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Modeling of the 13-14 December 2001 IMPROVE 2 Case

Matt Garvert*, Cliff Mass, Brian Colle
University of Washington, Seattle, Washington

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1 Introduction

Despite recent advances in the ability of mesoscale models to accurately simulate synoptic and mesoscale features associated with storm systems, quantitative precipitation forecasting (QPF) remains a problem. Previous studies have indicated that some QPF errors can be traced to mesoscale models' bulk microphysical parameterizations (BMPs), which are used to simulate cloud and precipitation processes (Colle and Mass, 1999; Colle et al., 1999, 2000). In order to isolate errors in BMPs, it is important to confirm that the model is accurately depicting the dynamics and mesoscale features associated with storm systems. Only after ensuring the mesoscale models' thermal structure, kinematics, and mesoscale features are correctly depicted, can the microphysical aspects of the simulations be evaluated. In order to compile a comprehensive data set needed to isolate errors in BMP schemes from kinematic or dynamic errors in the model, the IMPROVE II field experiment was undertaken in November and December 2001 (Stoelinga et al., 2003). This paper will focus on modeling of the 13-14 December 2001 storm system which occurred during the IMPROVE II field campaign.

2 Synoptic Situation

2.1 Overview

During 13-14 December 2001 an intense baroclinic zone traversed the IMPROVE II study area. This baroclinic zone was associated with a strengthening surface low pressure center located to the north (Woods et al., 2003).

The precipitation band associated with the baroclinic zone began to impact the study area at 1800 UTC 13 December 2001. Coinciding with the commencement of precipitation, southwest winds increased and veered with height indicating substantial warm air advection. Four

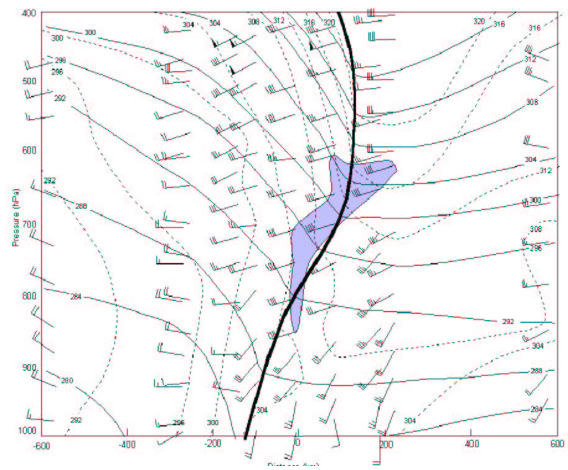

Figure 1: Time height cross section derived from radiosondes at Salem and Creswell, Oregon. Theta ^{0}K in solid lines, theta-e ^{0}K in dashed lines, wind barbs in m s^{-1}. Bold solid line is approximate position of front. Shaded region indicates position of low level jet. For more information see Woods et al. (2003)

hours later at 2200 UTC, the nose of the upper baroclinic band crossed Salem at about 600 mb as depicted in Figure 1.

SPOL data (Medina and Houze, 2003), soundings, and profilers indicated a low-level jet with an enhanced area of strong southwest winds of approximately 40 m s^{-1} at a height of 3-4 km. As time progressed, this area of enhanced winds decreased in height to 2-3 km and then became indistinguishable from the mean flow. The low-level jet position and timing appeared to correspond with the passage of the mid level front as shown in Figure 1. As the low-level jet impinged upon the higher terrain of the Cascades, radial velocity measurements from RHI scans and P3 Doppler winds indicated the jet appeared to rise in height following the terrain. More analyses using the P3 Doppler winds will illuminate the jet's interaction with the terrain and its role in enhancing orographic precipitation.

By 00Z 14 December 2001, the back edge of precipitation associated with first rainband was clearly evident. RHI scans, SPOL radar, SBAND, and surface observa-

*Corresponding author: Matt Garvert, University of Washington, Department of Atmospheric Science. e-mail: *mgarvert@atmos.washington.edu*

tions, indicated a subsequent area of subsidence. Cold air advection was also apparent above 850 mb, while the lower levels still indicated southwesterly winds and warm air advection.

A second precipitation band later crossed the study area and was associated with the passage of the surface front. RHI scans indicated this precipitation feature was more shallow and convective then the previous band. Behind this front, surface wind direction veered to the northwest, surface pressure began to rise, and cold air advection was present at all levels. The precipitation band also coincided with a shallow area of potential instability which may account for its more convective nature.

After the passage of the surface frontal feature, the nature of the precipitation became more cellular and convective. Orographic enhancement of precipitation was obvious in radar and satellite pictures with radar echos concentrated on the windward slopes of the Cascade and coastal mountains. Cold air advection continued at all levels until 12 UTC 14 December 2001.

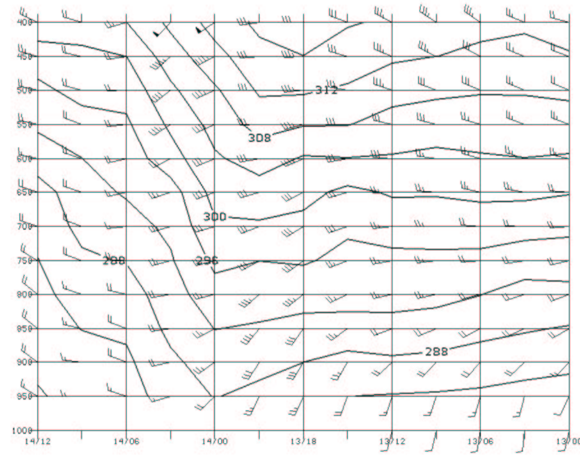

Figure 2: Time height cross section centered at Salem from 0000 UTC 13 December through 1200 UTC 14 December. Model derived winds in m s^{-1} and theta-e in ^{0}Kelvin

3 Model Description

The Penn State-National Center for Atmospheric Research (PSU-NCAR) version 3.5 was employed in nonhydrostatic mode to simulate the 13-14 December 2001 system. A large 36 km domain with a 12 km nest was run for 36 hours to capture the larger scale synoptic features associated with the storm system. The model was initialized on 00 UTC 13 December 2001 by interpolating a modified AVN 0000 UTC 13 December 2001 initialization to the MM5 grids. The 0000 UTC 13 December AVN grid was modified by incorporating surface and upper-air observations using a Cressman-type analyses scheme (Benjamin and Seaman, 1985). Additional analyses were generated using similarly modified gridded AVN forecasts every 6 hours and then linearly interpolating in time to provide lateral boundary conditions for the 36 hour domain.

To ensure the most accurate simulation, analysis nudging using Four Dimension Data Assimilation was employed for the first twelve hours of the forecast. The FDDA scheme applies Newtonian relaxation technique to nudge the models' wind, temperature, and moisture towards a modified AVN surface and upper air initialization of 12 UTC 13 December 2001 (Stauffer and Seaman, 1990; Stauffer et al., 1991).

Thirty-two unevenly spaced full sigma levels were used in the vertical, with maximum resolution in the boundary layer. The simulation used the updated, version 3.6 explicit moisture scheme of Reisner 2 (Thompson et al., 2003), Grell cumulus parameterization (Grell, 1993) and the MRF planetary boundary layer scheme (Hong and Pan, 1996).

In addition to the 36 and 12 km domains, 4 km and 1.33 km nests centered over the study area were run for 30 hours initialized at 06 UTC 13 Dec 2001. The 4 km grids was initialized by lineally interpolating forecast analysis from the 12 km MM5 simulation. No nudging was undertaken in the inner domains. The inner domains also contained thirty-two unevenly spaced full sigma levels and the updated version 3.6 Reisner 2 explicit moisture scheme (Thompson et al., 2003). The MRF planetary boundary layer scheme (Hong and Pan, 1996) was applied, but due to the high resolution of the inner domains, no cumulus parameterization was needed.

4 Model Comparison with Observations

4.1 Synoptic Comparison

The model was able to accurately depict the synoptic evolution of the 13-14 December 2001 storm system. The outer domains captured the intensification of the surface low pressure center between 1200 UTC 13 December 2001 and 0000 UTC December 14, 2001, strengthening the low from an open trough to a 984 mb low pressure center located over southern Vancouver Island. The location of the modeled low pressure center was slightly south of the actual position but the depicted pressure gradient and air flow over the study area matched closely with observations. The upper air evolution of the storm system also compared closely with NCAR reanalysis grids, showing the position of a jetstreak at 300 mb and the rapid amplification of a 500 mb shortwave as it dived southward over the study area. The frontal feature which traversed the study area was also well simulated in the model. Figure 2 indicated the model was able to simulate the forward-tilted baroclinic zone in the lower levels. The structure and onset of the precipitation band was also well depicted by the model. Comparing model reflectivity with RHI scans cutting northeast through the first band showed that the model was able to capture the vertical depth and intensity of precipitation associated with the baroclinic zone (Medina and Houze, 2003).

Subsidence behind the upper level front and the corresponding definitive back edge of the precipitation band were also indicated by the model. The correct timing, intensity, and structure of the rain band indicates the model appeared to accurately depict the main synoptic scale forcing associated with the upper level baroclinic zone.

Although the model was able to accurately depict the structure and timing of the frontal feature, its wind speeds were 5-10 m s^{-1} weaker than the observed low-level jet between 700 and 850 mb for a two hour period during frontal passage. Outside of this time period and height, the winds speed and direction was well depicted by the model. The model also did not develop a well-defined precipitation band associated with the surface frontal passage. Despite the fact the model indicated the presence of a surface feature passing over the study area (surface wind shift from the southeast to westnorthwest and rise in surface pressure), there was no organized area of precipitation. Instead the model depicted multiple bands of convective precipitation. After 0400 UTC 14 December 2001, the model showed cold air advection and orographically enhanced postfrontal precipitation similar to the observed situation.

Despite the relatively accurate modeling of the synoptic features associated with the storm system, the quatitative precipitation forecasts showed large errors. Figure 3 displays the 4 km domain's percentage of predicted precipitation. The best bias scores, within 20 percent of observed, occurred in areas where orographic forcing is less pronounced, such as coastal areas and the Willammete Valley. Meanwhile an overprediction was evident in the windward slopes of the Oregon Cascades and along the lee slopes. The 1.3 km domains which was centered over the study area produced similar results as the 4km.

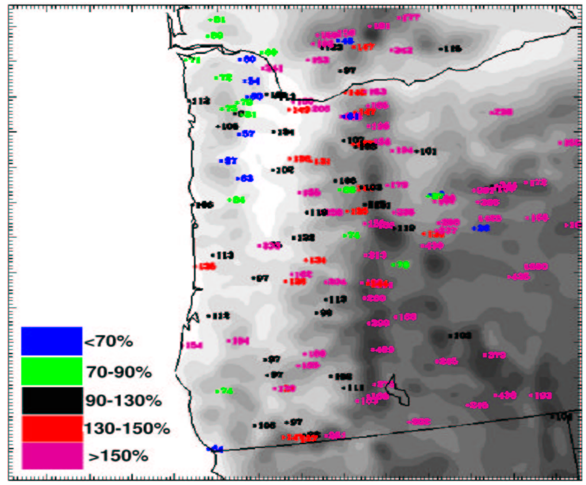

Figure 3: Numbers are percent of observed precipitation for 1400 UTC 13 December through 0800 UTC 14 December for the 4km domain. Terrain features are shaded for reference.

4.2 Terrain-Induced Mesoscale Features

In situ flight measurements of the P3 provided ample observations of mesoscale forcings associated with terrain. Figure 4 shows the vertical velocity as measured from P3 flight level data derived from the accelerometer. Although this vertical velocity should not be taken as absolute values, it can provide a important gauge of the presence of areas of upward or subsiding motions. The image illustrates the effect of the terrain features on the vertical velocities during the passage of the upper level front. During this time period, winds were from the southwest between 30-40 ms^{-1} with the large area of precipitation associated with the first rainband covering the flight track.

The most apparent signature in vertical velocity fields is the large area of subsidence downwind of the higher peaks (over 2 km) of the Cascades as seen in a north-south flight section from point D and I in Figure 4. The areas of subsidence were measured at a height of 4.0 km and were accompanied with a 3 degree Celsius rise in temperature as the air descended off the higher slopes and warmed adiabatically. Figures 5 and 6 show the model vertical velocity fields of the 4 km and 1.3 km domains respectively. The model appears to accurately simulate the amplitude and position of subsidence downwind of the higher crests. However the models also warm the air almost 3 degrees more than observations (not shown). Subsequent flights of the P3 over the area at later periods continue to suggest the position and strength of the mountain waves along the Cascades were well depicted in the model. Additionally, the warm bias of the model was not evident during later periods. Future analysis using P3 Doppler radar should provide more comprehensive information on the depth and amplitude of the mountain waves which then can be compared with model depictions.

The second area of interest is along another north-south section of the flight track between point B and G in Figure 4. In this section the P3 flew at a height of 2.5 km over foothills, which reach upwards to 1 km (Figure 7). It is clear that these foothills have a impact on vertical velocity with small areas of positive vertical velocity collocated with areas where southwesterly winds would impinge upon higher terrain and be forced upward. Addi-

P3 Observed Vertical Velocity cm s^{-1}

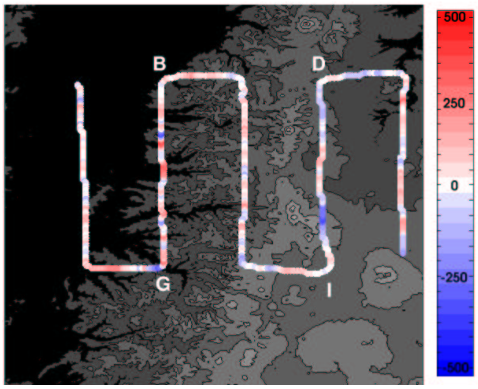

Figure 4: From 2202 UTC 13 December 2001 to 0055 UTC 14 December 2001. Terrain features are shaded for reference

4 km Modeled Vertical Velocity cm s^{-1}

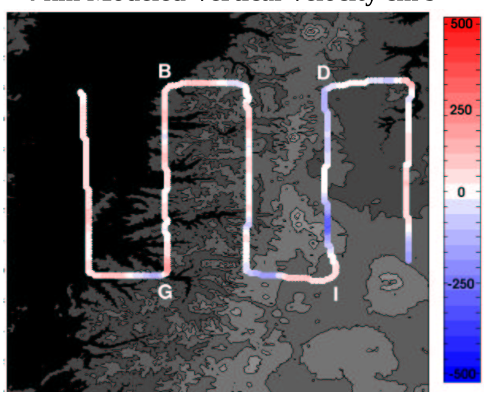

Figure 5: From 2202 UTC 13 December 2001 to 0055 UTC 14 December 2001. Terrain features are shaded for reference

1.3 km Modeled Vertical Velocity cm s^{-1}

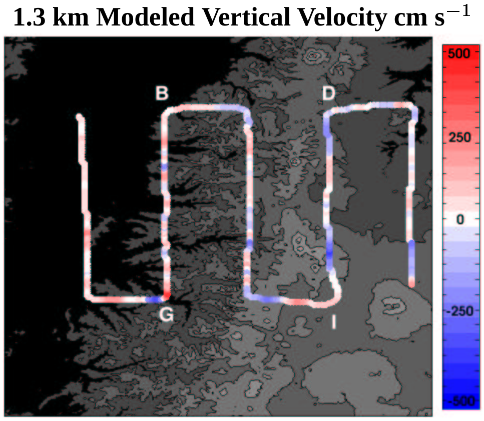

Figure 6: From 2202 UTC 13 December 2001 to 0055 UTC 14 December 2001. Terrain features are shaded for refererece

tionally, small areas of subsidence are located where the air flow descended the higher foothills. Figure 7 also shows the modeled vertical velocity for the 4 and 1.3 km domains. It is clear that the 4km domain appears to have a difficult time resolving these small scale features. The 1.3 km domain better simulates the position and amplitude of undulations in the vertical velocity associated with the underlying terrain. Subsequent flights over this terrain support the conclusion that the higher resolution 1.3 km domain is able to capture the small scale contributions of the foothills to the vertical velocity field, while the 4 km domain had difficulty resolving these features.

Further analysis using in situ microphysical measurements and P3 Doppler information needs to be done to assess the impact that these small scale feature have on the microphysics budget. Preliminary results, using cloud liquid water probes and P3 Doppler radar, indicate the possibly significant introduction of cloud liquid water contributed to the microphysics budget in areas were the smaller-scale terrain induced significant vertical velocities.

5 Conclusion

The Fifth Generation Penn State / NCAR Mesoscale Model was utilized to simulate a storm system which affected the IMPROVE 2 study area during 13-14 December 2001. The storm system was characterized by strong low level cross barrier flow, heavy precipitation, and the passage of an intense baroclinic zone. Extensive verification was performed to compare the model depiction with the large array of observational assets available during the time period, including in situ plane measurements, profilers, upper air radiosonde measurements, radar data, and surface observations.

By applying a four dimensional data assimilation technique (FDDA) on the outer grids of the simulation, the model accurately represented the synoptic and mesoscale features of the storm. The model properly captured the strong cross barrier flow, forward tilting vertical structure of the baroclinic zone, and the major precipitation band associated with the passage of a upper level baroclinic zone. The higher resolution domains appeared to capture the presence of orographically induced mesoscale features including mountain waves. Deficiencies in the model simulations were evident in regards to the strength of the low level jet associated with the upper level front and the presence of an organized precipitation band collocated with the surface frontal feature.

Additional analysis and verification including comparisons with P3 Dual Doppler radar, will be done to ensure that errors in models thermal, kinematic and mesoscale features are isolated and, if possible, corrected. Model comparisons with microphysical data will also be com-

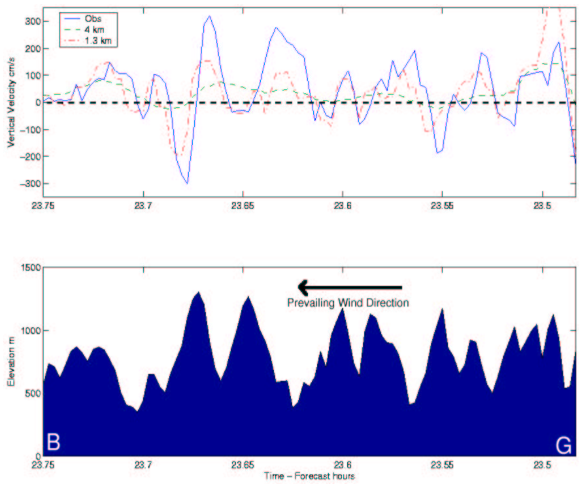

Figure 7: North-south cross section from G to I. Upper panel is P3 observed (blue solid line), 4 km predicted (green dash line), and 1.3 km predicted (red dot-dash line), vertical velocities in cm s^{-1}. Bottom panel is underlying terrain.

pleted to determine the effect small scale mesoscale features have on QPF.

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