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High Resolution Simulations and Microphysical Validation of an Orographic Precipitation Event Over the Wasatch Mountains During IPEX IOP3

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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 IPEX field experiment offers an opportunity to investigate orographic precipitation mechanisms and microphysical processes over the relatively narrow (< 10-km half width) Wasatch mountains of northern Utah (Schultz et al. 2002). These microphysical results can be compared with other field studies such as IMPROVE-2. Shafer et al. (2005) described the synoptic flow and development of a mid-level trough during the third Intensive Observing Period (IOP3) of IPEX. Meanwhile, Cox et al. (2005) presented the observed kinematic and precipitation structures of IOP3 using conventional data, in situ airborne data from the NOAA WP-3D, and two University of Oklahoma Doppler on Wheels (DOW) X-band radars, which were located 20-km upstream of the Wasatch. The purpose of this IPEX study is fourfold: (1) to use the MM5 to better understand the three-dimensional flow and precipitation evolution around the Wasatch, (2) to verify the MM5 precipitation forecasts with decreasing horizontal grid spacing, (3) to validate the model microphysics over a relatively narrow mountain barrier (i.e., the Wasatch Mountains) using aircraft data and a model microphysical budget, and (4) to determine the processes responsible for the formation of the windward convergence zone and precipitation region.

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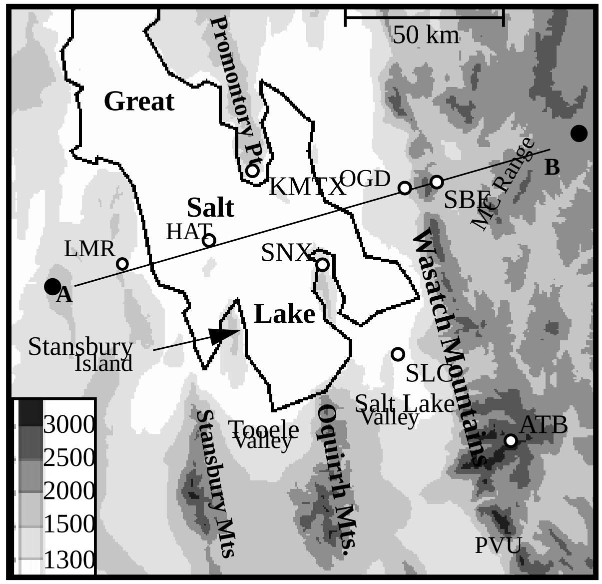

Figure 1. IPEX IOP region showing terrain, WSR-88D location (MTX), surface stations, and P-3 flight track along line A-B.

2. MODEL SETUP

The MM5 (version 3.5) was used in non-hydrostatic mode to simulate IOP3 and to provide additional sensitivity simulations. For this simulation, stationary 1.33-, 4-, and 12-km domains were nested within a 36 km domain using one-way nest interfaces. Initial atmospheric conditions at 1200 UTC 12 February 2000 were generated by interpolating the National Centers for Environmental Prediction (NCEP) GFS model analysis (1-deg resolution) to the MM5 grid. The 6-hourly GFS analyses were linearly interpolated in time in order to provide the evolving lateral boundary conditions for the 36-km domain. The Great Salt Lake temperature was set to 6 ^{o}C, as observed at the Hat Island Mesowest site maintained by the University of Utah.

The control (CTL) simulation used the Reisner2 explicit moisture scheme from version 3.6 of the MM5 (Thompson et al. 2004). The Grell convective parameterization (Grell et al. 1994) was applied, except for the 4- and 1.33-km domains, where convective processes were resolved explicitly. The planetary boundary layer (PBL) was parameterized using NCEP's MRF scheme (Hong and Pan 1996). Klemp and Durran's (1983) upper-radiative boundary condition was applied in order to prevent gravity waves from being reflected off the model top.

3. IPEX IOP3 ANALYSIS

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. 2005), resulting in a 700-600 mb wind shift from southwesterly to west-northwesterly around 2100 UTC 12 February.

At 1800 UTC 12 February (Fig. 2a), 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. 2b). 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}), and the 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 a windward partial blocking response. The greater flow deflection than perhaps the Fr_m suggests is explored with additional model simulations and discussion below.

Figure 3a,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. 3c. 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 4a shows the 6-h precipitation for the 1.33-km domain between 1800 UTC 12 February and 0000 UTC 13 February, while Fig. 4b shows the simulated percent of observed precipitation at the available gauge locations. As observed (Cox et al. 2005), 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.

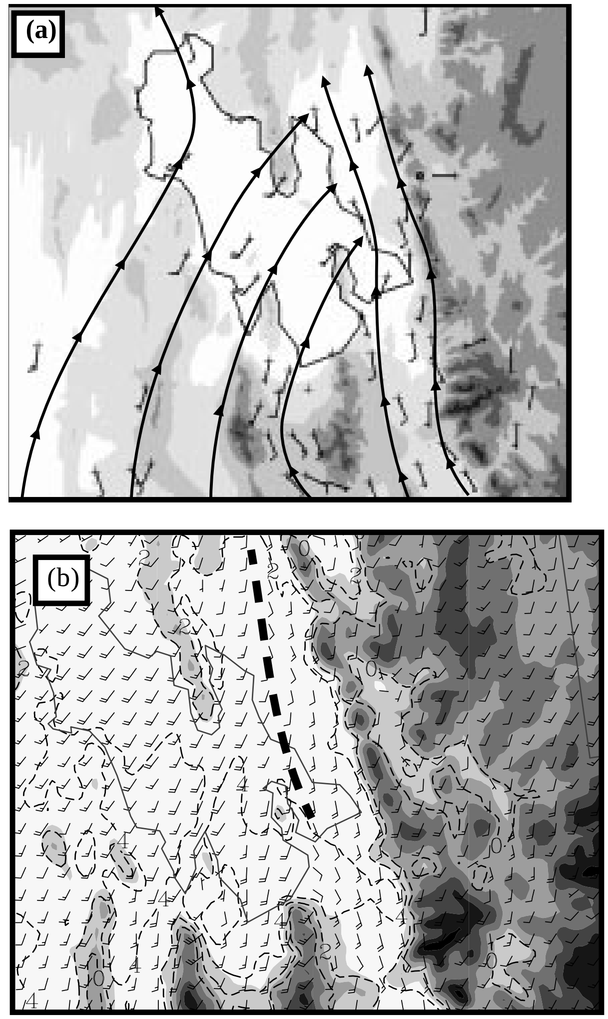

Figure 2. (a) Manual streamline analysis at 1800 UTC 12 Feb Full and half barbs denote 5 and 2.5 m s^{-1}, respectively. (b) Model analysis showing 10-m winds and 2-m temperatures every 1 ^{o}C. A dashed line marks the convergence boundary.

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 a narrow

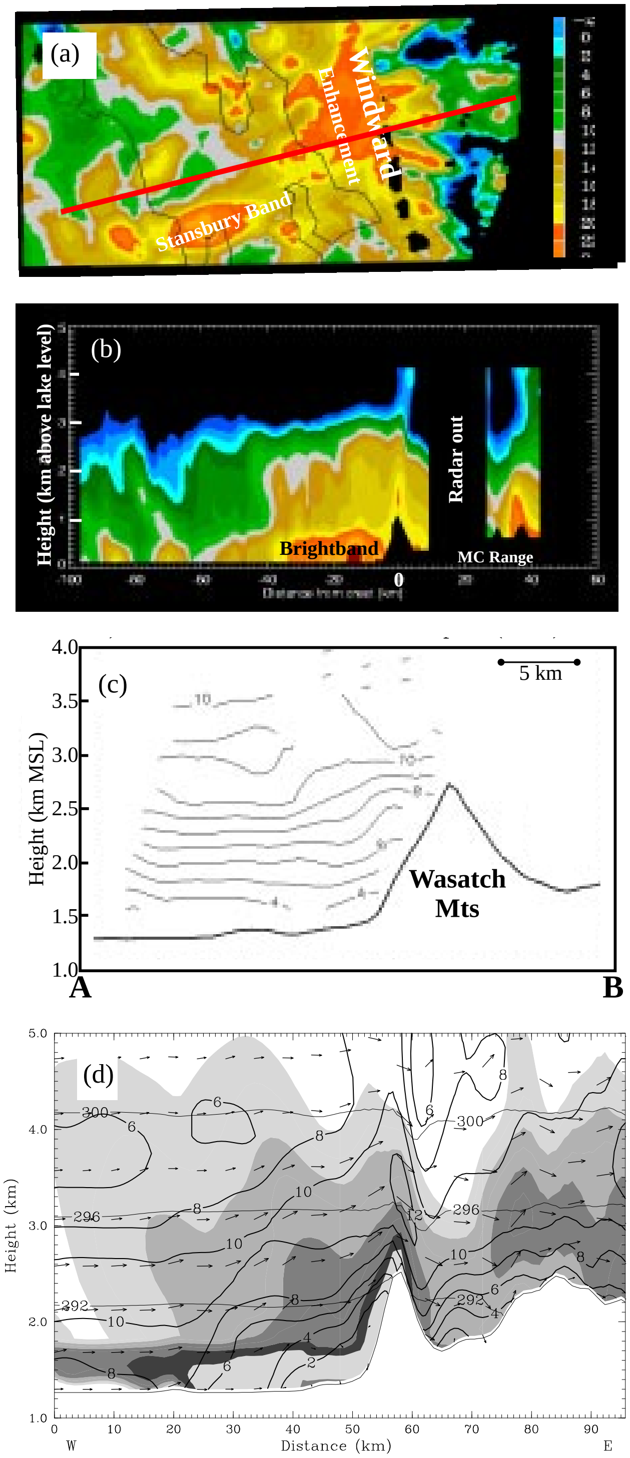

Figure 3. (a) KMTX reflectivity (2265 m MSL) at 1830 UTC 12 Feb 2000. (b) Cross section of reflectivity for the red line in (a). (c) Cross-barrier flow (m s-1) as derived by the upstream DOW radars for the AB portion of the red section. (d) Cross section from 1.33-km MM5 showing circulation vectors, reflectivity, and cross-barrier wind speed (m s-1).

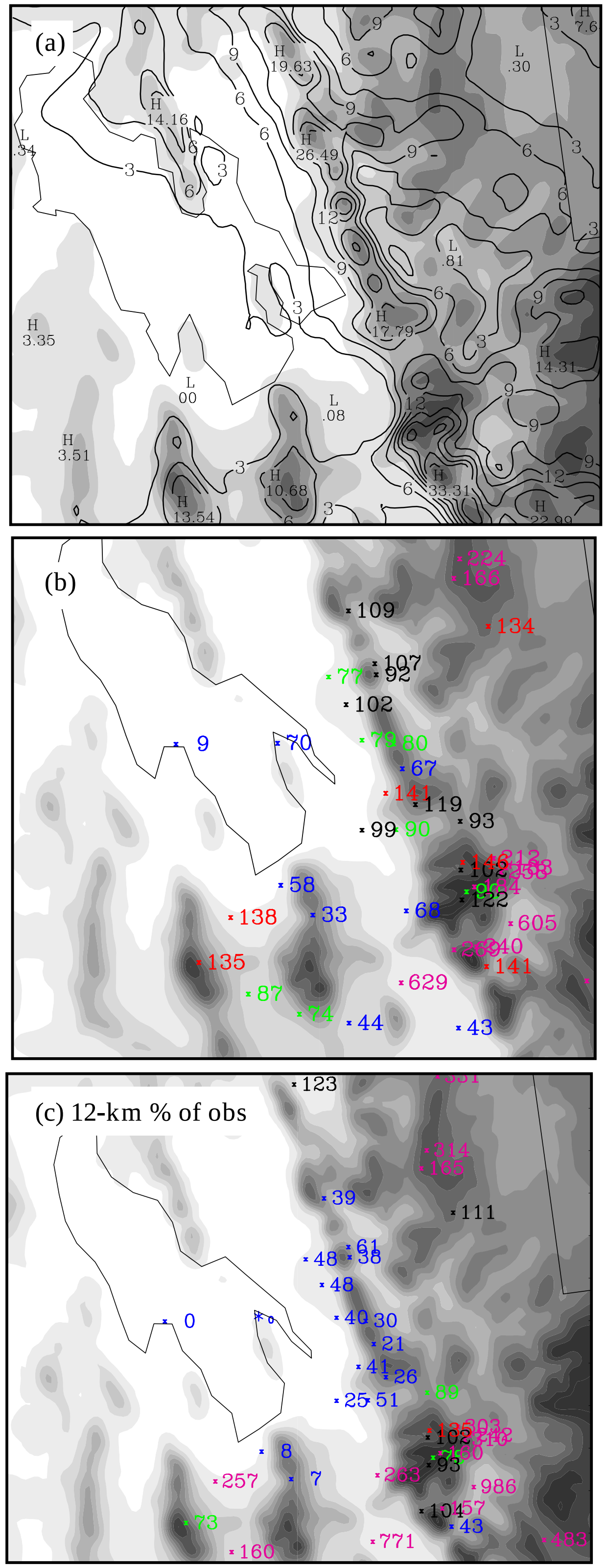

Figure 4. (a) Simulated precipitation (every 3 mm) from the 1.33-km domain from 1800 UTC 12 Feb - 0000 UTC 13 Feb 2000. (b) Model percent of observed precipitation at 1.33-km grid spacing. (c) Same as (a) except for the 12-km grid spacing. Terrain from the 1.33-km domain is shaded for reference.

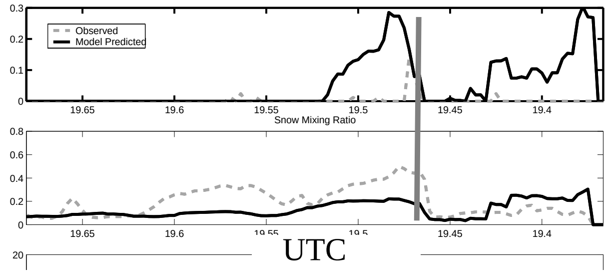

Figure 5. (a) Flight-level time series of liquid water mixing ratio (g kg^{-3}) from the King probe (dashed) and 1.33-km MM5 (solid) at 3756 m MSL. (b) Same as (a) except for the snow mixing ratio derived from the composite 2DGC-2DP particle size spectra (gray dashed) and 1.33-km MM5 (black). The location of the crest is shown by the gray solid line.

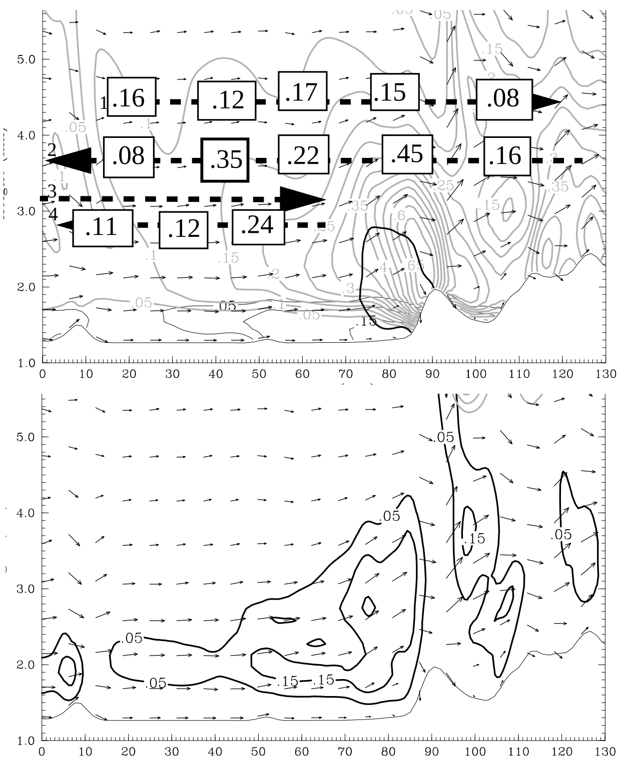

Figure 6. Cross section for the fixed Nos experiment along BC averaged between 1900 and 2000 UTC 12 February showing snow (gray) and graupel (bold) every 0.05 g kg^{-1}, rain (thin solid) every 0.10 g kg^{-1}, and circulation vectors in the cross section. The NOAA P3 legs are shown by the dashed lines 1-4, with select observed snow mixing ratios (g kg^{-1}) in the boxes. (b) Same simulation as (a) except for cloud water (solid) every 0.10 g kg^{-1} and cloud ice (gray) every 0.02 g kg^{-1}.

peak; rather, 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 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. 4c). 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 other wider barriers, such as the Cascades and Sierras, where 12-km grid spacing has been shown to be sufficient, at least 4-km grid spacing is needed top resolve the narrow Wasatch.

The NOAA P3 aircraft completed four stacks of west-southwest to east-northeast oriented flight legs across the central Wasatch (AB line on Fig. 1) over a six hour period when the storm produced the largest amount of precipitation. These flight legs were executed at altitudes corresponding to critical air temperatures for microphysical processes (-5˚ to -20˚ C). A subset of these observations is emphasized in this study. A more detailed comparison and the methods to obtain flight-level mixing ratios of cloud water and snow can be found in Colle et al. (2005).

The model cloud water and snow mixing ratios are compared to the P-3 observations in Figs. 5a and b, respectively, for the four flight legs aloft between 1900 and 2000 UTC. Graupel was not included in the comparisons, since little was observed or simulated at P-3 flight-level. Furthermore, even though the model considers graupel as heavily rimed snow (density = 400 kg m^{-3}), it was not included for the snow comparisons since little riming was observed in the particle imagery. At 3756 m (Fig. 5a), some cloud water (0.1 g kg^{-1}) was observed by the NOAA P3 over the crest, while the model produced over twice as much as observed over the windward slope and to the east of the Wasatch. Some of the excessive snow and cloud water in the model with the lee wave may be the result of too little simulated subsidence over the lee slope (not shown), resulting in a broader positive vertical velocity maximum further downwind and excessive deposition and condensation. In contrast, there was twice as much snow observed upstream of the Wasatch (0.4 g kg^{-1}) than simulated (Fig. 5b), which suggests that the underprediction of snow aloft in the model was compensated by having too much cloud water aloft. At 3130 and 2812 m (not shown), the model also produced two to three times more cloud water than observed upstream of the Wasatch, while the model underpredicted the snow at these levels by about 50%. The model produced excessive cloud water upstream of the Wasatch even though the simulated vertical velocities were weaker than observed (not shown).

Colle et al. (2005) showed that using a different intercept for the snow size distribution can produce relatively large differences in snow and cloud water aloft. The control Reisner2 uses a snow intercept parameter that depends on temperature (NosT) (Thompson et al. 2004). As compared to a fixed Nos = $2x10^{7}$ m^{-4} in other well-known BMPs. A simulation using a fixed Nos for IPEX was completed, which yielded more positive results (Fig. 6). As compared to the CTL for the

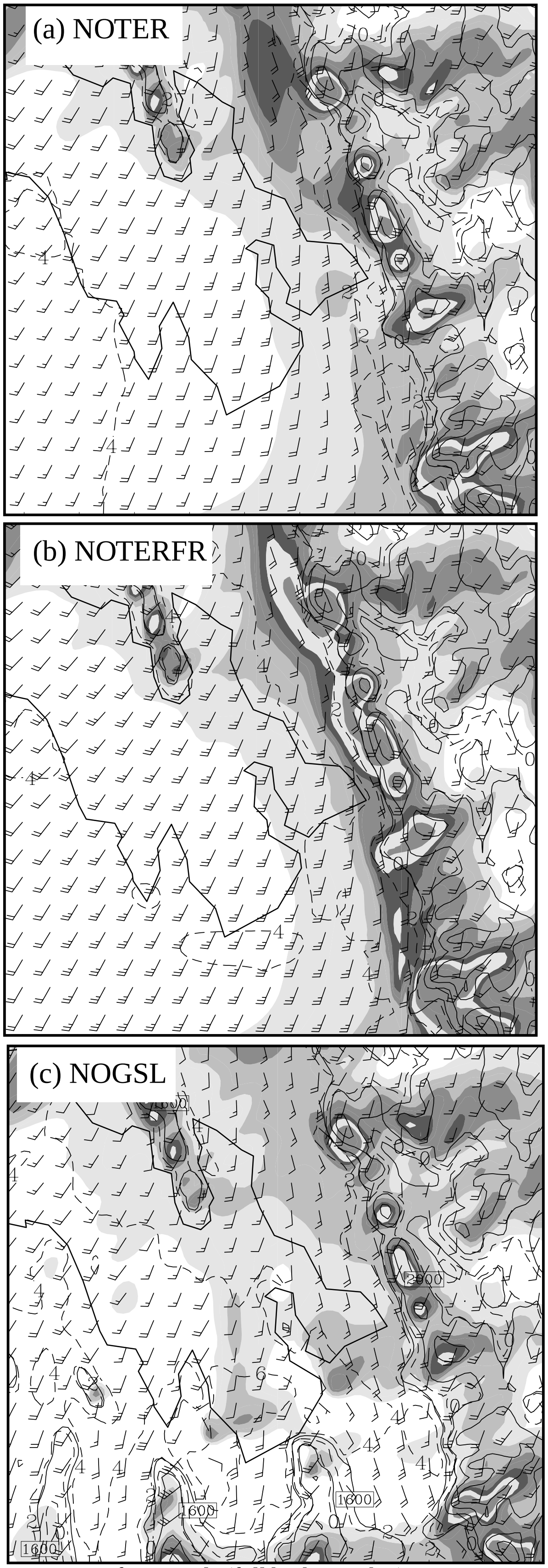

Figure 7. Surface winds (full barb = 10 kts), temperature (dashed every 2 ^{o}C), and model reflectivities (shaded using scale on Fig. 5a) for the (a) CTL, (b) NOTER, (c) NOTERFR, and (d) NOGSL experiments at 1800 UTC 12 February (hour 6).

cross section averaged between 1900-2000 UTC 12 February (Fig. 6a), the fixed Nos nearly doubles the amount of snow aloft from 0.35 to 0.65 g kg^{-1}, and it reduces the amount of graupel and super-cooled water by a factor of two. As a result, as compared to the NOAA P3 flight legs (bold numbers on Fig. 6a), the snow underprediction is less than 0.1 g kg^{-1} over the Wasatch, and the cloud water is within 0.05 g kg^{-1} of the observed. The fixed Nos only increased the 6-h surface precipitation over the central Wasatch and slightly upstream by 1-3 mm (5-10%) (not shown), which actually improved the verification slightly. These fixed NOS simulations suggest that there were many more smaller ice particles in the observations which could grow at the expense of the cloud water as compared to the CTL run.

In order to quantify the impact of upstream terrain and the GSL on the flow and precipitation structures, a series of MM5 sensitivity experiments were completed by systematically removing certain terrain features. The GDAS pressure-level analyses were used to obtain data for areas below the removed terrain, since GDAS can not resolve these small-scale terrain features. First, a simulation was completed in which the terrain to the south of the Lake was removed and replaced by flat land (NOTER run). Without the ridges to the south and their associated downslope warming, the surface temperatures were 1-2 ^{o}C cooler over the southern GSL and adjacent to the Wasatch than in the CTL by 1800 UTC 12 February (Fig. 7a). The cooler temperatures and enhanced pressure gradient adjacent to the Wasatch results in 2-3 m s^{-1} stronger flow in the NOTER run, but the location of the upstream convergence zone to the east of the GSL in the NOTER is similar to the control. The upstream flow convergence was 20-30% stronger in the NOTER immediately west of OGD (not shown), resulting in a somewhat greater precipitation enhancement in the NOTER adjacent to the Wasatch. The largest kinematic differences with the NOTER are immediately to the north of the Oquirrh Mountains, where the absence of flow splitting results in only weak convergence in the NOTER run. The cooler temperatures adjacent to the Wasatch did slow the eastward advance of the windward convergence boundary in the NOTER run by a few hours after 1800 UTC (not shown). Overall, even without the terrain to the south, significant blocking and upstream enhancement of the precipitation occurred.

It is interesting that the upstream scale of the ageostrophic southerlies for the NOTER run extends further west of the Wasatch near the southeast corner of the GSL than the northeast corner of the Lake (Fig. 7a). This suggests that the reduced friction over the GSL may allow the greater southwesterly momentum to extend farther eastward than to the south of the Lake. To test this hypothesis, a simulation was completed in which the flat land to the south was replaced by water at the same temperature of the GSL (NOTERFR run). As a result, this simulation is analogous to the situation along the West Coast, in which flow over water encounters an elongated coastal barrier. With the larger area of upstream water in the NOTERFR run (Fig. 7b), the surface winds are 3 m s^{-1} stronger and slightly more southwesterly than the NOTER simulation. As a result of the stronger ambient southwesterlies in the

NOTERFR run, the upstream scale of the blocked flow is reduced by 5-10 km as compared to the CTL and NOTER, especially to the southeast of the GSL. However, the flow is still blocked by the Wasatch in the NOTERFR run. The combination of stronger upstream southwesterlies and the nearly terrain-parallel flow results in stronger low-level convergence and more intense precipitation 5-10 km upstream of the Wasatch than the control simulation.

To further isolate the impact of the GSL on the flow blocking and precipitation structures, the Lake was replaced with a flat land surface and a ground temperature similar to that just west of the Lake (NOGSL run). With the increased surface friction over the Lake in the NOGSL run the flow was 2-3 m s^{-1} weaker over the Lake than the control (Fig. 6c). The transition to south-southwesterly flow also extended 5-10 km further west in the NOGSL run. The low-level convergence was 30-40% weaker in the NOGSL than the control (not shown), which resulted in weaker precipitation enhancement west of the Wasatch in the NOGSL. This result in consistent with the hypothesis in Cox et al. (2005), in which the differential surface drag to the east of the Lake enhanced the wind transitions and low-level convergence to the east of the Lake. Therefore, the GSL is an important factor in modulating the flow blocking response adjacent to the central Wasatch.

4. CONCLUSIONS

This paper investigates the kinematic flow and precipitation evolution of a winter storm over and upstream of the Wasatch Mountains (IPEX IOP3) using a multiply nested version of the Pennsylvania State University-National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5). Validation using in-situ aircraft data, radiosondes, ground-based radar, and surface observations showed that the MM5, which featured four domains with 36-, 12-, 4-, and 1.33- km grid spacing, realistically simulated the observed partial blocking of the 8-12 m s^{-1} ambient southwesterly flow and development of a convergence zone and enhanced lowland precipitation region upwind of the initial Wasatch slope.

Accurate simulation of the observed precipitation over the central Wasatch Mountains (within 25% of observed at all stations) required a horizontal grid spacing of 1.33 km. Despite close agreement with the observed surface precipitation, the Reisner2 bulk microphysical scheme produced too much supercooled cloud water and too little snow aloft. A model microphysical budget revealed that the Reisner2 generated over half of the surface precipitation through riming and accretion, rather than snow deposition and aggregation as implied by the observations. Using an intercept for the snow size distribution that allows for greater snow concentrations at warmer temperatures improved the snow predictions aloft and reduced the cloud water overprediction.

Sensitivity studies illustrate that the reduced surface drag of the Great Salt Lake (GSL) enhanced the convergence zone and associated lowland precipitation enhancement upstream of the Wasatch Mountains. The presence of mountain ranges south of the Great Salt Lake appears to have weakened the along-barrier flow and windward convergence, resulting in a slight decrease in windward precipitation enhancement.

5. ACKNOWLEDGEMENTS

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