NOAA/NCEP Operational Hurricane Weather Research and Forecast (HWRF) Modeling System

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Prediction of track and intensity of a tropical cyclone (TC) is one of the many challenging problems in meteorology, but is very important for issuing timely warnings for many agencies engaged in disaster preparedness and mitigation. Hurricane forecasting is one of the most important areas of modeling at the Environmental Modeling Center (EMC) of the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP). The Hurricane Weather Research and Forecast (HWRF) modeling system for hurricane prediction, developed by scientists at EMC, in collaboration with various academic and government agencies, is a sophisticated, high-resolution, atmosphere-ocean-land coupled model designed to resolve inner-core features of hurricanes for providing accurate forecast guidance through improved representation of multi-scale, spatio-temporal interactions of storm circulations within the large-scale environment. The HWRF modeling system became operational at NCEP starting with the 2007 hurricane season. The HWRF model provides high-resolution track, intensity, and structure forecast guidance to the operational forecasters at the National Hurricane Center (NHC) and Central Pacific Hurricane Center (CPHC) for all tropical cyclones in their areas of responsibility (North Atlantic and Eastern North Pacific, and Central North Pacific, respectively). Recent efforts supported by NOAA's Hurricane Forecast Improvement Project (HFIP) allowed the HWRF team to expand the applications of the HWRF modeling system (henceforth to be referred to simply as 'HWRF') for tropical cyclone forecasts in all global oceanic basins, providing real-time forecast guidance to the operational forecasters at the Joint Typhoon Warning Center (JTWC), National Weather Service (NWS) Pacific Region (PR) and several international tropical cyclone forecast agencies across the world.

HWRF has undergone annual upgrades and continuous improvements since 2007 through a carefully designed testing, evaluation and implementation plans. A series of significant and foundational improvements were made to the operational HWRF in terms of resolution and physics improvements implemented in 2012 (Figure 1) as a result of collaboration with many NOAA

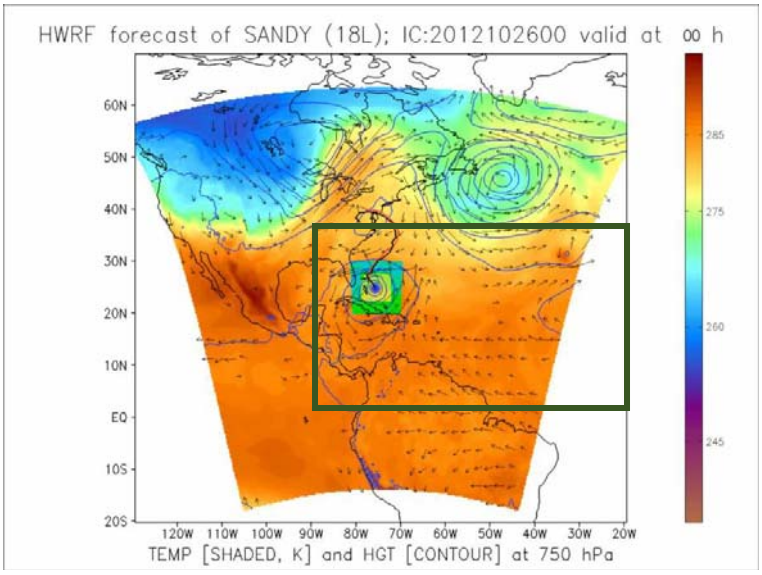

Figure 1: Triple nested configuration of NCEP Operational HWRF Model consisting of two high-resolution telescopic storm-following two-way interactive nests operating at 9 km and 3 km near the storm center embedded in a storm-centric outer domain (27 km). Dark green box indicates the location of the MPIPOM Ocean Model coupled to HWRF.

agencies under Hurricane Forecast Improvement Project (HFIP). For the first time, a very high resolution air-sea coupled model operating at a cloud permitting resolution of 3km near the storm center was implemented during the 2012 hurricane season, paving way for significant improvements in hurricane intensity forecasts that have been stagnated for more than two decades. In 2013, for the first time, real-time assimilation of Tail Doppler Radar (TDR) data collected by NOAA P3 aircraft reconnaissance missions was made possible through the implementation of an advanced regional hybrid (Ensemble-3 Dimensional Variational) data assimilation system. In 2014, HWRF upgrades included increased vertical resolution to 61 levels and raising the model top to 2 hPa, and coupling to a modern Message Passing Interface Princeton Ocean Model (MPIPOM) for all operational basins.

The current version (FY15) of operational HWRF system proposed for operational implementation in May 2015 is an advanced coupled system including ocean and land models. The model resolution is further increased to have the triple-nest capability (18/6/2km) that includes a cloud-resolving innermost grid operating at 2 km horizontal resolution and 61 vertical levels. In the FY15 HWRF upgrades, the physics schemes are further improved based on observational findings and advanced vortex initialization data assimilation techniques for better representation of the inner core storm structure of the storms. In order to better represent deep convection, micro-physics is upgraded to the Ferrier-Aligo scheme; the GFDL slab model is replaced by the multi soil level NOAH Land Surface Model which will improve track and intensity forecasts of landfalling hurricanes; the scale-aware Rapid Radiative Transfer Model for General Circulation Models (RRTMG) is introduced to HWRF physics with partial cloudiness, replacing the old GFDL radiation scheme; and FY15 upgrades also include well-tuned PBL, momentum and enthalpy exchange coefficients in the surface physics based on observations. The newly upgraded data assimilation system allows us to assimilate more observations, such as satellite data, Tail Doppler Radar (TDR), and tcvitals MSLP data along with dropsonde data in real time, using advanced 40-member HWRF ensembles.

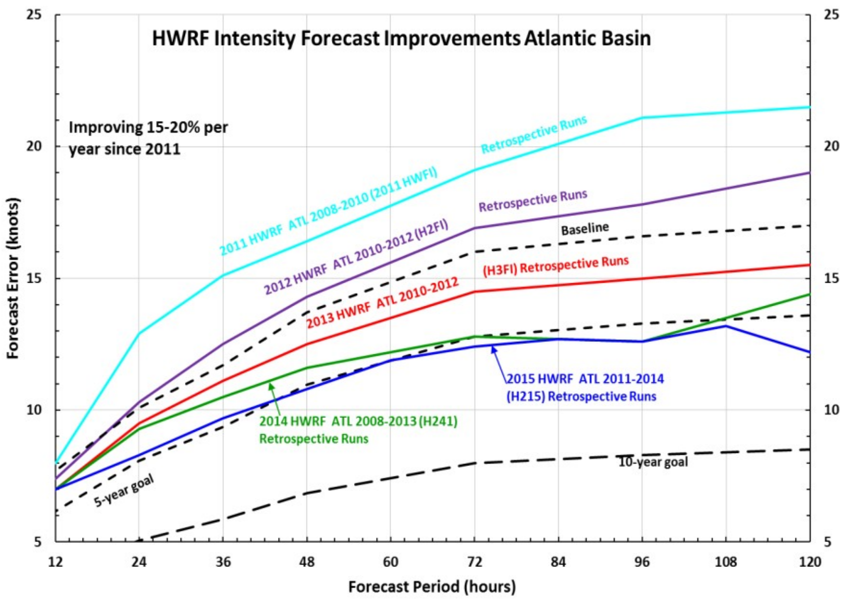

Figure 2: Progress of intensity improvements from HWRF over the years

Real time and retrospective experiments have demonstrated that HWRF track and intensity forecasts have constantly improved and outperformed other dynamic models, and beginning for the first time since 2013, it outperformed the statistical models and NHC's official forecasts for tropical cyclone intensity (subjectively made by the hurricane specialists) by about 15%, with track forecast skills competitive to the best performing NCEP GFS global model skills. In additional to steady improvements in the track forecast skill every year, the operational HWRF has conclusively demonstrated the positive impact of resolution on storm size and structure forecasts. Figure 2 illustrates the steady but significant intensity forecast improvements from the operational HWRF as evaluated through several seasons of retrospective evaluation of model upgrades.

HWRF emerged as a state-of-the-art hurricane modeling system outperforming many regional dynamic hurricane models; and became one of the best regional hurricane forecast models in the world. It has gained worldwide reputation for its accurate track and intensity forecasts. It has been run by many tropical cyclone forecast centers for all ocean basins worldwide for both research and operational purposes. HWRF is also implemented at the India Meteorological Department (IMD) in New Delhi for operational tropical cyclone forecasts over the North Indian Ocean basin. Several international tropical cyclone forecast agencies, including Vietnam's Institute for Meteorology, Hydrology, and Environment (IMHEN), China's Shanghai Typhoon Institute (STI), Taiwan's Central Weather Bureau (CWB), and Oman's Directorate General of Meteorological Affairs and Air Navigation (DGMAAN) have also adopted HWRF for their operational needs. The concept of an operational hurricane model available as a research tool and supported through a dedicated community modeling framework at NOAA's Developmental Testbed Center (DTC) allowed further expansion and outreach of the HWRF modeling system to many academic and research organizations across the world, facilitating accelerated model development, research, and transition to operations.

Starting from 2015, HWRF forecasts will be running operationally at NCEPEMC and will provide tropical cyclone forecast guidance for all global oceanic basins, including Northern Atlantic, Eastern North Pacific, Central North Pacific, Western North Pacific, Northern Indian Ocean, and Southern Hemispheric basins. Real-time HWRF forecast products are disseminated through the Automated Tropical Cyclone Forecast (ATCF) system, the NCEP EMC Website (http://www.emc.ncep.noaa.gov/gc_wmb/vxt), NCEP ftp servers (ftp://ftp.ncep.noaa.gov/pub/data/nccf/com/hur/) and NCEP Model Analysis and Guidance website (http://mag.ncep.noaa.gov/tropical-guidance-model-storm.php).

A single deterministic hurricane model can only provide one of the many possibilities of tropical cyclone evolution. It is imperative that we need adopt the ensemble approach for representing the uncertainty and improve the predictability of the tropical cyclone path, intensity, structure, and rainfall forecasts. HWRF team at EMC have started experimenting with a 20-member high-resolution ensemble forecasts starting with the 2013 hurricane season. The HWRF based ensemble prediction system (HWRF-EPS) takes into account un- certainties in storm initial position and intensity, large scale environment, model physics including stochastic sub-scale convective triggers, and PBL height. As expected, the ensemble mean outperformed the single deterministic forecasts from the operational HWRF. Future plans include further development of HWRF ensembles for operational purposes.