ANALYSIS OF MOUNTAIN RIDGE ICE DETECTOR MEASUREMENTS IN UTAH DURING FIVE WINTER SEASONS

Prepared for

The Six Agency Committee – California
Central Arizona Water Conservation District
Southern Nevada Water Authority
Utah Division of Water Resources

by

David P. Yorty
Shauna M. Ward
Mark E. Solak
Don A. Griffith, CCM

North American Weather Consultants, Inc.
8180 S. Highland Dr., Suite B-2
Sandy, Utah 84093

Report No. WM 14-12

September 2014
ANALYSIS OF
MOUNTAIN RIDGE ICE DETECTOR MEASUREMENTS IN UTAH
DURING FIVE WINTER SEASONS

Prepared for
The Six Agency Committee – California
Central Arizona Water Conservation District
Southern Nevada Water Authority
Utah Division of Water Resources

by
David P. Yorty
Shauna M. Ward
Mark E. Solak
Don A. Griffith, CCM

North American Weather Consultants, Inc.
8180 S. Highland Dr., Suite B-2
Sandy, Utah 84093

Report No. WM 14-12

September 2014
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glossary of Terms</td>
<td>iv</td>
</tr>
<tr>
<td>Executive Summary</td>
<td></td>
</tr>
<tr>
<td>1.0 Introduction and Background</td>
<td>1</td>
</tr>
<tr>
<td>2.0 Sensor Suites</td>
<td>5</td>
</tr>
<tr>
<td>2.1 Brian Head</td>
<td>6</td>
</tr>
<tr>
<td>2.2 Skyline</td>
<td>7</td>
</tr>
<tr>
<td>2.3 Dry Ridge</td>
<td>9</td>
</tr>
<tr>
<td>3.0 Analysis Results for Periods of Observed Riming</td>
<td>10</td>
</tr>
<tr>
<td>3.1 Icing Relative to Synoptic-Scale Weather Situation and Storm Precipitation Periods</td>
<td>11</td>
</tr>
<tr>
<td>3.1.1 Icing Relative to Synoptic-Scale Storm Situation</td>
<td>11</td>
</tr>
<tr>
<td>3.1.2 Icing Relative to Storm Precipitation Periods</td>
<td>15</td>
</tr>
<tr>
<td>3.1.3 Additional Analysis of Icing Occurrence According to Synoptic and Precipitation Categorizations</td>
<td>19</td>
</tr>
<tr>
<td>3.2 Icing vs. Precipitation Rate</td>
<td>26</td>
</tr>
<tr>
<td>3.3 Storm Temperature Structure During Icing Periods</td>
<td>28</td>
</tr>
<tr>
<td>3.4 Atmospheric Stability During Icing Periods</td>
<td>33</td>
</tr>
<tr>
<td>3.4.1 Results of the Two-Site Stability Analyses in the Skyline Area</td>
<td>36</td>
</tr>
<tr>
<td>3.4.2 Two-Site Stability Analysis in the Brian Head Area</td>
<td>39</td>
</tr>
<tr>
<td>3.4.3 Stability Analysis in the Uinta Basin</td>
<td>40</td>
</tr>
<tr>
<td>3.4.3.1 Methodology of the Uinta Basin Stability Analysis, 2009-12</td>
<td>41</td>
</tr>
<tr>
<td>3.4.3.2 Results of the Uinta Basin Stability Analysis, 2009-12</td>
<td>42</td>
</tr>
<tr>
<td>3.4.3.3 HYSPLIT Modeling in the Uintas Region</td>
<td>46</td>
</tr>
<tr>
<td>3.4.3.4 Uinta Basin Stability Analysis Based on Dry Ridge Icing Data</td>
<td>47</td>
</tr>
<tr>
<td>3.4.4 Summary of Low-Level Stability Indications in Utah</td>
<td>48</td>
</tr>
<tr>
<td>3.5 Icing and Wind</td>
<td>48</td>
</tr>
<tr>
<td>3.6 Seasonal and Diurnal Distribution of Icing</td>
<td>55</td>
</tr>
<tr>
<td>3.7 Cloud-Top Temperature Associated with Icing</td>
<td>60</td>
</tr>
<tr>
<td>4.0 Case Studies</td>
<td>64</td>
</tr>
<tr>
<td>4.1 High Uintas/ Dry Ridge Ice Detector</td>
<td>64</td>
</tr>
<tr>
<td>4.2 Brian Head Ice Detector</td>
<td>72</td>
</tr>
<tr>
<td>4.3 Skyline Ice Detector</td>
<td>83</td>
</tr>
<tr>
<td>5.0 Conclusions and Recommendations</td>
<td>89</td>
</tr>
<tr>
<td>5.1 Conclusions/Key Finding</td>
<td>89</td>
</tr>
<tr>
<td>5.2 Recommendations</td>
<td>91</td>
</tr>
<tr>
<td>5.3 Acknowledgements</td>
<td>91</td>
</tr>
</tbody>
</table>
# Table of Contents

## Section

| References | |

## Figure

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ice detector sites</td>
</tr>
<tr>
<td>2</td>
<td>Locations of ice detector and ETI precipitation gage in the Skyline area</td>
</tr>
<tr>
<td>3</td>
<td>Schematic of Goodrich model 0871LH1 freezing rain detector</td>
</tr>
<tr>
<td>4</td>
<td>Sensor suite at Brian Head</td>
</tr>
<tr>
<td>5</td>
<td>Sensor suite at Skyline UDOT</td>
</tr>
<tr>
<td>6a</td>
<td>Dry Ridge site photo</td>
</tr>
<tr>
<td>6b</td>
<td>Dry Ridge site sensors and equipment</td>
</tr>
<tr>
<td>7a</td>
<td>Synoptic pattern classification during icing periods at Brian Head</td>
</tr>
<tr>
<td>7b</td>
<td>Synoptic pattern classification during icing periods at Skyline</td>
</tr>
<tr>
<td>7c</td>
<td>Synoptic pattern classification during icing periods at Dry Ridge</td>
</tr>
<tr>
<td>8a</td>
<td>Brian Head icing distribution with respect to precipitation periods of 0.01” or more during storm events</td>
</tr>
<tr>
<td>8b</td>
<td>Skyline icing distribution with respect to precipitation periods of 0.01” or more during storm events</td>
</tr>
<tr>
<td>8c</td>
<td>Dry Ridge icing distribution with respect to precipitation periods of 0.01” or more during storm events</td>
</tr>
<tr>
<td>9a</td>
<td>Temperature distribution during icing periods at Brian Head</td>
</tr>
<tr>
<td>9b</td>
<td>Temperature distribution during icing periods at Skyline</td>
</tr>
<tr>
<td>9c</td>
<td>Temperature distribution during icing periods at Dry Ridge</td>
</tr>
<tr>
<td>10</td>
<td>Stability analysis surface site locations</td>
</tr>
<tr>
<td>11</td>
<td>Skyline stability analysis results</td>
</tr>
<tr>
<td>12</td>
<td>Seasonal distribution of atmospheric stability at Skyline during icing, associated with a site temperature between –5 and –15 C</td>
</tr>
<tr>
<td>13</td>
<td>Monthly five-season averages of the percentage of well-mixed and potentially seedable icing periods with a site temperature between –5 and –15 C</td>
</tr>
<tr>
<td>14</td>
<td>Synoptic category average of the percentage of well-mixed and potentially seedable icing periods during November - April with a site temperature between –5 and –15 C</td>
</tr>
<tr>
<td>15a</td>
<td>Overall percentages of seedable periods for November – April on Uintas south slope</td>
</tr>
<tr>
<td>15b</td>
<td>Seasonal stability analysis results along southern slope of the Uintas</td>
</tr>
<tr>
<td>16</td>
<td>Estimated percentage of seedable periods based on Dry Ridge Icing Data</td>
</tr>
<tr>
<td>17a</td>
<td>Dry Ridge winds for all icing periods 2013-2014</td>
</tr>
<tr>
<td>17b</td>
<td>Dry Ridge winds for icing colder than -5 C 2013-2014</td>
</tr>
<tr>
<td>18a</td>
<td>Brian Head winds for all icing periods 2013-2014</td>
</tr>
<tr>
<td>18b</td>
<td>Brian Head winds for icing colder than -5 C 2013-2014</td>
</tr>
</tbody>
</table>
Table of Contents
Continued

Figure                                       Page
19a  Skyline winds for all icing periods 2013-2014 .................................................................53
19b  Skyline winds for icing colder than -5 C 2013-2014 ...........................................................54
20a  Brian Head five-season icing totals by hour of the day .........................................................57
20b  Brian Head five-season icing totals by hour, smoothed ..........................................................57
21a  Skyline five-season icing totals by hour of the day...............................................................58
21b  Skyline five-season icing totals by hour, smoothed ...............................................................58
22a  Dry Ridge 2013-2014 icing totals by hour of the day ............................................................59
22b  Dry Ridge 2013-2014 icing totals by hour, smoothed ...............................................................59
23   Cloud-top temperature vs icing for 15-minute period at Brian Head ......................................62
24   Cloud-top temperature vs snowfall rate for 15-minute period at Brian Head ..........................63
25   Precipitation, temperature, icing, and wind data at Dry Ridge for March 30, 2014 ............66
26   Mesowest surface data at 1200 MDT on March 30, 2014 ...........................................................67
27   HYSPLIT plume dispersion forecast 1900-2100 MDT on March 30, 2014 .................................68
28   Precipitation, temperature, icing, and wind data at Dry Ridge for April 26, 2014 ...............70
29   HYSPLIT plume dispersion forecast on April 26, 2014 .............................................................71
30   Precipitation, temperature, icing, and wind data at Brian Head for December 3-4, 2013 ....74
31   HYSPLIT plume dispersion forecast in southwest Utah on December 3, 2013 .......................75
32   Precipitation efficiency in 2-hour time blocks at Brian Head for December 3-4, 2013 ........75
33   Brian Head precipitation, temperature, and icing on January 30-31, 2014 ..............................78
34   HYSPLIT plume dispersion forecast in southwest Utah on January 30, 2014 .........................79
35   Precipitation efficiency in 2-hour time blocks at Brian Head for January 30-31, 2014 ........79
36   Brian Head precipitation, temperature, icing, and wind data on Feb 28-Mar 1, 2014 ...........81
37   HYSPLIT plume dispersion forecast in southwest Utah on March 1, 2014 .............................82
38   Skyline precipitation, temperature, icing, and wind data on February 27, 2014 ...................84
39   HYSPLIT plume dispersion forecast on February 27, 2014 .......................................................85
40   Skyline precipitation, temperature, icing, and wind data on March 26-27, 2014 ..................87
41   HYSPLIT plume dispersion forecast on March 26, 2014 .........................................................88

Table                                            Page
1   NAWC Winter Cloud Seeding Criteria .................................................................2
2   Icing Data Periods .................................................................................................5
3a  Brian Head Icing Totals by Synoptic/Precipitation Sub-Category .................................20
3b  Skyline Icing Totals by Synoptic/Precipitation Sub-Category .................................20
3c  Dry Ridge Icing Total by Synoptic/Precipitation Sub-Category ..................................20
4a  Brian Head Storm Period Sample Sizes ..................................................................22
4b  Skyline Storm Period Sample Sizes .......................................................................22
4c  Dry Ridge Storm Period Sample Sizes ..................................................................22
Table of Contents
Continued

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5a</td>
<td>Brian Head Icing Intensity Maxima (15 min)</td>
</tr>
<tr>
<td>5b</td>
<td>Skyline Icing Intensity Maxima (10 min)</td>
</tr>
<tr>
<td>5c</td>
<td>Dry Ridge Icing Intensity Maxima (15 min)</td>
</tr>
<tr>
<td>6a</td>
<td>Brian Head Icing Percentages –5 C or Colder</td>
</tr>
<tr>
<td>6b</td>
<td>Skyline Icing Percentages –5 C or Colder</td>
</tr>
<tr>
<td>6c</td>
<td>Dry Ridge Icing Percentages -5 C or Colder</td>
</tr>
<tr>
<td>7a</td>
<td>Frequency of 15-minute Icing Periods at Brian Head, by Icing Intensity and Snowfall Rate</td>
</tr>
<tr>
<td>7b</td>
<td>Percentage Distribution of Data in (7a) by Icing Rate</td>
</tr>
<tr>
<td>7c</td>
<td>Percentage Distribution of Data in (7a) by Snowfall Rate</td>
</tr>
<tr>
<td>8</td>
<td>Percent Cloud-Top Temperatures Warmer than -25/-15C for a Number of Icing Cycles</td>
</tr>
</tbody>
</table>

GLOSSARY OF RELEVANT METEOROLOGICAL TERMS, ETC.

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

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

**Cap cloud**: A shallow, orographically-induced cloud that often forms near a mountain crest. These situations are believed to present little if any cloud seeding opportunity due to the very limited vertical extent of the cloud (often just a few hundred feet).

**Cold-core low**: A typical mid-latitude type of low pressure system, where the core of the system is colder than its surroundings. This type of system is also defined by the cyclonic circulation being strongest in the upper levels of the atmosphere. The opposite is a warm-core low, which typically occurs in the tropics.
**Condensation**: Phase change of water vapor into liquid form. This can occur on the surface of objects (such as dew on the grass) or in mid-air (leading to the formation of clouds). Clouds are technically composed of water in liquid form, not water vapor.

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

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

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

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

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

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

**Diurnal Cycle**: Refers to the daytime/nighttime cycle with emphasis on the variation in solar heating input to the earth’s surface at a given location, and the corresponding effects on meteorology

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

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

**El Nino**: A reference to a particular phase of oceanic and atmospheric temperature and circulation patterns in the tropical Pacific, where the eastern tropical Pacific warms, the western tropical Pacific cools, and the prevailing easterly trade winds weaken or dissipate. Often has an effect on mid-latitude patterns as well, such as increased precipitation in southern portions of the U.S. and decreased precipitation further north. The opposite phase is called La Nina.
Front (or frontal zone): Reference to a temperature boundary with either incoming colder air (cold front) or incoming warmer air (warm front); can sometimes be a reference to a stationary temperature boundary line (stationary front) or a more complex type known as an occluded front (where the temperature change across a boundary can vary in type at different elevations).

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

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

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

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

HYSLIT model: Hybrid Single Particle Lagrangian Integrated Trajectory Model, developed as a joint effort by NOAA and the Australian Bureau of Meteorology. This model is typically used to forecast the movement and dispersion of near-surface pollutants, and utilizes archived or forecast meteorological data in its calculations.

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

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

Lapse Rate: The rate at which an air parcel cools (warms) as it ascends (descends). The moist adiabatic lapse rate applies to a saturated air parcel (with a humidity of 100%), and the dry adiabatic lapse rate applies to an unsaturated parcel.

Longwave (or longwave pattern): The longer wavelengths, typically on the order of 1,000 – 2,000+ miles, of the typical ridge/trough pattern around the northern (or southern) Hemisphere, typically most pronounced in the mid-latitudes.
**Low-Level Jet:** A zone of maximum wind speed in the lower atmosphere. Can be caused by geographical features or various weather patterns, and can influence storm behavior and dispersion of cloud seeding materials.

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

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

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

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

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

**Neutral Stability:** Refers to a well-mixed atmosphere with no thermodynamic stability to restrict vertical movement of an air parcel.

**NOAA:** National Oceanic and Atmospheric Administration, which includes the National Weather Service.

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

**Nuclei:** Small particles that aid water droplet or ice particle formation

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

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

**Positive (ly) tilted trough:** A normal U-shaped trough configuration, where an incoming cold front would generally be in a northeast–southwest orientation.
**Rawinsonde:** Commonly referred to as a sounding, a vertical profile of the atmosphere based on observations from an instrument package attached to a weather balloon. These observations include temperature, dew point, wind speed and direction.

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

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

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

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

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

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

**Sounding:** A vertical profile of the atmosphere based on observations from an instrument package attached to a weather balloon. These observations include temperature, dew point, wind speed and direction. See also rawinsonde.

**Stability:** In reference to thermodynamic stability of the atmosphere, either an increase in temperature with height or a decrease slower than the dry/moist lapse rates. Stability within a given layer of the atmosphere will restrict vertical mixing of the air mass to varying degrees. Stability in a given layer can be categorized according to the amount of heating at the bottom of the layer, or cooling at the top, necessary to eliminate the stability. NAWC’s 2-site method of stability categorization for a layer uses four categories: Neutral (N), Slightly Stable (SS), Moderately Stable (MS), and Very Stable (VS).

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

**Stratiform:** Usually used in reference to precipitation, this implies a large area of cloud cover and precipitation that has a fairly uniform intensity except where influenced by terrain, etc. It is the result of larger-scale (synoptic scale) weather processes, as opposed to convective processes.
**Sublimation:** The phase change in which water in solid form (ice) turns directly into water vapor. The opposite process is deposition.

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

**Supercooled Liquid Water (SLW)** Tiny cloud droplets remaining in the liquid phase at temperatures below the freezing point (32 F or 0 C).

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

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

**Trough axis:** The longitudinal (north-south) band corresponding to a trough minimum

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

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

**Vector:** Term used to represent wind velocity (speed + direction) at a given point

**Velocity:** Describes speed of an object, often used in the description of wind intensities

**Vertical Wind Profiler:** Ground-based system that measures wind velocity at various levels above the site
Executive Summary

The 2013-2014 season was the fifth year of ice detector data collection for two previously established sites at Skyline and Brian Head, and the second year of data at the Dry Ridge site in the Uinta Range. The Dry Ridge site replaced a previous site (Chepeta) in the Uintas, and the second year of data confirms that the Dry Ridge site has adequate exposure for measuring supercooled liquid water (SLW). The establishment of these sites, as well as analysis of the data, is funded by the Lower Colorado River Basin States. The goal of the current study is to better understand relevant meteorological conditions associated with the occurrence of ridge-top SLW, in an effort to improve winter season operational cloud seeding, which seeks to convert this SLW into additional snowfall. This report contains summary results of the data analysis for the five seasons, looking at individual and combined season results.

Categorization of the icing periods at Brian Head, Skyline, and Dry Ridge with regard to synoptic-scale weather patterns is summarized for the available data. This analysis continues to show the greatest icing activity occurring after the passage of the trough axis at 500 mb for both Brian Head and Skyline, although significant icing can also occur pre-frontally and between the cold front and trough passage. The Dry Ridge site is much different in this regard, with the vast majority of the measured icing so far occurring during pre-frontal, southerly wind situations. Similar categorization of icing periods has been conducted with regard to storm precipitation periods. Results of the analysis continue to indicate that the most frequent icing activity is observed between or during precipitation periods within an overall storm event.

Icing periods are also summarized by site (or equivalent ridge-top) temperature for the individual and combined season data. A large portion of the icing (approximately 40-60%) occurred within the –5 to –15 C range, which is considered favorable for cloud seeding with silver iodide, with a considerable amount of icing also observed at warmer temperatures. Only a small percentage of observed icing (generally 1 - 4% depending on the site) occurred at temperatures colder than –15 C, suggesting that little seeding opportunity generally exists at these cold temperatures.

The issue of low-level stability during ridge-top icing periods is an important one in regard to ground-based cloud seeding operations conducted from valley and foothill locations. Analyses of low-level stability during potentially seedable icing periods have been conducted by comparing surface data at varying elevations in several areas of Utah. These include the Skyline area, Brian Head area, and along the southern slopes of the Uintas. The HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) model with NAM (North American Model) meteorological data has been utilized as a comparative analysis method in the Skyline area and Uintas region, to better understand the likely patterns of seeding material dispersion from ground-based sites during storm periods. The results of these various stability and dispersion analyses have suggested that most seeding target areas in Utah (typically characterized by north-south oriented mountain barriers) have adequate atmospheric mixing for effective lower-elevation ground-based seeding during approximately 70% or more of winter season storm periods when ridge-top SLW is present in a favorable temperature window. Low-level inversions and atmospheric stability can vary substantially due to varying terrain profiles, and some areas such as the Uinta Basin in northeastern Utah exhibit more frequent and persistent
low-level inversions and cold pooling during the winter season. The most significant low-level stability and basin cold air pooling occurs during the December through February period and, at least in some areas such as the Uinta Basin, is strongly correlated with the presence of low elevation snow cover.

Icing occurrence and intensity has been compared to site wind speed and direction. The distribution of icing occurrence with respect to winds shows the influence both of synoptic-scale processes as well as local channeling of wind based on surrounding terrain. The local channeling due to the terrain surrounding a given site results in large variations in the wind distribution from site to site. This result has implications regarding the location of ground-based seeding sites in reference to surrounding terrain, as well as synoptic-scale meteorological conditions associated with the development of significant SLW.

Analysis has also been conducted regarding the seasonal/diurnal distribution of the observed ridge-top icing activity. A general afternoon minimum in observed icing activity has been noted at some sites, with the most significant diurnal variability generally associated with spring storm periods. Seasonally, some of the heaviest icing occurs during the spring season (particularly during the month of April), although heavy icing is commonly observed in early-season (e.g., November) storms as well. In-depth analysis of seasonal and diurnal variability in icing activity, along with associated meteorological factors, suggests that there are likely several inter-related variables. One of the primary meteorological variables is the dominant air mass lifting mechanism (e.g., orographic vs convective). There are several other inter-related factors, which are all relevant to the targeting of SLW with seeding material. An interesting conclusion of this analysis is that spring storm periods may have particularly favorable conditions from ground-based seeding, particularly during the afternoon hours (i.e. cold storm periods with a high sun angle).

A new analysis was conducted this season, utilizing cloud-top temperature (CTT) data corresponding to periods of heavier icing (3 or more cycles per 15-minute period) at the Brian Head site. The analysis of this data suggests that there is a good deal of complexity in the relationship between CTT and site icing occurrence, resulting in a poor correlation between the two variables. For this reason, traditional cloud-top temperature data (i.e. the temperature of the highest cloud layer) may be of little utility in gaging cloud seeding potential for winter orographic-type storm situations. IF a representative CTT could easily be obtained, corresponding to the top of a lower cloud layer associated with the precipitation process and directly adjacent to the mountain crest, this may be of more use in gaging the natural efficiency and seeding potential in a cloud system.

Several case studies are presented in the report, three based on data from the Dry Ridge site, and two each based on data from Brian Head and Skyline. These cases studies highlight some differences between the ice detector sites, and well as patterns that have been observed with regard to icing and the associated meteorology.

The incorporation of ice detection systems has improved real-time seeding opportunity recognition, as well as our understanding of the processes involved in producing supercooled water and the associated cloud seeding opportunity in winter storms.
Analysis of Mountain Ridge Ice Detector Measurements In Utah
During the 2009-10 through 2013-14 Winter Seasons

1.0 Introduction and Background

Supercooled liquid water (SLW) is the target of winter cloud seeding operations aimed at snowpack enhancement in several areas of the mountainous west, including Utah. SLW in Utah often develops at low altitudes above the windward slopes of mountain barriers during stormy weather, in many instances impinging on the higher mountain ridges, producing rime ice accumulation on trees and structures (Super, 1999). In addition to the presence of sufficient amounts of SLW, there are several other factors of importance for successful cloud seeding operations. When SLW is present, silver iodide becomes an active seeding agent at temperatures below approximately −4 to −5 C, with its effectiveness increasing at lower temperatures. There is also a practical lower bound (usually near −15 C) below which significant amounts of SLW are uncommon, and the natural efficiency of the cloud system is such that seeding effects may be insignificant. Effective seeding also depends on the ability for silver iodide nuclei released at ground level to reach appropriate regions of the cloud in a timely manner, and for sufficient time 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 is a crucial factor with regard to seeded snow particle fallout. Finally, another key factor is the ability of the project meteorologist to identify situations when all these factors are favorable for cloud seeding for a given target area, in real time. Although some detailed and technical analyses are included in this report, they were conducted with the goal of utilizing the available ice detector data to help the project meteorologist identify the likely development of good seeding situations. Table 1 summarizes the generalized cloud seeding criteria that NAWC utilizes in these ground-based seeding programs. In addition to this, various meteorological factors are recognized as helping to optimize cloud seeding potential, as discussed in this report. An important point of emphasis is that each storm situation is unique, and the ice detector data are valuable both in real-time decision making as well as later analyses of storm events.

Two high-mountain ice detector sites were operated by North American Weather Consultants during the 2009-2010 winter season, and three sites were operated during the following four seasons. Funding for establishment of these sites, their maintenance and data analysis has been provided by a consortium of Lower (Colorado River) Basin States (LBS) water interests as part of their support of enhancements to existing cloud seeding projects for areas that contribute to the flow of the Colorado. Funding for the LBS-funded enhancements to cloud seeding projects in Utah is administered through the Utah Division of Water Resources.
Table 1
NAWC Winter Cloud Seeding Criteria

1) Cloud bases are below the mountain crest height.

2) Low-level winds would favor the movement of silver iodide nuclei from their release points into the intended target area.

3) No low-level atmospheric inversions or stable layers that would restrict the vertical movement of the silver iodide nuclei between the surface and at least the -5º C (23º F) level or colder.

4) The temperature at the mountain crest height should be -5 to -15º C, except in some strongly convective situations where seeding at warmer temperatures may be effective.

5) The temperature at the 700-mb level (approximately 10,000 feet elevation) should be -15º C or warmer.

Surveys of existing meteorological stations and other prospective ice detector locations in Utah’s mountains yielded an initial list of three priority sites, one at the Brian Head Ski Area in southern Utah, another named Skyline in central Utah above (east of) the town of Fairview, and a third near Chepeta Lake in the east-central Uinta Mountains of northern Utah. A fourth potential site at Boulder Summit in southeastern Utah has been considered as well. Following two seasons of data collection, it was determined that the Chepeta site in the Uintas was too sheltered for ice detector measurements, and in 2012 it was re-located to Dry Ridge, located a few miles west of Moon Lake at 11,450 feet elevation. These locations are shown in Figure 1. Figure 2 shows the location of the Skyline site and nearby supporting precipitation gage. A nearby ice detector site above the town of Fairview is also shown, for which data has been obtained in some past seasons as a comparison to the Skyline ice detector data.

Earlier SLW measurements using ridge-top ice detectors in Utah to assess and describe winter cloud seeding potential have been reported in Solak et al (1988) and Solak et al (2005). Results for the first three seasons (2009-10 through 2011-12) of the current ice detector analysis project have been summarized in previous reports to the Lower Basin State sponsors, also available on NAWC’s website at http://www.nawcinc.com/publications.html.

The Brian Head and Skyline ice detector sites are located at or near the summit of a prominent mountain barrier. The icing observed at those site can be considered indicative of “excess” in-cloud supercooled liquid water (SLW), i.e., SLW that is not involved in the windward slope precipitation process. This “excess” SLW can be viewed, to varying degrees depending on a few key factors, as potentially convertible.
via cloud seeding to precipitation reaching the surface, thus increasing the natural precipitation efficiency. The Dry Ridge site is south of the summit of the Uinta Range. Icing there represents either a) SLW entering the south slope watershed in southerly-component flow or b) carry-over or excess SLW in northerly-component flow situations. Each ice detector represents a point measurement, and therefore the occurrence of SLW in the vicinity may be more frequent than indicated (such as in situations where SLW remains above the instrument elevation).

Figure 1. Active ice detector sites (squares), previous site at Chepeta (red circle) and potential site in southeastern Utah (blue circle).
Figure 2. Locations of ice detectors and ETI precipitation gage in the Skyline area; data from the nearby Fairview ice detector has been available for analysis in some past seasons.

It should be noted that the winter of 2009-2010 was characterized as a moderate to strong El Nino situation, while the 2010-2011 and 2011-2012 seasons were essentially the opposite, with a moderate La Nina in place. The 2012-2013 and 2013-2014 seasons were characterized by a minimal La Nina situation. El Nino and La Nina events are part of what is known as the El Nino Southern Oscillation (ENSO) cycle, characterized by changes in ocean temperatures in the equatorial Pacific which can influence weather patterns in the mid-latitudes as well. The El Nino phase of the cycle is associated with warmer ocean temperatures in the eastern Pacific equatorial zone, and the La Nina phase is associated with cooler water temperatures in that zone. The current data set now represents all phases of the ENSO cycle, although this is not meant to imply that it is completely representative of long-term climatology. Another point worth noting is that the various sites’ data analysis periods varied somewhat during the four seasons. The data periods available for the ice detector sites are summarized in Table 2, and are not complete winter seasons in all cases.
Table 2.
Icing Data Periods

<table>
<thead>
<tr>
<th>Season</th>
<th>Brian Head</th>
<th>Skyline</th>
<th>Dry Ridge</th>
<th>Fairview*</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009-2010</td>
<td>Oct 14 – Dec 8;</td>
<td>Nov 2 – May 31</td>
<td>Dec 1 – Mar 23</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Feb 17 – May 31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010-2011</td>
<td>Oct 5 – May 31</td>
<td>Nov 10 – May 12</td>
<td>Dec 1 – May 31</td>
<td></td>
</tr>
<tr>
<td>2011-2012</td>
<td>Oct 12 – May 22</td>
<td>Oct 9 – May 22</td>
<td>Dec 1 – May 31</td>
<td></td>
</tr>
<tr>
<td>2012-2013</td>
<td>Oct 1 – May 31</td>
<td>Oct 1 – May 31</td>
<td>Oct 2 – May 31</td>
<td></td>
</tr>
</tbody>
</table>

* Operated by Emery County

2.0 Sensor Suites

The ice-detecting sensor is the key measurement at each site. At each installation the Goodrich Model 0871LH1 Freezing Rain Detector is used. Its sensing probe accumulates ice, via capture of supercooled liquid water 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. A schematic of the sensor is shown in Figure 3.

![Schematic of Goodrich Model 0871LH1 freezing rain detector (dimensions in inches).](image)
The ice detector sites were also equipped with instrumentation to measure various other meteorological parameters, as described in the following sub-sections.

2.1 Brian Head (37.683 N, 112.836 W, 10,900’)

The ice detection system at Brian Head Resort in southwestern Utah is a stand-alone installation consisting of the following.

- Goodrich Freezing Rain Detector, Model 0871LH1
- 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
- Campbell Scientific Datalogger System, Model CR1000
- Cellular Telephone Modem

Figure 4 shows the sensor suite. The data are recorded via an onsite datalogger. Real-time data access is available via a password-protected internet link using Vista Data View software hosted by Meteorological Solutions Inc.
2.2 Skyline (39.636 N, 111.329 W, 9,330’)

Ice detection components have been added to an existing Utah Department of Transportation (UDOT) Skyline meteorological system in central Utah. The full site suite consists of the following. The components that have been added to the existing sensor suite are indicated using an asterisk.

- Goodrich Freezing Rain Detector, Model 0871LH *
- Temperature/Relative Humidity Sensor
- Wind Speed and Direction Sensor
- Thies Precipitation Rate Sensor, Model TC041-L *
- Two solar panels *
- Battery bank for powering and deicing the ice detector *
Figure 5 shows the Skyline sensor suite. The data are recorded onsite via UDOT’s datalogger. Real-time data access is available via a password-protected internet link using Vista Data View software hosted by Meteorological Solutions Inc.

Data were available again this season from a high-resolution ETI weighing-type rain gage in the Skyline area, installed and operated by NAWC in support of the project, as was done during the previous seasons. The gage was provided by the Utah Division of Water Resources, and was installed at a location approximately 2.5 miles north of the ice detector site.
2.3 **Dry Ridge** (40.60 N, 110.65 W, 11,540’)

With the cooperation of the U. S. Forest Service (USFS), ice detection components and meteorological sensors have been added to an existing USFS communications tower SNOTEL system at their Dry Ridge site, at an elevation of 11,540 feet. The tower is located at the highest point of a broad ridge, well above timberline. The full site suite consists of the following.

- Goodrich Freezing Rain Detector, Model 0871LH1
- Campbell Scientific (Thies) Optical Precipitation Sensor, Model TC041-L
- CSI Temperature Sensor, Model 107-L10
- R.M. Young Alpine Wind Speed and Direction Sensor, Model 05103-45
- Campbell Scientific Datalogger, Model CR1000
- Two Solar Panels
- Marine Deep-Cycle Batteries
- Cellular telephone modem
- Yagi Antenna

Figures 6a and 6b show the Dry Ridge sensor site and equipment. Real-time data access was available via a password-protected internet link using Vista Data View software hosted by Meteorological Solutions Inc.
Figure 6b. Dry Ridge site sensors and support equipment

3.0 Analysis Results for Periods of Observed Rimming

Investigation of the various seasonal meteorological aspects of icing occurrences in light of other key winter storm characteristics can reveal important relationships that lead to improved seeding opportunity recognition and potentially improved cloud treatment. The following sections summarize the primary observations resulting from these analyses. These analyses are based on observations at the Brian Head, Skyline, and Dry Ridge sites.

The 2013-2014 season brought roughly average icing activity to all three sites, based on the data collected so far. Because the analyses are based on the occurrence of SLW as measured at these sites, combined results of the ice detector site data will naturally be weighted somewhat more heavily toward the seasons with greater icing activity.
3.1 Icing Relative to Synoptic-Scale Weather Situation and Storm Precipitation Periods

3.1.1. Icing Relative to Synoptic-Scale Storm Situation

Pre- and post-frontal/trough air masses differ by definition, and their “seedability” can differ as well. The five seasons’ data have been partitioned according to this distinction.

The occurrence of icing cycles at the detector sites was examined with regard to the synoptic situation for storm events during all five seasons. The observed icing during significant events was divided into five categories, based on the synoptic-scale weather situation at each measurement site when the icing was observed:

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 is the standard 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 Brian Head, Skyline, and Dry Ridge sites. A greater amount of icing was observed at the Brian Head and Skyline sites during post-500-mb trough situations than for any other synoptic category. However, the Dry Ridge site, located on the southern slope of an east-west oriented mountain barrier (the Uintas), exhibited a much different icing pattern relative to the synoptic weather pattern. The vast majority of icing at Dry Ridge was observed in southerly wind (generally pre-frontal) situations, with 59% of the icing observed in the “pre-frontal” synoptic category for the 2-seasons of data. The “closed low” category contained the least amount of icing, about 6% of the total observed icing activity at all three sites. This is at least partially related to the fact that the occurrence of closed lows is somewhat less frequent than other storm types, although it may be that closed lows also tend to generate less crest-height SLW.

One important item of note regarding the Dry Ridge site is that its location on the southern side of the east-west oriented Uinta Range is believed to be very influential in the observed icing patterns there. The crest of the Uintas, located to the north of the site, results in a general downsloping wind pattern in northerly component flow (as opposed to upsloping winds in the vicinity of Dry Ridge during southerly or pre-frontal storm periods). Although significant amounts of SLW are likely to develop over the Uintas in either northerly or southerly cross-barrier flow, the location of the SLW will vary due to the fact that it normally develops near or upwind of the crest. This means that seeding from the northern side of the Uintas is expected to be effective during
northerly wind periods, even though the Dry Ridge site will likely not measure icing
during most of these northerly storm periods.

Figure 7a.  Synoptic pattern classification during icing periods at Brian Head,
individual and combined seasons.
Figure 7b. Synoptic pattern classification during icing periods at Skyline, individual and combined seasons.
Figure 7c. Synoptic pattern classification during icing periods at Dry Ridge, individual and combined seasons.
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 occurs 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 opportunity occurs during storm sequences, helping to sharpen our operational procedures and convincing us of the real-time and post hoc value of the ice detector measurements. The combined results of the five seasons so far should yield a fairly representative picture of the relationship between icing occurrence and synoptic-scale weather patterns, as well as highlighting how these patterns may differ between one measurement site and another. As additional seasons’ data are obtained (particularly at the Dry Ridge site), the representativeness of the sample will continue to improve.

3.1.2 Icing Relative to Storm Precipitation Periods

The relationship of icing (riming) occurrence to area precipitation was investigated, via comparison of icing to time series of precipitation occurrence at the Brian Head site for all five seasons, the Skyline site for the past four seasons (the period for which high-resolution site precipitation data are available there), and the Dry Ridge site for two seasons. This analysis is based on data from the on-site optical precipitation sensors. The threshold chosen to define precipitation periods in the analysis is 0.1”/hour of snowfall (roughly equivalent to 0.01”/hour of water content).

A high-resolution ETI precipitation gage with data at 15-minute intervals, operated in support of the project at a similar elevation approximately 2.5 miles north of Skyline, was used to supplement the Skyline site precipitation records during a period of missing precipitation data at the site this season.

Figure 8 details the results of this analysis. At Brian Head, roughly 31% of the icing in the five-season data set was observed between precipitation periods within a storm event. About 25% was observed during precipitation periods, and 22% after the precipitation during a particular storm had ended. Approximately 12% of the icing was observed before storm precipitation began. The analysis also indicated that about 9% of the observed icing was associated with storm events that produced essentially no precipitation.

A similar analysis for Skyline for the four seasons of available optical sensor precipitation data shows about 38% of the icing occurring between storm precipitation periods. However, a larger percentage (48%) was observed during precipitation periods at Skyline, with a small percentage before and after storm precipitation (4% and 9%, respectively). Very little icing at Skyline was classified as occurring without precipitation.
Figure 8a. Brian Head icing distribution with respect to precipitation periods of 0.01”/hr (0.1”/hr snowfall) or greater during storm events.
Figure 8b. Skyline icing distribution with respect to precipitation periods of 0.01”/hr (0.1”/hr snowfall) or greater during storm events.
Figure 8c. Dry Ridge icing distribution with respect to precipitation periods of 0.01”/hr (0.1”/hr snowfall) or greater during storm events.
Dry Ridge analysis has also indicated a large percentage of icing occurring between precipitation periods (32%). This was followed by 26% of icing cycles indicated during storm periods in which no precipitation was measured (or the precipitation rate did not reach 0.1”/hour). Moderate amounts of icing were measured before and during precipitation with 17% and 16%, respectively. The smallest amount of icing, in general, was indicated during periods after precipitation had fallen at Dry Ridge.

The precipitation vs. icing analyses are quite valuable, because they provide an approximation of relative storm precipitation efficiency. Another result noted in earlier reports, and consistent with subsequent data, is that seeding opportunities can persist for a few to several hours after precipitation has ended in a given storm sequence. This has been suspected in the past, but these data provide confirmation and a better sense of the magnitude of the seeding opportunity. The late stages of a storm are frequently characterized by colder air masses, which is important for seeding given the greater effectiveness of silver iodide at colder temperatures. Also, post-trough situations tend to be associated with a greater occurrence of lower- and mid-level moisture (necessary for riming), in contrast to pre-frontal situations when moisture is fairly often confined to the upper atmospheric levels in Utah. Thus, these post-trough and post-precipitation periods can present very good seeding opportunities, especially if the air mass has become well mixed at elevations below the crest height.

### 3.1.3 Additional Analysis of Icing Occurrence According to Synoptic and Precipitation Categorizations

Utilizing the five synoptic and the five precipitation categories as described in Sections 3.1.1 and 3.1.2, respectively, allows a more complete analysis of icing occurrence according to each resulting sub-category. This provides additional information which can be useful for identifying general patterns which, in turn, can aid in seeding opportunity recognition. In order to classify the data in this way, both the ice detector data and corresponding high-resolution precipitation sensor data are necessary. This means that a total of five seasons of data are available for this sub-category analysis at Brian Head, four seasons at Skyline (due to lack of a site precipitation sensor there the first season), and two seasons at Dry Ridge.

Tables 3 a, b, c show the observed icing totals in the main categories and sub-categories for a) Brian Head, b) Skyline, and c) Dry Ridge. In each table, the total numbers of observed icing cycles (de-icing heat cycles) for the combined seasons of operation are shown.
Table 3a.
Brian Head Total Icing Cycles by Synoptic/Precipitation Sub-Category
(5 seasons of data)

<table>
<thead>
<tr>
<th>Category</th>
<th>Before Precip</th>
<th>During Precip</th>
<th>Between Precip</th>
<th>After Precip</th>
<th>No Precip</th>
<th>Category Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-frontal</td>
<td>180</td>
<td>357</td>
<td>191</td>
<td>202</td>
<td>66</td>
<td>996</td>
</tr>
<tr>
<td>Between Front/Trough</td>
<td>85</td>
<td>201</td>
<td>287</td>
<td>110</td>
<td>7</td>
<td>690</td>
</tr>
<tr>
<td>Post 500-mb</td>
<td>116</td>
<td>405</td>
<td>671</td>
<td>389</td>
<td>187</td>
<td>1768</td>
</tr>
<tr>
<td>Closed Low</td>
<td>7</td>
<td>51</td>
<td>82</td>
<td>115</td>
<td>0</td>
<td>255</td>
</tr>
<tr>
<td>Undefined</td>
<td>133</td>
<td>46</td>
<td>81</td>
<td>141</td>
<td>129</td>
<td>530</td>
</tr>
<tr>
<td>Category</td>
<td>521</td>
<td>1060</td>
<td>1312</td>
<td>957</td>
<td>389</td>
<td></td>
</tr>
</tbody>
</table>

Table 3b.
Skyline Total Icing Cycles by Synoptic/Precipitation Sub-Category
(4 seasons of data)

<table>
<thead>
<tr>
<th>Category</th>
<th>Before Precip</th>
<th>During Precip</th>
<th>Between Precip</th>
<th>After Precip</th>
<th>No Precip</th>
<th>Category Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-frontal</td>
<td>8</td>
<td>125</td>
<td>75</td>
<td>0</td>
<td>5</td>
<td>213</td>
</tr>
<tr>
<td>Between Front/Trough</td>
<td>3</td>
<td>91</td>
<td>57</td>
<td>4</td>
<td>1</td>
<td>156</td>
</tr>
<tr>
<td>Post 500-mb</td>
<td>15</td>
<td>101</td>
<td>103</td>
<td>43</td>
<td>1</td>
<td>263</td>
</tr>
<tr>
<td>Closed Low</td>
<td>1</td>
<td>13</td>
<td>20</td>
<td>1</td>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>Undefined</td>
<td>6</td>
<td>88</td>
<td>73</td>
<td>29</td>
<td>9</td>
<td>205</td>
</tr>
<tr>
<td>Category</td>
<td>33</td>
<td>418</td>
<td>328</td>
<td>77</td>
<td>21</td>
<td></td>
</tr>
</tbody>
</table>

Table 3c.
Dry Ridge Total Icing Cycles by Synoptic/Precipitation Sub-Category
(2 seasons of data)

<table>
<thead>
<tr>
<th>Category</th>
<th>Before Precip</th>
<th>During Precip</th>
<th>Between Precip</th>
<th>After Precip</th>
<th>No Precip</th>
<th>Category Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-frontal</td>
<td>52</td>
<td>47</td>
<td>96</td>
<td>12</td>
<td>13</td>
<td>220</td>
</tr>
<tr>
<td>Between Front/Trough</td>
<td>2</td>
<td>12</td>
<td>11</td>
<td>1</td>
<td>9</td>
<td>35</td>
</tr>
<tr>
<td>Post 500-mb</td>
<td>1</td>
<td>0</td>
<td>5</td>
<td>6</td>
<td>19</td>
<td>31</td>
</tr>
<tr>
<td>Closed Low</td>
<td>8</td>
<td>3</td>
<td>10</td>
<td>4</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>Undefined</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>60</td>
<td>67</td>
</tr>
<tr>
<td>Category</td>
<td>64</td>
<td>62</td>
<td>122</td>
<td>29</td>
<td>101</td>
<td></td>
</tr>
</tbody>
</table>
As shown in Table 3a, the greatest amount of icing at Brian Head, by far, occurred in the “post 500-mb trough/between precipitation” sub-category. At the Skyline site (Table 3b), the greatest amount of icing occurred in the “pre-frontal/during precipitation” sub-category. However, it must be noted in the case of Skyline that a fairly anomalous event, a warm “atmospheric river” case of December 17-23, 2010, accounted for 72 of the 125 icing cycles in this sub-category (as well as a large number of those in the neighboring “pre-frontal/between precipitation” sub-category. A large number of icing cycles (123 of the 202) in the “pre-frontal, after precipitation” category at Brian Head occurred during an intense period of icing on December 2, 2012. Aside from this, the sub-categories with the largest amounts icing at both Brian Head and Skyline are fairly well distributed between a larger number of storm periods. At Dry Ridge, for the two seasons of data available so far, the “pre-frontal/between precipitation” sub-category has by far the largest icing total. Recall that the vast majority of icing at Dry Ridge in general was observed during southerly wind flow situations (with most of these classified as pre-frontal), probably due to the unique topography there in comparison to the other sites.

Tables 4 a,b,c show the number of storm periods represented in each sub-category for the three sites.
### Table 4a.
Brian Head Storm Event Sample Sizes

<table>
<thead>
<tr>
<th></th>
<th>Before Precip</th>
<th>During Precip</th>
<th>Between Precip</th>
<th>After Precip</th>
<th>No Precip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-frontal</td>
<td>19</td>
<td>37</td>
<td>27</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Between Front/Trough</td>
<td>13</td>
<td>52</td>
<td>51</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>Post 500-mb</td>
<td>9</td>
<td>54</td>
<td>64</td>
<td>48</td>
<td>10</td>
</tr>
<tr>
<td>Closed Low</td>
<td>4</td>
<td>8</td>
<td>11</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>Undefined</td>
<td>10</td>
<td>12</td>
<td>5</td>
<td>11</td>
<td>9</td>
</tr>
</tbody>
</table>

### Table 4b.
Skyline Storm Period Sample Sizes

<table>
<thead>
<tr>
<th></th>
<th>Before Precip</th>
<th>During Precip</th>
<th>Between Precip</th>
<th>After Precip</th>
<th>No Precip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-frontal</td>
<td>3</td>
<td>27</td>
<td>18</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Between Front/Trough</td>
<td>3</td>
<td>44</td>
<td>28</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Post 500-mb</td>
<td>3</td>
<td>38</td>
<td>29</td>
<td>28</td>
<td>1</td>
</tr>
<tr>
<td>Closed Low</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Undefined</td>
<td>3</td>
<td>19</td>
<td>14</td>
<td>13</td>
<td>3</td>
</tr>
</tbody>
</table>

### Table 4c.
Dry Ridge Storm Period Sample Sizes

<table>
<thead>
<tr>
<th></th>
<th>Before Precip</th>
<th>During Precip</th>
<th>Between Precip</th>
<th>After Precip</th>
<th>No Precip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-frontal</td>
<td>9</td>
<td>10</td>
<td>12</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Between Front/Trough</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Post 500-mb</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Closed Low</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Undefined</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>18</td>
</tr>
</tbody>
</table>
The maximum icing intensity, or number of icing cycles per time period (15 minutes at Brian Head and Dry Ridge, 10 minutes at Skyline) for each sub-category is shown in Tables 5 a,b,c. The greatest icing intensity, in general, appears to be in both post-trough synoptic situations and between precipitation periods. However, a 15-minute maximum (9 cycles) was recorded at Brian Head during a period of very light precipitation on December 2, 2012.

### Table 5a.
Brian Head Icing Intensity Maxima (15 min, 5 seasons data)

<table>
<thead>
<tr>
<th>Category</th>
<th>Before Precip</th>
<th>During Precip</th>
<th>Between Precip</th>
<th>After Precip</th>
<th>No Precip</th>
<th>Category Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-frontal</td>
<td>7</td>
<td>9</td>
<td>3</td>
<td>8</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Between Front/Trough</td>
<td>3</td>
<td>3</td>
<td>7</td>
<td>4</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Post 500-mb</td>
<td>5</td>
<td>8</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Closed Low</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Undefined</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Category</td>
<td>7</td>
<td>9</td>
<td>8</td>
<td>8</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

### Table 5b.
Skyline Icing Intensity Maxima (10 min, 5 seasons data)

<table>
<thead>
<tr>
<th>Category</th>
<th>Before Precip</th>
<th>During Precip</th>
<th>Between Precip</th>
<th>After Precip</th>
<th>No Precip</th>
<th>Category Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-frontal</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Between Front/Trough</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Post 500-mb</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Closed Low</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Undefined</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Category</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

### Table 5c.
Dry Ridge Icing Intensity Maxima (15 min, 2 seasons data)

<table>
<thead>
<tr>
<th>Category</th>
<th>Before Precip</th>
<th>During Precip</th>
<th>Between Precip</th>
<th>After Precip</th>
<th>No Precip</th>
<th>Category Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-frontal</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Between Front/Trough</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Post 500-mb</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Closed Low</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Undefined</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Category</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
Despite some sample size issues in the sub-category analysis (especially the 2-season data at Dry Ridge) and the variability between the sites, it seems quite clear that post-500 mb trough situations present some of the best seeding potential in most areas, with heavy icing occurring in both the “between precipitation” and “during precipitation” post-trough subcategories. In the latter, heavy icing during post-trough precipitation may represent an ideal situation where the natural precipitation process is active, but perhaps inefficient. This result is suggestive of situations where a heavy cloud deck exists near crest level, of sufficient depth for meaningful precipitation development, and a lack of natural seeding due to precipitation from a higher cloud deck. This makes sense meteorologically, since the presence of a higher/deeper cloud deck with a cloud-top temperature colder than about –25 C is generally most frequent in pre-frontal situations, and least frequent following the 500-mb trough passage. The 500-mb trough passage is normally followed by subsidence and clearing skies near and above this level, with most cloud development and precipitation activity in the post-trough synoptic category being due to orographic and/or convective processes, which can present good seeding opportunity (Griffith et al, 2013).

Tables 6 a,b,c show the percentage of icing associated with a site temperature of –5 C (the upper nucleation temperature for silver iodide) or colder for each category and subcategory at Brian Head, Skyline, and Dry Ridge. The “post-trough” and “between front/trough” categories are the coldest in general, with the vast majority of icing in a seedable temperature range. The “pre-frontal” and “undefined” categories represent the lowest percentages of icing occurring at a temperature of –5 C or colder, which is not surprising especially considering that most of the synoptically “undefined” icing periods represent zonal or weak ridge situations. “Closed low” icing periods appear highly variable in terms of temperature and suffer from small sample size issues, but so far these appear much colder at Brian Head than at Skyline, which is likely due at least in part to the elevation difference between the sites. In any case, the majority of the post-trough icing periods (~60% or greater) appear to be cold enough for silver iodide seeding, at least for those occurring during precipitation. These situations also tend to have excellent atmospheric mixing.

At Dry Ridge, although many of the subcategories in Table 6c show 100% of the icing occurring at temperatures colder than -5 C (while other subcategories show much lower percentages of icing occurring at these colder temperatures), some of these percentages may be misleading due to the small sample size from two seasons of data, as illustrated in Tables 3b and 4b. Note that the pre-frontal subcategories with some of the greatest total amounts of icing at Dry Ridge also tend to have lower percentages of icing colder than -5 C.
### Table 6a.
**Brian Head Icing Percentages –5C or Colder (5 season data)**

<table>
<thead>
<tr>
<th>Category</th>
<th>Before Precip</th>
<th>During Precip</th>
<th>Between Precip</th>
<th>After Precip</th>
<th>No Precip</th>
<th>Category Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-frontal</td>
<td>31%</td>
<td>31%</td>
<td>40%</td>
<td>6%</td>
<td>5%</td>
<td>26%</td>
</tr>
<tr>
<td>Between Front/Trough</td>
<td>98%</td>
<td>82%</td>
<td>79%</td>
<td>95%</td>
<td>100%</td>
<td>85%</td>
</tr>
<tr>
<td>Post 500-mb Trough</td>
<td>97%</td>
<td>80%</td>
<td>96%</td>
<td>61%</td>
<td>100%</td>
<td>85%</td>
</tr>
<tr>
<td>Closed Low</td>
<td>86%</td>
<td>84%</td>
<td>98%</td>
<td>90%</td>
<td>NA</td>
<td>91%</td>
</tr>
<tr>
<td>Undefined</td>
<td>50%</td>
<td>59%</td>
<td>17%</td>
<td>57%</td>
<td>42%</td>
<td>46%</td>
</tr>
<tr>
<td>Category Average</td>
<td>62%</td>
<td>63%</td>
<td>79%</td>
<td>56%</td>
<td>65%</td>
<td></td>
</tr>
</tbody>
</table>

### Table 6b.
**Skyline Icing Percentages –5C or Colder (4 seasons data)**

<table>
<thead>
<tr>
<th>Category</th>
<th>Before Precip</th>
<th>During Precip</th>
<th>Between Precip</th>
<th>After Precip</th>
<th>No Precip</th>
<th>Category Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-frontal</td>
<td>50%</td>
<td>11%</td>
<td>8%</td>
<td>NA</td>
<td>40%</td>
<td>12%</td>
</tr>
<tr>
<td>Between Front/Trough</td>
<td>33%</td>
<td>52%</td>
<td>56%</td>
<td>50%</td>
<td>0%</td>
<td>53%</td>
</tr>
<tr>
<td>Post 500-mb Trough</td>
<td>100%</td>
<td>60%</td>
<td>42%</td>
<td>86%</td>
<td>100%</td>
<td>60%</td>
</tr>
<tr>
<td>Closed Low</td>
<td>100%</td>
<td>31%</td>
<td>15%</td>
<td>100%</td>
<td>0%</td>
<td>23%</td>
</tr>
<tr>
<td>Undefined</td>
<td>67%</td>
<td>23%</td>
<td>14%</td>
<td>28%</td>
<td>56%</td>
<td>23%</td>
</tr>
<tr>
<td>Category Averages</td>
<td>76%</td>
<td>35%</td>
<td>29%</td>
<td>62%</td>
<td>38%</td>
<td></td>
</tr>
</tbody>
</table>

### Table 6c.
**Dry Ridge Icing Percentages –5C or Colder (2 seasons data)**

<table>
<thead>
<tr>
<th>Category</th>
<th>Before Precip</th>
<th>During Precip</th>
<th>Between Precip</th>
<th>After Precip</th>
<th>No Precip</th>
<th>Category Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-frontal</td>
<td>100%</td>
<td>55%</td>
<td>54%</td>
<td>100%</td>
<td>92%</td>
<td>70%</td>
</tr>
<tr>
<td>Between Front/Trough</td>
<td>100%</td>
<td>75%</td>
<td>73%</td>
<td>100%</td>
<td>56%</td>
<td>71%</td>
</tr>
<tr>
<td>Post 500-mb Trough</td>
<td>100%</td>
<td>NA</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Closed Low</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>NA</td>
<td>100%</td>
</tr>
<tr>
<td>Undefined</td>
<td>100%</td>
<td>NA</td>
<td>NA</td>
<td>100%</td>
<td>78%</td>
<td>81%</td>
</tr>
<tr>
<td>Category Average</td>
<td>100%</td>
<td>61%</td>
<td>61%</td>
<td>100%</td>
<td>82%</td>
<td></td>
</tr>
</tbody>
</table>
3.2 Icing vs. Precipitation Rate

Some additional analyses were conducted regarding the issue of icing intensity vs. precipitation rate. Previous investigation, particularly in case studies of individual storm events as shown in the previous NAWC ice detector data analysis reports, has highlighted the effect of precipitation scavenging of SLW as evidenced by a frequent decrease in icing occurrence during periods of heavier snowfall. This is believed to be particularly true in cases of widespread and significant snowfall originating from a higher cloud deck, which can scavenge much of the SLW in a lower deck (such as one situated near the mountain crest height). The relationship between icing rate and precipitation rate is considered to be a key factor, in that it addresses the relative precipitation efficiency of storm systems or periods of storm systems, since cloud seeding for precipitation augmentation seeks to identify and treat periods of decreased efficiency.

Of the current ice detector sites in operation, the Brian Head site is ideal for this investigation due to the large range of icing intensities there (ranging from 1 cycle to as many as 8+) during individual 15-minute observation periods in the data set. Table 7a, produced from the 5 seasons of data at Brian Head, show the frequency of data periods with icing, classified according to icing and precipitation rates. To help remove the effect of sample size differences in Table 7a, Tables 7b and 7c were produced, showing the percentage distributions of icing categories by precipitation rate (7b) and precipitation categories by icing rate (7c). Essentially what this does is to illustrate the reduction in measured SLW at higher precipitation rates, presumably due to scavenging of the SLW by falling snow. Examination of Table 7b shows that while most of the single-cycle icing periods (bottom row) were associated with no snowfall or only very light snowfall rates, well over 10% of these periods were associated with more significant snowfall rates above 0.3”/hr (the two columns on the right). Heavier icing periods, in contrast, occurred in progressively lower percentages for the 0.3 – 0.8” and > 0.8”/hr snowfall rate categories, with none of the 4+ icing periods associated with snowfall rates above 0.3”/hr.

Table 7c shows a similar pattern. Of the 15-minute periods with icing and extremely light or no snowfall (left column), around 77% contained only 1 icing cycle, and 3% contained 4 or more cycles. Of the 15-minute icing periods with the most significant snowfall (right column), 1.5% had 4 or more icing cycles, and a greater percentage of these periods (over 85%) had only a single icing cycle.
Table 7a.
Frequency of 15-minute Icing Periods at Brian Head, Categorized by Icing Intensity and Snowfall Rate

<table>
<thead>
<tr>
<th></th>
<th>Snowfall &lt; 0.1&quot;/hr</th>
<th>Snowfall 0.1 - 0.3&quot;/hr</th>
<th>Snowfall 0.3 - 0.8&quot;/hr</th>
<th>Snowfall &gt; 0.8&quot;/hr</th>
<th>Category Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>4+ icing cycles</td>
<td>74</td>
<td>12</td>
<td>12</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>3 icing cycles</td>
<td>118</td>
<td>15</td>
<td>10</td>
<td>3</td>
<td>146</td>
</tr>
<tr>
<td>2 icing cycles</td>
<td>360</td>
<td>44</td>
<td>32</td>
<td>15</td>
<td>451</td>
</tr>
<tr>
<td>1 icing cycle</td>
<td>1881</td>
<td>360</td>
<td>252</td>
<td>114</td>
<td>2607</td>
</tr>
<tr>
<td>Category Total</td>
<td>2433</td>
<td>431</td>
<td>306</td>
<td>134</td>
<td></td>
</tr>
</tbody>
</table>

Table 7b.
Percentage Distribution of Data in (7a) for each Row (Icing Rate)

<table>
<thead>
<tr>
<th></th>
<th>Snowfall &lt; 0.1&quot;/hr</th>
<th>Snowfall 0.1 - 0.3&quot;/hr</th>
<th>Snowfall 0.3 - 0.8&quot;/hr</th>
<th>Snowfall &gt; 0.8&quot;/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>4+ icing cycles</td>
<td>74.0%</td>
<td>12.0%</td>
<td>12.0%</td>
<td>2.0%</td>
</tr>
<tr>
<td>3 icing cycles</td>
<td>80.8%</td>
<td>10.3%</td>
<td>6.8%</td>
<td>2.1%</td>
</tr>
<tr>
<td>2 icing cycles</td>
<td>79.8%</td>
<td>9.8%</td>
<td>7.1%</td>
<td>3.3%</td>
</tr>
<tr>
<td>1 icing cycle</td>
<td>72.2%</td>
<td>13.8%</td>
<td>9.7%</td>
<td>4.4%</td>
</tr>
</tbody>
</table>

Table 7c.
Percentage Distribution of Data in (7a) for each Column (Snowfall Rate)

<table>
<thead>
<tr>
<th></th>
<th>Snowfall &lt; 0.1&quot;/hr</th>
<th>Snowfall 0.1 - 0.3&quot;/hr</th>
<th>Snowfall 0.3 - 0.8&quot;/hr</th>
<th>Snowfall &gt; 0.8&quot;/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>4+ icing cycles</td>
<td>3.0%</td>
<td>2.8%</td>
<td>3.9%</td>
<td>1.5%</td>
</tr>
<tr>
<td>3 icing cycles</td>
<td>4.8%</td>
<td>3.3%</td>
<td>3.3%</td>
<td>2.2%</td>
</tr>
<tr>
<td>2 icing cycles</td>
<td>14.8%</td>
<td>10.2%</td>
<td>10.5%</td>
<td>11.2%</td>
</tr>
<tr>
<td>1 icing cycle</td>
<td>77.3%</td>
<td>83.5%</td>
<td>82.4%</td>
<td>85.1%</td>
</tr>
</tbody>
</table>

Although these tables point out the somewhat inverse relationship between precipitation rates and SLW density as inferred by icing counts, it is important to emphasize (as mentioned previously in this section) that significant snowfall and
significant icing sometimes occur simultaneously. This is important in terms of identifying situations that may be ideal candidates for increasing the natural precipitation via cloud seeding.

3.3 Storm Temperature Structure During Icing Periods

The temperature structure of the cloud bearing layer up to about 500 mb (~18,000 feet), and particularly below the 700-mb (~10,000 foot) level, is a major factor regarding the seedability of a given cloud system. Three key factors pertaining to the atmospheric temperature structure, especially in relation to use of ground-based seeding, are:

- The height of the seeding material maximum (warm) nucleation activation temperature threshold (~ -5 C) relative to the mountain barrier height.
- The temperature range within the SLW layer, since that affects natural and induced ice particle habits (shapes) and their growth rates.
- The degree to which the atmosphere from the surface to the top of the SLW layer is thermodynamically stable or unstable.

The temperature factors can be reasonably well assessed (accounted for) by monitoring of the mountain barrier summit temperature. The stability issue is more fully explored in the next sub-section.

The maximum (warmest) nucleation activation temperature threshold for the fast-acting silver iodide formulations acting as condensation-freezing nuclei, as used in Utah, is approximately −4 C to −5 C with the nucleation rate increasing exponentially at colder temperatures. For ground-based seeding releases in (especially) stratiform clouds, it is thus thought that cloud systems with mountain summit temperatures warmer than −5 C offer little opportunity for enhancement using silver iodide. This is due to the relatively weak upward vertical air motion associated with stratiform-type cloud systems. Orographic (terrain-induced) lift can help loft ground-based releases, but consideration must be given to the prevailing wind velocities at varying heights and the barrier shape in terms of the time (distance) available for ice particle growth and eventual fallout into the intended target region. Research has suggested that seeding plumes from ground-based releases fairly commonly rise to 1,000 feet or more above the terrain, even in stratiform situations (Super, 1999). The more-convective cloud types loft the seeding material even higher into the SLW zone, allowing effective ground-based treatment in even warmer situations. Airborne seeding could potentially be more effective in warmer/stratiform circumstances if other conditions (e.g., winds and SLW concentrations) are favorable. Ground-based seeding with liquid CO₂ or propane can expand the warm end of the seedable temperature range somewhat if certain cloud conditions and barrier configuration factors are satisfied.
Earlier research has indicated that the natural precipitation efficiency of some cloud systems can be quite high and that glaciogenic seeding 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.

The data were analyzed to characterize the seasonal temperature characteristics from the cloud seeding perspective. The ice detector site at Brian Head is at 10,900 feet elevation, at or above the summit height of the mountainous terrain in the region, with the only exception being nearby Brian Head Peak (11,300 feet). The Skyline site is at the summit of the mountain ridge at ~9,330 feet. The Dry Ridge site is at 11,450 feet in elevation. Figure 9 shows the seasonal distribution of barrier height temperatures during each 10 or 15 minute observation period with sufficient icing to trigger the detectors’ de-icing heaters. The more southerly location of Brian Head could make it prone to warmer summit temperatures. However, the high elevation of this site is an offsetting factor in this regard. The temperature distribution for icing periods at Brian Head is seen in Figure 9a. (It should be noted that, since 2-degree increments were most reasonable for displaying the data in these figures, statistics regarding the −5 to −15 C temperature window were calculated separately and are summarized in the text). A majority (~60%) of the total measured icing at Brian Head, during the five seasons of data, occurred within the favorable summit temperature window of −5 C to −15 C. Approximately 3.9% of the icing periods were below −15 C at Brian Head, and 34.3% occurred at temperatures warmer than −5 C. A significant amount of icing below −15 C would suggest that seeding opportunity is being missed at colder temperatures, according to the generalized seeding criteria used in Utah, but the observed low percentage in this category suggests that in general, little seeding opportunity exists at summit temperatures colder than −15 C.

Similar plots for Skyline (elevation ~9,330 feet) are shown in Figure 9b. For the five-season data set at Skyline, 41% of icing occurred at temperatures between −5 and −15 C. Just over 1% of icing was observed at temperatures colder than −15 C, and 58% of icing occurred at temperatures warmer than −5 C.

One noticeable feature of the data from the last two seasons (2012-13, 2013-14) is that a larger percentage of observed icing occurred at temperatures warmer than -5 C than was observed in general during the five seasons of data.

Figure 9c shows the icing temperature plots for Dry Ridge. At Dry Ridge, about 59% of the icing occurred within the -5 to -15 C temperature range. About 39% was observed at warmer temperatures and 2% at colder temperatures. Although the 2012-13 season had approximately 53% of the icing periods warmer than the seedable criteria, this last season (2013-14) had a different temperature distribution, with only 20% of the icing measured in an environment too warm for seeding. Note that although the Dry Ridge site is the highest of the three in elevation, and also situated fairly far
north within the state, the majority of the icing there occurred during southerly wind situations, likely helping to explain the relative warmth of the temperatures associated with some of the icing there.

**Figure 9a.** Temperature distribution during icing periods at Brian Head, individual and combined seasons
Figure 9b. Temperature distribution during icing periods at Skyline, individual and combined seasons
Figure 9c. Temperature distribution during icing periods at Dry Ridge, individual and combined seasons
The data from these three sites suggests that very little seeding opportunity is being missed at the cold end of the spectrum, although real-time monitoring of ice detector data (at all sites) may lead to recognition of some seedable storm periods at temperatures below −15°C. At the warm end of the temperature spectrum, a significant amount of icing (roughly around a third to half of the total, depending on the site) has been 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-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 much colder.

Additionally, the average site temperature was compared for periods with various icing intensities. This comparison was primarily based on data from Brian Head, which exhibits a wide range of icing intensities from 1 cycle to as many as 8+ cycles during individual 15-minute observation periods. This comparison at Brian Head showed that the average temperature associated with the more intense icing periods (with 4 or more cycles in 15 minutes) was somewhat warmer than that for the 1-cycle periods (−5.6°C vs. −7.8°C, respectively). A similar examination of icing data at Skyline shows a very warm average temperature (−1.5°C) for periods with 2+ icing cycles, although there are only 26 such periods in the data set. The average temperature at Skyline for all single-cycle icing periods was −4.8°C. The average site temperature for all icing periods was −7.5°C at Brian Head and −4.9°C at Skyline. A similar pattern was noted at Dry Ridge. Median temperatures are similar to the mean values in this analysis.

### 3.4 Atmospheric Stability During Icing Periods

To affect precipitation increase by cloud seeding, silver iodide nuclei must reach supercooled cloud regions at or colder than approximately −5°C to nucleate SLW droplets. 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 (Super, 1999). This is the pool of SLW to be tapped by cloud seeding. However, if the stormy air mass has a stable temperature lapse rate, valley level silver iodide releases can be trapped, i.e., their upward vertical transport inhibited. Conversely, in an air mass exhibiting an unstable lapse rate, seeding plumes are readily lofted by thermals and orographic lift. Thus, it is important to assess the icing data with thermodynamic stability in mind. Low-level stability is sometimes referred to as a temperature inversion, although true temperature inversions (where temperature increases with height in a given layer) actually represent only a subset of possible stable temperature profiles.

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. NAWC has used this method for stability analyses 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. One primary advantage of this method is the ability to conduct thermodynamic stability analyses in any area that temperature and dew point data are available from sites at appropriate elevations, with a time resolution (usually hourly or better) determined by the available data.

NAWC utilized data from surface sites to estimate low-level thermodynamic stability during periods with recorded icing in the data set. Temperature and dew point information at Spring City (5,800’), south-southwest of the Fairview area, was compared to site temperatures at Skyline (9,330’) during icing periods for the three seasons of data. This comprehensive stability analysis was conducted for the Skyline site because it is representative of much of the north-south oriented mountain/valley terrain profile in many of Utah’s seeded areas. Referencing a skew-T plot allowed the dry and moist adiabatic lapse rates to be compared to the difference in temperature between a corresponding valley and mountain 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 degrees C of stability),
MS   Moderately stable (~ 2-4 C of stability) and
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 valley or foothill seeding site. A slightly stable situation would likely be seeded also, 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 areas of good vertical mixing. Seeding from valley sites would generally be avoided in a moderately or very stable situation, although seeding material initially trapped by a thermodynamically stable atmosphere may sometimes become effective later if the situation changes. Seeding from foothill or higher elevation sites may be utilized in these more stable situations when possible.

The primary analysis of stability for the Skyline area, as presented in Section 3.4.1, is based on this two-surface site method and is an update of that presented in previous reports. The Skyline area is particularly favorable for this type of analysis due
to the alternating mountain/valley terrain profile, oriented in a north-south direction, which is similar to most of the cloud seeding target areas in Utah. Additionally, stability indications obtained by the two-surface-site method in the Brian Head area, the Salt Lake City/Snowbird area, and the Uinta Basin, are included along with those obtained in the Skyline analysis. Analysis site locations around the state are indicated in Figure 10.

The reader should note that much of the information contained in this section of the report is from earlier analyses which were similarly described in the 2013 report, although some updates and additions have been made where appropriate. The various low-level stability analyses have been retained in this year’s report in order to demonstrate the full scope of the recent analysis that has been conducted by NAWC on this topic, as this is an important issue for ground-based seeding programs in the mountainous western United States.

Figure 10. Stability analysis surface site locations, with multiple locations within the red outline near the Uintas and Uinta Basin
3.4.1 Results of the Two-Site Stability Analyses in the Skyline area

For stormy periods at the Skyline site, it was found that during the period of November – April where the site temperature (approximately the 700-mb level) was between –5 and –15 C, about 57% of the icing periods during the five seasons of data were associated with a generally well-mixed atmosphere down to the valley floor. Another ~27% of these periods were rated as “slightly stable” for the three-season period, for a total of ~85% (after rounding) where seeding effectiveness would probably NOT be seriously impaired by atmospheric stability. The percentages for the four stability categories are shown in Figure 11. Another important indication in this analysis is that very little thermodynamic stability occurs during the spring months after about March 1, so that the late-season seeding operations extension period funded by the Lower Basin States (which normally begins mid-March) should be generally free of seeding limitations due to low-level stability. The seasonal distribution of stability for the Skyline area, for the three-season data set, is shown in Figures 12 and 13.

![Figure 11. Skyline stability analysis by category, five-season composite; ground-based seeding potential is implicated for the neutral (N) cases, with likely seeding potential for the slightly stable (SS) cases as well.](image-url)
Figure 12. Seasonal distribution of atmospheric stability categories during icing periods at the Skyline detector site, associated with a site temperature between –5 and –15 C, 5 winter seasons. Corresponding stability categorizations are labeled at right. Icing periods that fall on the 0 line at the bottom of the plot are the neutral (well-mixed) cases, with increasing stability indications with height above this line in the plot.
Figure 13. Monthly five-season composite of the percentage of well-mixed (blue) and all potentially seedable (red) time periods when SLW is occurring at the Skyline site and the site temperature is between –5 and –15 C. The “potentially” seedable periods in this plot (red trace) include periods that are rated as either well-mixed or only slightly stable. Sample sizes: Nov=29; Dec=56; Jan=79; Feb=95; Mar=76; Apr=88

Thermodynamic stability in the Skyline area was also examined in relation to the various synoptic scale weather situations as described in Section 3.3. The results are shown in Figure 14. The stability during icing periods for the three seasons thus far are quite similar for most of these synoptic categories, with 85% or more of the icing periods likely to be seedable from valley locations when the site temperature was in a favorable range. The exception to this is pre-frontal situations, when only 35% of these icing events were rated as well-mixed from the valley floor, and just over 74% were rated as either well-mixed or slightly stable, i.e. with good seeding plume dispersion likely.
Figure 14. Synoptic category five-season averages of the percentage of well-mixed (blue) and all potentially seedable (red) time periods when SLW is occurring at the Skyline site during the November – April seasonal period, and the site temperature is between –5 and –15 C. The “potentially” seedable periods in this plot (red trace) include periods that are rated as either well-mixed or only slightly stable. Category sample sizes (left to right): 34, 128, 193, 15, 53.

3.4.2 Two-Site Stability Analysis in the Brian Head area

A more abbreviated stability analysis was conducted for the Brian Head area using the basic two surface-site temperature methodology, focusing on storm periods with significant amounts of icing and site temperatures below –5 C. That analysis used the Cedar City airport as a valley temperature comparison site during storm events where temperatures were in the “seedable” range and there was substantial icing activity at the Brian Head site. The analysis was based on significant storm events during all five seasons, although the 2009-2010 season had missing ice detector data from December 8 – February 11. Altogether, about 40% of the periods examined appeared to be entirely well mixed, and another ~34% were rated as “slightly stable”. Approximately 18% were in the “moderately stable” category, and around 9% were rated as “very stable”. These results are similar to those for the Skyline site, with seeding material likely to have reasonable vertical dispersion in approximately 74% of storm periods when crest-level temperatures are cold enough for effective seeding and crest height icing is occurring.
3.4.3 Stability Analyses in the Uinta Basin

The Uintas Region differs dramatically from the north-south oriented basin and range topography that exists over much of Utah and the Great Basin region. The Uinta Basin lies south of the east-west oriented Uinta Range, with the main portion of the basin being fairly round although elongated somewhat in the east-west direction. The Uinta Basin is bounded on the north by the Uinta Range, with the crest elevation ranging from approximately 8,000 to 12,000 feet MSL. It is bounded by the Wasatch Plateau on the west (generally 8,000 to 9,000 feet MSL), the Tavaputs Plateau on the south (generally 7,000 to 9,000 foot crest height) and various ranges and plateau areas to the east, in northwest Colorado (generally 6,500 to 8,000 foot elevation range). The Uinta Basin reaches elevations below 5,000 feet MSL in its central, lower portion. Although it is not technically a closed basin, as the Green River runs through the Uinta Basin and cuts southward through the Tavaputs Plateau, the long, narrow and winding nature of the canyon along the Green River’s course out of the basin means that for meteorological purposes it essentially acts as a closed basin. This unique topography often results in a semi-permanent winter cold pool or inversion in the Uinta Basin, which may persist for most of the winter season. A feedback loop may also develop between snow cover and the basin cold pool, with each helping to reinforce the other.

A North American Weather Consultants report (Sutherland, 1979) discusses temperature inversion characteristics based on storm period rawinsonde observations at a site near Roosevelt, Utah (elevation 5,171’) in the Uinta Basin during the 1977-1978 winter season. This was the first rawinsonde data available in this area for examining low-level stability and its potential impact on cloud seeding operations. A total of 102 rawinsonde soundings were conducted from this location during the December – April period. Sutherland notes that the Uinta Basin soundings were distinctly different and showed a much greater degree of low-level stability than similar soundings conducted in some other locations around the state (which include Beaver, Blanding, and Milford in the central and southern portions of the state). It is stated that some type of temperature inversion was present in about three-quarters of the Roosevelt (Uinta Basin) soundings, which were essentially all conducted during storm events. Sutherland also notes that deep (or “elevated” inversions, as they are referred to in the report) were much more common there than shallow, surface-based inversions. While the shallow, surface-based inversions show a strong diurnal dependence (occurring primarily during the night and early morning) and little or no seasonal dependence, the deeper or elevated inversions exhibited the opposite characteristics with a strong seasonal dependence (generally occurring in December – February) but little or no change according to the time of day. In this study, the 13 surface-based inversions had a mean depth of about 1340 feet AGL, while the base and top height of the elevated inversions averaged 1480 feet and 2620 feet AGL, respectively. Sutherland also states that the deeper, elevated inversions were more common in the warm-sector (pre-frontal) portion of storm events and were less common post-frontally, although only about half of the observed cold frontal passages were strong enough to mix out the deeper inversions when they existed. Finally, Sutherland mentions the likely
role of snow cover in the Uinta Basin and its assumed impact on the magnitude and persistence of the inversions.

The description of inversion (which could also be referred to as basin cold pool) behavior in the 1979 report agrees very well with what NAWC has observed during the past 11 winter seasons of the currently active seeding program on the south slope of the Uintas, beginning in the 2002-2003 season. Although there are no rawinsonde data in the Uintas area currently available for analysis, the aim of this particular analysis is to expand on the previous analysis of stability and cold pool behavior in the Uinta Basin and along the southern flank of the Uinta Range, utilizing surface data at various elevations and NAWC’s previously established 2SS analysis method. This methodology can be applied to sites at multiple elevations to provide estimates of stability between the basin and crest height.

In the summer of 2012, NAWC began a new analysis of stability in the Uinta Basin as described in the following sections. The analysis methodology and results, as well as implications for cloud seeding programs of this type, are discussed in a published journal article in the Journal of Weather Modification entitled “Low-Level Stability During Winter Storms in the Uinta Basin of Utah: Potential Impacts on Ground-Based Cloud Seeding” (Yorty et. al., 2013). This journal article is also available on the NAWC website (www.nawcinc.com/publications.html).

3.4.3.1 Methodology of the Uinta Basin Stability Analysis, 2009-2012

Because of a lack of ice detector data in the Uintas prior to the 2012-2013 season, data were collected at hourly intervals during periods that were judged to have cloud seeding potential based on NAWC’s generalized cloud seeding criteria as summarized in Table 1. The data were collected for the November – April period during the 2009-2010, 2010-2011, and 2011-2012 winter seasons, when the High Uintas Seeding program was active. The storm periods selected for this analysis also had southerly component wind flow at and below crest height, most often from the southwest, generally representative of warm-sector (pre-frontal) conditions when seeding may be considered from south-side sites. These storm periods include periods when seeding was actually being conducted from south-side sites, as well as periods which appeared to have seeding potential apart from thermodynamic stability considerations. The sample size for these three seasons is 575 individual hourly observations during 30 storm periods, ranging in length from a few hours to a few days.

Observations from multiple automated stations were utilized in a variation of NAWC’s 2-site analysis (2SS) method, which can be adapted to include data from multiple sites at various elevations. Data from paired sites can be used to estimate the amount of thermodynamic stability in the layer between the site elevations. Data were collected from sites at elevations ranging from 11,000 feet in the High Uintas seeding target area to around 5,000 feet in lower portions of the Uinta Basin.
3.4.3.2 Results of the Uinta Basin Stability Analysis, 2009-2012

For the November – April period as a whole, data collected for this study suggests that seeding from near the bottom of the Uinta Basin (e.g. Duchesne) would only mix out effectively about 33% of the time during these storm periods with southerly component winds, using the 2SS analysis method. This reinforces the decision not to locate seeding sites in lower portions of the Uinta Basin, and compares reasonably well (considering differences in seasonal period and methodology) with the result of the Sutherland study in which only 25% of soundings from the Uinta Basin were found to be free of inversions during storm periods.

The data indicate that mid-elevation areas on the southern flank of the Uintas (roughly between 6,500 and 8,000 feet in elevation) often exhibit a large amount of site-to-site surface temperature variability, perhaps varying due to measurement site exposure and/or variations in topography. Sites located in canyon bottoms may be impacted by cold air drainage through these canyons, and may differ significantly from other sites in the same elevation range. The mid-elevation data sites are most representative of current southern flank seeding site locations, however, and the 2SS analysis results for these sites, as a whole, suggest that seeding material would be likely to mix out effectively in close to half (48%) of the storm periods in the current study.

Analysis of SNOTEL temperature data higher in the target area suggests that adequate dispersion of seeding material from near the 9,500 foot level would likely occur about 88% of the time, far better than for the lower and mid-elevation locations.

It should be noted that the results which are considered “likely” to result in adequate dispersion of material are based on combining analysis results having “N” and “SS” stability ratings, meaning there is less than 2 degrees C of integrated thermodynamic stability in the layer examined (in this case, the elevation band between a given site and the 11,000 foot level).

Figure 15a shows the overall “seedable” percentages for the entire November – April period.
Figure 15a. Overall percentages of “seedable” (N or SS) cases for November – April at various elevations on Uintas south slope

Results of the analysis also suggest a very strong seasonality to the cold pool development in the Uinta Basin. In this particular analysis, the month of December had the largest total amount of storm period data, with 173 of the 575 hourly analysis points (30% of the total). These December events were also the most stable of any month, with indications of essentially 0% seedability from the bottom of the Uinta Basin during the December set, 17% and 28% from two mid-elevation sites, and 73% from a high elevation site. These December events in the analysis were all during either December 2009 or December 2010, both months in which substantial snow cover was present in the Uinta Basin. Thus, the December portion of the data set is likely representative of many of the worst-case cold pool scenarios, and it appears that the mid-elevation southern flank sites were greatly affected by these deep cold pool events. There were indications of lesser amounts of thermodynamic stability extending up to near or above 9,500 feet in some of these December events.

Another month that is well represented in the data set is April, with 116 of the 575 hourly analysis point, or 20% of the total. As expected, the April events exhibit the least amount of thermodynamic stability of any month in the analysis. The analysis results suggest that 80% or more of the April storm periods in the analysis set were seedable from all elevations, including the lower portion of the Uinta Basin. Most of the lower-level stability observed during March and April (particularly April) appears to be of the shallow nocturnal variety.

The months of November and February have the smallest sample sizes in this data set, with 30 analyzed hourly observation periods in November and 75 in February. Typically, these are transition months representing the development and dissipation, respectively, of the persistent winter cold pool and inversion conditions in the Uinta Basin. The seasonality of these basin cold pools is highly correlated with sun angle, which of course reaches a minimum about December 21. It is believed that snow cover in the Uinta Basin also plays a significant role in the strength and seasonality of their
development. In some years, the accumulation of a substantial winter snowpack in the Uinta Basin may prolong the existence of a deep cold pool into early March.

Due to the somewhat irregular seasonal distribution of storm periods in the 3-season data set, attempting to sub-divide the November – April season into smaller units (such as individual months) presents serious sample-size problems, particularly in regard to the number of storm events used to compile the data. However, examination of the data shows strong seasonal trends in lower-level stability along the southern slope of the Uinta Range, and some conclusions can be drawn. These results are illustrated in Figure 15b.

For the December - January period, it appears that very few (probably less than 5%) of the storm periods would be seedable from the lower portion of the Uinta Basin, based on the surface data at Duchesne. This is the portion of the season when the sun angle is lowest, making conditions favorable for the development of deep and persistent temperature inversions and cold pools in the Uinta Basin. Indications for this mid-winter period are highly variable for the mid-elevation areas, making a definitive conclusion more difficult in these areas based on surface data alone. It appears that likely between 20-40% of the mid-winter storm periods have adequate dispersion for seeding at the mid elevations. For higher elevations within the target area (~9500’), it appears that perhaps 75-80% of the December - January periods would likely have adequate mixing.

During the spring portion of the operational season (In this analysis, March 15 through the month of April) stability does not appear to be a frequent concern. The sun angle is high enough during this period that any snow cover at lower and mid elevations tends to melt quickly, and any low-level inversions that develop tend to be shallow and limited mainly to the night and early morning hours. The current data suggests that mixing is adequate for dispersion of material at lower and mid elevations in well over 80% of spring storm periods, and in nearly all spring storm periods from higher-elevation sites. In fact, the southern slope of the High Uintas can be a favored location for daytime convective development during the spring, which may present favorable seeding opportunities from south-slope sites.

The remainder of the operational season (November, as well as February through early March) is believed to be quite variable in terms of the potential development of inversions and cold pools in the Uinta Basin. It is likely that factors such as low-elevation snow cover may play a particularly important role in regulating the development and behavior of Uinta Basin cold pools during the early and later portions of the winter season.
Percentages of “seedable” (N or SS) cases for Dec – Jan

Percentages of “seedable” (N or SS) cases for late Mar – Apr

Percentages of “seedable” (N or SS) cases for Nov, Feb, early Mar

Figure 15b. Seasonal stability analyses results along southern slope of Uintas
Similar to the analysis conducted in the study for central Utah and the Salt Lake City areas (Yorty et al., 2012), the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model was utilized to compare with likely seeding material dispersion estimates based on surface data using the 2-site (or multiple-site) analysis technique. The HYSPLIT model was developed as a joint effort between the U.S. National Oceanic and Atmospheric Administration (NOAA) and Australia’s Bureau of Meteorology, and uses meteorological forecast and analysis data to approximate the three-dimensional trajectory and dispersion of particles emanating from a single point or multiple points, during a specified time period. The HYSPLIT model can be used in conjunction with either archived or real-time meteorological model analysis and forecast data. For this study, the model was used in the context of comparing ground-based (modeled) plume behavior with that inferred by the two-surface-site stability analysis along the southern flank of the Uintas and in the Uinta Basin. Archived North American Model (NAM) 12-km resolution model data were used in HYSPLIT to simulate ground-based plume releases from three sites in central Utah. The HYSPLIT model accepts additional input data including latitude/longitude of the release sites and height of the release relative to the surface, start time and duration of the simulated particle release, emission rates, and the grid size and spacing for each modeled period. The terrain surface elevation at each release point is determined by the model data that is used (in this case, the 12-km NAM).

Although the comparison of the HYSPLIT output with NAM data to the 2SS indications has shown very good agreement in some other areas, including central Utah as well as the Salt Lake City area (Yorty et al., 2012), in the Uinta Basin region this did not prove to be the case. In many cases, it was found that HYSPLIT model was suggesting significant plume dispersion from lower and mid elevation locations in cases where the 2SS analysis showed extreme low-level stability, including an inverted low-level temperature profile. Additional investigation showed that the NAM data used in the HYSPLIT modeling contained much warmer lower-level temperatures for the Uinta Basin and southern Uintas flank areas than surface data indicated. In some cases, NAM model data was as much as 5-10°C warmer than observations in the lower Uinta Basin, and commonly 1-4°C warmer than observations at mid-elevation sites. Additional examination of the NAM model boundary conditions and initialization revealed that very few, if any, surface observations from the Uinta Basin are utilized in the model initialization. This implies that model fields in the Uinta Basin are interpolated from conditions at first-order stations in the region. The difficulty that the model has in dealing with cold pools and inversions confined to basin areas is highlighted in (Reeves and Stensrud, 2009).

Despite the NAM model’s current inability to initialize and model the behavior of cold pools that are confined to the Uinta Basin, there are other storm periods in the analysis where the lower-level air mass was quite stable over the region as a whole, yielding model results that agreed very well with 2SS indications. One of the more
noteworthy observations for thermodynamically stable warm-sector (southerly wind component) storm periods in general, based on the HYSPLIT modeling, is that much of the lower level air mass on the southern side of the Uintas often appears to be diverted westward around the Uinta Range. Easterly flow was observed in lower portions of the basin in most of these warm-sector storm situations, including periods with southwesterly large-scale flow at the 700-mb level and above. Easterly component flow was also commonly observed in mid-elevation areas (roughly 6,500 to 9,000 feet) on the southwestern side of the Uinta Range due to channeling of winds around the western side of the higher terrain barrier. During warm-sector storm periods, surface pressure on a synoptic scale is generally lower to the north and west, frequently resulting in a westward channeling of the lower level air mass on the southern side of the Uintas. This is most pronounced during thermodynamically stable situations when most of this air mass is too stable for widespread ascent over the range. This may result in deepening of the cold pool on the western side of the Uinta Basin, where some of it likely spills over the Wasatch Plateau to the west of the basin, at an elevation of around 8,000 feet, in some of the deeper cold pool situations. This is in good agreement with other surface observations in this region, which have commonly indicated easterly component flow around the southwestern side of the Uintas during warm-sector storm periods.

3.4.3.4 Uinta Basin Stability Analysis Based on Dry Ridge Icing Data

Adding to the previous work described in the above subsections (3.4.2 and 3.4.3), thermodynamic stability analysis was conducted for the 2012-2013 and 2013-2014 seasons using periods of measured icing at Dry Ridge, using the same surface-site stability analysis methodology (described in Section 3.4.4.1). The stability analysis utilizing Dry Ridge ice detector data was based on icing periods with a temperature colder than -5 C and southerly component flow (suggesting the potential use of south-side seeding sites). The results of this new analysis appear somewhat similar to the published analysis results in Yorty et al., 2013 (summarized in Section 3.4.4.2 of this report), although the storm event sample size based on actual ice detector data meeting the specified criteria is fairly small at this point. Additional seasons of ice detector data will be important in order to fully analyze and document the stability characteristics of the Uinta Basin and Uintas south slope area.

Figure 16 shows the estimated “seedable” percentage based on thermodynamic stability, for different elevation ranges along the southern side of the Uintas. This is based on data during 19 storm periods with measured icing at Dry Ridge during the 2012-2013 season and 18 storm periods during the 2013-2014 season with southerly component flow and a site temperature colder than -5 C. Figure 16 can be compared to Figure 15a in Section 3.4.4.2, which shows the results based on 2009-2012 warm sector storm periods for which the initial analysis was conducted. Due to the limited sample size of the Dry Ridge ice detector data thus far, this associated stability analysis results have not been seasonally sub-divided.
Figure 16. Estimated “seedable” percentage (rated as “neutral” or “slightly stable”) for various elevation ranges, for relevant storm periods with icing at Dry Ridge during the 2012-2013 and 2013-2014 seasons. This figure can be compared to Figure 16(a) in Section 3.4.4.2.

3.4.4 Summary of Low-Level Stability Indications in Utah

In summary, implications are that valley or foothill-based seeding material releases in most areas of Utah are likely to experience timely and effective dispersion to the barrier crest height in a large percentage (likely ~75%) of crest-height icing periods when temperatures are cold enough for seeding. These findings are considered representative of most of the seeding target areas in Utah, and are significant and particularly relevant in that they focus on stormy periods when SLW is being generated by orographic lift.

3.5 Icing and Wind

For the 2013-2014 season, wind plots were produced for all icing events at the three sites, as well as for the icing occurring at temperatures colder than -5 C. This comparison helps to provide additional insight regarding the types of wind patterns that are likely favorable for seeding operations. Previous analyses (such as those presented in the 2012 report) have dealt with related issues such as terrain channeling of the observed site winds. These observations are useful regarding the siting of seeding locations relative to the surrounding terrain, as well as opportunity recognition during real-time operations. For example, seeding generators located near canyons or terrain “catch” areas are likely to be particularly effective due to the lifting of a large amount of the lower level air mass over the mountain barrier.
Figure 17 contains wind plots for the Dry Ridge icing periods during the 2013-14 season, with all icing periods represented in 17(a) and only icing colder than -5°C in 17(b). Similar plots for Brian Head and Skyline are shown in Figures 18 a,b and 19 a,b. As noted in previous reports, the Skyline winds are likely poorly representative of larger scale weather conditions due to local terrain channeling of winds near the site, but are shown in this section for comparison with the other sites. It was also demonstrated (as described in the 2012 report) that significant channeling of surface winds occurs at the Brian Head site, with site winds frequently northerly to northeasterly in association with northwesterly winds in the surrounding environment.

Figure 17a. Dry Ridge winds for all icing periods, 2013-2014
Figure 17b. Dry Ridge winds for all icing periods colder than -5 C, 2013-2014
Figure 18a. Brian Head winds for all icing periods, 2013-2014
Figure 18b. Brian Head winds for all icing periods colder than -5 C, 2013-2014
Figure 19a. Skyline winds for all icing periods, 2013-2014
Figures 17-19 demonstrate, as would be expected, that icing events associated with more northerly component winds tend to also be associated with temperatures colder than -5 C. It is particularly evident in the Brian Head plots (Figures 18 a,b) that the many of the heavy icing periods associated with southerly component winds were also warm, while nearly all of the the heavy icing associated with northerly component winds occurred at temperatures colder than -5 C. It also appears that of all the icing occurring at temperatures colder than -5 C, that associated with southerly component winds tends to be somewhat lighter in nature than for northerly component winds. At Dry Ridge, however, where the vast majority of the icing occurred during southerly wind periods, some of the heavier (2-cycle) icing periods were observed at temperatures colder than -5 C. These plots also serve to highlight the differences between the ice
detector sites in terms of observed wind direction when icing is occurring. Rather than simply drawing general conclusions about icing and wind direction, these insights can be useful to the meteorologist in terms of seeding operations targeted to specific mountain barriers, based on an understanding of how the various seeding target areas differ meteorologically.

3.6 Seasonal and Diurnal Distribution of Icing

As has been discussed in previous reports, it is likely that significant seasonal and diurnal differences occur in most areas with regard to the general seedability of storm events. Ice detector observations have shown a tendency for heavy icing during spring storm events (the month of April in particular), with fall (e.g. November) also having a fair number of heavy icing events. Spring storm periods in the mountainous western U.S. are likely to present some ideal seeding opportunities based on observed temperatures and atmospheric mixing, associated with convective activity and some heavy icing episodes.

Close examination of some of the data suggests a possible window of particularly favorable conditions occurring during the afternoon hours (roughly 1200 – 1800 local standard time) in a climatological sense. It is likely that observed diurnal variations are highly seasonal in nature, occurring mainly during the spring months when the sun angle is highest for the November – April seasonal period. Curiously, a general minimum in total icing activity is observed in much of the icing data during the midday or afternoon hours, but with significant variations apparent in this pattern from site to site and within the winter-spring seasonal period. The midday/afternoon icing minimum is likely due to a combination of several factors, including warming temperatures (potentially to near or above freezing at the site), changes in cloud base height which may rise to well above the mountain crest in the afternoon hours, and possible effects of solar radiation on the rate of ice accumulation on the icing sensor itself. Of these factors, the change in cloud base height during many spring storm events may be the most significant, resulting in a situation where the icing sensor is below the cloud base even though there may be a lot of SLW development at a higher altitude.

A closer look at the data from the Brian Head site (particularly favorable for such an analysis) hints at some potential factors that may suggest significantly more seeding potential during the afternoon hours (likely to be most significant during spring storm events). Although the total icing activity, and particularly the number of 15-minute observation periods with icing, is significantly lower during the afternoon hours, it was discovered that the average icing intensity (cycles per 15 minutes) is higher during this period when icing is observed. Further, the average precipitation rate during periods with icing is largest during the afternoon hours, which has some possible implications in terms of both thermodynamics and cloud structure/microphysics. Essentially, during many storm periods when the sun angle is relatively high, a significant amount of convective activity occurs, in contrast to mostly orographic lifting of the lower level air.
mass at other times in the vicinity of major mountain barriers. Not only does the higher
sun angle tend to eliminate lower atmospheric thermodynamic stability (thus making
conditions particularly favorable to ground-based seeding), but the structure and
microphysics of the clouds may differ significantly during these periods of higher sun
angle than during most other cold season storm periods. Some of the icing observed
at the ice detector sites occurs in association with either a shallow, non-precipitating
orographic cloud near/upwind of the crest (“cap cloud” situation), or in situations when
precipitation is occurring from a higher cloud deck but the supercooled cloud is still
shallow and may have little or no contribution to the precipitation process. In these
situations, cloud seeding effectiveness may be limited by the shallow vertical extent of
the supercooled cloud, and/or the limited vertical dispersion of seeding material above
the crest. In contrast, higher average precipitation rates during observed afternoon
icing periods hints that SLW occurring during periods of higher sun angle may more
frequently be directly associated with active precipitation development directly over the
mountain barrier. SLW during these periods is more likely to have a large vertical
extent, with cloud seeding material potentially dispersed through a deep layer of
supercooled cloud. Of course, the mountain crest height temperature is less of a
constraint (on the warm end of the range) during these periods as well, since seeding
material may quickly be carried to elevations far higher than the mountain crest.
Figures 20 through 22 show the total observed icing by hour of the day in the current
data set for Brian Head, Skyline, and Dry Ridge.

Monthly analysis of the diurnal cycle of icing occurrence based on 5 seasons of
data at Brian Head and at Skyline supports the general idea that the spring season is
associated with a strong afternoon minimum in icing (likely centered around 1400-1500
MST). This signal appears particularly strong at Skyline during March and April, and at
Brian Head in March, and is most evident when the hourly data are smoothed to reduce
noise. However, there still appear to be some sample size limitations when looking at
the data this way, with some particularly significant individual icing events strongly
influencing the observed trends when looking at data for an individual month. Diurnal
cycle trends during the other months (November – February) were quite variable and
appear to be mainly determined by individual storm events with a large amount of icing,
making the data very inconclusive so far as to whether any significant diurnal patterns
exist during these months.

Based on all of the above factors, it is believed that cold (winter-type) storm
events during time periods with a high sun angle are likely to present particularly
favorable seeding opportunities in many cases, even though observed icing at the
detector sites may be substantially reduced during periods of high sun angle.
Figure 20a  Brian Head five-season icing totals by hour of the day

Figure 20b  Brian Head five-season icing totals by hour, smoothed
Figure 21a  Skyline five-season icing totals by hour of the day

Figure 21b  Skyline five-season icing totals by hour, smoothed
Figure 22a  Dry Ridge two-season icing totals by hour of the day

Figure 22b  Dry Ridge two-season icing totals by hour, smoothed
3.7 Cloud-Top Temperature Associated with Icing

Cloud-top temperature (CTT) is a meteorological parameter that may have significant implications with regard to the “seedability” of a system or portion of a storm event. It has long been understood (Mielke et al. 1981) that some precipitation systems, particularly those with cold cloud tops, can be fairly efficient naturally due to abundant ice particle production and fallout from colder cloud tops which removes lower-level supercooled cloud droplets. This assumes, of course, that there are no significant dry layers in which falling snow or ice crystals from colder cloud regions can evaporate between cloud layers. Cloud decks with relatively warm tops (in general warmer than -25 C, and especially those with tops warmer than about -15 C) can be naturally inefficient and are believed to be the best candidates for seeding. For this reason, it was considered desirable to include a cloud-top temperature dataset and analysis in conjunction with the other meteorological variables in the ice detector data analysis.

Cloud-top temperature is more difficult to obtain than other measurements in our analysis, since for this project area it is not measured in the same way as other meteorological parameters. For this study, cloud top temperatures were obtained from the National Climatic Data Center (NCDC) via custom data orders of archived satellite data for specified date/time ranges, corresponding to periods of heaviest icing (3 or more cycles per 15-minute period) at Brian Head. The NCDC weather and climate toolkit software was used to determine a representative cloud-top temperature at the latitude/longitude of the Brian Head site for each of the heavy icing periods. It was believed that analyses of these cloud top temperature data might provide helpful information regarding the occurrence of icing periods in our data set. We recognized a significant limitation in the available data, namely the lack of representative rawinsonde (balloon sounding) data during stormy periods, which would help to identify any dry layers between higher and lower cloud decks.

A note of clarification is appropriate here. To objectively address the microphysical relationships important to cloud seeding, and to investigate the true relationship between cloud top temperature and cloud seedability, we would need to determine (if possible) the temperature at the top of the cloud volume involved in the precipitation process (i.e. the effective cloud top), not the temperature of higher clouds such as cirrus that may reside across the region. Unambiguous determination of the effective cloud top temperature requires direct measurement which is beyond the current scope of the seeding projects where the ice detection systems are operated. Nonetheless, we attempted to investigate the CTT/seedability by analyzing some infrared CTT data.

The current CTT analysis included 245 data points (15 minute periods) with at least 3 icing cycles in a 15-minute measurement period at the Brian Head ice detector site, during the previous 5 winter seasons of data. Over 60 separate storm events were represented by these heavier icing periods. Figure 23 is a scatterplot of infrared
satellite-derived CTT versus icing for the analyzed data set. This sample seems to exhibit no obvious correlation between the two, likely due to the limitations in determining the effective CTT. Further analyses were conducted to look more closely at potentially important variables. Since colder cloud tops are generally believed to be associated with naturally efficient storms, one would also expect the snowfall rate to generally increase with decreasing (colder) cloud top temperatures. Plotting cloud top temperatures versus the Brian Head site snowfall rate (Figure 24) also did not show an obvious correlation for this subset of the data, again likely due to the CTT data limitations.

Computing the overall CTT statistics for this set of heavy icing periods revealed that just over 41% of them had cloud top temperatures warmer than -25 C, and about 27% were warmer than -15 C. The remainder (majority) of these heavy icing periods appeared to be associated with relatively cold cloud tops. Table 8 shows these percentages in relation to the number of icing cycles per 15-minute period. This means that over half of these time periods with intense icing activity were associated with fairly cold cloud tops (below -25 C), where the upper portions of the higher clouds most likely consisted of all ice, as SLW becomes relatively rare at temperatures colder than about -20 or -25 C in winter storms. Closer analysis of a few storm events with some of the coldest cloud top temperatures in the data set (colder than -55C) uncovered at least a couple of cases with very substantial dry layers in the mid-levels apparent at the closest available RAOB sounding site (near Las Vegas). Some dry layers were quite significant and likely representative of a large geographic region including the Brian Head area. Since there are no known measurements near Brian Head that could objectively indicate a continuous cloud layer from the site to the effective cloud top (where the CTT should ideally be measured for this type of analysis), there is no simple way to identify data points that correspond with (relatively common) situations with dry layers or multiple layers of clouds. However, it is clear that if one could obtain a CTT for only the cloud layer in which icing was measured (i.e. an effective cloud-top temperature), some of the very cold cloud-top temperatures would be much warmer. The large potential difference between CTT (obtained from the uppermost cloud layer) and the effective cloud top temperature of a lower layer directly involved in icing activity is a major difficulty involved in attempting to use CTT to estimate the seedability of a given storm period.

One insight into this problem stems from our previous work with this type of icing detector data in Utah, suggesting a (negative) correlation between icing occurrence and precipitation rate during a given storm event, presumably due to scavenging of supercooled water droplets by falling snow. The fact that the current data set showed no substantial correlation between CTT and precipitation rate for these heavy icing periods (Figure 24) may offer an additional clue as to why many of these heavy icing periods were associated with quite cold infrared satellite-derived CTT. It is likely that the amount of snowfall being produced in cloud layers significantly above the mountain crest is much more closely related (in a negative sense) to SLW occurrence than is infrared satellite CTT.
In summary, infrared satellite-derived CTT analysis showed many periods with fairly cold CTT (colder than -25 C) during periods of heavy icing at the Brian Head site. The implication is that the relationships between the temperature of the highest cloud layer and other meteorological variables (including SLW) are quite complex, and that infrared satellite-derived CTT by itself may not be an especially useful parameter in determining seedability in these types of winter storm events over mountainous terrain.

**Figure 23.** Scatterplot of cloud top temperature versus number of icing cycles measured in a 15-minute period at Brian Head.
Figure 24. Scatterplot of cloud top temperature versus Snowfall rate measured in a 15-minute period at Brian Head.

Table 8. Percent of Cloud Top Temperatures (CTT) Warmer than -25C or -15C For Each Number Of Icing Cycles

<table>
<thead>
<tr>
<th>Icing Cycles</th>
<th>CTT Warmer Than -25C</th>
<th>CTT Warmer Than -15C</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>32%</td>
<td>21%</td>
<td>145</td>
</tr>
<tr>
<td>4</td>
<td>64%</td>
<td>45%</td>
<td>58</td>
</tr>
<tr>
<td>5</td>
<td>42%</td>
<td>25%</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>50%</td>
<td>25%</td>
<td>16</td>
</tr>
<tr>
<td>7</td>
<td>50%</td>
<td>30%</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>0%</td>
<td>0%</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>0%</td>
<td>0%</td>
<td>1</td>
</tr>
<tr>
<td>ALL</td>
<td>41.4%</td>
<td>27.5%</td>
<td>245</td>
</tr>
</tbody>
</table>
4.0 Case Studies

Analysis of individual storm periods can also reveal useful information regarding the characteristics of the storm types that present significant seeding opportunity, including the synoptic weather patterns most likely to produce good seeding candidates in Utah. Further, seedability can vary considerably within storm periods. The case study approach sheds useful light on the factors that are important to assessing seedability as storm systems evolve and traverse Utah.

4.1 High Uintas / Dry Ridge Ice Detector

The availability of ice detector data at Dry Ridge provides a newer point of comparison to the pre-existing sites, and two storm events were selected from the 2013-2014 season for case study analysis based on the Dry Ridge data.

March 30, 2014

A small upper level low pressure trough was approaching Utah on the morning of March 30. The temperature at 700-mb was near 0 C ahead of the front in the morning and was expected to cool to -5 C by the afternoon. There were 7 icing cycles observed at Dry Ridge between about 0900MST and 1100MST that morning as winds were from the southwest (Figure 25). Around 1300 MDT lower level winds in Salt Lake City were veering to northwest. Within the next two hours seeding generators were turned on for northwest flow as the temperature measured at the Dry Ridge site was around -8 C. The Salt Lake City radar continued to show precipitation throughout the afternoon and early evening hours. Winds were from the northwest throughout the latter half of the day. Periodic rain/snow showers were seen in the Salt Lake City area. By around 2200 MST radar echoes were tapering off and seeding ended. SNOTEL data indicated precipitation totals ranging from 0.3 – 0.8" (water equivalent) throughout the target region.

With this spring storm event, the atmosphere was well mixed and stability was not an issue. Temperatures at 700-mb were, however, too warm for seeding (temperatures warmer than -5 C) until the front passed in the afternoon. Mesowest surface observations around 1300 MST on March 30 (1-2 hours before the front crossed the Uintas) show temperatures in the upper 50’s F in the Uinta Basin with high elevation mountain temperatures in the 20’s F (Figure 26). Indications of the cold front are also shown in Figure 25 as wind barbs northwest of the Uinta Mountains (behind the cold front) are from the northwest with surface temperatures in the 30s and 40s F while winds south and east of the Orem area (ahead of the cold front) are still from the southwest with surface temperatures in the 50s to 60s F. Within the next couple hours the cold front had crossed the Uinta Mountains and Basin and surface temperatures cooled into the 40s F with winds changing to a west-northwest direction.
Since temperatures were generally too warm for seeding until after the frontal passage and corresponding wind shift, HYSPLIT modeling was only conducted for the time period when some seeding generators were running. When predicted plume behavior is modeled for all the program’s seeding site locations (even though in reality most were not active), the wind field was such that only a few generator sites to the north and west as well as two high elevation sites were predicted to reach the target area (Figure 27). To the north of the Uinta Range, the winds had mostly a westerly component making it so only sites south of the Utah/Wyoming boarder could potentially reach the target area.

The Dry Ridge site indicated snowfall from around 0600 MDT through midnight with icing only indicated before noon (refer Figure 25). Icing is usually observed from the Dry Ridge site in pre-frontal conditions (Section 3.1) likely due, at least partially, to its location on a southern peak in the Uinta Range where supercooled water is best measured during winds with a southerly component. This does not necessarily mean that supercooled water was no longer present over the Uinta Mountains after 1200 MDT on March 30, but may rather mean that conditions just were not right for the point sensor to measure the supercooled liquid.
Figure 25. Precipitation, temperature, icing, and wind data from Dry Ridge for March 30, 2014.
Figure 26. Mesowest data at 1200-1300 MDT March 30, 2014, showing the wind shift during a cold frontal passage.
Figure 27. HYSPLIT model forecast of potential plume dispersion from 1900 – 2100 MST (post-frontal) on March 30, 2014.
April 26, 2014

A low pressure system was moving in over Utah on April 26, 2014 with precipitation falling mostly ahead of the main cold front. The morning sounding from Salt Lake City indicated a 700-mb temperature of -2 C. The cloud deck extended up to 30,000 feet with cloud bases appearing to be above mountain crest. The temperature at the Dry Ridge site was around -4 C to -5 C throughout the morning (Figure 28). Southwest flow dominated throughout much of the state ahead of the approaching front and precipitation continued to fall over the majority of the region. Temperatures at Dry Ridge remained around -5 C until around 1600 MDT (4:00 pm) when the cold front came in and the winds shifted from southwest to northwest (Figure 28). Most of the precipitation that fell on April 26 came ahead of the cold front with little afterwards. Since cloud bases were somewhat high, 700-mb temperatures warmer than -5 C, and precipitation tapering off when temperatures started cooling; no seeding was conducted during this event. There were 25 icing cycles observed at Dry Ridge between 0515 and 1515 MDT on April 26. All icing was observed ahead of the cold front in wind flow with a southerly component.

Although this was not a seeded period, HYSPLIT plume modeling was conducted using available ground-based site locations. The HYSPLIT modeling indicated winds from the south and even slightly from the southeast from seeding plumes southwest of the Uinta Range (Figure 29). Dispersion plumes indicate that all sites to the south of the target region would have been favorable for seeding the clouds; however, temperatures were judged to be too warm for seeding during this event.

This case is fairly typical of icing cycles recorded at the Dry Ridge site, with the most icing usually observed during winds with a southerly component ahead of an approaching cold front. Due to the Dry Ridge site location on a southern ridge in the Uinta Range, icing measured during southerly flow is probably more a result of the site location rather than most supercooled liquid only existing in pre-frontal conditions. There is likely supercooled liquid present in wind flow with a northerly component as well its measurement is just missed by the southerly location of the Dry Ridge site. For the April 26 case, precipitation was lacking and clouds were thinning after the frontal passage which is why seeding was not conducted; lack of icing cycle measurements alone from the Dry Ridge site would not be enough evidence for a lack of supercooled water to hold off seeding operations during this event.
Figure 28. Precipitation, temperature, icing, and wind data from Dry Ridge for April 26, 2014.
Figure 29. HYSPLIT model of potential seeding plume dispersion for April 26, 2014 from 1000 – 1100 MDT. Seeding was not conducted unfavorable seeding conditions.
4.2 Brian Head Ice Detector

December 3-4, 2013

A strong cold front worked its way across Utah on December 3-4, 2013. Temperatures at the Brian Head site were around -1 C early in the morning on December 3 and cooled to stay below -5 C by around 1300 MST. Seeding generators were turned on as the front approached site locations with most sites in southern Utah going on between around 1700 and 1800 MST. The Brian Head sensor suite indicated precipitation falling from about 1500 MST (3:00 pm) on December 3 through about 0600 MST (6:00 am) on December 4, with a maximum snowfall rate around 2.9 inches per hour (Figure 30). A total of 14 icing cycles were observed during this event with 10 icing cycle between about 1600 MST and 2000 MST on the evening of December 3. Winds were from the southwest until just before midnight when the flow became northerly, so the first batch of icing occurred in southwesterly flow with the second batch (around 0900 MST on December 4) occurred in northerly flow. Seeding generators were turned off in the morning on December 4 as temperatures at Brian Head had cooled to below -15 C and skies were clearing.

HYSLIPIT modeling for all potential seeding sites during the period indicated very favorable seeding conditions over the target area during the seeded period (Figure 31). Plume dispersions indicate that winds were still southwesterly on the east side of many of the mountain barriers with north winds of the west side. Some model plumes well to the west of Cedar City even indicated winds from the northeast. Many of these seeding generators used during this event were west of target regions. Sites south of the target areas as well as the two sites west of Cedar City show plumes not reaching the target areas were not used during this event. SNOTEL sites around southern Utah indicated between 0.6 – 1.2 inches of snow water equivalent from this storm.

This case is a good illustration of changes in precipitation efficiency during a frontal passage. Figure 32 is a chronological plot of the relative precipitation efficiency in 2-hour time blocks, obtained by comparing the precipitation and icing amounts in each time block. The presence of SLW, as evidenced by ice detector de-icing cycles, is considered to be indicative of untapped (seedable) SLW, thus less than optimal precipitation efficiency. The term relative is used to highlight the relationship between icing and precipitation during a given period. High precipitation combined with low icing (lower right portion of the plot) would suggest relatively high efficiency. Conversely, a high amount of icing in conjunction with little or no precipitation (upper left portion) would suggest relatively low efficiency. This event shows an increase in icing and precipitation during the first 4 hours of the storm under south-southwest flow with temperatures around -7C, followed by a decrease in icing observed as temperatures
cooled to -9C with precipitation continuing to increase, the final 4 hours show a
decrease in icing and precipitation after the wind shifted to northerly and temperatures
cooled to -14C.
Figure 30. Brian Head precipitation, temperature, and icing on December 3-4, 2013.
Figure 31. HYSPLIT forecast plume dispersion around 2100 MST on December 3, for potential seeding sites in southwestern Utah. Black outlines show the approximate seeding target areas.

Figure 32. Relative precipitation efficiency in 2-hour blocks, the first (black ring) starting at 1400 on December 3 and the final time block ending at 0200 on December 4. Average temperature and wind direction for the time block are indicated next to arrows.
Precipitation was falling over much of Utah in the morning of January 30. Most of this moisture was descending from a high cloud deck with cloud tops up to 30,000 feet. Temperatures at 700 mb were warmer than -5°C so seeding generators were not turned on. The Brian Head site indicated precipitation starting around 0900 MST (9:00 am) that ended shortly after 1800 MST (6:00 pm) as shown in Figure 33. Temperatures remained around the -5°C threshold until after 1800 MST when a cold front moved through the area; however, precipitation ended before temperatures cooled very much. Wind speeds started to taper off about the time precipitation ended (just after 1800 MST) as the wind direction changed from west-southwesterly to northwesterly. The highest wind speeds were observed during the heaviest snowfall, with sustained speeds of 15 m/s and gusts to 25 m/s (bottom 2 panels of Figure 31). A total of 21 icing cycles were measured between about 1200 MST (noon) on January 30 and 0400 MST (4:00 am) on January 31. Icing continued to be measure after the precipitation ended around 1800 MST on January 30, however, low level cold air was moving into southern Utah creating stability within the atmosphere as the storm seemed to be tapering off, therefore, no seeding was conducted during this time. As a note, seeding was conducted on the evening of January 31 as conditions seemed favorable (with precipitation picking up again in Figure 31) even though no icing cycles were measured during this time.

HYSPLIT modeling for all potential seeding sites indicated favorable plume dispersion over the target area during the heaviest precipitation on the around 1700 to 1800 MST (5-6 pm) on January 30, however temperatures were still borderline warm for seeding at this time (Figure 34). Plume dispersions indicate that winds were southwesterly. Some model plumes well to the west of Cedar City appear shorter in the simulation results, possibly an indication of low level stability and much lighter wind speeds at lower elevations. For most sites the simulation shows dispersion over a large area within the first hour, consistent with the fairly high wind speeds measured at the Brian Head site during this time.

The relative precipitation efficiency was also analyzed with this case and is shown in Figure 35. This storm exhibited a little more variability than the December 3-4 event, with a slight decrease in precipitation and an increase in icing during the first 2-hour block (black ring shown in the figure). Within the next 2 hours both icing and precipitation increased, followed by a decrease in precipitation and an increase in icing as temperatures started to cool. The next 2 hours exhibited a flow change from southwest to west-northwest as both icing and precipitation dropped to almost zero. Precipitation was not evident during the last 4 hours of the event, although icing
increased for 2 hours before dropping to zero at the end of the storm event. Precipitation was mostly observed during the beginning of this storm as the flow was from the southwest and temperatures were -5 to -6°C, indicating that most snow fell before the cold front passed. Little precipitation was observed after the flow changed to west-northwest and the temperature at Brian Head cooled below -6°C.
Figure 33. Brian Head precipitation, temperature, and icing on January 30-31, 2014.
Figure 34. HYSPLIT forecast plume dispersion around 1800 MST on January 30, for potential seeding sites in southwestern Utah. Black outlines show the approximate seeding target areas.

Figure 35. Relative precipitation efficiency in 2-hour blocks, the first (black ring) starting at 1200 on January 30 and the final time block ending at 0200 on January 31. Average temperature and wind direction for the time block are indicated next to arrows.
February 28 – March 1, 2014

On February 28 a storm system that hit southern California was working its way into southern Utah. Precipitation started in the region that evening; however, temperatures were too warm with the Brian Head site indicating -3 C. Seeding operations began around 2130 MST and continued overnight. Most precipitation overnight seemed to occur before temperatures decreased to within the seedable range, with the Brian Head site indicating precipitation until about midnight on February 28 (Figure 36). The temperature there finally reached -5C by around 0200 MST on March 1. Later that morning some lingering orographic/convective clouds were present over the southwest corner of Utah and seeding continued in areas of southern Utah until around noon on March 1. Heavy icing was indicated at Brian Head during this event with a total of 102 icing cycles. Icing continued from about noon on February 28 to about noon on March 1, with the heaviest icing just before midnight as 7 icing cycles were indicated within a 15 minute period. Icing was apparent through a range of temperatures with this event as icing began with a temperature around -3 C and continued until the temperature was in the -8 to -9 C range. Winds indicated at Brian Head were persistent from the south-southwest with speeds increasing to about 20 m/s with gusts to over 40 m/s during the period of maximum icing (see Figure 31). Storm totals for February 28 through March 1 ranged from 1.1 - 1.5 inches of snow water equivalent from SNOTEL sites in the target area.

Temperatures were not ideal for seeding in this situation until after 0200 MST on March 1 when the temperature cooled below -5 C and continued to cool. The Brian Head site no longer indicated precipitation during the better seeding conditions, although the Cedar City weather radar showed patchy areas of precipitation around southern Utah throughout the morning on March 1. HYSPLIT modeling from all potential seeding sites during the heavy icing period at Brian Head (Figure 37) indicated that sites to the south of and within the target areas were best for this event as the winds remained from the south. Only sites with favorable seeding plumes for south to southwest winds were used during this event.
Figure 36. Brian Head precipitation, temperature, icing, and wind data on February 28 – March 1, 2014.
Figure 37. HYSPLIT forecast plume dispersion around 2200-2300 MST on March 1, for potential seeding sites in southwestern Utah. Black outlines show approximate seeding target areas.
A weak cold front moved over Utah on February 27 bringing a fair amount of precipitation with it. Temperatures at 700-mb level remained above -5 C throughout this event so seeding was not conducted. The Skyline site indicated precipitation starting around 0800 MST and continued until about 2300 MST, with the greatest snowfall intensity around 1300 MST and 2200 MST with measured snowfall rates of over 5 inches per hour (Figure 38). Temperatures at Skyline were around -2 C until just before 1400 MST when temperatures started to cool reaching a little below -4 C at around 1700 MST and remained between -4 C and -5 C throughout the rest of the storm period. A total of 32 icing cycles were observed between 1100 and 2300 MST. Winds remained from the southwest throughout the day with the strongest speeds of 12 miles per hours with gusts to 22 mile per hour around 1400 MST. The inverse relationship that is often observed between precipitation rate and supercooled liquid water (a decrease in icing during heavier snowfall periods) is apparent in the plot in Figure 38.

HYSPLIT modeling of potential plume dispersion indicated good dispersion of seeding plumes in a west-southwest wind pattern (Figure 39). Had temperatures been cooler, all but a few of these sites would have been favorably located for seeding during this time period.
Figure 38. Skyline precipitation, temperature, icing, and wind data on February 27, 2014.
Figure 39. HYSPLIT forecast plume dispersion 1500-1600 MST on February 27, for potential seeding sites in central Utah. Black outlines show approximate seeding target areas.
March 26-27, 2014

A frontal system crossed Utah around midday on March 26. Seeding began around 1400 MDT for portions of central Utah as Skyline was reporting a temperature around -4 C, cooling with time (Figure 40). Weak convection accompanied this system creating good conditions for transport of seeding material to high altitudes. Frequent icing cycles at Skyline warranted continued seeding overnight. Icing was indicated from around 1400 MDT on March 26 through about 0900 MDT on March 27, with the majority of the icing observed between 2000 MDT on March 26 and 0400 MDT on March 27. A total of 20 icing cycles were observed at Skyline during the storm event. Snowfall rates varied throughout the two day storm with periods of very heavy snowfall indicated from 0500 to 1700 MDT on March 27. Seeding generators were turned off around 1900 MDT on March 27. The Skyline site temperature remained between -4 and -6 C throughout most of the storm. Given the convective nature of the atmosphere during this event, even the relative warm temperatures were not considered to be a serious impediment to seeding. Winds varied from southwest to northwest throughout the storm period and wind speeds were generally light. SNOTEL sites around the Skyline area indicated 0.8 – 1.3 inches of snow water equivalent from this two-day storm.

HYSPLIT modeling indicated a generally westerly wind pattern, veering somewhat from southwest at lower elevations to northwest near and above crest height. (Figure 41). Modeled plume dispersion appeared good from all potential seeding sites.
Figure 40. Skyline precipitation, temperature, icing, and wind data for March 26-27, 2014.
Figure 41. HYSPLIT forecast plume dispersion for all potential seeding sites in central Utah 2100 – 2200 MDT on March 26, 2014. Black outlines show approximate target areas.*

* NOTE: Figure shows all potential seeding sites during the core seeding program. This event was during the Lower Basin spring extension period of the program, so only the eastern sites were utilized.
5.0 Conclusions and Recommendations

Some general conclusions are summarized in this section. Additional seasons of data collection will help increase confidence in these conclusions.

5.1 Conclusions / Key Findings

- 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 analysis of the data continues to yield considerable insights into winter storm seedability. We consider the ridge-top ice detector systems to constitute an exceptional value to the seeding programs.

- The ice detector data, paired with surface and rawinsonde data as well as plume modeling, indicate that in the majority (70% to 80%) 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. This conclusion is considered applicable to most of the seeding target areas and ground-based sites in Utah, although some likely exceptions (such as the Uinta Basin, and some valley bottom locations) have been identified.

- The late-season seeding extension period for the Lower Basin States (which normally begins mid-March) appears to be generally free of any seeding limitations due to low-level atmospheric stability. Low-level stability is most common during the winter months of December through February, although at least half of the December – February storm periods with significant SLW appear to be seedable from lower-elevation ground based sites in most of the Utah target areas.

- Icing at a given location is sensitive to the surrounding terrain and instrument exposure, as well as site-specific wind conditions. One implication is that lifting of the low-level (valley) air mass over significant mountain barriers tends to be much more efficient in certain areas, such as canyons and terrain “catch” areas. This is often an important consideration in terms of the location of ground-based seeding sites.

- During storm periods, icing intensity tends to be negatively correlated, in an approximately linear way, with precipitation intensity. This makes intuitive sense, since the amount of SLW at any given time and location is a function of the rate of SLW production (due to lifting of a saturated air mass) minus the rate of its decay (due to scavenging by precipitation, the nucleation process, and riming on solid surfaces). Intense icing activity is most often observed between significant precipitation periods during storm events.
A large proportion of barrier summit height icing activity has been observed in the 
–5 to –15 C temperature range (the range generally used as a primary seeding 
criterion), although the percentage varies from site to site. In general, it appears 
that about 40-60% of icing activity occurs within this range, with most of the 
remainder observed at warmer temperatures. Only a small portion (generally 1-
4%) was observed at temperatures colder than -15 C.

Icing activity is positively correlated with wind speed, which is due to two primary 
factors: a) the rate of forced orographic lift over the local terrain, and b) flux past 
the icing sensor, both of which increase as wind speed increases.

Of five synoptic categorizations (pre-frontal, post-frontal/pre-500-mb trough, post-
trough, closed low, and undefined), the post-trough situations have been 
associated with the greatest amount of icing at the Skyline and Brian Head sites 
during the past four seasons. Dry Ridge (although having only one season of 
data so far) appears much different, with the vast majority of icing in the pre-
frontal category. This is believed to be due to the location of the Dry Ridge site 
on the southern side of the east-west oriented Uinta Range. Only a small 
percentage of icing has been observed in association with closed low situations.

Icing is observed more frequently after the end of storm-related precipitation than 
before the onset of precipitation, although the majority of icing activity occurred 
either between or during precipitation periods within storm events. In addition, it 
was found that any pre-precipitation icing typically begins within a few hours prior 
to the initial onset of precipitation, but that icing may continue for several or 
ocasionally 12+ hours after storm precipitation ends. This may not be true for 
the Dry Ridge site, however, which so far appears to have very little post-trough 
ic ing. This is likely related to differences in the topography surrounding these 
sites.

There appears to be a general minimum in observed icing activity during the 
afternoon hours, although subdividing the data yields significant site-to-site and 
month-to-month variations that likely suffer from sample size limitations. Based 
on various meteorological factors, it is likely that spring season storm periods and 
the afternoon period (despite the observed icing minimum) may be particularly 
favorable for ground-based seeding operations.

Because the ice detector is a fixed-point measurement, there may be significant 
SLW in the vicinity at times (for example, at a higher elevation) that the icing 
sensor does not detect. Thus, the measurements are believed to be 
underestimates of the total SLW occurrence.

Cold infrared satellite-derived cloud tops (colder than -25 C) were found to be 
associated with nearly 60% of the heaviest icing periods (3 or more cycles per 15 
minute period) at Brian Head. Complexities in utilizing such cloud top
temperature data (such as the presence of separate cloud layers interspersed with dry layers during a storm period) may limit the utility of this type of cloud-top temperature data for assessing seedability of a storm.

- Analysis of the periods of heaviest icing, within a seedable temperature range, suggests that the early and late portions of the season, as well as well-mixed, post-trough situations, seem favored for heavy icing. The data suggest that the month of April may have the highest frequency of very seedable situations with greater amounts of SLW.

5.2 Recommendations

- Continue operation of the ice detector site network and analysis of site data.
- Consider a slight relocation of the Skyline ice detector site due to potential nearby terrain influences.
- Continue operation of optical precipitation sensors at these site installations.
- Establish additional strategically located ice detector site(s) as budgets will allow.

Based on the utility of the data from the current ice detector sites, real-time and in post-hoc analyses, it is considered worthwhile to establish additional sites in strategic locations in Utah. A good candidate site location is the Boulder Summit / Aquarius Plateau area shown in Figure 1, a high elevation area tributary to the Colorado River.

5.3 Acknowledgements

The support and cooperation of the following agencies and individuals is gratefully acknowledged.

- Lower Basin States; Tom Ryan with the Metropolitan Water District of Southern California; funding for the ice detector equipment, acquisition, installation, and post-season data analysis. The LBS contributors include:
  - The Six Agency Committee – California
  - Central Arizona Water Conservation District
  - Southern Nevada Water Authority
• Utah Division of Water Resources; Todd Adams and David Cole; administration of funds for the ice detection systems initiative and provision of high-resolution ETI precipitation gages.

• Utah Department of Transportation for site use and data link at Skyline.

• Brian Head Ski Area; Mac Hatch, Mountain Operations Manager, for site use and access.

• Bryce Jackson; installation and operation of ETI precipitation gage near the Skyline ice detector site
REFERENCES


Sutherland, 1979: An Inversion and Cloud Top Analysis of Soundings made during the Utah Seeding Program. NAWC report to the Utah DWR, April 1979.

Yorty et al., 2012: Low-Level Atmospheric Stability During Icing Periods in Utah, and Implications for Winter Ground-Based Cloud Seeding. J. Wea. Modif., Vol. 44, pp. 48-68.
