Verification of WRF for the 4-5 December 2001 IMPROVE-2 Event over the Central Oregon Cascades

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1. Introduction

Quantitative precipitation forecasts (QPFs) from operational numerical models have been relatively slow to improve during the last two decades. In areas of topography, some of the QPF problem has been attributed to deficiencies in bulk microphysical parameterizations (BMP) (Colle and Mass 2000), as well as difficulty in simulating orographic forcing on 1-10 km scales (Garvert et al 2005a).

In order to verify and improve BMPs, in-situ microphysical measurements as well as thermodynamic and kinematic observations were collected during the IMPROVE project in 2001 (Stoelinga et al. 2003). Previous studies of the 13-14 December 2001 IMPROVE-2 event over central Oregaon Cascades showed snow overprediction aloft in the Penn State-NCAR Mesoscale Model (MM5), which resulted in overprediction in the immediate lee of the Cascades during a period of strong low-level cross barrier flow (Garvert et al. 2005a, 2005b).

This paper investigates the 4-5 December 2001 IMPROVE-2 IOP, which featured cross barrier flow (20-30 m s^{-1}) that was half as strong as the 13-14 December 2001 event. As a result, the orographic upslope forcing was less, thereby providing a useful contrast with the well-documented 13-14 December 2001 event. The goal of this study is to verify the Weather Research and Forecasting (WRF) model precipitation and microphysical forecasts. A companion preprint in this workshop evaluates the low-level kinematic forecasts by WRF for this event (Colle et al. 2006).

2. Data and methods

MM5 version 3.7 and WRF version 2.1.1 were utilized to simulate the 04-05 December 2001 IMPROVE-2 event (IOP6). A 36-km domain and 12-km nest were run for 30 hours to simulate the larger-scale features of the event. This domain covers a large area of the eastern Pacific and Pacific Northwest (not shown). The model initial and time dependent boundary conditions were derived from the NCEP GFS forecast initialized at 1200 UTC 04 December 2001. Thirty-two unevenly spaced half-sigma levels were used in the vertical, with maximum resolution in the boundary layer. Control simulations used updated explicit moisture scheme of Reisner2 (Thompson et al. 2004), updated Kain-Fritsch cumulus parameterization, and ETA PBL. Model domain setup and primary physics were chosen to be as similar as possible between MM5 and WRF. A separate 4-km domain with a 1.33 km nest centered over the study area was run for 24 hours initialized at 1200 UTC 04 December 2001 by linearly interpolating the 12-km forecast for boundary conditions. Cumulus parameterization was turned off for these inner domain simulations. Control simulations of MM5 and WRF used the Thompson scheme (Thompson et al. 2004), while three BMP sensitivity tests were run with WRF using a modified Thompson scheme available as of May 31, 2006 (Greg Thompson, personal communication 2006), Purdue Lin scheme, and WSM-6 BMP (Hong et al. 2004) down to 4 km grid spacing.

The primary observational facilities and locations during IMPROVE-2 are described in Stoelinga et al. 2003. Microphysical measurements from NOAA P3 and Convair aircrafts provide the opportunity for direct microphysical verification of model simulations.

3. Precipitation and microphysical evaluation

IOP6 is characterized by a landfalling baroclinic wave and moderate cross-barrier flow, which forced deep orographic precipitation. Both MM5 and WRF realistically simulated the synoptic scale circulations, including 300-mb winds over 60 m s^{-1}, 500-hPa trough along the coast, and cross barrier flow up to 20 m s^{-1} at 850 hPa at 0000 UTC 05 December 2001 (not shown).

S-Pol radar and model-derived reflectivities at 0100 UTC 05 December 2001 show a broad area of precipitation over the Cascades (Figs. 1a,b). NOAA P-3 radar reflectivities and wind vectors were combined from leg2 to leg4 over the Cascades between 2352 UTC 04 and 0057 UTC 05 December 2001 following Bousquet and Smull (2003). Localized higher reflectivity cores at 2.5 km ASL are found over the windward ridges as southwest wind crossed the barrier (Fig. 2a). Weaker reflectivities were found in the Willamette Valley and in the lee of Cascades. The 1.33-km WRF at this level was able to simulate the upslope enhancement and localized high dBZ values. However, the large reflectivity gradient to the east of Oregon Cascade crest in the model is shifted 20 to 30 km downstream as compared with available P-3 radar observations, which suggests that the model advected more snow into the lee than observed.

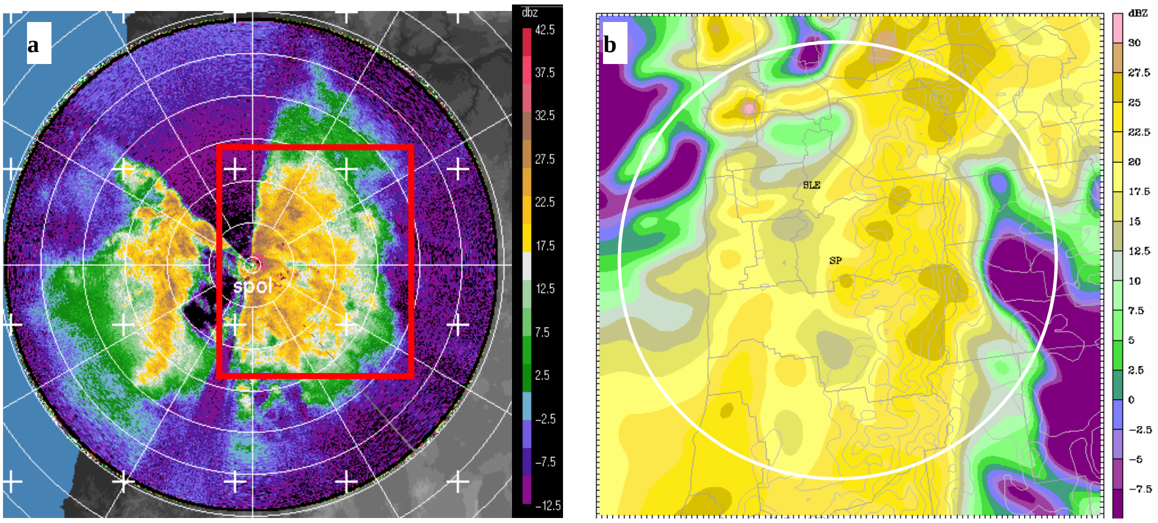

Figure 1. (a) NCAR S-Pol radar reflectivities at the 0.5^{o} elevation scan and (b) 4-km WRF reflectivities (shaded) at 700 hPa at 0100 UTC 05 December 2001. The box in (a) shows the location of the P3 tail Doppler observations in Fig. 2a.

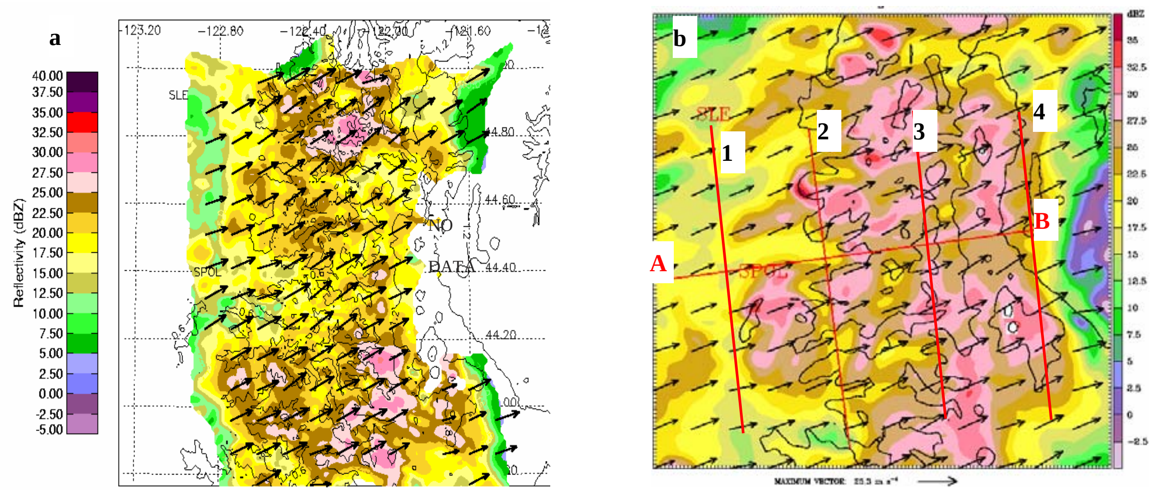

Figure 2. (a) NOAA P-3 dual Doppler reflectivities and winds at 2.5 km ASL between 2352 UTC 04 and 0057 UTC 05 December 2001. (b) Same as (a) except for the 1.33-km WRF at 0100 UTC 5 December. The flight legs of the P3 are shown in (b).

To verify the model microphysical fields, the 1.33-km MM5 and WRF simulated hydrometeor mixing ratio were interpolated in time and space to the P-3 flight tracks. The cloud water (CLW) measurements and mass concentrations of ice were determined using the method described by Woods et al. (2005). For the north-south leg2 in Fig.2b from 2352 UTC 04 December to 0007 UTC 05 December 2001 (Fig. 3), there was 0.06-0.2 g m^{-3} of CLW observed, with temperatures ranging between -9 and -10 ^{o}C. MM5 overpredicted CLW by~0.06 g m^{-3} along most of the leg, while WRF predicted more comparable values to the observations. The P3 ice mass concentrations were 0.15 g m^{-3}, while both MM5 and WRF predicted an average value of 0.32 and 0.28 g m^{-3} ice mass (snow plus graupel), respectively. For leg 3 (not shown), both WRF and MM5 also predicted approximately 2 times larger ice mass concentration. This snow overprediction was found in another IMPROVE IOP (Garvert et al. 2005b, Colle et al. 2005).

Figures 4a,b show the 1.33 km MM5 and WRF 12-h precipitation from 2200 UTC 04 to 1000 UTC 05 December, 2001. A two hour shift in the model precipitation verification was applied given the fact that both models simulated the passage of the mid-level trough at 700 mb two hours later than observed (not shown). However, the time shift had little impact on the precipitation results shown below. Both MM5 and WRF produced lighter precipitation in the valleys and heavy precipitation over ridges. However, MM5 produced 20-30% more precipitation than WRF, especially over the northern half of the Oregon Cascades. The reasons for these differences are still under investigation, but it appears the MM5 had somewhat lower stabilities than WRF, and the precipitation was somewhat more convective over the Cascades later in the event. The model bias score plots show overprediction in the 1.33-km MM5 (Fig. 4 c,d). In contrast, the WRF precipitation was within 20% of the observations, especially over the windward upslope region.

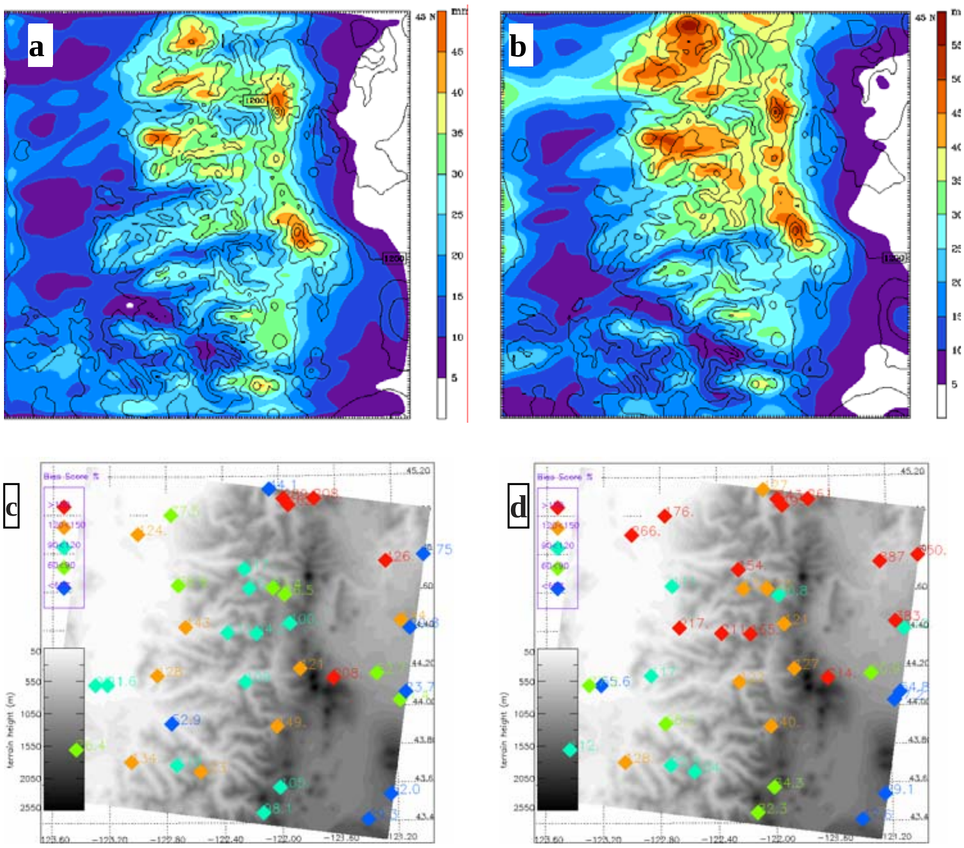

Figure 4. (a) 1.33-km WRF and (b) 1.33-km MM5 12-h precipitation total in mm between 2200 UTC 4 December and 1000 UTC 5 December (10-22h).(c) WRF and (d) MM5 1.33-km precipitation percentage of observed for the same time period in (a).

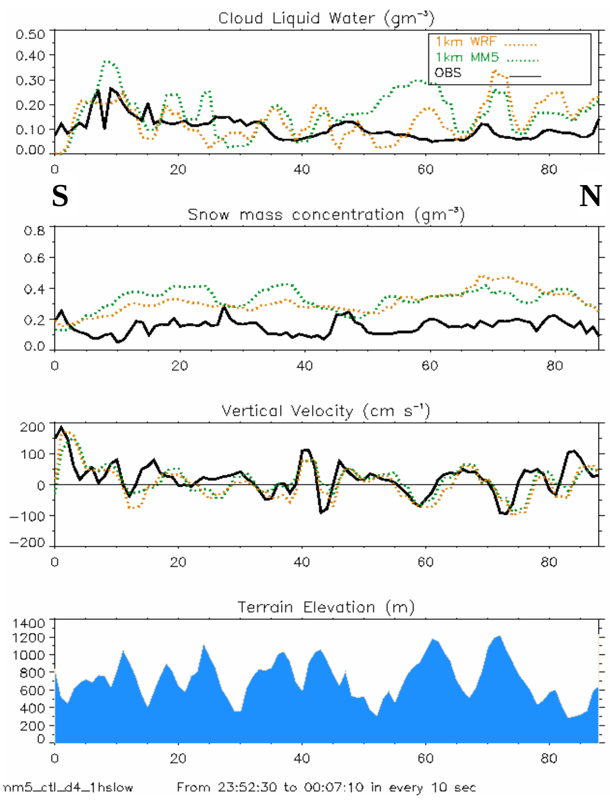

Figure 3. 1.33-km MM5 (green) and WRF (orange) cloud water, ice (graupel and snow) mass, vertical velocity, and underlying terrain along the P-3 flight leg2. Solid black lines are observed measurements.

4. Comparison of four BMPs in WRF

To further investigate and understand BMP's sensitivity in the WRF-ARW, four different BMPs were run down to 4-km grid spacing with identical model configuration and settings as the control run except the BMPs. The schemes tested include the WSM-6 (Hong et al. 2004), Purdue-Lin, Thompson (Thompson et al. 2004), and new Thompson scheme (Thompson et al., in preparation). Table 1 lists the mean snow, graupel, and CLW mass concentrations along legs 1-3 for the NOAA P-3 and each BMP. The Thompson scheme overpredicted snow mass concentrations, but had comparable CLW to the observations. In contrast, the newly modified Thompson scheme (as of 25 May 2006) predicted roughly two times more snow than the Thompson in WRF V2.1.1. The WSM-6 predicted snow relatively well without counting cloud ice, but with much less CLW than observed, while the Purdue Lin scheme predicted too much graupel and too little snow. Clearly, there are large uncertainties in WRF microphysical schemes for this event.

Figure 5 shows the CLW, snow, graupel, rain, and cloud ice mixing ratios (g kg^{-1}) along the UW Convair leg2 (AB in Fig. 2b) for the four BMP members. The new Thompson scheme predicted less CLW and graupel, and approximately two times more snow than the original Thompson scheme. Cloud ice is mainly above 6 km in Thompson and new Thompson, while cloud ice is more prevalent in the Purdue-Lin and WSM-6 scheme. One reason might be that cloud ice is converted to snow at smaller sizes in the Thompson scheme. More widespread of cloud ice in Lin scheme may also be due to the different saturation adjustment method. Compared with UW Convair measured ice mass (indicated as numbers in Fig.6b), Thompson scheme showed slightly underprediction of snow above 4 km ASL, which transitioned to lower level ice mass overprediction at P-3 level at 2-3 km ASL.

Table 1. Microphysical comparisons of four BMP simulations for P-3 legs 1-3. See Fig. 2b for leg locations.

Run name	P-3 leg1 (-6 ^{o}C, 1850 m) **snow/graupel/CLW**	P-3 leg2 (-9.5 ^{o}C, 2450 m) **snow/graupel/CLW**	P-3 leg3 (-15 ^{o}C, 3350 m) **snow/graupel/CLW**
Thompson (WRF)	**0.23/0.01/0.05**	**0.34/0.02/0.05**	**0.16/0.00/0.04**
Purdue-Lin (WRF)	**0.01/0.09/0.02**	**0.02/0.12/0.03**	**0.05/0.04/0.02**
WSM-6 (WRF)	**0.04/0.07/0.00**	**0.10/0.07/0.00**	**0.12/0.01/0.00**
New Thompson (WRF)	**0.44/0.00/0.02**	**0.54/0.00/0.02**	**0.31/0.00/0.02**
Thompson (MM5)	**0.15/0.03/0.06**	**0.26/0.03/0.06**	**0.19/0.00/0.04**
Observed	**0.05/0.02/0.06**	**0.08/0.07/0.10**	**0.06/0.01/0.03**

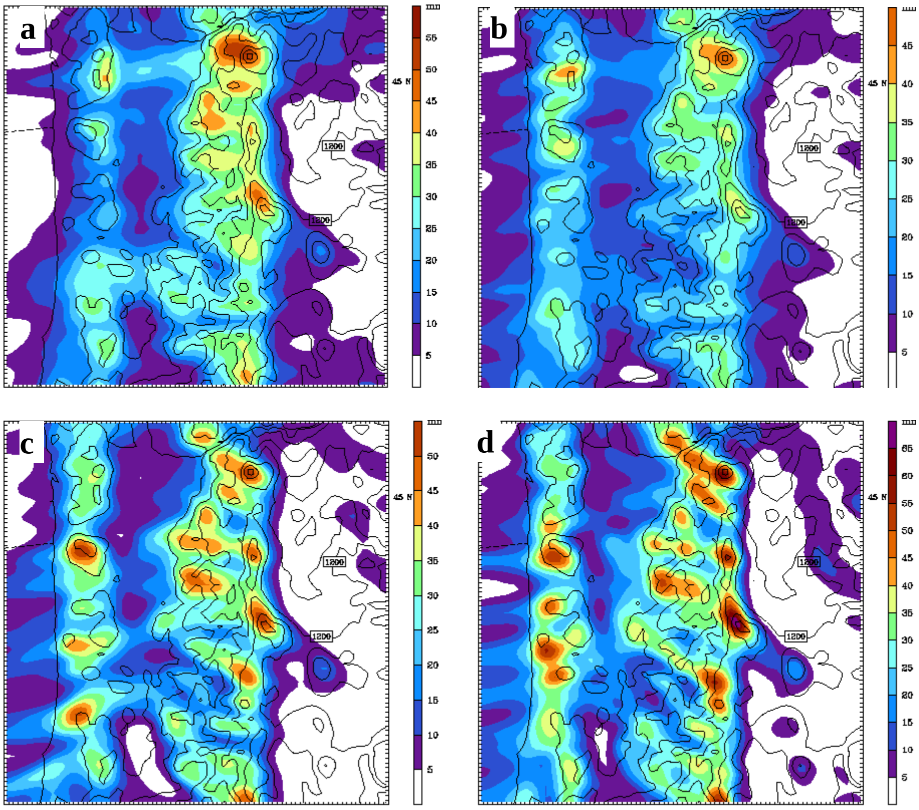

Figure 5. 2200 UTC 04 to 1000 UTC 05 December 2001 precipitation totals in mm from 4-km WRF simulation using (a) new Thompson, (b) Thompson, (c) WSM-6, and (d) Purdue Lin scheme, respectively.

Figure 6 shows the 12-h surface precipitation totals from the four simulations. First, the newly modified Thompson predicted more precipitation than the original Thompson. However, less precipitation was predicted in new Thompson in the Oregon coastal range. Purdue-Lin scheme predicted a similar precipitation pattern as WSM-6, with approximately 20% larger precipitation than WSM-6. More localized precipitation bull eyes in these two schemes are a result of more graupel in these two runs. As a result, bias score figures (not shown) displayed more overprediction for new Thompson and localized overprediction for WSM-6 and Lin. In addition, all the four simulations underpredicted precipitation 60-80 km downwind of Oregon Cascades crest.

5. Summary

This paper has presented WRF and MM5 simulations using Thompson scheme for IMPROVE-2 IOP6. Both models used the same version of Thompson, but MM5 generated much more precipitation and had surface overprediction. The divergence in the forecast between WRF and MM5 occurred after the IOP flight period, which suggests that the orographic precipitation predictability for this case goes beyond microphysics. The WRF-Thompson did produce a good short-term precipitation forecast, but apparently for the wrong microphysical reasons aloft, considering that the snow was overpredicted around 2.5-3.5 km. This suggests that the observations had more riming and accretional growth below flight level than the WRF. There are large precipitation differences among the WRF BMP schemes. Future work will more closely evaluate the microphysical pathways for these schemes.

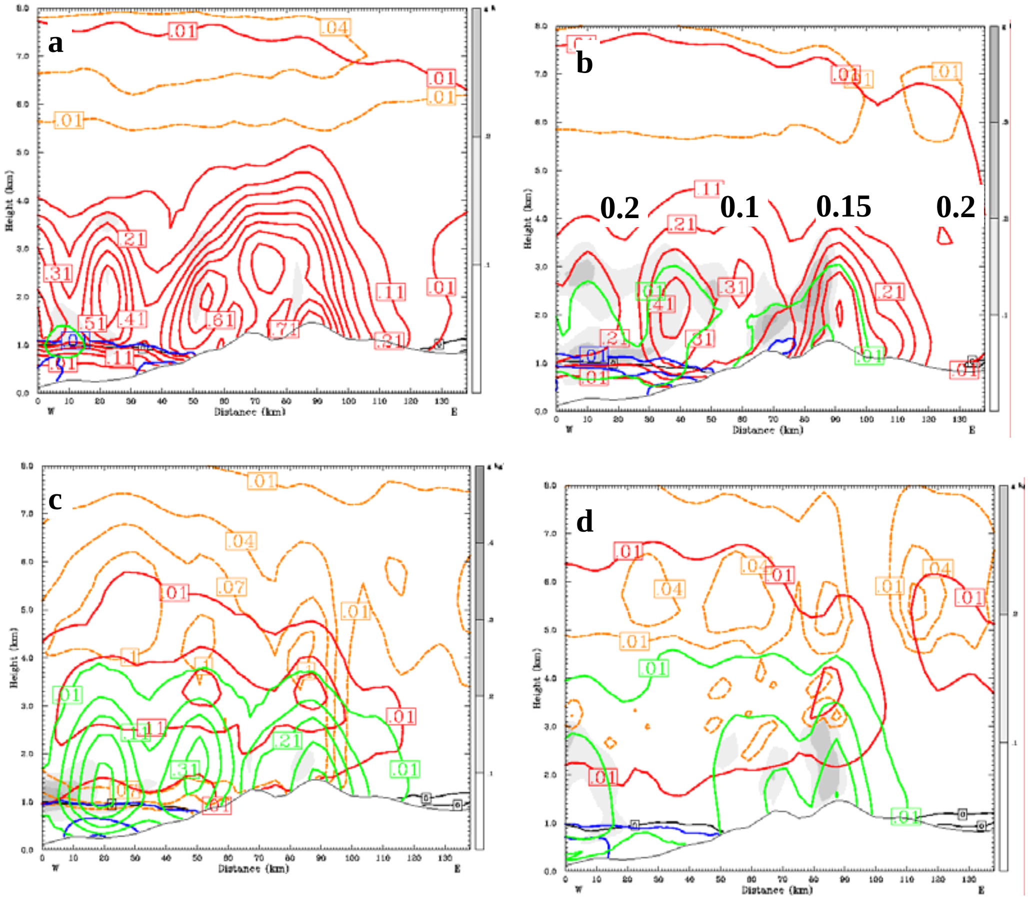

Figure 6. Cloud water (gray shaded every 0.1 g kg^{-1}), cloud ice (dashed orange every 0.03 g kg^{-1}), snow (red solid every 0.1 g kg^{-1}), graupel (green solid every 0.1 g kg^{-1}), rain (blue solid every 0.1 g kg^{-1}), and freezing level (black solid) along the cross section of line AB in Fig. 2b at 0200 UTC 05 December 2001 from simulations using (a) new Thompson, (b) Thompson, (c) WSM-6, and (d) Purdue Lin scheme. The numbers in (b) show the UW Convair derived ice mass (g m^{-3}) at 4.25 km ASL.

6. Acknowledgements

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7. References

Bousquet,O.and .F.Smull, 2003:Airflow and precipitation fields within deep Alpine valleys observed by airborne Doppler radar. *J. Appl.Meteor.*, **42**,1497–1513.

Colle, B. A., and C. F. Mass, 2000: The 5–9 February 1996 flooding event over the Pacific Northwest: Sensitivity studies and evaluation of the MM5 precipitation forecasts. *Mon. Wea. Rev.*, **128**, 593–617.

Colle, B. A., M. F. Garvert, J. B. Wolfe, C. F. Mass and C. P. Woods,2005:The13–14December2001 IMPROVE-2 Event. Part III: Simulated microphysical budgets and sensitivity studies. *J.Atmos.Sci.*,**62**, 3535–3558.

Colle, B. A.Y.L. Lin, B.F. Smull, and Nicholas A. Bond, 2006: Verification of WRF over complex terrain and coastal regions using field data and ensembles. WRF workshop (this issue), Boulder, CO.

Garvert, M. F., B. A. Colle, and C. F. Mass, 2005a: The 13-14 December 2001 IMPROVE-2 event. PartI: Synoptic and mesoscale evolution and comparison with a mesoscale model simulation. *J. Atmos.Sci.*,**62**, 3474–3492.

Garvert, M. F., C. P. Woods, B. A. Colle, C. F. Mass, P. V. Hobbs, M. P. Stoelinga, and J. B. Wolfe, 2005b: The 13–14 December 2001 IMPROVE-2 event. Part II: Comparison of MM5 model simulations of clouds and precipitation with observations. *J. Atmos. Sci.*, **62**, 3520–3534.

Hong, S.-Y., Dudhia J., 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.

Stoelinga, M., and Coauthors, 2003: Improvement of Microphysical Parameterization through Observational Verification Experiments. *Bull. Amer Meteor. Soc.*, **84**, 1807–1826.

Thompson, G., R. M. Rasmussen, and K. Manning, 2004: Explicit forecasts of winter precipitation usingan improved bulkmicrophysics scheme. PartI: Description and sensitivity analysis. *Mon. Wea.Rev.*, **132**, 519–542.

Woods, C. P., M. T. Stoelinga, J. D. Locatelli, and P. V. Hobbs, 2005: Microphysical processes and synergistic interaction between frontal and orographic forcing of precipitation during the 13 December 2001 IMPROVE-2 event over the Oregon Cascades. *J. Atmos. Sci.*, **62**, 3493–3519.