LOW-LEVEL ATMOSPHERIC STABILITY DURING ICING PERIODS IN UTAH, AND IMPLICATIONS FOR WINTER GROUND-BASED CLOUD SEEDING

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ABSTRACT

In mountainous regions where winter season cloud seeding is conducted for the purpose of higher-elevation snowpack augmentation, the frequency and character of low-level atmospheric stability can significantly impact transport of cloud-seeding material released from valley and foothill locations over higher elevation target areas. A two-surface-site (2SS) method was developed to estimate stability in the layer from the valley/foothill surface to mountain-top height (approximately 700 mb) in Utah, using available surface temperature and dew point data. The method yields approximations of integrated stability in the layer, which were classified according to their likely impact on operational seeding, and can be expressed in terms of the low-level warming, or upper-level cooling, required to yield a neutral lapse rate (well-mixed environment). The stability estimation method was applied to stormy periods during three winter seasons when mountain-top icing was documented via ground-based high elevation icing rate sensors, and when temperatures were adequately cold for activation of silver iodide particles as ice-forming nuclei. That partitioning method identifies periods when silver iodide seeding potential likely exists. The indications of the 2SS analysis method are that seeding material releases from most valley/foothill locations are likely to undergo timely and effective dispersion to mountain barrier crest height during a large percentage (~75%) of icing periods exhibiting apparent silver iodide seeding potential.

Comparisons of the 2SS method stability estimates to similar rawinsonde-derived estimates showed good correspondence in over 80% of the cases analyzed, providing some confidence in the utility of the 2SS method in the absence of available rawinsonde data. Comparisons were also made between 2SS stability estimates and modeled seeding plume behavior using the NOAA HYSPLIT (Hybrid Single Particle Lagrangian Intregrated Trajectory) model with NAM (North American Model) meteorological input data during icing periods. Agreement between modeled plume behavior and stability indications of the 2SS method was found in over 80% of the modeled periods. Results of these comparisons provide confidence in the overall stability climatology for icing periods as presented in this paper, as well as the real-time operational utility of the 2SS method in areas where other data (e.g., rawinsonde) are not available.

The analyses presented here comprise a portion of a more comprehensive study, based on data from several ice detector sites in Utah. Support for the establishment of these sites, and for analysis of the data, was provided by a consortium of Lower Colorado River Basin States.

1. INTRODUCTION

To affect precipitation increase by winter orographic cloud seeding with silver iodide, the seeding material must reach supercooled cloud regions at or colder than approximately –5 C to nucleate supercooled liquid water (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 terrain on the windward slopes (Super, 1999). This is the pool of SLW to be tapped by cloud seeding. Complexities involved in the targeting of ground-based seeding material releases have been studied in Utah (Super and Huggins, 1992). One of the major factors involves potential thermodynamic stability of the atmosphere near and below crest height. If the stormy air mass has a stable temperature lapse rate, valley 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.

During the winter season in Utah (December – February in particular), lower-level inversions commonly develop in basins and lower-elevation regions during periods of clear or fair weather. Surface snow cover can contribute significantly to the development of valley inversions. During stormy weather, increased wind, as well as mid- and upper-level cooling which typically accompanies a trough passage, will often dissipate existing valley cold pools or inversions in most areas. For this reason, analyses of low-level thermodynamic stability during stormy periods with seeding potential are particularly valuable. Warm and cold frontal zones, of course, can produce some degree of thermodynamic stability on their own. However, during the winter season it is commonly pre-existing lower level stability and inversion zones, formed during clear weather and persisting to some degree during a subsequent storm event, that can pose the most significant problems for ground-based seeding in terms of the dispersion of seeding material.

The nature of thermodynamic stability is such that, in cases where a high-resolution thermodynamic profile (such as a nearby rawinsonde sounding) is not available, temperature and dew point data from surface observations at differing elevations can be used to develop estimates of the integrated stability in the intervening layer. 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 in order to reach a nearby mountain crest elevation. One primary advantage of this method is the ability to conduct a thermodynamic stability analysis in real time in any mountainous area where temperature and dew point data are available from sites at appropriate elevations.

2. METHODOLOGY

Ridge-top ice detector measurements from several sites in Utah were utilized in support of this low-level stability study. Analysis of periods during which icing was recorded at these sites yields results that are relevant to potential ground-based cloud seeding operations during storm periods. The ice detector site data includes icing and temperature data at 10 to 15 minute intervals, which allows the data set to be further refined to focus on periods when the crest-level temperatures is favorable for seeding with silver iodide (i.e., between –5 and –15 C). Ice detector data used in these analyses include data from Skyline in central Utah (9330') and Brian Head in southwest Utah (10,900') during the 2009-2010 and 2010-2011 winter seasons, and data from Snowbird (11,000') in the Wasatch of northern Utah during the 2003-2004 season (Figure 1). The Brian Head and Skyline ice detector sites are located in seeding target areas associated with a long-standing operational program in Utah (Griffith et al., 2009) and are being funded by a consortium of lower Colorado River Basin states as part of an ongoing study. The Snowbird ice detector site was part of a similar study conducted by North American Weather Consultants (Solak et al., 2005).

Data from surface sites (typically two), comparing valley observations to nearby crest-level temperature data (referred to as the 2SS method), was used to estimate low-level thermodynamic stability during periods with recorded icing in the data set. Figure 1 shows the locations of the valley sites as well as the mountain crest (ice detector) sites used in these comparisons. In central Utah, temperature and dew point information at Spring City (5,800'), south-southwest of the Skyline area, was compared to site temperatures at Skyline (9,330') during icing periods for the two seasons of data. The observed valley site dew point is used to determine the neutral lapse rate at which free mixing takes place if a parcel is lifted (i.e. dry adiabatic, pseudo-adiabatic, or, typically, a combination of the two). This analysis is easily conducted with the aid of a thermodynamic skew-T chart, comparing the resultant temperature of a parcel lifted from the valley floor to crest height with the observed temperature at the crest. The primary focus of the stability analysis was in the Skyline area because it is centrally located in Utah and is considered representative of much of the north-south oriented mountain/valley terrain profile in many of the state's seeded areas, as well as some other portions of the Intermountain West. In the 2SS analysis, the surface temperature at a valley site is thermodynamically adjusted to the elevation of the ridge-top site, using the appropriate lapse rate, for comparison with the observed ridge-top temperature. The observed dew point at the valley site is used for selection of the lapse rate (dry and/or moist) used in this adjustment. The comparison 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 the layer. Thermodynamic stability was divided into four categories, based on 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:

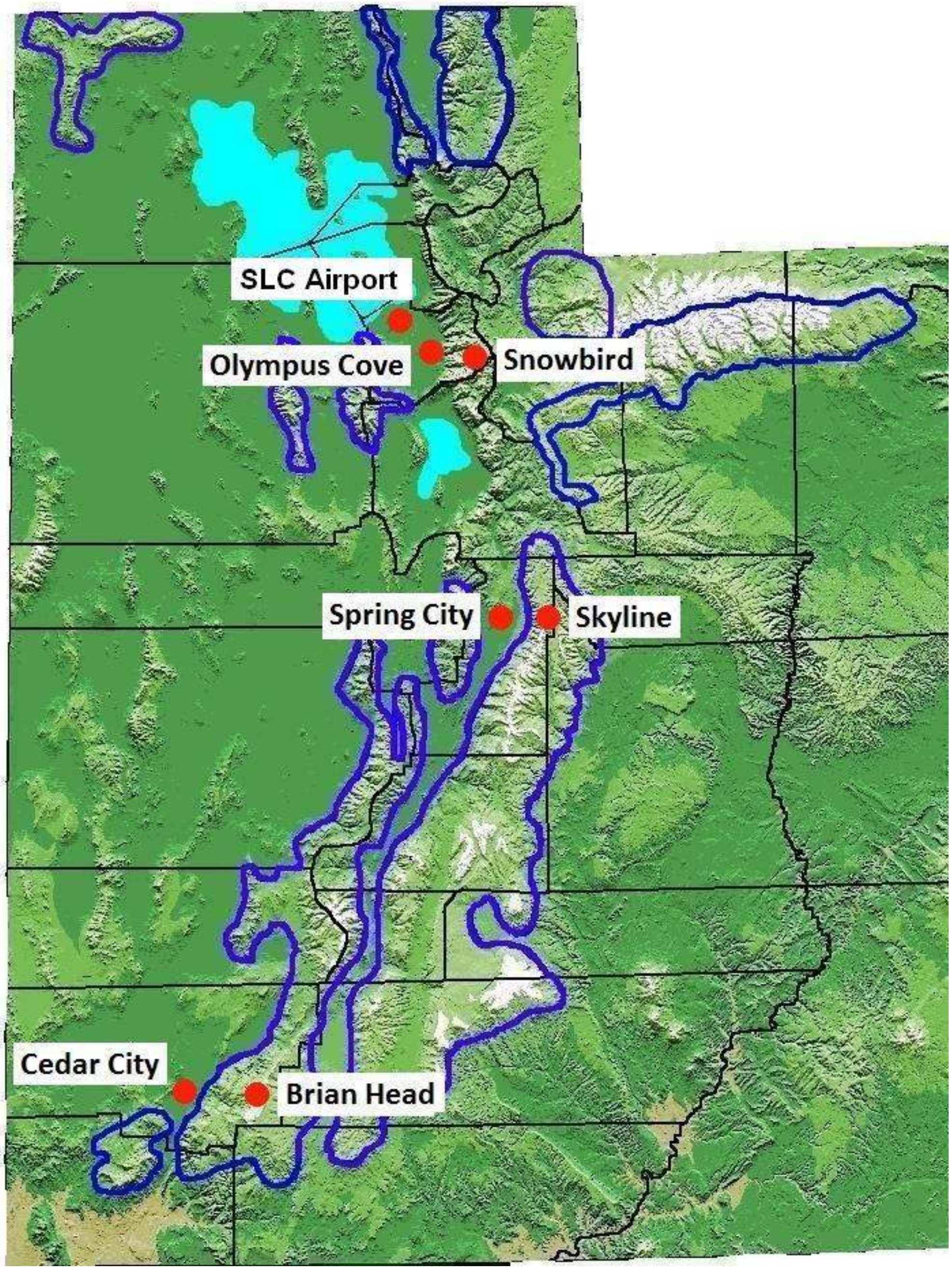

Figure 1. **Map of 2-site-stability analysis locations, including the ice detector sites at Snowbird, Skyline, and Brian Head**

N Neutral or well-mixed (no apparent stability in the layer),
SS Slightly stable ($\leq$2 degrees C of stability),
MS Moderately stable (~ 2-4 C of stability) and
VS Very stable ($\geq$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 also likely be seeded in an operational setting, because there is potential for atmospheric forcing mechanisms to overcome such a minor amount of stability, and because local temperature variations of a few degrees may easily result in areas of free 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 become effective later as the situation changes.

In addition to the stability analysis for the Skyline area, similar analyses utilizing the two-surface-site method were conducted for the Salt Lake City/Snowbird area, as well as the Brian Head area (all shown in Figure 1). Results of the analyses utilizing the 2SS method are presented in Section 3.0.

Systematic comparisons were made between stability indications based on the 2SS method and those derived by alternate methods. This was an important aspect of this study, as it lends additional support to the results that are presented. These comparative analyses include weather balloon (rawinsonde) soundings, which generate detailed thermodynamic profiles of the atmosphere, and HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) modeling of ground-based plume dispersion. Section 4 presents further details regarding the methodology as well as the results of these comparative stability analysis techniques.

3.0 RESULTS OF THE TWO-SITE STABILITY ANALYSES

For 246 icing periods at the Skyline site during the November – April portion of 2009-2010 and 2010-2011 seasons, where the site temperature (at approximately the 700-mb level) was between –5 and –15 C, about 62% of the icing periods were associated with a generally well-mixed atmosphere down to the valley floor. Another 19% of the periods were rated as "slightly stable" for the two-season period, for a total of ~81% where seeding from valley or foothill sites would likely be effective. Figure 2 shows the overall November – April distribution of the 2SS method stability characterizations in the Skyline area. Another important indication in the analysis is that nearly all of the periods with MS and VS stability characterizations occurred from December through mid-February. This is illustrated in Figure 3, a scatterplot of the observed seasonal variation of stability. Figure 4 shows monthly averages of the percentage of icing periods rated "N" (well-mixed periods) as well as those rated either N or SS (periods in which seeding from the valley would likely be effective).

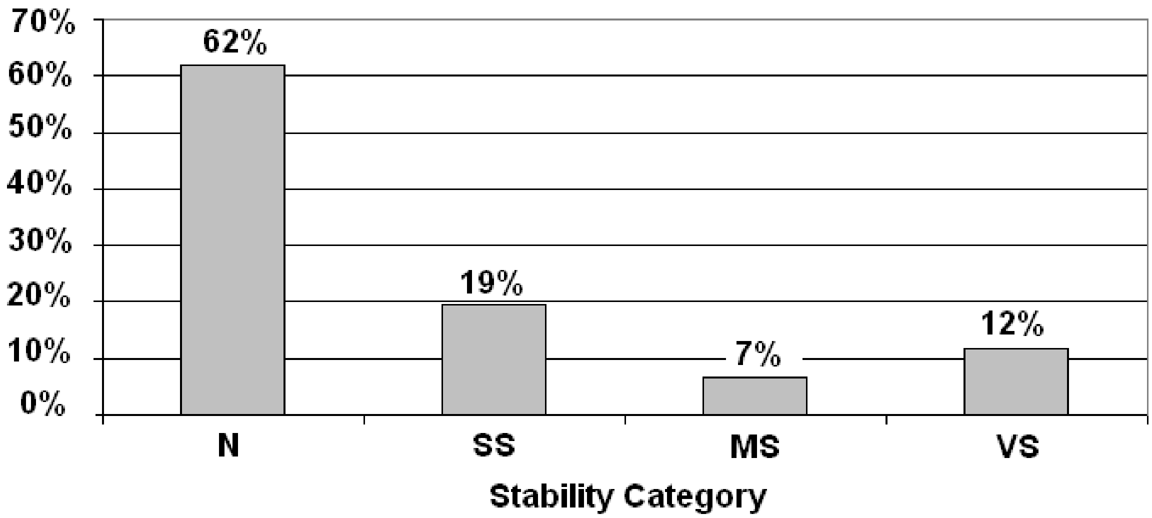

Figure 2. **Skyline area stability analysis results for 246 icing periods associated with ridge-top temperatures between –5 and –15 C**

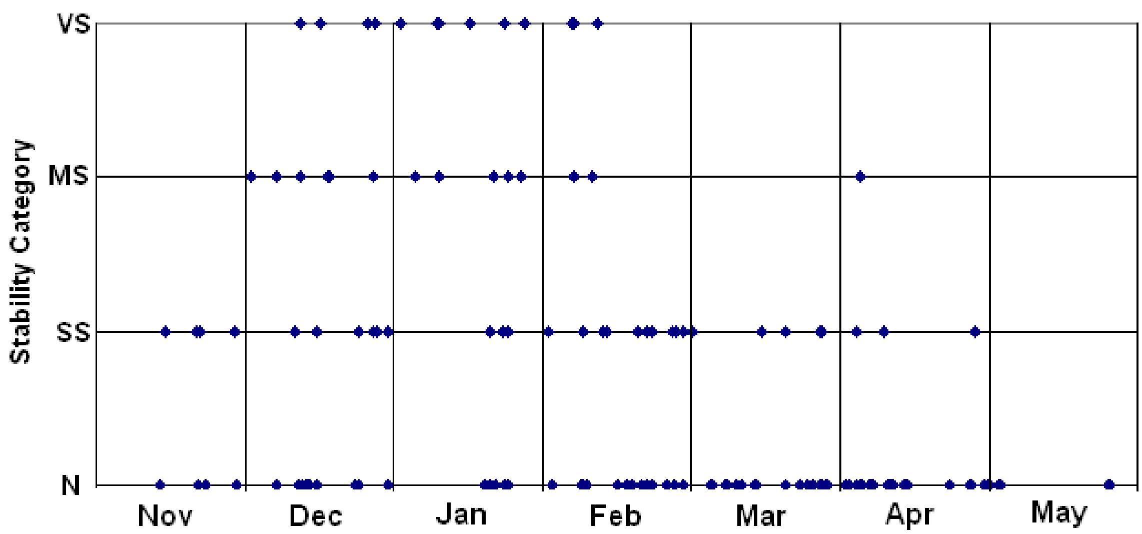

Figure 3. **Seasonal distribution of low-level stability characterizations based on the 2SS method, during icing periods at the Skyline detector site associated with site (ridge-top) temperatures between –5 and –15 C.**

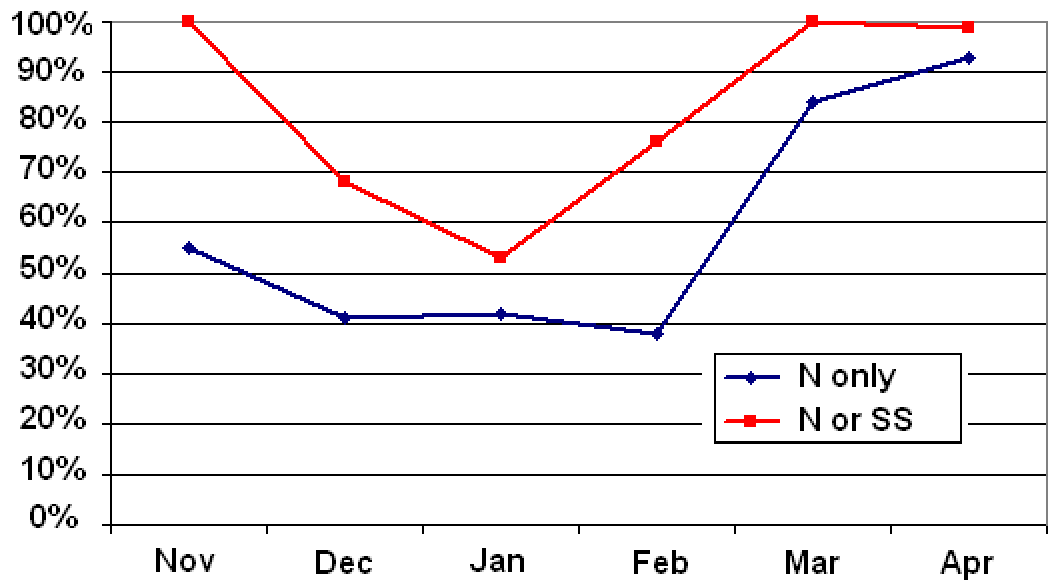

Figure 4. Monthly averages of the percentage of well-mixed (N) periods (blue), and N or SS periods (red) when SLW is occurring at the Skyline site and the site temperature is between –5 and –15 C. These characterizations are based on the 2SS analysis method.

A more abbreviated stability analysis was conducted for the Brian Head area using the 2SS methodology, focusing on periods with significant amounts of icing and site temperatures below –5 C during 35 storm events. That analysis used the Cedar City airport as a valley temperature comparison site. Approximately half of the periods examined appeared to be well-mixed or neutral (N), and another ~25% were rated as SS. About 20% were rated as MS and less than 5% as VS. These results are similar to those in the Skyline area, with seeding material likely to have reasonable vertical dispersion in about 75% of the storm events when crest-level temperatures are cold enough for effective seeding and crest height icing is occurring.

A comparison was also made between the 2SS evaluation results for Skyline icing periods between November 24 and April 4 of both (2009-10 and 2010-11) seasons and similar Salt Lake City/Snowbird area analysis results available during that seasonal period in 2003-2004. This comparison between the Olympus Cove/Snowbird and Spring City/Skyline 2SS method results suggested somewhat greater stability in the Salt Lake City area than in central Utah, although the differences probably fall within the normal range of season-to-season variability. For the Skyline area, approximately 75% of the icing periods in this November 24 – April 4 subset were rated as either N (53%) or SS (22%). In the Olympus Cove/Snowbird 2003-2004 data set, 59% of the icing periods were rated as either N (30%) or SS (29%).

Implications of these analyses are that seeding material releases from valley or foothill sites are likely to experience timely and effective dispersion to the barrier crest height in a large percentage (75% or greater) of periods when SLW is present at crest height and temperatures are cold enough for seeding with silver iodide. 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. The focus on periods with seeding potential provides a refined and much more meaningful assessment of seasonal seedability and determination of the appropriate treatment strategy than would a general analysis of low-level stability apart from the ice detector data. It addresses head-on the question of the potential for ground-based seeding material releases from valley and foothill locations to effectively capitalize on seasonal seeding opportunities where SLW is known to exist.

4.0 COMPARISONS OF STABILITY ANALYSIS METHODOLOGIES

4.1 Two-Site-Stability vs. Rawinsonde Analysis

An initial set of 435 15-minute icing periods in the 2003-2004 Snowbird ice detector data, with a site temperature between –7 and –17 C (to approximate a generalized crest-height temperature of –5 to –15 C) were evaluated using the 2SS method with data from Olympus Cove (a foothill site at 5,070 ft or approximately 850 mb) and Snowbird Hidden Peak (a mountain-top site at 11,000 ft or approximately 670 mb). Refer to Figure 1 in Section 3 for site locations. The 2SS stability categorizations for 67 of these periods were compared with stability estimates derived from corresponding Salt Lake City rawinsonde soundings. The 67 periods were selected from the set of 435 based on their occurrence within 3 hours of an available rawinsonde, and were found to be very well representative of the entire set.

The correspondence between stability as derived from the surface measurements, to that derived from the sounding data, was rated as good or excellent in 54 (81%) of the periods examined, meaning that in these cases there was agreement between the two analysis methods to within about one degree C of thermodynamic stability. Of the other 13 period comparisons rated as “fair” or “poor”, having a discrepancy of more than 1 C in the stability estimates, 7 had greater thermodynamic stability indicated by the sounding than that using the 2SS method, and in 6 cases the sounding indicated less stability. Thus, the composite stability evaluation results obtained using the 2SS method are very similar to those derived from the soundings (compare Figures 5 and 6). The primary difference was a few more cases rated SS rather than N when utilizing the sounding data, but with essentially the same total percentage (~60%) in these two categories as a whole for the atmospheric layer between the Olympus Cove and Snowbird elevations.

A comparison was also made of the 2SS integrated stability between the Olympus Cove and Snowbird elevation (5070’/11,000’) vs. the Salt Lake City airport and Snowbird elevation (4200’/11,000’) in the rawinsonde data for the 67 periods (compare Figures 6 and 7). The result showed a substantial dependence on elevation in terms of

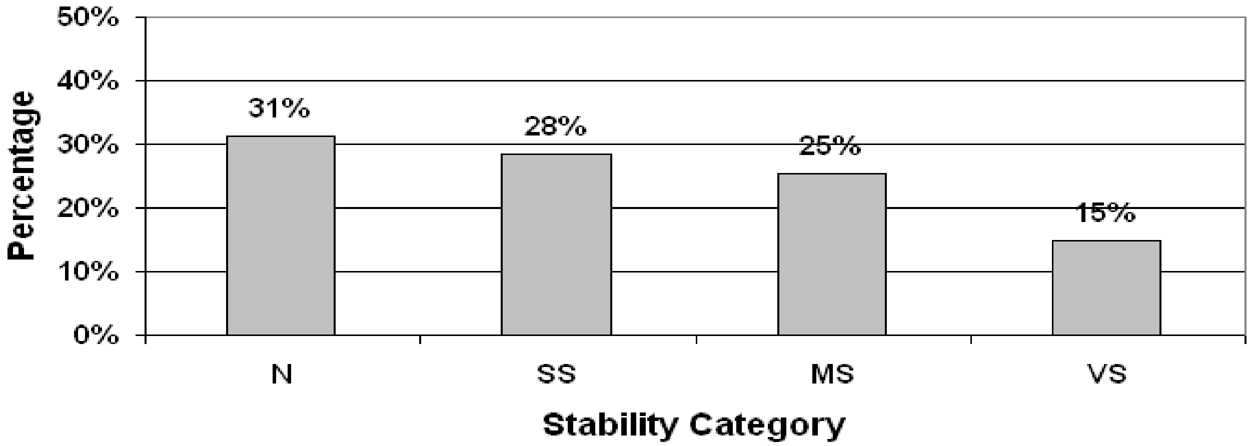

Figure 5. **Two-surface site stability analysis results (Olympus Cove vs. Snowbird) based on 67 icing periods used in the comparison with rawinsonde data**

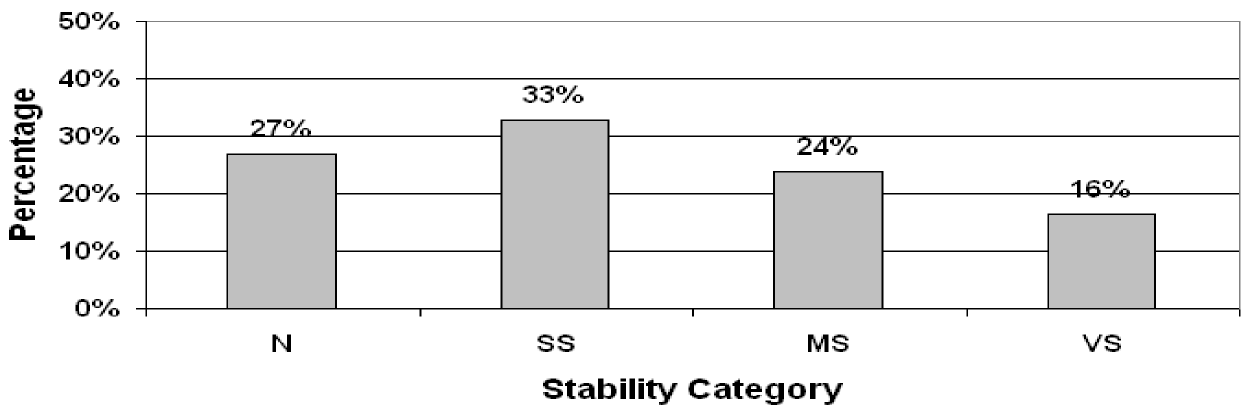

Figure 6. **Rawinsonde analysis results between the Olympus Cove and Snowbird elevations, based on the 67 comparison periods**

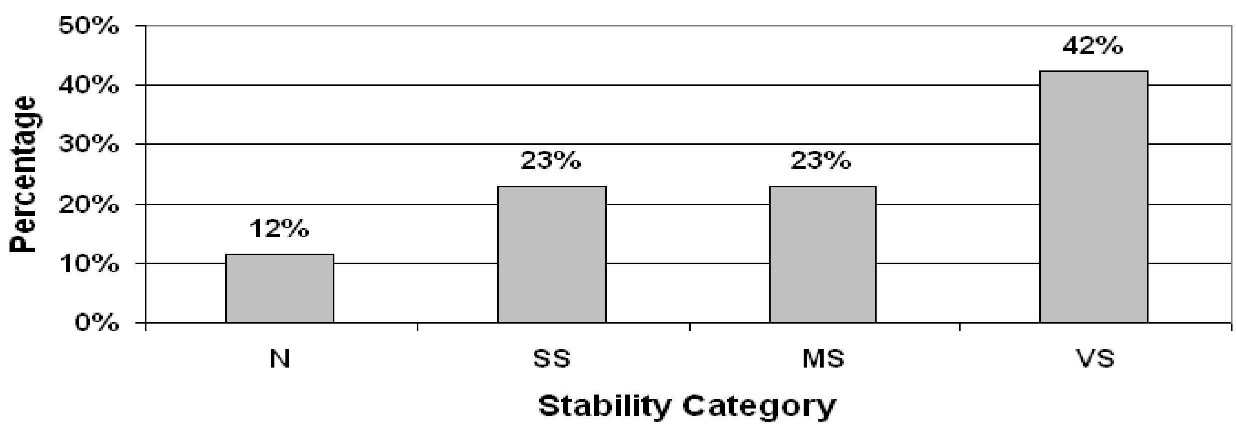

Figure 7. **Rawinsonde stability analysis results between Salt Lake City airport and Snowbird elevation, based on the 67 comparison periods**

the integrated stability, with only 35% of the analyzed periods rated as either N or SS from the airport surface elevation compared to 60% from the Olympus Cove elevation. Sounding analyses implied that only about 12% of the sounding analysis periods were entirely well-mixed from the airport elevation, compared to 27% from the Olympus Cove elevation. Analysis of the rawinsonde data showed that during the 67 periods overall, approximately 40% of the integrated stability in the Salt Lake City airport vs. Snowbird layer occurred below the elevation of Olympus Cove, i.e. in the lowest 870 feet of the atmosphere. This is an important finding in terms of site location for ground-based seeding operations, as foothill locations are likely to be substantially more suitable than valley bottom sites.

4.2 Two-Site-Stability vs. HYSPLIT Modeling Analysis

A fairly rigorous analysis of plume dispersion in central Utah was performed using the HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) Model. 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 in central Utah. 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). Model terrain was examined and release points were selected to compare releases from various surface elevations (shown as sites A, B, and C in central Utah which are at approximately 4,600', 5,800', and 7,200' in elevation, respectively). The elevation differences allow for a comparison of the modeled plume dispersion behavior based on starting elevation. Figure 8 shows the terrain profile of the NAM model data used in the analysis, and the modeled release sites. This includes locations in the Salt Lake City area (sites 1, 2, and 3) which were used for a baseline analysis of HYSPLIT model performance in regard to atmospheric stability, which was conducted in the Salt Lake City area and is summarized in the following section.

4.2.1 HYSPLIT Model Performance Baseline Analysis

As part of the overall HYSPLIT modeling study on plume behavior and thermodynamic stability, a baseline analysis of modeled plume behavior was conducted. The baseline analysis utilized three hypothetical seeding sites selected in

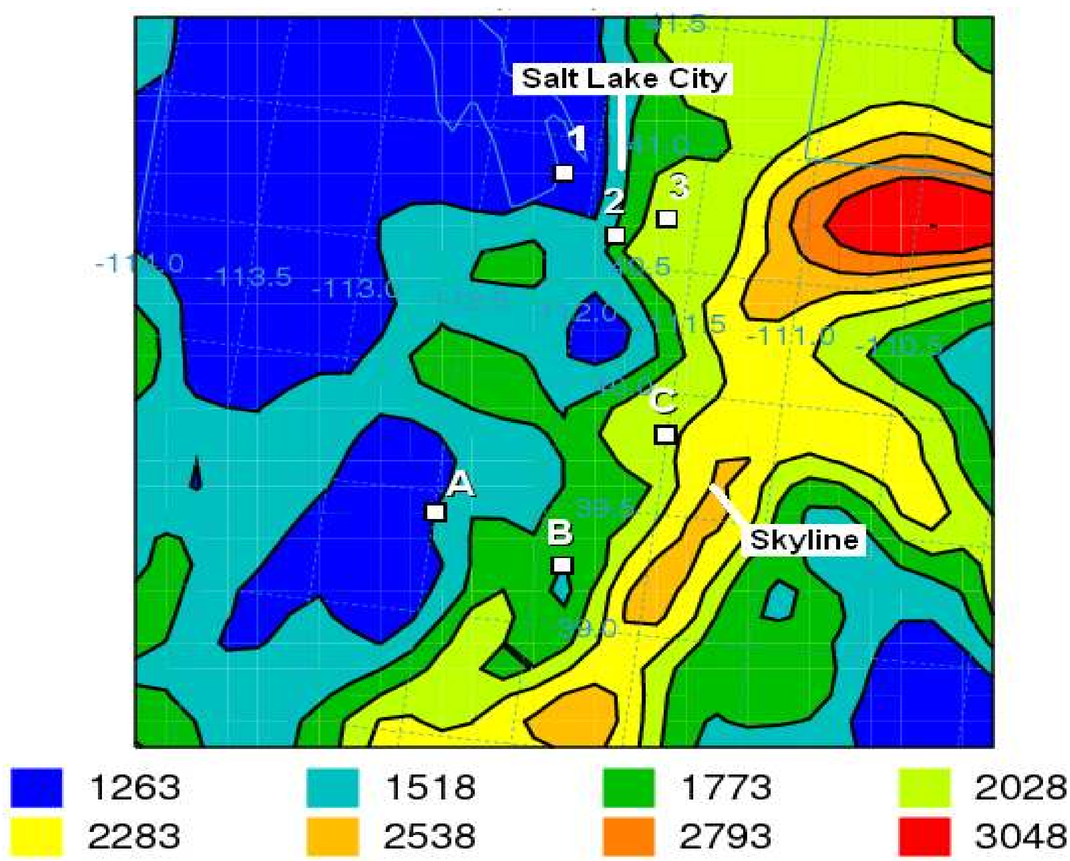

Figure 8. NAM model terrain profile and HYSPLIT plume modeling release site locations (units are in meters)

the Salt Lake City area, roughly 80-100 miles north of the Skyline area. The analysis compared upper air soundings at Salt Lake City to modeled plume behavior in order to assess the utility of the HYSPLIT modeling analysis as applied in central Utah. The three Salt Lake City area plume modeling locations, shown as 1, 2, and 3 in Figure 8, represent model terrain elevations of approximately 4200’, 5000’, and 6800’, analogous to the three central Utah sites used in the comparison of HYSPLIT vs. 2SS stability indications. Sixteen soundings from the 2009-2010 and 2010-2011 seasons were selected for the HYSPLIT–rawinsonde comparison in the Salt Lake City area. A variety of thermodynamic profiles including well-mixed, shallow surface inversions, elevated inversions, and deep stable layers were represented in the comparison data. Figure 9 shows the comparison between a sounding profile with a near-surface inversion, and corresponding HYSPLIT output. In this case, a modeled plume release from site 1 remains trapped near the surface after 2 hours, while releases from the other two sites disperse quite well. The plume dispersion in this case illustrates not only the effect of thermodynamic stability, but also the utility of modeling plumes from different release elevations.

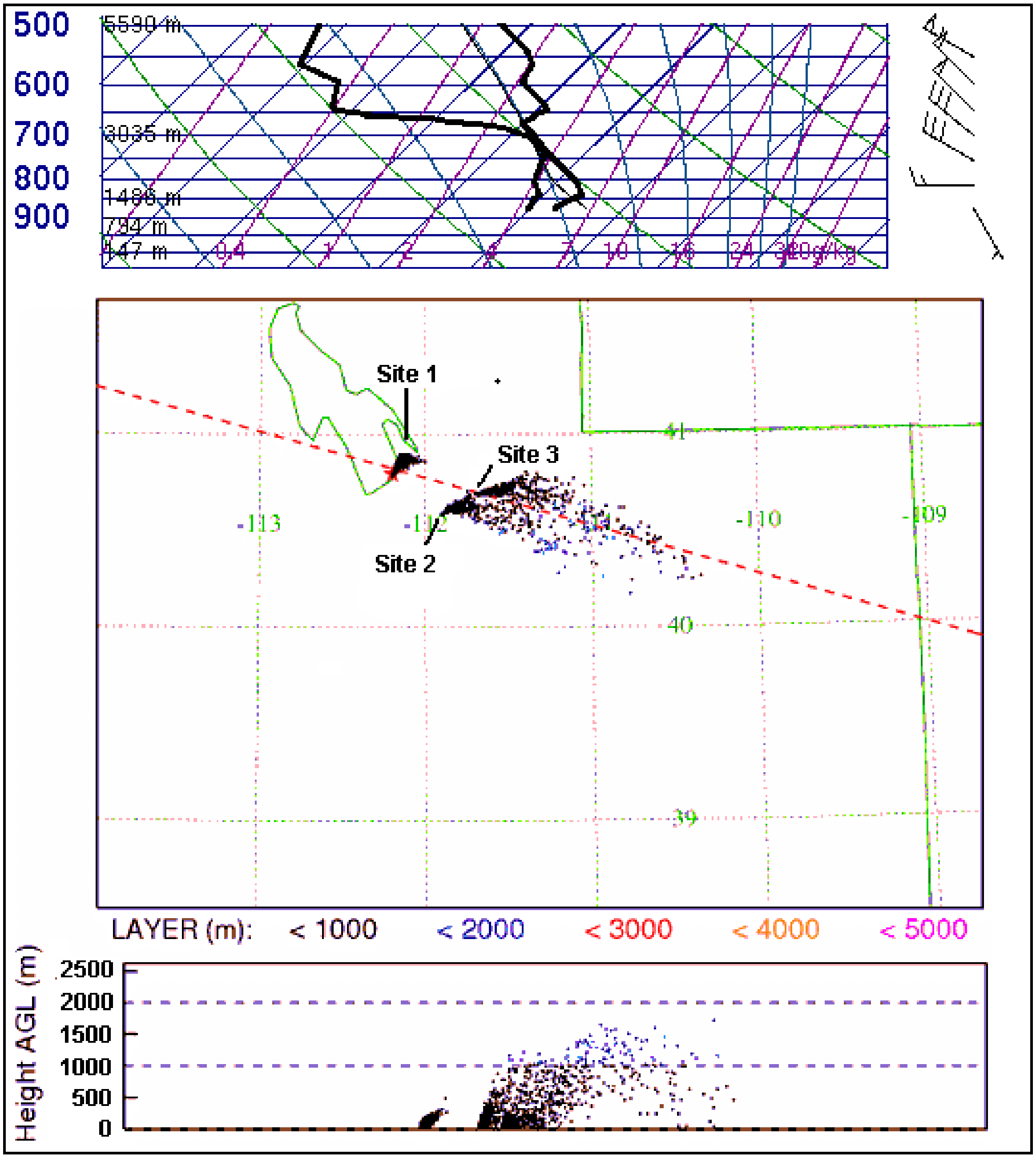

Figure 9. Salt Lake City rawinsonde skew-T diagram to 500 mb (upper panel), and corresponding HYSPLIT output for the morning of January 22, 2011. Middle panel shows plume locations and directional orientation of the vertical cross section (red dotted line), with the vertical cross section displayed in the lower panel. Note that the vertical cross section is plotted on an AGL scale in HYSPLIT, representing the height above the model terrain elevation at each point.

Generally good correspondence was found between the sounding profiles and HYSPLIT output in the analysis. The Salt Lake City area modeling results provided support for some general statements about indicated plume behavior in HYSPLIT, which, as a result, can be applied to the central Utah modeling analysis with reasonable confidence:

- In well-mixed cases without any thermodynamic stability, vertical plume dispersion in HYSPLIT tends to be very uniform without any sharp vertical gradients in concentration observed

- Examination of sites with differing release elevations is useful in comparing plume behavior, especially during shallow inversion situations

- The strength of the lower level wind field is an important factor affecting not only the horizontal but the vertical dispersion rates of the plumes due to turbulence

- The amount of restriction to vertical dispersion in a given layer (visually discernible as a vertical gradient in the concentration of a modeled plume) is correlated to the amount of thermodynamic stability in the layer.

The HYSPLIT–rawinsonde comparisons provided some validation of, and enhanced confidence in, the utility of the HYSPLIT model as a tool in our central Utah stability analyses.

4.2.2 Central Utah HYSPLIT Modeling Methodology

The primary HYSPLIT modeling analysis was conducted for the three central Utah locations (A, B, C in Figure 8), for 76 stormy periods where icing activity was identified in the Skyline 2009-2010 and 2010-2011 ice detector data sets, and represents a large subset of the data periods used for the two-site Skyline stability analysis (Section 3). Most of the periods used for the HYSPLIT simulation were 3 or 4 hours in length, although some were only 2 hours.

Plume modeling results for each of the 76 time periods were compared to the corresponding stability rating for that time period (N, SS, MS, or VS) based on the 2SS method. The comparison results were rated (excellent, good, fair, or poor) based on the agreement between modeled plume behavior and the stability ratings as defined in the 2SS method. For example, a case rated as “N” in which modeled plumes disperse upward quickly and uniformly would show excellent agreement, as would a case rated “VS” where the modeled plumes from the lower (valley) release sites remain essentially trapped near the surface. Of particular interest are the SS cases, in which thermodynamic stability is sufficiently weak that it might not be readily detected in an operational situation where detailed three-dimensional data are lacking, or in which seeding operations would probably not be curtailed due to the minor amount of stability. The SS cases are situations in which warming of less than 2 C at a valley release site or cooling of less than 2 C at crest height would be required to eliminate thermodynamic resistance to vertical dispersion of a plume within this layer. Model terrain height was the primary factor considered when selecting the three plume modeling sites in central Utah, rather than an attempt to replicate the exact latitude/longitude of the Spring City and Skyline surface measurement sites. This is because the NAM 12-km resolution model terrain height at those two locations is different than the actual terrain height, and modeled plume behavior is particularly sensitive to the surface site elevation (based on model terrain). It is also worth noting that plume modeling site “B” is at essentially the same elevation as the actual elevation of Spring City.

Figures 10 and 11 show examples of HYSPLIT output for two of the modeled periods in central Utah. In Figure 10, an icing period with well-mixed northwesterly flow (rated N based on Spring City/Skyline data in 2SS analysis) shows excellent plume dispersion in both the horizontal and vertical, with all plumes traversing the crest. The model indicated plume dispersion to over 2,000 m (over 6,000 ft) AGL within a couple hours. In Figure 11 (rated “SS” based on Spring City/Skyline data in the 2SS analysis), a shallow but fairly strong inversion exists at lower elevations and traps plume A near the surface, shown here after 2 hours. Plume B (with a model elevation approximating the actual elevation of Spring City) exhibits good vertical dispersion in the model, although a light wind field limits the rate of horizontal dispersion. Plume C disperses quickly up to 1000 m AGL, bringing it up to roughly the crest height elevation.

4.2.3 Results of HYSPLIT Analysis

Overall, the results of the HYSPLIT analysis agree well with the stability ratings obtained using the 2SS method. For the 76 modeled periods in this comparative analysis, 40 (53%) had a comparison rating of “excellent”. An additional 22 (29%) were rated as “good”, for a total of approximately 82% rated as either “good” or “excellent”. This means that plume behavior as implied by the 2SS stability categorizations is very similar to indicated plume behavior using HYSPLIT. This result is also very similar to the 81% “good or excellent” agreement between the 2SS and rawinsonde analyses in the Salt Lake City area as discussed in Section 4.1.

For the 24 modeled periods which were rated SS in central Utah, a large majority exhibited plume behavior that showed some degree of lower-level trapping of material at valley sites A and B, but a significant amount of plume material (e.g. ~ 50% or more in many cases) was able to overcome the thermodynamic stability and disperse vertically to near crest height within a few hours. For these 24 modeled cases in particular, in which some minor inhibition to vertical dispersion would be expected, modeled plume behavior was in excellent agreement for 16 (67%) of the cases and good agreement in another 5 (21%) of the cases (for a total of 87% either “good” or “excellent).

The modeling results imply that in a large majority of periods rated as SS, and nearly all the cases rated as “N”, ground-based releases from valley and foothill

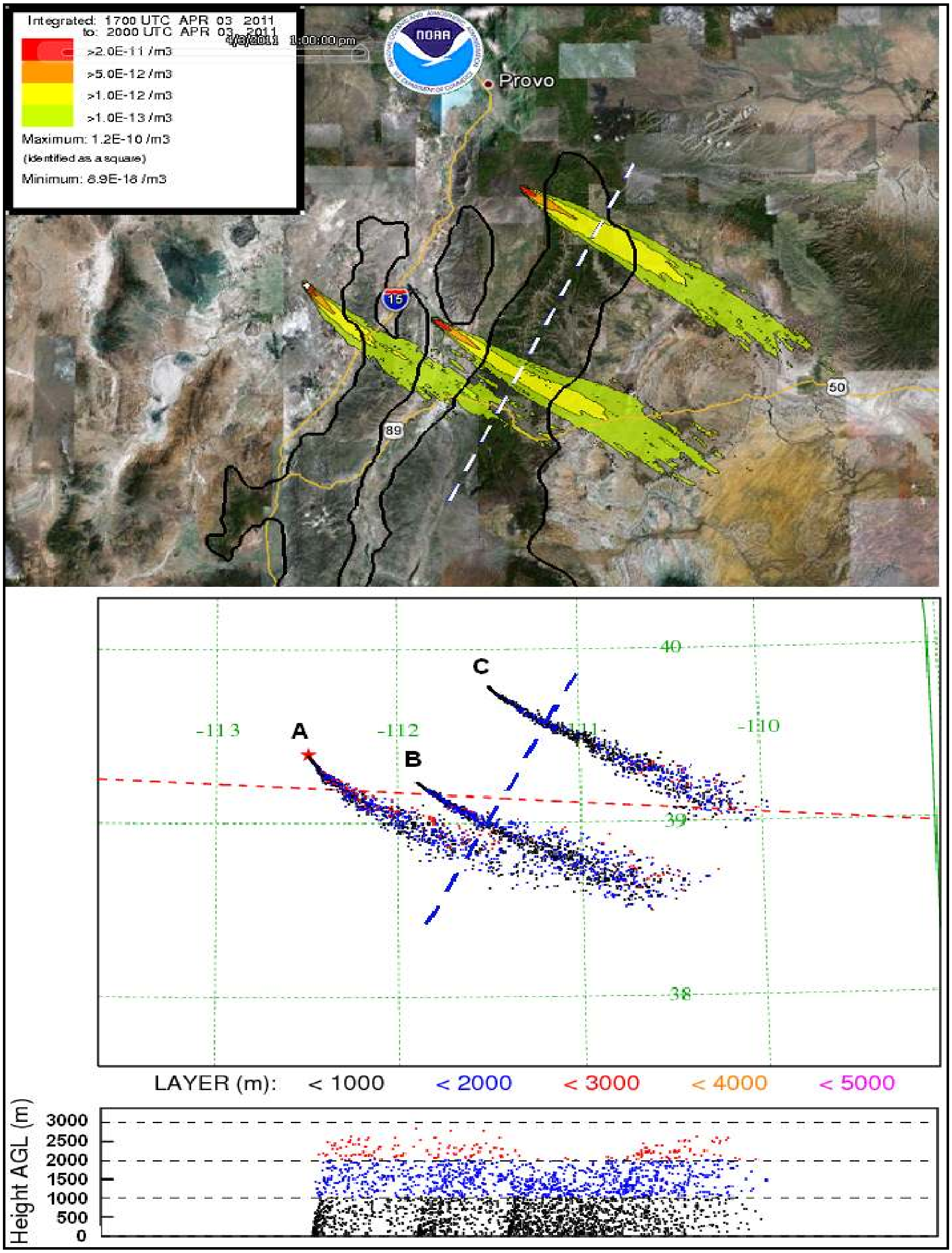

Figure 10. **HYSPLIT output for simulated surface-based particle releases on April 3, 2011. White/blue dotted lines mark the approximate location of the main barrier crest in central Utah. The red dotted line in the middle panel depicts the orientation of the vertical cross section plotted below it.**

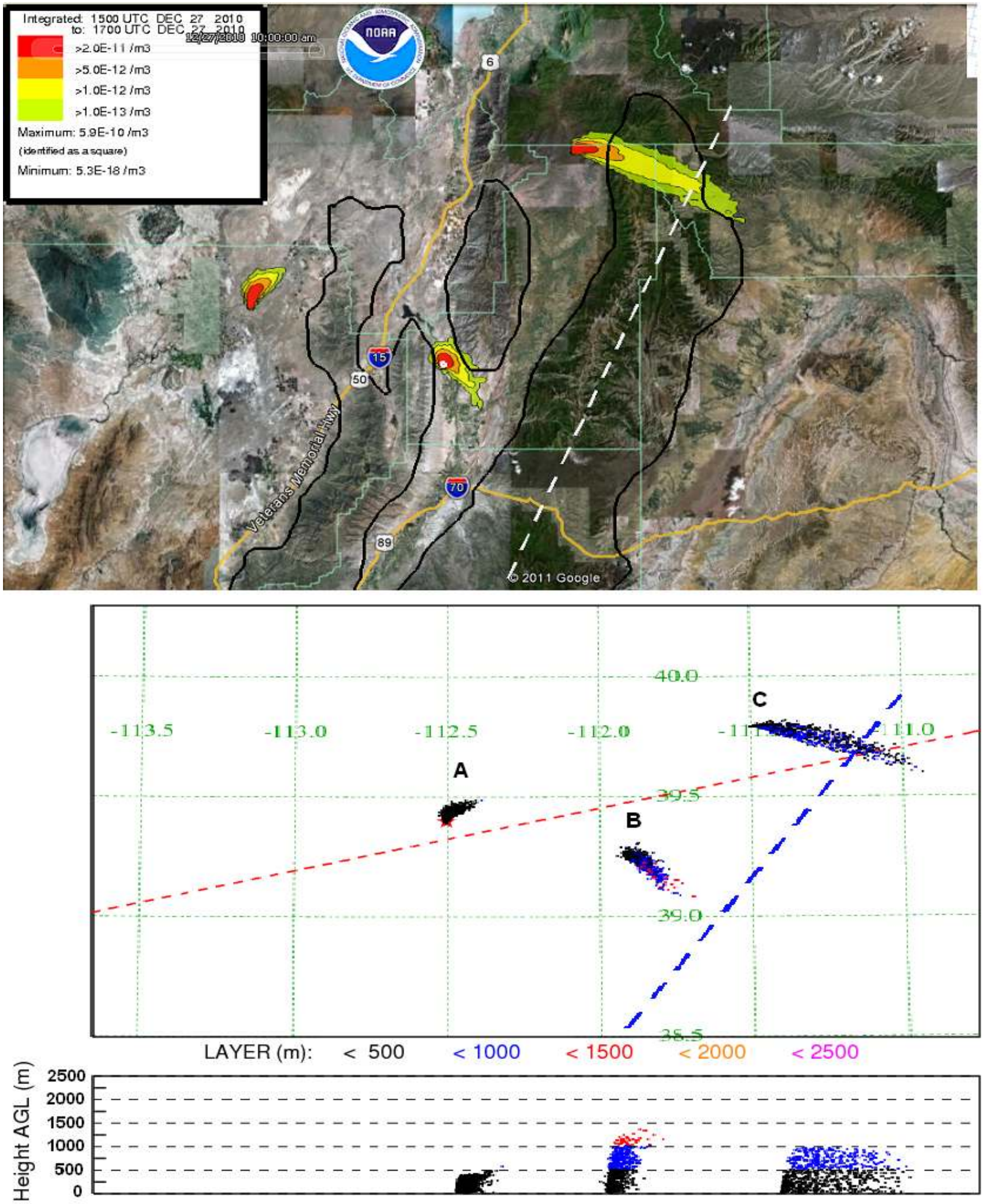

Figure 11. HYSPLIT output for simulated surface-based particle releases on December 27, 2010. White/blue dotted lines mark the approximate location of the main barrier crest in central Utah. The red dotted line in the middle panel depicts the orientation of the vertical cross section plotted below it.

locations would likely reach an effective seeding elevation in substantial concentrations within a couple of hours.

Closer examination of the 76 modeled periods with regard to wind direction showed that those with a northerly wind component throughout the valley – crest height layer (generally post-frontal situations) exhibit the least amount of stability overall, according to both the 2SS analyses and HYSPLIT model results. Periods with a southerly component throughout this layer (generally pre-frontal situations) exhibited a little more stability. Finally, periods where wind direction changed dramatically with height tended to have the most thermodynamic stability. The vast majority of this latter set had veering wind patterns, usually southerly at low elevations and west-northwest near crest height. Agreement between HYSPLIT and 2SS indications was also somewhat poorer in this latter set than in cases where wind direction was more consistent with height.

It is believed that the 14 (18%) periods with “fair” or “poor” agreement between HYSPLIT and 2SS indications are affected by some weaknesses or limitations inherent to each method. The 2SS method as currently utilized does not take wind velocities into account, and to do so would be very difficult since near-surface stability often results in nearly calm surface winds even though the wind field may be strong just above the surface. Such differential velocities in the near-surface layer can generate a good deal of turbulence and gravity waves, which may fairly quickly mix part of a surface-based plume into the overlying air mass despite the presence of an inversion (Heimbach and Hall, 1996; Heimbach et al., 1997). Conversely, there are a few cases in this analysis where even a small amount of low-level stability appeared to trap an entire plume near the surface because there was a deep layer of nearly calm winds and thus very little atmospheric turbulence. In such situations, the HYSPLIT model has the advantage of factoring in the three-dimensional winds and turbulence, which the two-site analysis method does not. On the other hand, there is some question as to how well the model can resolve shallow near-surface inversions given its resolution limitations, especially in terms of topography. A shallow near-surface inversion limited to a narrow valley (a valley which may not even exist in the model terrain) could present a real obstacle to surface-based seeding which would be accounted for via a surface observation but likely not in the model. In such cases, the two methods can be complementary. It is also worth noting that in the cases where stability implications were significantly different between the HYSPLIT modeling results and 2SS indications, these differences were observed in both directions (rather than one method showing a systematic bias toward greater stability). This is consistent with the comparison results of the rawinsonde vs. 2SS comparisons, and gives greater confidence in the overall 2SS analysis results when a reasonable sample size is available.

A related issue that was examined in the context of the HYSPLIT modeling is the depth of plume dispersion above crest. Plumes from site B in the model analysis were examined, due to a) its 1,768 m (5,800’) model elevation, b) relative proximity to the main barrier, and c) the relative frequency of periods where this plume appeared to cross the barrier crest. For 44 modeled periods where the wind direction was favorable and a significant portion of plume B appeared to cross the barrier, a maximum dispersion height was estimated for the portion of the plume that was over the barrier. The estimates ranged from 500 - 2,000 m (approximately 1,600 – 6,500 feet), with a mean of approximately 1,150 m (~3,800') and a median value of ~1,000 m (3,300'). This is somewhat higher than, but still similar to, indications based on aircraft observations from experimental cloud seeding programs in this area (Super, 1999) which suggest that valley-based seeding plume dispersion is generally limited to less than 1,000 m above crest height during winter storm situations. Some of these experimental programs, which involved field observations as well as modeling, led to the conclusion that seeding plumes from valley release sites are sometimes confined to within several hundred meters above the barrier crest (Heimbach and Hall, 1994). Others have suggested frequent plume dispersion on the order of 1,000 m above the terrain especially during post-frontal and mildly convective situations (Griffith et al., 1992; Holroyd et al., 1995). Limited terrain resolution in the NAM model as used with HYSPLIT may influence the results obtained in the current study.

In general, the HYSPLIT plume modeling results in central Utah show good agreement with the assumptions about the impact of thermodynamic stability on ground-based seeding effectiveness which are inherent in NAWC's 2SS method. This is encouraging, and lends additional support to the overall study results obtained using the 2SS method. Table 1 provides a summary of the comparisons between HYSPLIT and 2SS indications.

Table 1
Comparative Results of HYSPLIT vs. 2-Site-Stability Analyses, Frequency of Occurrence

		Stability Sub-Categories Based on 2-Surface Site Method				Wind Direction Sector, Northerly vs. Southerly Component		
Comparison Rating	All Periods	N	SS	MS	VS	Southerly	Northerly	Mixed or other
Excellent	40 (53%)	16 (53%)	16 (67%)	5 (45%)	3 (27%)	18 (53%)	14 (70%)	8 (36%)
Good	22 (29%)	11 (37%)	5 (21%)	2 (18%)	4 (36%)	10 (29%)	6 (30%)	6 (27%)
Fair	12 (16%)	2 (7%)	2 (8%)	4 (36%)	4 (36%)	4 (12%)	0	8 (36%)
Poor	2 (3%)	1 (3%)	1 (4%)	0	0	2 (6%)	0	0
Total	76	30	24	11	11	34	20	22

The application of HYSPLIT modeling to periods with various stability classifications is somewhat analogous to modeling work presented by Heimbach et al. (1998) for various composite sounding profiles, although the current study is focused specifically on measuring integrated stability within the valley-to-crest layer and inferring probable material dispersion patterns during periods with SLW. HYSPLIT does not model SLW or any microphysical processes related to seeding effectiveness. Nevertheless, some of the observations presented in the Heimbach,1998 paper were also seen in the present analysis, such as the tendency for plumes to drift to the north or northwest near the surface in some stable cases despite westerly winds above the surface, as well as the important role of forcing mechanisms in the transport of seeding material from valley sites over the barrier.

One might ask at this point why the entire stability study is not based on HYSPLIT modeling rather than the 2SS method. There are a few reasons for this. One is that modeling of plume behavior for operational cloud seeding is a new application of HYSPLIT. A second reason is that the HYSPLIT modeling is much more time consuming than the two-surface site analysis method. This becomes a major factor operationally, or when analyzing a very large number of observed icing periods. A third reason is that the archived meteorological model data readily available for use with HYSPLIT has fairly coarse terrain resolution, with the NAM 12-km data being one of the higher resolution options. This makes it difficult to accurately represent a given ground-based seeding site using the model data, since the model elevation at a given location may differ from the real elevation by as much as 1,000 feet (300 m) or more. Limited model resolution may also result in missing critical features such as strong but very shallow near-surface inversions at a given location, which a surface temperature analysis would take into account. For this reason, plume behavior as modeled using HYSPLIT with NAM data should not be interpreted as a "gold standard". However, this comparison between the two methods certainly provides useful information. It is likely that future modeling improvements, including better terrain resolution of operational meteorological models, will aid in the targeting of seeding material for this type of operational program.

5.0 SUMMARY AND POTENTIAL APPLICATION OF STABILITY ANALYSIS RESULTS

Several overall conclusions were derived from this study, regarding the frequency, strength, and seasonality of low-level stability occurrence in Utah during periods potentially seedable with silver iodide, as well as regarding analysis methodology. These can be summarized as follows:

Primary Conclusions Based on 2SS Analysis of Icing Periods

- During the primary operational cloud seeding season (November – April), for periods **when supercooled liquid water is present at temperatures favorable for seeding with silver iodide**, adequate dispersion of seeding material is expected from most valley and foothill sites approximately 75% of the time. Results vary seasonally, with a general maximum in low-level stability during December and January, and infrequent stability observed during March and April. These results are based primarily on two seasons of data and are not considered a complete climatology.

- Foothill locations may be substantially more suitable for ground-based seeding than valley bottom locations.
- Plume dispersion may reach 1,000 m (approximately 3,000 ft) or more above crest height in many cases, according to model estimates.

Analysis Methodology

- The two-site-stability analysis method is useful for evaluating the likely effectiveness of ground-based seeding from valley and foothill locations, both in real time and post-hoc, in the absence of rawinsonde data. The primary limitation of this method is the difficulty in measuring and assessing the impacts of wind on the dispersion of seeding material.
- The stability categorizations (N, SS, MS, VS) as defined in association with the 2SS method provide operationally useful partitioning of dispersion behavior. This partitioning can also be applied to rawinsonde data using the same methodology.
- The HYSPLIT model provides reasonable guidance regarding the likely dispersion of ground-based seeding material. One of the primary limitations is terrain resolution of the model data currently available for use with HYSPLIT.

We believe that the analysis results regarding the frequency, strength, and seasonality of low-level stability during icing periods are representative of much of Utah, and potentially of similar topography in other portions of the western United States. Experience with surface data analysis in support of ground-based seeding operations has shown that low-level stability can vary significantly from one locality to another, based on the wide variability of terrain profiles in Utah. It is hoped that establishment of additional high elevation ice detector sites in other locations, as well as data from future seasons, will provide a more complete climatology of low-level stability during seedable storm periods in Utah.

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