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SEEDING AGENT THRESHOLD ACTIVATION TEMPERATURE HEIGHT, AN IMPORTANT SEEDABILITY CRITERION FOR GROUND-BASED SEEDING

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Abstract. Reanalysis of the Colorado River Basin Pilot Project data set indicates the -5°C height, chosen to represent the height of the threshold activation temperature of AgI nuclei, to be a significant criterion for anticipating seeding effects from ground-based seeding systems. In association with criteria of cloud top temperature and wind speed for analyzing the stable or neutral stages of winter orographic storm systems, it separates the sample into cases with and without apparent seeding effect.

1. INTRODUCTION

North American Weather Consultants (NAWC) recently completed a study on the wintertime cloud seeding potential in the Mogollon Rim area of Arizona. The study was under contract with the Salt River Project as a portion of their study of the potential use of cloud seeding during drought periods, sponsored by the Bureau of Reclamation, Division of Atmospheric Resources Research.

The initial task of the Salt River Project study was the specification of seedability criteria for the determination of seeding potential. The results were then used for completion of the study. This article presents briefly some of the findings of the initial task and shows the importance of including a representative height of the threshold activation temperature of AgI nuclei for the specification of seedability criteria for the stable or neutral phase of winter orographic storm systems.

2. BACKGROUND

One of the most important aspects in estimating the seeding potential of an area is specification of seedability criteria. Research programs over the years have demonstrated that seeding wintertime clouds can produce increases, but can also produce decreases as well, depending upon atmospheric conditions and seeding techniques.

Comprehensive evaluations of the Bureau of Reclamation's Upper Colorado River Basin Pilot Project (CRBPP) emphasized that both positive and negative effects can be produced by seeding wintertime storms in the Western United States (Elliott et al., 1978a). Factors found to influence seeding effects in this study included atmospheric stability, strength of wind normal to the barrier, water content of the clouds, and cloud top temperatures.

An outgrowth from the CRBPP evaluations was the development of some generalized seedability criteria based upon an analysis of six winter research programs conducted in the Western United States (Vardiman and Moore, 1978). Seeding on most of these programs was from ground generators using a silver iodide, sodium iodide, acetone solution between 20 and 50 g/hr per generator. This analysis demonstrated the dependence of seeding effects on four basic considerations:

1) the atmospheric mixing available to carry seeding materials into the clouds;
2) the water available for conversion to precipitation;
3) the ice nuclei supply available for precipitation initiation;
4) the time available for nucleation growth and fallout of precipitation.

The study indicated that positive seeding effects occurred at mountain crest under stable or unstable conditions when a "crest" trajectory was present (i.e., a seeded snow crystal would fall at the crest), where moderate to high cloud moisture was present (i.e., cloud base saturated mixing ratio was greater than 3 g/kg), and the lifted cloud top temperature (ice top) was between -10 and -30°C. Decreases occurred at the crest for unstable clouds with a "blow-over" trajectory (i.e., a seeded snow crystal would fall beyond the crest), with "low" cloud moisture (i.e., cloud base saturated mixing ratio less than 5 g/kg), and lifted cloud top temperatures (ice top) colder than -30°C.

Hill (1980a) questioned some of the limits indicated by Vardiman and Moore, because rawinsonde data on the CRBPP prior to 1973 were processed in the same manner as that collected later. The early data are known to contain errors in relative humidity (Morrisey and Brousaides, 1970). These errors could influence the interpretation of cloud top height.

Based on the University of Wyoming cloud physics aircraft flights on the CRBPP, Marwitz and Cooper (1980) found little vertical deflection of the airflow in the stable storm stages and suggested that "the observed cloud top temperature over the upwind valley would probably be a better measure of the coldest ice nucleation temperature able to affect the precipitation". They also suggested that the stability (mixing) indices used by Vardiman and Moore (1978) and Elliott et al. (1978a) were not adequate to separate the stable and unstable stages of the storms.

Subsequent to the Vardiman-Moore analysis, Rottner et al. (1980) found that a considerable number of unrandomized not-seeded cases had been included in the analysis. Reanalysis did not completely support the prior results. A recent study by Hill (1980b) proposes that different seedability criteria should be considered; Hill argues for strong winds normal to the barrier, while Vardiman and Moore indicate some upper limit to the wind.

NAWC proposed therefore to reanalyze the CRBPP data set, originally analyzed by Elliott et al. (1978a) and by Vardiman and Moore (1978), to evaluate and redefine seedability criteria for winter orographic storm systems. This reanalysis then served as input to the assessment of seeding potential in the Salt River Project area.

3. DATA PROCESSING

The Bureau of Reclamation provided NAWC with computer tapes of the Durango soundings, compiled for the Vardiman-Moore study of multiple projects, and of the CRBPP hourly precipitation data. NAWC's rawinsonde processing computer program OMNIMBUS was used to process the soundings and determine the various indices needed in the analysis.

Precipitation data for the same six crest locations used by Vardiman and Moore for the CRBPP were used in the reanalysis, with a three-hour average associated with each individual sounding. Vardiman and Moore had used a six-hour precipitation average associated with an individual sounding, whereas Elliott et al. used three of the locations to obtain a six-hour precipitation average associated with an average of sounding parameters from two successive soundings.

NAWC proposed that the rawinsonde data from CRBPP be reanalyzed by either eliminating "daytime" soundings taken prior to 1973 or correcting them for solar radiation errors to eliminate possible bias (Hill, 1980a). Rawinsonde relative humidity data between 1964 and 1971 or 1972 contained two sources of error, one from poor shielding of the temperature sensing element, the other from poor ventilation of the hygristor (Morrisey and Brousaides, 1970; Rhea, 1978). To compensate for the poor ventilation, Rhea employed a relative humidity correction factor of 1.09 based on data of Morrisey and Brousaides.

In applying a correction factor to 1964-72 rawinsonde relative humidity data for other analyses, NAWC has de-emphasized insolation-induced errors, considering that the data being processed were for storm periods when solar insolation-induced error was limited by cloud cover. To obtain guidance on how best to process the early CRBPP soundings, NAWC studied other rawinsonde data.

Salt Lake City soundings from 1964-71, with a relative humidity correction of 1.09, were compared to those from 1971-79. The soundings were separated into day and night, with the 00Z sounding classed as day. A 15% lower frequency of occurrence of clouds based below 3 km and thicker than 1 km was found for the daytime soundings. However, when low-based, thick clouds did occur little difference was indicated in the mean base and top heights in the two sets of data. Based on this study, the 1.09 ventilation correction was adopted for the early CRBPP soundings without any correction to daytime soundings for solar insolation error.

The CRBPP data set was separated into not seeded, seeded and contaminated categories. Each of these was divided into three seeded classifications: 1) complete pooling (entrapment of AgI nuclei in the valleys), 2) partial pooling, and 3) no pooling. Since the reanalysis was considered exploratory in nature, not-seeded cases were not restricted to the declared experimental periods. Contaminated cases and seeding modes were taken from the earlier analysis of Elliott et al. (1978a). A complete pooling seeding mode was assumed in those situations when, although generators were on, seeding nuclei would not be expected to be dispersed upward into the cloud due to low level atmospheric stability and/or low level winds blowing parallel to the barrier. Subsequent experimental units could therefore be contaminated due to carry-over of the seeding material. In the reanalysis, contaminated cases were considered seeded and complete pooling cases were excluded.

4. CRBPP REANALYSIS

The seeding "windows" established by Vardiman and Moore (1978) were not supported by this reanalysis of the CRBPP data set. In fact, most seed/no-seed ratios for the previously identified favorable categories were less than 1. The interpretation from testing Hill's (1980b) criteria was that the requirement of strong winds normal to the barrier (i.e., greater than 8 m/s at crest height) is not suitable for evaluating seeding effects of a seeding program as conducted on the CRBPP (i.e., ground-based with silver iodide, sodium iodide, acetone solution).

Prior to the reanalysis, alternate and new indices of meteorological variables had been proposed for the analysis in addition to those used by Vardiman and Moore (1978) and Elliott et al. (1978a). Of those investigated, the results are presented for the stable or neutral category employing four meteorological variables and indices (Table 1).

The conditional instability depth index also had been used by Elliott et al. (1978a) to divide cases into stable or neutral, and unstable categories. For their analysis the stable or neutral category included those cases with a sounding- determined conditional instability depth of 75 mb or less. Because Marwitz and Cooper (1980) suggested this would not necessarily separate the two categories, the division for this reanalysis considered the height of the base of the conditional instability as well as the depth. The stable or neutral category contained those cases with conditional instability depth of 75 mb or less and cases with greater depth but with the base of conditional instability above 650 mb. In the CRBPP, 650 mb is just below average crest height. Cases with conditional instability bases above 650 mb were assumed to be non-convective in nature.

The threshold activation temperature of pure AgI nuclei was found by Vonnegut (1947) to be between -3°C and -5°C. Many theoretical and laboratory studies of cloud seeding materials and their nucleating capabilities have been conducted during the ensuing years. Laboratory test results reported by Blair et al. (1973) indicated a -8°C threshold activation temperature for nuclei from AgI-NaI solutions. More recently, Dennis (1980) states "The threshold of activity for typical generator products is around -5°C" and this was chosen for the analysis.

To become effective as a seeding agent the ground-released AgI must be dispersed upward into the cloud where temperatures are colder than -5°C. If for some reason this level is not attained (i.e. a complete pooling seeding mode, cloud base too high or -5°C level too high) a seeding effect at the crest could not occur. The effect of a -5°C level being too high is illustrated in Figure 1 (adapted from Elliott et al., 1978b), which provides a profile view of relative concentrations of AgI aloft, computed for the American River Basin for an average storm type sounding. For the temperature profile shown, AgI nuclei concentrations aloft do not exceed background nuclei concentrations until just upwind of the crest. The diffusion computations employed the Gaussian plume diffusion model in association with Pasquill- Gifford stability types, using a source strength of 20 g/hr and the CSU effectiveness curve for a NAWC generator burning a silver iodide, sodium iodide, acetone solution. In this instance the -5°C height is approximately the same as the average crest height, and seeding increases would not be expected upwind of or on the crest. Cloud bases were restricted to the average crest height or lower for the CRBPP reanalysis.

Table 1 Variables studied and defining indices

Meteorological Variable	Index
Mixing Available	Conditional instability depth
Nuclei Available	Rawinsonde cloud top temperature
Time Available	700 mb normal wind speed
Supercooled water available . for modification by ground .. released seeding material	Threshold activation temperature height

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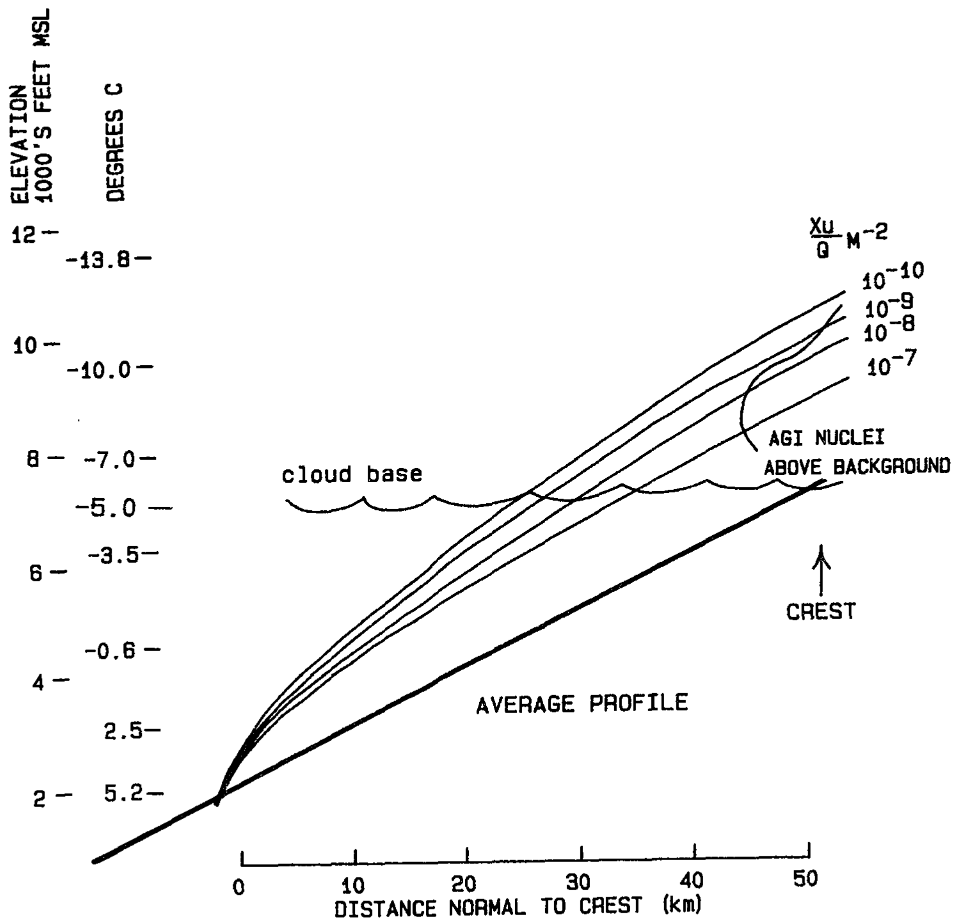

Fig. 1 Type A postfrontal D stability profile view of relative concentrations aloft. (adapted from Fig. 4-22 from Elliott et al., 1978b)

5. RESULTS

Various combinations of partitions of cloud top temperature, 700 mb normal wind speed and -5°C height limits were investigated to arrive at upper limits of 10 m/s for the 700 mb normal wind speed and 3000 m for the -5°C height. In the CRBPP, 3000 m is 800 m below the average crest height. With these limits of wind speed and -5°C height, the seed/no-seed ratio was greater than 2.10 when cloud tops were warmer than -20°C. This ratio was also obtained for cloud tops warmer than -29°C. When the -5°C height was above 3000 m the seed/no-seed ratio was approximately 1.00 for these cloud top temperature partitions.

The most critical parameters appear to be the normal wind speed and a representative height of the threshold activation temperature of the seeding agent. In the CRBPP data set, the number of cases decreases as cloud top temperatures are decreased below -29°C, so no optimum cloud top temperature is clearly defined. In the stable or neutral optimum "window", listed in Table 2, -29°C is suggested as a possible cut-off value.

Table 2 Stable or neutral optimum seeding "window"

Rawinsonde observed cloud top temp	$\geq$ -29°C
700 mb normal wind	$\leq$ 10 ms^{-1}
-5°C height	$\leq$ 3000 m
Numbers of seed/no-seed cases	36/40
Avg. seed/no-seed precip. (mm/3 hr)	1.58/0.74
Ratio	2.14
Probability (rank sum test, one-tailed)	.00034

It was stated earlier that not-seeded cases were not restricted to the declared experimental periods on CRBPP. The reanalysis was considered exploratory in nature and it was desired to have as large a sample size as possible. An identification of the no-seed cases above revealed that twelve cases (30%) were not from declared experimental periods. An exclusion of these cases from the no-seed sample gave a seed/no-seed ratio of 2.33.

This reanalysis of the CRBPP data set provides strong support for favorable cloud seeding responses from ground based generators during stable or neutral stages of winter orographic storm systems. The findings are specifically for the San Juan Mountains of Southwestern Colorado, as well as for a ground-released silver iodide, sodium iodide, acetone complexed seeding agent. Any transfer of the suggested optimum seeding criteria to other areas requires consideration of differences in topography as well as differences in seeding agents.

6. ACKNOWLEDGEMENTS

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