Numerical Simulation of Cloud Seeding Effects During a Four-Day Storm Period

by

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ABSTRACT

This paper is a summary of portions of a thesis by Hjermstad (1996) and is done to illustrate the potential for mesoscale models to depict the distribution and changes in precipitation caused by cloud seeding in orographic situations. The thesis covers a four day time period in April 1995. The domain of the numerical model, 320 km by 320 km in the horizontal, covers much of Western South Dakota and some of Eastern Wyoming and is centered on the Black Hills of South Dakota. The four-day storm period illustrates changing atmospheric conditions, from primarily rain generation to snowfall production. The cloud seeding is only effective on the third day of the storm period, which is reported on here.

1. Introduction

We have been simulating the effects of cloud seeding for a number of years, concentrating primarily on cloud scale models. In the past few years we have been applying the Clark three-dimensional, time-dependent mesoscale model to conditions in the Black Hills of South Dakota and Wyoming. A recent numerical simulation involved a four-day storm period in April of 1995. The results indicated that the seeding worked on only one of the four days and produced a redistribution of, as well as changes in, precipitation over the area. Other work in the topic of orographic cloud seeding is given in Heimbach and Hall (1994), Holroyd et al. (1995), Meyers *et al.* (1995) and Bruintjes *et al.* (1995). Earlier work is illustrated in Fritsch and Chappell (1981).

2. Brief Model Description

The dynamic framework is that of the three-dimensional, time-dependent nested grid model of Clark and associates (Clark, 1977; Clark and Farley, 1984; and Clark and Hall, 1991). The microphysical framework is that of Lin *et al.* (1983) and uses bulk water equations for cloud water, cloud ice, snow, rain, and graupel/hail. The cloud seeding physics follow the treatment of Hsie *et al.* (1980), which allows for a cloud seeding agent and the physical effects it induces to be simulated. Farley et al. (1994) discusses our initial implementation of this cloud seeding treatment in the Clark model, in that case being applied to a convective cell. The seeding agent can be simulated as being released by ground generators or aircraft and traced throughout the atmosphere. The material only becomes activated if it is in supercooled cloud. Simulated seeding began 10 m after model start-up.

Normally, an inert gas such as sulfur hexafluoride (SF_6) is traced in the model to determine the best placement of silver iodide (AgI) ground generators, and then the release of AgI is simulated. The seeding rate is 20 g h^{-1}. Natural cloud ice forms at -15°C on this day and AgI first activates cloud ice at -5°C.

The model uses two domains in this simulation. The outer domain has horizontal grid intervals of 8 km and a vertical resolution on 500 m. The inner domain uses 4 km horizontal and 250 m vertical resolution. A smoothed topography and 3D depiction of the Black Hills is shown in Fig. 1. Model simulations were carried out to 360 min of simulated real time.

3. Synoptic Situation

The four-day storm period is characterized by the approach from the northwest, and passage to the south, of an upper level cold trough. At the surface the Black Hills are under the influence of a stationary front to the west and a surface high pressure system to the north for the first two days, leading to easterly winds at the surface in Rapid City on the eastern slope of the Hills. As the upper trough moves through the area a surface low organizes and moves south and east of the Black Hills, leading to northerly winds at the surface for the last two days of the storm period.

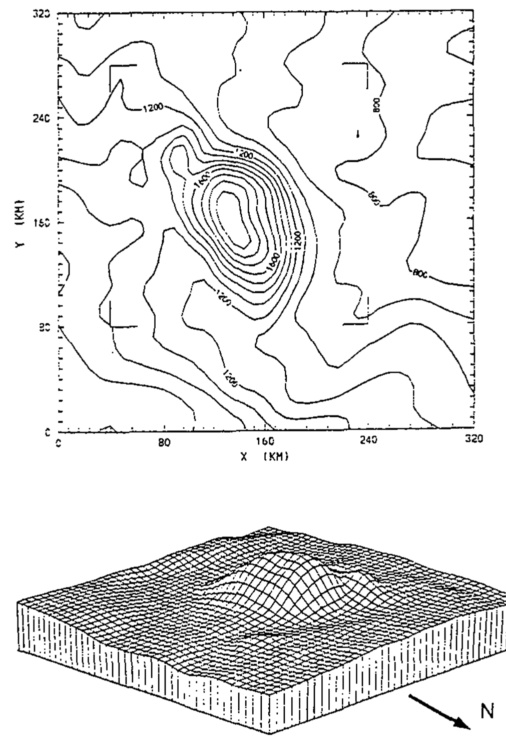

Fig. 1: a) X-Y plot of the model domain used in the study. Inner model domain is indicated by right angle markers. Topography is contoured at an interval of 100 m. b) Three-dimensional depiction of the model topography viewed from the northeast (upper right-hand corner of a).

The first two days are too warm for ice phase (glaciogenic) cloud seeding to be effective. Also, the vertical wind shear makes it difficult to target the seeding material. The third day gives colder conditions and very little directional wind shear in the lower atmosphere so that simulated seeding in the model is very effective. The fourth day the atmosphere cools and has ample clouds at colder temperatures to supply sufficient cloud ice to initiate precipitation naturally in the model.

4. Results

Day 3 results of the four-day storm period are described next. Figure 2 shows the dispersal of AgI from the five ground generators and a vertical cross section of the AgI after three hours of real time simulation. The material from the eastern most generator slips around the eastern slope of the Hills and is not captured by the supercooled cloud. The other four generators provide ice nuclei to the supercooled cloud water forming in the orographic uplift. The vertical cross section shows how rapidly the silver iodide is used up in the airflow over the mountains. The mixing ratio units of the seeding agent in Fig. 2 are convenient from a modeling standpoint, but are not very meaningful to the average reader. By way of example, the 0.1 ng kg^{-1} contour at the crest of the Black Hills in Fig. 2, at a temperature of -10°C (see Fig. 4), converts to 2 to 3 active nuclei per liter, based on the activity curves given in Blair et al. (1973).

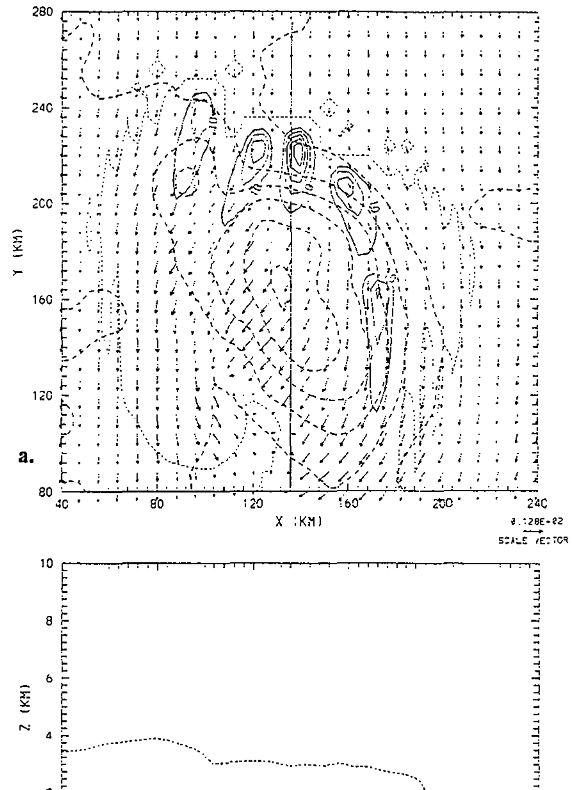

Fig. 2: SEED CASE. a) Surface locations where the inert tracer and AgI were released for DAY 3, but these contours are for the AgI field. The short dashed contour is for 1.E-6 nanog kg^{-1}. b) Y-Z cross-section of the AgI-field at X = 136 km. The contour interval is 0.1 nano g kg^{-1} for a and b. The topography is indicated by thick dashed contours in a at intervals of 200 m, the center contour is 2000 m.

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Figure 3 shows how much and how extensive the cloud water field is at the surface for the no-seed case. More than 0.24 g kg^{-1} exist over the northern Hills. The two vertical cross sections show the vertical extent of the supercooled cloud water. Of note is the region of cloud water above the surface in the southern Hills, shown in Panel b. This secondary maximum leads to natural precipitation in that region, because it occurs at colder temperatures than does the cloud water in the north (see Fig. 4 for a cross section of temperature in the north-south plane).

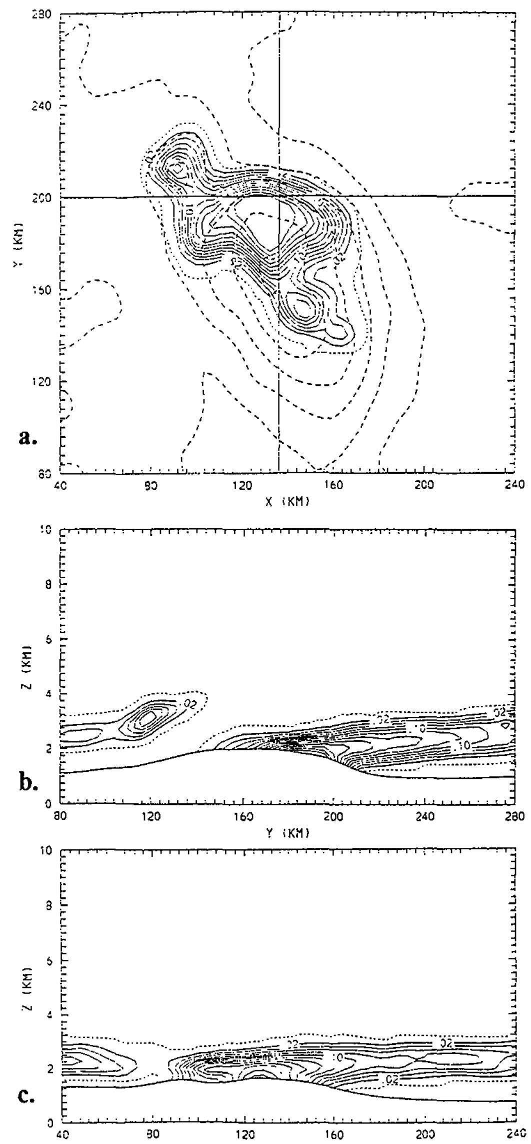

Fig. 3: NO SEED CASE. a) Inner model cloud water field at the surface at 180 min for DAY 3. Thick dashed lines are the topography with a 200 m contour interval. Thin solid lines are cloud water contours in g kg^{-1}. b) Inner model Y-Z cloud water cross-section at X = 136 km. c) Inner model X-Z cloud water cross-section at Y = 200 km. The contour interval is 0.02 g kg^{-1} for all panels. The short dashed lines indicate the 0.001 g kg^{-1} contour.

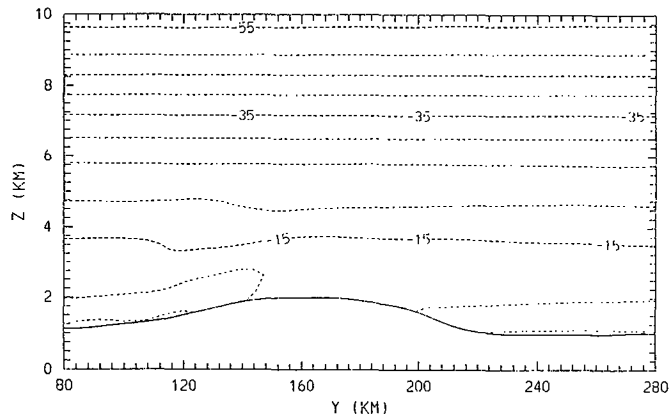

Fig. 4: SEED CASE Y-Z cross-section of the temperature profile at X = 136 km for DAY 3 at 180 min. Contour interval is 5°C.

Figure 5 shows the cloud water at the surface in the seeded case and a vertical cross section of the cloud water after three hours of simulated real time. The area and amount of supercooled cloud water have shrunk considerably in the north. The cross section shows little change above the surface in the south. The depletion is caused by the cloud seeding which has formed cloud ice that transforms to snow. The simulated cloud seeding began after only 10 minutes of simulated real time.

This figure (Fig. 5) shows that cloud water is also depleted north of the seeding generators. This happens because of a reversal of wind direction aloft (above 3 km) that carries the seeded cloud ice and snow to the northern region of the model domain.

Figure 6 compares the snowfall in liquid equivalents in the no-seed and seed cases after 180 minutes of simulated real time. There has been some snow in the southern Black Hills in the no-seed case. In the seed case, snow has occurred in both the northern and southern Hills. A similar snow pattern appears in the no-seed case at 360 minutes, but is less in quantity than in the seed case. Figure 7 shows those results. Snow in the northern portions of the domain is caused by the wind reversal aloft. At 360 minutes the total snowfall in the no-seed case is about 9,500 kilotons versus 12,200 kilotons in the seeded case, a 28% increase in precipitation. This net increase results from a 100% increase in the north and a 50% decrease in the south. The distance between the two maxima is about 100 km.

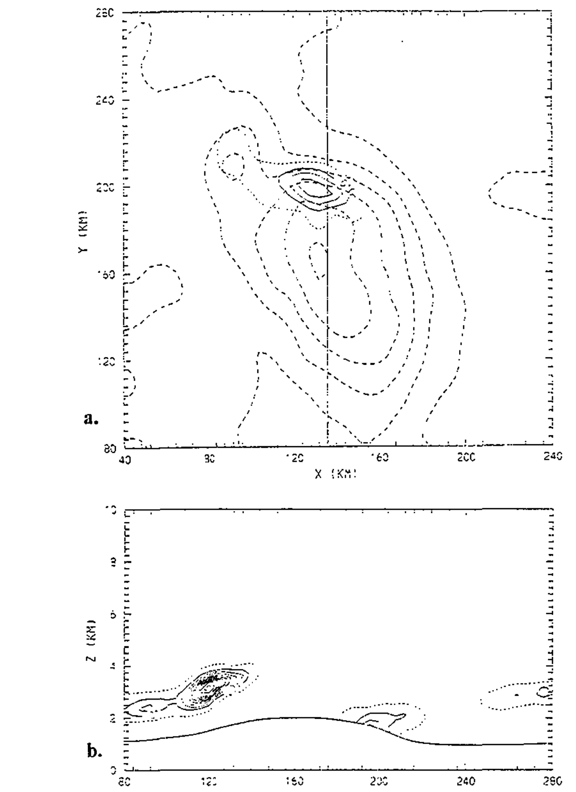

Fig. 5): SEED CASE. a) Inner model cloud water field at the surface at 180 min for DAY 3. b) Inner model Y-Z cloud water cross-section at X = 136 km. Thin solid lines are cloud water mixing ratio (0.01 g kg^{-1}). Other aspects of the presentation are as described in Fig. 3.

Which simulated real time is closer to reality? Probably the later time is closer to reality, although we do not konw how long suitable cloud conditions existed. This was an extensive storm system that produced precipitation over a four-day period. More than three feet of snow fell in Deadwood in the northern Hills and extensive areas of one to two feet of snow fell in the northern Hills, mostly on the last two days of the storm period. We do not claim complete, faithful simulation of the precipitation in this case, but present the results as preliminary and intriguing.

Only one radiosonde was used as input to the model for each of the four days (hence, four different radiosonde runs). We did not continue the model runs from one day to the next, varying smoothly the input data. Each day was initialized with the appropriate radiosonde data and run for six hours of simulated real time. The model was not "tweaked" to provide a wide range of results.

5. Discussion

These results apply through a six hour simulation starting from a morning sounding for the day. The actual winds switched more to the northwest as the day progressed, but the model was not updated. The actual precipitation for the day is given in Figure 8. The northern maximum is picked up by the model, but

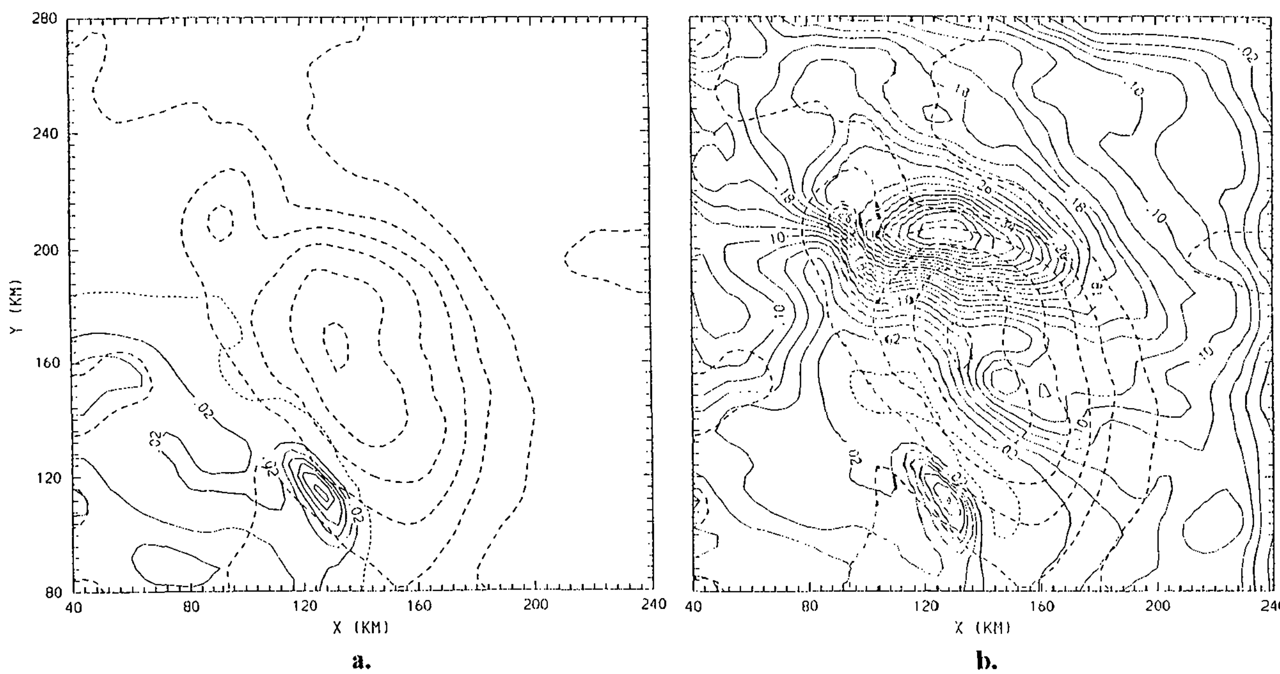

Fig. 6: a) No seed case, b) seed case for surface snow accumulation (0.02 mm intervals, thin solid lines) at 180 min for DAY 3. Thick dashed lines are the topography with a 200 m contour interval. The thin dashed line is the 0.01 mm contour.

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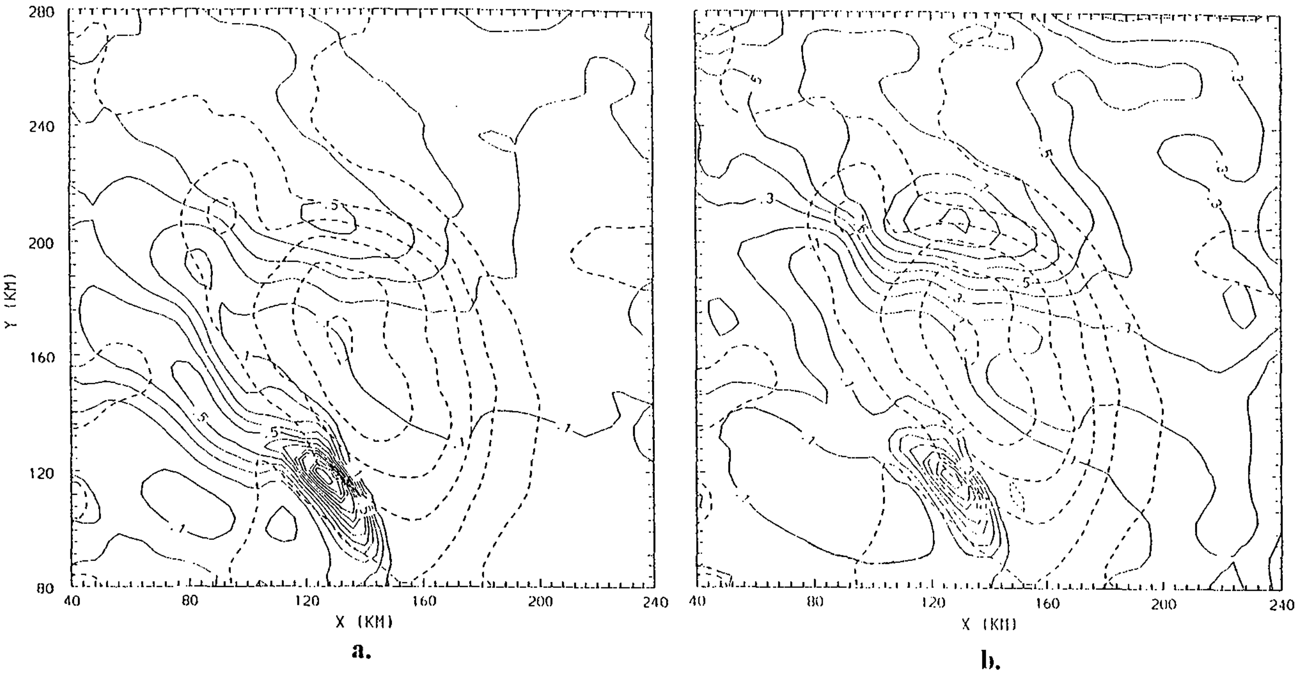

Fig. 7: a) No seed case, b) seed case for surface snow accumulation (0.1 mm interval, thin solid lines) at 360 min for DAY 3. Other aspects as in Fig. 7.

the maximum is misplaced in the south. Other studies with the model (Hjelmfelt and Farley, 1992) show that the winds at Rapid City change little as the winds in the northern Black Hills shift from NE to NW. The NW winds would tend to move the southern convergence zone more to the southeast. Later versions of the Clark model have the capability to assimilate changing conditions during the integrations. A longer time integration would probably have resulted in different percentage changes in precipitation.

The predicted amounts of precipitation are in liquid equivalents, but are still far short of those observed with no actual cloud seeding having been done (Fig. 8). If these results were in steady state, the amounts and rates of precipitation could be extrapolated to a 24-hour time period. That would bring the amount of snow predicted within a factor of two. In another study of snowfall in the Hills the model is within 20% of the actual snowfall. Grid resolution has something to do with the underprediction and a finer resolution would improve the situation.

A reviewer of this paper stated that because the seeding was active from 10 min after the start of simulation until 360 min, one could speculate that seeding was very effective in the first 180 min in the northern region of the domain without reducing the precipitation in the southern region. However, after 180 min seeding did not make much difference in the

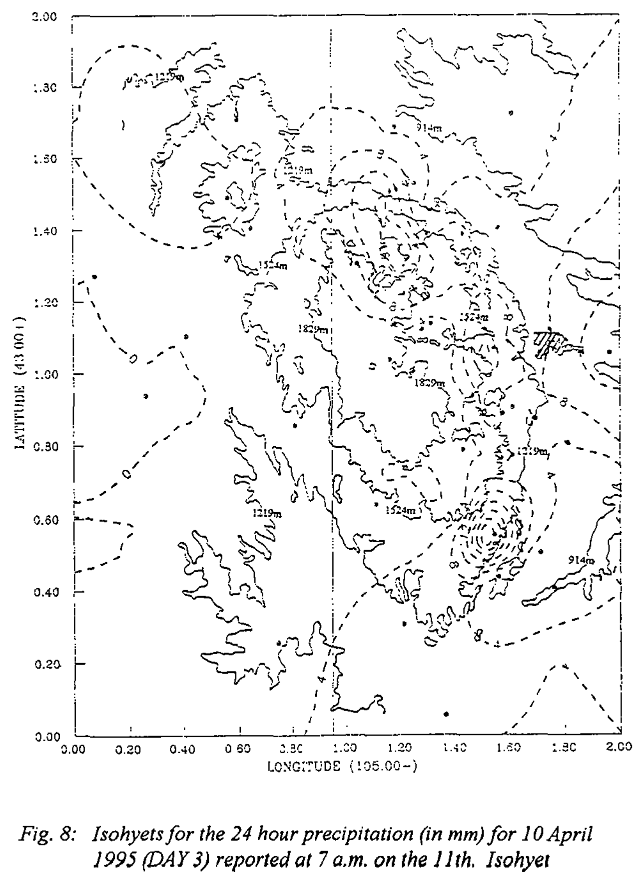

Fig. 8: Isohyets for the 24 hour precipitation (in mm) for 10 April 1995 (DAY 3) reported at 7 a.m. on the 11th. Isohyet contours are heavy dashed lines with an interval of 4 mm. The line down the center is the Wyoming/South Dakota border. The 1219 m topographical contour can be compared with the 1200 m contour in the numerical model results.

northern region but decreased the precipitation in the southern region. Could this be a case of overseeding after 180 min? Although it seemed that seeding redistributed the precipitation, it may be more a timing effect that seeding is effective up to a certain limit and that instead of continuous seeding other strategies of seeding are needed. We thank the reviwer for these insightful comments.

The bulk water microphysics were designed for convective clouds in the northern plains. The initiating temperature of natural ice is a critical parameter. It had observational support for our work with convective clouds but lacks that observational basis for these orographic, stratiform clouds. Rasmussen's work in the WISP experiment may provide useful data regarding coalescence thresholds and ice initiation.

The first two days of the storm period produced precipitation, perhaps through a drizzle process. The model has no such process at this time. Normally, in convective clouds the coalescence process is not activated until water contents of at least 2 g kg^{-1} are achieved. The stratiform clouds in this case rarely exceeded values of 0.2 g kg^{-1}. The amount of time available for the various processes to work may aid in these stratiform clouds.

Surface friction was not activated in the model for these simulations because of its incorrect influence on precipitation near the model boundaries. This has been corrected in later versions of the model. The friction is important for producing the convergence region in the southern Hills under northerly flow.

6. Conclusions and Final Remarks

- Cloud seeding in this four-day storm period in an orographic situation works selectively.

  On Day 1 the atmosphere was too warm;
  On Day 2 the atmosphere produced clouds that were still too shallow and too much vertical wind shear prohibited the seeding material from reaching the clouds;
  Day 3 conditions appeared to be suitable for cloud seeding to be effective;
  Day 4 atmospheric conditions had become colder so that natural precipitation processes worked effectively.

- The seeding results on DAY 3 indicated a near 100% increase in snowfall in the northern Black Hills and almost 50% decrease in the southern Hills. The total change was from 9,500 kilotons in the unseeded case to 12,200 kilotons in the seeded case, a 28% increase in precipitation. However, this result depends on the time of analysis and further model runs and analyses are needed.

- For the unseeded cases, the general cloud and precipitation patterns and the dynamics of the airflow were simulated reasonably well by the Clark model. In general, the precipitation amounts were underestimated.

- The model is useful for determining the proper placement of ground generators.

- The ice microphysics processes, developed for convective storms, need some improvements to properly simulate the cold season stratiform precipitation. A drizzle process parameterization would also help.

- Winds near the surface at Rapid City may not be representative of the winds in the northern Black Hills.

- The activation of surface friction in the numerical model may improve the simulation and is needed.

These results are illustrative of what can be done with mesoscale models that include cloud seeding effects. As noted above several improvements need to be made in the model, some microphysical and some dynamical. However, the results show very plausible scenarios for cloud seeding effects in different atmospheric conditions. The effects of the seeding can be a redistribution, as well as a change in the precipitation. And nothing may happen at times.

For water resources it is important to store the water in reservoirs. The actual Pactola reservoir in the northern Black Hills would have received additional water from the cloud seeding in this type of atmospheric condition.

The influence of the seeding on the snowfall in the southern Hills was unexpected by us. The depletion of the water substance in the north, or a change in the airflow dynamics, may have caused the changes. Additional analysis is needed. However, this illustrates the sensitivity of the results to the cloud seeding, given the configuration of the model. A concentrated effort is needed to develop various mesoscale numerical models, and possibly even weather service regional models with appropriate cloud seeding routines, to provide guidance to cloud seeding efforts.

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