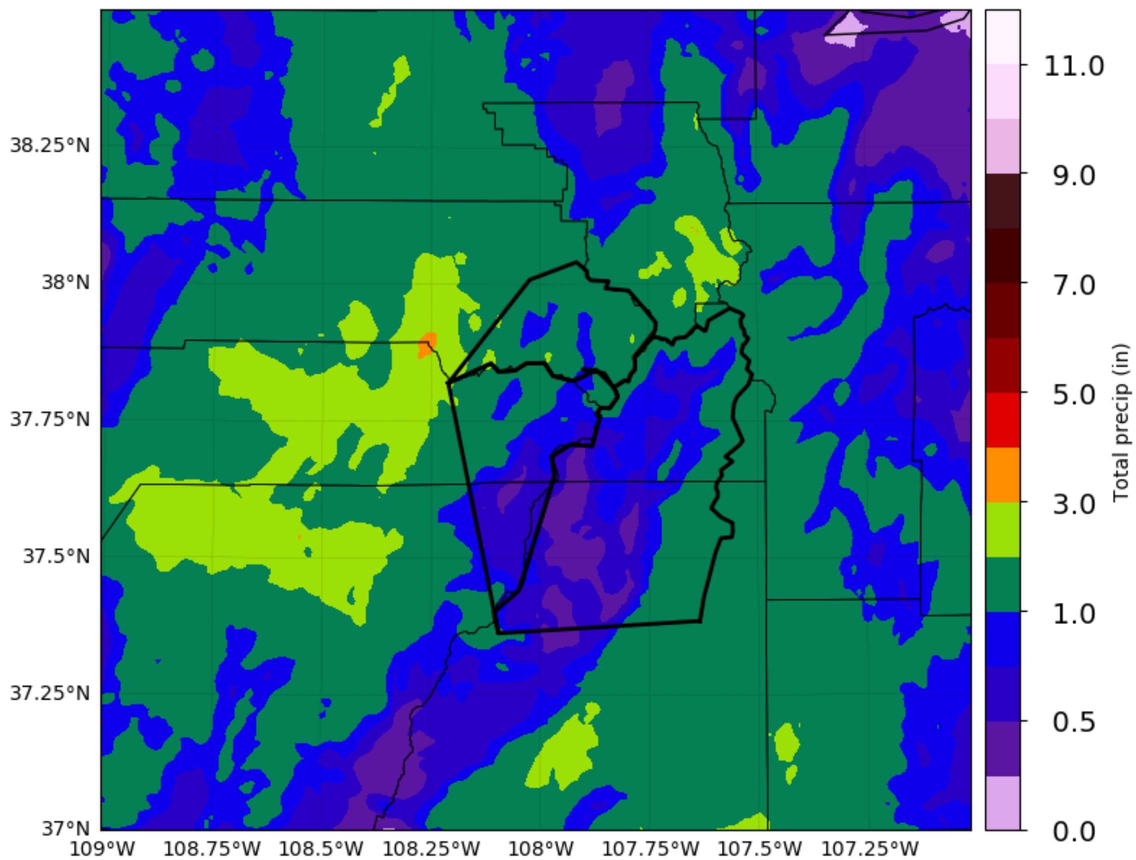


Figure 68. *Total liquid equivalent precipitation for the model run between 23 March 2017 0000 UTC – 24 March 2017 1500 UTC, The heavy black lines indicate the approximate headwaters of the Dolores, Animas, and San Miguel Watersheds.*

Table 15. *Total precipitation at the ski resorts and NRCS SNOTEL sites during the model precipitation period. Snowfall data period from 1200 UTC 23 March and 1200 UTC 24 March 2017. Snow Water Equivalent data period from 23 March 2017 0000 UTC – 24 March 2017 1500 UTC.*

Ski Resort	**Storm Period Snowfall (in)**
Silverton	36
Telluride	20
Purgatory	6
NRCS SNOTEL	**Snow Water Equivalent (in)**
Lizard Head	0.8
Lone Cone	0.7
Molas Lake	0.5

Cloud Seeding Potential

The results of the numerical model simulation show that cloud seeding opportunities were present over the western and northwestern San Juan Mountains for much of the storm period. Cloud seeding opportunities were present for more than 40% of the storm period over the highest terrain of the San Miguel and Dolores watersheds and the highest terrain of the La Plata

Mountains (Fig. 69). The SW-NE vertical cross-section shows that the most favorable cloud seeding locations are again tied to the higher terrain of the Dolores Watershed, on the upslope faces of the highest terrain (Fig. 70). In this case much of the cloud seeding opportunities are shifted into the San Miguel Watershed, north of Mt Wilson. In addition most of the cloud seeding periods occurred while precipitation was falling (Fig. 71).

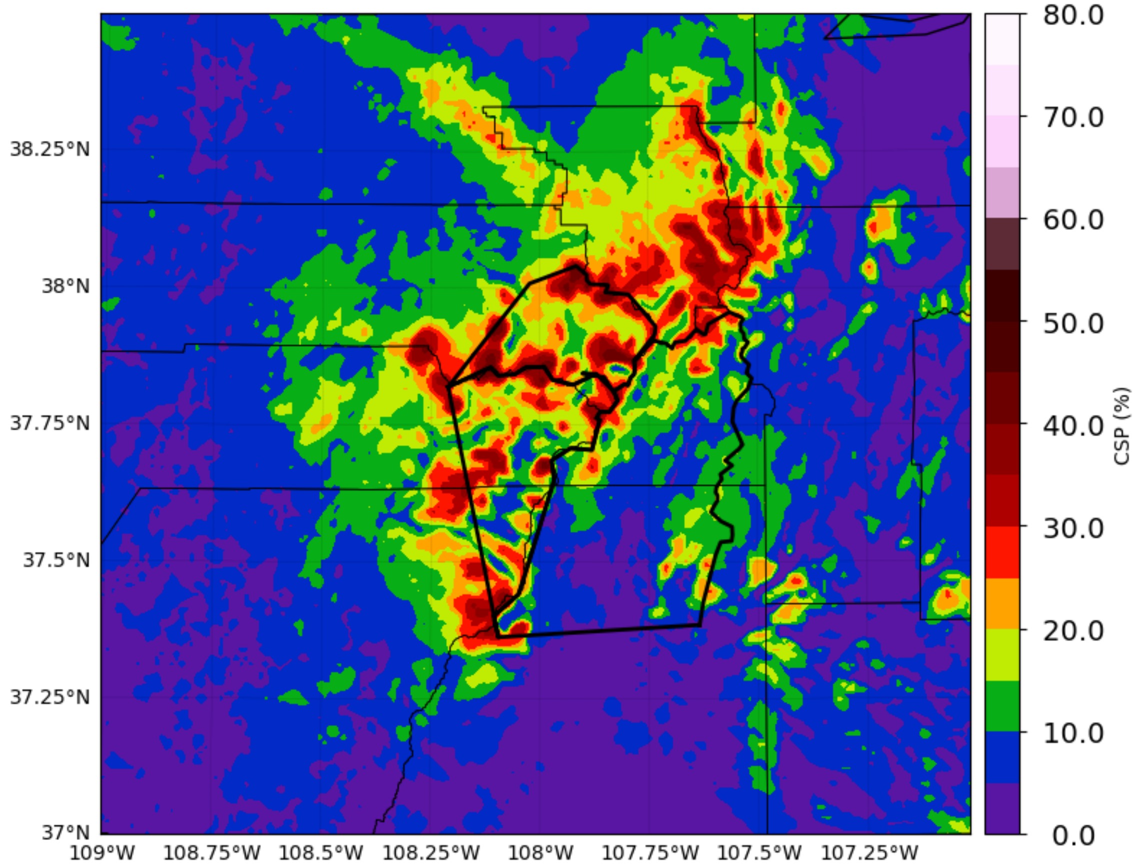


Figure 69. *Horizontal view of the percent of time cloud seeding conditions were present across the region from 23 March 2017 0000 UTC – 24 March 2017 1500 UTC.*

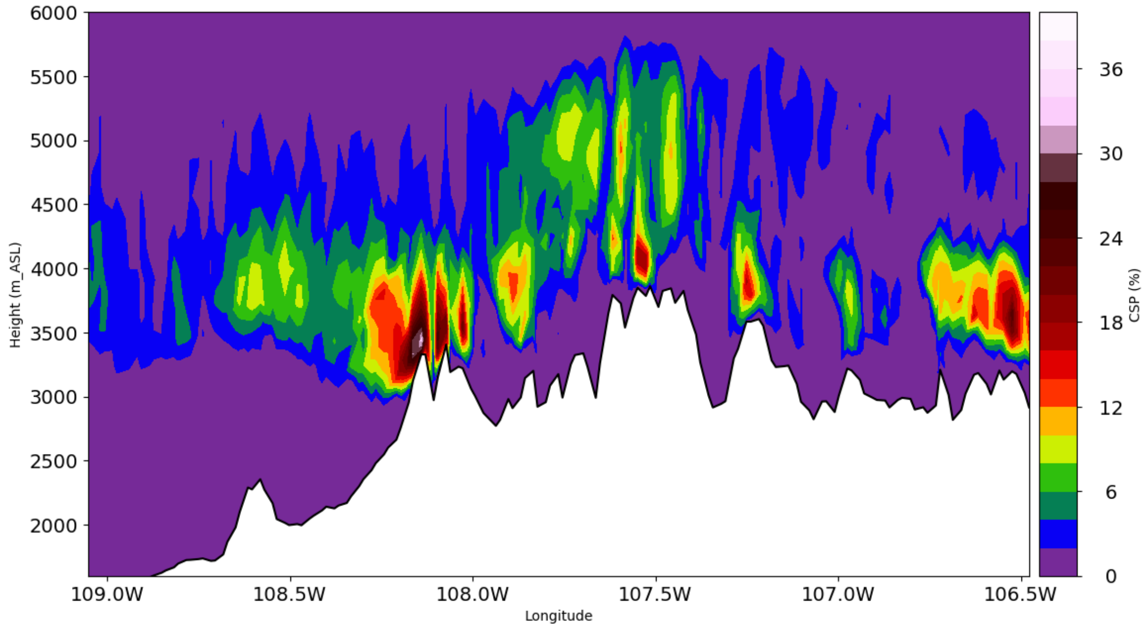


Figure 70 (a). *Southwest to northeast vertical cross-section of the percent of time cloud seeding conditions were present from 23 March 2017 0000 UTC – 24 March 2017 1500 UTC. See Fig E.4 for cross section location.*

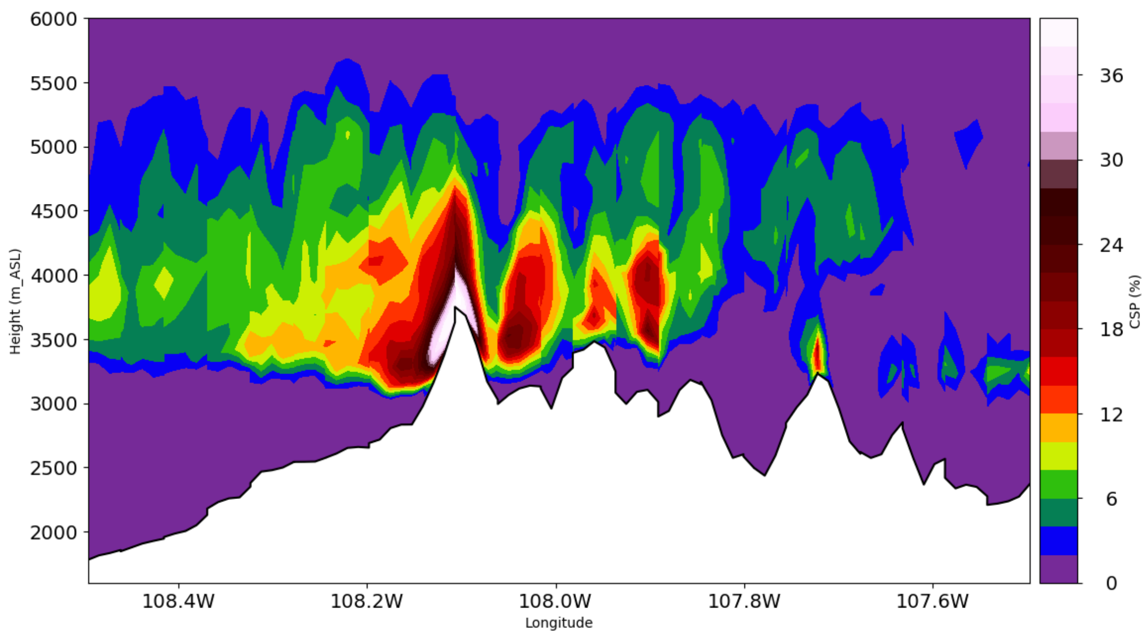


Figure 70 b. *Northwest to southeast vertical cross-section of the percent of time cloud seeding conditions were present from 23 March 2017 0000 UTC – 24 March 2017 1500 UTC. See Fig E.4 for cross section location. The high point near 108.1 W Longitude is Mt Wilson along the Dolores/San Miguel Divide.*

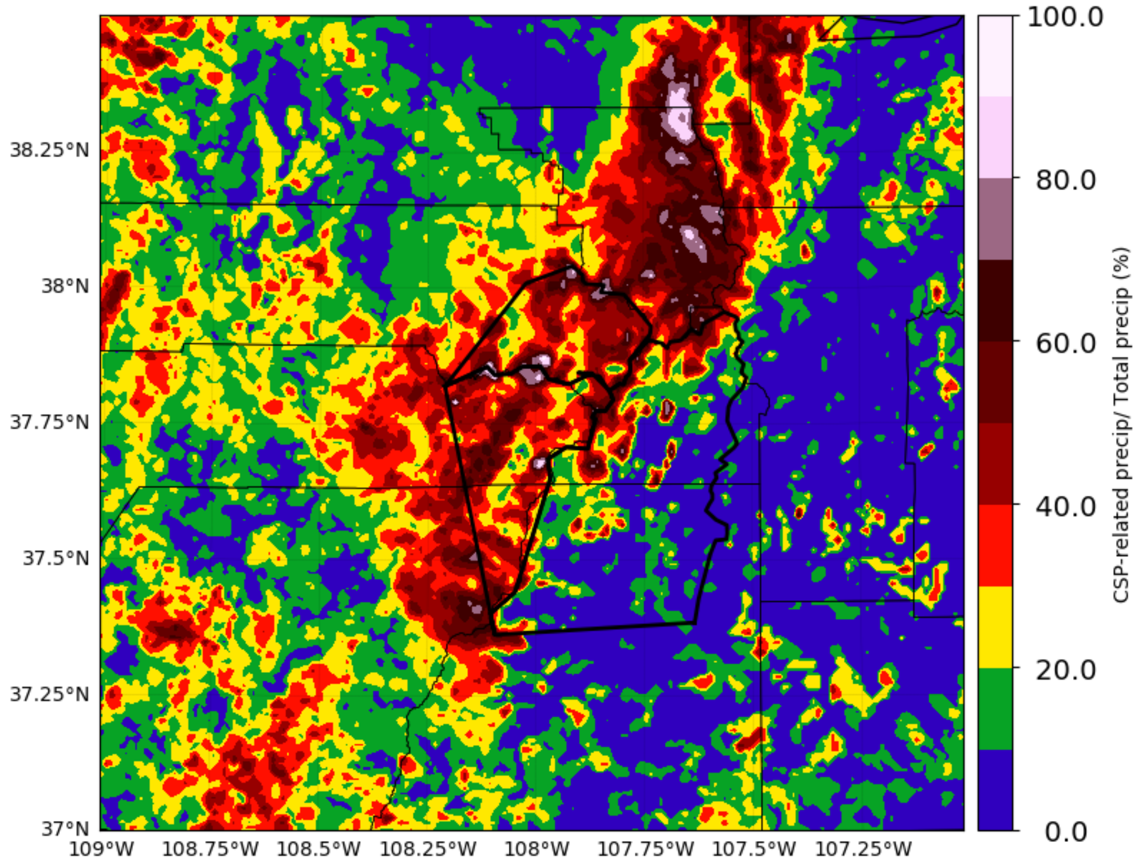


Figure 71. *The percent of time when modeled cloud seeding conditions were present and precipitation is also falling. High values suggest mixed phase clouds (ice and liquid water).*

Results from plume model

Particles were released from all of the San Juan generators during the entire storm period. The particles were tracked as they moved with the winds away from the generator for their interactions with supercooled temperatures (T) colder than -5^{o}C and seedable clouds (T < -5^{o}C and cloud liquid water). Figure 72 shows an example of each of the San Juan network generator's efficiency at 0400 UTC 24 March 2017.

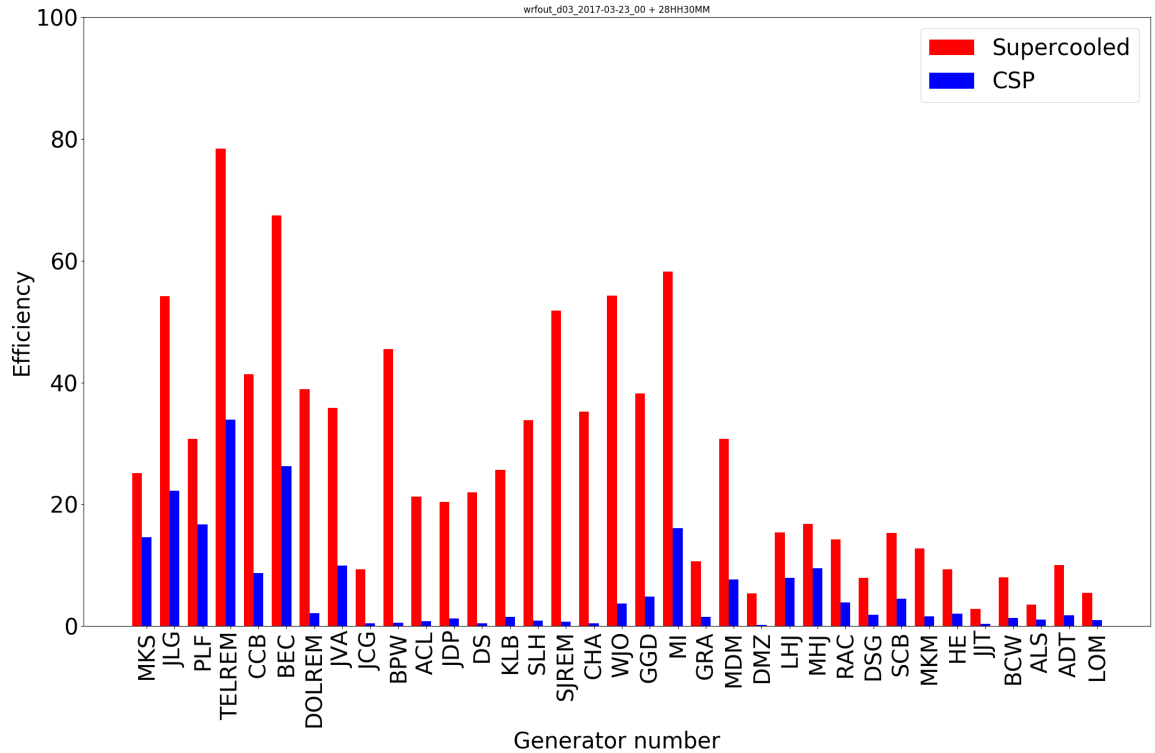
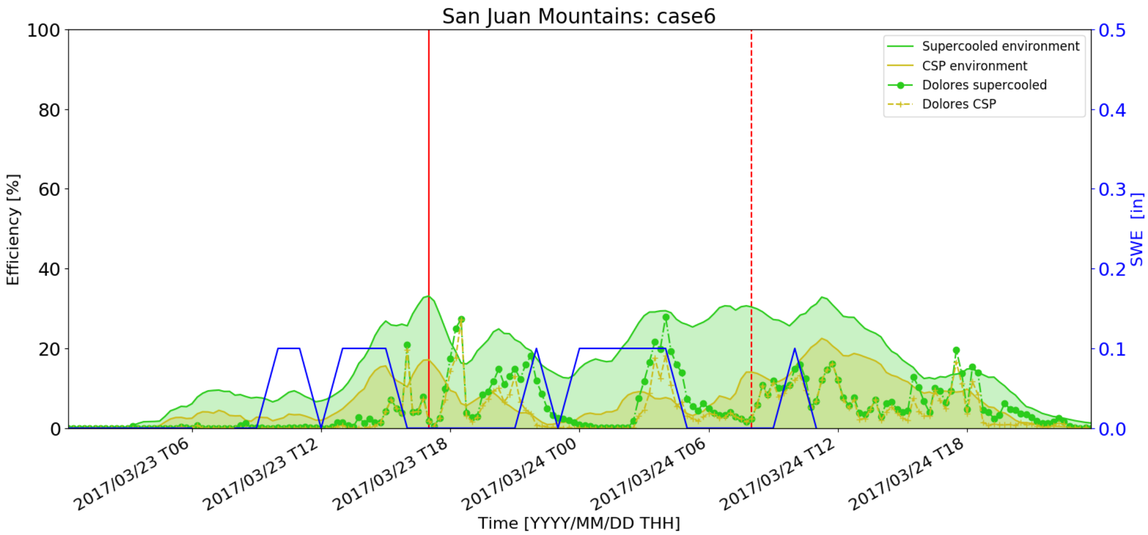


Figure 72. *Individual generator plume efficiencies for cloud seeding particles reaching temperatures between -5C and -18C (red) and model clouds with supercooled liquid water and temperatures between -5C and -18C (blue). See Fig E.4 for generator locations.*

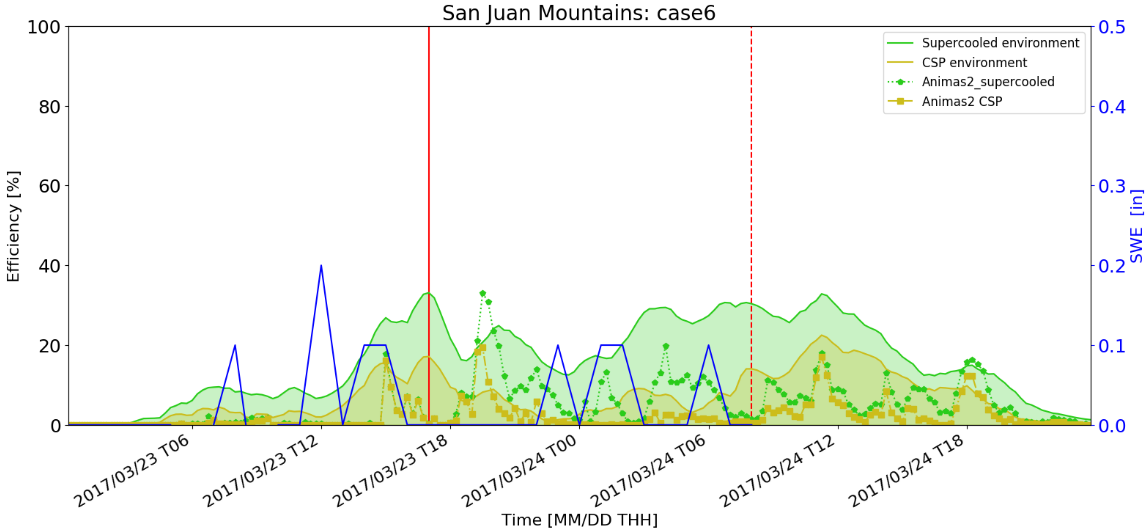
The analysis of the generator plumes with all the storm times produced the percent of particles released from all of the generator plumes which interacted with seedable clouds over the greater San Juan Mountains during the Case 1 storm period (Fig. 73 a, b, c). The seeding efficiency for the Dolores (Fig. 73 a), Animas (Fig. 73 b), and San Miguel (Fig. 73 c) headwaters region were also computed.

The results for the greater San Juan Mountains show that generator network would have delivered about 10% of the released ice nuclei into the target area. This was the case for the greater San Juan Mountains as well as the individual watersheds.

Analysis of the actual period when operational cloud seeding was conducted (between red and red-dashed lines) suggests that the cloud seeding plume reached seedable clouds over the target area about 10% of the time. The results also suggest that the generator operations were initiated at the correct time but should have been continued overnight and until about or just after 1800 UTC 24 March 2017


San Juan Mountains: case6
Supercooled environment
CSP environment
Dolores supercooled
Dolores CSP
Efficiency [%]
SWE [in]
Time [YYYY/MM/DD THH]
2017/03/23 T06
2017/03/23 T12
2017/03/23 T18
2017/03/24 T00
2017/03/24 T06
2017/03/24 T12
2017/03/24 T18

(a)


San Juan Mountains: case6
Supercooled environment
CSP environment
Animas2_supercooled
Animas2 CSP
Efficiency [%]
SWE [in]
Time [MM/DD THH]
2017/03/23 T06
2017/03/23 T12
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2017/03/24 T00
2017/03/24 T06
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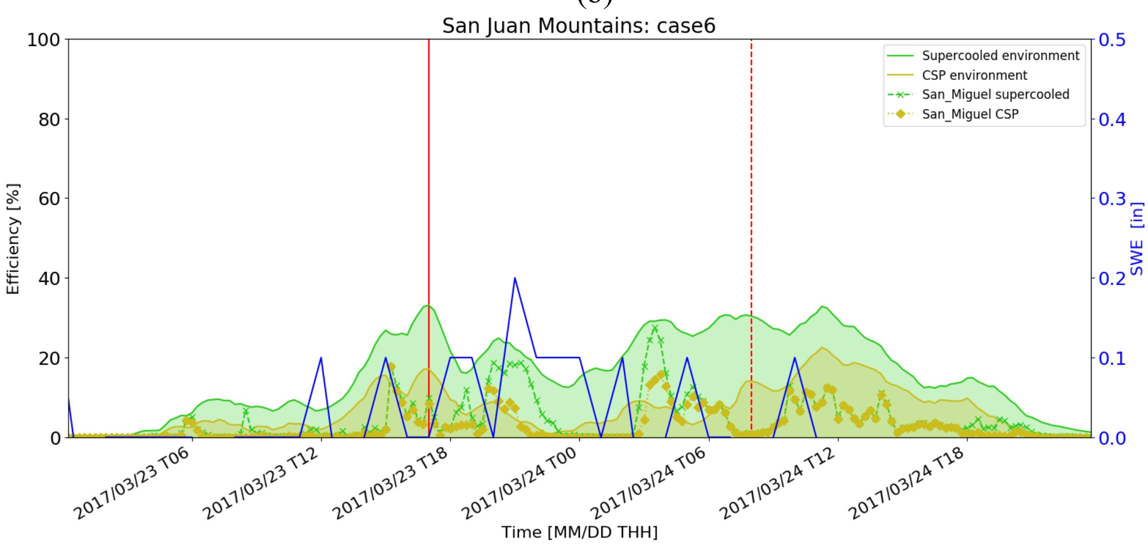
2017/03/24 T18

(b)


San Juan Mountains: case6
Supercooled environment
CSP environment
San_Miguel supercooled
San_Miguel CSP
Efficiency [%]
SWE [in]
Time [MM/DD THH]
2017/03/23 T06
2017/03/23 T12
2017/03/23 T18
2017/03/24 T00
2017/03/24 T06
2017/03/24 T12
2017/03/24 T18

(c)

Figure 73. *Generator efficiency plots for all generators across the San Juan Mountains (green shading percent of particles reaching temperatures colder than -5^{o}C), (orange shading percent of particles reaching seedable clouds), red lines show start and end times of the operational cloud seeding conducted during this storm. (a) Dolores Watershed (green dashed line percent of particles reaching temperatures colder than -5^{o}C), (orange dashed line percent of particles reaching seedable clouds), blue line shows hourly precipitation rate in the Dolores Watershed. (b) same as (a) except for Animas watershed, (c) same as (a) except for San Miguel Watershed.*

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