Use of WRF for Winter Precipitation Enhancement Studies

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1. INTRODUCTION

Precipitation enhancement has been a focus of study within the NCAR Research Applications Laboratory (RAL) for over a decade. One of the primary objectives of research in this area is to understand precipitation processes and how advertent modification of a cloud may augment precipitation. While aircraft-based studies are very useful in documenting precipitation processes of the natural clouds, a more spatial and temporal assessment of precipitation development is required. The WRF-ARW modeling system has been selected to perform numerical modeling studies addressing this problem.

WRF has been applied to study precipitation enhancement activities in two different regions, Puglia, Italy and Wyoming. This presentation will discuss winter precipitation enhancement strategies for these areas, a seeding module developed to facilitate studies, and some preliminary results.

2. WINTER PRECIPITATION ENHANCEMENT

When clouds are slow to produce ice naturally, treatment with glaciogenic (ice forming) agents may increase precipitation efficiency. Typically silver iodide (AgI) is used as the seeding agent for winter precipitation enhancement programs. The process begins with the release of seeding agent from the ground or from aircraft. The seeding agent is then transported and dispersed by the winds into the target cloud over the mountain. When the seeding agent encounters super-cooled liquid water (SLW), ice nucleates rather quickly producing large numbers of ice particles. Within several minutes these ice particles grow sufficiently large through diffusion, riming (collecting cloud droplets), and/or aggregation to begin to fall. The cloud thus has a net increase in precipitation mass, which leads to increased precipitation at the surface.

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Many of the cloud seeding studies conducted in the past have looked for increased precipitation at the ground without fully understanding each link in the glaciogenic seeding chain of events leading to precipitation enhancement. Recently, fine scale numerical models, such as WRF (Jensen et al., 2005) and the Regional Atmospheric Modeling System (RAMS) (Cotton et al., 2006) have been used to look more closely at transport and dispersion of seeding material as well as microphysical and possibly dynamical responses to the seeding. The remainder of this paper discusses the results of two such studies performed for Italy and Wyoming using the WRF-ARW core.

Italy

Winter systems that produce precipitation over the Puglia province of Italy have a variety of origins, ranging from northern Europe to the Mediterranean. Upper air wind patterns between 700-500 hPa are generally from a westerly direction. The orography to the west and the land-sea interface to the east of the region determines the mesoscale characteristics of the wind flow patterns, cloud structures and precipitation patterns. Radar-derived precipitation patterns during 2004-2005 winter suggest that widespread precipitation occurs throughout the region during December and January with more banded precipitation occurring in November, February, and March. Maximum precipitation appears to occur over land during the month of June. The goal of our Italian study was to assess the feasibility of using glaciogenic seeding techniques during the winter months to increase precipitation over land to help this agricultural area.

Although the intent of the project was to conduct microphysical studies as well as modeling studies of the region, equipment limitations impeded cloud microphysical measurements and seeding trials. Thus, modeling case studies were performed to study the potential for precipitation enhancement throughout the region. A seeding module, described in Section 3, was developed to simulate the release of a seeding agent from an aircraft. The seeding material was then activated as ice nuclei within the Thompson cloud microphysics scheme. Results from this study are presented in Section 4 and summarized in Section 5.

Wyoming

Long-term (30-year) seasonal snowfall averages indicate that between 200 and 250 inches of snow typically falls each winter in the mountain regions of Wyoming. Most of the precipitation and snow during the winter months are associated with orographically enhanced frontal systems, which bring westerlies at mid-levels but complex orographic flow near the surface.

In 2004, the State of Wyoming Water Development Commission conducted a feasibility study for winter precipitation enhancement over three ranges: Wind River, Sierra Madre, and Medicine Bow. The findings of the study led the State of Wyoming to fund a 5-year Pilot Program for cloud seeding over these three ranges. NCAR/RAL is tasked with conducting the independent evaluation of this program, including developing the experimental design and performing post-season analyses.

One tool being used to complete these tasks is the WRF-ARW modeling system coupled with both the newly developed seeding module and the Second Order Closure Integrated Puff dispersion model (SCIPUFF). Results of a preliminary investigation are presented in Section 4 and summarized in Section 5.

3. SEEDING MODULE

This module was developed from the observation nudging code implemented in the Real-Time Four Dimensional Data Assimilation (RT-FDDA) system developed at RAL (Liu et al., 2006). The module is contained in a separate directory and required modification to the Registry and minor modification to other standard WRF code. The seeding module allows for a fair amount of user flexibility, including three types of seeding material categories and two types of dispersal. There are categories for two glaciogenic (ice forming) species commonly used in precipitation enhancement, silver iodide and propane, as well as one hygroscopic (droplet forming) species. Release may be simulated from either a ground based generator or an airborne release strategy.

A separate section was added to the WRF namelist to allow the user to specify the domain the seeding material should be released on, maximum number of release times, and the release rate. The code then uses a separate input file in which the user defines the latitude, longitude, pressure, seeding material type, and dispersal method.

Preliminary results of seeding material transport on a 1 km grid were compared with tracer dispersion in SCIPUFF driven by the same 1 km meteorological data. While the initial plume starts off more disperse then in SCIPUFF, the general path of material transport appears to be similar.

The seeding material object is also passed into the Thompson cloud microphysical scheme to simulate activation of ice due to seeding. This activation assumes the Cooper form of ice nucleation, which follows the formula:

$$N = 0.005 \exp[0.304(T_0 - T)]$$

where N is the number of ice crystals initiated (L^{-1}), T_o = 273.15 K, and T is the ambient temperature (K) (Thompson et al, 2004). A simple algorithm was added to activate a maximum of 1000 L^{-1} ice particles in the core of the plume when it reaches an area of water saturation and temperatures ranging between -5° and -15° C. A simple sink term was added to reduce the seeding material by 50% as activation occurs. The preliminary results suggest this seeding module should be very useful for future precipitation enhancement studies. A more sophisticated source and sink algorithm is planned for future research.

4. CASE STUDY RESULTS

All case studies were performed using a four domain set up with grid spacings of 27, 9, 3, and 1 km. The domains were configured to best capture the mesoscale flow while fitting into the memory of the linux-pc cluster available for computation. A control run and multiple seeded runs were completed for these case studies.

Italy

A case study of an idealized seeding mission to increase precipitation was performed for 9-10 December 2004. This day was characterized by a mass of clouds in a moist unstable atmosphere associated with a weakening low pressure system over Sicily. The model-predicted locations and characteristics of the synoptic conditions agreed well with observations. The period of most precipitation occurred between 18:00 and 23:00 UTC on 9 December 2004. Initial WRF simulations showed a concentrated region of cloud water at 3-5 km MSL (750-550 hPa). Temperatures in this region were between

-3° and -18° C, so most of the liquid water was supercooled. Figure 1 shows a substantial amount of SLW over land during this period.

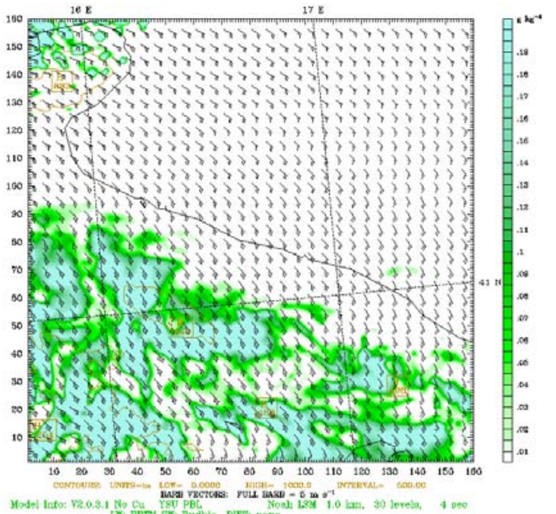

Figure 1. Cloud water field at 20:30 UTC on 9 December 2004 over the Puglia, Italy region. Grid spacing is 1 km. Wind barbs are shown every 5 km.

A flight track was generated to mimic the delivery of seeding agent to the horizontally widest region of SLW. Figure 2 shows the seeding material dispersion at 20:30 UTC, 30 minutes after the initial release occurred at 700 hPa. After transport and diffusion by the model, the location of the maximum in seeding material was at 670 hPa, which corresponds to the -5° C level. There appears to be enough seeding material located in the supercooled region to provide an increase in snow mixing ratio and consequently a slight increase in the simulated radar reflectivity at 1 km.

Figure 3 provides a comparison between radar reflectivity calculated for the control and seeded runs. In some areas, reflectivities increase sharply in response to seeding and in some areas snow developed where previously no snow was observed (not shown). While the differences in snow development and reflectivity between control and seeded simulations are quite clear, the differences in precipitation are less substantial but still on the order of 10-20%.

Wyoming

WRF is being used in several capacities for this study. On primary focus at this time is on using aircraft, surface and radiometer observations taken during January to March 2006 to validate model simulations. These case studies will then be used in determining the most optimal

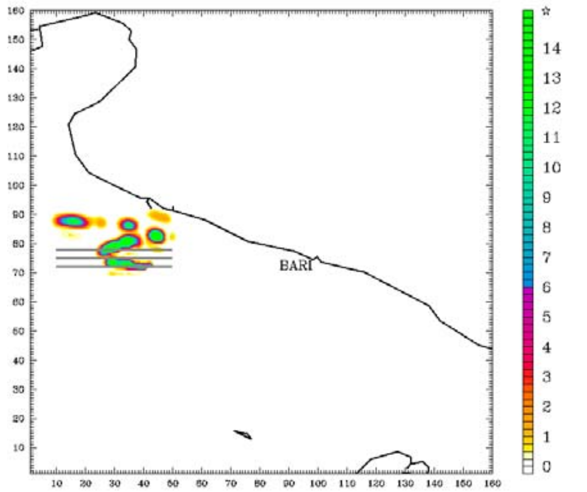

Figure 2. Horizontal cross-section of seeding plume at 20:30 UTC on 9 December 2004 at 700 hPa. Grid spacing is 1 km.

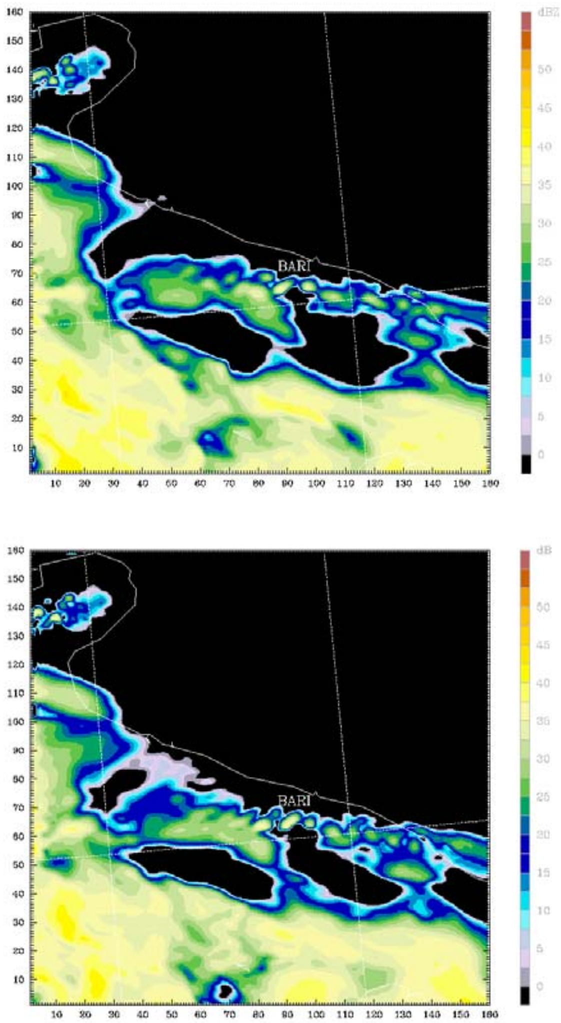

Figure 3. Simulated reflectivity field at 20:30 UTC on 9 December 2004 for control (top) and seeded (bottom) runs. Grid spacing is 1 km.

locations for ground-based seeding generators given environmental constraints.

Simulations of a snow event on 15 March 2006 were conducted and compared with aircraft observations. Figure 4 shows a plot of the simulated cloud water field at the flight altitude of 4.2 km with the aircraft measured liquid water content (LWC) superimposed. LWC values greater than 0.1 g m^{-3} are indicated by blue dots. Temperatures at this altitude were between -17° and -20° C, indicating that all liquid at this level was supercooled and amenable to seeding.

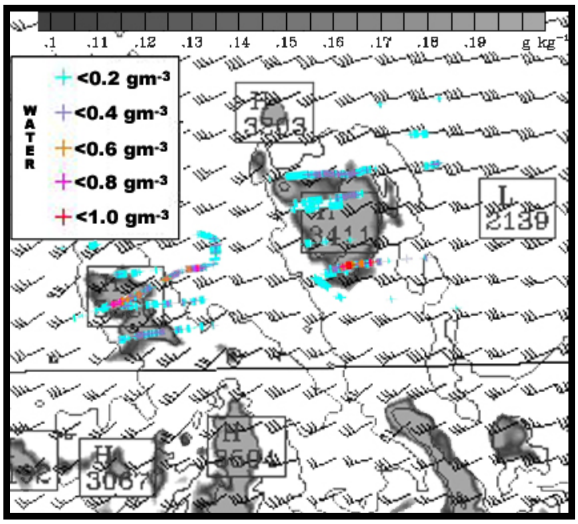

Figure 4. Simulated cloud water at 1700 UTC on 15 March 2006 overlaid with aircraft observations of liquid water content at same time. Grid spacing is 1km. Wind barbs are shown every 10 km. Simulated field and measurements were taken at 4.2 km.

The model appears to correctly capture the location of SLW over the mountains but appears to miss an area of enhanced SLW between the two ridges. Quantitatively, the model predicted the maximum SLW fairly well. Similarly, the model appears to capture the main features of the snow field. Special observations by two radiometers and surface stations still need to be incorporated into the validation. SCIPUFF simulations as well as ground-based generator simulations have not been analyzed at this time. Based on previous studies, it is expected that the seeding transport signature in the WRF simulation will be similar in direction but much more diffuse than that in SCIPUFF.

5. SUMMARY

WRF-ARW has been adapted for use in studies of winter precipitation enhancement. The seeding module was patterned after the observation nudging code developed for RT-FDDA for determining the location and time in the simulation of each release point. It then releases a passive tracer at a specified rate from each point. 34This module allows for three types of seeding material categories and two types of dispersal. There are categories for two glaciogenic (ice forming) species commonly used in precipitation enhancement, silver iodide and propane, as well as one hygroscopic (droplet forming) species. Release may be simulated from either a ground-based generator or an airborne release strategy. The seeding module was then coupled to the Thompson cloud microphysics scheme for ice activation and seeding material removal.

Preliminary results from Wyoming indicate that the Thompson scheme implemented in WRF simulates cloud microphysical properties well enough to continue using it for precipitation enhancement research. The results of airborne seeding simulations for Italy indicate that unless seeding material is directly injected into regions of substantial amounts of cloud liquid water at temperatures between -5° and -15° C, seeding will not have a significant effect on precipitation. Results not shown here also indicated that mixing of seeding material in these cloud systems is very limited, and thus neither cloud-base or cloud-top seeding will be effective. Simulations of ground-based seeding is currently being tested. Preliminary generator location and plume dispersal tests suggest that plume transport is handled reasonably well using 1 km grid spacing, however a sub-grid scale algorithm should be developed to better handle the quantitative characteristics of the plume dispersion.

Acknowledgements

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