Simulations of Snowpack Augmentation in the Colorado Rocky Mountains

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Abstract. In this paper we summarize a project designed to evaluate the feasibility of using a mesoscale model to support cloud seeding operations and the physical evaluation of seeding responses. The model used was the Colorado State University Regional Atmospheric Modeling System (RAMS). RAMS provided forecasts of precipitation and winds for the 2003-2004 winter season. Detailed evaluation of model forecast orographic precipitation was performed for 30 selected operational seeding days. In addition, the model was run to emulate cloud seeding operations performed by Western Water Consultants. It was shown that the model can be a useful forecasting aid in support of the seeding operations. But, the model over-predicted precipitation, particularly on moist southwest flow days. This was likely due to over-simulated convection when little or only relatively shallow convection actually occurred. The model also exhibited virtually no seeding response in terms of precipitation. Possible reasons for that are discussed.

1.0 INTRODUCTION

The Colorado Weather Damage Modification Program (WDMP) research project involved a physical evaluation of the Denver Water (DW) operational winter orographic cloud seeding program in the central Colorado Rockies for the winter season 2003-2004 using the Colorado State University Regional Atmospheric Modeling System (RAMS). The project was piggy-backed onto the DW operational program contracted by Western Water Consultants (WWC), LLC. The target area was the Blue, Upper Blue, Snake, Williams Fork, and Upper South Platte River drainage basins above 9,000 feet elevation (see Figure 1). The area within the target boundary was about 3,700 km^2. From February 10 through March 2004 only the Upper South Platte River basin and along the Continental Divide above the Upper Blue River basin was to be targeted. A collaborative generator network (funded by DW, ski areas, and other entities) consisted of up to 56 generators that were available for seeding operations. Using a finest grid spacing of 3-km, RAMS was run first in real-time to provide operational support to the DW cloud seeding program. RAMS was subsequently rerun for the period of operations with a number of improvements derived from assessments of the real-time runs, and then rerun with simulated seeding generators releasing seeding material (AgI) at rates, time periods, and locations consistent with the operational program (Hartzell et al., 2005).

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In Section 2.0 we describe the RAMS setup, in Section 3.0 we summarize the results from this project, in Section 4.0 we provide an overall discussion of the results and in Section 5.0 we provide recommendations for future operations.

2.0 RAMS SETUP

The 2003-2004 prototype real-time forecast version of RAMS@CSU was based on version 4.3. The physics of the model is described in some detail in Cotton et al. (2003). Briefly, the microphysics of the model is a bulk microphysics scheme in which the size-distribution of all hydrometeors is determined by a prescribed generalized gamma distribution. In contrast to most bulk models, however, the physics is explicitly represented by emulating a bin model including explicit activation of cloud droplets and ice particles on cloud condensation nuclei (CCN) and ice nuclei (IN), stochastic collection among all hydrometeors using state-of-the-art collection kernels, and a bin representation of sedimentation of hydrometeors. The ice phase is composed of pristine or vapor-grown ice crystals including a variety of habits defined by temperature, snow which represents partially-rimed vapor-grown ice particles, aggregates, graupel, and hail or frozen raindrops.

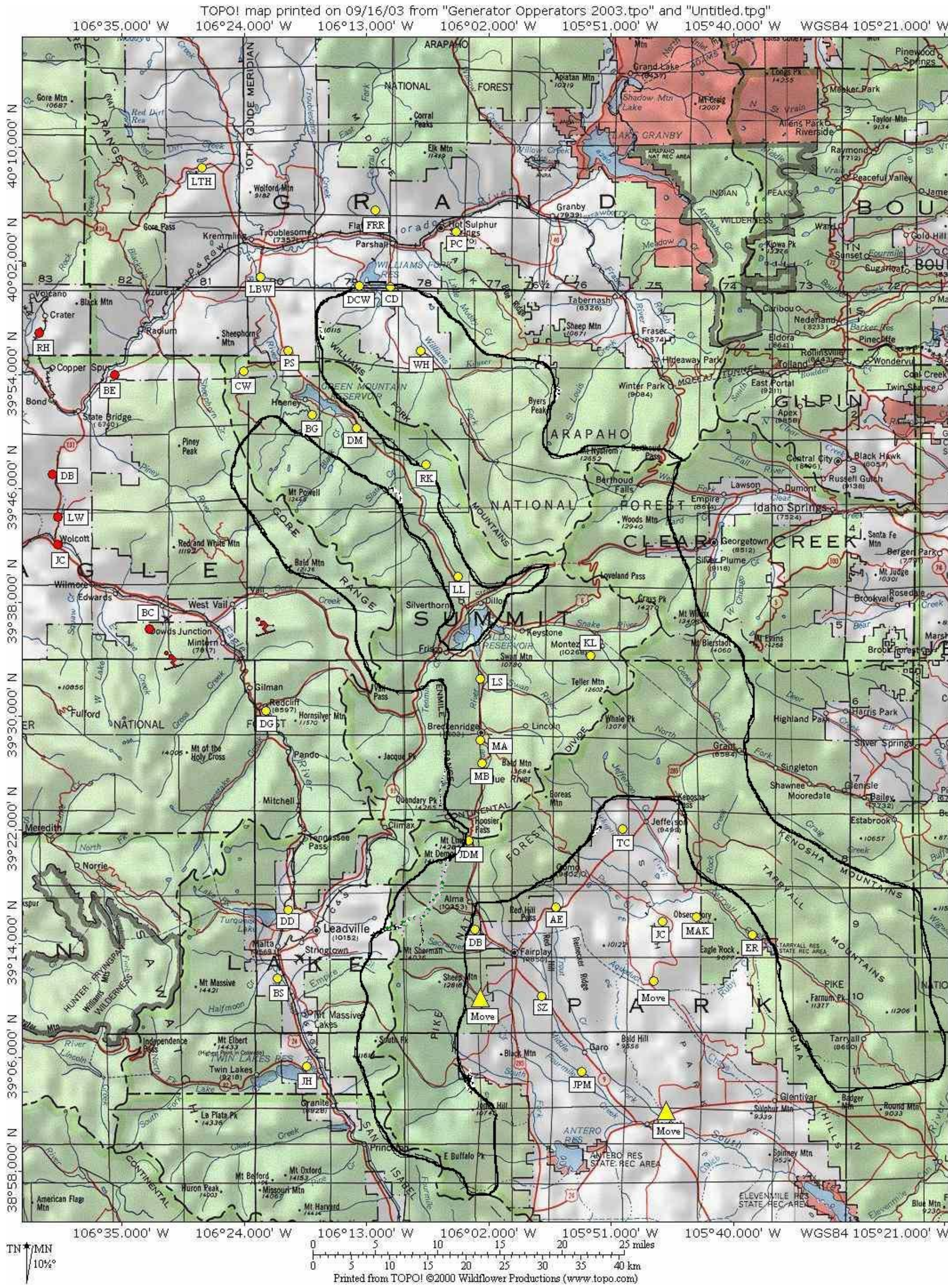

Figure 1. Intended target area for the DW 2003-2004 Program. Generator sites are indicated by yellow circles and triangles (operated by Denver Water) and by red circles (operated by Vail ski area). Several of the 56 total generators are off the figure to the south and west.

Natural ice activation is simulated using a generalization of the Meyers et al. (1992) formula:

$$N_i = N_{IFN}\exp[12.96(S_I - 1)];$$
$$T<-5C;\ r_v > r_{si}$$

supersaturation with respect to ice, and

$$T<-2C;\ r_v > r_{rw}$$

supersaturation with respect to water.

The variable N_{IFN} is a forecast variable in RAMS which can vary both vertically and horizontally whenever such data are available. Normally we use measurements in field campaigns with the CSU continuous flow diffusion chamber to infer N_{IFN}. In the absence of those measurements N_{IFN} is based on the estimates reported in Meyers et al. (1992) and allowed to drop off in concentration with height consistent with observed lapse in large aerosol concentrations. Recent measurements at the Storm Peak Laboratory in the Park Range of Colorado by DeMott (personal communication) suggest that IFN concentrations are probably lower than Meyers original estimates. However, sensitivity experiments using these lower background IFN values did not change the results appreciably.

Secondary ice particle production by the rime-splinter mechanism following Mossop (1976) is also simulated.

A seeding algorithm was added into the model based on sources of IFN from ground-based seeding generators. Figure 2 shows the activation data that we used to simulate IFN production at each generator site. AgI was then added as another prognostic IFN field.

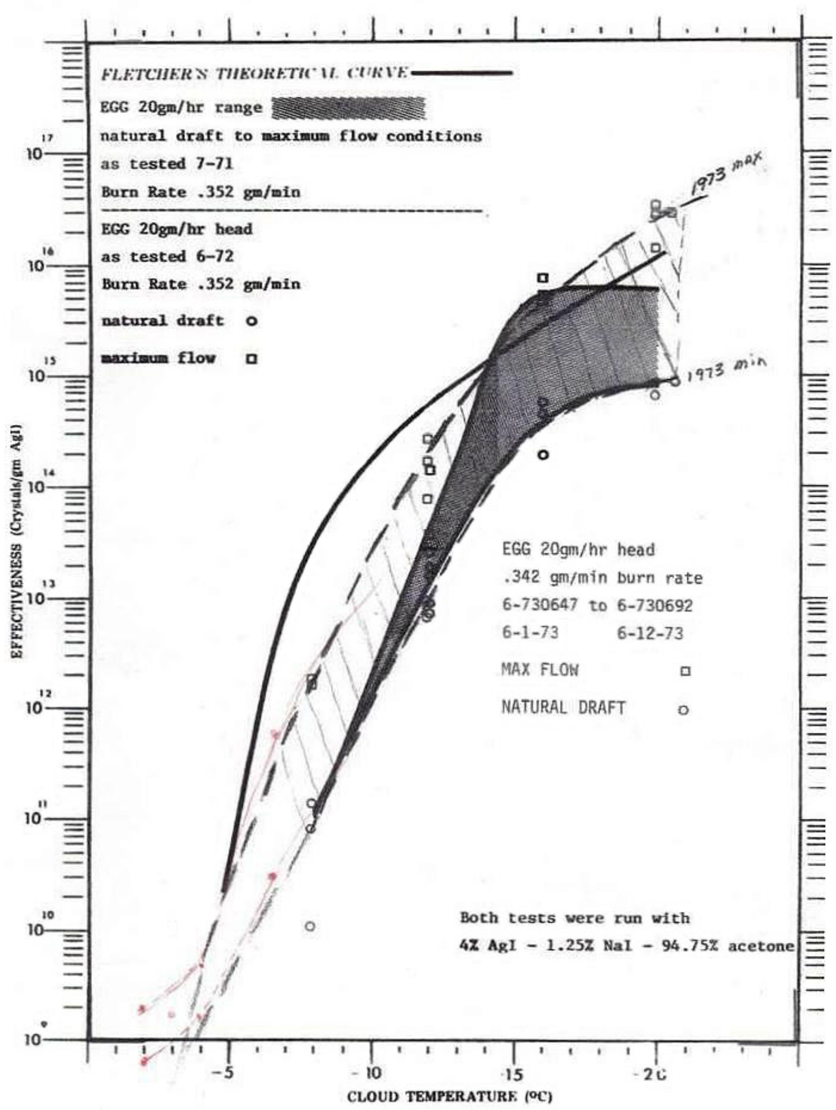

Figure 2. Calibrated AgI activity for the generators used by WWC. The dashed line labeled “1973 max,” including the acetone-induced activation enhancement at warmer temperatures, is the fit used in the model. Provided by Larry Hjermstad. (WWC used a 4% AgI solution with sodium iodide as a carrier in acetone along with 1% moth balls to improve nuclei activation between –2.5°C and –8.0°C.)

The model was set up on a cluster of PCs. The forecast model configuration has three interactive nested grids. Grid 1 has 48-km grid spacing that covers the entire conterminous United States. Grid 2 has 12-km grid spacing that covers all of Colorado, most of Wyoming, and portions of adjacent states. Grid 3 has 3-km grid spacing for 98 x 98 grid points covering a 294 km x 294 km area (86,436 km^2) that is relocateable anywhere within Grid 2. Figure 3 shows RAMS Grid 1 covering the contiguous U.S. with nested Grids 2 and 3. Figure 4 shows the 12-km regional grid, and Figure 5 shows the 3-km fine grid with the project target area and some town IDs.

Vertical grid spacing on all grids starts with 300 m spacing at the lowest levels and is stretched to 750 m aloft, with a total of 32 vertical levels extending into the stratosphere. The model is initialized with 0000 UTC Eta model analysis fields and run for a period of 48 hours, with the lateral boundary region of the coarse grid nudged to the Eta 3-hr forecast fields. A 48-hr run typically begins at 0300 UTC (2000 MST) when the 0000 UTC Eta forecast data are available. The run takes 4-5 hours of computer time to finish, and is completed by 0200 MST. Because RAMS has been able to reproduce high-elevation snowfall amounts with considerable accuracy (Gaudet and Cotton, 1998; Wetzel et al., 2004), it was believed that RAMS could be useful in forecasting the effects of cloud seeding on precipitation for an entire winter season.

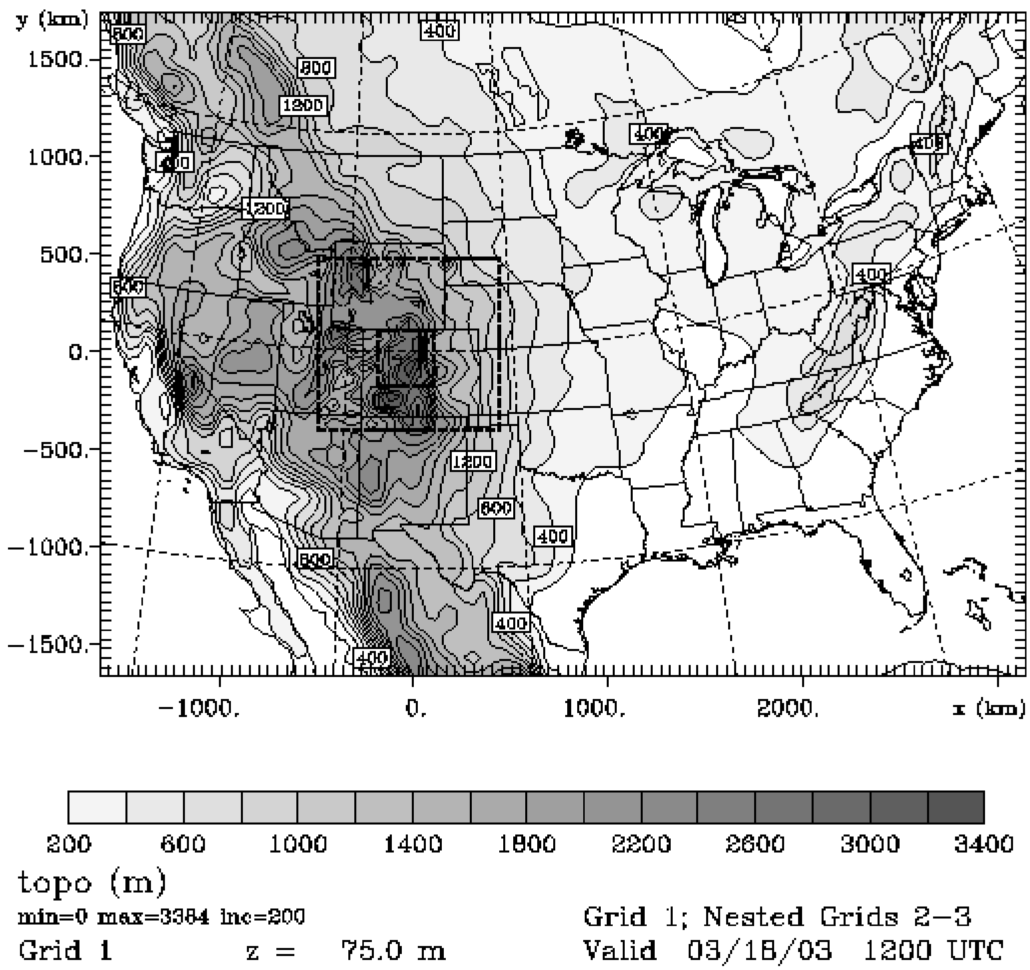

Figure 3. RAMS Grid 1 (48-km parent grid with nested Grid 2 and Grid 3).

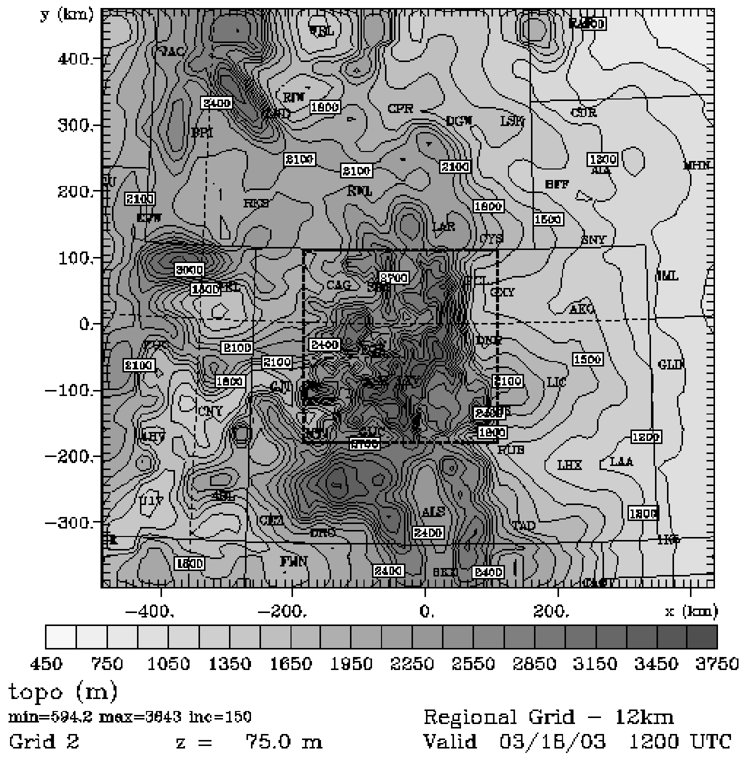

Figure 4. RAMS Grid 2 (12-km regional grid).

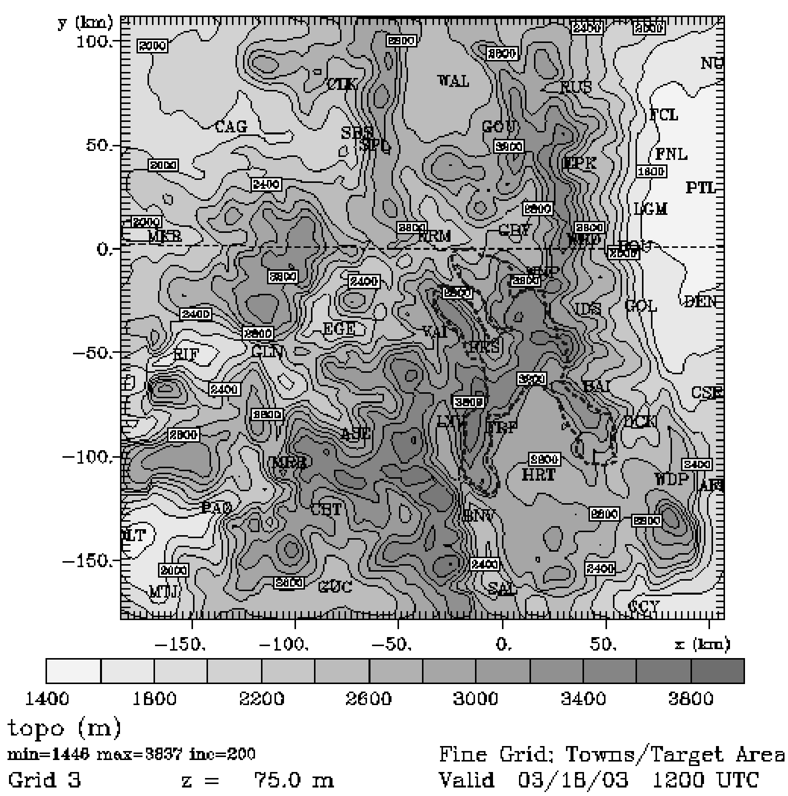

Figure 5. RAMS Grid 3 (3-km fine grid with target area).

3.0 RESULTS

We briefly summarize the results of this project. For further details the reader is referred to the final technical report (Hartzell et al., 2005) at the website: http://rams.atmos.colostate.edu/clseeding/prog-reports.html

The major results of this research project are as follows:

- WWC (Larry Hjermstad) pointed out the forecast model exhibited a warm temperature bias at 700 mb which reduced its effectiveness as a decision tool for determining if seeding operations should proceed. Causes of the warm bias were determined and fixes were made in mid-February 2004. The entire winter season was re-run to provide a better estimate of natural and seeded precipitation. However, the model fixes did not entirely eliminate the low-level warm bias.

- WWC (Larry Hjermstad) found that after the model fixes had been implemented in mid-February 2004 and the RAMS real-time forecast 0000 UTC cycle was run on the new PC cluster, the forecast output that was posted on the Web site was very useful. The low-level warm temperature problem had been greatly reduced and the model provided timely input for operational cloud seeding decision making. There were numerous forecast products and parameters to evaluate. In addition to the 2-hr forecast presentations, the animated forecast loops provided a quick visual picture of changes over time.

- The thirty cloud-seeding days were selected for use in detailed post-season research evaluations. The 30 days were chosen as the "best" representative examples of cases with potential seedability, with a characteristic "targeting wind" for each case ranging from south-southwest through west to north-north-west. When compared to measured 24-hr precipitation at 61 SNOTEL sites the model exhibited a mean precipitation bias of 1.88. The highest bias areas included the Target Area. The lowest bias areas were in more upwind areas in northwesterly and southwesterly events. Possible sources of those biases are discussed in the final report and are currently still under investigation.

- The model control simulations produced a reasonable qualitative pattern of total precipitation and its topographic dependence for the 30 selected days. The 30-day simulated precipitation total showed only light precipitation over the entire SE leg and south half of the SW leg of the target area. Thus the model suggests little orographic precipitation potential and perhaps little cloud seeding potential over the two south legs of the target area.

- The model forecast precipitation data were evaluated against SNOTEL data using MRBP statistical analysis procedures. The results from the evaluation show that the model is describing the non-seeded and seeded simulation equally well. While the signal of the fits is strong (all P-values about 1.0E-6 or less), the agreement measures are not outstanding (all fall between 0.18 and 0.26).

- Comparison of model-predicted non-seeded precipitation (control) versus seeded precipitation revealed that there was essentially no difference between the 86-day seed and control average totals (difference of -1.0 mm) or the 30 days selected for model precipitation evaluation seed and control average totals (difference of -0.2 mm).

- Lagrangian trajectory analyses of six selected days of the subset of 30 days selected for precipitation evaluation revealed that particles are generally being transported to the target area as intended. On average, 54% of those particles are 50-500 m AGL, with another 34% in the layer 500-1000 m AGL, which are levels suitable for AgI seeding.

- The Lagrangian analyses confirm that generators should not be used when the targeting wind would not carry their plumes over the target area. Low level trapping of particles can become moderate in nocturnal inversions, but significant numbers of particles escape the inversions and are transported by the targeting wind as intended. It appears that generators located on the lee side of mountain ranges may be in stagnation zones or rotors associated with high amplitude mountain waves, leading to moderate local trapping.

4.0 DISCUSSION

The very small differences between seed and control precipitation predicted by the model were very disappointing and not expected at the onset of this project. Possible causes of such low seedability:

- The model predicted seedability could be real; however, because of the model over precipitation prediction bias and low amounts of supercooled liquid water content, this possibility is doubtful.

- The background CCN and IN concentrations are unknown but instead are determined by our selected background concentrations. Too low a background CCN concentration would make clouds more efficient in natural precipitation formation thereby lowering seedability. Too high background IN concentrations would likely lead to lower seedability.

- There is circumstantial evidence that the model-predicted supercooled liquid water content is too low, thereby lowering seedability.

- The evaluated over-prediction bias in precipitation may lead to reduced opportunities for precipitation enhancement in the model.

- Banded patterns of seed - no seed differences on daily totals suggest a possible very weak dynamic response to seeding. This pattern of differences results in much of the target area being in regions of reduced precipitation.

- The low-level warm temperature bias in the model results in delayed AgI nuclei activation and reduced effectiveness of the seeding agent. However, this effect has overall a small impact on seedability.

- The simulated transport and diffusion of seeding material from the generator sites is getting into the clouds too far downwind of the generator sites. However, the particle modeling suggests that seeding material is delivered to the target area at levels suitable for seeding, which argues against the notion that seeding material is not getting into the intended seeding zones.

5.0 RECOMMENDATIONS

It is recommended that additional modeling studies are warranted because this was only a one-year contract and research funding was limited. One of the first things that needs to be done is to determine the cause of the model over-prediction bias in precipitation. Another is to explore the various hypotheses that have been put forward to explain the very small differences between seed and no-seed precipitation amounts. Still another area to explore is the low amounts of SLW in the 2-hr vertically integrated maps over the target area; additional sensitivity tests would be useful. Also, it would be desirable to rerun all or at least the 30 selected days with higher resolution to determine if increased resolution reduced the precipitation bias and/or the seed, no-seed differences.

In support of future operational cloud seeding projects in which a model is used as part of the evaluation technique, it is urged that background CCN and IN concentrations be measured. Preferably this would be airborne but in lieu of that longer term ground-based measurements, particularly from higher-terrain sites, would be desirable. Other items that would be very useful in such a project would be a vertically-pointing radiometer near the summit on the target mountain barrier for SLW detection, and the use of scanning cloud radar for identifying regions of liquid water in the clouds and to follow precipitation morphology. In addition the combination of model predictions and new observations such as cloud radar and radiometers could be used in a very sophisticated method of evaluation of an operational seeding project.

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