The Transition of Research into the NCEP Operational HWRF System: Guidance for the Joint Hurricane Testbed Announcement of Opportunity

1. EMC Mission

The National Centers for Environmental Prediction, Environmental Modeling Center (NCEP/EMC) is responsible for developing significant improvements into NCEP's operational forecast systems to increase both the scope and quality of NCEP's products. Ranging from seasonal to interannual prediction and climate reanalysis to hourly rapid updates, NCEP/EMC has advanced the quality of its products and is ready to make further improvements through model enhancements and new computing resources. The NCEP production suite contains global and regional atmospheric prediction systems, real-time ocean and waves, hurricanes, air quality and hydrological systems. Modernization of the NCEP production suite is underway with construction of the NOAA Environmental Modeling System (NEMS) that is a software framework compatible with the community-based Earth System Modeling Framework (ESMF). The NEMS is being implemented in a phased approach beginning with the North American Model (NAM) that became operational in October 2011.

2. The Hurricane Weather Research and Forecast (HWRF) System

The atmosphere-ocean coupled Hurricane Weather Research and Forecast (HWRF) modeling system is developed and supported by the Environmental Modeling Center (EMC) and runs in the National Centers for Environmental Prediction (NCEP) production suite on the NOAA Weather and Climate Operational Supercomputing System (WCOSS). The operational HWRF model is based on WRF NMM dynamic core and consists of multiple movable two-way interactive nested grids that follow the path of the simulated storm. To significantly improve operational tropical cyclone forecast guidance, the hurricane modeling team at NCEP/EMC implemented several changes to the 2014 version of the HWRF model implemented in June 2014. One of the main upgrades is increasing the number of vertical levels from 42 to 61 with model top raised from 50 hPa to 2 hPa. With increased vertical resolution, HWRF now has the capability of assimilating satellite data that usually peaks at upper levels of the atmosphere, in addition to alleviating the model top wave reflections. Apart from increase in the vertical resolution, domain sizes of the intermediate and innermost moveable nested domains are increased by 20% and 10% respectively, compared to those of the 2013 operational HWRF. The horizontal extent of the nested domains is expanded in order to produce more accurate prediction of the structure of large storms like Hurricane Sandy (2012). The hurricane ocean model coupled to HWRF is also upgraded from low resolution (1/6^{o}) single-processor Princeton Ocean Model (POM) to higher resolution (1/12°) three dimensional Princeton Ocean Model (MPI-POM) with a single trans-Atlantic basin that can run on multiple processors for efficient computational performance. The ocean coupling for Eastern Pacific is configured to use the same three-dimensional MPI-POM, replacing the 1-D POM for that basin. HWRF model employs a suite of advanced physics developed for tropical cyclone applications. These include modified versions of the GFDL surface physics, land surface model and radiation, Ferrier Microphysics, NCEP GFS planetary boundary layer, SAS deep convection and shallow convection. More information on the HWRF system can be found in the HWRF Scientific Documentation (Tallapragada et al. 2013) and at the EMC HWRF web page. Operational HWRF modeling system and its development branches are available to the researchers in the community modeling framework maintained and supported by DTC, and can be accessed from DTC HWRF repository as well as from the DTC website.

3. The Operational HWRF Upgrade Process

3.1 The NCEP Production Suite

The NCEP production suite (NPS) is composed of numerical model systems spanning spatial and time scales of the Rapid Update Cycle (RUC) to Climate Forecast System (CFS). This includes all major components of the system including data acquisition and processing, data assimilation, the model cores and all associated post processing, GRIB grid generation and visualization.

3.2 Supercomputing to Support the Production Suite

The two high performance computing (HPC) systems within the operational Central Computing System (CCS) have now been replaced with the new NOAA Weather and Climate Operational Supercomputer System (WCOSS) with the primary facility set up in Reston, VA and the backup facility in Orlando, FL. These two systems, known as Tide and Gyre, are identical in configuration but reside in two geographically diverse locations to ensure continuity of operations. Functionally, the WCOSS consists of the NPS and the Transition-to-Operations (T2O) HPC systems. The NPS (or production HPC system) executes the operational production of the model runs from which the weather, climate, ocean and wave forecasts are made. Currently the NPS produces and disseminates over 1.5 million operational model products each day to government agencies, commercial interests, and to the public. The T2O (or development machine) hosts work that supports model enhancements and next generation forecast models destined for NPS operations. The T2O serves as a critical link in the chain from research and development to operations. During normal modes of operations, the NPS runs on the Primary system and the T2O runs on the Backup system. If the Primary system or site fails, T2O is suspended and NPS runs on the Backup system.

Following are the attributes for WCOSS HPC:

- Identical Systems (per site)
- IBM iDataPlex/Intel Sandy Bridge/Linux
- 208 trillion calculations/sec
- 10,048 processing cores
- 2,590 trillion bytes of storage

Recent enhancements to the computing in NOAA also provides unprecedented opportunity to conduct research and development on high-performance linux clusters shared by different agencies within NOAA, namely Jet (Boulder, CO), Zeus (Fairmont, WV) and GAEA (Oak Ridge, TN). Among these, Jet cluster is owned and specially designed by NOAA's Hurricane Forecast Improvement Project (HFIP) and allows researchers to test and experiment the next generation global and regional modeling efforts geared towards improving the hurricane forecast skill. Details of these machines are provided in the hyperlinks for each of these machines and also from EMC model transition team webpage.

3.3 Linkage between HWRF Upgrades and NCEP Production Suite

The transition of research into the NCEP production suite is a complex process involving scientific enhancements, efficient coding requirements and rigorous testing standards. The operational environment requires NCEP management to make decisions among incremental improvements in skill, the level of additional cost, product delivery time requirement, and risk associated with the system improvements.

New ideas and concepts must be rigorously tested in the operational system to ensure that the changes do not have unanticipated negative consequences in other parts of the numerical model production suite. Considering the interdependence of modeling systems in the NPS, the test plan generally includes three parts of assessments: impacts from upstream model changes, interference with other changes within the same model, and impacts on the downstream model. For example, the Global Forecast System (GFS) is used to provide initial and lateral boundary conditions to the HWRF and GFDL hurricane regional models. Therefore, when a change (e.g., model physics, resolution, additional data to be assimilated, etc.) is made to GFS, these systems must be re-assessed with the new GFS system over a statistically significant sample. This is because even if the upgraded GFS testing shows a positive impact to global statistics, it is possible that the HWRF and GFDL systems could result in a degradation in tropical cyclone track and/or intensity forecast skill. A proposed change has also to be tested combined with other proposed changes in the same model system to ensure the combined results of all proposed changes will not degrade the model performance. HWRF downstream dependencies (e.g. wave model) need to be noticed and tested whenever a new change is introduced in HWRF system. Outside organizations are naturally frustrated with what appears to be a slow, inefficient and risk adverse implementation process. However, operational implementation will always require rigorous testing of systems to mitigate the risk of degradation in service or system failures. Implementation rates are also dependent on computational and human resources. It is noted that NCEP is continuously examining ways to make the process more efficient and must do a better job of explaining the process to the research community to ensure realistic expectations are established.

3.4 The HWRF Development Cycle

Upgrades to the HWRF system are performed on an annual cycle that is dependent on the hurricane season and upgrades to the Global Data Assimilation System (GDAS) and GFS. There are basically 2 phases of development. The first is developmental testing that occurs prior to and during the hurricane season (roughly 1 April to 30 October) where potential upgrades to the system are tested individually but in a systematic and coordinated manner.

The pre-implementation testing starts in November and is designed to test the most promising developments assessed in the development phase to define the HWRF configuration for the upcoming hurricane season. The results of the pre-implementation testing must be completed and the final HWRF configuration locked down by 15 March. Once frozen, the system is handed off to NCEP Central Operations for implementation by 1 June. The cycle is then repeated for the next set of proposed upgrades to the HWRF system. During the hurricane season (1 June to 30 November) changes are not made to the operational HWRF in order to provide forecasters with consistent and documented numerical guidance performance characteristics

3.5 HWRF Development Priorities

EMC, in partnership with NHC, is responsible for developing a plan for potential model upgrades. Priorities are obtained from the operational HWRF performance documented during the previous hurricane seasons and results obtained during the pre-implementation testing for the current hurricane season. The development priorities are then communicated to the community through the EMC HWRF Web page, the Joint

Hurricane Testbed (JHT), and the DTC for inclusion into their Announcements of Opportunities. The HWRF development priorities are also provided to the community through the Hurricane Forecast Improvement Project (HFIP). The goal of the FY14 annual upgrade is to address known problems/issues identified during the previous seasons such as:

a) Weak storms continued posing significant challenge
b) Moisture initialization in the model less than optimum
c) Cold start (very first cycle) cases behave different (worse) than the warm start
d) Land interactions and cold temperature bias over land
e) Smaller nest domains to contain large storms; insufficient vertical resolution for satellite DA
f) Coarse resolution of ocean model, inadequate conditions for choice of ocean domain in the Atlantic, 1-D coupling in the East Pacific

Given the above issues, the main focus areas for development, testing and evaluation for the FY14 implementation include the following specific activities:

1. Increase the vertical resolution of atmospheric model to 61 levels with higher model top of 2 hPa
2. *Upgrade HWRF physics suite to include RRTM-G, Modified Ferrier microphysics, NOAH LSM (withdrawn).*
3. Upgrade the ocean model (POM) to 1/12^{o} MPI POM with unified trans-Atlantic basin and 3D ocean for Eastern Pacific basin. Upgrade the coupler to run on multiple processors.
4. Further improvements to HWRF vortex initialization scheme and HWRF Data Assimilation System
5. Additional operational forecast products from HWRF to include simulated brightness temperatures for new satellite sensors, several new variables for

downstream applications and 6-minute ATCF output. Special storm centric helicity & tornadic potential fields for landfalling storms at the request of SPC.

6. Pre-implementation tests based on proposed Q1FY15 GFS upgrades

3.6 HWRF Pre-Implementation Testing for FY14

Although the performance of the FY2013 HWRF model in the 2013 hurricane season and previous retrospective testing showed very significant improvement as compared to previous HWRF implementations and all other operational regional models, there is still room to improve both intensity and track prediction skills, as both the track and intensity forecast errors are currently still larger than the observational errors. Especially, it is known that the FY13 HWRF model tends to overestimate initially weak storms and underestimate initially strong storms. This tendency amplifies with time because of the cycling nature of the HWRF vortex initialization procedure, and it will contribute towards degradation of HWRF forecasts. In addition, the number of vertical level and the model top are also not comparable to the global GFS model, which incapacitates the model from assimilating full satellite information. Also, the model physics contains some issues at the cloud resolving resolution. As such, the main focus areas of the FY14 HWRF development are to 1) improve model configuration to facilitate subsequent development of new physics and data assimilation techniques, and 2) improve the model physics to allow the model to take advantage of the advanced physics schemes.

In an unprecedented effort, HWRF team, with support from HFIP and several partners within NOAA as well as academia, started pre-implementation testing of the HWRF system in late 2013 and continued testing various configurations to determine a final configuration for the 2014 implementation. In the FY14 upgrade, there were two major components that were carried out and evaluated by EMC and NHC consisting of 1) an infrastructure upgrade (i.e., the baseline configuration) that is aimed to improve the HWRF structure to accommodate future development of more advanced physics and assimilation techniques, and 2) a physics upgrade that focused on different high-resolution physics options. For the infrastructure upgrade (T14C), major changes included *i*) vortex initialization modifications to match the initial maximum wind speed over the lands, fix the bug of calculating south-west corner of initialization domain, remove cold starts for the first cycle of named/numbered storm through cycling of vortex from Invest cases, and use storm center in the procedure instead of using parent domain center, *ii*) increase the number the vertical level from 43 to 61 vertical levels and model top from 50mb to 2 mb to facilitate the satellite data assimilation, *iii)* extension of the innermost domain and the intermediate domain by ~ 20% to allow for better resolving the storm scale processes, and *iv*) an improved data assimilation configuration that applied regional hybrid GSI analysis for both D2 (9km) and ghost (3km) domains, assimilated the conventional data and TDR, GSPRO, satellite derived wind, brightness temperature from IR instruments (HIRS, AIRS, IASI, GOES Sounder) and MW instruments (AMSU-A, MHS, ATMS), changed the 3-hourly FGAT to hourly FGAT to provide more accurate first guess fields, and added some further refinements in TDR data assimilation including advanced thinning strategies and removal of surface pressure flag (include it in assimilation); add dropsonde data in the inner core when available (especially temperature and moisture data).

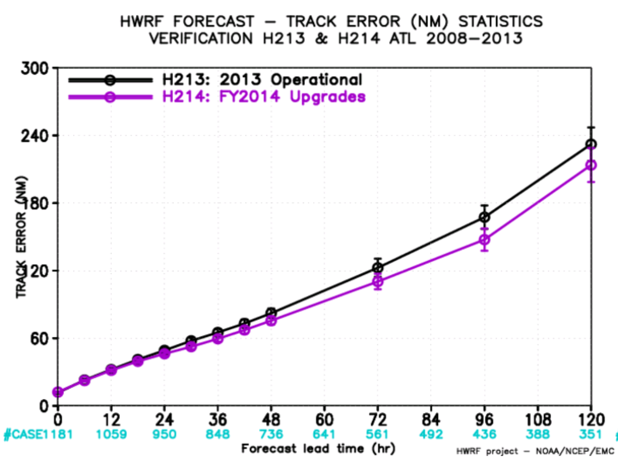
Testing of the new infrastructure upgrade during retrospective experiments from 2008-2013 with more than 10000 simulations in the Atlantic and East Pacific basins showed that this infrastructure upgrade could reduce both the track and intensity forecast errors by ~10% in the Atlantic basin. In the Eastern pacific, it is somewhat neutral with some improvement in the track but intensity bias showed some significantly more negative bias as compared to the FY13 version.

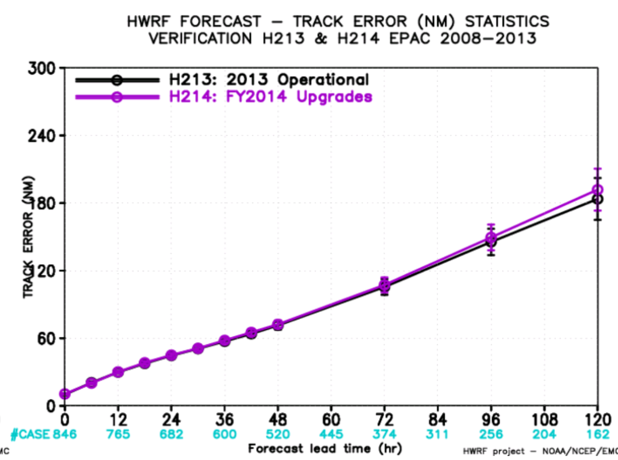
	Infrastructure/DA upgrades				Dynamics/Physics upgrades					Final
	H14A	H14B	H14C	T14C	Nest motion (H140)	NOAH LSM (H141)	Upgraded Ferrier (H142)	RRTMG (H143)	Ocean (H144)	H214
Description	1. Sat Da with more vertical levels 2. Extended d2/d3 3. Upgraded vortex initialization 4. GSI upgrade 5. Invest cycling	1. No Sat DA	Sat DA only for D01	Same as H14C except no DA in d01, use GFS analysis	New nest motion and high-freq. products	NOAH LSM	Separate species, Frime advection with other upgrades	Radiation	MPI-POM with new coupler	Combination of Best Performing components *need to do test runs with new GFS in WCOSS
Person	All	All	All		Sam	Young	Weiguo	Chanh	Zhan/URI	All
Cases	Whole 2011,2012 and 2013 storms 2008, 09, 10 TDR cases	As in H14A	As in H14A		Priority cases	Priority cases	Priority cases	Priority cases	Priority cases	Whole 2011,2012 and 2013 storm
Due date	Feb. 15	Feb. 15	Feb. 15		Feb. 15	Feb. 15	Feb. 15	Feb. 15	Feb. 15	March 31
Platform	Jet	Jet	Jet		Jet	Jet	Jet	Jet	Jet	Jet/WCOSS

Table 1. List of the configuration being evaluated and tested during the FY14 implementation conducted by EMC for the HWRF model upgrades.

For the physics upgrade, a set of 5 different physical options have been tested on top of the baseline configuration T14C. Table 1 lists all physics configurations planned for implementation in the FY14 upgrade, which consisted of replacing the simple slab land surface model to Noah LSM, a new longwave and shortwave radiation scheme RRTMG, an improved micro physical scheme (Ferrier-Aligo), and a new ocean model with three-dimensional ocean model in the Eastern Pacific basin. While each individual physics upgrades showed significant improvement in track and intensity forecast skill, it turned out that their combination did not show any benefit on top of the infrastructure upgrade T14C in the Atlantic basin. In the Eastern pacific, the negative bias of the intensity was even worse than T14C. This led to the final decision of postponing the physical upgrades and retaining only the new nest improvement and the new ocean model, as these changes did not seem to deteriorate the overall performance of the baseline configuration T14C.

Given issues with physics upgrade, the final FY14 configuration (H214) was a combination of the infrastructure upgrade T14C and the new ocean model in the Eastern Pacific. Figure 1 shows the verification of H214 as compared to FY13 version for a retrospective testing of 5 seasons from 2008-2013. Comprehensive testing for 2008-2013 hurricane seasons for Atlantic with H214 demonstrated significant improvement in model forecast skill for track and intensity forecasts for the Atlantic Basin (~10% improvement) as compared to the 2013 operational version. The impacts are however neutral for the track forecasts for 2010-2013 Eastern Pacific basin hurricane seasons with a slight degradation for intensity errors. Results also suggested a decrease of the positive bias for the Atlantic basin but increase in negative bias for Eastern Pacific. Note that H214 tends to have some issues with very strong storms for which it could not intensify as fast as the FY13. While such issue with intensification of strong storms could be of concern for very intense storms, it is expected that the moderate intensification of the FY14 version will help reduce the over-intensification of weak storms it inherited in the previous versions of the HWRF model so far.





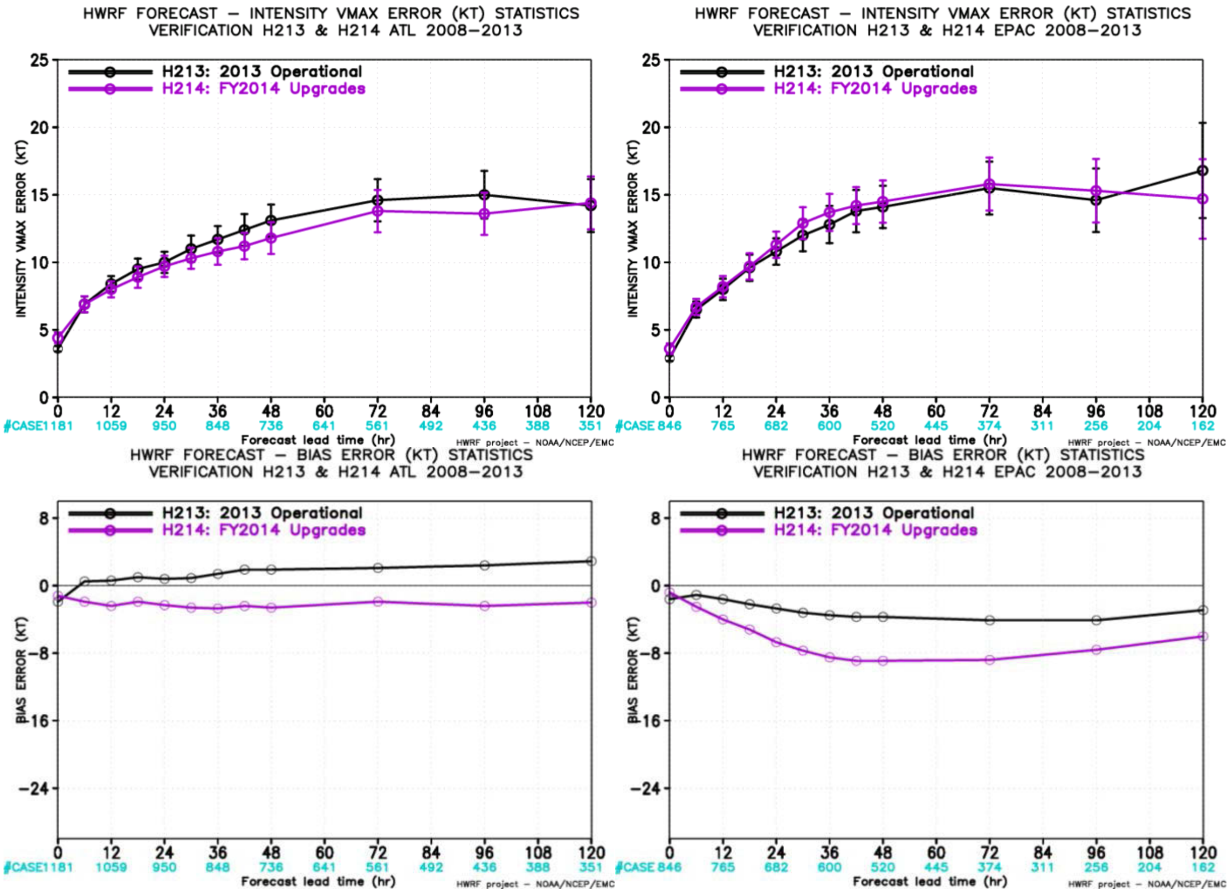


Figure 1. Verification of the track, absolute intensity, and bias intensity errors of the FY2014 upgrade (H214) with respect to the FY2013 version (H213) for 5 seasons 2008-2013 in the Atlantic basin (left panels) and the Eastern Pacific basin (right panels).

3.7 Role of DTC in HWRF development and community support

EMC, in collaboration with the DTC, created the Community HWRF by merging the operational NCEP code based on WRF v2.0 onto the general WRF community code repository (currently v3.5a) in order to create a single modeling system for research and operations. The DTC began supporting the community HWRF in April 2010, after a tutorial on WRF for hurricanes. Since then, three additional tutorials (two in the United States – 2011 and January 2014; and one overseas in Taiwan in May 2014) and an online tutorial was provided to the users, researchers, and developers of the hurricane models. The Community HWRF model is closely related to the operational HWRF, and DTC is providing code management, code downloads datasets, documentation, tutorials, and a helpdesk. DTC also has setup repositories for the vortex initialization, ocean model, coupler, and vortex tracker. While the operational HWRF was designed to run on NOAA HPC systems, the Community HWRF has the added capability of running on various platforms with both the Portland Group and Intel compilers.

NCEP/EMC started drawing code from the community HWRF repository to use in operations starting in 2011. Any new HWRF developments will become part of the community code, keeping the operational code synchronized with the community code in subsequent years. With this code management process, research and operations will be using the same code base, making it much more effective for new research and developments to be adopted in operations. DTC has also assembled a functionally equivalent operational environment to test and evaluate new HWRF developments over extended retrospective periods. JHT AO responders are encouraged to take advantage of this setup and support from DTC to have an accelerated and efficient R2O/O2R procedure.