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OBSERVATIONS OF RIME ICING IN THE WASATCH MOUNTAINS OF UTAH: IMPLICATIONS REGARDING WINTER SEASON CLOUD SEEDING

Mark E. Solak *, David P. Yorty and Don A. Griffith
North American Weather Consultants
Sandy, Utah, USA

1. INTRODUCTION

It has long been recognized that the presence of excess supercooled liquid water (SLW) is the pivotal (although not sole) ingredient for glaciogenic cloud seeding for the purpose of precipitation augmentation. However, in the absence of SLW, the otherwise important additional factors are simply airmass characteristics. Thus, it is helpful to understand the frequency of occurrence of SLW and the range of meteorological conditions which characterize its occurrence. North American Weather Consultants (NAWC), thanks to the cooperation of a local ski area, established a mountain-top SLW measurement site southeast of Salt Lake City, Utah, in the Wasatch mountain range. The site was operated from late November 2003 through early April 2004, providing a continuous record for the period of about four months. A typical winter season during which SLW could be expected to occur would span five-six months, so the observational period is thought to underestimate the usual total winter season SLW occurrence in the region, probably by about 20-25%.

2. THE SITE AND SENSOR SUITE

The SLW measurement site was established atop a 3,354 m msl peak in the Wasatch Mountains, located 35 km southeast of downtown Salt Lake City. It is located 11 km up (east) from the mouth of Little Cottonwood Canyon, a deep-cut canyon oriented west to east from its mouth at 1,550 m elevation to the summit of the Wasatch range. The mountain ridge summit is located about 2 km east of the SLW site. Thus, SLW observed at this measurement site can be considered largely excess not depleted by the precipitation process on the west (upwind) slopes of the mountain range. An area map is provided in Figure 1. The terrain in the vicinity receives nearly 13 meters of snowfall during an average winter season. The measurement location is very convenient to NAWC's offices in Sandy and is accessible by tram.

The SLW measurement sensor was a Rosemount model 872B icing rate detector. A photo of the sensor is shown in Figure 2. The vibrating sensing element protruding from the domed strut accumulates rime during icing conditions. Ice buildup on the sensing element changes its vibration frequency, which is measured by the detector's electronics. At a preset mass of ice bonded to the element, the electronics send an icing signal to the data system. The icing signal also triggers an internal heater which clears the sensing element of ice. After a short cool-down period, the sensor is again able to accumulate ice.

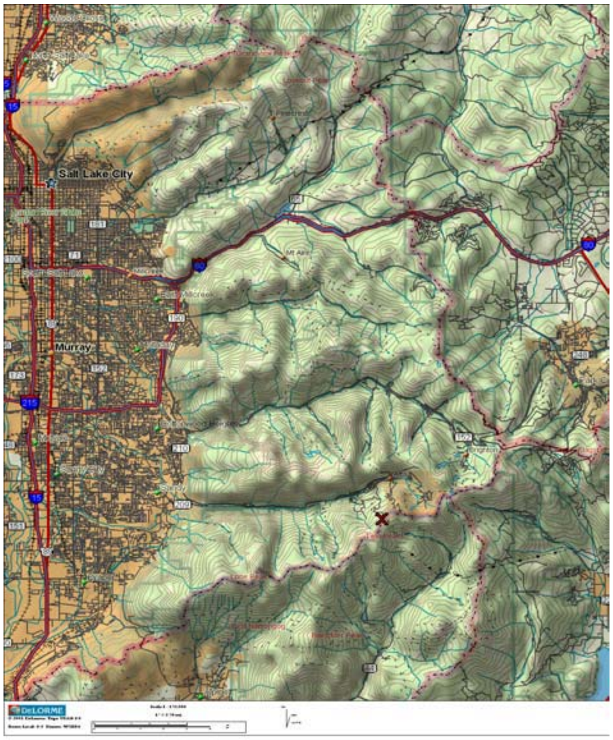

Figure 1. Project area, with SLW site shown by an X.

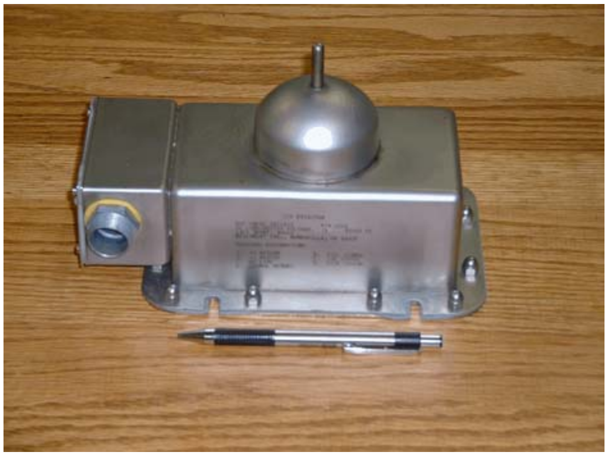

Figure 2. Rosemount ice detector, model 872B.

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* *Corresponding author address:* Mark E. Solak, North American Weather Consultants, 8160 S. Highland Dr., Ste. A-2, Sandy, UT 84093; email: nawc@nawcinc.com.

In addition to the icing rate detector installed by NAWC, a temperature sensor and cup/vane wind system operated by the ski area are located atop the peak. A heated tipping bucket precipitation gage, also operated by the ski area, is located at approximately 2,750 m elevation about 1 km northwest of the peak. Data from all systems are recorded at 15-minute intervals via computerized datalogger systems. The ski area kindly granted NAWC access to their systems' data in further support of our SLW measurements.

In all the following discussions, we should remain mindful that the SLW observations are at a fixed point, and that the sensor is not always within the SLW layer/region. The SLW layer could occur above or below the sensor elevation. We also recognize that a single season of measurements does not necessarily constitute a comprehensive or representative climatology.

3. SLW OCCURRENCE AND DISTRIBUTION

During the four-month measurement period, 619 individual sensor deice cycles were recorded during the occurrence of thirty to forty storm events, depending on how a storm is defined. The full measurement season SLW (rime mass) occurrence (November 24, 2003 through April 2, 2004) by month was as follows: November - 5%, December - 21%, January - 17%, February - 39%, March - 13% and April - 5%.

4. METEOROLOGICAL CHARACTERISTICS DURING RIMING

A few basic characterizations of the seasonal riming environment were made, specifically temperatures and winds during SLW occurrences.

Temperature characteristics are obviously important in cloud seeding, given a) the temperature dependence of silver iodide nucleating properties and b) cloud physics considerations. Site temperatures (at 3,354 m msl) during riming events ranged from 0C to -22C. The distribution of temperature for all deice cycle appears in Figure 3, while Figure 4 pertains to 16 riming episodes which, when ranked according to their rime ice production at the detector site, collectively produced 50% of the total observational period riming.

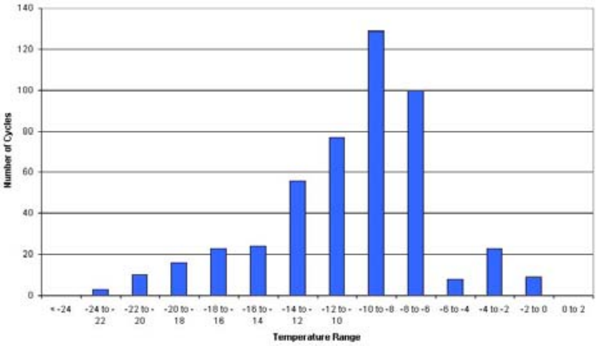

Figure 3. Distribution of temperature for all deice cycles.

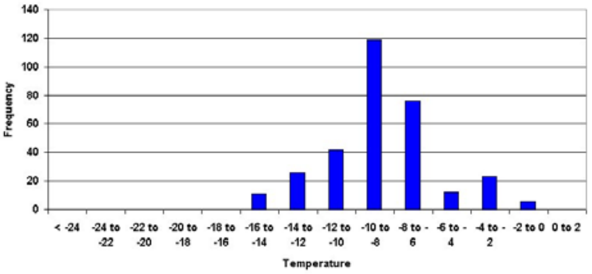

Figure 4. Distribution of temperature for heaviest riming episodes.

In each plot, the most common temperature range is -7C to -10C (-5C to -8C at 700 mb), which is at or colder than the -5C nucleating activity temperature threshold for silver iodide particles. Many of the ridges and peaks in northern Utah rise to near or above that level, with numerous peaks of 10,000 to 12,000+ feet in elevation. NAWC's temperature criteria for seeding in this region include, among other important factors, a 700 mb temperature of -5C or colder. In Figure 3 (showing all riming events), 86% of the sensor deice cycles occurred when the 700 mb temperature was -5C or colder. In Figure 4 (the top 16 riming episodes as described earlier), 81% of the sensor deice cycles occurred when the 700 mb temperature was -5C or colder.

Recognizing that a temperature range (window) for cloud seeding effectiveness exists, including a limit at its colder end, a final consideration is elimination of riming events which occurred when 700 mb temperatures were -15C or colder. This criterion reflects the fact that, at some point, natural ice crystal production yields sufficiently high precipitation efficiency that cloud seeding will not appreciably improve that efficiency. In Figure 3, this eliminates an additional 5% of the riming cycles. Thus, the percentage of riming cycles occurring within what is considered to be the desirable temperature window (-5C to -14C at 700 mb) is 81%. Since none of the deice cycles in Figure 4 occurred at temperatures colder than the desirable temperature limits, the percentage occurring within that desirable range is also 81%. Some relatively new seeding formulations reportedly produce nucleation at temperatures as warm as -4C and show somewhat less temperature dependence of nucleating ability (DeMott, 1999), and faster acting formulations have been reported (Feng and Finnegan, 1989; Finnegan, 1999), so the favorable temperature window could be potentially be enlarged somewhat in some circumstances. On the other hand, others may argue that the temperature limit at the cold end of the so-called seeding window may be somewhat warmer, e.g., as noted in Sassen and Zhao (1993), clouds with tops colder than -12C appeared (in lidar, radiometer and other observations) to efficiently convert SLW to ice particles.

The colder temperature distribution, preferred wind sector during riming periods, and the greater proportion of the SLW periods within the temperature range considered favorable for cloud seeding reported here differ from those noted in Super (1999), in which findings from central and southern Utah by others, e.g., Huggins (1995) and Sassen and Zhao (1993), were summarized. The colder temperatures in this current article may well be due to differing winter storm climatology, differences in regional/local topography and possibly some influence of the Great Salt Lake (GSL).

Decades of winter weather monitoring across Utah indicate that, fairly frequently, cold fronts associated with cyclones moving through the Pacific Northwest and eastward lose their vigor 50-100 km south of the Great Salt Lake.

Super (1999) notes that during two winter seasons in central Utah in the early 1990's, SLW existed in pre-frontal southwest flow and typically disappeared after frontal passage, as soon as the Plateau top winds shifted to northwestly. That finding may be due also, in part, to the fact that the central Utah observation site (about 100km south of Little Cottonwood Canyon) discussed in Super (1999) which is on the Wasatch Plateau east of the town of Fairview, is a second barrier site in northwest flow. The northwest flow SLW in that region may well have been depleted in large part by/over the first barrier located southwest of Utah Lake and about 25 km northwest of the central Utah observation site.

The comparatively long fetch across the GSL allows strong first-barrier orographic lift up the western slopes of the steep Wasatch Range.

A frequency plot of site wind direction during riming periods is found in Figure 5. It shows a bimodality fairly consistent with our understandings from earlier observations in the region. However it does reflect site-specific terrain influences, in particular in channeling of orographic flow up the west-east oriented Little Cottonwood Canyon. In the broader sense, the maximum frequency of riming in westerly flow makes sense, since it also represents essentially barrier-normal flow. Less pronounced channeling of orographic flow is induced in the sector bracketing south flow. A planned analysis of free-air winds using representative NWS soundings from nearby Salt Lake City will produce a better summary of wind characteristics over the broader region of northern Utah.

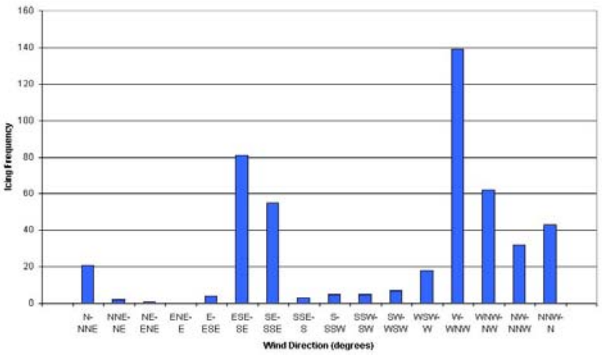

Figure 5. Site wind directions during riming periods.

5. QUARTILE ANALYSIS OF RIMING PERIODS

During the measurement period, 619 individual sensor deice cycles were recorded during a total of 124 riming periods. For this operations-oriented analysis, riming periods are not storms. Rather, they are defined as blocks of time with less than three hours between sensor deice cycles. Three hours is considered to be a reasonable lower limit for operational cloud seeding opportunity recognition and timely conduct of seeding. Of the 619 total deice cycles, 570 occurred during riming 75 qualifying periods, i.e., those with more than one deice cycle.

The 75 multiple deice cycle periods comprising the 570 cycles were ranked by number of cycles per qualifying riming period. Quartiles defined by riming mass (number of deice cycles) were then determined and descriptive statistics were developed for each quartile. This first-cut quartile analysis provides generalized information regarding the bulk occurrence of SLW without consideration of the cloud seeding temperature window. It simply documents the overall SLW occurrence within multiple-cycle riming periods. Summarized key statistics appear as the upper entries in each cell of Table 1. All temperatures listed in Table 1 are site temperatures (3,354 m msl).

A second iteration in this analysis was to consider only the riming periods characterized by 700 mb temperatures within the favorable temperature window, i.e., those at 700 mb temperatures from -5C to -14C. Stability considerations and cloud or cloud system types are not accounted for in this iteration. The lower entry in each cell of Table 1 presents the same descriptive statistics, but only for the riming periods that occurred within the favorable temperature window. All temperatures listed in Table 1 are site temperatures (3,354 m msl).

From Table 1, a few key points.

- The (short) season riming occurrence spanned nearly 500 hours and more than 400 hours within the favorable temperature range,
- The proportion of the total SLW accumulation during operationally feasible riming periods occurring within the favorable temperature range is about 82%
- The favorable temperature range first quartile comprises 19% of total duration, whereas the fourth quartile is 33% of total duration.
- The first quartile riming periods (n=4) are longer in average duration and characterized by greater riming rates than others. It is clear that operational recognition of first quartile events is important. Their average duration of nearly 19 hours certainly qualifies them as operationally feasible.
- Average values of duration and riming rate decrease from the first through the fourth quartiles.
- Average wind velocities are quite consistent among the quartiles.

TABLE 1. Summary Statistics of Riming Periods by Quartiles

	No. of Periods	Avg Site Temp (C)	Avg Wind Speed (m/s)	Total Duration (hrs)	Avg Duration	No. Cycles	Avg Icing Cycles	Avg Icing Cycles per Hour
1st quartile	4	-5.50	7.60	67.80	16.94	144	36.00	2.13
	4	-8.75	7.46	75.80	18.94	123	30.75	1.93
2nd quartile	9	-9.11	8.50	136.00	15.11	147	16.33	1.17
	8	-9.13	8.75	92.50	11.56	113	14.13	1.35
3rd quartile	17	-10.47	7.78	120.70	7.10	136	7.89	1.17
	15	-10.57	7.59	106.10	7.07	114	7.60	1.20
4th quartile	45	-12.32	8.60	167.00	3.71	143	3.11	0.92
	36	-10.31	8.44	133.9	3.72	117	3.25	0.97
Total	75			491.5		570		
	63			408.3		467		

6. RELATIVE PRECIPITATION EFFICIENCY

Using precipitation measurements at a nearby site (1 km northwest), the apparent relative precipitation efficiency of storms and periods of storms was assessed by comparing riming rates with precipitation rates during storm periods. The storm selection was limited to events with at least some riming sometime during the storm period. Distinct periods of apparent efficiency and inefficiency are found in the site records. In many cases, rather orderly transitions in apparent precipitation efficiency have been documented, rather than short interval vacillations. A few examples of the evolving relationship between riming and precipitation are shown in Figures 6-9.

Riming rates decreased as precipitation rates increased in some examples, indicating a more efficient precipitation process. In a few instances, precipitation was measured for extended periods, but with no deice-cycle magnitude riming. Figure 6 is a good example, showing a storm period of December 25-26, 2003. Analysis of local rawinsonde data indicate that the SLW site would have been in-cloud for the full period. Moist southerly flow produced sustained precipitation, but no deice cycles occurred through 1200 MST on the 25th, reflecting an apparently very efficient precipitation process. Riming occurred for a period of about four hours as the mid-levels moistened ahead of a broad area of deeper and colder-topped clouds, a period of low efficiency which transitioned into an extended period of apparent high efficiency. 700 mb temperatures ranged from -3 to -6C for the period until a cold front passed near noon on the 26th. Even with steady cooling of the airmass and lowering of cloud tops during the afternoon-evening hours of the 26th, no riming was indicated while precipitation continued and finally ended at about midnight. The storm period shown in the figure produced 61-62 mm of precipitation. This case is a premier example of apparently highly limited seeding opportunity in a major winter storm.

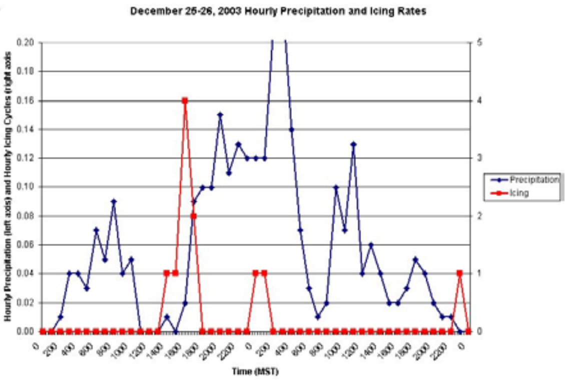

Figure 6. Hourly precipitation and riming rates, December 25-26, 2003.

Many periods of sustained apparent inefficient precipitation production, i.e., periods with substantial riming and little or no precipitation, were noted. Examples can be seen in Figures 7, 8 and 9.

The January 27-28, 2004 example (Figure 7) resulted from orographic lift of a moist lower level airmass, with 700 mb temperatures ranging from -7C to -8C (-9 to -10C at the sensor elevation) throughout the riming period and winds from the northwest. For the period shown in the figure, precipitation was 3-4 mm.

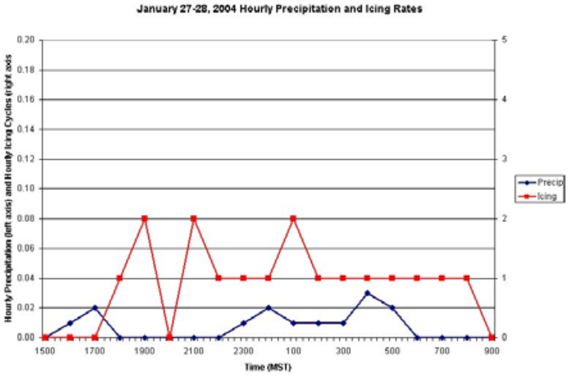

Figure 7. Hourly precipitation and riming rates, January 27-28, 2004.

The February 19, 2004 case (Figure 8) was associated with a deep trough moving through the west, with 700 mb temperatures of -6 to -10C (-7.5 to 12C at the sensor elevation) during the riming period and winds from the northwest. For the period shown in the figure, precipitation was about 6 mm.

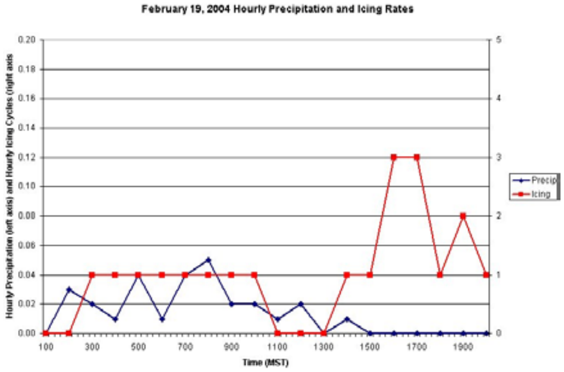

Figure 8. Hourly precipitation and riming rates, February 19, 2004.

The February 22-23, 2004 example (Figure 9) began with a period of about twelve hours with little precipitation, but with sustained significant riming. The 700 mb temperatures were -5 to -8C (-7 to -9.5C at the sensor elevation) during the riming period and winds were from the northwest. After a break in the riming of about three hours as temperatures warmed somewhat, another extended period of riming occurred, again with light precipitation. During this latter period, 700 mb temperatures ranged from -5 to -6C (-7 to -8C at the sensor elevation). The overall period produced about 15-16 mm of precipitation.

As can be seen in the figures, in most cases, orderly transitions between periods of apparent efficiency and apparent inefficiency are frequently observed in the records, and the periods are of sufficient duration for operational seeding adjustments if/when the necessary data are available real-time. In all these considerations, we must be mindful that the SLW observations are at a discrete point, not always within the SLW layer/region, so the riming data will tend to underestimate the overall SLW occurrence.

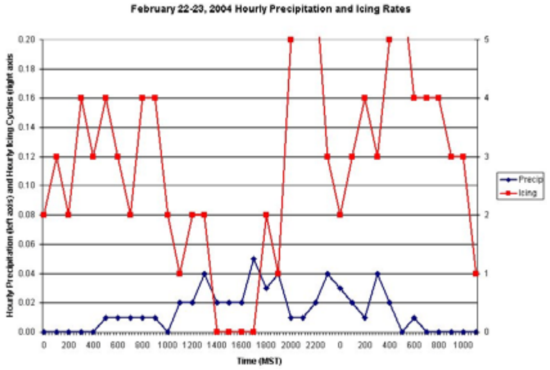

Figure 9. Hourly precipitation and riming rates, February 22-23, 2004.

7. SUMMARY

Mountain-top measurements of rime ice accumulations during the winter season of 2003-2004 in the Wasatch Range southeast of Salt Lake City, Utah, were analyzed to estimate and characterize the seasonal occurrence of supercooled liquid water during more than thirty storms, specifically toward initial assessment of winter cloud seeding opportunities for precipitation augmentation in the region. The data indicated substantial periods of supercooled liquid water occurrence and colder than anticipated temperatures overall during riming periods, given indications during similar (SLW) measurements made at a site in central Utah, about 100 km south (Super, 1999), where "Plateau top (2750 m) temperatures were colder than -4C during less than 25 percent of the (observation) hours." In many cases, rather orderly transitions in apparent precipitation efficiency have been documented and many periods of sustained inefficient precipitation production were noted. These and other findings suggest substantial cloud seeding opportunity for snowpack augmentation and provide insights regarding seeding opportunity recognition

8. CONCLUSIONS

- Ice detector measurements at mountain ridge locations can provide useful information for assessment of seeding opportunity.
- In this northern Utah example, the frequency and duration of SLW occurrence and the temperature range during riming periods indicate substantial potential for glaciogenic seeding.
- Periods of apparent precipitation inefficiency occur regularly and are of sufficient duration for real-time identification, assuming proper instrumentation and data access.

9. PLANS

The SLW data from the 2003-2004 winter deserve additional analysis. As time and budgets allow, we hope to look at the cloud seeding implications in more depth. Beyond the availability of SLW, a) vertical and horizontal transport and dispersion questions and b) time and distance for nucleated particle growth and fallout should be investigated.

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