P1.8 A MODEL BASED FEASIBILITY STUDY OF GLACIOGENIC SEEDING DURING A WINTER OROGRAPHIC PRECIPITATION EVENT IN WYOMING

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1. INTRODUCTION

The technique of glaciogenic seeding of orographic clouds has been used for decades to increase the snowpack of a region, which in turn increases the run-off into a given watershed. Mesoscale models have recently been used for assisting in the placement of ground based generators and the evaluation for glaciogenic seeding experiments.

A multipart feasibility study on conducting cloud a seeding program for winter snowpack augmentation in Wyoming was undertaken by Weather Modification Incorporated and the National Center for Atmospheric Research (NCAR) on behalf of the Wyoming Water Development Commission. The commission was specifically interested in two project areas, the Wind River Range and the Sierra Madre/Medicine Bow Ranges. NCAR was responsible for the modeling portion of the study.

The standard version of the Weather Research and Forecasting Model (WRF) was used to investigate the dispersion of seeding material during the 7-8 February 2004 winter orographic precipitation event. Of particular interest is the targeting and the amount of seeding material that reaches the supercooled liquid water regions of the clouds to determine optimal locations for seeding generators in a potential experiment.

2. MODEL SET-UP

The Weather Research and Forecast Model (WRF) version 2.0.2 was deployed on a linux-based cluster. The Eulerian-Mass core was used as the dynamical solving routine for the system. Nesting was implemented in this version of WRF, allowing for a four domain system to be set up for simulations over the two areas of interest, Wind River and Sierra Madre/Medicine Bow Ranges.

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For the most part, the model was run using the default physics values. The two differences were the inclusion of a passive tracer in the model (described in Section 3) and the use of different cloud microphysics schemes. The model sensitivity to cloud microphysics schemes was assessed using simulations of Domains 1 and 2 using the ETA AWIP final analysis grids (40 km grid spacing) at 12 UTC on 7 February 2004. The case study, using the WRF single moment 6-class scheme, was initialized using the same data and, with all four domains, run for a total of 48 hours. Results from the sensitivity studies are provided in Section 4 and from the case study for the Wind River region in Section 5.

3. TRACER IMPLEMENTATION

As a first step of implementation, a passive tracer was added to one grid cell on the inner nested domain to simulate the dispersion of the potential seeding material. A release rate equivalent to 2.4×10^{16} nuclei/hour of tracer was added at the source point or “generator” location during each time step (Bureau of Reclamation, Denver, 1989). The tracer was then dispersed using the horizontal and vertical advection schemes available with the EM core.

An initial attempt to look at the influence of local flows on generator placement was conducted by extending the code to allow for three tracers sources to represent multiple generators. An example of dispersed tracer over the topography resulting from the local wind flow is shown in Figure 1.

The four-grid configuration included two-way interactive nesting. In Domain 1, the wind flow is primarily northerly over the regions of interest and the tracer looks like a large oblate region over western Wyoming. A slight shift to the north-northeasterly winds is resolved in Domain 2 as well as the concentration of the tracer on the southwestern side of the range. Domain 3 and resolves a general northeasterly flow across the range and shows a weak mesoscale circulation.

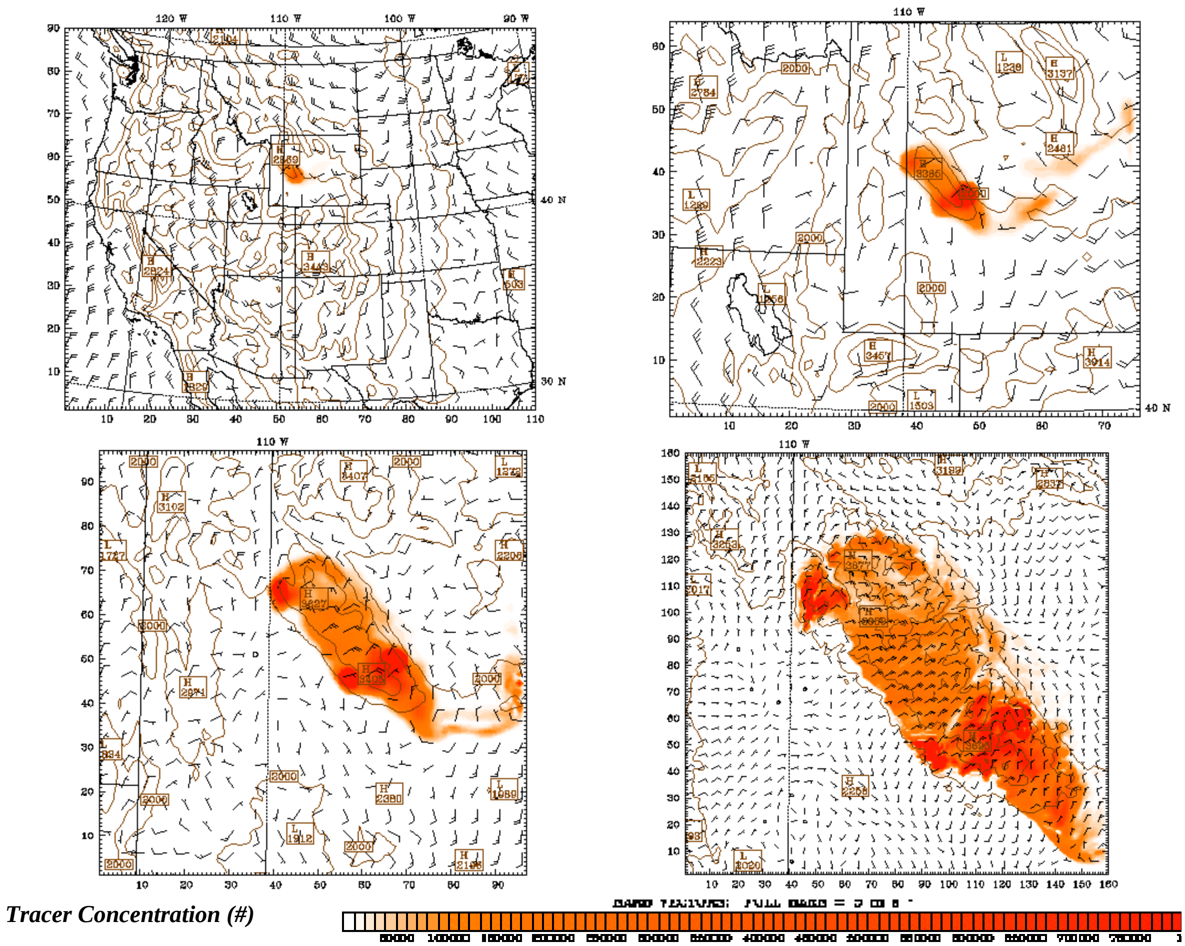

Figure 1. Tracer concentration in the lowest model layer on Domain 1 (upper left), Domain 2 (upper right), Domain 3 (lower left), and Domain 4 (lower right) released from three sources. Wind barbs are in m/s, and terrain in meters. Time is 18 UTC on 7 February 2004.

on the upwind (eastern) side of the mountain. The 3 km grid spacing allows for better resolution of the tracer path and concentration near each point source. As expected, Domain 4 provides much more information about the local structure of the winds and shows that the tracer remains highly concentrated in a thin line from the northern generator.

4. COMPARISON OF MICROPHYSICS

Sensitivity studies were undertaken to identify the most representative microphysics package for a winter orographic scenario. The new standard WRF Single Moment cloud microphysics scheme (Hong et al., 2004), predicting mixing ratios for six hydrometeor categories, was compared with a more standard one-moment scheme (Lin et al., 1983) and a prototype cloud microphysics scheme. The latter scheme was developed at NCAR (Thompson et al., 2004) and was implemented in WRF model shortly after the Version 2.0.2 release.

The Thompson module developed the greatest amount of liquid water near the surface but little to no primary ice and moderate amounts of snow. The Lin scheme developed small amounts of all three species during the 12 hours of simulation. The WSM6 scheme developed no cloud water in Wyoming at 25 m AGL but generous amounts if primary ice. Temperatures at this level were approximately –5 °C and thus the presence of such large quantities of primary ice (0.2 g kg^{-1}) may be excessive in WSM6. This observation makes Lin and Thompson modules appear to be better candidates. However, primary ice in both schemes was still not present at 5 km (-20 to –23 °C). Primary ice should start developing at approximately –10 °C. A slight modification to some of the parameterised variables in the Thompson scheme have been recommended (Hall, 2004) which may improve its response to the development of primary ice.

At this time, the Thompson scheme only runs successfully on a single processor of the cluster. For this reason, the WSM6 scheme was selected for use during the case study.

5. CASE STUDY: 7-8 FEBRUARY 2004

This case was selected as being representative of a moderate snowfall case for both the Wind River and Medicine Bow/Sierra Madre regions. It also provides an interesting case where the upslope conditions changes from southwest to north-northeasterly. Diagnostic simulations indicate that regions of super-cooled liquid water developed in the Wind River range first. This case study will thus concentrate on this particular area of interest.

At 12 UTC on 7 February, 2004, a deep extra tropical cyclone was centered along the border between Montana, Saskatchewan, and Manitoba. The remnants of a previous stationary front extended into the eastern section of Wyoming and the cold front stretched from Montana down through Idaho and close to Reno, Nevada. A ridge of high pressure dominated the Four Corners region up to about 850 mb. This system tilted towards the west at upper levels, providing baroclinic support for it to deepen. Light snow was reported by the Medicine Bow and Sierra Madre SNOTEL sites. By 00 UTC on 8 February, the upper level support had caught up with the surface features and the trough axis extending from the Northwest Territory (north of Manitoba) through Montana, Utah, and the southern tip of California. The front was stationed over the areas of interest and southwesterly winds dominated. Light snow had been falling over the Medicine Bow/Sierra Madre Ranges and had started to develop on the southwestern side of the Wind River Range. As the system moved out of the mountains in Colorado, surface winds changed to north-northeasterly and the maximum snowfall for the event occurred around 06 UTC on 8 February. This snow fell on the southeastern side of the Wind River region. By 12 UTC on 8 February, most of the snowfall had ceased due to the onset of northerly winds behind the cold front.

The synoptic features simulated by WRF appear to be well placed when compared with both the surface and upper air charts provided by NCEP. Model output shows snow developing in the Wind River area on the extreme northwestern slope and the higher peaks of the central section by 15 UTC. By 18 UTC, there was ice and cloud water prevalent along the entire western slope.

Figure 2 shows the cloud ice and cloud liquid water at 3 km MSL at 21 UTC on 7 February 2004. Temperatures at this level range from -2 to –10 °C. The northern source of tracer appears to be providing ample quantities of tracer, and hence potentially seeding material, at 21 UTC downstream from the Wind River range, while the southern sources appear to be missing the small regions apparent in the simulation.

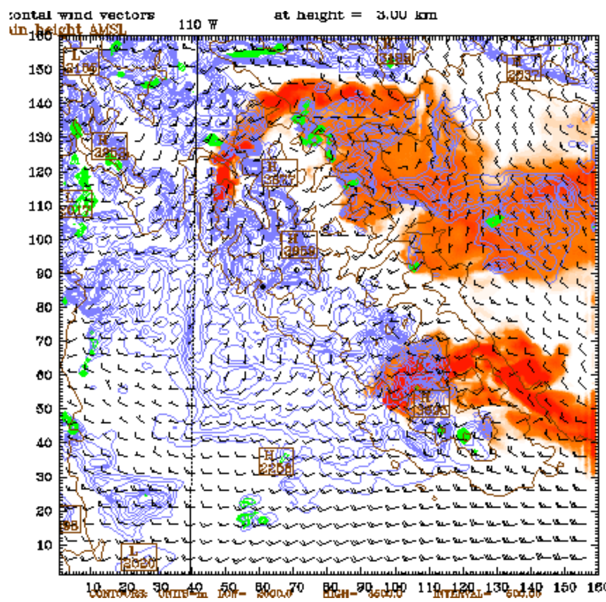

Figure 2. Tracer concentration (orange), cloud water (green contours), and ice (blue contours) at 21 UTC on 7 February 2004. Dark orange greater than 10^ kg^{-1}. Contour intervals for both cloud water and ice are 0.005 g kg^{-1}. Maximum contour is 0.2 g kg^{-1}

By 00 UTC on the 8th, the ice cloud had moved to the eastern slope and at 06 UTC northeasterly flow and strengthening upslope forced ample SLW present at low levels in the east central sections of the range. The SLW then progressed to the southern tip of the range by 09 UTC. In the simulation, the cloud water and ice started tapering off until around 15 UTC (not shown here). Qualitatively these results follow the observed trend of more precipitation falling in the southern portions of the region.

Plots (not shown here) at 5 km MSL, or -16 to 18 °C, show bands of ice and cloud water perpendicular to the synoptic flow, indicating the presence of gravity waves at this level. These waves are induced by flow over a mountain barrier in a stably stratified atmosphere and have been reported in similar simulations by Bruintjes et al. (1994).

Clouds, and especially SLW, are found in the rising portions of the gravity wave. Cloud water, due to upslope, reaches a maximum mixing ratio of 0.12 g kg^{-1} at 06 UTC on the 8th. Cloud water in the gravity waves reaches a maximum of 0.51 g kg^{-1} at 06 UTC on the 8^{th}. This suggests that, if gravity waves are present, they are likely to produce 4 to 5 time more (SLW) content then that produced by upslope conditions and provide an excellent opportunity for precipitation enhancement.

6. SUMMARY

A model-based study was performed to assess the feasibility of using glaciogenic seeding operations for snowpack augmentation in the Wind River and Medicine Bow mountain ranges in Wyoming. The modeling results can be summarized as follows:

- As expected during the passage of a winter storm, the wind flow patterns and associated liquid water content regions show rapid temporal and spatial changes depending on the evolution of the system.
- The Tracer/Seeding material released on the upwind side of the mountain barriers from a single generator initially spreads to a plume of approximately 10 km wide for a distance of approximately 10 km away from the generator with a rate of 1 km horizontal spread for every 1 km distance away from the generator. After 10 km the rate of spread decreased somewhat.
- The vertical extent of the plume remained less than approximately 500 m AGL and follows the slope of the mountain and sinks again the lee of the mountain. However, once in the lee of the mountain the material is lifted into some of the gravity waves that are excited by the topography.
- Gravity waves and associated liquid water content regions were evident in all the simulations and were forming in lines in the lee of the mountain peaks orthogonal to the wind direction. These gravity waves contained substantially larger amounts (5 to 10 times) of SLW than the upslope SLW regions. This is very similar to the results found in observational and modeling studies in northern Arizona (Bruintjes et al.,. 1994).

The implications for the design of cloud seeding experiments are as follows:

- Real-time numerical model simulations are essential for determining wind-flow and SLW regions and should be used for both temporal and spatial guidance in operating seeding generators.
- Ground-based generators could be used to target the SLW regions in the lowest 500m associated with forced lifting over the mountains.
- Seeding with aircraft appears to be the a good to target the SLW above 500 m AGL and in the gravity waves.
- Indiscriminate seeding with generators by leaving them on during the entire storm period results in a large amount of seeding material being wasted.

Further work is needed to understand the potential impacts of glaciogenic seeding in the mountains of Wyoming. Comparison of model results with SNOTEL sites will give an indication of how well the model microphysics are representing the natural snowfall. The code can also be extended to include activation of the glaciogenic seeding material and evaluate the potential increases in snowpack.

7. ACKNOWLEDGEMENTS

This research was supported through a sub-contract from Weather Modification Incorporated, which was under contract to the State of Wyoming Water Development Commission.

8. REFERENCES

Bureau of Reclamation, Denver Office, 1989: Winter seeding potential on the Mogollan rim. Report prepared for Arizona Department of Water Resources. R-89-02.

Bruintjes, R.T., T.L. Clark, W.D. Hall, 1994: Interactions between topographic airflow and cloud/precipitation development during the passage of a winter storm in Arizona. *J. Atmos. Sci:* **51**, 4867.

Hall, W.D., 2004: *personal communication*

Hong, S.-Y., J. Dudhia, and S.-H. Chen, 2004: A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation. *Mon. Wea. Rev*., **132**, 103-120.

Lin, Y.-L., R.D. Farley and H.D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. *J. Appl. Meteor*. **22**, 1065-1092.

Thompson, G., R.M. Rasmussen, and K. Manning, 2004: Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part I: Description and sensitivity analysis. *Mon. Wea. Rev*., **132**, 519-541.