ANALYSIS OF ICE DETECTOR OBSERVATIONS AT MOUNT CRESTED BUTTE, COLORADO DURING THE 2014-2015 WINTER SEASON

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ABSTRACT: North American Weather Consultants has operated a cloud seeding program to impact select target areas in the Upper Gunnison River Basin of Colorado each winter since the 2003-2004 winter season. Since the presence of supercooled liquid water (SLW) is the key ingredient that renders portions of some winter storms “seedable”, provisions were made to acquire and install a ground based icing meter, which measures the occurrence of SLW, along with some supporting meteorological instruments at an exposed location on Mt. Crested Butte located north of Gunnison, Colorado. This system was installed in the fall of 2014 and then operated throughout the 2014-2015 winter season.

Various analyses were performed based upon the observance of SLW at this location. Analyses of meteorological features during icing events included: temperature, precipitation, wind direction and speed, synoptic pattern, and low-level stability. Since ground based generators are used on this program and the Gunnison Basin is known for cold temperatures caused by trapping of cold air and the presence of atmospheric inversions, special attention was given to determine if such inversions might occur when “seedable” conditions were present. In other words, do winter storms typically scour out any pre-existing low-level atmospheric inversions that may form during clear weather conditions? To provide additional information on this question, the NOAA HYSPLIT model was run for each seeded storm that occurred during the 2014-2015 winter season. These model runs resulted in predicted plume trajectories from each ground based generator.

It needs to be emphasized in the following conclusions and key findings that all of these are based upon only one winter season of data. Additional seasons of data would lead to more climatologically representative conditions associated with icing at the Mt. Crested Butte site.

- A large proportion of barrier summit height icing activity was observed in the -5 to -15 °C temperature range (the range generally used as a primary seeding criterion). In general, it appears that about 75% of icing activity occurs within this range, with most of the remainder observed at warmer temperatures (16%). A smaller portion (~9%) was observed at temperatures colder than -15 °C.
- Of five synoptic categorizations (pre-frontal, post-frontal/pre-500-mb trough, post-trough, closed low, and undefined), the pre-frontal situation was associated with the greatest amount of icing at the Mt. Crested Butte site during one season of data with 46% of icing events. As a consequence, most icing events were associated with south-westerly winds aloft.
- The ice detector data paired with surface data and modeling indications suggests that in ~63-70% of icing periods, atmospheric stability would not significantly inhibit orographic lofting of lower elevation ground generator seeding plumes into the SLW zones in winter clouds associated with storms passing over the target area.
• HYSLIPIT computer model runs as well as plots indicating the amount of stability during each seeded storm event were compiled for the 2014-2015 winter season. These predicted plumes for the seeded cases indicated successful transport of seeding material over the intended target area in a large majority of the cases.

1. INTRODUCTION

A necessary ingredient for glaciogenic cloud seeding to augment precipitation is supercooled liquid water (SLW). SLW is typically found in nature as cloud droplets that remain unfrozen even though their temperatures are below 0 °C. In a clean laboratory environment, such droplets may remain unfrozen down to a temperature of -39 °C (Schaefer, 1948). Certain types of dust or bacteria in the atmosphere can act as ice nuclei, which may interact with supercooled cloud droplets causing them to freeze at much warmer temperatures than -39 °C. Discoveries in the late 1940’s demonstrated that microscopic sized particles of silver iodide could have the same impact on supercooled cloud droplets as naturally occurring ice nuclei (Vonnegut, 1947). Numerous research studies and theory demonstrate that if SLW exists in natural storm clouds there is the potential to increase the amount of precipitation that falls from such clouds if they are “seeded” with silver iodide nuclei (Super, 1999).

For optimal seeding it is important to know if there is SLW present and where it is located. One method used for point measurements of SLW involves placing ice detectors near mountain peaks. Over mountainous terrain during the winter months in Utah, SLW has been shown to frequently develop at low altitudes (< 1 km) above the windward slopes during stormy weather (Super, 1999), (Yorty et al. 2012), (Yorty et al. 2013) and (Griffith et al. 2013). This is not only a feature of mountainous areas in the Intermountain West, but likely occurs globally in other mountainous terrain. In many instances SLW impinges on the higher mountain ridges, producing rime ice accumulation caused by freezing of supercooled cloud drops on objects such as trees or structures (Griffith et al. 2013). Therefore, it is likely that point measurements located near ridges on windward slopes could help determine when SLW is present. This helps with real-time decision making for cloud seeding operations to augment mountainous precipitation. Figure 1 provides a photo of rime ice accumulation on a ski lift at Brian Head Ski area in southern Utah following a winter storm. Rime ice results from the freezing of SLW on structures and surfaces. The horizontal icicle-like appendages typically grow into the wind over time.

North American Weather Consultants (NAWC) has conducted a winter cloud seeding program in the Upper Gunnison River Basin each winter since the 2003-2004 winter season (Griffith et al. 2011). This program employs a network of approximately 20 ground-based, manually operated silver iodide generators to seed selected periods of naturally occurring winter storms deemed to be “seedable”. Some generators are located west of the West Elk Mountains to the west of the primary target areas. Generator elevations in this group range from 5740 to 8480 feet MSL. A second group of generators are located within the Gunnison Valley and foothill to mountainous locations. The elevations of the generators in this group range from 7570 to 9670 feet MSL. Figure 2 provides the locations of the generators used in the 2015-2016 winter program.

2. MT. CRESTED BUTTE ICE DETECTOR SITE

In support of this program, a high-mountain ice detector site was installed at an elevation of approximately 11,400 feet on the north side of the summit of Mt. Crested Butte in Colorado in the fall of 2014. Funding for the equipment acquisition and installation was provided by the Colorado Water Conservation Board and the three Lower Colorado River Basin States. NAWC contracted with Meteorological Solutions, Inc. (MSI) headquartered in Salt Lake City, Utah to assemble and install this system. The site was operated by NAWC during the 2014-15 winter season. There was an existing tower at the site (known as the
Wind Tower site, located at 38° 53′ 19″ N, 106° 56′ 42″ W) which was used in the installation. The site included a Goodrich Model 0871LH1 Freezing Rain Detector, CSI Temperature Sensor Model 107-L10, R.M. Young Alpine Wind Speed and Direction Sensor Model 05103-45, Thies Precipitation Rate Sensor Model TC041-L, and Campbell Scientific Data Logger System Model CR1000. The data were recorded via the onsite data logger with 15 minute data time resolution. Real-time data access was available via a password-protected internet link using Vista Data Vision software hosted by Meteorological Solutions Inc. Figure 3 provides a photo of the site.

A schematic of the icing sensor is shown in Figure 4. The ice detector sensing probe accumulates ice on a small vertical probe via capture of SLW droplets during stormy conditions, at temperatures colder than freezing. An internal heater deices the probe when a predetermined mass of ice is bonded to the probe, and an icing cycle is recorded. The sensor then cools, and can once again begin to accumulate ice if icing conditions are present.

Surrounding terrain and trees may play a role in how much icing is observed. There is some potential blockage to the south due to Mt. Crested Butte with a crest elevation of 12,162 feet (approximately 560 feet higher than the detector site). Perhaps of some importance is the fact that Mt. Crested Butte is a rather isolated prominent feature which is separated from the major mountain barriers to the north (Sawatch) and to the west (West Elks). This fact may impact the amount of icing that is observed in ways that may be difficult to quantify. A more typical situation involves a substantial mountain barrier, identified as the target area of a winter cloud seeding program. The conceptual model in this situation regarding the production of SLW in winter storms is that the lifting of a moist air mass over the barrier (an orographic effect) can generate SLW over the upwind slopes of the barrier (Super, 1999). Mt.
Figure 2: Ground Based Manually Operated Seeding Generator Locations, 2015-2016 Winter Season

Figure 3: Mt. Crested Butte Icing Meter Site (photo courtesy of Meteorological Solutions, Inc.).

Figure 4: Schematic of Goodrich Model 0871LH1 Freezing Rain Detector (dimensions in inches) (diagram courtesy of Campbell Scientific).
Crested Butte is less of an obstacle to wind flow than the larger surrounding mountain ranges. The question might be whether winds flow around (instead of over) Mt. Crested Butte in which case the orographic effect and possibly the production of SLW would be less. Of course some storms bring SLW with them without the need for orographic forcing to generate SLW. Another factor to consider is that the West Elk Mountains located west of Mt. Crested Butte may remove SLW from storms as they pass over these mountains leaving less moisture in the air mass as it passes over Mt. Crested Butte (i.e. perhaps less icing). This process is referred to as the “rain shadow” effect. The fact that the icing meter site is at approximately the same elevation as the barrier summit of the West Elks may lessen this effect. These are complex issues; nonetheless there was SLW observed during the 2014-2015 winter season at the icing meter site on a number of occasions. Data from the ice detector site were collected from October 8, 2014 through April 21, 2015. This allowed for continuous monitoring of icing and associated observations during the period of seeding operations from November 15, 2014 through April 15, 2015. Post-season analyses were conducted to explore possible relationships between icing and the other meteorological parameters.

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3. RESULTS

It needs to be emphasized that the results being reported are from only one winter season of data collection. Additional seasons of data will be needed to more closely resemble the actual climatology of the stratifications of the data associated with the icing events, which include: 1) temperature, 2) wind direction and speed, 3) precipitation, 4) synoptic pattern, and 5) low-level stability. Each of these stratifications is discussed in the following.

3.1 Temperature

Temperature is important in seeding activities since different types of ice nuclei are most
effective within specific temperature ranges. The maximum (warmest) nucleation activation temperature threshold for the fast-acting silver iodide formulations acting as condensation-freezing nuclei, as used in this project, is approximately \(-5\) °C with the nucleation rate increasing exponentially at colder temperatures. The temperature range within the SLW layer also affects natural and induced ice particle habits (shapes) and their growth rates. Earlier research indicated that the natural precipitation efficiency of some cloud systems can be quite high and that glaciogenic seeding (ice phase seeding like that caused by silver iodide) of those cloud systems will likely not yield appreciably more precipitation than is occurring naturally (Griffith et al. 2013). Naturally high production of ice particles in these clouds is thought to produce near-optimum ice particle concentrations in the precipitation formation regions of the clouds. It is believed that a mountain-top temperature colder than approximately \(-15\) °C is one indication that this naturally efficient situation likely exists. Another indication could be deep clouds with cold cloud top temperatures; e.g., \(\leq -25\) °C (Grant and Elliott, 1974). A statement from an analysis of a more recent research program conducted in the Snowy Mountains of southeastern Australia (Manton and Warren, 2011) provides support to the above; “An analysis of cloud top temperatures indicated that natural precipitation tended to increase as cloud top temperatures decrease, in other words deeper clouds are more efficient in producing precipitation.” However, if icing is being measured in colder situations it is believed that seeding would help nucleate ice particles and therefore increase precipitation efficiency. Therefore, icing measurements are useful in detecting the presence of liquid water.

Figure 5 shows the distribution of the Mt. Crested Butte site temperatures during each 15-minute observation period with sufficient icing to trigger the detectors’ de-icing heater. For this first season of data the majority of icing cycles were measured between \(-6\) °C and \(-8\) °C. Approximately 75% of the total measured icing during one season of data occurred within the favorable seeding criteria summit temperature window of \(-5\) °C to \(-15\) °C. Approximately 9% of the icing periods were colder than \(-15\) °C, and 16% occurred at temperatures warmer than \(-5\) °C. A significant amount of icing at temperatures colder than \(-15\) °C would suggest that seeding opportunity is being missed at colder temperatures, according to NAWC’s generalized seeding criteria, but the observed low percentage in this category suggests that in general, little seeding opportunity exists at summit temperatures colder than \(-15\) °C. Real-time monitoring of ice detector data may lead to recognition of some seedable storm periods at temperatures below \(-15\) °C. At the warm end of the temperature spectrum, a small amount of icing (roughly 16%) was observed at temperatures warmer than \(-5\) °C. Regarding the warm end of the spectrum, it should also be emphasized that at least some of the icing occurrence at these warmer temperatures is likely seedable from valley or foothill based sites, primarily during spring storm situations with relatively deep atmospheric mixing. Well-mixed atmospheric conditions often allow some of the seeding material to be quickly carried to elevations well above the crest height, where temperatures are colder.

3.2 Wind Direction and Speed

A wind scatterplot was produced for all icing cycles that were observed during the season (Figure 6). This helps to provide additional insight regarding the types of wind patterns that are likely favorable for seeding operations. This figure illustrates that most of the icing was observed in southwesterly wind situations (i.e. winds blowing towards the northeast). There are a few cases with an easterly component, but overall most icing situations have westerly component winds, this is expected as storms typically move from west to east and hence why most seeding generators are placed west of the intended target areas. It is possible that there is some blocking due to terrain, as Mt. Crested Butte sits almost due south of the ice detector site. Therefore, if any nearby terrain blockage did occur it would be from this direction (approximately 180°).
Figure 5: Temperature Distribution during Icing Periods for 2014-2015 Winter Season.

Figure 6: Winds for all Icing Periods, 2014-2015 Winter Season.
3.3 Precipitation

There was some uncertainty regarding precipitation rates measured by the optical Thies precipitation sensor at the Mt. Crested Butte site, an issue which may be better resolved after additional observations. However, overall trends in the data suggest that the greatest amount of icing was observed during lower precipitation rates or during periods without any indications of precipitation. These results are similar to findings from ice detector data in Utah, which have indicated a decrease in measured icing at higher precipitation rates (Yorty et al. 2012). Xue et al. 2013 modeling work also indicates that seeding efficiency is inversely proportional to the precipitation rate. This has been noted in case-study analyses where a negative correlation is often observed between icing and precipitation rate within a given storm period, which is believed to be due to scavenging of SLW in the vicinity of the site by precipitation falling from higher cloud layers.

3.4 Synoptic Pattern

Icing periods were also compared to the synoptic weather pattern of a passing storm with the goal of utilizing the available ice detector data to help the project meteorologist identify the storm types that present good seeding situations for future operations. However, it is important to realize that each storm situation is unique, making the ice detector data valuable both in real-time decision making and post analyses of storm events.

Synoptic-scale storm situations, such as pre- and post-frontal/upper trough air masses, differ by definition, and their “seedability” as measured by the amount of liquid water present can differ as well. When icing was observed during significant storm events, NAWC meteorologists then classified it as one of the following synoptic scale weather situations:
1) Pre-frontal (warm sector of storm event, no cold frontal passage observed yet at the site).
2) After cold front and before main trough axis; the 500-mb level was used for defining the position of the trough axis.
3) Behind the main trough axis.

4) Associated with a closed low.
5) Associated with a zonal (westerly flow) pattern, or difficult to define the synoptic situation based on available data.

Results of the analysis are shown in Figure 7. For the 2014-2015 season of data the “pre-frontal” synoptic category had the most icing periods with 46%. The least amount of icing occurred in closed low situations (2%). Note that this is for only one season of data so these percentages may not be indicative of a more climatological average of icing for each synoptic category.

Some ambiguity exists in classification of certain synoptic situations, particularly for systems that evolve from one type into another (for example, from a classic mid-latitude frontal system into a closed low). The closed low category in this analysis is reserved for systems that have a well-defined closed circulation during most of their time of impact, making it difficult to identify relevant cold front or trough passage times. Some situations (such as zonal or weak ridging conditions) during which icing cycles are measured are not easily classified, and the associated icing is categorized as having an “undefined” synoptic situation.

These analysis results are particularly valuable in highlighting when seeding opportunities occur during storm sequences, helping to sharpen operational procedures and demonstrating the value of the real-time and post hoc data from ice detector measurements.

3.5 Low-Level Stability

Effective ground-based seeding also depends on the ability for silver iodide nuclei released at ground level to reach appropriate regions of the “seedable” clouds in a timely manner. In addition, sufficient time is required after nucleation for ice particle growth within the cloud and fallout within the seeding target area. A well-mixed atmosphere at lower elevations, which is related to the vertical temperature profile, is a crucial factor for the transport of silver iodide nuclei. Wind speed, direction, and the location of the target
area also impact our ability to target the effects of seeding in the intended target areas. Another key aspect is the ability of the project meteorologist to identify situations in real-time when all these factors are favorable for cloud seeding in a given target area.

The nature of thermodynamic stability is such that, in cases where a high-resolution thermodynamic profile (such as a nearby weather balloon sounding) is not available, data from surface observations at differing elevations can be used to obtain an estimate of the integrated stability in the intervening layer. The nearest National Weather Service radiosonde station is in Grand Junction, Colorado but this location is not representative of the Upper Gunnison River Valley so there are no direct observations of lower level inversions in this area. NAWC has used a method developed in-house (referred to as the 2SS method) to estimate stability in various locations, by utilizing temperature and dew point observations from two (or more) surface observation sites (Yorty et al. 2012). This type of thermodynamic stability analysis can provide an approximation of the amount of thermodynamic resistance (if any) that a valley or foothill based air parcel would need to overcome to reach a nearby mountain crest elevation.

NAWC utilized data from surface sites to estimate low-level thermodynamic stability during periods with recorded icing at Mt. Crested Butte using the 2SS method. Temperature and dew point information at a site southwest of Paonia, Colorado called Jay (elevation 6,270’), a site east of Montrose, Colorado (elevation 8,060’), and a site in Gunnison, Colorado (elevation 7,680’), were compared to site temperatures at Mt. Crested Butte (elevation 11,400’) during icing periods for the 2014-2015 season of data. Another valley site in the town of Crested Butte, Colorado (elevation 8,860’) was used in the analysis, however, only temperature (not dew point temperature) data were available at this location. Temperature measurement sites used in this analysis are indicated in Figure 8.

When dew point temperatures were needed for analysis using the Crested Butte site, those from Gunnison, the closest site with dew point temper-
Figure 8: Map of Seeding Target Area, Icing Site Detector Location (yellow square) and Stability Analysis Surface Site Locations (red dots).

Temperatures, were used. Utilizing a standard skew-T plot allowed the dry and moist adiabatic lapse rates to be compared to the difference in temperature between a corresponding valley or foothill site and the Mt. Crested Butte icing site, with the dew point from the valley site used to determine the appropriate lapse rate for comparison. This allows an estimate to be made of whether or not the atmosphere is freely mixing from the surface to the elevation of the downwind mountain barrier summit, and in cases where there is stability, an estimate of the overall degree of stability in this layer. This thermodynamic stability is expressed here in terms of the equivalent temperature increase at a valley location, or decrease at the crest height, that would be needed to overcome the stability and allow free vertical mixing in the layer.

Thermodynamic stability was divided into four categories:

N Neutral or well-mixed (no apparent stability in the layer)
SS Slightly stable (<2 °C of stability)
MS Moderately stable (2 to 4 °C of stability)
VS Very stable (>4 °C of stability)
A well-mixed situation implies that there is no thermodynamic restriction of upward vertical atmospheric motion that would impede the lifting of seeding material from a lower elevation seeding site over the mountain crest. A slightly stable (SS in the above classification) situation would likely also be seeded, as there is a good chance that forcing due to existing wind fields may be enough to overcome such a minor amount of stability, or that local temperature variations of a few degrees may result in situations with good vertical mixing. Seeding from valley sites would generally be avoided in moderately or very stable situations (MS and VS), although seeding material initially trapped by a thermodynamically stable atmosphere may sometimes become effective later if the stability situation improves. Seeding from foothill or higher elevation sites may be utilized in these more stable situations when possible with the proviso that SLW is present in such situations.

For icing periods during the November – April period when the temperature at the Mt. Crested Butte site was between -5 and -15 °C, a four valley site average of about 63% of the icing periods were associated with atmospheric conditions that were unrestricted by stability (neutral or slightly stable conditions). The percentages of the four stability categories for each of the four valley/foothill sites are shown in Figure 9. The specifics for the data in Figure 9 are provided in Table 1.

The Gunnison site is located in a valley between mountains and is likely an area where cold air gets trapped in the lowest elevations of the Gunnison River Valley prior to the passage of winter storms through the area. Most of NAWC’s seeding generators are located at higher elevations or outside of the Gunnison valley for this reason. Therefore, the Montrose and particularly the Crested Butte Town sites are likely more representative of areas where stability may limit seeding. Results from these sites suggest that ground seeding will likely be unrestricted by stability approximately 70% of the time.

The thermodynamic stability analysis was also subdivided by month. An important indication in this analysis is that very little thermodynamic stability occurs during the spring months after about the first week of March, so late season seeding would likely be unrestricted by stability approximately 70% of the time.

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Table 1: Stability Categories Based on Four Valley or Foothill Sites

<table>
<thead>
<tr>
<th></th>
<th>Gunnison</th>
<th>Montrose</th>
<th>Jay</th>
<th>CB Town</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>13</td>
<td>19</td>
<td>18</td>
<td>20</td>
<td>70</td>
</tr>
<tr>
<td>SS</td>
<td>24</td>
<td>28</td>
<td>24</td>
<td>29</td>
<td>105</td>
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<tr>
<td>MS</td>
<td>15</td>
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<td>70</td>
<td>66</td>
<td>70</td>
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<td>276</td>
</tr>
<tr>
<td>Seedable (N and SS)</td>
<td>52.9%</td>
<td>71.2%</td>
<td>60.0%</td>
<td>70.0%</td>
<td>63.4%</td>
</tr>
</tbody>
</table>

should generally be free of seeding limitations due to stability. For the one season examined, only slight stability was observed in the month of November. The more stable occurrences were during the mid-winter months of December, January and February. The seasonal distribution of stability between the Crested Butte town site and the Mt. Crested Butte ice detector site is shown in Figure 10.

4. HYSPLIT MODELING

In recent years, NAWC has been using an atmospheric diffusion model known as HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) to calculate the dispersion of silver iodide plumes in real-time. The HYSPLIT model is the newest version of a complete system for computing simple air parcel trajectories in complex dispersion and deposition simulations. One version of this model computes the advection of a single pollutant particle, or simply its trajectory.

Eighteen HYSPLIT model runs, as well as plots indicating the amount of stability (using the method discussed in section 3.5) during each seeded storm event, were compiled for the 2014-2015 winter season. HYSPLIT model run times were chosen based on when good precipitation seemed to be occurring within the target region. Dispersion from all generator sites was modeled although normally only a sub-set of the available generators were activated during any particular storm event.

Figure 11 provides an example of one of these HYSPLIT runs. Figure 12 provides a plot of the four different 2SS values for the February 20th storm period associated with the HYSPLIT plot from this storm. Figure 12 demonstrates that the 2SS values can vary during storms both in time and space. In space there can be differences between the four different temperature observation locations. For example, near the beginning of the storm the 2SS values from Gunnison are much more stable than those from the other three locations. Table 2 was prepared summarizing the results from the eighteen HYSPLIT runs. In Table 2 some remarks refer to generator locations; the term “west” is used for the generators located west of the West Elk Mountains (north of Montrose in Figure 2). The term “east” refers to the locations of the remainder of the generators located throughout the Gunnison Valley, foothill and mountainous areas.

These predicted plumes for the seeded cases indicated successful transport of seeding material over the intended target areas in a large majority of the cases, seeming to confirm the hypothesis that low level-stability indications of ~ 2 °C or less (rated slightly stable) are normally treatable using NAWC’s existing generator network. Figure 12 suggests that frequent HYSPLIT runs, perhaps every three hours during storm periods, might be necessary to more completely assess the apparent success of seeding plume trajectories passing over the intended target areas.
Figure 10: Seasonal Distributions of Atmospheric Stability Categories from Crested Butte Town Site during Icing Periods. Corresponding Stability Categories are labeled on the Right. Icing Periods that fall on or below the 0 line are the Neutral or Well-mixed Cases, with Increasing Stability Indicated with Height above the Zero Line, any Cases with 10 °C or More Stability are plotted on the Top Line.

Figure 11: HYSPLIT Plume Dispersion Simulations, 1400-1500 MST February 20, 2015.
Figure 12: Degrees of Stability for February 20, 2015 Case

Table 2: Summary of Results from HYSPLIT Runs, Average Stability 2SS Values from the Four Observation Sites. Times in MST except MDT for last two cases.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Ave. 2SS</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/15/14</td>
<td>2200-2300</td>
<td>-1.0</td>
<td>Good transport, all sites</td>
</tr>
<tr>
<td>11/16/14</td>
<td>0100-0200</td>
<td>0.0</td>
<td>Good transport, all sites</td>
</tr>
<tr>
<td>11/23/14</td>
<td>0000-0100</td>
<td>+1.2</td>
<td>Good transport, all sites</td>
</tr>
<tr>
<td>12/13/14</td>
<td>2200-2300</td>
<td>+0.2</td>
<td>Good transport, all sites</td>
</tr>
<tr>
<td>12/22/14</td>
<td>1300-1400</td>
<td>-2.3</td>
<td>Good transport, all sites</td>
</tr>
<tr>
<td>12/25/14</td>
<td>2100-2200</td>
<td>+3.5</td>
<td>Weak storm, good transport higher sites, fair lower sites</td>
</tr>
<tr>
<td>1/12/15</td>
<td>2300-0000</td>
<td>+2.4</td>
<td>Good transport higher sites, fair lower sites</td>
</tr>
<tr>
<td>2/4/15</td>
<td>0900-1000</td>
<td>+3.0</td>
<td>Good transport east sites, fair west sites</td>
</tr>
<tr>
<td>2/10/15</td>
<td>2000-2100</td>
<td>+2.8</td>
<td>Good transport east sites, fair west sites</td>
</tr>
<tr>
<td>2/16/15</td>
<td>1300-1400</td>
<td>-1.5</td>
<td>Good transport</td>
</tr>
<tr>
<td>2/20/15</td>
<td>1400-1500</td>
<td>-2.0</td>
<td>Good transport</td>
</tr>
<tr>
<td>2/21/15</td>
<td>1600-1700</td>
<td>-1.5</td>
<td>Good transport east sites, fair west sites</td>
</tr>
<tr>
<td>2/22/15</td>
<td>1800-1900</td>
<td>+3.4</td>
<td>Atypical easterly flow, good transport all sites</td>
</tr>
<tr>
<td>3/1/15</td>
<td>0200-0300</td>
<td>+2.0</td>
<td>Good transport</td>
</tr>
<tr>
<td>3/2/15</td>
<td>1800-1900</td>
<td>+1.0</td>
<td>Good Transport</td>
</tr>
<tr>
<td>3/3/15</td>
<td>1800-1900</td>
<td>-0.5</td>
<td>Good transport</td>
</tr>
<tr>
<td>3/20/15</td>
<td>0200-0300</td>
<td>0.7</td>
<td>Good transport</td>
</tr>
<tr>
<td>3/25/15</td>
<td>0600-0700</td>
<td>-0.5</td>
<td>Good transport</td>
</tr>
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</table>
5. CONCLUSIONS

It needs to be emphasized that the following conclusions and key findings are based upon only one winter season of data. Additional seasons of data would lead to more climatically representative conditions associated with icing at the Mt. Crested Butte site.

Although some meteorological patterns show good correlation to the occurrence of “seedable” conditions providing reasonable prediction capability, it has become clear that real-time monitoring of the ice detector data is of significant value in seeding opportunity recognition. Further, post-hoc analyses of the data can yield considerable insights into winter storm “seedability” for this location.

A large proportion of barrier summit height icing activity was observed in the -5 to -15 °C temperature range (the range generally used as a primary seeding criterion). In general, it appears that about 75% of icing activity occurs within this range, with most of the remainder observed at warmer temperatures (~16%). A smaller portion (~9%) was observed at temperatures colder than -15 °C. Therefore, the -5 to -15 °C criteria seems reasonable, however, it is helpful to have ice detectors to determine cases which might be “seedable” at colder temperatures if liquid water is known to be present.

Of five synoptic categorizations (pre-frontal, post-frontal/pre-500-mb trough, post-trough, closed low, and undefined), the pre-frontal situation was associated with the greatest amount of icing at the Mt. Crested Butte site during one season of data with 46% of icing events. This pattern seems to differ from analysis of icing data at two Utah locations that indicate the most significant icing occurs in post 500-mb trough conditions (Griffith, et al. 2013). However, the Mt. Crested Butte ice detector has only been taking measurements for one season of data and may not represent a climatological average.

The ice detector data paired with surface data indicated that in ~63-70% of icing periods, atmospheric stability would not significantly inhibit orographic lofting of lower elevation ground generator seeding plumes into the SLW zones in winter clouds associated with storms passing over the target area. There were indications that sites located in the lowest elevations of the Gunnison River Valley would experience more impacts from stability than sites located at higher valley and foothill locations.

HYPLIT computer model runs, as well as plots indicating the amount of stability during each seeded storm event, were compiled for the 2014-2015 winter season. These predicted plumes for the seeded cases indicated successful transport of seeding material over the intended target area in a large majority of the cases seeming to confirm the hypothesis that the 2SS method low-level stability indications with approximately 2 °C or less of stability (rated slightly stable) are treatable from NAWC’s existing generator network.

Since the ice detector is a fixed-point measurement, there may at times be significant SLW in the vicinity (for example, at a higher elevation) that the icing sensor does not detect. Thus, these measurements are believed to be underestimates of the total SLW occurrence in this area. A means is available to measure the total SLW column in the atmosphere above a given point using a portable microwave radiometer.

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REFERENCES


