WRF Simulations of Hurricane Irene during its Interaction with the U.S. East Coast

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Introduction

During the period when Hurricane Irene was moving northward along the U.S. east coast, the storm encountered increasing wind shear and cooler sea surface temperatures and was slowly weakening as it tracked from the Carolinas to New England. Despite this, Irene caused widespread and significant impacts along the East Coast, from severe flooding from the mid-Atlantic states into eastern New York and western New England, to widespread wind damage and power outages across a large portion of southern and central New England. The objective of this study is to conduct a number of retrospective Weather Research and Forecasting Model (WRF) simulations in an effort to reconstruct the storms surface wind field and rainfall during the period of August 27–29, 2011. The Advanced Research WRF (ARW) version of the model is used.

Methodology

The initial WRF simulation, which is referred to as Test1a, used a 12-km resolution parent domain and a 4-km nested grid with 40 vertical levels. Figure 1 shows the modeling domains. The grids were two-way interactive for Test1a. The Kain-Fritsch cumulus parameterization scheme was used on the 12-km domain, while convection was explicitly simulated on the 4-km grid. The WSM5 microphysics scheme, the YSU PBL scheme, and the NOAH land surface model were implemented on both domains. The National Centers for Environmental Prediction (NCEP) 1 degree final analysis (FNL) data were used for the initial and lateral boundary conditions along with the Real Time Gridded 1/12 degree sea surface temperature data. The hurricane was initialized using just the FNL data. Tropical cyclone bogussing was not used since the storm had a large circulation envelope, a poorly defined inner core structure, and a highly asymmetric wind field while it was along the East Coast during the modeling period. Analysis nudging FDDA was performed on the 12-km domain using the FNL gridded analysis data. Additional simulations were conducted to examine the sensitivity of the model to the PBL and cumulus parameterization schemes. The schemes were based in part on previous WRF modeling studies (Davis et al. 2008 and LI and PU 2009). A final test simulation was conducted to examine the effect of initializing the storm 24 hours earlier. Table 1 shows a summary of the test simulations examined.

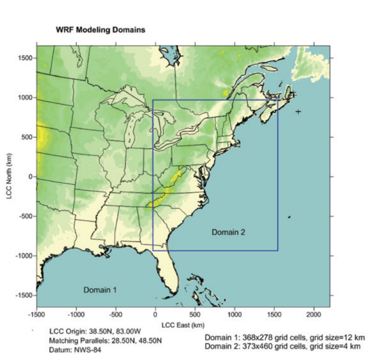

Figure 1. WRF 12-km and 4-km domains.

The WRF surface wind field was compared against the Hurricane Research Division's HWIND analysis, as well as with observations at selected land-based surface stations and buoys.

Figure 2 shows a plot of five surface stations used for validation. These include Cape Lookout and Cape Hatteras, North Carolina; Bishops Head, Maryland; Buzzards Bay, Massachusetts; and Providence, Rhode Island. For comparisons with direct observations, time series plots were constructed from the observations and compared against time series from the WRF simulation at the observation locations and the root mean square errors were computed.

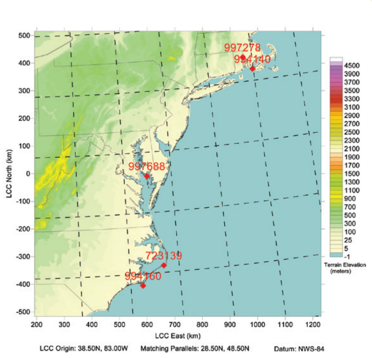

Figure 2. Surface meteorological stations used in the evaluation.

Table 1. Summary of WRF sensitivity simulations

WRF Test Run	Nesting	Cumulus	PBL	Initialization
Test1a	2-way	Kain-Fritsch	YSU	8/27/2011 1200Z
Test1b	1-way	Kain-Fritsch	YSU	8/27/2011 1200Z
Test2a	1-way	Kain-Fritsch	Mellor-Yamada	8/27/2011 1200Z
Test2b	1-way	Betts-Miller-Janjic	YSU	8/27/2011 1200Z
Test2c	1-way	Tiedtke	YSU	8/27/2011 1200Z
Test3	1-way	Kain-Fritsch	YSU	8/26/2011 1200Z

Results

Figure 3 shows wind vector plots from Test1a and indicate that the WRF track of Irene fits quite well with the best track data from the National Hurricane Center. At 1200 UTC on August 28, 2011 (right plot of Figure 3), there is a small south-westward error by about 30-km compared to the best track data suggesting the model storm was slightly slower than indicated by the observed data.

Figures 4 and 5 show the WRF layer 1 spatial wind speed analysis at 0500 and 1900 UTC on August 28, 2011, compared to the HWIND analysis at 0430 and 1930 UTC. The WRF layer 1 wind field (about 11 m) compared reasonably well with the HWIND analysis but did show somewhat higher wind speeds covering larger spatial areas than indicated by the HWIND analysis, particularly over the ocean east of the center.

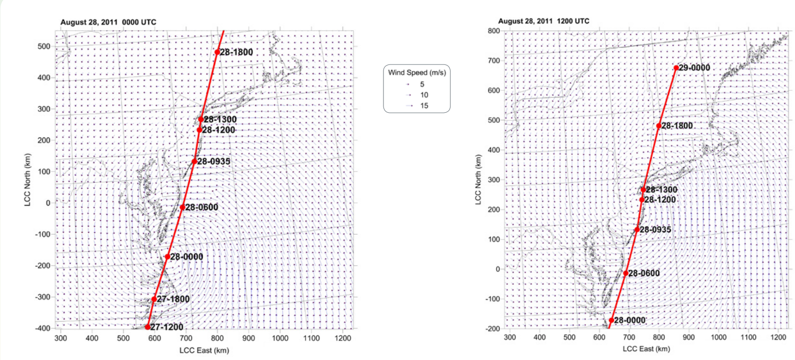

Figure 3. WRF layer 1 wind vectors on the 4-km domain at 0000 UTC (left) and 1200 UTC (right) August 28, 2011. The red line shows the observed track of Hurricane Irene.

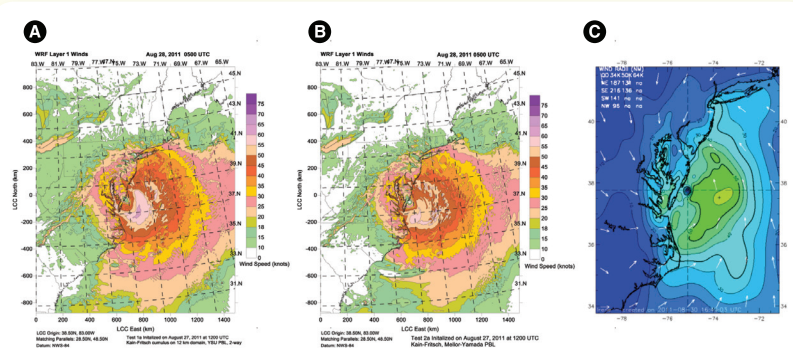

Figure 4. WRF layer 1 wind speed analysis (A) at 0500 UTC for test1a, (B) 0500 UTC for test2a, and (C) the HWIND wind analysis (Courtesy of the Hurricane Research Division) at 0430 UTC on August 28, 2011.

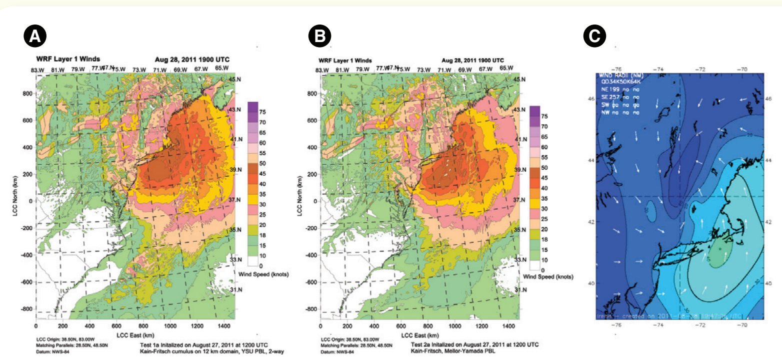

Figure 5. WRF layer 1 wind speed analysis (A) at 1900 UTC for Test1a, (B) 1900 UTC for test2a, and (C) the HWIND wind analysis (Courtesy of the Hurricane Research Division) (B) at 1930 UTC on August 28, 2011.

The peak winds from the WRF simulations were consistent with maximum winds from the best track data. These plots show that WRF overestimated the spatial extent of the maximum wind speeds compared to the HWIND analysis. The various sensitivity simulations showed very similar spatial patterns. The WRF model wind speed was most sensitive to the choice of the PBL scheme (see Figure 4B and Figure 5B). Test2a showed that using the Mellor-Yamada PBL versus the YSU PBL showed a tendency for lower wind speeds.

Time series plots of WRF and observed data are provided in Figure 6, showing an over prediction of the layer 1 winds over the stations near and along the storm track, but much closer agreement with observations at stations well east of the storm center. This may be the result of the slight south-westward error in the model storm track and also errors in the prediction of the core wind field. Computed RMSE values ranged from about 4–7 m/s at stations located along and near the storm track to about 1–2 m/s at stations east of the center.

Comparisons between the various test simulations showed the greatest differences occurring at the stations along the storm track. Test3, which initialized the storm 24 hours earlier, showed stronger winds overall on spatial wind plots (not shown). The winds at Bishops Head, Maryland show much stronger winds from Test3 compared to the other simulations. The key difference with Test3 is the initialization time. The FNL 1 degree analysis data did not appear to correctly initialize the storm structure for the Test3 simulation resulted in a stronger wind field during the simulation than actually occurred.

The total 24-hour rainfall pattern was compared against the Advanced Hydrologic Prediction System (AHPS) multi-sensor precipitation analysis (Figure 7). The results show that the spatial pattern of total storm rainfall along the East Coast was well simulated by WRF. However, WRF overestimated the rainfall amounts for the control run particularly in the northern mid-Atlantic region and into eastern New York where it showed too much areal coverage of 8–10 in. rainfall amounts when compared to the AHPS multi-sensor analysis. The multi-sensor analysis showed a broad swath of 6–8 in. amounts and pockets of rainfall totaling 8 in. or more. The sensitivity simulations showed that the rainfall on the 4-km domain was not sensitive to the use of the different cumulus parameterization schemes implemented on Domain 1. The simulation that showed the closest fit to the multi-sensor analysis was Test2a using the Mellor-Yamada PBL scheme in place of the YSU scheme. This WRF run showed much less over-prediction and the areas of peak rainfall were in much more agreement with the observed analysis.

Concluding Remarks

The WRF FDDA simulations showed that the WRF model realistically simulated the overall structure and movement of Hurricane Irene (Figure 8). The peak winds were all similar in each simulation. But the spatial coverage of the axis of maximum wind east of the center was overestimated by WRF when compared to the HWIND analysis. The model was most sensitive to the choice of the PBL scheme and insensitive to the cumulus parameterization scheme on the parent domain.

Improvements in the model performance may be possible through different data assimilation strategies and use of better initial fields such as analysis data from the GFDL Hurricane Model and the HWRF analysis data.

References

Davis, Christopher, Wei Wang, Shuyi S. Chen, Yongsheng Chen, Kristen Corbosiero, Mark DeMaria, Jimy Dudhia, Greg Holland, Joe Klemp, John Michalakes, Heather Reeves, Richard Rotunno, Chris Snyder, and Qinghong Xiao, 2008: Prediction of Landfalling Hurricanes with the Advanced Hurricane WRF Model. Monthly Weather Review, 136:1990–2005.

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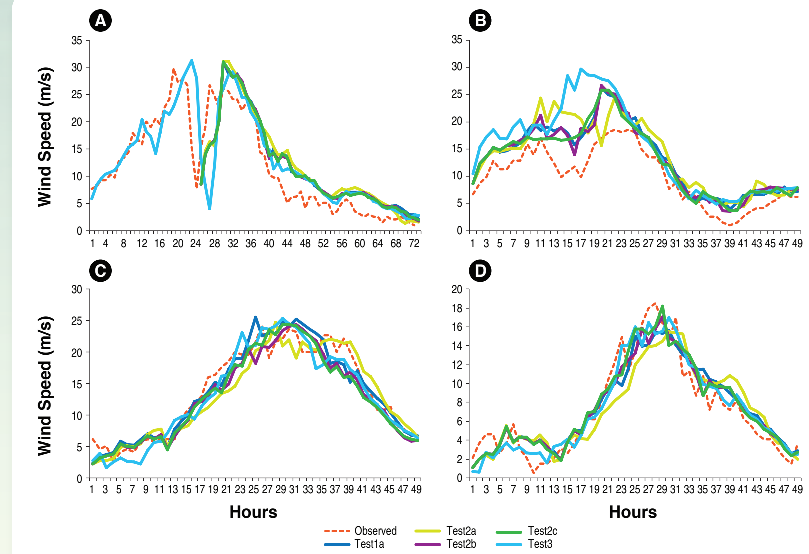
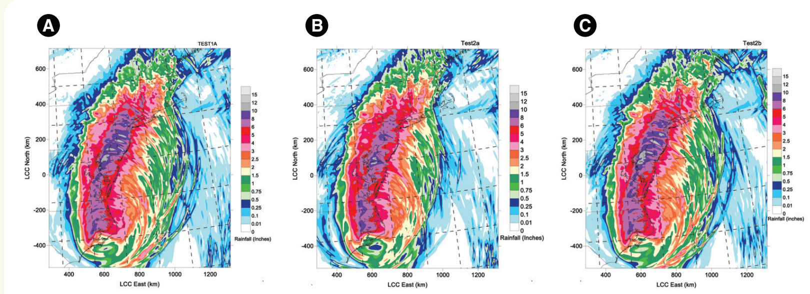


Figure 6. Time series plots of surface wind speed at Cape Lookout, North Carolina (A), Bishops Head, Maryland (B), Buzzards Bay, Massachusetts (C), and Providence, Rhode Island (D). Time in hours is referenced to start of simulation. The plot at Cape Lookout (A) is shown for 72 hours to show full test3 result.



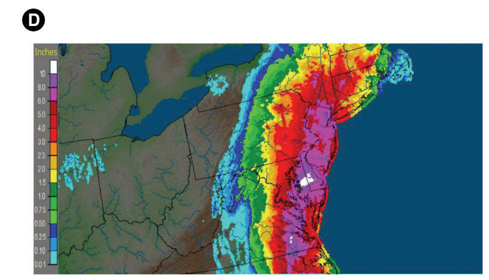


Figure 7. 24-hour total rainfall ending on August 28, 2011, at 1200 UTC from Test1a (A), Test2a (B), Test2b (C) on the 4-km domain, and observed rainfall from the AHPS Multi-Sensor Precipitation Analysis (D).

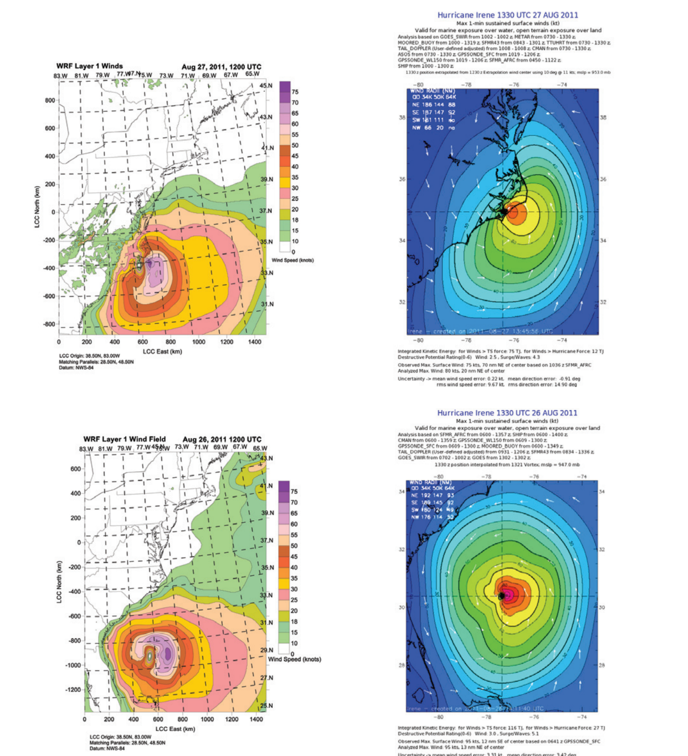


Figure 8. Position and strength of WRF maximum wind speed axis on August 27, 2011, at 1200 UTC (top) matches closely with the HWIND analysis compared to August 26, 2011, 1200 UTC (bottom) where WRF showed a poorer representation of the inner core surface wind structure.