FEASIBILITY/DESIGN STUDY FOR A WINTER CLOUD SEEDING PROGRAM FOR THE ABAJO AND LA SAL MOUNTAIN RANGES, UTAH

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ABSTRACT

North American Weather Consultants (NAWC) received funding from the three Lower Colorado River Basin States (Arizona, California and Nevada) to perform a feasibility/design study for a winter cloud seeding program. The proposed program would target two smaller mountain barriers located in southeastern Utah, the Abajo and La Sal Ranges. The Lower Basin States are interested in these barriers since they contribute runoff to the Colorado River. American Society of Civil Engineers (ASCE) guidelines were followed in the conduct of the study. NAWC compiled site-specific climatologies for these two barriers with a focus on parameters of interest in the design of cloud seeding programs. Both ground-based and airborne seeding modes, utilizing silver iodide, were considered and both recommended for deployment depending upon the funding that might be available to conduct a program. Estimates of increases in precipitation and resultant increases in streamflow were made. An estimated total of 10,852 acre-feet of additional annual runoff in an average year was calculated. Benefit to cost studies were performed. One study concluded that the program would not be economically feasible to local agricultural interests near the two barriers. A NAWC analysis suggested that a program would be economically feasible for downstream water users driven by the value of streamflow that would enter Lake Powell. A cloud seeding program designed to target winter storms affecting the Abajo and La Sal Mountain Ranges was considered technically feasible. Such a program was also considered economically feasible but only if the predicted augmented streamflow reaches Lake Powell. According to the two primary criteria established by the ASCE (technical and economical), the proposed program was therefore considered conditionally feasible. One winter season of data collection and analysis of microwave radiometer observations in the Moab, Utah area was recommended.

1.0 INTRODUCTION

North American Weather Consultants (NAWC) has been operating several winter cloud seeding programs over mountainous regions of Utah since 1974 with the goal of augmenting the amount of snow that falls in these target areas (Griffith, *et al*., 2009). The augmented snowfall would then increase the spring and summer runoff, which could increase irrigated agricultural and municipal water supplies. Four target areas have been consistently seeded since 1988: Northern Utah, the Western Uintas, the south slopes of the High Uintas and a number of mountain ranges located in central and southern Utah.

Funding for these programs comes from local water interests (e.g., water conservancy districts), cost share support from the Utah Division of Water Resources and in recent years from the three Lower Colorado River Basin States (Arizona, California and Nevada). Funding from the latter group in recent years has been provided to augment some of these operational programs. Last year NAWC requested funding to conduct a feasibility/design study for the Abajo and La Sal Mountain ranges located in southeastern Utah. NAWC had conducted a few previous programs over these ranges but they represent some unique challenges thus the proposal to conduct a feasibility/design study. The request to perform such a study was approved by the Lower Basin States. All work funded by the Lower Basin States that NAWC conducts, is contracted and managed by the Utah Division of Water Resources (UDWRe).

2.0 ASCE GUIDELINES

NAWC followed guidelines established by the American Society of Civil Engineers (ASCE, 2016) in conducting weather modification feasibility/design studies, which are summarized in the following:

"The term "feasibility study" refers to the examination of the local climate and cloud characteristics, to determine whether or not cloud seeding technology has a reasonable expectation of increasing precipitation. The term "program assessment" refers to the evaluation of the program itself when it is actually conducted.

The feasibility of a program depends largely upon two factors. First, is there a scientific basis for the work proposed that could yield the desired additional precipitation? This is discussed in detail in Section 4. Secondly, even if such a basis exists, is the cost of implementing a program based on the known science affordable? The latter depends heavily upon the combination of available financial resources and the expected return in additional water, in other words, the benefit/cost ratio.

When possible, the feasibility study for a program should draw significantly from previous research and well-conducted operational programs that are similar in nature to the proposed program (e.g., similar topography, similar precipitation occurrences, etc.). Percentage increases obtained from such programs can be used in the development of benefit/cost analysis for the proposed program".

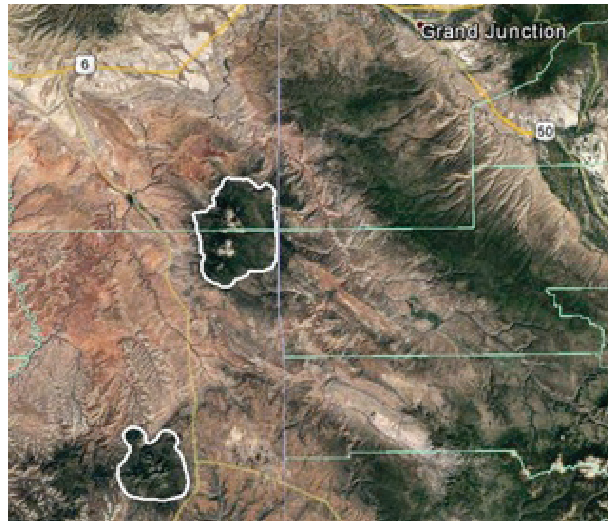

FIG. 1. Abajo (lower) and La Sal (upper) ranges with prospective seeding target areas in white outlines.

3.0 TARGET AREAS

The Abajo and La Sal Mountains (ABLA), the proposed target areas, are located in southeastern Utah. They are relatively small mountain barriers compared to other Utah mountain ranges. These mountain ranges are part of the Colorado Plateau province west of the greater ranges of the Rocky Mountains. The intended target areas are defined as those areas above 7,500 feet MSL located in these two mountain ranges. Figure 1 provides the locations.

4.0 TARGET AREA CLIMATOLOGY

Natural Resources Conservation Service (NRCS) SNOTEL data at Camp Jackson and La Sal Mountain (8968 and 9560' respectively) shows annual precipitation totals near 30", varying between less than 20" in some years to well over 40" in others. Precipitation distribution is somewhat bi-modal, with winter storms affecting these areas from roughly November – April and summer (monsoon-type) showers/thundershowers from July – October. June is the driest month in both areas with a distinct minimum in climatological precipitation, while there is not a distinct fall minimum. Between half and two-thirds of the annual precipitation generally occurs during the

Table 1. Comparison of seasonal period total precipitation to November - April.

Month	La Sal SNOTEL Average	Camp Jackson SNOTEL Average
December - March	13.2” (68% of Nov-Apr)	12.0” (73% of Nov - Apr)
November - March	16.0” (82% of Nov-Apr)	14.3” (87% of Nov - Apr)
Mid Nov - Mid Apr	16.4” (85% of Nov-Apr)	14.2” (87% of Nov - Apr)
November - April	19.4”	16.4”

November – April seasonal period in the Abajo and La Sal ranges (average data through 2010 shows 56% and 57% during this period for Camp Jackson and La Sal Mountain, respectively). April 1 snow water equivalent averages 10-12” of snow water at these sites but these amounts are highly variable from one season to another. Roughly, half of the annual precipitation (the vast majority of which falls during the November – April season) is in the form of snow at these high elevation sites.

Table 1 compares precipitation averages for shorter seasonal periods to the November – April period. Accumulated precipitation data during the past five November – April seasons (water years 2011 – 2016) were utilized to identify storm days with an average of roughly a quarter inch or more at the two SNOTEL sites (Camp Jackson and La Sal Mountain). Often one of the sites had significantly more than the other during the 111 storm days included in the analysis. A representative 700-mb (about 10,000 foot level) temperature, wind speed and wind direction was estimated based on available archived data from the Storm Prediction Center website. Figure 2 shows the overall distribution of temperature for the analyzed periods. This figure indicates that ~ 76% of the cases had temperatures of -5 °C or colder which would indicate silver iodide being an effective ice nucleating agent ~76% of the time. Figure 3 shows the 700-mb temperature vs. wind direction for the analyzed periods. Note the small number of observed precipitation periods with winds between about 50 and 170 degrees,

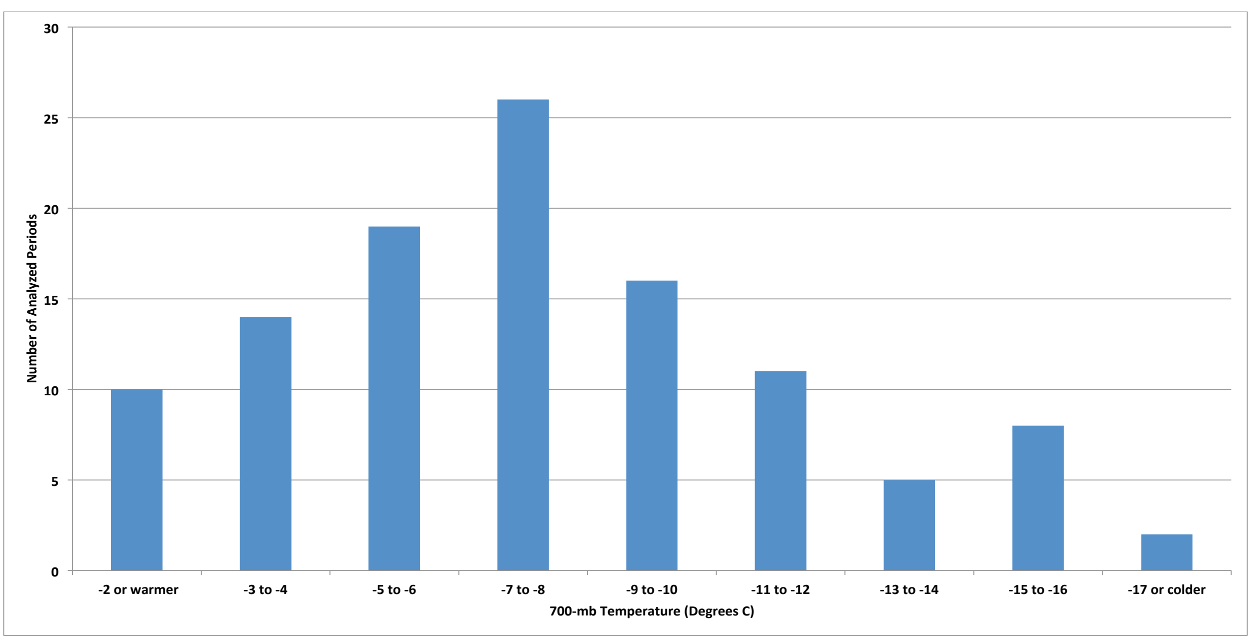

Fig. 2. Temperature distribution during analyzed storm periods.

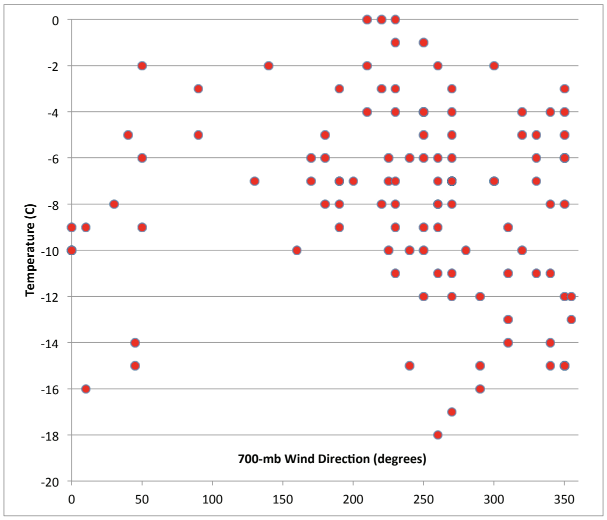

FIG. 3. 700 mb wind direction versus 700 mb temperature for analyzed periods.

although there are a number of northeasterly (> 50 degrees) cases. The highest concentration of observed precipitation periods were in periods of southwesterly winds (180 – 270 degrees) with a secondary maximum from the northwest through north directions (about 320 – 360 degrees). Temperatures, in general, were warmest for the southerly (as well as the small number of easterly) wind periods. Nearly all the colder temperature cases (below about –10 °C) were associated with northerly-component winds, and these cases are in general likely to be the most seedable from ground-based sites due to the nature of the nucleation and precipitation processes, and the limited geographic area of these mountain ranges.

5.0 DEVELOPMENT OF PROGRAM DESIGN AND SEEDING INCREASE ESTIMATES

An operational period of November 15 through April 15 is recommended based upon the climatology of the area and the likelihood of generating positive seeding effects during this period.

Silver iodide is the seeding agent recommended to be used in the conduct of the ABLA program. NAWC recommends manually operated ground based generators and airborne seeding. The use of airborne seeding would be a function of the costs versus potential program benefits.

It is proposed that two networks of ground based, manually operated silver iodide generators be installed for this program, one for the Abajo target area and the other for the La Sal target area. These generators would be sited at local residences or ranches at which the residents agree to be trained in their operation. These residents would operate the generators as requested by the program meteorologist(s). Approximately 5-7 generators would be installed for each target area.

The results of the climatology work suggest that the favored site locations would be southwest, west and northwest of the target areas. Selection of site locations would include consideration of the topography of the target and surrounding areas, land ownership and location of residences. Finding locations at some locations upwind of the Abajo Range may be problematic due to sparsely populated areas and land ownership (e.g., Indian tribal lands).

NAWC does not recommend the installation of remotely operated ground generators for either the Abajo or La Sal Ranges. These are very small mountain barriers and the associated seeding effects from remote sites near the top of the barriers would occur on the lee slopes or beyond.

Aircraft seeding was recommended assuming there would be a favorable benefit/cost ratio. One seeding aircraft should be adequate to effectively seed both target areas.

The primary reasons that airborne seeding was considered for the ABLA program are that:

1. Aircraft seeding may be conducted when the temperatures near crest level are too warm for silver iodide released from the ground to be effective. In other words, the aircraft can be flown at or near the –5 °C level in these storms, assuming there is liquid water present at these altitudes, thus having the potential for augmenting the natural

snowfall in the target areas.

2. Due to the rather small sizes of the two target barriers, there is the question of whether seeding plumes released from ground sources may flow around instead of over the intended target barriers.

A detailed analysis of storm periods affecting the target area was performed for a five-season period (water years 2012-2016) for the November - April season. Precipitation data from two SNOTEL sites (La Sal Mountain in the La Sal Range and Camp Jackson in the Abajo Range) were considered. The data were obtained from the NRCS website. A total of 111 storm periods during these seasons were analyzed.

Since low-level stability could prevent seeding material from reaching the –5 °C level over the target areas, potential stability was classified into four categories: Well-mixed or neutral conditions (no stability problems evident which should mean that silver iodide particles released near the surface can be transported over the mountain barriers in the storm winds), slightly stable, moderately stable, and very stable. These categories correspond roughly to situations when less than 2 °C of surface heating would be necessary to mix out the atmosphere (slightly stable), 2-4 °C (moderately stable), and more than 4 °C (very stable). Cases that were well mixed or slightly stable were considered suitable for lower elevation ground-based seeding, while more stable cases would require remote high-elevation ground-based seeding or aircraft seeding. This stability analysis was developed in earlier studies which consisted of obtaining valley surface temperature and dew point observations then lifting a surface parcel (through dry and wet adiabatic processes) to the height of the target mountain barrier. This temperature was then compared to a temperature observation at or near the crest line. This method, referred to as the 2SS method that provides indications of its applicability to determine the impact of inversions on seeding plume rise has been documented in previous studies (Yorty, *et al.*, 2012; Griffith, *et al.*, 2016).

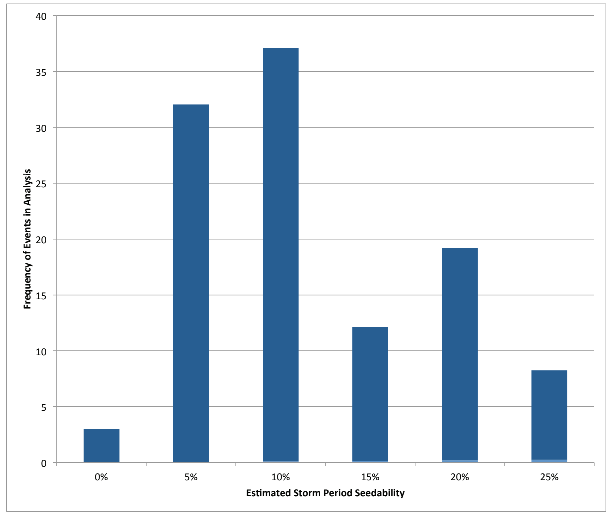

Fig. 4. Frequency distribution of the estimated seedability of storm periods in the analysis. (0% = 3 periods; 5% = 32 periods; 10% =37 periods; 15% = 12 periods; 20% = 19 periods; 25% = 8 periods)

NAWC utilized results from a well-known, randomized research program conducted in the Climax region of the central Colorado Rocky Mountains in two phases, Climax I (1960-65) and Climax II (1965-70) (Mielke, *et al.,* 1981) as well as ridge-top ice detector data funded by the Lower Basin States during the 2012-2016 winter seasons to estimate the potential seeding effects in the ABLA program. Ice detector data at Brian Head (in southwestern Utah) and Skyline (in central Utah) during the 111 storm periods in question were considered for the basic storm "seedability" estimates. The Climax experiments in Colorado in the 1960s utilized ground-based releases of silver iodide in 24-hour treatment periods. The detailed statistical analyses indicated that precipitation was increased by 25%-41% (depending upon whether a single or double ratio analysis was used) when 500mb (approximately 18,000 feet) temperatures were in the –4 to +12.2 °F (–20 to –11 °C). These results were statistically significant at the .05 level. Other reports on the two Climax programs indicated positive effects of seeding at 500mb temperature ranges of ~ –5.80 to –14.8 °F (–21 to – 26 °C). One report (Hess, 1974) indicated approximately 10% increases in this 500-mb temperature range. Estimates of storm period seedability based on

Table 2. Summary of November - April precipitation increase estimates.

Seeding Mode	La Sal Range (La Sal SNOTEL)		Abajo Range (Camp Jackson SNOTEL)	
	Percentage	Precipitation (in)	Percentage	Precipitation (in)
Manual Ground Increase	2.9%	0.56	2.0%	0.33
Remote Increase	1.0%	0.19	NA	NA
Aircraft Increase	7.9%	1.53	9.2%	1.51
All Methods	11.8%	2.29	11.2%	1.84

these considerations (cloud-top temperature and observed icing) in the current study ranged from 0 to 25% potential precipitation increases due to seeding, with this (estimated) seedability distribution for the storm periods shown in Figure 4. These initial estimates were made for the storm periods in general, before the analysis was sub-divided between the La Sal and Abajo ranges.

The basic seeding potential (expressed as a percentage increase to the natural storm precipitation) during storm periods in the five-season analysis was sub-divided between different seeding modes or methods: ground-based seeding potential, remote seeding potential (for the La Sal Range only), and aircraft seeding potential. The seeding potential for a given storm period was delegated to ground-based seeding if a) the low-level air mass was classified as well-mixed or only slightly stable, and b) the 700-mb temperature was –5 °C or colder. Similarly, the seeding potential was delegated to remote, high-elevation seeding sites if low-level stability was classified as "moderate" or higher and the 700-mb temperature was –5 °C or colder. Seeding potential was counted as aircraft-only for cases where the 700-mb temperature was above –5 °C regardless of stability considerations. The estimated increases are summarized in Table 2.

6.0 EVALUATION METHODOLOGY

The La Sal SNOTEL (La Sal Range) and Camp Jackson SNOTEL (Abajo Range) were used to establish target/control regression equations, which can be used to evaluate any seeding programs in these ranges. November – April seasonal precipitation totals at these sites were correlated with potential control sites in Utah and surrounding states to determine the best set of controls for each target site. Potential control sites in Arizona, Colorado, Nevada, New Mexico, Utah, and Wyoming were examined to determine how well they were correlated with the two target sites. A separate set of best-correlated control sites was established for each (La Sal SNOTEL and Camp Jackson SNOTEL). The historical (non-seeded) period with data available for these regressions were the 1982-2016 water years (La Sal) and the 1986-2016 water years (Camp Jackson). The 2013 water year was excluded from the latter due to seeding for the Abajo Range that season.

The potential control sites examined for this analysis have been utilized as controls for other seeding programs, and have previously been determined (based on double-mass plots, etc.) to have stable historical data records (Griffith, *et al.*, 2009). After the individual control site correlations were determined for the La Sal and Camp Jackson SNOTEL sites, a control site group was established for each with the goal of maximizing the overall correlation (r-value) as well as providing good geographic bracketing of the corresponding target sites. Linear and multiple regression equations were established which can be used to estimates the effects

Table 3. Estimated average streamflow increases without remote generators for the La Sal Mountains, based on estimates of seasonal precipitation increases.

Seeding Mode	La Sal Range (La Sal SNOTEL)			Abajo Range (Camp Jackson SNOTEL)		
	Precip. %	Streamflow %	Increase in A.F.	Precip. %	Streamflow %	Increase in A.F.
Manual Ground Increase	2.9%	6.3%	1,303	2.0%	6.3%	991
Aircraft Increase	8.9%	19.4%	3,999	9.2%	28.9%	4,559
All Methods	11.8%	25.7%	5,302	11.2%	35.2%	5,550

of seeding should a seeding program move forward in these target areas. The r^2 values for these equations ranged from 0.83 to 0.86.

7.0 POTENTIAL BENEFITS

The estimated average November – April precipitation increases were used to estimate potential increases in March – July streamflow by developing regression equations that related precipitation to streamflow. Using these equations provides a means to estimate the streamflow increases by inserting percent increases in precipitation for different values of precipitation; for example a November – March average value or a 25% below and a 25% above average November – March value.

Since remotely controlled ground-based generators were dropped from consideration it may be assumed that aerial seeding would be effective in seeding conditions where remotely controlled generators were considered. Consequently, Table 3 provides estimates of streamflow increases for an average November – April precipitation season for just two seeding modes; manually operated ground generators or one seeding aircraft.

8.0 PRELIMINARY BENEFIT/COST ANALYSIS

The Utah Division of Water Resources performed an analysis of the potential economic benefits to agricultural interests located near the proposed two target areas (Summers 2017). The primary

Table 4. Combined Abajo and La Sal Target Area estimated costs per acre foot and estimated benefit/cost ratio for streamflow reaching Lake Powell.

Seeding Mode	Est. Increase Streamflow	Est. Cost	Cost/A.F.	Benefit/Cost for $100/ A.F.	Benefit/Cost for $200/A.F.
Manual Ground Generators	2,294	$77,000	$33.57	2.98	5.96
Seeding Aircraft	8,558	$263,800	$30.83	3.24	6.49
Combined Ground and Aircraft	10,852	$340,800	$31.40	3.10	6.37

conclusion from this report is as follows:

"It appears the cloud seeding program is not economically feasible within areas of close proximity to the two possible target areas given the water supply, land use and crop yield data incorporated in this study. This is because the normal water supply used in the analysis is sufficient for the crops being grown in the area with only minimal shortages. However, during seasons of drought the b/c ratio is considerably higher but still less than 1.0".

This report does indicate this program could perhaps be economically feasible for downstream water users. NAWC considered this possibility in the context of the estimated augmented streamflow due to cloud seeding reaching Lake Powell. One Bureau of Reclamation report suggests this water may be valued in the range of $100 to $200/A.F. (Pilot System Conservation Program, Lower Colorado River Region, 2014). These numbers were used to calculate potential benefit/cost ratios for the program. Table 4 provides the results for the two target areas combined for an average water year.

The American Society of Civil Engineers (ASCE 2016) suggests that proposed cloud seeding programs should potentially achieve benefit/cost ratios of ~5/1. Data from the above table indicate this is predicted to be the case as the value of additional streamflow reaching Lake Powell approaches $200/A.F.

9.0 SUMMARY AND RECOMMENDATIONS

A cloud seeding program designed to target winter storms affecting the Abajo and La Sal Mountain Ranges located in southeastern Utah is considered technically feasible. Such a program is also considered economically feasible but only if the predicated augmented streamflow reaches Lake Powell. According to the two primary criteria established by the ASCE (technical and economical), the proposed program is therefore considered conditionally feasible.

Since several assumptions were made in developing the preliminary program design, it is recommended that a microwave radiometer be operated for one winter season to provide additional atmospheric data for use in finalizing the design. The radiometer is a passive system that provides vertical profiles of temperature, relative humidity and liquid parameters in a continuous fashion through the entire atmosphere above the radiometer. NAWC was fortunate to have such a radiometer installed last winter for our Upper Gunnison River Colorado winter cloud seeding program. Funding for the installation and operation of this device was provided by the Colorado Water Conservation Board and the three Lower Colorado River Basin States. This unit was a Radiometrics, Inc. (headquartered in Boulder, Colorado) microwave radiometer, model MP-3000A. Figure 5 provides a photo of this unit. Deployment of such a unit upwind of the La Sal Mountains would provide important information on several parameters including the presence of supercooled liquid water, which is the target of winter silver iodide seeding programs. All data from such a system is stored offering the opportunity for detailed post data collection analyses. For example, with a special analysis program known as RAOB, a thermodynamic diagram known as a Skew-T, can be generated at any specific time during the winter period. Skew-T's could be produced for potentially seedable storm periods. Several items could then be addressed, such as what are the cloud top temperatures during these storm periods? How much

Fig 5. Radiometrics Microwave Radiometer.

supercooled liquid water is observed during storm periods with cold cloud top temperatures? Does the radiometer indicate any low-level inversions during potentially seedable periods, which would restrict the effectiveness of ground-based silver iodide seeding? What are the wind direction and speeds during potentially seedable conditions (important in terms of targeting of the effects of seeding)?

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