Sensitivity Study of a Simulated Winter Storm to WRF Model Physics over Complex Terrain

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1. INTRODUCTION

The WRF model generally simulates fronts and cyclones reasonably well as baroclinic instability is a well understood phenomenon. However, simulating the timing and detailed structures of fronts and cyclones over complex terrain remains a challenge (Cheng and Steenburgh 2007). Part of the problem lies in the fact that numerical models do not resolve the underlying orography adequately.

Several studies have examined the sensitivity of fronts and cyclones to model physics over the ocean or flat terrain in mesoscale models (e.g., Zhang et al. 1999). Nonetheless, fewer studies have examined the sensitivity of fronts and cyclones over complex terrain to model physics in the WRF model at very high resolution. Physics parameterizations in the WRF model, including multiple choices of land surface model (LSM), planetary boundary layer (PBL), radiation, and microphysics schemes were formulated and mainly tested for idealized scenarios and/or over flat terrain. Thus, it is important to evaluate the performance of these schemes and their combined performance for complex terrain.

In this study, we simulated the 16 – 18 April 2009 winter storm in Colorado using the NCAR/ATEC WRF-ARW-based Real-Time Four-Dimensional Data Assimilation (RTFDDA) and forecasting system (Liu et al. 2008). A series of high resolution sensitivity experiments (∆x = 3.3 km) were conducted with different combinations of surface layer, LSM, PBL, and microphysics in WRF to study the performance and roles of these physics processes in simulating the aforementioned winter storm. This study is part of a NCAR-Xcel Energy joint development of a WRF-RTFDDA based wind forecasting system. The goal of this study is to understand the impact of WRF physics options for explicit prediction (i.e. without sub-grid cumulus parameterization) of winter storms over complex terrain.

2. SYNOPTIC WEATHER

A north-south oriented cold front from the April 16-18 storm propagated toward southeast and stalled over the Front Range region from 1200 UTC 16 April to 0000 UTC 18 April (Fig. 1) when the cutoff low associated with this storm stalled as it approached the Four Corners region (not shown). As a result, several feet of snow fell in the Front Range area.

Figure 1. Surface analysis courtesy of weather.unisys.com valid at 1200 UTC 16 April 2009 (top panel); 0000 UTC 17 April 2009 (bottom panel).
3. METHODOLOGY

The modeling study used the three-level nested grid setup proposed for the Xcel RTFDDA operation. The model contains a very large fine grid mesh at $\Delta x = 3.3$ km, covering the Rocky Mountains and the states in the Great Plains so that the flow in the complex terrain associated with the Rockies can be better resolved (Table 1; Fig. 2).

<table>
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<tr>
<th></th>
<th>$N_x$</th>
<th>$N_y$</th>
<th>$N_z$</th>
<th>$\Delta x$</th>
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<td>113</td>
<td>36</td>
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<tr>
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<td>252</td>
<td>231</td>
<td>36</td>
<td>10 km</td>
</tr>
<tr>
<td>Grid 3</td>
<td>540</td>
<td>570</td>
<td>36</td>
<td>3.3 km</td>
</tr>
</tbody>
</table>

Table 1. The WRF grid configuration.

WRF was cold started on 0000 UTC 16 April 2009 with initialization and boundary conditions from GFS. We conducted eight sensitivity experiments by varying the surfaced layer scheme, LSM, PBL scheme, and microphysics (Table 2). We also conducted additional experiments with different radiation options but they are not shown to economize space.

<table>
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<tr>
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<th>surface layer</th>
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<th>PBL</th>
<th>microphysics</th>
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<td>Noah</td>
<td>YSU</td>
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</table>

Table 2. List of Experiments. M-O = Monin-Obukhov; MYJ = Mellor-Yamada-Janjic; TKE = turbulent kinetic energy.

4. RESULTS

The different sensitivity experiments generally had similar results for the large-scale synoptic flow (not shown). Furthermore, WRF generally simulated the large-scale flow well. For example, the cutoff low associated with the April 16-18 storm was excellently simulated by WRF as it approached the Four Corners region as compared to GFS analysis (Fig. 3). Since vorticity is a derivative of the velocity fields, the higher resolution WRF naturally showed more detailed structures than GFS.

The 6-h accumulated precipitation from radar estimate (courtesy of CISL from NCAR) at 0600 UTC 17 April showed a north-south-oriented band of precipitation from central Texas to north-central and eastern Colorado and eastern Kansas and Nebraska as well as western Oklahoma (Fig. 4). All of the WRF simulations showed similar patterns in the accumulated precipitation albeit with different fine-scale structures. Due to limited space, only exp. SLPM1111 is shown. The general pattern in accumulated precipitation from GFS was quite similar to that of WRF but WRF offered more detailed mesoscale structure as the finest grid mesh had a grid spacing of 3.3 km. This is not surprising as the initial and boundary conditions...
of WRF came from GFS. Both GFS and WRF produced precipitation in the high terrains of the Utah, Colorado, and Wyoming which was notably absent in the radar estimate. This does not mean that GFS or WRF was incorrect as the radar coverage generally does poorly in these areas.

The northwest-southeast-oriented precipitation band from north-central Colorado to southeastern Colorado in GFS and WRF matched the pattern as in the radar estimate. However, GFS overestimated the precipitation amount. WRF does a better job than GFS as the precipitation was not as intense. The major discrepancy in GFS and WRF occurred in the observed precipitation band in central Texas. Both GFS and WRF shifted the band slightly eastward and were not as intense as in the radar estimate.

Figure 3. 500-hPa geopotential height (contours at every 30 m) and absolute vorticity (shading; in units of $10^{-5}$ s$^{-1}$) superposed with wind barbs (half barb = 2.5 m s$^{-1}$; full barb = 5 m s$^{-1}$) for GFS analysis (top panel); exp. SLPM1111 from domain 3 (bottom panel).

Figure 4. 6-h accumulated precipitation (mm) valid at 0600 UTC 17 April 2009 for radar estimate (top panel); GFS forecast (middle panel); exp. SLPM1111 from domain 3 (bottom panel).
From the results shown in the above, WRF does well in simulating the large-scale dynamics. It would be of interest to see how WRF performed at a point forecast since numerical models are often used in point forecasts. Figure 5 shows the wind speed time series at a meteorological tower in Northern Colorado (40.9°N, 103.9°W) near the Colorado/Nebraska border. This area is near the I-80 corridor, notorious for its high wind speed conditions. GFS generally underpredicted the wind speed. This is not surprising as the GFS model is quite coarse and cannot resolve the underlying orography which can play a role in affected the wind in complex terrain.

All of the WRF experiments captured the surge in wind speed at the Northern Colorado from site 2100 UTC 16 April to 0200 17 April due to the advancing cold air from the north (Fig. 5). Certainly, the fact that the higher resolution WRF was able to better resolve the underlying terrain helped to provide a better wind speed forecast than GFS. Comparing the different experiments, we found that for this case, the WRF physics setup that performed the best was, Monin-Obukhov (Janjic) surface layer scheme/Mellor-Yamada-Janjic PBL scheme with RUC LSM (Exp: SLPM2221 in Fig.5). Due to the constraint of space, the results from the different microphysics experiment will not be discussed. We are in the process of conducting detailed analysis of the output of the model experiments.

4. DISCUSSION AND CONCLUSION

WRF generally simulated the large-scale dynamics well. With the higher resolution in WRF, it simulated the precipitation field better than the coarser GFS, especially over complex terrain. Nonetheless, both GFS and WRF had problems simulating a precipitation band in central Texas at the correct location and magnitude.

In terms of point forecast at a site near the Colorado/Nebraska border with climatologically high wind speed, WRF outperformed GFS in predicted the wind speed surge as cold air advanced from the north. GFS generally underpredicted the wind speed in this location was unable to capture surge in wind speed. The problem with GFS was most likely due to the coarse resolution and its inability to resolve the underlying orography. For this event at this location, the physics combination with Monin-Obukhov (Janjic) surface layer scheme, Mellor-Yamada-Janjic PBL scheme, and RUC LSM produced the most favorable wind variation in this Northern Colorado site in comparison with observations.

5. ACKNOWLEDGEMENT

This research has been supported by Xcel Energy.

6. REFERENCES

