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Advances in the WRF model for convection-resolving forecasting

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Abstract. The Weather Research and Forecasting (WRF) Model has been designed to be an efficient and flexible simulation system for use across a broad range of weather-forecast and idealized-research applications. Of particular interest is the use of WRF in nonhydrostatic applications in which moist-convective processes are treated explicitly, thereby avoiding the ambiguities of cumulus parameterization. To evaluate the capabilities of WRF for convection-resolving applications, real-time forecasting experiments have been conducted with 4 km horizontal mesh spacing for both convective systems in the central U.S. and for hurricanes approaching landfall in the southeastern U.S. These forecasts demonstrate a good potential for improving the forecast accuracy of the timing and location of these systems, as well as providing more detailed information on their structure and evolution that is not available in current coarser resolution operational forecast models.

1 Introduction

The WRF modeling project is a multi-agency effort intended to develop a next-generation mesoscale forecast model and data-assimilation system that will advance both the understanding and prediction of mesoscale weather, and accelerate the transfer of research advances into operations. The model is being developed as a collaborative effort among NCAR's Mesoscale and Microscale Meteorology (MMM) Division, NOAA's National Centers for Environmental Prediction (NCEP) and Forecast System Laboratory (FSL), the Department of Defense's Air Force Weather Agency (AFWA) and Naval Research Laboratory (NRL), the Center for the Analysis and Prediction of Storms (CAPS) at the University of Oklahoma, and the Federal Aviation Administration (FAA), along with the participation of a number of university scientists. The model is designed to improve fore-

cast accuracy across scales ranging from cloud to synoptic, with priority emphasis on horizontal grid resolutions of 1–10 km.

The WRF model is well suited for a wide range of applications, from idealized research simulations to operational forecasting, and has the flexibility to accommodate future enhancements. A research version of WRF is maintained and supported for broad community use, and as of September 2005 over 3200 users have registered to download the model code. Over half of these users are distributed across some 67 foreign countries. Annual WRF users workshops and biannual tutorials are offered to assist a rapidly growing user base. Numerous real-time forecasting experiments are being conducted by both WRF partners and community users to evaluate WRF performance in a variety of forecast applications (see http://wrf-model.org/plots/wrfrealtime.php).

The WRF model is also transitioning into use in a number of operational forecast centers. NCEP is currently running versions of WRF in their High Resolution Window Domains, and as members of their Short-Range Ensemble Forecasts. NCEP is adapting WRF to become the basis for their North American Meso Model, Rapid Refresh Model, and Hurricane Forecast Model over the next year or two. AFWA and the US Navy are also transitioning to WRF for forecasting in their worldwide theatres in the near future. In addition to applications in the US, operational centers in South Korea, India, Israel, Taiwan, and Greece are implementing new forecast systems based on WRF.

2 Model characteristics

The WRF software has a modular, hierarchical design that provides good portability and efficiency across a range of foreseeable parallel computer architectures. The infrastructure supports multiple dynamic cores and physics options, model coupling, two-way interacting moving nested grids, and interoperability with other common modeling infrastructures such as the Earth System Modeling Framework
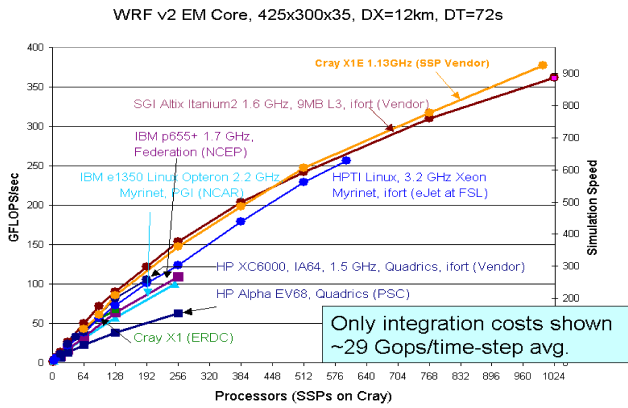

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Fig. 1. WRF ARW performance tests on major supercomputer systems.

Fig. 2. Idealized simulations conducted with the ARW version of WRF. **(a)** Horizontal cross-section of temperature fluctuations in a 3-D LES simulation of the PBL with a 50 m grid. **(b)** Potential temperature contours in a 2-D simulation of a density current with a 100 m grid at 5, 10, and 15 min. **(c)** Cloud field and surface temperature at one hour in a 3-D simulation of a splitting supercell in a horizontally homogeneous environment with a 1 km grid. **(d)** Potential temperature contours in a 2-D mountain-wave simulation with a 20 km grid without rotation. **(e)** Horizontal cross-section of surface temperature, winds, and condensed water (shaded) in a 3-D simlation of a baroclinic wave in a channel at 6 days with a 100 km grid.

(ESMF) (Michalakes et al., 2005). Performance benchmarks on major supercomputers are conducted on an ongoing basis and periodically updated on the web at http://www.mmm.ucar.edu/wrf/bench. Figure 1 illustrates the recent benchmark performance for a 48 h 12 km resolution case over the continental US domain, depicting good scaling over as many as 1024 processors (Michalakes, personal communication).

The WRF modeling system presently supports two different dynamic solvers, the Nonhydrostatic Mesoscale Model (NMM) core developed by NCEP as a nonhydrostatic enhancement of the operational Eta Model, and the Advanced Research WRF (ARW) core developed by NCAR. In evaluating WRF for convection-resolving applications, we have utilized the ARW core for the forecasts discussed in this study. The ARW integrates the nonhydrostatic, compressible equations with an Arakawa C-grid staggering using a terrain-following hydrostatic pressure vertical coordinate. It conserves mass, momentum, dry entropy, and scalars using the flux form for all prognostic equations. The numerics employ 3rd order Runge-Kutta split-explicit time differencing together with higher order advection (typically 5th order upwind or 6th order centered differencing, and an option for monotonic advection). The ARW supports two-way interacting moving nested grids and offers numerous physics packages adapted from the MM5 and Eta models and contributed by the research community. Technical details of the ARW system are presented in Skamarock et al. (2005). To verify the integrity of the ARW solver over a wide range of applications, idealized simulations have been conducted over a wide range of grid resolutions and demonstrated good agreement with known solutions or previous research results (see Fig. 2).

3   Convection-resolving MCS forecasting

Because cumulus parameterization becomes increasingly problematic as the numerical resolution in NWP models continues to advance, we are placing increased emphasis on convection-resolving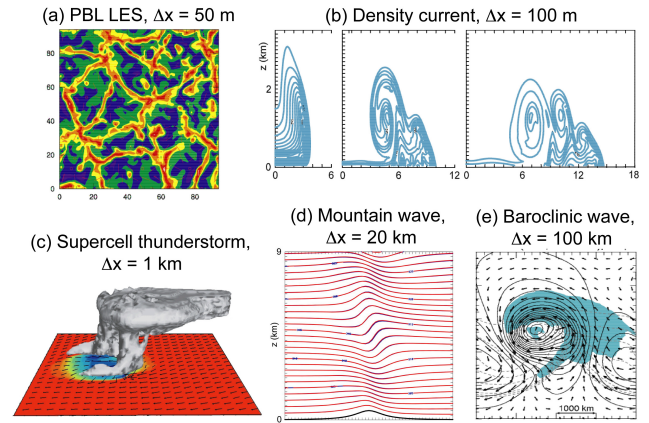 forecast applications. Moving toward convection-resolving model grids provides the opportunity to bypass the dilemma of cumulus parameterization, but raises numerous other issues that need to be addressed. These issues include: requirements for small-scale observations and data assimilation, refinements in model physics, and new approaches for model verification. Recent investigations of convective-scale numerical forecasting have demonstrated the potential for improved forecasting of convective events, but also deficiencies related to the issues mentioned above (cf. Bernadet et al., 2000; Ducrocq et al., 2002; and Kotroni and Lagouvardos, 2004). We have begun testing the capabilities and limitations of WRF in forecasting convective events with horizontal grids of 4 km and below, relying on the explicit treatment of convection, without cumulus parameterization.

As part of this testing, we have conducted real-time forecasts during the spring and early summer months in the central U.S. for the past three years. These forecasts were conducted with a 4 km horizontal grid over domains ranging from 2000×2000 km in 2003 to 3900×3000 km in 2005, centered over the central plains of the U.S. These forecasts were conducted using explicit microphysics, with no cumulus parameterization. Although a 4 km grid is too coarse to resolve detailed aspects of convection, studies have shown the 4 km should be capable of resolving the major features of convective systems (cf. Weisman et al., 1997). Forecasts were initialized from 40 km Eta model analyses at 00:00 UTC each day and run out to 36 h. ARW forecasts for these three spring/summer forecast experiments are
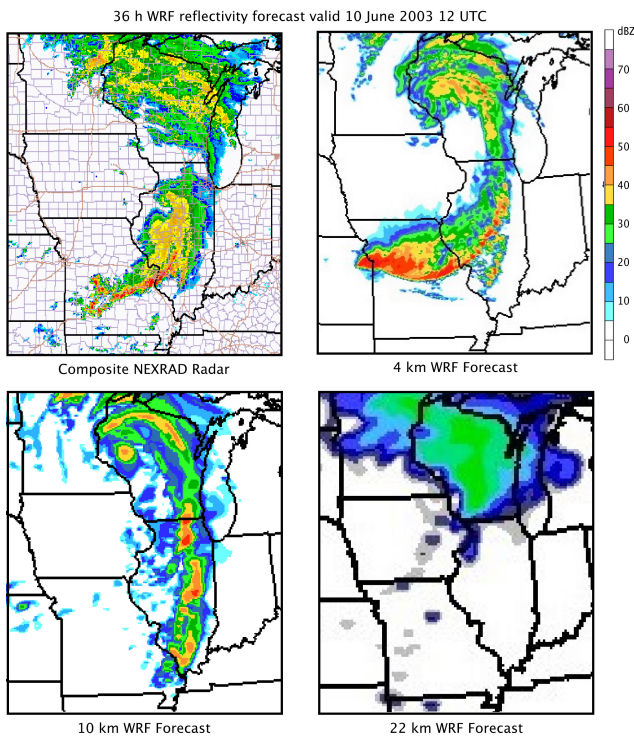
36 h WRF reflectivity forecast valid 10 June 2003 12 UTC

Fig. 3. 36 h WRF reflectivity forecast valid 10 June 2003 12:00 UTC. The 4 km forecast has no cumulus parameterization, while the 10 km and 22 km forecasts utilize the Kain-Fritsch cumulus parameterization. The composite NEXRAD radar reflectivity is included for comparison.

archived at: http://www.joss.ucar.edu/bamex/catalog (2003); http://www.joss.ucar.edu/wrf-2004/catalog (2004); and http://www.joss.ucar.edu/wrf-2005/catalog (2005). Further details of the model configuration are discussed by Done et al. (2004) and Weisman et al. (2004).

An illustration of the capabilities of the convection-resolving forecasts is displayed in Fig. 3, depicting the 36-hour 4 km WRF forecast for radar reflectivity valid on 10 June 2003 at 12:00 UTC. While there was little convective activity early in the forecast, a strong baroclinic system developed during the forecast period, producing a concentrated line of convection extending across Illinois and Missouri at 36 h. At this resolution the cellular structure of the squall line is quite apparent. For comparison, forecasts are also included in Fig. 3 for 10 km and 22 km grids, both using a Kain-Fritsch cumulus parameterization. At 10 km, the structure and location of the squall line is noticeably degraded, while at 22 km, the line is not present in the resolved microphysics (although precipitation occurs in that area through the cumulus parameterization).

During the 2003 forecast experiment, there was significant variation of the number of mesoscale convective systems (MCSs) from day to day, as indicated in Fig. 4. The 4 km WRF forecasts captured this variability quite well, with a somewhat lower correlation in the 10 km forecasts. The superior behavior of the 4 km forecasts is reflected in the
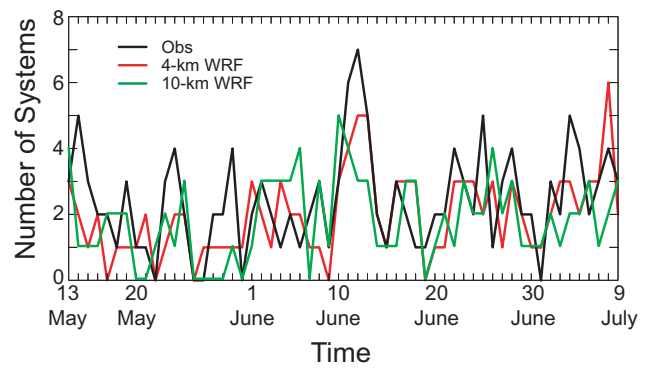

Fig. 4. Time series for the number of MCSs forecast and observed each day during the 2003 forecast experiment. The black line represents the number observed MCSs, while the red and green lines represent the number of MCSs forecast with the 4 km and 10 km WRF, respectively (from Done et al., 2004).
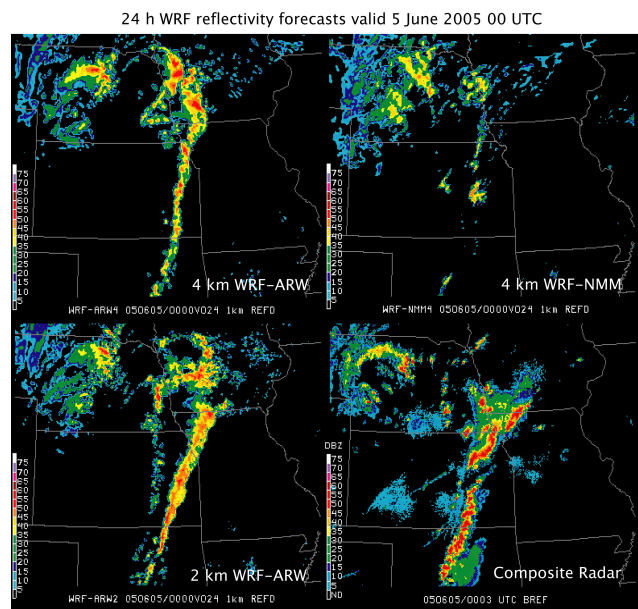
24 h WRF reflectivity forecasts valid 5 June 2005 00 UTC

Fig. 5. 24 h forecast for an intense squall line forming across Kansas and Oklahoma at 00:00 UTC on 5 June 2005. Forecast reflectivity fields displayed for the 4 km WRF ARW (upper left), 2 km WRF ARW (lower left), and 4 km WRF NMM (upper right), together with the composite radar observations (posted at http://www.spc.noaa.gov/exper/Spring_2005/archive/20050429/).

anomaly correlation for each forecast time series with the observed series; the 4 km forecasts have a correlation of 0.57, while correlation for the 10 km forecasts is 0.35 (Done et al., 2004).

An example of a convective forecast from the 2005 program is shown in Fig. 5 for the case of an intense squall line that formed over Kansas and Oklahoma on 5 June 2005. The 4 km WRF ARW forecast accurately captures the timing, structure, and location of the line, as shown in the 24 h forecast. The University of Oklahoma was also conducting real-time forecasts during this experiment using a 2 km horizontal grid. These forecasts tended to be quite similar to the 4 km
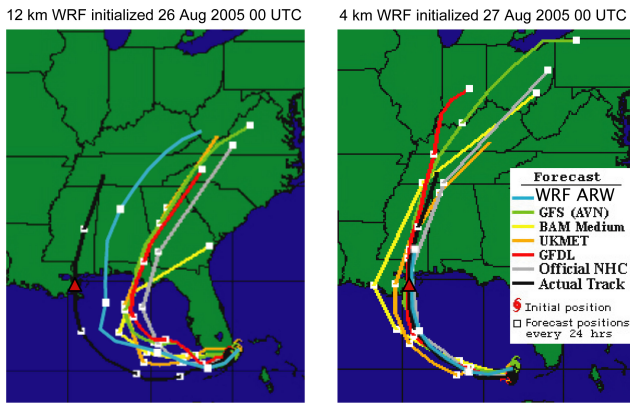
Fig. 6. Track forecasts for Hurricane Katrina from a number of models initialized at 00:00 UTC on 26 August 2005 (86 h prior to landfall – left panel) and at 00:00 UTC on 27 August 2005 (62 h prior to landfall – right panel). The location of landfall near the Louisiana-Mississippi border is indicated by the red triangle.

Fig. 7. Maximum radar reflectivity forecast in 4 km nested moving grid forecast at landfall 62 h after initialization at 00:00 UTC on 27 August 2005. The corresponding reflectivity from the Mobile, Alabama radar is displayed for the area indicated by the red box.

forecasts, but provided more details of the cellular convective structure (see Fig. 5). For comparison, the corresponding 24 h forecast from the WRF NMM is also displayed in Fig. 5; at this time the squall line is not yet well established as it developed slightly later in the NMM forecast.

Overall, these real-time experiments revealed surprising ability to forecast convective systems out to 36 h. In comparison with coarser-grid forecasts, the 4 km WRF forecasts provided a much better indication of the likely mode of convection (bow echoes, mesoscale convective vortices, supercell lines) as well as the timing and location of convective initiation. Beginning with coarse resolution (40 km) initial data, we found that realistic convective scale structure spins up quickly over the first 6 h of the forecasts, consistent with the rapid development of kinetic energy at these scales documented by Skamarock (2004). The higher resolution forecasts also produced more accurate representation of gust fronts and system propagation, although there was occasional development of some spurious isolated convection. There are some systematic biases in the forecasts in that they tend to overpredict precipitation and convective systems tend to decay more slowly than observed. However, the improved realism of the forecasts has provided significant value to forecasters, even for forecasts that do not exhibit improved quantitative accuracy in the timing and location of convection. The convection resolving forecasts are quite sensitive to the microphysical parameterization used in the model, suggesting that this is an important area for further research in advancing storm-scale NWP.

4 Convection-resolving hurricane forecasting

High-resolution hurricane forecasts offer the opportunity to better resolve the eyewall structure and convective rainbands, and thereby improve the prediction of hurricane track and intensity. To assess the potential benefits of higher resolution, we have also conducted real-time forecasts with a 4 km grid
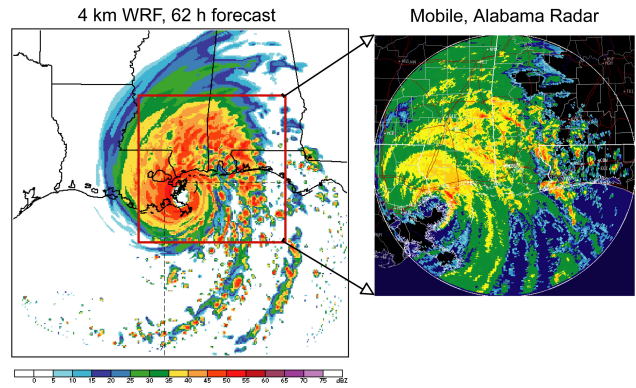
for hurricanes approaching landfall in the southeastern U.S. during the hurricane seasons in 2003–2005. For the 2005 season, we implemented a nested moving mesh in which a 4 km grid is nested within a larger outer 12 km grid and moves automatically to remain centered on the hurricane as determined by an a vortex tracking algorithm (Michalakes, et al., 2005). The moving nest provides a significant increase in computational efficiency by permitting a smaller nested domain needed to contain the hurricane during the forecast period.

Forecasts have been conducted for all of the major landfalling hurricanes during this period (Isabel in 2003; Charlie, Florence, Ivan in 2004; and Katrina, Rita, Wilma in 2005). These forecasts demonstrate highly realistic hurricane structures, even for the major rainbands. The intensity and track forecasts are quite accurate, and the heavy precipitation is well represented, despite the simple microphysics.

Hurricane Katrina provides a good illustration of the performance of the high-resolution WRF hurricane forecasts. Katrina moved northward across the Gulf of Mexico as a category five hurricane, and came ashore near New Orleans on 29 August 2005 as a strong category three storm. The hurricane caused 1181 deaths and over $200 billion in damage, making Katrina the most expense natural disaster in U.S. history. The WRF forecasts were initialized from the 1/6 degree (approximately 18 km) GFDL analyses, and run with a 12 km grid until the hurricane was within three days of landfall, after which forecasts were initialized and run with the 4 km moving nest. Figure 6 displays track forecasts for WRF along with a number of operational models. The 12 km WRF forecast initialized on 26 August 00:00 UTC (86 h prior to landfall) predicted landfall near Mobile, Alabama, about 150 km east of the actual location near the Louisiana-Mississippi border. At this time, however, other operational models were tracking significantly farther to the east, and the official forecast was estimating landfall in the middle portion of the Florida panhandle. By 00:00 UTC on 27 August (62 h prior to landfall), all of the model tracks had
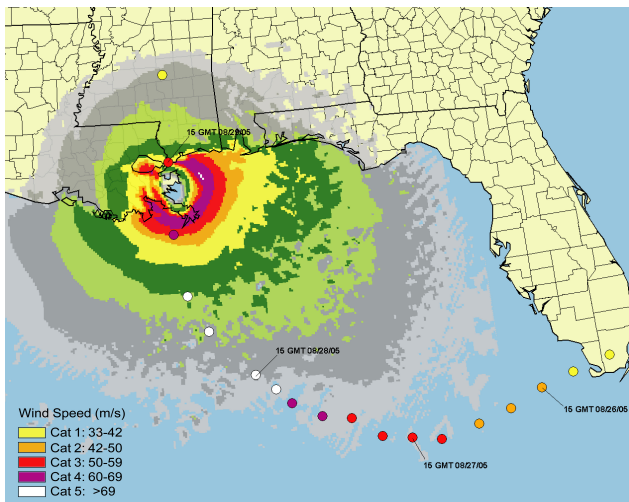
Fig. 8. Surface winds in the 4 km nested moving grid forecast at landfall 62 h after initialization at 00:00 UTC on 27 August 2005. Colored circles represent the actual strength and location of the hurricane during the forecast period.

shifted significantly to the west; the 4 km WRF forecast, as well as most of the operational models, were in good agreement with the actual track.

Figure 7 displays the maximum reflectivity in the model forecast initialized on 27 August 00:00 UTC at the time of landfall at 62 h into the forecast. The overall distribution of precipitation agrees well with the observed reflectivity recorded by the radar at Mobile, Alabama at this time, with the heavy precipitation wrapping around the northern flank of the hurricane, and rainbands spiraling away from the hurricane to the southeast. This behavior is typical of other 4 km WRF hurricane forecasts, in which there is often remarkable correspondence between forecast and observed rainbands.

Hurricane Katrina reached category five strength crossing the central Gulf of Mexico (Fig. 8) and then decreased in strength, transitioning to category three as it came onshore. The WRF forecast hurricane intensified more slowly, reaching category 5 strength approaching landfall and rapidly decreasing to category 3 as observed as Katrina came onshore. The eyewall diameter was somewhat larger than observed, a tendency also seen in other hurricane forecasts that requires further evaluation.

5 Summary

The convection-resolving WRF forecasts for hurricanes and mesoscale convective systems display realistic convective-scale features that provide a more accurate depiction of the structure and evolution of these systems. While these experimental forecasts demonstrate the potential for improved forecasts, significant challenges remain in seeking to fully realize that potential. Smaller scale features become increasingly important in high-resolution forecasts and little of this information is contained in convectional

analyses. More small-scale observations are needed for operations (such as Doppler radar) as well as sophisticated data-assimilation techniques to make the best use of these data. It will be important to adopt cycling data-assimilation, in which the previous high-resolution forecast provides the first guess for the next assimilation cycle, in order to maintain fine-scale structures in the model from one forecast period to the next. Further improvements in the treatment of model physics such as cloud microphysics, radiation, and PBL processes are also needed, as most of the parameterized physics packages used in NWP models have been developed for large-scale coarser grid applications. Finally, new verification techniques to evaluate model performance are required that properly assess the new kinds of information provided by these forecasts.

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