3.5 A CASE STUDY OF MESOSCALE AND PLUME DISPERSION MODELING FOR A FEBRUARY 2004 CLOUD SEEDING EVENT IN THE WALKER RIVER BASIN OF CALIFORNIA/NEVADA

Arlen W. Huggins*
Darko Koracin
Domagoj Podnar
Ming Xiao
Desert Research Institute, Reno, Nevada

1. INTRODUCTION AND BACKGROUND

Mesoscale numerical models are now used extensively in real time forecasting applications. Their capabilities in simulating air flow over complex terrain surpasses that of standard forecast models because they can now be run efficiently at high spatial resolution. Mesoscale modeling has also been used in weather modification research. In wintertime orographic cloud studies researchers have been applying numerical models to cloud seeding problems for at least 20 years. However, a recent National Research Council report (NRC, 2003) still regards cloud modeling issues as one of the key uncertainties in weather modification research.

Operational winter orographic cloud seeding programs rely primarily on seeding clouds using ground-based generators, where typically some type of silver iodide aerosol is released to act as an ice nucleant at temperatures colder than -5°C. Ensuring transport of AgI to the -5° level is one of the fundamental problems to be addressed in designing a successful cloud seeding program.

Relatively recent modeling studies by Bruintjes et al. (1995) in Arizona, and Heimbach et al. (1998) in Utah have shown relatively good agreement between mesoscale model predictions of plume transport and actual observations of plume positions. Huggins et al. (1998) used a numerical cloud model (MM5) and a Lagrangian particle dispersion model (LAP) to study seeding plume transport and dispersion during cloud seeding experiments in the Lake Tahoe Basin of the Sierra Nevada. In this experiment seeding plume predictions were verified by real time collections of snow samples that were found to contain above-background concentrations of silver during times when model plumes were over the collection site.

The Sierra Nevada near Lake Tahoe has been the focus of numerous cloud modeling studies, however other regions of the Sierra Nevada, where operational cloud seeding has taken place for years, have not been studied so extensively. In particular the Walker River Basin about 150 miles south of Lake Tahoe, part of Nevada's cloud seeding program, has had very little research attention. This area offers some unique challenges to cloud seeding operations. The very high terrain of the Sierra Nevada bound the basin on the west. With the prevailing southwesterly through westerly winds during winter storms, the optimum placement of ground generators would be to the west of the Sierra Nevada crest. However, these regions are mainly wilderness areas where generators are not allowed. The current program primarily sites ground generators to target mountainous areas in the interior of the Walker Basin, predominantly downwind of the Sierra Nevada. The airflow in these downwind areas, and its effect on seeding plume transport and dispersion, have not been studied in detail and are the focus of the modeling study reported here.

This research is part of the U. S. Bureau of Reclamation Weather Damage Modification Program (WDMP) that focuses on the WDMP task of studying snowfall augmentation for drought mitigation. The Nevada WDMP is designed to evaluate the impacts of wintertime cloud seeding on the snowpack and streamflow in a watershed. This new mesoscale modeling effort was undertaken to study airflow and cloud development over the complex terrain where cloud seeding is conducted, and to evaluate cloud seeding generator positioning under a variety of storm conditions.

2. MODEL DESCRIPTION AND STUDY AREA

The seeding plume dispersion simulation was based on Mesoscale Model 5 (MM5, Grell et al., 1995) simulations as input to a Lagrangian random particle dispersion model (LAP) developed at Desert Research Institute (DRI). These models has been applied to studies of the transport and dispersion of atmospheric pollutants and tracers in complex terrain, as well as the transport and dispersion of cloud seeding agents (see e.g., Koracin et al., 1998 and Huggins et al., 1998).

LAP estimates the dispersion of pollutants by tracking a large number (on the order of millions) of hypothetical particles in the model domain. The fate of the particles is determined by the simulated atmospheric fields (from MM5) and a modeled direct link between the turbulent transfer and dispersion. Environmental atmospheric parameters are available at every point in the domain from MM5 in an Eulerian framework. LAP is capable of treating multiple sources (point, line, areal and volume) without restrictions on position and movement. Prescribed temporal variations in emission rates are permitted. In the case of cloud seeding generators with a known source emission rate, the model can predict the magnitude of concentrations in all three dimensions. Meteorological input to the LAP model includes three-dimensional fields of U, V and W wind components and potential temperature simulated by MM5.

For the cloud seeding simulation particles in LAP are

---

* *Corresponding author address:* Arlen W. Huggins, Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512-1095: e-mail: arlen.huggins@dri.edu

tagged by source. Each particle is assigned a certain mass which depends on the emission rate and particle release rate of the seeding generator. For the Walker Basin study a ground seeding operation using four generators (point sources) with an AgI emission rate of 27 grams h^{-1} was simulated.

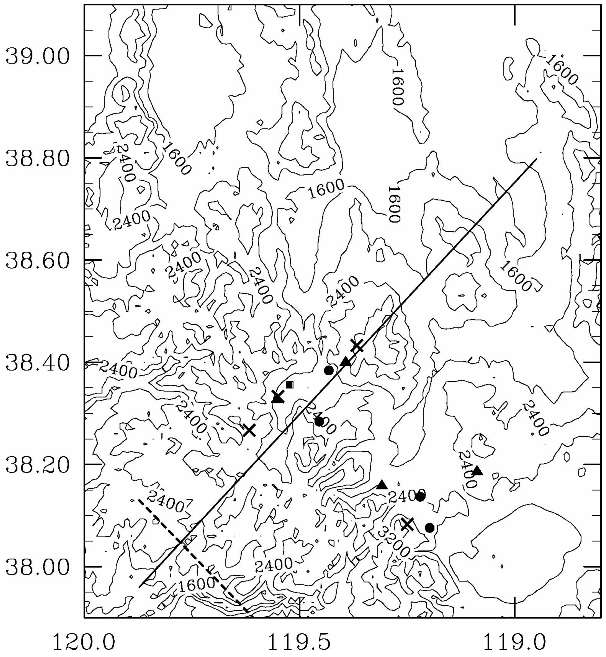

Figure 1. Map of terrain for the innermost domain of MM5. Marked locations include a microwave radiometer (square), SNOTEL (X), seeding generators (circles) and snow sampling sites (triangles). Dashed line is the seeding aircraft flight track for 2 Feb 2004 and the solid line is where MM5 cross-sections were analyzed.

For the current study MM5 was set up with four nested domains over the western U. S. and eastern Pacific Ocean. The innermost domain (4) with 1-km horizontal resolution was centered on the Walker River Basin. The topography of Domain 4 is shown in Fig. 1, together with the locations of ground-based seeding generators, a microwave radiometer, several SNOTEL sites, and four sites where snow samples were collected for trace chemical analysis. One flight track used for aircraft seeding is also shown in Fig. 1.

3. 2-3 FEBRUARY 2004 CASE STUDY

The storm period of interest occurred on 2 February 2004. MM5 was initialized with National Center for Environmental Prediction (NCEP) gridded data from 0000 UTC on 2 February and run for a 48-hour simulation through 0000 UTC on 4 February. Simulations used NCEP reanalysis data every 12 hours to adjust lateral boundary conditions for the model. Domain 4 was run at 1-km resolution over an area of about 12,000 km2. The main period of interest was a ground seeding operation conducted between 1440 UTC 2 February and 1440 (all times UTC) 3 February, and an aircraft seeding event that occurred from 1729 - 1935 on 2 February.

3.1 MM5 Meteorological Results

Although the primary reason for running MM5 was to develop the input fields for the LAP model, the meteorological fields themselves provided valuable information on how winds, clouds and precipitation evolved over the Sierra Nevada and Walker Basin during the 48-hour simulation. The MM5 results agreed well with synoptic observations of a winter cyclonic storm and cold front passing through the region. Comparison with nearby soundings also showed good agreement with wind fields during the first 12 hours of the cloud seeding operations that took place in the pre-trough and pre-cold frontal environment.

After 12 hours of simulation (at 1200 2 Feb) MM5 showed moderate south-southwest flow above mountain level over the Walker Basin and the development of precipitation over the western slopes of the Sierra Nevada. In agreement with nearby soundings southwesterly winds strengthened over the next 12 hours in the period when ground seeding began and aircraft seeding was conducted. Satellite and radar images showed a cold frontal cloud/precipitation band centered on the Walker Basin at about 2300 on 2 February. MM5 timed this precipitation feature quite well, showing maximum precipitation over the Walker Basin in the period between 2200 2 February and 0100 3 February.

The evolution of water vapor, cloud water and precipitation from MM5 were compared to observations in the Walker Basin. Integrated cloud water and water vapor are compared to microwave radiometer measurements of similar parameters in Fig. 2 (see instrument locations in Fig. 1). The trend in MM5 integrated water vapor matches the radiometer vapor trend reasonably well although MM5 appears to have underestimated vapor throughout the storm. In the cloud water trace MM5 peak values were of similar magnitude to radiometer liquid measurements, but were generally offset from radiometer maxima. The broad

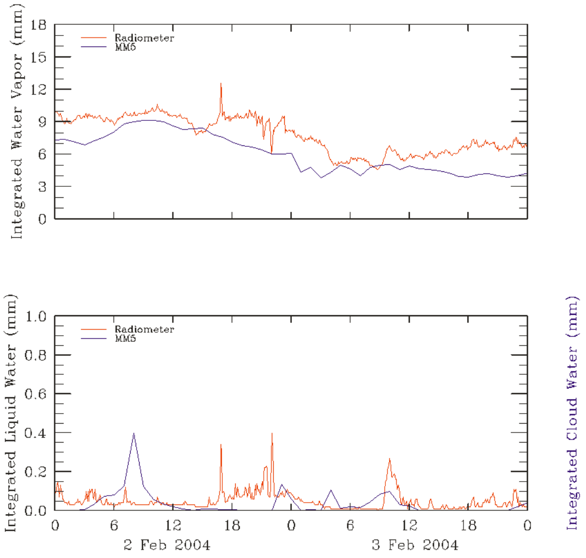

Figure 2. Comparison of MM5 and microwave radiometer integrated water vapor (top) and integrated cloud water (bottom) for 2-3 Feb 2004.

radiometer liquid maximum that developed ahead of the cold front (1700 2 Feb - 0000 3 Feb) was not predicted by MM5, and the large MM5 maximum near 0800 on 2 February was not seen by the radiometer.

Precipitation accumulation is compared for two sites in Figs. 3 and 4. Figure 3 shows a remarkable correspondence between model and measurement for Leavitt Lake near the Sierra Nevada crest. However, Fig. 4 indicates MM5 precipitation did not compare as well at Lobdell Lake located in a mountain range downwind of the Sierra Nevada. Here the model started precipitation too soon, underestimated precipitation in the main frontal band, and ended precipitation too soon.

Model-predicted wind, potential temperature, and mixing ratio are shown in the vertical cross-sections of Fig. 5. The cross-section location, roughly orthogonal to the mountain barrier is shown in Fig. 1. The positions of two seeding generator sites and the aircraft seeding track relative to the cross-section are also shown in Fig. 5. At the time shown (2000 UTC on 2 February) the upper level winds were approximately parallel to the orientation of the cross-section.

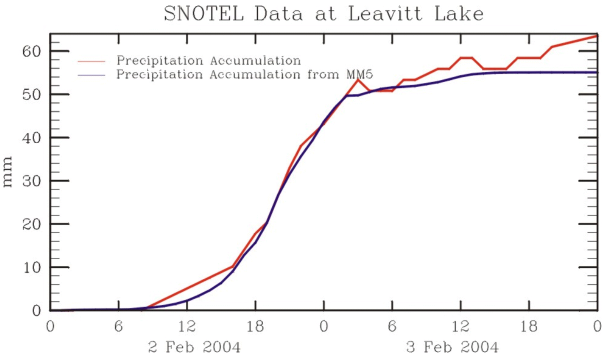

Figure 3. Comparison of precipitation accumulation from MM5 (red) and Leavitt Lake SNOTEL (black).

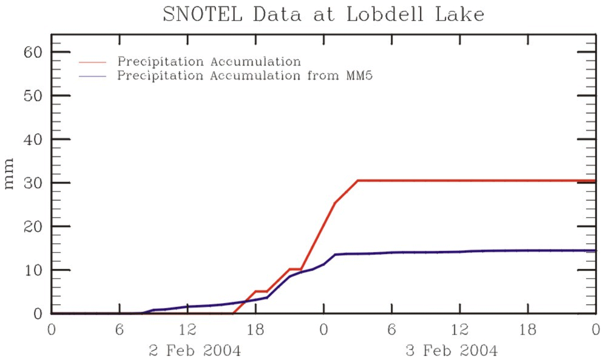

Figure 4. As in Fig. 3, except for Lobdell Lake SNOTEL.

The wind vectors and potential temperature contours depict a series of waves induced by the terrain. The vertical motion downwind of the Sierra Nevada is stronger than that shown over the main barrier at 0-40 km. A broad region of upward motion and accompanying enhanced cloud mixing ratio appear on the windward slope of the Sierra Nevada. The seeding aircraft flew in this region (at 5 km and 15°C), and detected supercooled liquid water nearly continuously at concentrations of 0.1-0.3 g m^{-3}. Winds and cloud conditions appear to be optimum for aircraft and ground-based seeding. Radiometer measurements from Fig. 2, which showed nearly continuous detection of supercooled cloud liquid from 1400 2 February to 0300 3 February, suggest that the extent of the cloud downwind of the Sierra Nevada was likely underestimated (as was precipitation) by MM5 in this period.

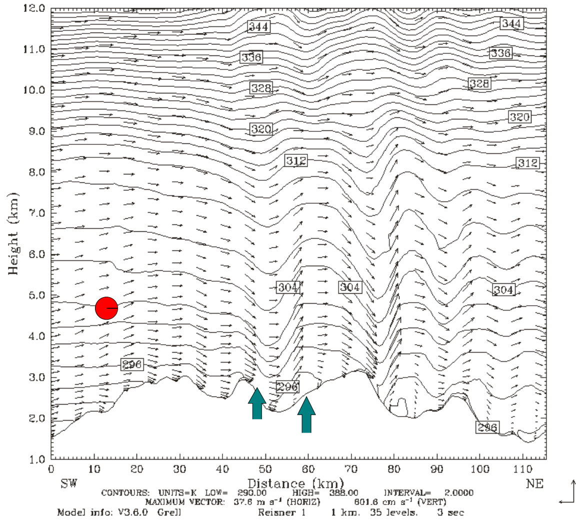

Figure 5a. Cross-section analyzed from MM5 output at the location shown in Fig. 1. Vector winds (arrows) and potential temperature (lines) are shown at 2000 on 2 Feb. Red circle shows seeding aircraft track orthogonal to the cross-section and large arrows show ground generator locations.

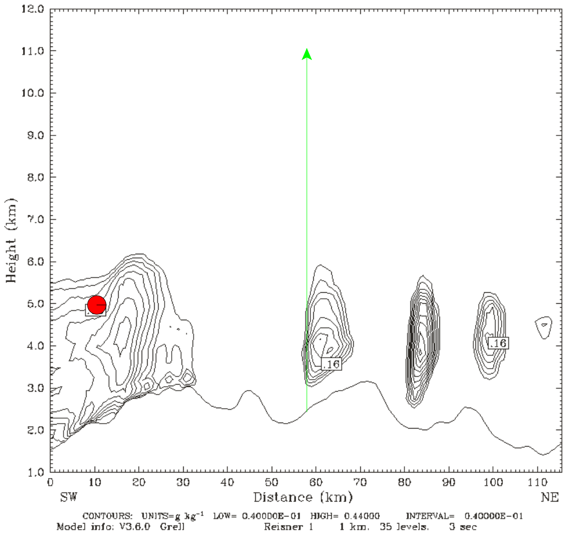

Figure 5b. As in Fig. 5a, except showing contours of MM5 cloud water mixing ratio (g/kg). Green line shows radiometer location and zenith sampling direction.

Earlier and later cross-sections showed that the wave positions downwind of the Sierra changed as the winds varied. Likewise the positions and magnitude of cloud mixing ratio maxima varied with wave positions and intensities. At 2000 the first wave downwind of the Sierra is relatively broad, as is the cloud region associated with it. In the previous hour, with stronger winds, the wave and cloud region were narrower. Noting the two seeding generator positions in Fig. 5, it is apparent that winds and vertical motion needed to transport seeding material into the cloud regions over the interior mountains will vary within a storm. The cross-sections indicated that the better situations occurred with lighter and more southerly winds.

3.2 LAP Plume Dispersion Results

The MM5 three-dimensional fields at 15-min output served as meteorological input to the LAP dispersion model. The seeding sources were the four sites shown in Fig. 1, each releasing material at a simulated rate of 27 grams h^{-1}. Once the simulated release begins LAP keeps track of all particles, so concentrations in each grid cell can be determined at each time step. Stored information from the entire simulation can be used to create a variety of single images and animations to study the particle dispersion in three dimensions over time.

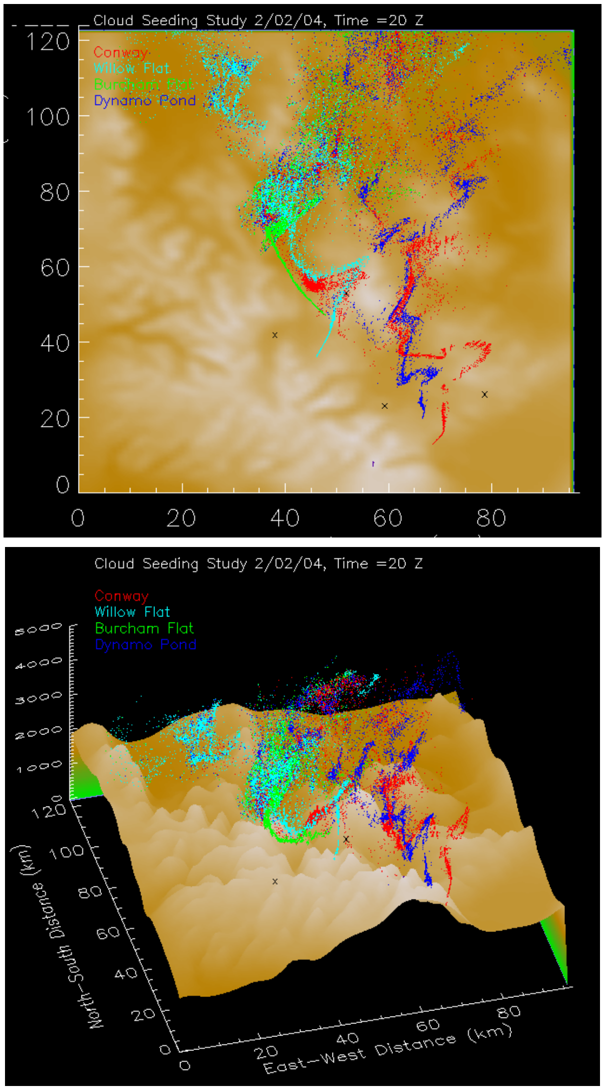

Figure 6. Plan view (top) and perspective view of Walker Basin from the southwest (bottom). Shown are LAP simulated particle plumes from four generator sites at 2000 on 2 Feb (matches cross-section time in Fig. 5).

Figures 6 and 7 show examples of LAP seeding plume positions at two times during the 2-3 February storm. Figure 6 shows plumes during prefrontal southwesterly winds at 2000 on 2 February. Plumes show the combined effects of terrain-following and mountain-induced waves. Plume transport was appropriate for seeding material to interact with clouds over the interior ranges of the Walker Basin. Vertical transport also appeared to be adequate for AgI to reach the -5° C level. The plumes at this time are representative of LAP plume predictions between 1500 and 2300.

The set of panels in Fig. 7 shows plumes at 0000 on 3 Feb at a time near or shortly after frontal passage when cloud layer winds began to shift to a more westerly direction. Plume transport was predicted to be markedly

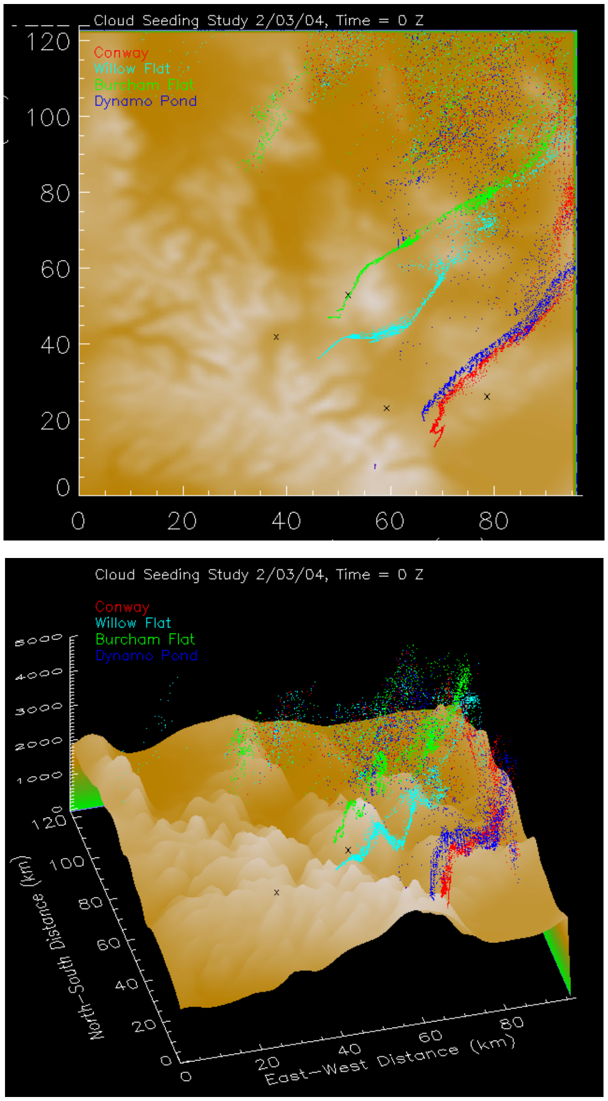

Figure 7. As in Fig. 6, except for 0000 on 3 Feb 2004.

different in this westerly flow pattern. The plumes experienced less horizontal spread and passed over distinctly different regions of the Walker Basin. The influence of mountain-induced waves is clearly seen in the cyan-colored plume. All four plumes passed over higher terrain with seeding potential. At the right boundary of Fig. 7 the plumes begin to ascend the Wassuk Range, a dramatic north-south oriented barrier that also receives a moderate snowpack. Although vertical and horizontal plume transport appeared adequate for reaching potential cloud seeding target regions, seeding effectiveness would still depend on plumes reaching liquid cloud regions at locations that would allow time for ice crystal growth and fallout. MM5 results, as well as radiometer and satellite cloud observations, indicated such conditions occurred over the basin through at least 0600 on 3 February. Snow samples collected at the locations shown in Figs. 6 and 7 were found to have silver concentrations higher than what is considered the background level for this region, indicating that the actual AgI plumes did interact with cloud regions during the 2-3 February storm period. For further details on snow chemistry measurements, refer to Huggins et al. (2004) in these preprints.

4. SUMMARY AND CONCLUSIONS

As part of the WDMP the DRI conducted research related to winter snowpack augmentation. One task of the research involved atmospheric and dispersion mesoscale modeling to study air flow, cloud development and plume dispersion in the Walker River Basin. Operational cloud seeding for snowfall enhancement has been conducted in this region for many years without the benefit of detailed meteorological studies. The modeling study focused on a winter storm that affected the region on 2-3 February 2004. The MM5 model was run for a 48-hour simulation. Wind fields from MM5 were then used as input to a DRI Lagrangian particle dispersion model to evaluate the behavior of simulated plumes from actual ground-based cloud seeding generators locations in the Walker Basin.

Observations indicated that MM5 simulated the storm period reasonably well. The cloud characteristics and precipitation were simulated best on the windward side of the Sierra Nevada. In the downwind regions precipitation was underestimated and cloud water regions were less extensive than indicated by satellite and radiometer measurements. The plume dispersion simulation revealed the influence of terrain forcing and mountain-induced waves that had previously been neither observed nor modeled in this region. Although only two examples of plume patterns were presented, the entire simulation of plume dispersion over the 48-h period at 15-min time steps gave a unique view of how seeding plumes likely evolve during the passage of a winter storm. The seeding generators, although not shown to be optimally positioned for all wind situations, were shown to be well placed to seed the interior ranges of the Walker Basin with pretrough southwesterly flow that is typical of most Sierra Nevada storms.

As shown in earlier applications of mesoscale models to weather modification, the modeling techniques used here will be useful tools in both weather modification research and in the evaluation of operational programs. One very important progression in the method described here will be to link plume dispersion with model microphysics to provide a complete simulation of cloud seeding processes.

5. REFERENCES

Bruintjes, R. T., T. L. Clark and W. D. Hall, 1995: The dispersion of tracer plumes in mountainous regions in central Arizona: Comparisons between observations and modeling results. *J. Appl. Meteor.*, **34**, 971-988.

Grell, G. A., J. Dudhia and D. R. Stauffer, 1995: A description of the fifth-generation Penn State/NCAR mesoscale model (MM5). NCAR Tech. Note TN-398, Boulder, CO, 122 pp.

Heimbach, J. A., W. D. Hall and A. B. Super, 1998: Modeling AgI targeting effectiveness for five generalized weather classes in Utah. *J. Weather Mod.*, **30**, 35-50.

Huggins, A. W., V. Isakov and D. R. Koracin, 1998:Use of the MM5 mesoscale model and a LaGrangian particle dispersion model to simulate aerosol seeding plumes from ground-based generators. 14th Conf. on Planned and Inadvertent Weather Modification, Amer. Meteor. Soc., Everett, Wash., 596-599.

Huggins, A. W., R. Edwards and J. McConnell, 2004: Summary of trace chemical and physical measurements of snowfall in two Nevada cloud seeding target areas. Preprints 16th Conf. on Planned and Inadvertent Weather Mod., San Diego, CA, Amer. Meteor. Soc.

Koracin, D., V. Isakov and J. Frye, 1998: A Lagrangian particle dispersion model (LAP) applied to transport and dispersion of chemical tracers in complex terrain. Proc. 10th Joint Conf. on the Applications of Air Pollution Meteorology with the AWMA, Phoenix, AZ, Amer. Meteor. Soc., 227-230.

National Research Council, 2003: Critical issues in weather modification research. *The National Academies Press*, Washington, D. C., 131 pp.

Acknowledgment: This research is sponsored by the U. S. Bureau of Reclamation Weather Damage Modification Program under Cooperative Agreement 03FC810858.