# WINTER "CLOUD SEEDING WINDOWS" AND POTENTIAL INFLUENCES OF TARGETED MOUNTAIN BARRIERS

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**ABSTRACT.** The concept of "winter cloud seeding windows" is a familiar theme found in a number of earlier publications. More recent feasibility studies, physical observations and analyses of existing cloud seeding programs have indicated that some of this earlier thinking has considerable merit. The concept that deep winter storm systems with cold cloud tops often appear to be naturally efficient with little or no supercooled liquid water content is especially important. It appears from a variety of earlier sources of information and more recent observations that shallow, orographically induced clouds often contain supercooled liquid water and therefore offer good cloud seeding potential.

Several studies and observations suggest that shallow orographic clouds that contain supercooled liquid water frequently occur after the passage of a surface cold front and even after the passage of an upper level trough. If the occurrence of such clouds is viewed in the context of the orientation of the targeted mountain barriers, the question can be asked if mountain barrier orientations have any impact on the development of these types of "seedable" clouds? This is basically a question of the amount of up-barrier flow that accompanies these shallow orographic clouds. North American Weather Consultants (NAWC) has developed a conceptual model in which the barrier orientation that provides the best conditions for the formation of these kinds of clouds in the western United States (and perhaps elsewhere) are barriers with a north-south orientation, since post-frontal or post upper trough passage conditions will produce considerable up-barrier flow over these barriers accompanied by lowering and warming cloud tops. Fortunately, most mountain barriers in the western United States have such an orientation.

NAWC believes that recognition and verification of the above will be important in the design and conduct of future winter orographic cloud seeding programs. Placing "seedabilty" in the synoptic setting and relating "seedability" to barrier orientation will be important in estimating potential cloud seeding effects in different project areas in the future.

## 1. INTRODUCTION

The concept of identifying certain orographic winter storm conditions in real-time that should be susceptible to modification through cloud seeding is not a new one. Inference of such "seeding windows" has primarily been based upon two sources of information: 1) observations of supercooled liquid water (SLW), which is a necessary ingredient for modification of winter clouds using glaciogenic seeding agents and 2) statistical results from randomized research programs. Unless real-time measurements of SLW (e.g., microwave radiometers or ground-based icing rate meters) are available during the conduct of an operational winter orographic cloud seeding program, then some type of conceptual model that indicates the likely presence of "seedable" conditions can be quite useful in determining when cloud seeding operations should begin and end. Consequentially this paper takes another look at the concept of developing "cloud seeding windows" for use in real-time decision-making.

## 2. EARLIER STUDIES WITH INDICATIONS OF THE PRESENCE OF SUPERCOOLED LIQUID WATER AND/OR SEEDING INCREASES IN RELATION TO ATMOSPHERIC VARIABLES

Mooney and Lunn (1968) analyses showed that the most positive results of seeding were from seeding cold westerly events in a randomized winter program conducted in the Lake Almanor, California area. These cold westerly events were most likely post-frontal situations. Grant and Elliott (1974) defined seeding windows as a function of cloud top temperatures or, as a surrogate for such temperatures, the temperature at the 500 mb level. Indications of positive effects were observed with cloud top temperatures in the range of -10 to -24 $^0$C. Vardiman and Moore (1978) analyzed the results from several winter cloud seeding programs and concluded that increases at the mountain crest generally occur in 1) stable orographic clouds with a crest trajectory and cloud top temperatures between -10 to -30 $^0$C and 2) moderately unstable clouds with a crest trajectory, moderate to high water content and cloud top temperatures between -10 and -30 $^0$C. Hobbs, (1975), summarized results of airborne observations made over the Cascade Mountains of Washington as follows, "In pre-frontal conditions the winds near the surface over the western slopes of the Cascades are easterly and produce drying conditions but from 1.8 to 3.6 km the air is moist and from the southwest. Ice particles dominate over water droplets in the pre-frontal clouds and above the -10 $^0$C level riming is rare. In post-frontal conditions the air is more unstable, the winds are westerly at all levels, and the cloud tops are lower. The ratio of ice to water is less than in pre-frontal conditions and heavily rimed particles are common".

It is worth noting that the Cascade Mountains have a north-south orientation. A composite of

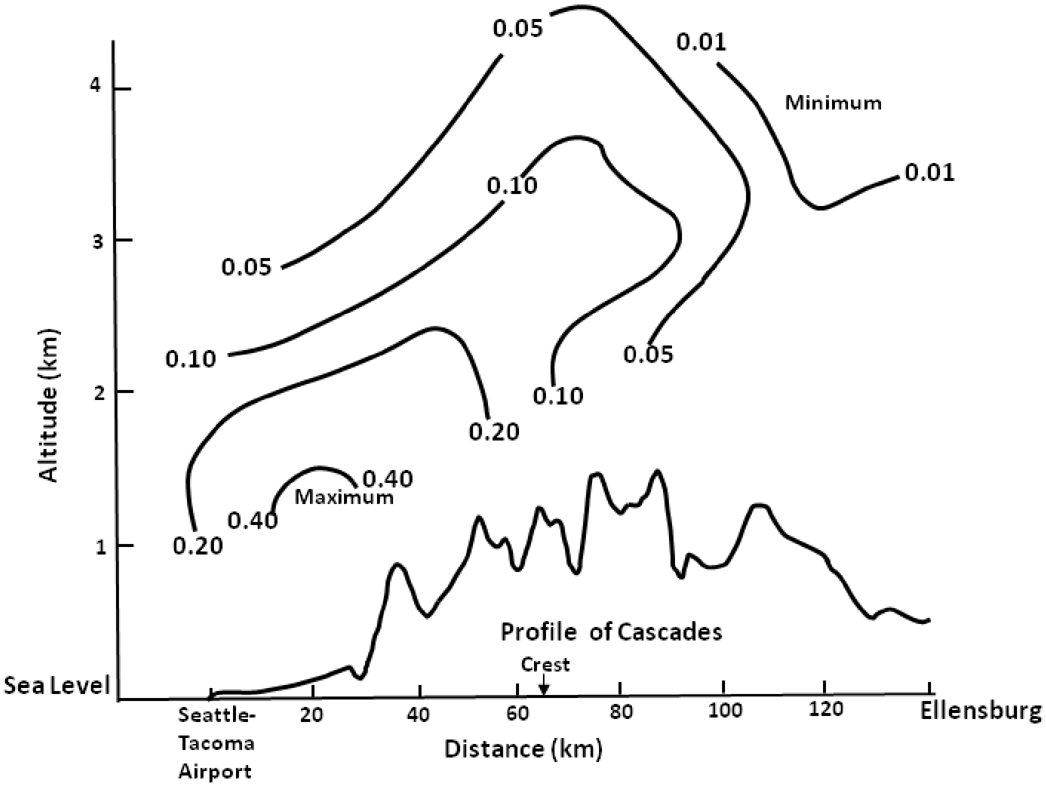

*Figure 1: Average Distribution of Liquid Water (g/m3) in Clouds over the Cascade Mountains as a Function of Altitude. Figure is from Hobbs, 1975 which is reprinted by permission of the American Meteorological Society.*

aircraft observations over the Cascades (from Hobbs, 1975), indicated a SLW accumulation zone over the upwind slopes extending to about the crest line (Figure 1).Cooper and Marwitz (1980), reporting on some aircraft observations taken in the San Juan Mountain region of southwestern Colorado, concluded that "opportunities for precipitation enhancement by seeding occur in the latter part of the storm sequence, are associated with the release of convective instability, and can be identified by the presence of a zone of horizontal convergence upwind of the mountain range." Hill (1980) concluded that winter cloud seeding potential in the northern Utah Mountains was highest when the cloud top temperatures were ≥ - 22 $^0$C and cross-barrier wind speeds at mountain top levels were 10 m/s or greater. Such conditions typically occurred in post-frontal conditions. Shaffer (1983) reported on some stratification results from the Colorado River Basin Pilot Project (CRBPP). Stratifications were performed using 700 mb wind data, the height of the -5 $^0$C level and estimated cloud top temperatures. Indications of a significant seeding effect was found for cases in which the 700 mb wind speed normal to the barrier was ≤10 m/s, the height of the -5 $^0$C level was ≤3 km and the cloud top temperatures were > -20 $^0$C. It is worth noting that the CRBPP target area, the San Juan Mountains, have a west to east barrier orientation.

Rauber and Grant (1986), reporting on the Colorado Orographic Seeding Experiment (COSE) conducted in northern Colorado, indicated that SLW was generally observed in shallow clouds with cloud top temperatures > -22 $^0$C. Reynolds and Dennis (1986) and Reynolds (1988) reporting on the Sierra Cooperative Pilot Project (SCPP) attempted to place the occurrence of "seedable" conditions into a synoptic setting. Their results indicate a bulk of the observed SLW occurred after the passage of an upper cold front and before the passage of a surface front in a region with lowering clouds tops that were formed primarily

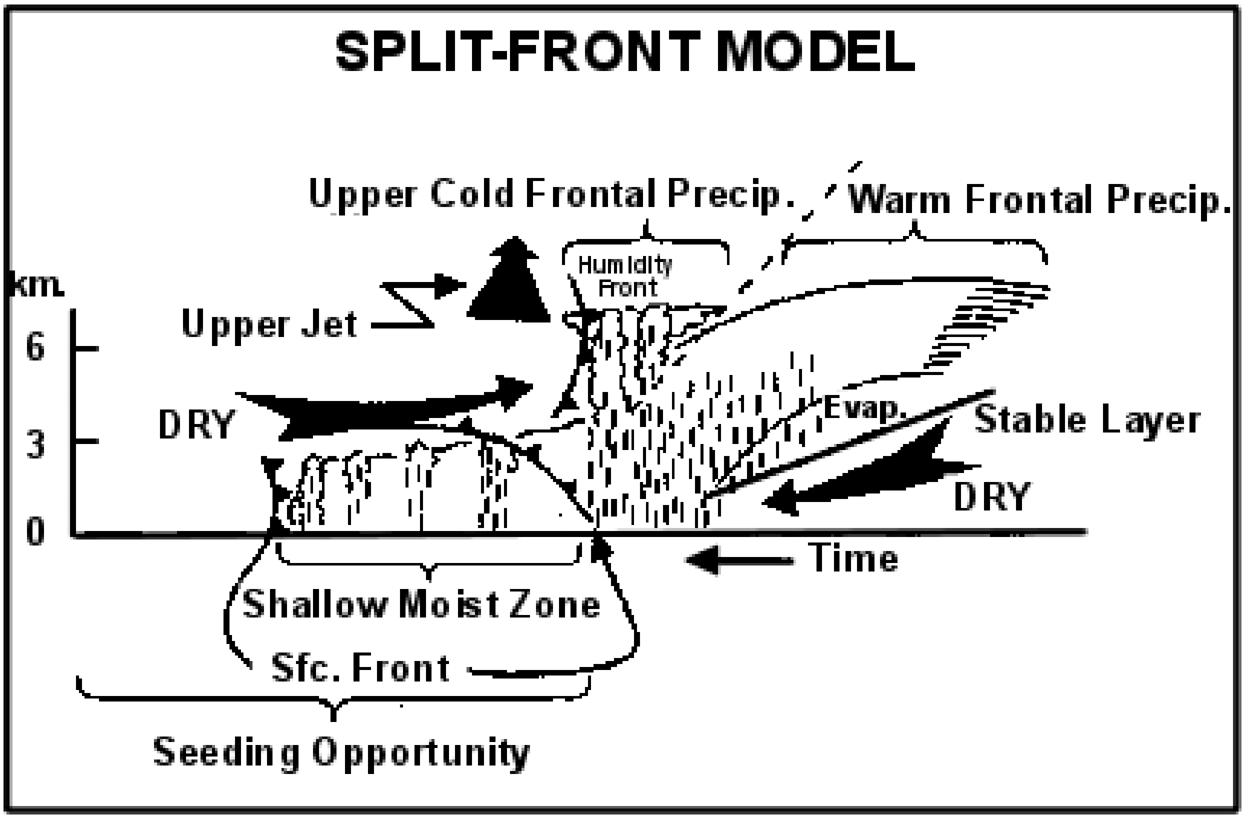

*Figure 2: Conceptual Model of a Split Front and Indicated Regions of Seeding Opportunity (Reynolds, 1988, Reprinted by permission, AMS Bulletin of the American Meteorological Society)*

due to orographic lift. They referred to this situation as a split-front. Figure 2, from Reynolds (1988), graphically depicts this feature. In general, the above information tends to indicate the presence of SLW or evidence of positive seeding effects in winter orographic storms being related to storm periods with cloud top temperatures > -20 to -25 $^0$C. There are some exceptions to this generalization. For example, Super and Heimbach (2009) provide some post hoc stratifications of six hour periods from the Bridger Range research program in Montana that "suggest that seeding was most effective during passage of deep, cold-topped cloud systems." It should be noted that their analysis had only limited data available at mandatory constant pressure levels from which estimated cloud top heights and temperatures could be derived.

## 3. MORE RECENT RELEVANT STUDIES

Super (1999) provides a summary article that discusses a variety of results from the Utah/NOAA Atmospheric Modification Program (AMP) conducted over the Wasatch Plateau of central Utah. A couple of key conclusions concerning the presence of SLW were: "1) orographic cloud SLW is usually found over the windward slopes and crests and rapidly diminishes further downwind, even as cloudy air moves across the relatively flat Plateau top which is about 10 km wide. The SLW is depleted by a combination of snowfall production and subsidence, 2) the SLW cloud is confined to a shallow layer above the Plateau. Most SLW amounts are usually negligible by 1,000 m above the terrain. Forced orographic uplift, weak embedded convection, and gravity waves all combine to produce the liquid condensate." NAWC developed a conceptual schematic of the location of this SLW zone in a north-south oriented barrier with a westerly component to the lower level winds (Figure 3). Such wind directions are typical of winter storms in the Intermountain West. The Wasatch Plateau does have a north-south orientation. This figure could be rotated 90$^0$ to simulate a west-east oriented barrier. A comparison of Figures 1 and 3 indicates the similarities between aerial observations over the Cascade Mountains and the conceptual diagram that was suggested by the results from the Utah NOAA program. A comprehensive winter research program was recently conducted over the Snowy Mountains of southeastern Australia from 2005 to 2009 (Manton, et al, 2011). A variety of analyses were performed investigating the potential effectiveness of the program (Manton and Warren, 2011). This program used a network of ground-based silver iodide generators to seed selected portions of naturally occurring winter storms. An analysis of cloud top temperatures indicated that natural precipitation tended to increase as cloud top temperatures decrease, in other words deeper clouds are more efficient in producing precipitation. There are indications that the effectiveness of seeding tends to increase as cloud top temperatures decrease within the range of -7 to -20 $^0$C. The -7 $^0$C cloud top temperature was used as an upper limit of cloud top temperatures as one of the criteria to declare an experimental unit. An analysis using the wind direction

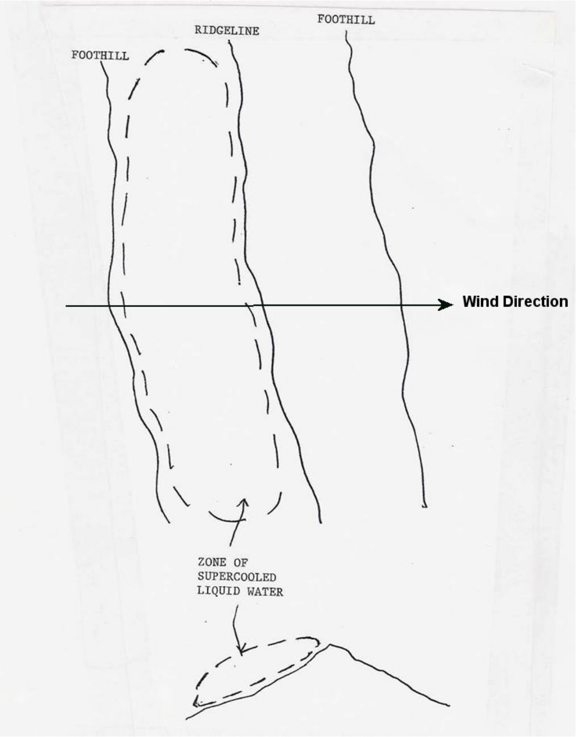

*Figure 3: Conceptual Depiction of a Preferred Supercooled Liquid Water Formation Zone over a North-South Oriented Orographic Barrier in Wintertime.*

at the height of the -5 $^0$C level indicated that a northerly component of this wind is important in maximizing the seeding effect. A quote from Manton and Warren, 2011; "The main range in the target area tends to have a northeasterly alignment, and so a reasonable a priori assumption is that the sensitivity to wind direction is related to the optimization of orographic lifting."

NAWC has collected SLW measurements at two locations in Utah for the past three winter seasons using ground-based icing rate meters (Yorty, et. al, 2012). These locations are at: 1) a Utah Department of Transportation site (Skyline) east of Fairview, Utah; in central Utah (the same location as the earlier NOAA/Utah research area) and 2) the Brian Head Ski area located in southwestern Utah. Both sites are at the crest of prominent north-south oriented mountain barriers. Temperature, precipitation and wind sensors were co-located with the icing rate meters. Icing data collected from these sites have been analyzed in a number of ways. Some of the more interesting indications after three seasons of data collection at these sites are discussed in the following. A few caveats regarding these indications are necessary. First, these are point, surface based observations. Icing may be occurring above or near these sites, which would not be detected. Second, these observations only span three seasons at this point so they certainly do not constitute a true climatology of icing at these sites.

The data were stratified into various synoptic categories. Two of these categories were: 1) post-frontal but pre upper 500 mb trough passage, and 2) post 500 mb trough passage. Figure 4 provides the distribution of icing events at the Brian Head site versus the various synoptic categories for three seasons of data. Figure 5 provides the same information for the Skyline site for three seasons of data. Somewhat surprisingly, ~ 50 - 70% of the icing events at these two sites occur under post-frontal pre 500 mb trough or post 500 mb trough conditions. Another analysis compared icing events in relation to the concurrent occurrence of precipitation. Figures 6 and 7 graphically summarize these relationships for the Brian Head (three seasons of data) and Skyline (two seasons of data) sites. These two figures indicate that icing frequently occurs between periods of precipitation which suggests that precipitation processes may effectively remove SLW in some situations (e.g. riming) but not in others. There is an understandable interest in the temperatures at which SLW occurs because of the temperature activation thresholds of various seeding agents (e.g., silver iodide and liquid propane). These threshold temperatures are generally considered to be ~ -5 $^0$C for silver iodide and -1 or -2 $^0$C for liquid propane. Figures 8 and 9 provide temperature distributions during icing periods for the two sites.

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. 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 generally thought that this condition exists if the mountain-top temperature is below approximately –15 $^0$C. Figure 8 shows the temperature distributions at 2 $^0$C intervals for three seasons of data at Brian Head. A more detailed stratification (1 $^0$C intervals, not shown) indicates that a large proportion (~72%) of the icing periods at Brian Head (3320 meters in elevation), occurred within a favorable summit temperature window of –5 to –15 $^0$C. This temperature range was selected to represent favorable conditions for silver iodide seeding bounded on the warm end by the activation temperature of silver iodide (-5 $^0$C) and on the colder end by temperatures at which natural ice nuclei concentrations normally become high enough to nucleate most of the SLW (-15 $^0$C). Approximately 3% of the icing events at Brian Head were < –15 $^0$C and 25% occurred at temperatures > –5 $^0$C. Figure 9 provides the three-season 2 $^0$C interval data set for Skyline (2845 meters in elevation). A more detailed stratification (not shown) indicates ~ 44% of the icing events occurred at temperatures between –5 and –15 $^0$C. Only ~1% of the icing events were observed at temperatures < –15 $^0$C, and 55% of the icing occurred at temperatures > –5 $^0$C.

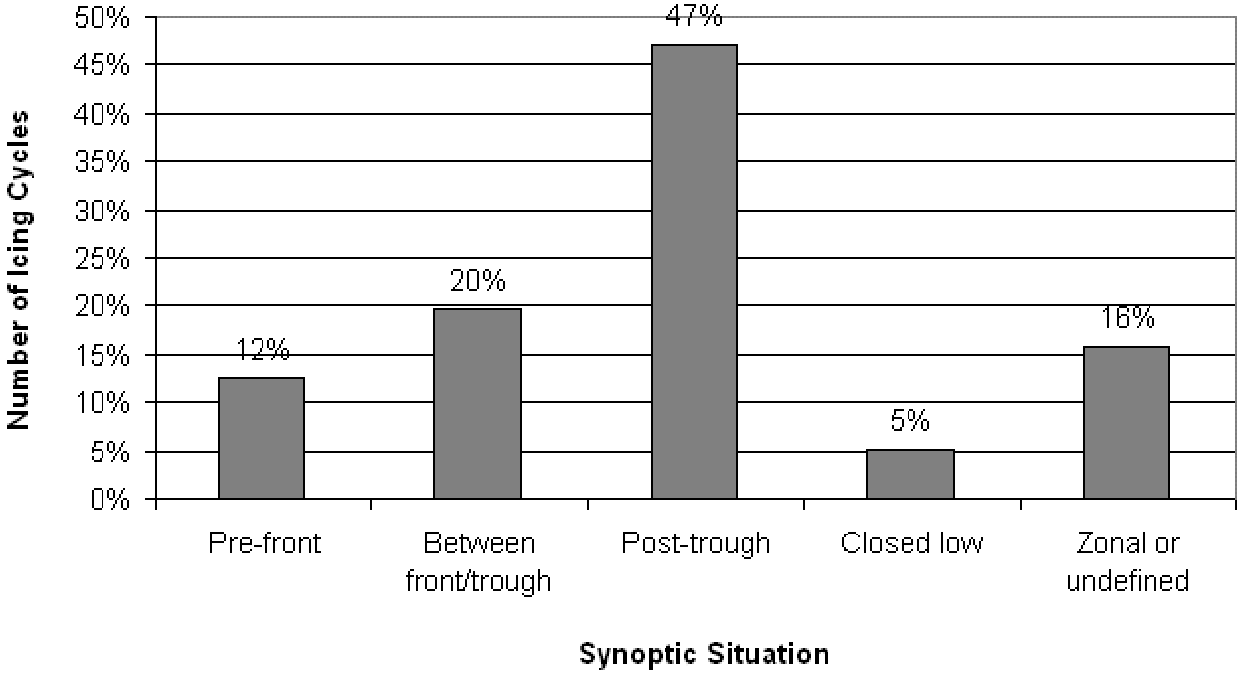

*Figure 4: Synoptic Pattern Classification for Three Winter Seasons (Water Years 2010, 2011, 2012) during Icing Periods at Brian Head (2416 icing cycles)*

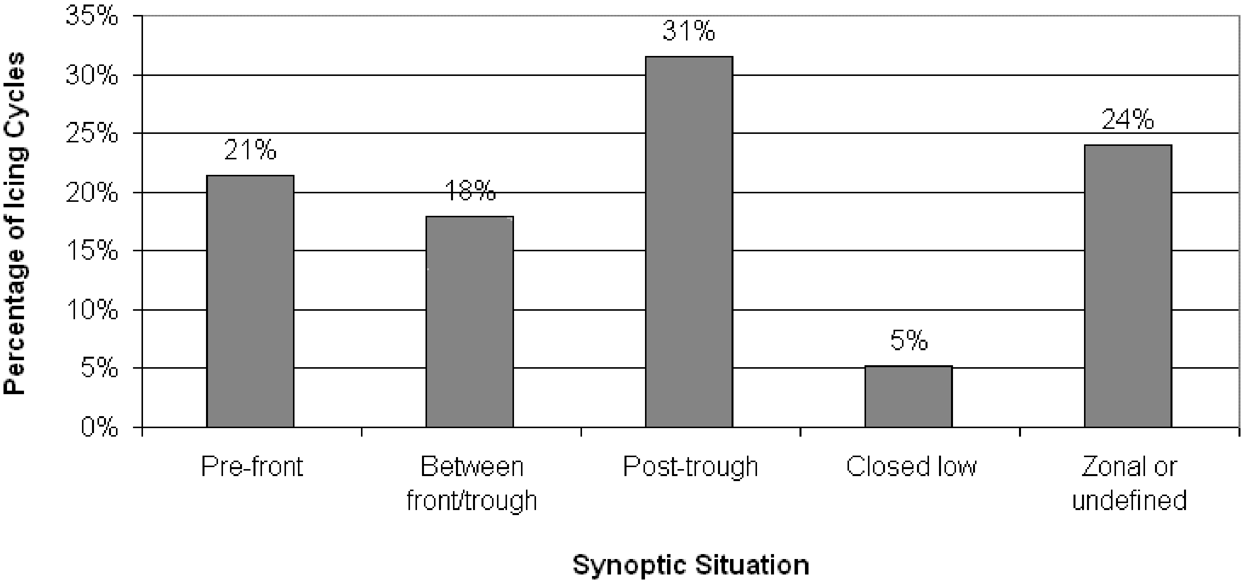

*Figure 5: Synoptic Pattern Classification for Three Winter Seasons (Water Years 2010, 2011, 2012) during Icing Periods at Skyline (772 icing cycles)*

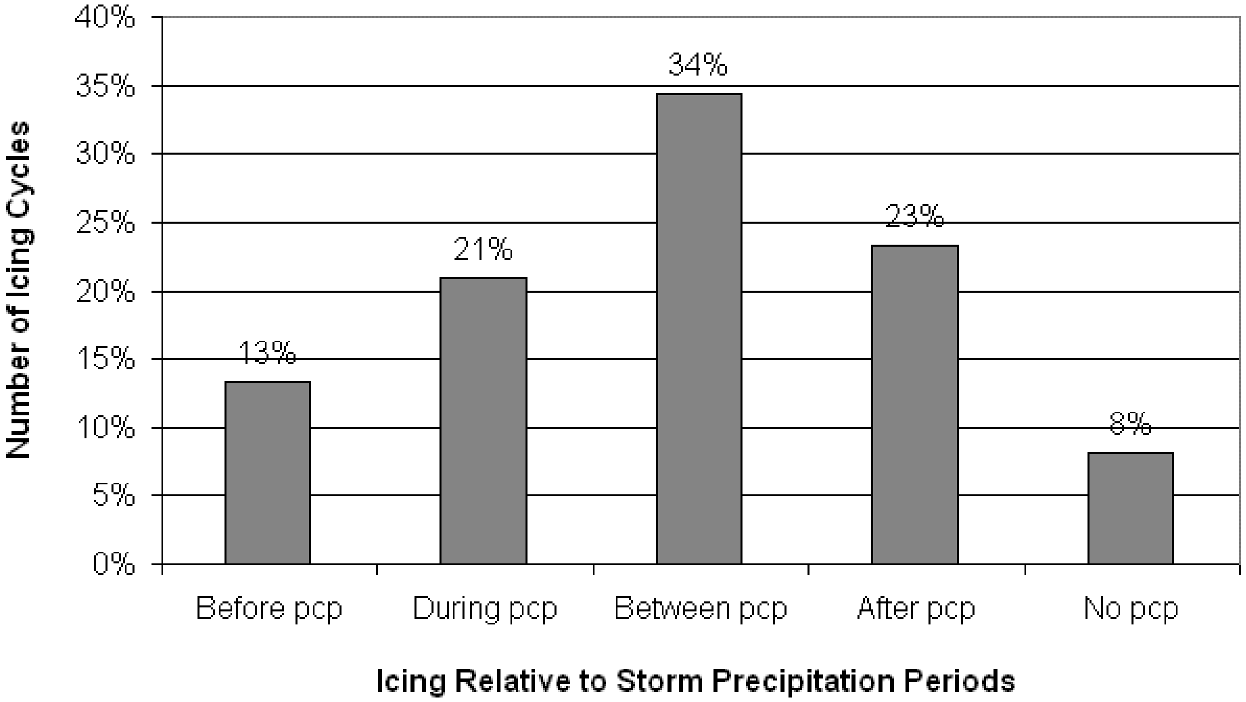

*Figure 6 : Brian Head Icing Distribution with Respect to Precipitation Periods of 0.01"/hr (0.1"/hr snowfall) or Greater during Storm Events, Three Winter Seasons (Water Years 2010, 2011, 2012; 2392 icing cycles).*

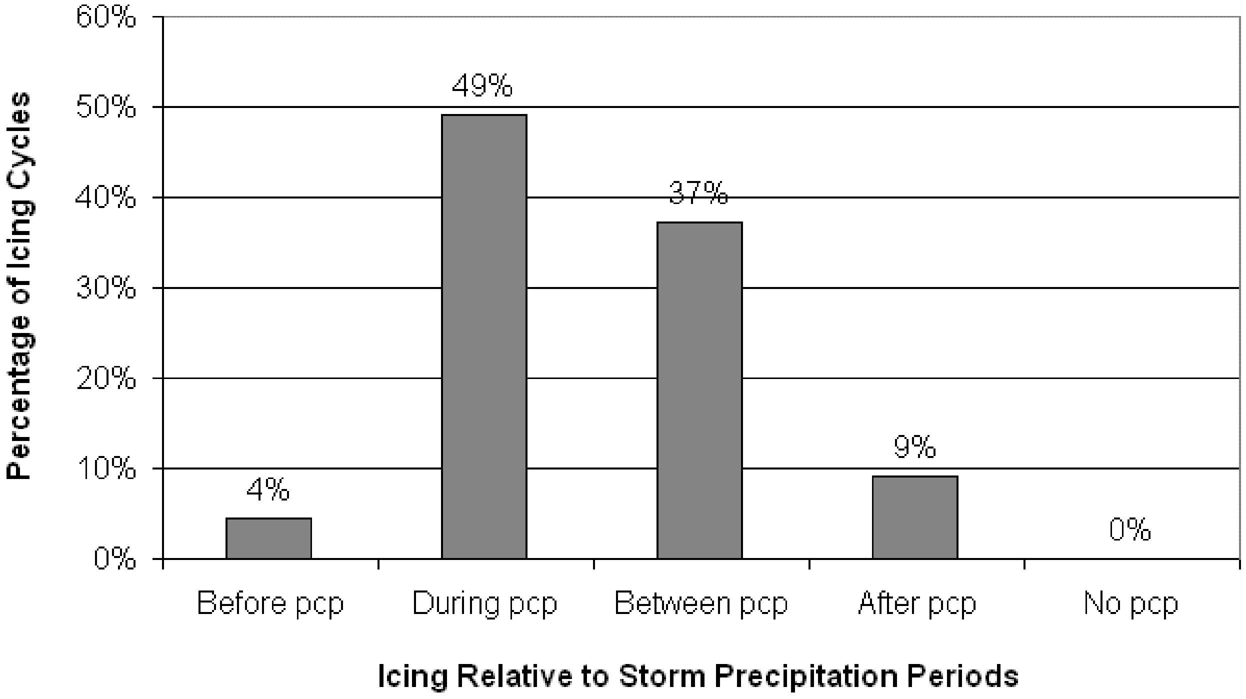

*Figure 7: Skyline Icing Distribution with Respect to Precipitation Periods of 0.01"/hr (0.1"/hr snowfall) or Greater during Storm Events, Two Winter Seasons (Water Years 2011, 2012; 564 icing cycles.*

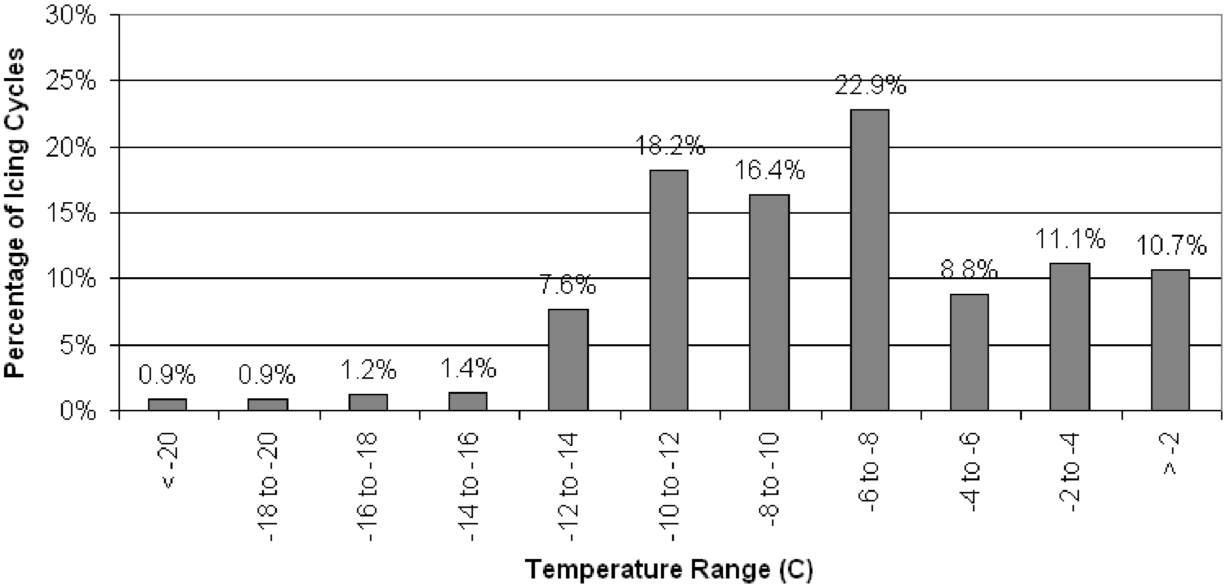

*Figure 8: Temperature Distribution during Icing Periods at Brian Head, Three Winter Seasons (Water Years 2010, 2011, 2012; 2541 icing cycles)*

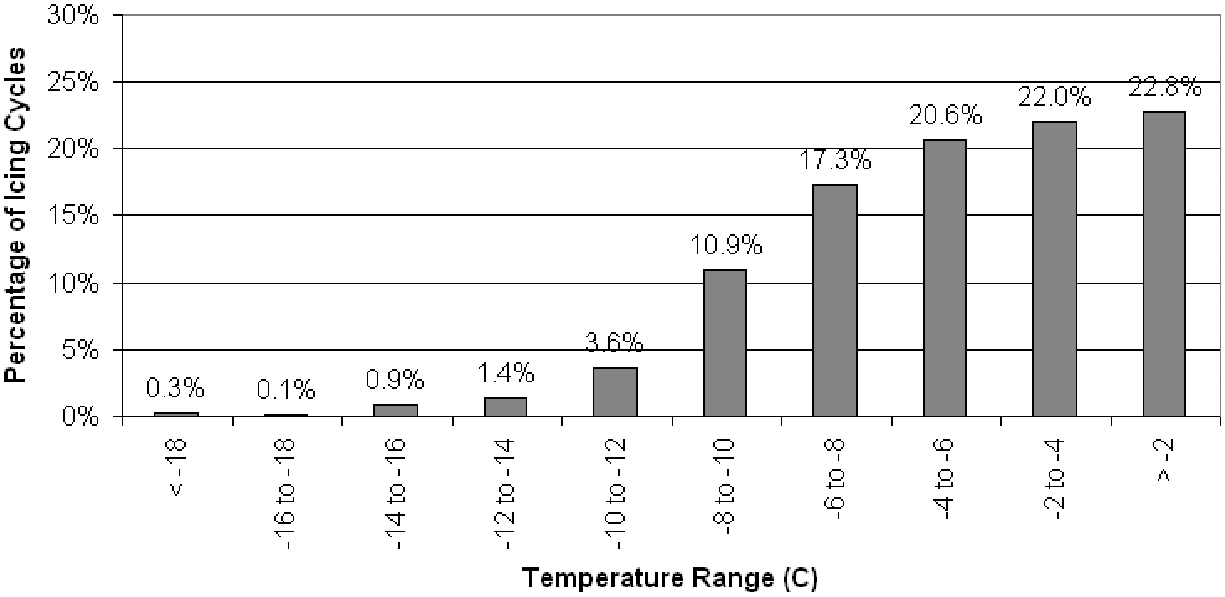

*Figure 9: Temperature Distribution during Icing Periods at Skyline, Three Winter Seasons (Water Years 2010, 2011, 2012; 771 icing cycles)*

## 4. INDICATED RESULTS FROM OPERATIONAL AND RESEARCH ORIENTED WINTER CLOUD SEEDING PROJECTS AND WINTER PROJECT FEASIBILITY STUDIES

NAWC has conducted annual evaluations of various operational winter cloud seeding programs being conducted in the western United States. Silverman (2010) has also conducted some analyses of long-term winter cloud seeding programs being conducted in the western United States. NAWC has also conducted several recent feasibility/design studies of potential winter seeding programs in Idaho and Wyoming. The results from these various studies along with results of some randomized research programs are summarized in Table 1.

A few comments are in order regarding this table. Most of the programs in the table use ground based, lower elevation silver iodide generators as the seeding mode. A few of these programs use both ground-based silver iodide generators and airborne silver iodide seeding (*e.g.*, the Kings River and San Joaquin River programs in California). A few of these programs also use high elevation, ground-based silver iodide generators (e.g., San Joaquin program in California). Estimated results from the feasibility studies are for lower elevation, ground-based generators (estimates were made in these studies of the additional estimated increases from high elevation remote ground generators and airborne seeding but these estimates are not provided in Table 1). Results reported by Silverman included some programs with target areas located on the lee-side of the Sierra Nevada Range in California (e.g., Carson-Walker, Eastern Sierra and Tahoe Truckee watersheds). These programs were not included in Table 1 since the focus of this paper is upon target areas primarily located on the upwind slopes of mountain ranges which is the more typical situation. The estimated results will obviously be dependent upon a number of factors such as generator spacing, opportunity recognition, equipment reliability, and overall skill of the operators in conducting the operations. Some of these factors may impact the estimated results in Table 1. Silverman (2010), using standard statistical procedures, reports estimated results as ranges, not specific values.

The approximate orientation of the target mountain barriers is included in Table 1. Information from this Table and from previous sections was used to develop a conceptual model of the "seedability" of winter orographic clouds as described in the next section.

## 5. CONCEPTUAL MODEL

Research programs, physical observations, analyses of operational cloud seeding programs and recent feasibility studies have indicated some of the earlier thinking regarding seeding potential, as indicated in the above references, has considerable merit. The concept that deep systems with cold cloud tops often appear to be naturally efficient with little or no SLW content is especially important. The activity of naturally occurring ice nuclei is known to increase as ambient temperatures decrease. Consequently, cold cloud top events will naturally nucleate large numbers of supercooled water droplets near their tops. As these nucleated ice crystals grow into snowflakes that then descend through the clouds, they will often "sweep out" the lower-level supercooled cloud droplets through the riming process. It appears from a variety of earlier sources of information and more recent observations that post-frontal relatively shallow orographically induced clouds often contain SLW and therefore offer good cloud seeding potential. Some post-frontal orographic clouds may develop without any or with only scattered clouds upwind of the mountain barriers. These post-frontal orographic clouds are often relatively young and therefore contain little natural ice.

When the occurrence of such clouds is viewed in the context of the orientation of the targeted mountain barriers, some interesting insights into the "seedablity" of winter orographic clouds emerge. Several studies and observations suggest that these shallow orographic clouds frequently occur after the passage of a cold surface front and even after the passage of an upper level trough. The more barrier normal and stronger the low-

*Table 1: Estimated Seeding Results in Winter Orographic Cloud Seeding Programs*

| **Area** | **Type of Analysis** | **Barrier Orientation** | **Est. % Increase** | **Reference** |
|---|---|---|---|---|
| South/Central Mts., UT | Target/Control | North-South | +4 to+14 | Griffith et al., 2009 |
| Ea. Tooele Co., UT | Target/Control | North-South | +16 to +21 | Griffith et al., 2009 |
| NW Box Elder Co. UT | Target/Control | North-South | +17 | Griffith et al. 2009 |
| Cache Co., UT | Target/Control | North-South | +10 to +17 | Griffith et al. 2009 |
| Western Uinta Mts., UT | Target/Control | West-East* | +5 | Griffith et al. 2009 |
| High Uinta Mts., UT | Target/Control | West-East | +3 | Griffith et al. 2009 |
| Gunnison Riv., CO. | Target/Control | North-South* | +16 | Griffith et al. 2011 |
| Boise Riv., ID | Feasibility | Northwest-Southeast | +2 | Griffith et al., 2012 |
| Little Wood Riv., ID. | Feasibility | Northwest-Southeast | +3 | Griffith et al., 2009 |
| Henrys Lake, ID | Feasibility | West-East | +3 | Griffith et al., 2010 |
| Palisades Res. , ID | Feasibility | Northwest-Southeast* | +4 | Griffith et al., 2010 |
| Salt and Wyoming Ranges, WY | Feasibility | North-South | +7 | Griffith et al., 2007 |
| Climax I & II | Seed/No-Seed Randomized | North-South* | +6 to +18 | Mielke et al., 1971 |
| Vail Ski Area, CO | Target/Control | North-South* | -2 to +29**<br>+8*** | Silverman, 2009; Griffith et al., 2010 |
| San Juan Mts., CO | Seed/No-Seed Randomized | West-East | 0 | Elliott et al., 1976 |
| Lk. Almanor, CA | Target/Control | Northwest-Southeast* | +2 to +7 | Silverman, 2010 |
| American Riv., CA | Target/Control | Northwest-Southeast | +2 to +8 | Silverman, 2010 |
| Mokelumne Riv., CA | Target/Control | Northwest-Southeast | -2 to +1 | Silverman, 2010 |
| Tuolumne Riv., CA | Target/Control | Northwest-Southeast | +2 to +8 | Silverman, 2010 |
| SanJoaquin Riv., CA | Target/Control | Northwest-Southeast | -1 to +3 | Silverman, 2010 |
| Kings Riv., CA | Target/Control | Northwest-Southeast | +1 to +7 | Silverman, 2010 |
| Kaweah Riv., CA | Target/Control | Northwest-Southeast | -4 to +1 | Silverman, 2010 |
| Kern Riv., CA | Target/Control | North-South | +3 to +11 | Silverman, 2010 |
| Snowy Mts., Australia**** | Seed-No-Seed Randomized | Northeast-Southwest**** | +14 | Manton and Warren, 2011 |

Table 1 References

| | |
|---|---|
| * | Complex Barrier, orientation problematical |
| ** | Small watersheds |
| *** | Combination of all watersheds |
| **** | In Southern Hemisphere, pre-frontal winds would be NW, post-frontal winds SW |

level wind flow becomes, the greater the moisture flux due to enhanced orographic lift. Those conditions favor augmentation of the precipitation through cloud seeding. The question then becomes what types of barrier orientations favor the development of these clouds? This is basically a question of the amount of up-barrier flow. NAWC has developed a conceptual model related to the barrier orientations that provide the best conditions for the development of these types of favorable conditions in the western United States (and perhaps elsewhere). This conceptual model theorizes that barriers with a north-south orientation enhance the likelihood of the development of SLW since post-frontal or post upper trough passage conditions often produce considerable up-barrier flow under west to northwest flow conditions. In addition, the post-frontal or post-trough situations are likely to have lower, thus warmer cloud top temperatures, which earlier discussions have indicated favor the development of SLW over the upwind slopes of these north-south oriented barriers. Fortunately, most mountain barriers in the western United States have such a north-south orientation.

However, some western U.S. mountain barriers have west-east orientations. Examples of such barriers include the San Juan Mountains in Colorado, the Uinta Mountains in Utah and the Centennial, Lions Head and Henrys Lake Mountains in northeastern Idaho/southwestern Montana. NAWC's contention is that these types of barriers will experience the best orographic lift during storms that have a pre-frontal or pre-trough southerly flow component. Observations indicate such storm periods typically contain deep clouds with cold cloud tops and therefore have limited seeding potential since natural occurring ice crystals formed in the upper levels of these clouds fall through the lower clouds and remove most of the SLW through riming. There is one major U.S. mountain barrier that is a mix of these two types; the Sierra Nevada in California. That barrier has more of a northwest to southeast orientation. The Wind River Range in western Wyoming is another smaller barrier that has a northwest-southeast orientation. Post-frontal, post-trough flow over these barriers does not have as strong an up-barrier component to the lower-level wind flow as do the more north-south oriented barriers. NAWC's experience in participating in research programs and conducting operational programs in the Sierra Nevada is that there is usually very limited activity following the passage of a cold front. As a consequence, the seeding potential is assumed to be lower over these west-east or northwest-southeast oriented barriers under post-frontal or post-trough conditions. Results provided in Table 1 seem to support this hypothesis. Some specific examples are discussed in the following.

NAWC's experience in conducting winter cloud seeding programs in Idaho is that a substantial portion of the precipitation occurs in pre-frontal conditions. The feasibility study for the Upper Boise Basin (Griffith, et al, 2012) indicates only 21% of the precipitation periods in this area would be considered "seedable" based upon cloud top temperatures being > -26 $^0$C. This finding supports the concept of deep pre-frontal clouds dominating precipitation production in that region. The 21% value can be compared to a similar feasibility study performed for the Salt and Wyoming Ranges located in southwest Wyoming (Griffith, et al, 2007). This study estimated that "seedable" periods based upon cloud top temperatures > -26 $^0$C occur 57% of the time. Drainages in eastern Idaho analyzed in a similar feasibility study (Griffith, et al, 2010), indicated "seedable" conditions occurred 37% of the time based upon cloud top temperatures being > -26 $^0$C. As a consequence the estimated seeding increases were +2% for the Boise River drainage, +3 to 4% for the Eastern Idaho drainages and +7% for the Salt and Wyoming Ranges. NAWC's experience in conducting programs in Utah that have north-south oriented barriers is that considerable amounts of orograhically enhanced cloud cover and precipitation occur under post-frontal conditions. These conditions are likely to be associated with cloud top temperatures > -20 to -25 $^0$ C. This can be the case even though temperatures aloft drop after frontal passages since cloud tops typically drop as well. A number of research programs have indicated this to generally be the case (Hobbs, 1975; Copper and Marwitz, 1980; Reynolds, 1986). Active post-frontal conditions in

Utah may explain why there are generally higher estimates of seeding increases in Utah for the north-south oriented barriers versus those Utah barriers with west-east orientations as in Griffith, et al, (2009).

This scenario of lowering cloud tops and consequent warming cloud top temperatures under post-frontal conditions appears to be related to increases in ground-based observations of SLW in Utah studies (Yorty, et al, 2012). When one also considers that glaciogenic seeding agents like silver iodide become more effective as ambient temperatures upwind of mountain barriers decrease following frontal passage, then the importance of these post-frontal conditions in terms of seeding potential can begin to be understood. As temperatures drop in the lower atmosphere upwind of mountain barriers, the number of effective silver iodide freezing nuclei increases exponentially (DeMott, 1988). It should be noted that airborne seeding could be conducted at higher altitudes to compensate for this temperature dependency but this approach assumes that zones of SLW are reaching these higher flight altitudes which may not be the case based upon research conducted in Utah (Super, 1999) that indicates SLW is typically found only to approximately 500 – 1000 m above the barrier crest height. Other complications can arise in airborne seeding when upwind mountain barriers are present and/or minimum clearance altitudes established by the FAA prevent aircraft flights at altitudes low enough to impact these zones of SLW. This complication is graphically portrayed in Figure 10.

## 6. CONCLUSIONS AND RECOMMENDATIONS

The potential to produce a glaciogenic seeding effect in natural occurring winter clouds through cloud seeding depends upon the presence of SLW in the clouds that are to be treated. It is therefore of primary importance that means of either directly detecting SLW or other more indirect means be employed to indicate the presence of SLW in real or near real-time. Such information is needed in order to schedule and then conduct the actual seeding operations. The identification of SLW is one of several considerations that need to be addressed in order to determine the “seedability” of winter clouds at a specific time. Another consideration is the geographical setting and orientation of the targeted mountain barrier(s). Such considerations help determine whether a given seeding mode (e.g., ground-based silver iodide generators) have the potential to induce microphysical effects in the clouds, which in turn, have the potential to create a desired result (i.e., increased snowfall in a specified target area). If no SLW is present or predicted to be present, then no seeding is warranted. In other words, the presence of SLW is a prerequisite in the conduct of any glaciogenic cloud seeding.

Considerable information has been gleaned from previous winter orographic research and operational cloud seeding programs related to the question of when and under what circumstances SLW occurs. Early programs in the 1960’s through 1980’s directly or indirectly. generally indicate that SLW occurs when cloud top temperatures are > -26 $^0$C. Later studies indicate the prevalence of SLW at relatively low elevations along the upwind slopes of mountain barriers rising to heights of perhaps 500 -1000 m above the mountain crest height. These studies also typically indicate the requirement of an upslope wind component needed to generate the SLW. Embedded convection has also been shown to be associated with higher amounts of SLW in these situations.

Some earlier as well as more recent studies indicate that the synoptic setting can often be related to the occurrence of SLW. For example, lowering cloud tops associated with post- frontal and even post upper trough situations with an up-barrier flow component have been shown to be frequently associated with SLW over the windward slopes of mountain barriers. These indications have been drawn from aircraft observations as well as surface based icing rate meter data. The SLW under these conditions is usually associated with lower ambient temperatures than the SLW that may occur under pre-frontal or pre-trough synoptic conditions. The SLW in the post-frontal or post-trough synoptic conditions frequently is <-5 $^0$C at crest height; an important finding when

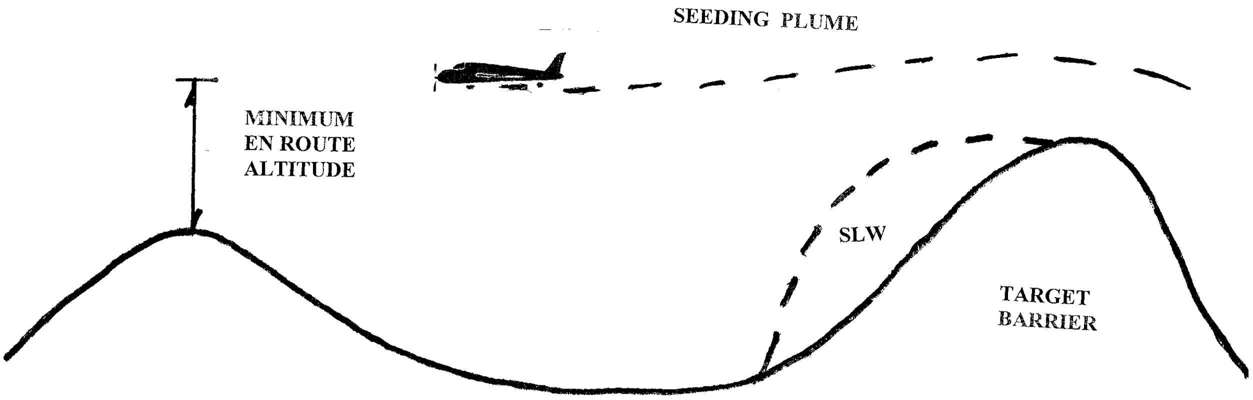

*Figure 10: Conceptual Depiction of an Aerial Seeding Plume Location in Relation to the Likely Location of Supercooled Liquid Water in a Winter Orographic Setting with Underlying Mountain Barriers*

considering the threshold activation temperature of silver iodide which is the most frequently used seeding agent in the conduct of wintertime orographic cloud seeding programs.

Analyses of direct SLW measurements, indications of positive seeding effects from both research and operational programs and indications of seeding potential from feasibility studies all seem to indicate the importance of the orientation of the targeted mountain barriers in determining the seeding potential of these barriers. North to south oriented barriers appear to offer a higher seeding potential than west to east oriented barriers. Among the reasons why this seems to be the case is that north to south oriented barriers often experience considerable cloud cover under post-frontal/post-trough synoptic conditions. These situations are associated with lower altitude cloud tops and significant up-barrier flow components; both ingredients noted in various studies cited in this paper to be conducive to the generation of SLW. The west to east oriented barriers (e.g., San Juans in Colorado and Uintas in Utah) often experience extensive pre-frontal/pre-trough cloud cover. As indicated in this paper, these conditions appear to contain less SLW and therefore less seeding potential due in part to the presence of deeper, colder clouds and the activation of natural ice nuclei at higher altitudes/colder temperatures. Ice crystals produced near cloud top then grow into snowflakes. As these snowflakes descend, they capture lower elevation SLW through the riming process, often effectively removing this lower elevation SLW leaving little or no cloud seeding potential. Another disadvantage of these types of situations is the higher temperatures of any low-level SLW that may occur which may render silver iodide nuclei less effective or even ineffective.

There are a few mountain barriers in the western United States that are a cross between north-south and west-east orientations. The most noteworthy mountain range in this category is the Sierra Nevada of California although the smaller Wind River Range in Wyoming is another example. These ranges have a northwest-southeast orientation. Post-frontal/post-trough up-barrier flow is often limited over these ranges due to that orientation (e.g., northwest winds basically become parallel to the barrier). As a consequence, these ranges may, on average, have less "seedable" SLW than the north-south oriented barriers. Fortunately, many of the mountain ranges located in the western United States are in the favorable north-south orientation category.

NAWC believes that recognition and verification of the above will be important in the design and conduct of future winter orographic cloud seeding programs. Placing "seedabilty" in the synoptic setting and relating "seedability" to barrier orientation will be important in estimating potential effects from different program areas. As a consequence, some targeting issues will also need attention. For example, when dealing with a west-east oriented barrier, placing a majority of the ground generators or conducting aircraft seeding flights north of these barriers may be appropriate. Similar reasoning for north-south oriented barriers might indicate the desirability of more generators (seeding flights) northwest instead of southwest of the intended target area(s).

Consideration needs to be given to means of obtaining estimated cloud top heights/temperatures and up-barrier wind components in real-time. Satellite and radar data may prove useful in determining cloud top heights and temperatures. Surface wind observations and NEXRAD vertical wind profiles can be useful in determining up-barrier flow components. High resolution atmospheric models may also provide information on both cloud tops and up-barrier flows.

A focus on obtaining SLW observations should be encouraged by the sponsors of research and operational winter orographic programs. Means of obtaining such measurements include: 1) surface based icing rate meters, 2) portable microwave radiometers and 3) airborne measurements. These measurements have obvious value in real-time decision-making but should also be subjected to detailed post-operation analyses in order to advance our knowledge about where and when SLW occurs in winter orographic storms in different geographical settings.

As atmospheric models, like the Weather Research and Forecasting Model (WRF), become increasingly sophisticated, there will likely be high resolution predictions of the presence and location of SLW in time and space. Once these predictions are validated, they should provide information of considerable value to those conducting orographic cloud seeding programs in the future.

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