LOW-LEVEL STABILITY DURING WINTER STORMS IN THE UINTA BASIN OF UTAH: POTENTIAL IMPACTS ON GROUND-BASED CLOUD SEEDING

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ABSTRACT. Low-level thermodynamic stability, an important consideration for winter season ground-based cloud seeding site selection and conduct of operations, varies considerably in and near mountainous terrain. Rawinsonde observations may sometimes be poorly representative of nearby areas, with significant lower-level atmospheric temperature variability common between basins and sometimes within a basin. Operational forecast models may lack the ability to resolve or properly initialize low-level stability or "cold pooling" specific to a given basin or portion of a basin. Analyses of surface observations, as well as plume dispersion modeling with HYSPLIT, can be used both for real-time operations and in post-hoc examinations of low-level stability specific to storm periods with cloud seeding potential. Analyses of this type have been performed in various portions of Utah, and a recent analysis in the Uinta Range and Uinta Basin area of northeastern Utah highlights both the geographic variability and the seasonality of basin cold pooling. The Uinta Basin analyses have shown much greater low-level thermodynamic stability during relevant winter storm periods than other portions of Utah. Strong correlation of stability to site elevation within the basin, as well as distinct seasonality, are observed.

1. INTRODUCTION

There are several factors of importance in classifying a given storm situation as "seedable". In the context of winter-season programs targeting significant mountain barriers, employing a glaciogenic seeding technique using silver iodide, the primary criteria for identifying a seedable storm period include the following:

- The presence of supercooled liquid water. This usually must be inferred by storm/cloud type and structure, although in some cases ice detector data may be available as an aid.
- Mountain barrier crest-height temperature below –5 ºC, except in strongly convective situations.
- Cloud bases near or below the mountain crest.

For periods in which the above general seedability criteria are met, a final factor of great importance to ground-based seeding in particular is the transport and dispersion of seeding material over the target area from available seeding sites. Along with wind speed and direction, low-level thermodynamic stability is a primary factor in the dispersion of cloud seeding material released from ground-based ice nuclei generator sites. Determination of a low-level stability profile can be fairly complex during the winter season in mountainous terrain, where mountain barriers are targeted in ground-based cloud seeding for the purpose of snowpack augmentation. Analyses of low-level thermodynamic stability profiles during storm periods have been conducted in various portions of Utah in earlier decades (Super, 1999; Sutherland, 1979), and some more recent analyses have been conducted by North American Weather Consultants in some of these same areas (Yorty et al., 2012).

Rawinsonde observations and forecast model data are useful in assessing temperature structure during winter storm periods, in support of ground-based seeding operations. However, the temperature structure of the lower atmosphere below crest height (which is often near 700 millibars in the western U.S.) can vary considerably between basins, and at the lowest levels even within a basin, so that a given sounding profile's near-surface parameters may be poorly representative of even nearby areas. Observational and modeling studies in Germany (Zängl, 2003a; 2005b) have shown the potential spatial variability of low-level thermodynamic stability in mountainous terrain. A high-resolution modeling study based on the Yampa Valley in Colorado (Billings et al., 2006) demonstrated the importance of factors such as terrain profile and snow cover, and the potential difficulty in modeling temperature profile evolution in complex terrain. Operational forecast model data may be lacking, both in terms of resolution and model initialization (Reeves and Stensrud, 2009), in ability to resolve variations of the low-level temperature profile in areas of complex terrain.

The importance of seasonality in regard to low-level thermodynamic has also been addressed for western U.S. basins including the Colorado Plateau Basin (Whiteman et al., 1999) and the Columbia River Basin (Whiteman et al., 2001). The December/January or December – February period are implicated as being the peak season for low-level thermodynamic stability in these mid-latitude (Northern Hemisphere) regions.

Recent analyses of thermodynamic stability in the Uinta Basin in northeastern Utah during winter season storm periods, and comparisons with similar analyses in other portions of Utah with differing topography, provide context for a discussion of thermodynamic stability and cold pool climatology as it relates to ground-based seeding operations. In discussions of low-level thermodynamic stability, there are several terms that may be used somewhat interchangeably, although each has its own particular meaning. The term "inversion" is often used to describe low-level stability, or cold air pooling within a basin, although strictly speaking (and as generally used in the current paper) it refers to a layer of the atmosphere in which the temperature increases with height.

Temperature inversions are layers of very strong thermodynamic stability, although in reality they constitute only a subset of possible stable situations. An atmospheric layer in which the lapse rate is less than the adiabatic lapse rate (specifically, the moist adiabatic rate in the case of saturation and the dry adiabatic rate in the case of sub-saturation) is by definition thermodynamically stable and will exhibit some degree of resistance to vertical mixing. This may be overcome in some cases by turbulence or forced uplift over terrain, but is often sufficiently strong to prevent or substantially limit vertical mixing and transport of an air parcel. The term "cold pool" is often used for mountainous regions, in reference to a low-level thermodynamically stable air mass that is confined to a basin. A strong cold pool during the winter season will often contain an inverted layer, which may extend to the surface or may be elevated, frequently residing near the top of the cold pool. Multiple inverted, or other very stable (such as isothermal) layers, may also be interspersed with layers that are well-mixed or have a lesser degree of stability.

Winter season low-level stability and cold pool behavior can vary dramatically between one location and another in the mountainous western United States, such that available rawinsonde soundings may not be well representative of other locations in the region. This may be especially true during storm events, as cold pooling tends to mix out of some basins (or portions of basins) much more easily than others. This is an important consideration in regard to ground-based seeding operations conducted from lower elevation sites.

2. METHODOLOGY

For storm periods classified as "seedable" based on the generalized criteria listed in Section 1.0, the impact of any low-level thermodynamic stability on the transport and dispersion of seeding material must be considered when utilizing ground-based seeding sites. Two methodologies have been used to assess low-level thermodynamic stability in situations where representative rawinsonde data may not be available. One is a comparative analysis of surface data at appropriate elevations, such as temperature and dew point data at a valley (or other) location that would be considered representative of a ground-based seeding site, in comparison to temperature data at a nearby mountain barrier site in a seeding target area. This analysis method involves a thermodynamic adjustment of the parcel from the lower site along the appropriate (dry and/or moist) adiabat to the elevation of the mountain site, and comparison of the resulting parcel temperature with the observation at the mountain site. The second stability analysis methodology involves plume dispersion modeling with the National Oceanic and Atmospheric Administration's Hybrid Single Particle Integrated Trajectory (HYSPLIT) model. The HYSPLIT modeling for these analyses utilized North American Mesoscale (NAM) model data.

Previous low-level stability analyses utilizing these methodologies have been conducted in central Utah (Figure 1), and in the Salt Lake City area, where comparisons to RAOB data were used as a baseline comparison as described in Yorty (2012). Some surface data analysis was also conducted in the Brian Head area of southwestern Utah. Classification of storm periods as seedable in Yorty (2012) was based primarily on the presence of supercooled water as measured by ridge-top ice detectors, as well as ridge-top temperatures within a seedable range for silver iodide (< -5 ºC), with these criteria implying seedability in a general sense. For each period in which general seedability was implied, integrated thermodynamic stability between the valley and adjacent mountain crest, deduced from surface observations at these elevations and the adiabatic (dry and/or moist) lifting of an air parcel from valley floor to mountain crest, was categorized based on the difference between the lifted parcel temperature and the observed crest height temperature. The result of such an analysis may be used to imply favorable or unfavorable conditions for seeding with ground-based sites, typically situated in valleys or foothills adjacent to the target area.

The surface site stability analyses were compared with HYSPLIT plume modeling results in the Yorty 2012 paper. The potential ability of winds and orographic forcing to overcome a given amount of thermodynamic stability is intrinsic to the HYSPLIT plume modeling results. Based on these comparisons, a 2 ºC threshold of integrated stability between a seeding site location and mountain crest (i.e., 2 ºC of valley warming and/or crest height cooling needed for completely uninhibited mixing) was determined to be a reasonable limit for inferring favorable ground-based seeding potential in most storm situations. Results presented in the Yorty paper, which focused primarily on surface data and HYSPLIT analyses for a large number of likely seedable storm periods in central Utah, yielded favorable indication for valley-based seeding during approximately 80% of the periods examined in that area. Brian Head area surface data during storm events yielded similar indications in southern Utah and surface observations in the Salt Lake City area showed strong elevation dependence in terms of thermodynamic stability characteristics.

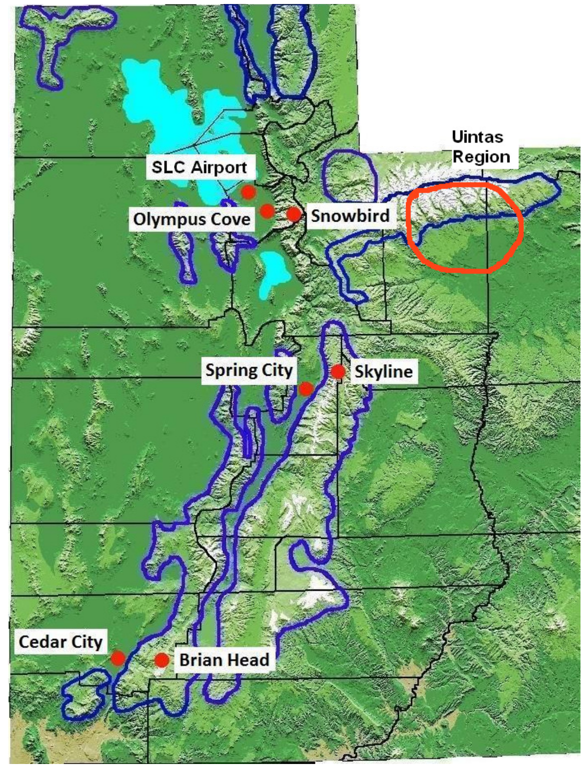

Figure 1: Surface (valley and ridge-top) sites used in stability analyses in Utah; Multiple sites were analyzed within the circled area in the Uintas region.

`3. ANALYSIS OF STORM PERIOD THERMODYNAMIC STABILITY IN THE UINTA BASIN

The Uinta Basin, located in northeastern Utah, lies immediately south of the east-west oriented Uinta Range (Figure 2), adjacent to an active ground-based cloud seeding program for the southern slope of the Uintas. The basin reaches elevations below 5,000 feet MSL (1,524 m) in its central, lower portion. It is bounded by crest elevations generally ranging from about 8,000 to 12,000 feet (2,438 – 3,658 m) in the Uinta Range to the north, 8000 to 9,000 feet (2,438 – 2,743 m) in the Wasatch Plateau to the west and Tavaputs Plateau to the south, and by surrounding topography generally in the 6,500 to 8,000 foot (1,981 – 2,438 m) range to the east, in Colorado. Although the Uinta Basin is not technically a closed basin, as the Green River traverses the basin and cuts southward through the Tavaputs Plateau, the long, narrow and winding nature of the canyon along the river's course mean that for meteorological purposes it is essentially a closed basin. This makes the Uinta Basin fertile ground for an analysis of low-level stability and cold pooling characteristics, and for examining cold pool variability with regard to terrain.

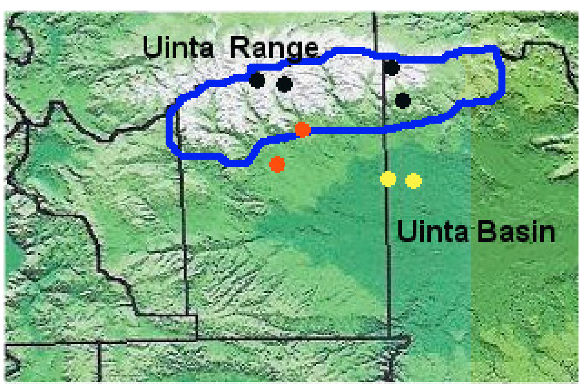

Figure 2: Approximate site locations for surface analysis in the Uintas region in northeastern Utah; surface data analysis was conducted for sites at varying elevations including lower Uinta Basin (yellow, near 5,000' MSL), mid-elevations (red, approx. 6,500 to 8,000'), and high elevation (black, above 9,000').

3.1 Previous stability analyses during storm periods in the Uinta Basin

The Uinta Basin often has strong and persistent cold pooling during much of the winter season, and therefore presents some unique challenges regarding low-level stability and ground-based seeding operations. A North American Weather Consultants report (Sutherland, 1979) discussed temperature inversion characteristics in the Uinta Basin, based on basin-specific sounding data obtained during the 1977-78 winter season. It was noted in this report that about 75% of winter storm period soundings from Roosevelt, in the lower Uinta Basin, had some type of temperature inversion present. It was also reported that deep or elevated inversions, extending to an average of about 2,600 feet (800 m) above the valley floor, were more prevalent in these soundings than shallow, surface-based inversions. The elevated inversions had a strong seasonal dependence (occurring primarily from December through February) while shallow inversions did not. The deeper inversions/cold pools observed in this early study were common during warm-sector portions of storm periods, and mixed out following a cold frontal passage in roughly half of the cases. Basin snow cover was also implicated as likely being a major contributor to the formation of deep persistent inversions.

3.2 Uintas region storm period stability analyses in the current study

Analyses of low-level stability in Utah focus primarily on the November – April period, which is the typical season for winter ground-based seeding programs. Analyses presented in this paper are based on data during three such seasons (2009-10, 2010-11, and 2011-12). Approximate surface site locations in the Uinta Range/Uinta Basin analysis (herein referred to as the "Uintas" region), are depicted in Figure 2. Additional sites in these areas, most having more limited data availability, were used in a comparative sense primarily for quality control purposes.

The NOAA HYSPLIT model, using North American Mesoscale (NAM) Model 12-km resolution data was again utilized as a comparative method for estimating three-dimensional plume dispersion from representative ground-based seeding sites in this study.

4. RESULTS

Although previous comparisons of HYSPLIT plume modeling to surface site stability analyses showed fairly consistent results in most areas of Utah (Yorty et al. 2012), substantial differences were found during the current study in the Uintas region, an area that was not examined in the earlier study. One primary reason for these differences is that in some cases the NAM fails to accurately initialize low-level thermodynamic stability (or a "cold pool") specific to particular basin areas (Reeves and Stensrud, 2009), which in the context of HYSPLIT modeling may result in overestimates of ground-based plume vertical dispersion rates. Despite this limitation, one noteworthy observation for thermodynamically stable warm-sector storm periods examined in the Uintas analysis is that much of the lower level air mass on the southern side of the Uinta Range often tends to be trapped in place, and in many cases at least a portion of it is diverted westward around the Uinta Range in the model (that is, an easterly low-level wind field is often observed over the Uinta Basin). Figure 3 shows this wind pattern in the modeling results for a thermodynamically stable storm period. This is consistent with surface observations during many warm-sector periods with southerly component winds, and has important implications in terms of cold pool configuration and targeting of seeding material specific to the seeding program in the Uinta Range.

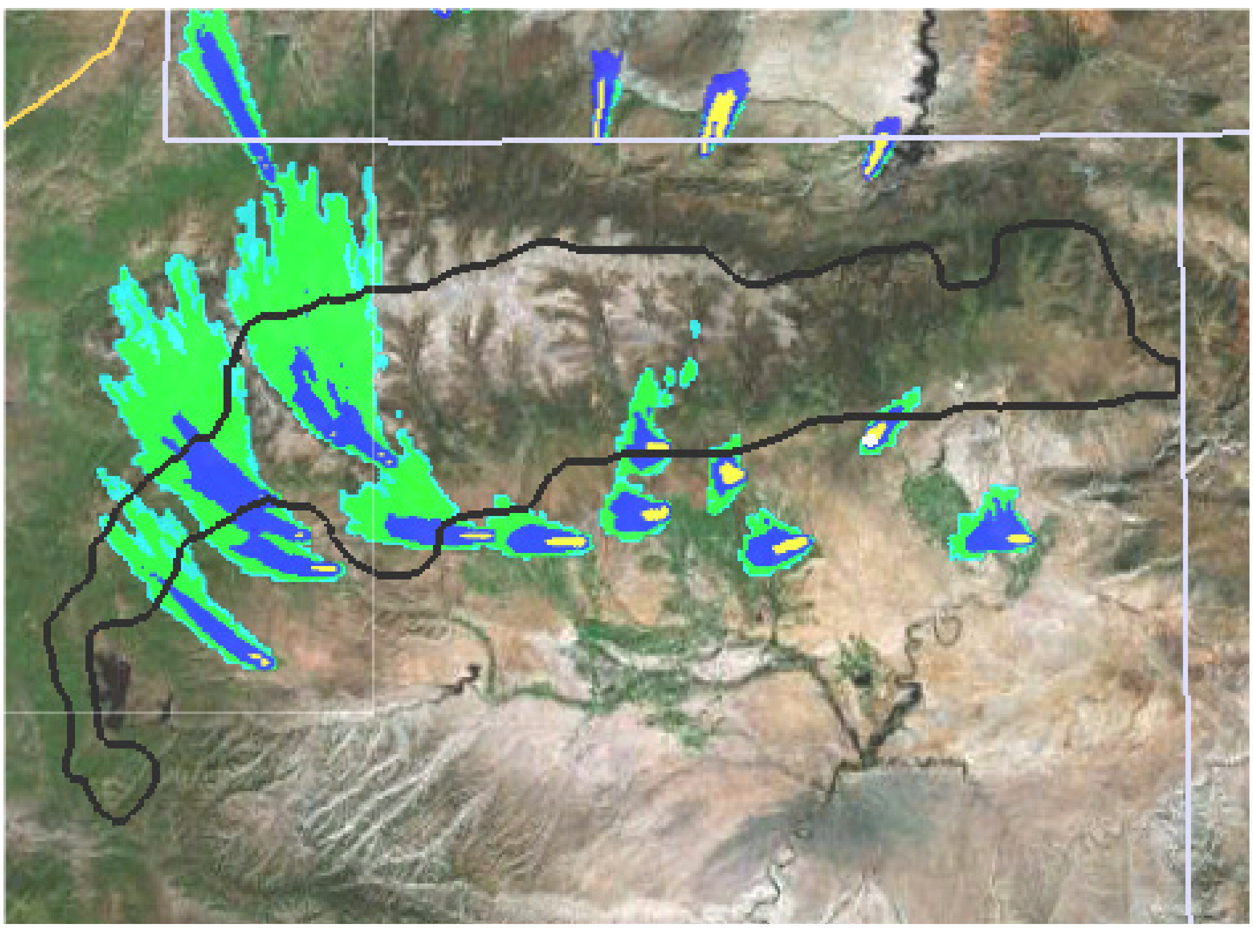

Figure 3: HYSPLIT model output for a storm period with low-level stability, depicting much of the low-level wind field over the Uinta Basin being diverted westward around the Uinta Range. Black outline shows approximate seeding target area.

4.1 Variations of low-level thermodynamic stability with respect to topography

In contrast to indications in central Utah in Yorty (2012) suggesting favorable dispersion in approximately 80% of likely seedable storm periods in central Utah during the November – April season, results of similar surface-based stability analyses along the southern slope of the Uintas suggest that about 33% of likely seedable periods have adequate dispersion for seeding from lower Uinta Basin locations near the 5,000 feet (1524 m) elevation level, and ~56% of these periods have adequate dispersion from mid-elevations (roughly 6,500 - 8,000 feet or 1,981 – 2,438 m). The mid-elevation sites in this analysis are most representative of current operational ground-based seeding sites. Figure 4 shows composite results for the three November – April seasons based on site elevation, as the percentage of likely seedable storm periods in which ground-based material would likely reach approximately the 11,000 feet (3,353 m) elevation (considered a representative crest height) in the target area. As discussed in Section 2.0, the seedable percentages obtained in these surface-site analyses are based on a threshold of 2 ºC difference between a lifted parcel temperature (lifted from the specified elevation to the crest height) and the observed crest height temperature. Periods where this difference exceeds 2 ºC are considered to be not seedable from ground-based sites at that elevation. Seeding from high elevation sites, if such were readily available, would clearly be the least impacted by thermodynamic stability.

As an example of the variability in low-level stability between different basin areas, Figure 5 shows a sounding from the nearest rawinsonde site (Salt Lake City), located approximately 80 miles (129 km) to the west-northwest of the analysis area, during a storm period in December 2010. A comparison sounding profile was constructed below approximately the 650-mb level, using surface observations at that time from varying elevations in the Uintas stability analysis area. This is a period that, aside from the low-level stability issue, met seeding criteria for the Uintas seeding program. Although this type of comparative analysis between rawinsonde and surface data has some potential pitfalls, it clearly demonstrates the degree of low-level temperature structure variability that can occur between basins in the same region.

4.2 Seasonality of low-level thermodynamic stability

The Uinta Basin stability analysis results exhibit very strong seasonality, with favorable predicted material dispersion from low elevation (5,000’ or 1,524 m) Uinta Basin sites indicated in less than

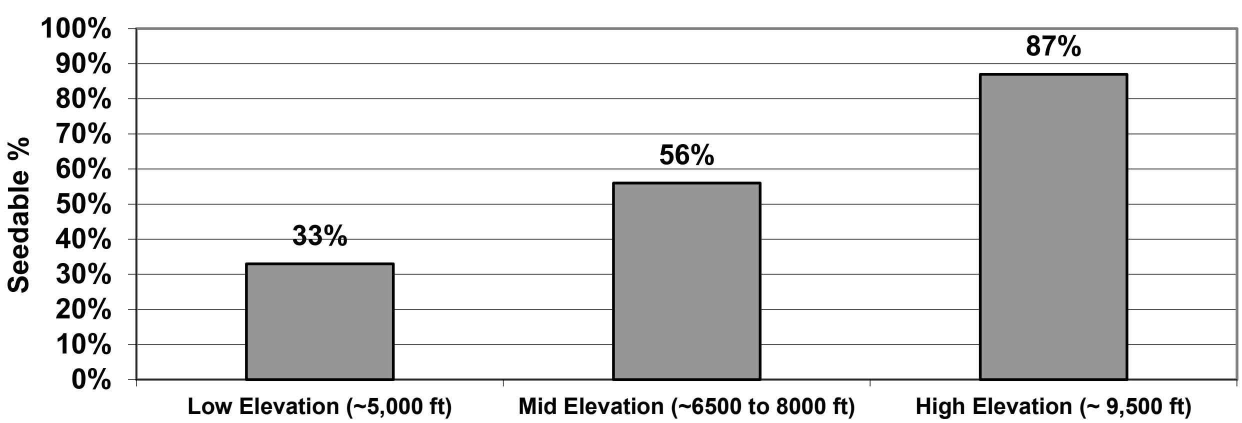

Figure 4: Indications of winter season (November – April) seedability indications along the southern slope of Uintas, for various elevation bands; likely percentage of seedable storm periods in which favorable vertical dispersion would occur from a ground-based site in a given elevation range.

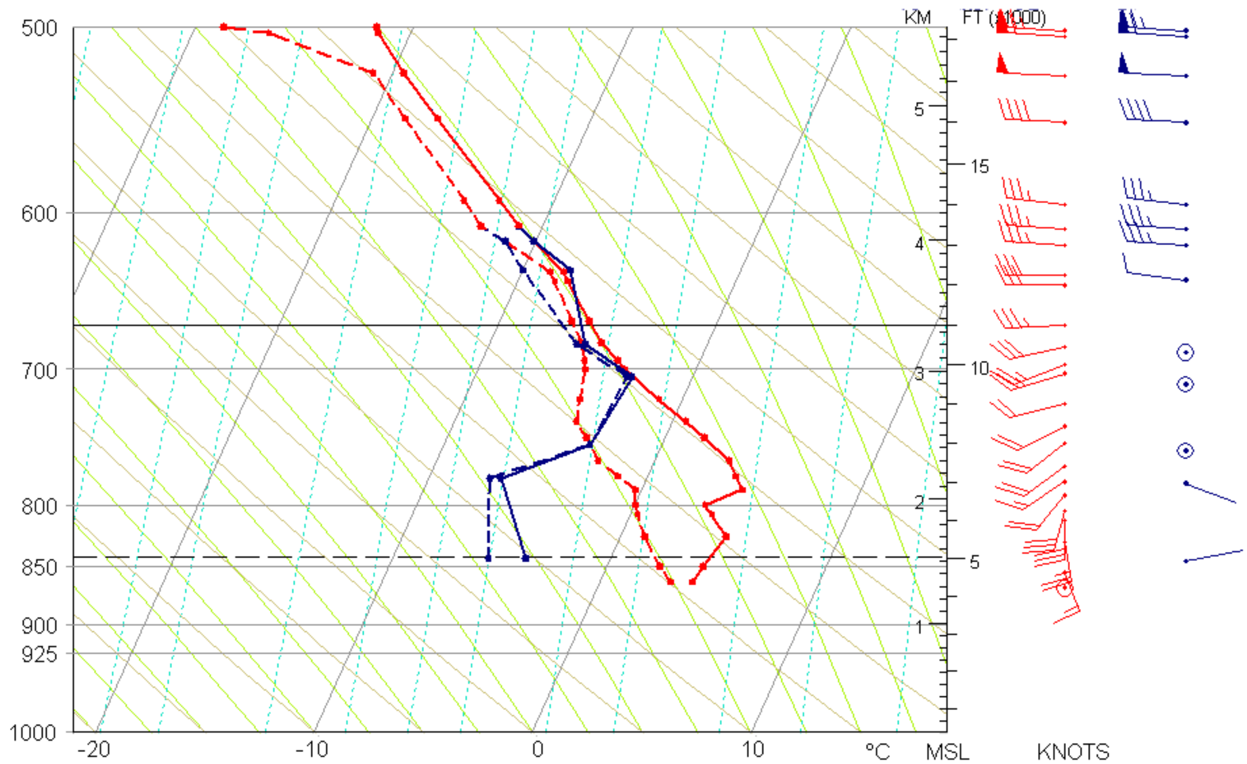

Figure 5: Salt Lake City rawinsonde data (red) in comparison to sounding profile below ~650 mb constructed from ground-based data along south slope of Uintas (blue), for a December 18, 2010 storm period. This comparison shows strong divergence in the temperature profile below ~700 mb, with Uinta Basin temperatures as much as 10° C colder in the lower levels.

10% of likely seedable December-January storm periods (Figure 6), but in more than 80% of these periods in spring (mid-March through April) as shown in Figure 7. For the mid-elevation locations (6,500 - 8,000' or 1,981 – 2,438 m), most representative of current ground-based seeding sites, the analysis suggests favorable dispersion in ~28% of the December – January periods, and in ~87% of the spring (mid-March through April) periods. Other seasonal periods including November, as well as February through mid-March, exhibit stability indications varying between the December-January (most stable) and mid-March through April (generally well-mixed) extremes. Comparison of Figures 6 and 7 highlights the degree of seasonal variability in the indications.

5. DISCUSSION/IMPLICATIONS

Recent work has demonstrated the utility of surface temperature and dew point observations in supplementing available rawinsonde and model data, particularly when examining low-level thermodynamic stability in support of winter cloud seeding operations in complex terrain. Although one must acknowledge the limitations of surface data in attempting to infer the three-dimensional distribution of temperature and wind fields in the vicinity of a seeding target area, the availability of such observations at varying elevations can be an important resource in this regard. Ground-based plume modeling with HYSPLIT can be a good complement to surface data analyses in attempting to infer the potential dispersion of seeding material in various storm situations.

Low-level thermodynamic stability that may inhibit ground-based seeding operations can take various forms, ranging from shallow near-surface (usually nocturnal) inversions, to deeper layers of stability that may include isothermal or inverted layers. Deep, persistent, multi-day cold pools may develop in some Utah basins during periods

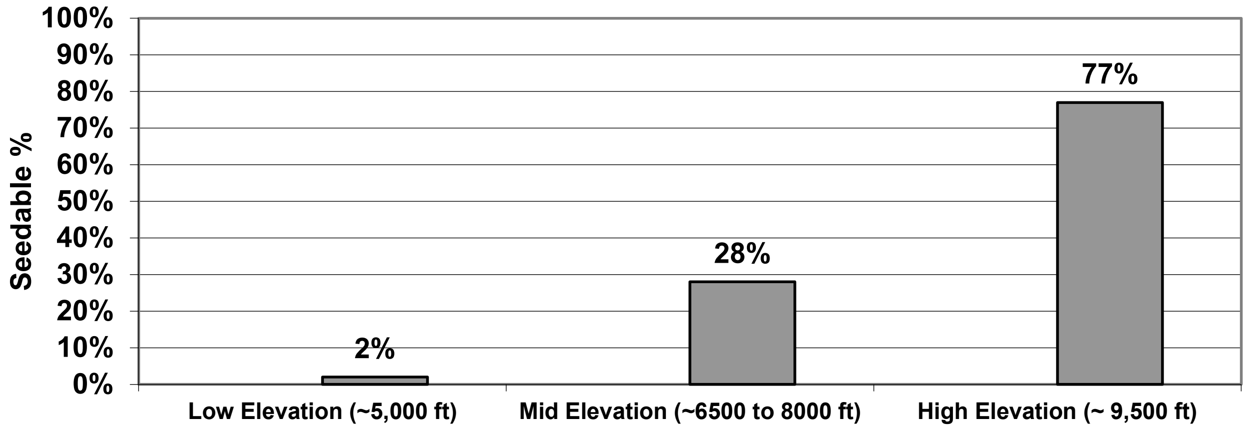

Figure 6. Indications of potential seedability from sites at various elevation bands along the south slope of the Uintas during December – January storm periods in analysis

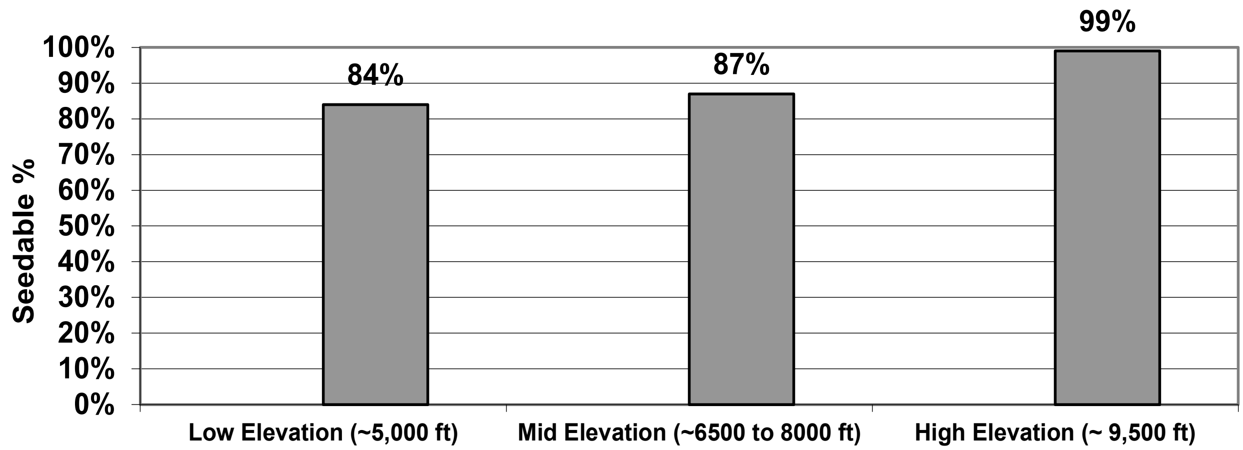

Figure 7: Indications of potential seedability from sites at various elevation bands along the south slope of the Uintas during late March and April storm periods in analysis

of clear winter weather and persist during subsequent storm events. Such cold pools appear to be most frequent during the months of December and January, near the time of minimum solar heating. The development of low-level thermodynamic stability, including inversion layers, primarily occurs during clear weather, either nocturnally or when the sun angle is low. Shallow, nocturnal inversions or stable layers may dissipate quickly when daytime heating is sufficient, or due to atmospheric mixing associated with storm activity. Deeper basin cold pools, however, may be very difficult to mix out in areas of restricting topography, and may persist during all or at least a portion of a given storm event.

Factors affecting development, strength, and persistence of basin cold pools include season and latitude (which are related intrinsically to sun angle and surface heating), terrain profile (particularly major barrier orientation), and snow cover. Thermodynamic stability at a particular location is often strongly correlated with its elevation relative to surrounding terrain, as valley bottom locations may be much more impacted by stability than mid-elevation sites. It is apparent that snow cover at lower and mid elevations plays a significant role in the development, strength, and persistence of multi-day cold pools during the winter season (Billings et al., 2006; Sutherland et al., 1979; Whiteman, 1982), although winter season cold air pooling is known to be common in some areas, such as the Uinta Basin, even in the absence of snow cover. Given that initial cold pool development often occurs during relatively clear winter weather (Dominger et al., 2011), and considering the very high albedo of snow, the presence of snow cover is likely to be particularly influential during clear weather periods. Basin areas where cold pools tend to remain trapped during warm-sector storm periods (perhaps contributing to additional snowfall and impeding snow melt during these periods) may experience a significant winter season feedback between atmospheric cold pooling and surface snow cover, with each helping to reinforce the other.

Surface observations during storm periods in Utah, during many years of operational seeding programs in various portions of the state, suggest that microclimates related to cold pool behavior are often fairly predictable. During a storm period, basin cold pools are influenced by synoptic-scale low-level pressure gradients, with overlying wind fields and temperatures also a significant factor affecting the potential mixing of the low-level air mass. The introduction of a synoptic-scale surface pressure gradient will typically cause a cold pool to deepen somewhat on the side of a basin with lower surface pressure, with the cold air potentially spilling over or through terrain gaps on that side of the basin (Zängl, 2003a), similar to water flowing over the side of a bowl. In a typical warm-sector storm period in Utah, for example, a surface pressure gradient in which pressure is lower to the north and west would favor southerly or southeasterly near-surface winds at low elevations in the absence of terrain channeling (even though warm sector winds would typically veer with height, to a more southwesterly direction near and above mountain crest level). Therefore, based on lower-level winds and pressure gradient patterns, basin areas with high terrain immediately to the north and northwest may experience the most persistent inversions or thermodynamic stability throughout these warm sector periods, due to accumulation and trapping of a pre-existing cold pool air mass. This helps to illustrate the impact of the terrain profile and mountain barrier orientation on the persistence and depth of cold pooling during storm events. It also demonstrates the importance of real-time surface observations in the conduct of ground-based seeding operations.

Along the southern slope of the Uintas, the 7,000 to 8,000 foot elevation range has been implicated as a potentially important threshold for avoiding stability problems associated with ground-based seeding. A High Uintas pre-program feasibility/design study identified this factor, partially based on earlier work (Sutherland, 1979), and the project design (i.e. seeding site selection) reflects that understanding. This is supported by the results of the most recent analysis, and an examination of the terrain profile and barrier orientation in this area. Seeding during post-frontal storm periods is normally conducted from the western and northern sides of the Uinta Range, when stability is less likely to be a concern, as is likely true of most western U.S. mountainous areas in general. Regarding seasonality, data strongly suggest that multi-day cold pool development essentially ends by early to mid March (and often earlier) at Utah's latitude, with excellent low-level mixing indicated for most spring storm events. In fact, the southern slope of the Uinta Range can be a favored area for convection during the spring season due to comparatively strong surface heating. Indicated seeding effects would likely exhibit meaningful seasonality, if and when a sufficient data set or analysis technique is able to overcome the high degree of natural (background) variability in precipitation patterns at short time intervals, which can be problematic when evaluating this type of non-randomized program.

Results of the current study highlight the degree of variability in low-level thermodynamic stability in mountainous terrain, and the importance of conducting a site-specific feasibility/design study prior to the commencement of a cloud seeding program. Basin cold pool behavior and climatology during the winter season in areas of complex terrain can be a significant factor in the placement of ground-based seeding sites, as well as in optimization of the real-time targeting of seeding material.

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