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Some Comparisons Between IMPROVE-2 and IPEX Kinematic and Precipitation Structures and Bulk Microphysical Verification

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1. INTRODUCTION

The development of new observational tools and high resolution operational models has sparked renewed interest and field studies in the area of orographic precipitation and microphysics. These studies are motivated in part because it has been suggested that mesoscale models have large deficiencies in their bulk microphysical parameterizations (Colle and Mass 2000), and we need better understanding of moist dynamics and precipitation production over terrain.

Addressing these issues requires detailed observations from many different geographic locations and barrier dimensions. As a result, during the late 1990s and early 2000s, a number of field studies collected in situ, radar, and aircraft data to better understand orographic precipitation processes and microphysics, such as the Mesoscale Alpine Project (MAP) over the European Alps during the Fall of 1999, California Landfalling Jets Experiment (CALJET) in the winter 1998, the Improvement of Microphysical PaRametrization through Observational Verification Experiment (IMPROVE) over the Pacific Northwest during 2001, and Intermountain Precipitation Experiment (IPEX) over the Wasatch Mountains of Utah during February 2000. These field studies provide data for a spectrum of barrier widths, ranging from the large Alps during MAP to the moderately-sized Cascades during IMPROVE II and the narrow (< 10-km half width) Wasatch during IPEX.

The objective of this study is to compare some precipitation structures and model verification from the Cascade barrier in IMPROVE-2 (Stoelinga et al. 2003) and the more narrow Wasatch in IPEX (Schultz et al. 2002). In particular, the 13-14 December 2001 event (IOP11) was investigated for IMPROVE-2 and the 12-13 February 2000 event for IPEX (IOP3). Cox et al. (2004) presents some of the observed kinematic and precipitation structures for IOP3 of IPEX, while Garvert et al. (2004a) and Woods et al. (2004) describe some of the 13-14 December intensive observations. This paper summarizes some of these observations and provides new insight through high resolution mesoscale model simulations and verification of bulk microphysical parameterizations.

The following questions are addressed in this study:

- How do the low-level flow and precipitation structures compare between IMPROVE IOP11 and IPEX IOP3.
- How well does a mesoscale model simulate the flow, precipitation, and microphysical structures?
- What are the microphysical pathways and sensitivities for both cases?

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Garvert et al. (2004a) describes the setup of the MM5 simulations for the IMPROVE-2 event using v3.5 of the model, which were nested down to 1.33-km grid spacing over the central Oregon Cascades (Fig. 1). The control run of the MM5 was initialized at 0000 UTC 13 December using the NCEP AVN model, and used the Reisner2 microphysics (Reisner et al. 1998; Thompson et al. 2003), which includes graupel and super-cooled

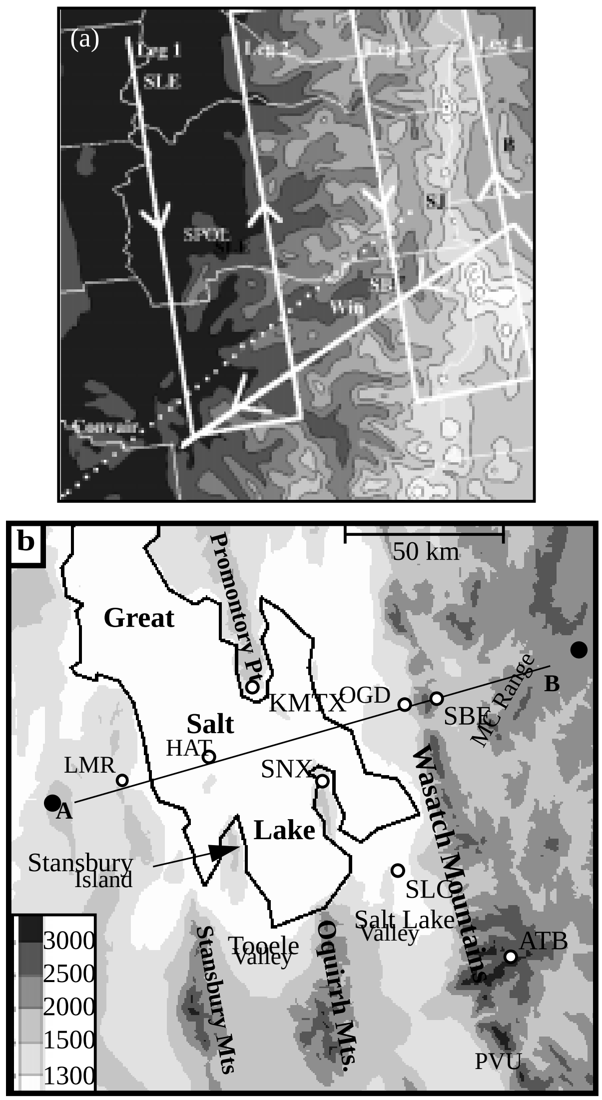

Figure 1. (a) IMPROVE-2 IOP region over the central Oregon Cascades showing terrain, flight-tracks (P-3 solid, Convair dashed). (b) IPEX IOP region showing terrain, WSR-88D location (MTX), surface stations, and P-3 flight track along line A-B.

water processes.The IPEX simulations down to 1.33-km grid spacing were initialized using the AVN at 1200 UTC 12 February 2000.

2. IMPROVE-2 ANALYSIS (13-14 DEC 2001)

At 0000 UTC 14 December, there was an occluded front that extended southward along the coast from a 984 mb surface low located over central Vancouver Island (not shown). Meanwhile, the leading edge of a baroclinic zone was approaching the IOP region between 650-750 mb (Garvert et al. 2004a). Coincident with the passage of the mid-level baroclinic zone was an area of enhanced southwest winds to 40 m s^{-1} centered around 750 mb, and the flow approaching crest-level was near 25 m s^{-1}, as derived by the P-3 Doppler velocities (Fig. 2a). The P-3 reflectivities for 1500 m ASL show that there was a broad area of orographically-enhanced precipitation over the windward slope of the Cascades (Fig. 2a), with some localized minima over some of the major windward valleys. Because of the strong southwesterly flow at crest level, there was a significant amount of precipitation spillover the Cascade crest.

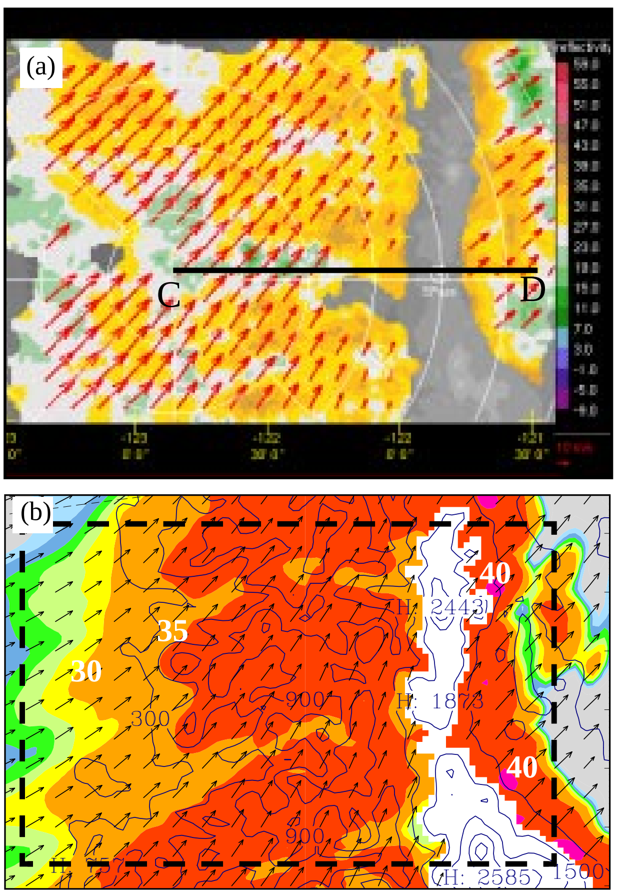

Figure 2. (a) Observed reflectivities (color shaded) and synthesized Doppler winds at 1.5 km ASL derived from the NOAA P3 aircraft as it flew north-south legs between 2300 and 0100 UTC over the Cascade windward slope (cf. Fig 1a). (b) Same as (a) except for a portion of the 1.33-km MM5 domain averaged between hours 23 and 25 of the simulation. Terrain is contoured every 200 m. The line CD is the location of the cross section for Fig. 3. The dashed box (b) shows the region for the average west-east cross section in Fig. 5.

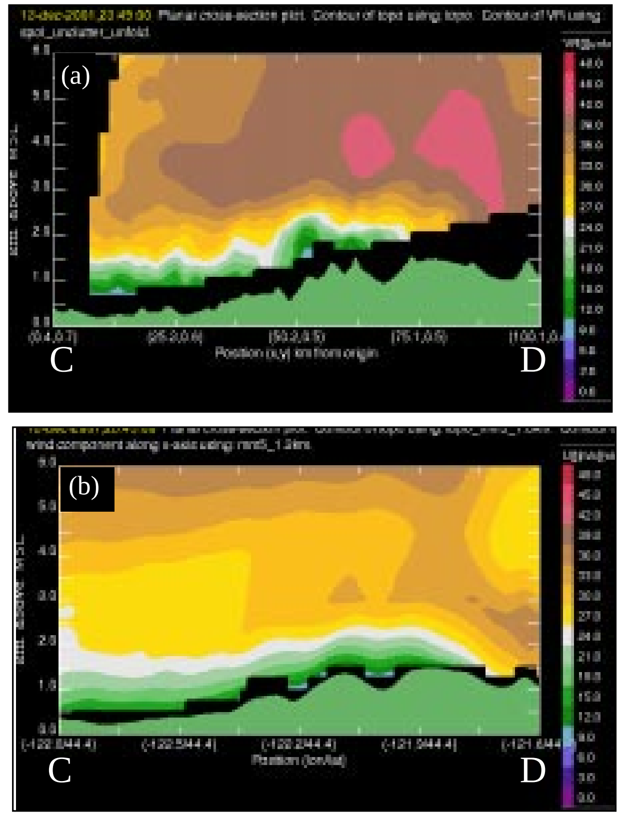

Figure 3. (a) Cross section across the Cascades at 2345 UTC 13 December of the radial velocities (in m s^{-1}) measured to the east of the Spol radar (Fig. 1a). (b) Same as (a) except for the MM5 (23.75h).

At Salem, OR (SLE on Fig. 1a) at 0000 UTC 14 December, the temperature profile below 700 mb was nearly moist neutral (not shown), with a moist N_m of 0.005 s^{-1}. As a result, the moist Froude number ($Fr_m = U/H_mN_m$) for this event was around 2 (lowest 2-km average U = 20 m s^{-1} and H_m =2000 m), which puts the flow in a regime with little or no flow blocking. There was a shear layer in the lowest 2-km approaching the crest (Fig. 3a), which Medina and Houze (2004) have shown is characteristic of orographic enhancement with stable flow. However, there was little flow deflection of air parcels approaching the crest at 1500 m (Fig. 2a).

The MM5 at 1.33-km grid spacing was able to realistically simulate this flow and precipitation for this event, although the cross-barrier flow aloft was underpredicted by about 5 m s^{-1} and there was slightly more windward flow deflection (Figs. 2b, 3b). As observed, the model produced an area of enhanced precipitation over the windward ridges. Both the model and observed had flow accelerations over the crest associated with a mountain wave at 0000 UTC 14 December 2001. The MM5 had some of the largest precipitation rates (15 mm in 1 h) in the immediate lee of the crest. This rate is nearly twice as large as observed in the immediate lee of the Cascades as shown by the surface precipitation verification (Fig. 4). Both upstream of the Cascades and in many of the narrow valleys of the windward Cascades, the MM5 is within 20% of the observed.

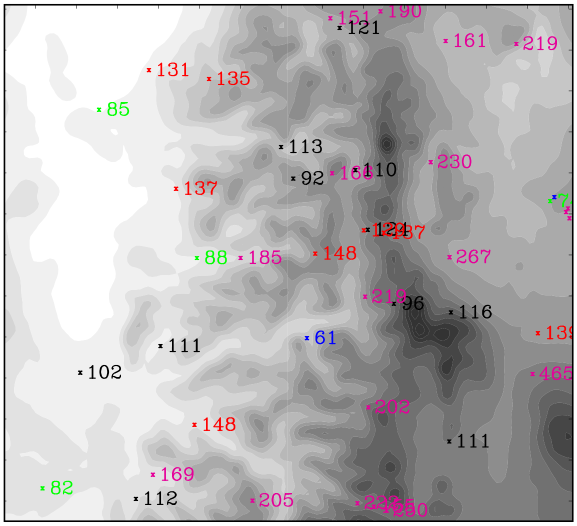

Figure 4. The 1.33 kmMM5 percent of observed precipitation for 1400 UTC 13 December 0800 UTC 14 December (14-32 h). Terrain is shaded for reference.

Figure 5 shows an average west-east cross section of the mixing ratios for snow, graupel, and rain averaged for 2300-0100 UTC 13-14 December for the dashed boxed region in Fig. 2b. During this two hour period there was a deep orographic cloud, with snow extending above 400 mb, graupel between 800 and 600 mb, and rain below 750 mb. Some of the individual peaks on the windward slope produced an enhanced upward motion and perturbations in the hydrometeor magnitudes. The snow maximum is around 600 mb over the crest and there is spillover into the lee.

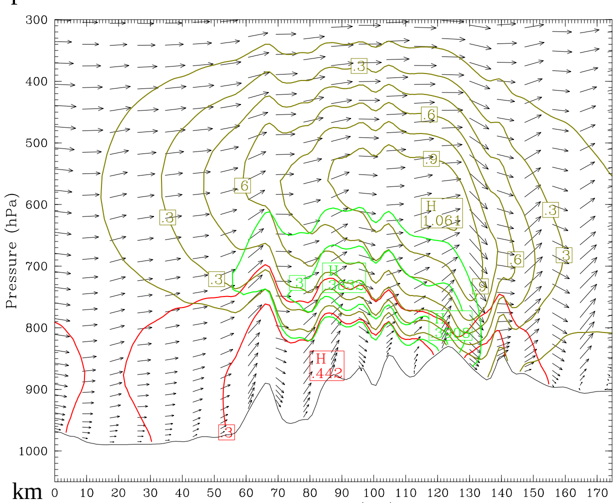

Figure 5. Average west to east cross section across the Cascades for the box in Fig. 1 showing mixing ratios of snow (dark yellow), graupel (green), and rain (red) every 0.15 g kg^{-1}. The average winds in the section are also shown.

The MM5 cloud water and snow mixing ratios were verified over the Cascades using the NOAA P-3 and Convair aircrafts (Fig. 1a). The P-3 completed a series of north-south flight legs over the windward slope between 2300 UTC 13 December 0100 UTC 14 December. The cloud water verification was completed for the control (CTL or Reisner2) simulation as well as several other sensitivity experiments which used either a fixed or mixing ratio dependent slope intercept (Nos) for snow number concentration (Snow Fixed and Snow q respectively), a 20% slower (Cox 1988) fallspeed for snow (Fallspeed), a Kessler autoconversion from cloud to rain (Kess) instead of the Berry formulation described in Thompson et al. (2003), or a 50% decrease in the threshold of riming (PSACW) to begin the autoconversion from snow to graupel.

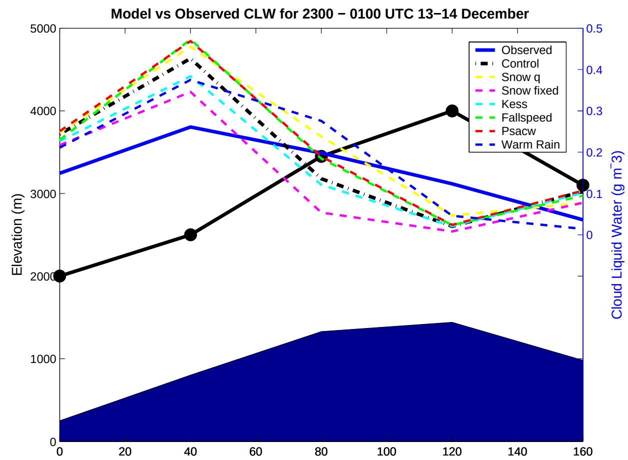

Figure 6. Cloud water verification averaged for each of the five north-south NOAA P-3 legs shown in Fig. 1a between 2300 UTC 13 December and 01 UTC 14 December. The observed cloud water amounts (in g m^{-3}) are shown by the solid blue line and each of the dashed Reisner2 experiments are listed in the inset. The average N-S altitude (in meters) of the P3 for each leg is given by the black dot in meters.

All experiments overpredict cloud water over the lower windward slope (by 0.2 g m^{-3}) at altitudes of 2-3 km, while there is underprediction (by 0.1 g m^{-3}) above the crest between 3 and 4 km, and all simulations are close to the observed 40 km downwind of the crest. Using a fixed Nos does help to reduce the overprediction at over the lower windward slope since more water vapor goes to depositional snow growth (not shown); however, it more dramatically underpredicts at higher altitudes over the crest, since the deposition removes too much available saturated water. In contrast, using a variable Nosqs results in less snow growth (Fig. 7), so the overpredictions are worse at lower levels and are less above the crest. Reducing the fall speed for snow in the Fallspeed run and allowing for more riming in PSACW also increases the overpredictions at lower levels, while there is little change compared to the CTL over the crest and immediate lee. Nosqs, PSACW, and COX all favor less snow aloft, therefore less cloud water is depleted. Using a Kessler autoconversion results in less overprediction at lower levels, but there is little change compared to the CTL near the crest.

Figure 6 shows the model ice-number verification results the Convair flight at 4.9 km ASL over the windward slope of the Cascades (Fig. 1a). As noted in Garvert et al. (2004b), since the back (western) edge of the upper-level precipitation shield was approximately 30 minutes too fast in the model relative to the Convair over the Willamette valley, a 16-19 h average was applied to the model data to focus on the pre-frontal stratiform precipitation shield. It is encouraging that the observed snow distribution aloft is primarily exponential as parameterized in the model using a Marshall-Palmer distribution (Fig. 7). However, the observed number distribution has a significantly steeper slope than all experiments involving different snow slope intercepts for snow, and the model mixing ratios are 2-3 times larger than observed (not shown). The Nosqs experiment has the best snow mixing ratio prediction; however, it has a much worse (broader) slope distribution, which dramatically underpredicts smaller ice particles. Meanwhile, there is little difference between a fixed Nos and NosT (CTL).

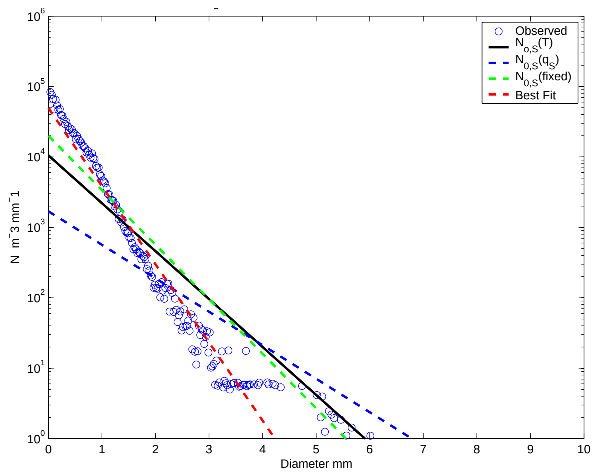

Figure 7. Ice number concentrations from the Convair aircraft at 4.9 km ASL over the windward slope (blue circles and red-dashed best fit) and MM5 number concentrations derived using the fixed Nos (green dashed), NosT (solid black), and Nosqs (blue dashed) experiments.

4. IPEX ANALYSIS (12-13 FEB 2000)

At 1200 UTC 12 February 2000, which is about 5 hours before the NOAA P-3 aircraft began collecting data over the Wasatch, a short-wave 500-mb trough extended from the Pacific Northwest southward to southern California, while a short-wave ridge was situated over the Rocky Mountains to the east (not shown). During the 6-h IOP3 period of intensive observations (1800 UTC 12 February -- 0000 UTC 13 February 2000), there was a mid-level (700-600 mb) trough that crossed the IOP area a few hours ahead of the 500 mb and surface-based trough passage (Cox et al. 2004), resulting in a 700-600 mb wind shift from southwesterly to west-northwesterly around 2100 UTC 12 February.

At 1800 UTC 12 February (Fig. 8a), there was surface southwesterly flow over the Great Salt Lake and to the west, with more southerly flow channeling within the Tooele and Salt Lake Valleys to the south. Meanwhile, there is terrain parallel southerly flow adjacent to the Wasatch as a result of flow blocking, which resulted in a low-level flow confluent zone 20-km upstream of the Wasatch. The MM5 at 1.33-km grid spacing realistically simulated the terrain-channeled flow and confluence upstream of the Wasatch (Fig. 8b). As observed (not shown), the model surface temperatures decrease from around 4 ^{o}C over the western Salt Lake to 2-3 ^{o}C just east of the Lake. This slight cooling suggests that there was some diabatic cooling from precipitation over this region, since the air was able to cool while crossing the lake that had a surface water temperature was 6 ^{o}C (not shown). The low-level blocked flow is evident in the OGD sounding in the model and observed at this time (not shown), as the low-level southerly flow near the surface veered to south-southwesterly by 750 mb, which is near crest-level.The upstream sounding at LMR (Fig. 1) suggested a moist static stability that was nearly moist neutral (N_m ~0.005 s^{-1}), which is similar to the IMPROVE-2 case, but the IPEX cross barrier flow was around 10 m s^{-1}. Therefore, the average Fr_m for this IPEX case at 1800 UTC was around 1, which favors more of a windward blocking response. The greater flow deflection than perhaps the Fr_m suggests is explored with additional model simulations and discussion below.

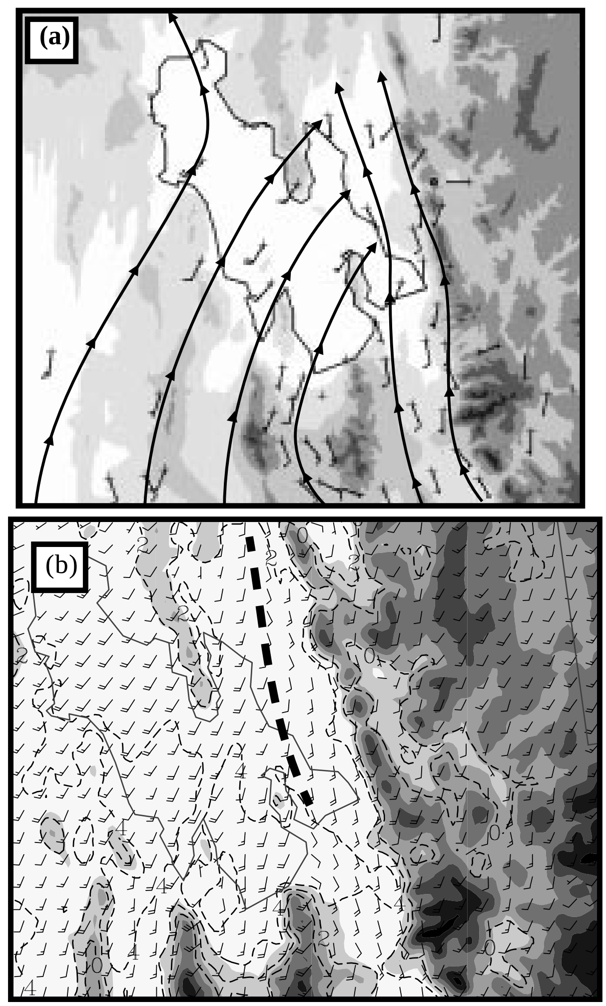

Figure 8. (a) Manual streamline analysis at 1800 UTC 12 Feb Full and half barbs denote 5 and 2.5 m s^{-1}, respectively. (b) Model analysis showing 10-m winds and 2-m temperatures every 1 ^{o}C. A dashed line marks the convergence boundary.

Figure 9a,b shows the KMTX radar reflectivities at 2260 m for 1830 UTC 12 Feb. Low-level flow blocking and convergence resulted in precipitation enhancement extending about 20 km upstream of the Wasatch. The greatest reflectivities aloft were located over the crest. Above mid-mountain the flow was partially blocked, as illustrated by the 5-10 m s^{-1} cross barrier flow in

Fig. 9c. The strongest cross-barrier flow was located around 3 km MSL, with reverse shear above this level. The flow near crest-level resulted in a significant amount of precipitation spillover into the lee of the narrow Wasatch. The 1.33-km MM5 realistically-predicted the cross-barrier flow and precipitation structures across the Wasatch at 1830 UTC (6.5 h).

As noted by Cox et al. (2004), the potential for flow blocking decreased as the cross-barrier flow deepened with the passage of the mid-level trough. As a result, the upstream convergence boundary and precipitation enhancement collapsed to within 5-10-km of the barrier by 0000 UTC 13 Feb. The MM5 realistically simulated this evolution (not shown), and also suggested that this was related to the increase in Froude number during the period.

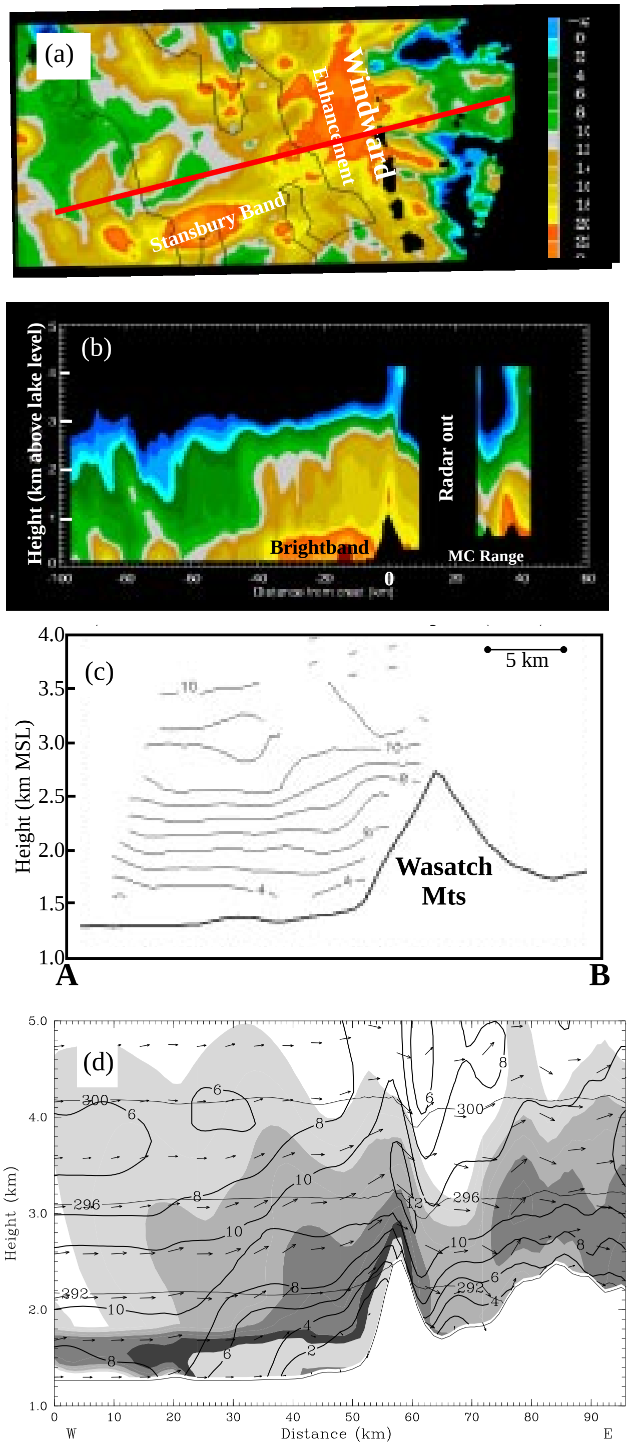

Figure 9. (a) KMTX reflectivity (2265 m MSL) at 1830 UTC 12 Feb 2000. (b) Cross section of reflectivity for the red line in (a). (c) Cross-barrier flow (m s-1) as derived by the upstream DOW radars for the AB portion of the red section. (d) Cross section from 1.33-km MM5 showing circulation vectors, reflectivity, and cross-barrier wind speed (m s-1).

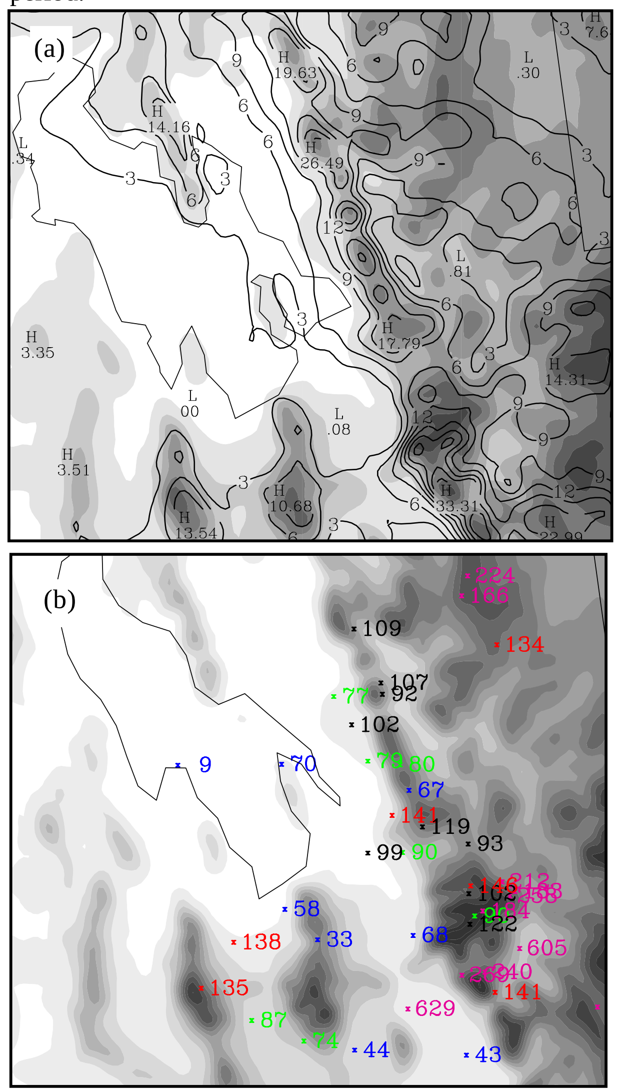

Figure 10. (a) Simulated precipitation (every 3 mm) from the 1.33-km domain from 1800 UTC 12 Feb - 0000 UTC 13 Feb 2000. (b) Model percent of observed precipitation at 1.33-km grid spacing. Terrain is shaded.

In order to determine the relative importance of the Great Salt Lake and the terrain to the south of the lake in upstream blocking during IPEX, additional MM5 simulations were completed removing these features (replaced as flat land). The lake was found to increase the low-level convergence by 50% in the model as a result of the greater southwesterly momentum off the lake (not shown), and shift the convergence line downstream somewhat, particularly to the north. The terrain to the south of the lake had little impact on the flow in the IOP region. Both surface heat and moisture fluxes had little impact on the blocking in this IPEX case, but without diabatic cooling effects from precipitation in the model, no convergence line developed. Overall, the kinematic flow upstream of the Wasatch was a complex interaction between flow blocking, differential friction, and diabatic cooling from precipitation.

Figure 10a shows the 6-h precipitation for the 1.33-km domain between 1800 UTC 12 February and 0000 UTC 13 February, while Fig. 10b shows the simulated percent of observed precipitation at the available gauge locations. As observed (Cox et al. 2004), the 1.33-km simulation produced a sharp gradient in 6-h precipitation 10-20 km upstream of the Wasatch as a result of the upstream flow blocking. The heaviest precipitation was generally located near the Wasatch crest, with the greatest near the IOP area (28 mm). Meanwhile, there was little or no precipitation to the west over the central and western Salt Lake. Over the central Wasatch near OGD the model was generally within 10% of the observed, and there was some (20-30%) underprediction 20-30 km upstream of the Wasatch. In contrast, there was overprediction (by 50-100%) in immediate lee of the higher and wider portions of the southern Wasatch Front.

The 1.33-km precipitation verification results were compared with the 4- and 12-km grid spacings over the same 1.33-km region. At 4-km grid spacing (not shown), the narrow Wasatch can not be resolved as an narrow peak; rather, the 4-km has a relatively steep slope extending to a broader plateau. However, the 4-km has a relatively steep slope extending to a broader plateau. However, the 4-km simulation was still able to simulate the development of nearly terrain-parallel flow

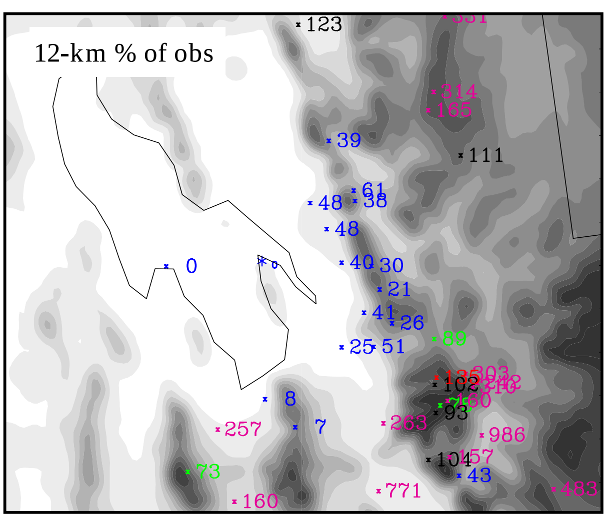

Figure 11. Same as Fig. 10 except for the 12-km grid spacing. 1.33-km terrain is shown as reference.

and confluence upstream of the Wasatch at 1800 UTC 12 February. As a result, the 4-km precipitation enhancement is similar to the 1.33 km domain (not shown), but there is 10-40% less precipitation in the 4-km near some of the steeper peaks (not shown). At 12-km grid spacing, there is only a gradual slope from west to the east of the Salt Lake (not shown). The 6-h precipitation over this region is less than half that of the 4-km domain, with the 12-km having less than 40% of the observed over the central and northern Wasatch and immediately upstream (Fig. 11). In contrast, the 12-km run has more overpredictions over the lower windward slope over the wider Wasatch to the south and has similar overpredictions to the lee of the crest as the higher resolution domains. Overall, unlike the Cascades, where 12-km grid spacing has been shown to be sufficient, at least 4-km grid spacing is needed top resolve the narrow Wasatch.

Preliminary comparisons between the cloud water and snow from the NOAA P-3 with the model at 1.33-km grid spacing suggests that the model overpredicted cloud water (by 10-20%) above 4-km ASL over the Wasatch, but significantly underpredicted (by 40-50%) the amount and concentration of snow aloft.

5. SOME IMPROVE-2 AND IPEX COMPARISONS

Both the IMPROVE-2 (13-14 Dec 2001) and IPEX (12-13 Feb 2000) events produced relatively heavy precipitation (> 25 mm in 6 hours) and a deep orographic cloud. The stability was relatively weak ($N_m = 0.005\ s^{-1}$) in both cases; however, the cross-barrier flow during IPEX was one-third that of IMPROVE-2. As a result, there was more potential for flow blocking during IPEX below mid-mountain level. During IPEX a low-level convergence boundary and enhanced precipitation extended 20-km upstream of the Wasatch barrier, while the orographic enhancement was limited to over the Cascade windward slope in IMPROVE-2. Both events had a significant amount of precipitation spillover the crest, either from the strong-cross barrier flow in IMPROVE-2 or the narrow Wasatch terrain in IPEX.

There were also microphysical differences between IMPROVE-2 and IPEX. There was 0.2 -0.3 g kg-1 of super-cooled water observed between 2000-3000 m during IMPROVE-2, while there was generally less than 0.1 g kg^{-1} in IPEX except right over the crest. As a result, there was relatively large amounts of snow riming and graupel in the IMPROVE-2 event, and little observed during IPEX. Therefore, IMPROVE-2 had less than half as much unrimed snow (0.2-0.3 g kg^{-1}) than IPEX (0.4-0.5 g kg^{-1}) upstream of the barrier.

The MM5 overpredicted the cloud water over the lower windward slope in IMPROVE-2, and underpredicted over the crest as too much cloud water was depleted via riming and deposition, thus leading to the snow overprediction. In contrast, the MM5 overpredicted the cloud water at upper-levels over the Wasatch crest in IPEX (not shown), and underpredicted snow by almost a factor of two over the barrier. Both the model and observed had little graupel at flight-level. The underprediction of snow aloft in IPEX may be related to insufficient resolution to generate the mountain circulation above the Wasatch, but since the surface precipitation over the Wasatch was well forecast, there is likely deficiencies between the partition between snow and cloud water closer to the crest. Future work will investigate these issues.

ACKNOWLEDGEMENTS

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