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HURRICANE FORECAST IMPROVEMENT PROJECT

2015 HFIP R&D Activities Summary: Recent Results and Operational Implementation

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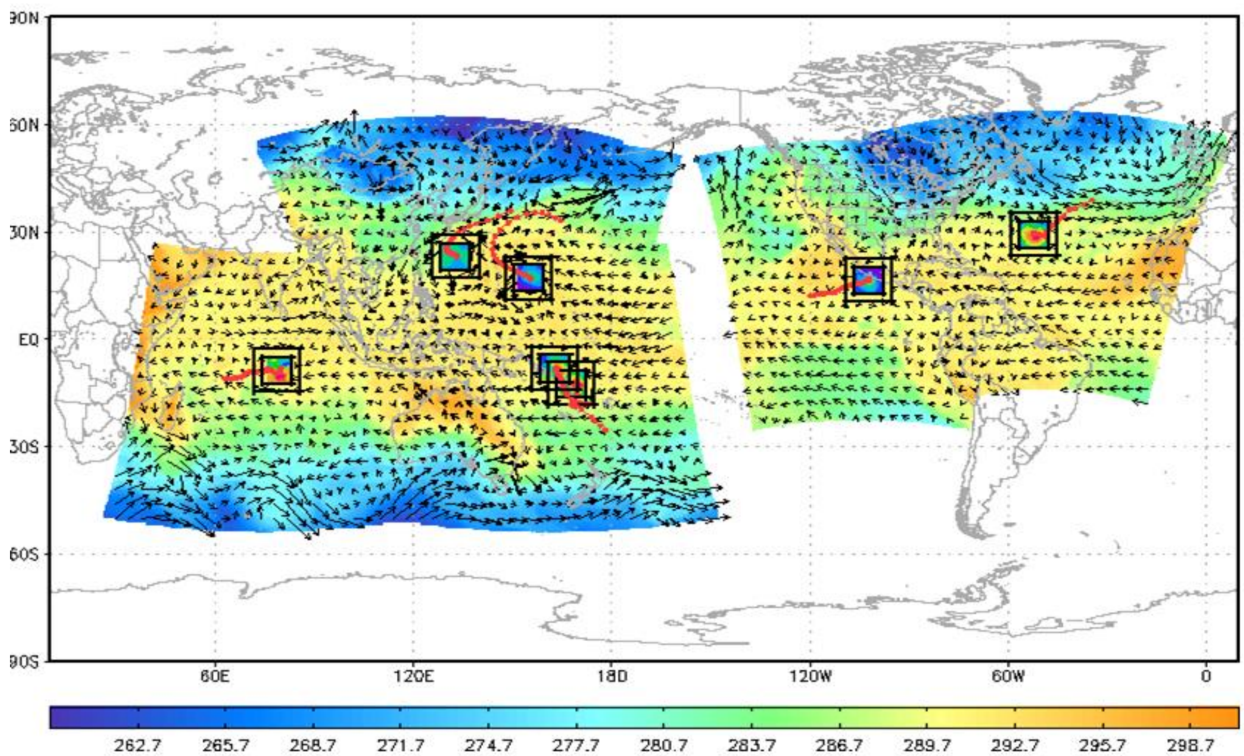

Global coverage of HWRF in all basins

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2015 HFIP R&D Activities Summary: Recent Results and Operational Implementation

S. Gopalakrishnan[6], F. Toepfer[11], R. Gall[15], F. Marks[6], E. N. Rappaport[9], V. Tallapragada[5], S. Forsythe-Newell[13], A. Aksoy[15], J. W. Bao[4], M. Bender[19], L. Bernardet[4], J. Cione[1], M. Biswas[7], J. Cangialosi[9], M. DeMaria[9], M.Morin[19], J. Doyle[10], J. L. Franklin[9], S. Goldenberg[6], George Halliwell[1], C. Holt[18], S. Jason[5], H. S. Kim[5], P. Kucera[7], N. Lett[12], P. McCaslin[4], A. Mehra[5], M. Mills[13], J. Moskaitis[10], S. Abarca[5], J. Sippel[5], S. Trahan[5], H. Tolman[5], R. Torn[14], X. Wang[16], J. Whitaker[4], D. A. Zelinsky[9], F. Zhang[17], X. Zhang[15], Z. Zhang[5].

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[1] Atlantic Oceanographic and Meteorological Laboratory (AOML), OAR/NOAA
[2] Cooperative Institute for Research in the Environmental Sciences, University of Colorado
[3] Development Testbed Center (DTC)
[4] Earth System Research Laboratory (ESRL), OAR/NOAA
[5] Environmental Modeling Center (EMC), NCEP/NOAA
[6] Hurricane Research Division (HRD), AOML/NOAA
[7] National Center for Atmospheric Research (NCAR)
[8] National Environmental Satellite Data Information Center NOAA
[9] National Hurricane Center (NHC), NWS/NOAA
[10] Naval Research Laboratory (NRL), Monterey
[11] National Weather Service Science and Technology Integration (OSTI), NWS/NOAA
[12] Science and Technology Corporation
[13] Syneren Technologies Corporation
[14] University at Albany, State University of New York
[15] University of Miami, CIMAS/AOML
[16] University of Oklahoma
[17] Pennsylvania State University
[18] Global Systems Division (GSD)/ESRL/OAR
[19] Geophysical Fluid Dynamics Laboratory (GFDL), OAR/NOAA

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Executive Summary

This report describes the activities and results of the Hurricane Forecast Improvement Project[1] (HFIP) in 2015. It should be generally noted that 2015, like 2014, was not a representative season for the Atlantic due to very low tropical cyclone (TC) activity and not many rapid intensification (RI) events. The major developmental focus in 2015 was on the Hurricane Weather Research and Forecasting[2] (HWRF) regional model and regional ensembles for track and intensity predictions. In 2015, HFIP was organized around two *streams*: Stream-1: Operational model development and Stream-2: HFIP experimental models which test and evaluate new techniques and strategies for numerical model forecast guidance prior to testing for possible operational implementation. Stream-2 also tests techniques that cannot be tested on current operational computers due to size and time requirements, but can be tested on HFIP's High Performance Computing Center (HPC) in Boulder, CO (also referred to as *Jet*). The HFIP HPC research studies look ahead to possible future operational computational capability. This report outlines HFIP, how it is organized, its goals, its models, and results from both the operational model development (Stream-1) and experimental model development (Stream-2).

Stream 1.0 Results and Accomplishments

- HWRF implementation consisted of increased horizontal resolution from 27/9/3 km to 18/6/2 km across all domains, continued improvement of the *Nest-Tracking-Algorithm*, advanced *vortex initialization*, and improved products.
- HFIP improved HWRF intensity forecasts from 2014 (Fig. 5). In fact, HWRF was the best intensity forecast guidance model in 2015 for the North Atlantic Basin (Fig. 6).
- HWRF is currently being run operationally in all TC basins, i.e., North Atlantic (NATL), East Pacific (EPAC), Central Pacific (CPAC), North West Pacific (WPAC), and North and South Indian (IO), and Southern Pacific (SP) oceans. HWRF continues to evolve as a unique TC forecast guidance tool using all ocean basins (See cover page image), and in fact, HWRF track prediction skills were as good as the Global Forecast System (GFS) over the WPAC in 2015 (Fig. 10). The expansion of HWRF for all global TCs ensures serving forecasters at Joint Typhoon Warning Center (JTWC), other NWS interests in the Pacific and Indian Ocean regions, and international TC forecast agencies get more accurate real-time operational forecast guidance for as many as 7 TCs from HWRF at any given time.
- HWRF showed some significant promise for detecting RI, and the probability of detection (POD) for RI forecasts (increase of $\geq$30 kts./24 hrs. intensity) as well as the false alarm rate (FAR) showed improvements over previous years (Fig. 9)
- However, some TCs such as TC Erika (issues with initialization and over-intensification), TC Joaquin (problems with initialization, prediction of shear and multi-scale interactions and poor track forecast) and TC Patricia (issues related to model resolution, initialization, under forecast of RI and peak intensity) demonstrated the need for further improvements in numerical guidance (Fig. 7 and Fig. 9).

[1] http://www.hfip.org/
[2] http://www.emc.ncep.noaa.gov/gc_wmb/vxt/HWRF/index.php

- The GFS, which serves as the backbone for track advancements, continues to progress under parallel development at EMC. The model provides excellent guidance superior to most other models, is comparable to the European Centre for Medium-range Weather Forecasts model (ECMWF) guidance, and exceeds the 5-year HFIP goal out to 4-day lead time.

Stream 2.0 Results and Accomplishments

- A 41-member, multi-regional model ensemble system consisting of HWRF (20 members), Coupled Ocean/Atmosphere Mesoscale Prediction System-Tropical Cyclone (COAMPS-TC) model (10 members) and Geophysical Fluid Dynamics Laboratory (GFDL) model (11 members) were run on the HFIP Jet System in real-time where COAMPS-TC & HWRF control consensus and the ensemble mean outperformed single-model counterparts in deterministic validation.
- The Basin-Scale HWRF was transitioned to the Development Testbed Center[3] (DTC) and is evolving to provide a unique capability for the community. Some of the results from this system are starting to demonstrate the need for developing high-resolution *moving nests* supporting the Next Generation Global Prediction System (NGGPS).
- The Advanced Circulation (ADCIRC) storm-surge forecast system for oceanic, coastal and estuarine waters was run in semi-real time using 20 member ensembles from HWRF.
- Stream 2.0 and other HFIP sponsored/run models in real time were displayed on the HFIP website where new products and improvements to existing products are made.

Future configuration of the Hurricane Forecast System

Based on six years of results from the HFIP, the projected future operational hurricane forecast guidance system is described in Table 1 below.

Table 1. Future Numerical Model Hurricane Forecast Guidance System

Component	Specifications
Global model ensemble with Hybrid Data Assimilation	20 members at 10-20 km
Multiple moving nests to 2-3 km horizontal resolution within the global model	Telescopic nests, one for each hurricane, using all available aircraft and satellite data in the inner core and near environment of hurricane.
Additional models to make a multi-model ensemble (possibly run as a global model with internal nests).	Multi-model (at least two – e.g. HWRF/HNMMB, COAMPS-TC)
Statistical Post Processing	Logistics Growth Equation Model (LGEM), Statistical Hurricane Intensity Prediction System (SHIPS), Statistical Prediction of Intensity from a Consensus Ensemble (SPICE), and others.

[3] http://www.dtcenter.org/

1. Introduction

This report describes the Hurricane Forecast Improvement Project (HFIP), its goals, proposed methods for achieving those goals, and recent results from the program with an emphasis on recent advances in the skill of operational hurricane forecast guidance. The first part of this report is very similar to previous versions of the annual report since it basically sets the background of the program. This year's version is shortened somewhat from previous years but some of the same material is repeated for reference. For more background information the reader is referred to earlier reports available at: http://www.hfip.org/documents/reports2.php. Acronyms are defined in the Appendix.

2. The Hurricane Forecast Improvement Project

HFIP provides the unifying organizational infrastructure and funding for NOAA and other agencies to coordinate the hurricane research needed to significantly improve guidance for hurricane track, intensity, and storm surge forecasts. HFIP's 5-year (for 2014) and 10-year goals (for 2019) are:

- Reduce average track errors by 20% in 5 years, and 50% in 10 years for days 1-5.
- Reduce average intensity errors by 20% in 5 years, and 50% in 10 years for days 1-5.
- Increase the probability of detection (POD)[4] for RI[5] to 90% at Day 1 decreasing linearly to 60% at day 5, and decrease the false alarm ratio (FAR) for rapid intensity change to 10% for day 1 increasing linearly to 30% at day 5 (the focus on RI change is the highest-priority forecast challenge identified by the National Hurricane Center).
- Extend the lead-time for hurricane forecasts out to Day 7 (with accuracy equivalent to that of the Day 5 forecasts when they were introduced in 2003).

While Stream 1 works within presumed operational computing resource limitations, Stream 2 activities assume that resources will be found to greatly increase available computer power in operations above that planned for the next five years. The purpose of Stream 2 is to demonstrate that the application of advanced science, technology, and increased computing will lead to the desired increase in accuracy, and other improvements of forecast performance. Because the level of computing necessary to perform such a demonstration is larger than can be accommodated by current operational computing resources, HFIP developed its own computing system at NOAA/OAR/ESRL in Boulder, Colorado.

A major component of Stream 2 (also known as the Demonstration Project) is an Experimental Forecast System (EFS) that HFIP runs each hurricane season. The purpose of the EFS is to evaluate the strengths and weaknesses of promising new approaches that are testable only with

[4] POD, Probability of Detection, is equal to the total number of correct RI forecasts divided by the total number of forecasts that should have indicated RI: number of correctly forecasted ÷ (correctly forecasted RI+ did not, but should have forecasted RI). FAR, False Alarm Ratio, is equal to the total number of incorrect forecasts of RI divided by the total number of RI forecasts: forecasted RI that did not occur ÷ (forecasted RI that did occur + forecasted RI that did not occur).

[5] RI for hurricanes is defined as an increase in wind speed of at least 30 knots in 24 hours. This goal for HFIP also applies to rapid weakening (RW) of a decrease of 25 knots in 24 hours.

enhanced computing capabilities. The progress of Stream 2 work is evaluated after each season to identify techniques that appear particularly promising to operational forecasters and/or modelers. These potential advances can be blended into operational implementation plans through subsequent Stream 1 activities, or further developed outside of operations within Stream 2. Stream 2 models represent cutting-edge approaches that have little or no track record; and therefore are not used by National Hurricane Center (NHC) forecasters to prepare their operational forecasts or warnings.

3. The HFIP Model Systems

HFIP believes that the best approach to improving hurricane track forecasts, particularly beyond four days, involves the use of high-resolution global models with at least some run as an ensemble. However, global model ensembles are likely to be limited by computing capability for at least the next five years to a resolution no finer than about 8-10 km, which is inadequate to resolve the inner core of a hurricane. It is generally assumed that the inner core must be resolved to see consistently accurate hurricane intensity forecasts (NOAA SAB, 2006). Maximizing improvements in hurricane intensity forecasts will therefore require high-resolution regional models or global models with moveable high-resolution nests, perhaps also run as an ensemble. Below we outline the modeling systems currently in use by HFIP.

a. The Regional Model

Although HWRF and GFDL are primary regional models under Stream 1, both COAMPS as well as Advanced Research WRF (ARW) are run under Stream 2. The COAMPS-TC/HWRF/GFDL combined 41 member ensemble is used to demonstrate the value of multi-model ensembles in TC tracks and intensity predictions. A 41-member ensemble-system consisting of 10 perturbed members from COAMPS-TC, 20 perturbed members from HWRF and 11 perturbed members from GFDL were run for the 2015 season. Similarly, the Penn State University group ran ARW- Ensemble Kalman Filter (EnKF) and HWRF-EnKF systems for demonstration of improved data assimilation (DA) techniques for TC intensity forecasting. Specifications of regional models used by HFIP in 2015 are shown in Table 2.

Table 2. Specifics of the HWRF and other regional model used by HFIP in 2015

Models	Domains / Horizontal Resolution (km)	Vertical Levels Core	Cumulus Parameterization	Microphysics	PBL	Land Surface	Radiation	Initial and Boundary Conditions	Initialization	SST
HWRF (OPS)	3 18/6/2 (6/2 following the storm)	61 NMM	Simplified Arakawa Schubert for 18/6 nests	Ferrier-Aligo	GFS Non-Local PBL	Noah	RRTMG	GFS	Hybrid GSI-EnKF with vortex initialization	MPIPOM
HWRF in non-NWS basins (WP/SH/SL/IO)	3 18/6/2 (6/2 following the storm)	43 NMM	Simplified Arakawa Schubert for 18/6 nests	Ferrier-Aligo	GFS Non-Local PBL	Noah	RRTMG	GFS	vortex initialization	GFS (static)

Models	Domains / Horizontal Resolution (km)	Vertical Levels Core	Cumulus Parameterization	Microphysics	PBL	Land Surface	Radiation	Initial and Boundary Conditions	Initialization	SST
GFDL (WP, HFIP version)	3 55/18/6 (18/6 following the storm)	42 GFDL	Simplified Arakawa Schubert	Ferrier	GFS Non-Local PBL	GFDL Slab Model	Schwarzkopf-Fels (LW) / Lacis-Hansen (SW)	GFS	GFDL Synthetic Bogus Vortex	MPIPOM
GFDL (Ens) 11 members	3 55/18/6 (18/6 following the storm)	42 GFDL	Simplified Arakawa Schubert	Ferrier	GFS Non-Local PBL	GFDL Slab Model	Schwarzkopf-Fels (LW) / Lacis-Hansen (SW)	GFS.	GFDL Synthetic Bogus Vortex with inner core perturbation	MPIPOM
HYCOM-Coupled HWRF	3 27/9/3 (9/3 following the storm)	61 NMM	Simplified Arakawa Schubert	Ferrier	GFS Non-Local PBL	GFDL Slab Model	GFDL Scheme	GFS	Vortex initialization	3D HYCOM
HWRF-HRD/EMC Basin Scale	3 27/9/3 (9/3 following each storm)	61 NMM	Simplified Arakawa Schubert	Ferrier	GFS Non-Local PBL	GFDL Slab Model	GFDL Scheme	GFS	Vortex initialization	GFS (static)
HWRF-HRD (HEDAS)	2 9/3 (3km following the storm)	61 NMM	Simplified Arakawa Schubert	Ferrier	GFS Non-Local PBL	GFDL Slab Model	GFDL Scheme	GFS	EnKF; 1-hour cycling; storm-relative obs processing	GFS (static)
AHW (NCAR) 15-member ensembles	3 36/12/4	36 ARW	Tiedtke (36/12 km only)	WSM6	YSU	NOAH LSM	RRTMG (LW+SW)	GFS (BC only)	96-member DART EnKF method in a 6-hour cycling mode	Pollard 1-D Column Ocean
COAMPS-TC© (HFIP version)	3 45/15/5 (15/5 km following the storm)	40 COAMPS	Kain Fritsch on 45 and 15 km meshes	Explicit microphysics (5 class bulk scheme)	Navy 1.5 Order Closure	Slab with the NOAH LSM as an option	Fu-Liou	GFS	Balanced vortex initialization (4D-VAR, EnKF options)	NCODA with parametric SST (1D)
COAMPS-TC© (OPS)	3 45/15/5 (15/5 km after the storm)	40 COAMPS	Kain Fritsch on 45 and 15 km meshes	Explicit microphysics (5 class bulk scheme)	Navy 1.5 Order Closure	Slab with the NOAH LSM as an option	Fu-Liou	NAVGEM	Balanced vortex initialization (4D-VAR, EnKF options)	NCODA with parametric SST (1D)

b. Initialization and Data Assimilation Systems

It is believed improved initial state for TC models should have significant positive impacts on track, intensity and structure predictions. A number of approaches are used to create the initial state for the regional models in the HFIP EFS:

1. Grid-point Statistical Interpolation (GSI): The GSI system developed by NCEP is a unified 3-dimensional variational (3D-VAR) data assimilation system for both global and regional applications, and is widely used by many modeling systems across NOAA and other agencies

(DTC 2012; Wu, et al, 2002; Parrish and Derber 1992; Cohn and Parrish, 1991). This system is used by NCEP GFS in operations since 2006.

2. Global Forecast System (GFS): Starting in 2012, GSI was transitioned to Hybrid Ensemble-Variational DA System (HEVDAS). HEVDAS is a combination of the GSI 3D-VAR and an ensemble-based system to define the background error matrix.

3. Vortex initialization: The initial vortex for regional models is produced by a vortex initialization procedure. In general, the vortex circulation is filtered from the *first guess* fields interpolated from global model; then a new vortex modified by the observed intensity is inserted back in the filtered environment. The new vortex is either the model balanced vortex cycled from the previous six-hour forecast, from a parent global model, or defined based on a synthetic vortex profile. On the first initialization for a particular storm, the size and intensity of the GFS vortex are modified based on real-time observations. In the HWRF system, the tropical cyclone vortex is generally cycled from the HWRF previous six hour forecast, and the vortex is relocated based on the observed position. The hybrid GSI-EnKF DA system uses the modified vortex and ambient fields as a first guess for assimilating data into the HWRF system. Vortex relocation is also utilized by the current operational GFS and Global Ensemble Forecast System (GEFS) in NCEP. An advanced vortex initialization and assimilation cycle for the operational HWRF consists of four major steps: 1) interpolation of the global analysis fields from the Global Data Assimilation System[6] (GDAS) onto the operational HWRF model grid; 2) removal of the GFS vortex from the global analysis; 3) addition of the HWRF vortex modified from the previous cycle's six-hour forecast based on observed location and strength (or use of a corrected GDAS or bogus vortex for a cold start); and 4) addition of observation data outside of the hurricane area using hybrid GSI. The flow-dependent portion of the background error covariance comes from a 6-h. HWRF ensembles (self-cycled since 2015) when tail Doppler radar (TDR) observations are available, and when TDR is unavailable it uses the 6-h. GDAS ensemble. The DA system is capable of ingesting inner core data to optimize the vortex initialization.

4. Naval Research Laboratory (NRL) Atmospheric Variational Data Assimilation System (NAVDAS): This is the system used to provide the initial conditions to NAVGEM. Previously a 3D-VAR system, it was upgraded in September 2009 to NAVDAS-Accelerated Representer (AR), a four-dimensional variational (4D-VAR) approach (Daley and Barker, 2001).

5. Ensemble Kalman Filter (EnKF): This is an advanced assimilation approach, somewhat like 4D-VAR, that uses an ensemble to create background error statistics for a Kalman Filter (Tippett et al, 2003; Keppenne, 2000; Houtekamer et al, 1998; and Evensen, 1994). Several HFIP models (e.g., AHW, HFIP GFS ensembles, Pennsylvania State University (PSU) etc., see Tables 4 and 5 above) are using the EnKF approach for DA. The Penn State group led by Professor Fuqing Zhang uses such an approach in both ARW and HWRF systems. The Hurricane Research Division (HRD)/AOML developed a variant of the EnKF based DA system using the HWRF model, known as the Hurricane Ensemble Data Assimilation System (HEDAS) as noted by Aksoy et al, (2012).

[6] https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-data-assimilation-system-gdas

c. The HWRF Community Code Repository and User Support

During 2009-2015, both the Environmental Modeling Center[7] (EMC) and the Developmental Testbed Center (DTC) worked to update the operational version of HWRF from version 2.0 to the current community version of HWRF, version 3.7a (Bernardet et al, 2015; Tallapragada et al, 2016). This makes the operational model completely compatible with codes in community repositories, allows researchers access to operational codes, and makes improvements in HWRF developed by the research community easily transferable into operations. This was one of the initial goals of the WRF program, and is supported by HFIP for developing a repository for a community-based hurricane modeling system which ensures the same code base can be used for research and in operations. Support provided by the DTC in 2015 included two in-person HWRF tutorials; one at NCEP in College Park, MD, and another at Nanjing University of Information Science and Technology (NUIST) in China. User support was expanded with an experimental version of HWRF called the "basin-scale" HWRF that was created at AOML/HRD in collaboration with NCEP/EMC under the support of NOAA's HFIP. This research system can support any number of high-resolution movable nests centered on TCs in either the Atlantic or East Pacific basin. Working with HRD, the DTC also supported the transition of this research version to the latest community repository, enabling users to access all advancements in the HWRF system including the end-to-end basin scale configuration (excluding ocean coupling and data assimilation).

[7] http://www.emc.ncep.noaa.gov/gc_wmb/vxt/HWRF/index.php

4. Meeting the HFIP Goals

a. The HFIP Baseline

To measure progress toward meeting the HFIP goals outlined in the introduction, a baseline level of accuracy was established to represent the state of the science at the beginning of the program. Results from HFIP model guidance could then be compared with the baseline to assess progress. HFIP accepted a set of baseline track and intensity errors developed by NHC, in which the baseline was the consensus (average) from an ensemble of top-performing operational models, evaluated over the period 2006-2008. For track, the ensemble members were the operational aids GFSI, GFDI, UKMI, NGPI, HWFI, GFNI, and EMXI, while for intensity the members were GHMI, HWFI, DSHP, and LGEM (Cangialosi and Franklin, 2011). Fig. 1 shows the mean errors of the consensus over the period 2006-2008 for the Atlantic basin, and the 5- and 10-year error goals represented in black; and these are labeled on the left side of the graph. A separate set of baseline errors (not shown) was computed for the eastern North Pacific basin.

The baseline errors in Fig. 1 are also compared to the errors of the same cases for the climatology and persistence model (CLIPER5) supporting track and the Decay Statistical Hurricane Intensity Forecast (Decay-SHIFOR5) model for intensity (NHC, 2009). Errors from these two models are large when a storm behaves in an unusual or rapidly changing way, and therefore are useful in assessing the inherent difficulty in a set of forecasts. When a track or intensity model error is normalized by the CLIPER5 or Decay-SHIFOR5 error, the normalization yields a measure of the model's skill.

Because a sample of cases from, for example, the 2013 season might have a different inherent level of difficulty from the baseline sample of 2006-2008 (e.g., as it had an unusually high or low number of rapidly intensifying storms), evaluating the progress of HFIP models in terms of forecast skill provides a more representative longer-term perspective. Fig. 1 shows the baseline errors and the 5- and 10-year goals as skill, represented in blue and labeled on the right side of the graph. Skill in the figure is the percentage improvement over the Decay-SHIFOR5 and CLIPER5 forecasts for the same cases. Note the skill baseline and goals for intensity at all lead times are roughly constant with the baseline representing a 10% improvement over Decay-SHIFOR5 and the 5- and 10-year goals; representing 30% and 55% improvements, respectively. It's important to remember, however, that normalization by CLIPER or (especially) Decay-SHIFOR5 can fail to adequately account for forecast difficulty in some circumstances. A hurricane season that features extremely hostile environmental conditions will lead to very high Decay-SHIFOR intensity forecast errors (as climatology will be a poor forecast in such years), but relatively low dynamical model and NHC official forecast errors (as few storms will intensify rapidly, making life easy on both models and forecasters). This combination of baseline and model errors yields an unrealistic skill estimate.

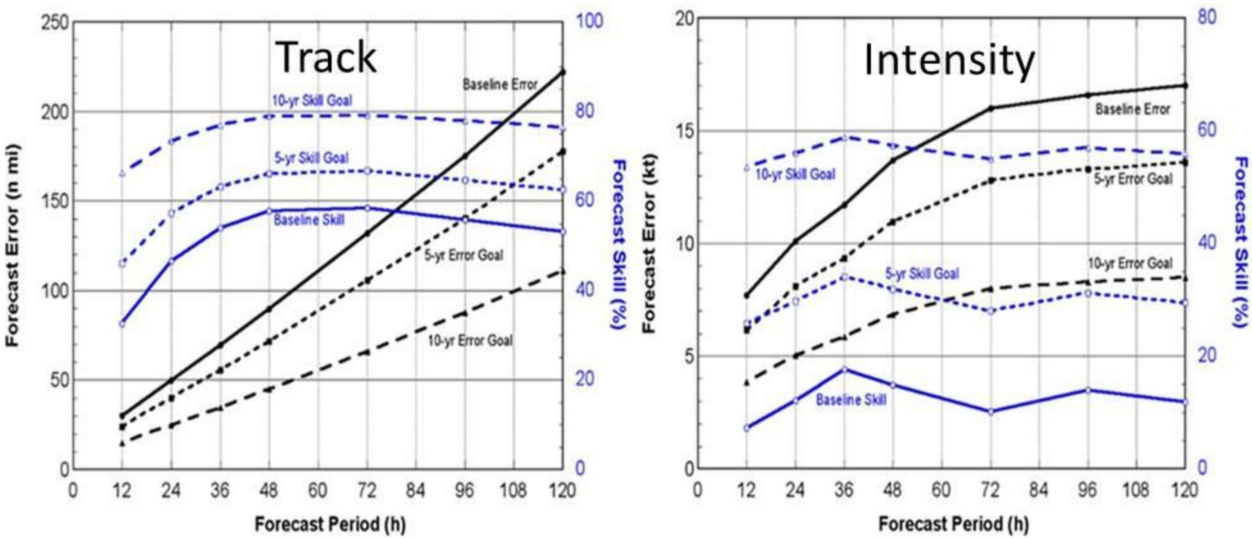

Figure 1: HFIP Track and Intensity Error Baseline and Goals.
The baseline errors (black lines) were determined from an average of the top-flight operational models during the period 2006-2008. The HFIP expressed goals (dashed lines) are to reduce this error by 20% in 5 years and 50% within 10 years. Comparisons of forecasts over non-homogenous samples, however, are best done in terms of skill. To obtain the 5-year and 10-year HFIP goal in terms of skill (blue lines-baseline skill in solid, HFIP goals dashed), the goals are expressed as the percentage improvement over the CLIPER5 errors (track) and Decay-SHIFOR5 (intensity) of the baseline sample (see text).

It is important to note that HFIP performance baselines were determined from a class of operational aids known as “early” models. Early models are those that are available to forecasters early enough to meet forecast deadlines for the synoptic cycle. Nearly all the dynamical models currently in use at tropical cyclone forecast centers, such as the GFS or the GFDL model (or “GFDL”), are considered “late” models because their results arrive too late to be used in the forecast for the current synoptic cycle. For example, the 12:00 Coordinated Universal Time or Zulu Time Zone (Z) GFDL run does not become available to forecasters until around 16:00Z, whereas the NHC official forecast based on the 12:00Z initialization must be issued by 15:00Z, one hour before the GFDL forecast can be viewed. It’s actually the older, 06:00Z run of the GFDL model that would be used as input for the 15:00Z official NHC forecast, through a procedure developed to adjust the 06:00Z model run to match the actual storm location and intensity at 12:00Z. This procedure also adjusts the forecast position and intensity at some of the forecast times as well and then applies a smoother to the adjusted forecast. This adjustment, called “interpolation” procedure, creates the 12:00Z “early” aid GFDI that can be used for the 15:00Z NHC forecast. Model results so adjusted are denoted with an “I” (e.g., GFDI). The distinction between early and late models is important to assessing model performance, since late models have an advantage of more recent observations/analysis than their early counterparts. However, it is interesting to note that although the early version loses about 3-5% of the skill for track forecasts compared to the late version, the skill for intensity forecasts are virtually the same for late and early versions (Goldenberg et al, 2015).

b. Meeting the Track Goals

Accurate forecasts beyond a few days require a global domain because influences on a forecast for a particular location come from weather systems at increasing distance from the local region over time. One of the first efforts in HFIP was to improve the existing operational global models. Early in the program it was shown that forecasts were improved, particularly in the tropics, by using a more advanced DA scheme than the one employed operationally at that time. A version of this advanced DA went operational in the GFS model in May 2012. Looking at a 2-year sample for the Atlantic basin (Fig. 3a) we're near the 5-year HFIP goal, at least through 72 hrs. In the East Pacific basin (Fig. 3b), for the 2-year sample, OFCL is well above the 5-year goal and seemingly within reach of the 10-year goal. However, TCs like Joaquin (2015) continue to pose challenges to track forecasting. Sustained HFIP research and developments may be necessary for further improvements in tracks of these outlier events. It is also expected that the Next Generation Global Prediction System (NGGPS) may be able to provide some accelerated progress in reaching the HFIP 10-year goal. Toward this end, there is a gradual transitioning of HWRF efforts to focus on hurricane forecast guidance within NGGPS. HRD and NWS are working to transition hurricane multiple moving 1-3 km high resolution nest capability within the NGGPS model that could be used for any TC within the global model (see Section 12 for details).

c. Reaching the Intensity Goals

HFIP expects that its intensity goals will be achieved through the use of regional models or eventually with global models that have moveable nests with a horizontal resolution finer than 3 km covering the hurricane's inner core. Some significant progress was made with the regional HWRF system meeting the 5-year HFIP intensity goal. In general, the operational HWRF model has started showing its potential for improved intensity forecasts, producing comparable and sometimes superior results versus statistical models and NHC official forecasts; as demonstrated through a large set of retrospective forecasts. In fact, on average HWRF produced the best intensity guidance of any single model for 2015 covering the Atlantic basin (Fig. 5). Results from HWRF model for intensity forecasts are presented in this report. In addition, early results suggest that output from individual HFIP models can be used in statistical models such as the Statistical Hurricane Intensity Prediction System (SHIPS), (DeMaria and Kaplan, 1994; NHC 2009) or Logistics Growth Equation Model (LGEM) (DeMaria, 2009; NHC 2009) to further increase the skill of the intensity forecasts. The eventual goal is to create regional models that will be able to interact within the global model. More specifically, there would be one set of nests for each hurricane in the global model thereby accomplishing both track and intensity forecast goals through a unified global-to-regional scale modeling system. In fact, the basin-scale HWRF, that was experimentally run under the Stream 2 activity this year was a step taken by HFIP towards the eventual creation of global nests.

5. Operational Hurricane Guidance Improvements

HFIP goals described in section 4 are considered met when the model guidance provided to NHC by National Centers for Environmental Prediction[8] (NCEP) reaches those goals. Since 2015 represents the sixth year of the project, it is expected to see progress toward meeting HFIP 10-year goals in both operational models and experimental models. In this section, emphasis is placed upon improvements in the hurricane forecasts from models that were fully operational in 2015. This includes the GFS and the HWRF operational regional models.

a. Track Guidance

In May of 2012, the GSI data assimilation system in the GFS was replaced by the hybrid data assimilation system. The hybrid system uses an ensemble to generate a flow dependent background error covariance matrix that is then used in the GSI for the analysis. In previous annual reports starting with the first one in 2010, the impact of changing the DA system in the global models was described, particularly the GFS from the 3D-VAR GSI to an ensemble based system, called (EnKF). The hybrid system is basically a combination of the EnKF and the GSI that has shown to provide somewhat better results than EnKF alone. The global hybrid system merge with regional models is considered an important mechanism for the transference of HFIP results into operations. In addition, the GFS underwent other improvements including improved physics and increased resolution. In 2014, the deterministic operational GFS was run at T574 (~27 km) and the GFS ensemble (GEFS) at T254 (~60 km). In January 2015, the resolution of the GFS was increased to T1534 (~13 km) and in December 2015, GEFS resolution was increased to T382 (~33 km).

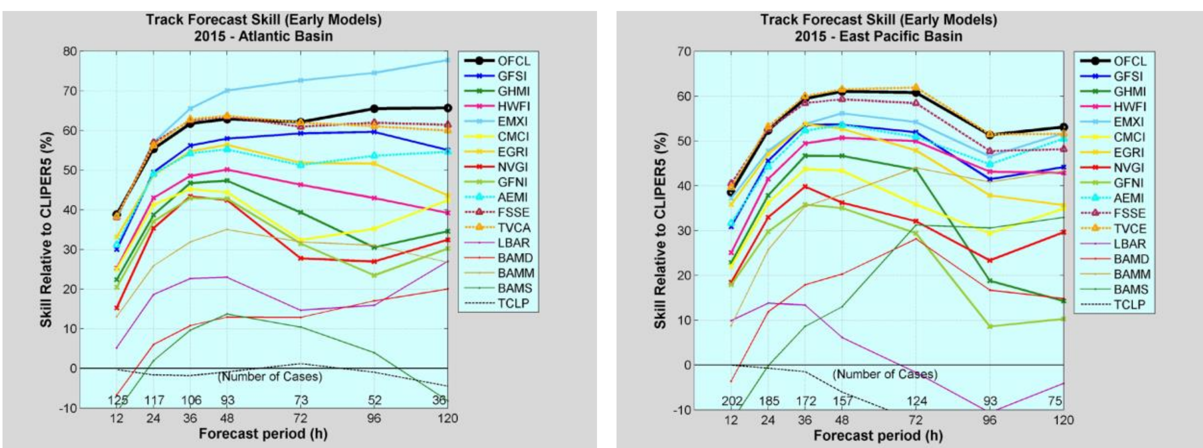

Figure 2: 2015 Seasonal track forecast skills over (a) Atlantic and (b) East Pacific basins.

In the 2015 season, over the Atlantic basin (Fig. 2a, left) the European model (EMXI) was the best performer and the only one that beat the official forecast at 36 h and beyond. The GFSI (operational GFS model) was a fair to good performer (second best individual model) with skill just below the official forecasts and the consensus models followed by GFS ensemble mean

[8] http://www.ncep.noaa.gov/

(AEMI), HWFI and the UK meteorological office model (EGRI). Over the East Pacific Basin (Fig. 2b, right), the FSU super ensemble (FSSE) was a strong performer, but not as good as TVCE (average of at least 2 of GFDI, HWFI, UKMI, GFSI, EMXI). The EMXI was the best

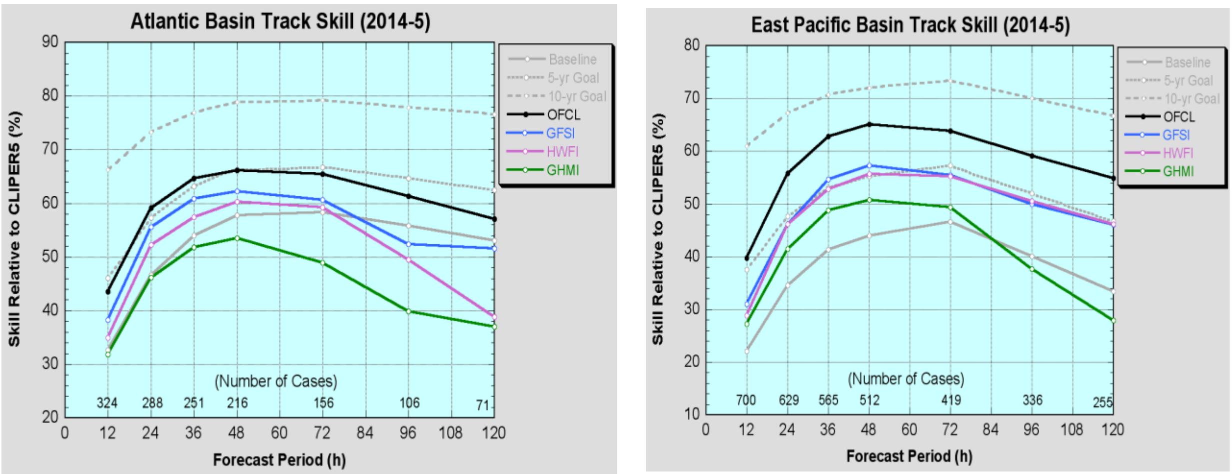

Figure 3: 2014-2015 Seasonal track forecast skills over (a) Atlantic and (b) East Pacific basins

individual model, but less skill than the official forecasts and consensus models. GFS ensemble mean, GFSI, HWFI, and EGRI were the next best models. The Atlantic Hurricane Joaquin was a forecasting challenge and illustrated the need for additional research to address model failures. Nevertheless, looking at a 2-year sample for the Atlantic basin (Fig. 3a, left) to get a more representative result shows that we're near the 5-year HFIP goal, at least through 72 hrs. HWRF is competitive but less skillful than the GFS. In the East Pacific basin (Fig. 3b, right), for the 2-year sample, OFCL is well above the 5-year goal and seemingly within reach of the 10-year goal. HWRF and GFS were neck and neck, and individually have both reached the 5-year goal.

b. A Note on Global Ensemble Forecast System for Track Guidance

NCEP's Global Ensemble Forecast System (GEFS) was upgraded in December, 2015. The horizontal resolution is increased from about 55km to about 33km for the first 192 hours (8 days) of model integration, and from about 70km to about 55km between 192 hours to 384 hours of model integration. The new GEFS also increases the vertical resolution from 42 levels to 64 levels throughout the model integration. The ensemble initialization method is modified by replacing the Bred Vector with the Ensemble Transform and Rescaling (BV-ETR) scheme in conjunction with the Ensemble Karman Filter (EnKF) scheme. The 6-hour forecasts of the 80 EnKF ensemble members of the Hybrid Data Assimilation system, from the previous cycle, are used to initialize the ensemble perturbations. This change unifies NCEP's global ensemble systems in data assimilation and forecast and will lead to reduction in computational resources. The Stochastic Total Tendency Perturbation (STTP) scheme is also modified by turning off the perturbations in surface pressure and improving the rescaling algorithm. In the 2015 season, over both Atlantic and East Pacific basins, the AEMI (GEFS with 6-hour interpolation) performed very similar to GFS in terms of track prediction skill (Fig. 2a and 2b). Fig. 4, for instance, shows one cycle of Hurricane Joaquin (including TC Ida) from the ECMWF ensemble system and GEFS. The deterministic track forecast from ECMWF was much more skillful than its ensemble members. The ECMWF ensemble had large spread and deterministic forecasts were outliers. Whereas the deterministic forecast from GFS had taken the storm west. The GEFS produced less spread but more meaningful ensembles for this cycle than the deterministic forecast. In either models, there was a large divergence between deterministic and ensemble forecasts; illustrating the need for research on the spread of ensemble members and divergence between ensemble and deterministic forecasts for track predictions.

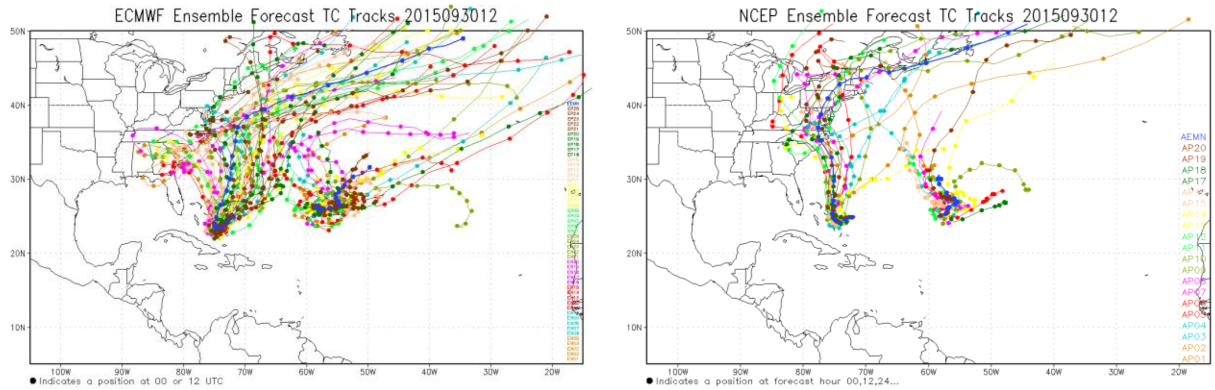

Figure 4: Ensemble predictions from 20150930 12Z ECMWF and GFS ensembles cycles.
Ensemble predictions from 20150930 12Z cycle (a) ECMWF and (b) GFS ensembles illustrate the need for research on the spread of ensemble members and divergence between ensemble and deterministic forecasts for track predictions.

c. Intensity Guidance: Hurricane WRF (HWRF)

1) Atlantic Basin

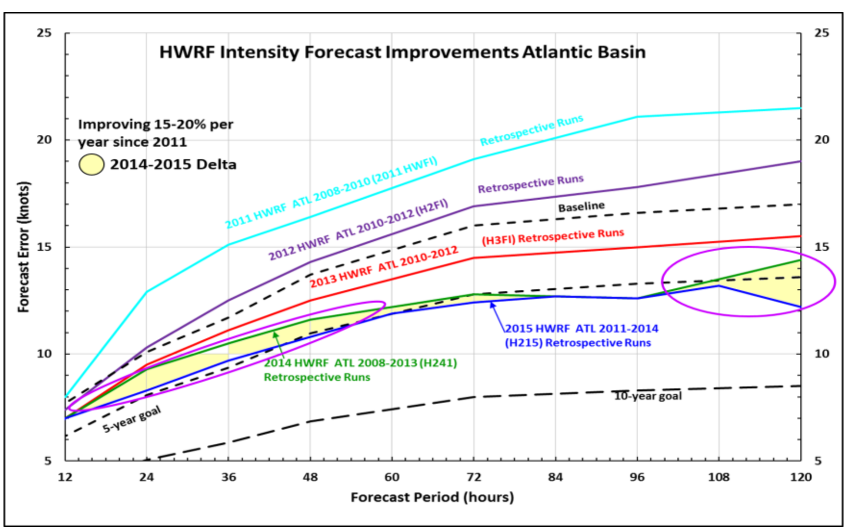

Figure 5: 2011-2015 HWRF Intensity Forecast Improvement for the Atlantic Basin.
HWRF Intensity Forecast Improvement for the Atlantic Basin Improvements from the 2011 to 2015 are shown as forecast improvements in intensity error over the time. Seasons for which models were run are depicted on each line. Note that some the samples (years) are not homogeneous between models. Significant evolution in accuracy and advancement toward the HFIP 10-year goal is shown by the ellipse over the 108 h. to 120 h. forecast period.

Fig. 5 portrays the progress of HWRF in forecasting intensity relative to HFIP goals. There is a steady decrease of intensity error from 2011 to the present by 15% to 20% per year; although some of the samples (years over which models were run) shown in the figure are not homogeneous. In fact, in terms of error related to the five-year goal, the 2014 version of HWRF met or exceeded that goal beyond 72 hours. This illustrates that accelerated progress is being made in meeting the 10-year goal. Consistent with Fig. 5, the HWRF was the most skillful model in the 2015 Atlantic season between 36-96 hours (Fig. 6). However, another striking feature in Fig. 5 is the consistently very low skill early in the forecast (purple ellipse). This is related to the ongoing problems with initialization of the models. This problem is not unique to HWRF (Fig. 6). All dynamical models seem to suffer from a common initialization problem, i.e. the inability of the model to represent the initial state of the atmosphere accurately due to incompleteness in observations to provide all variables at all model levels for accurate initialization. The initialization of dynamical models continues to be a high priority for HFIP. Keep in mind however, that statistical models as well as the "early" (aka interpolated) versions of dynamical models', show better results in the first 24 hours since the initial times are adjusted to the operational values. The results shown here are for the "late" (aka non-interpolated) versions and therefore the forecast errors at early lead times are generally larger than with the "early" versions.

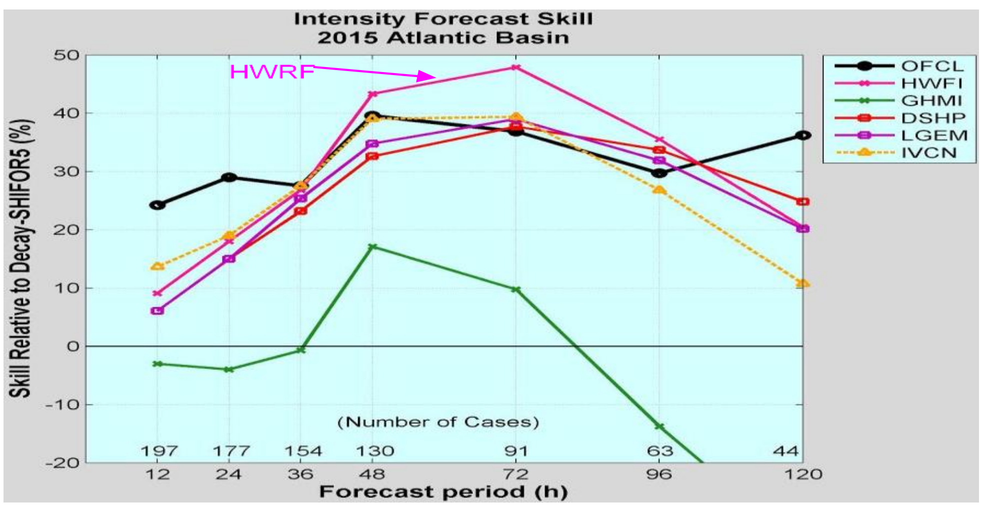

Figure 6: 2015 Hurricane season intensity forecast skills for the Atlantic

Fig. 6 shows the intensity results for the 2015 Atlantic season. HWRF was the best performer for 2015. In the 2014 season, the statistical model DSHP was the best performer. Whereas in the 2013 season, HWRF outperformed statistical models DSHP and LGEM. HWRF for 2015 beats these statistical models by at least a maximum of 10-15% between 36 and 96 hours. It should be noted that, since 2011, the HWRF model proved to be able to either outperform or at least to be comparable to the statistical model. Until 2011, none of the dynamical models have shown that kind of consistent skill. Tallapragada et al. (2014) attributed the improved forecasts to some important implementations: (a) higher-horizontal-resolution nest that better resolves convection and represents terrain effects; (b) PBL and surface physics for the higher resolution nest; and (c) improved representation of the initial conditions in the higher resolution nest. All of this may be credited to HFIP Streams 1 and 2 developments. Nevertheless, tropical cyclones like Erika (2015) and Patricia (2015) continue to pose challenges to intensity forecasting.

Sustained HFIP research and development are necessary for further improvements of rapid intensification and decay forecasts in these events. Erica was a classic case of a false alarm, i.e., storms will dissipate whereas models keep intensifying them. HWRF captured some of RI during Patricia's intensification, but with intensity errors at 48 hrs. that still exceeded 40 kts.

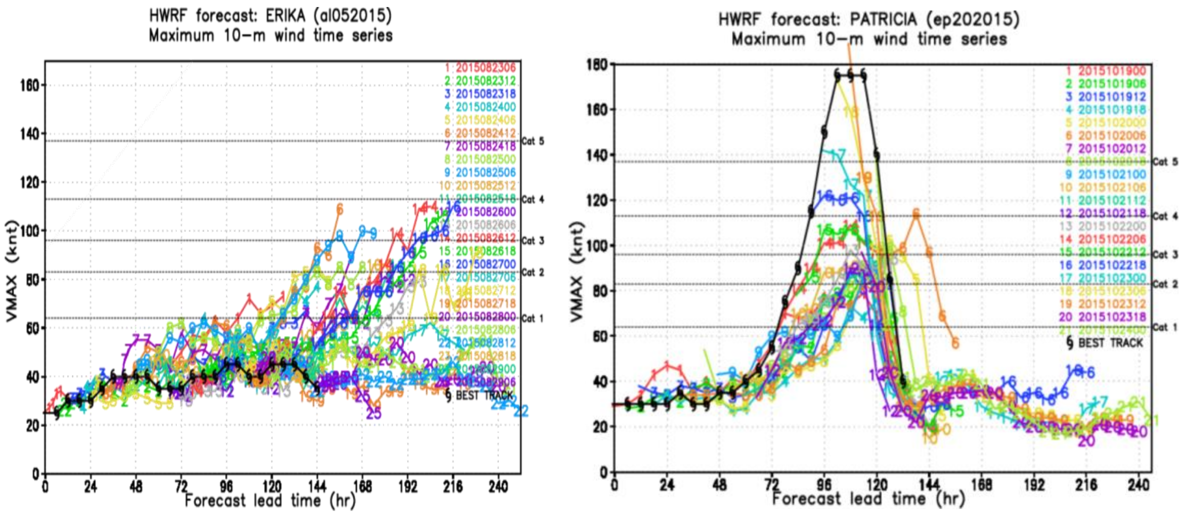

Figure 7: Evolution of intensity from various HWRF forecast cycles.
This figure depicts the intensity evolution derived from various forecast cycles for (a) Erika (an example of false RI in 2015) and (b) Patricia (case of under predictions). The black dotted line shows the best estimates of 10-m wind speed.

2) East Pacific (EPAC) Basin

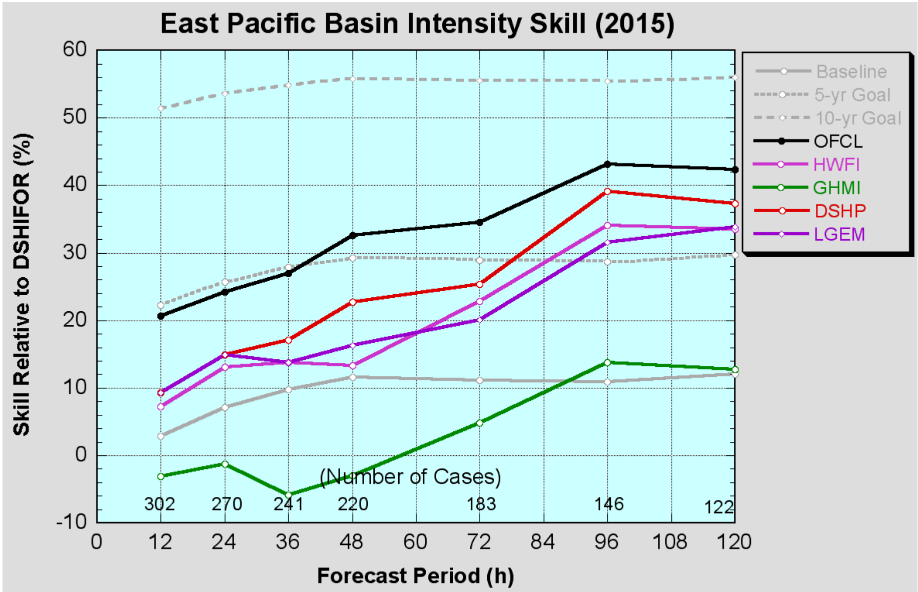

Figure 8: 2015 Hurricane season intensity forecast skills for the East Pacific Basin.

Fig. 8 provides the intensity forecast skill plot of the Eastern North Pacific basin for the 2015 hurricane season. The OFCL was at or well above the 5-year goal, as was some of the guidance. In this basin both the statistical models, DSHP and LGEM, performed well and so did the HWRF. The HWRF intensity forecast had large negative bias in the Eastern North Pacific that was likely due to use of the climatology of ocean temperature profile at initial time. Work is on-going under HFIP.

d. HWRF Improvements in RI/RW Predictions in Atlantic and Eastern North Pacific Basins

Improving RI/RW forecasts is one of the highest priorities for HFIP and was recognized as the most challenging aspect of TC research. Much of the lack of improvement in the RI forecast skill is rooted in our lack of understanding on when and how RI occurs in different environmental conditions and the historic inability of dynamical models to adequately predict not only the convection in the hurricane core, but also the large scale environmental factors such as shear and moisture that produce an RI event. The impressive intensity forecast performance from the new operational HWRF model demonstrated its improved ability in representing and forecasting RI. Verification of the probability of detection (POD) and the false alarm rate (FAR) of RI forecasts for Atlantic and E-Pacific basins during 2015, shown in Fig. 9, indicate further improvements in the POD for the 2015 HWRF model compared to the 2014 version. Specifically, the POD index for RI forecasts (an increase >30 kt. intensity change in 24 hrs.) in the 2015 HWRF model is 44.4% compared to 4.8% in 2014 over the Atlantic basin. The FAR remained very low. Similarly, in the Eastern North Pacific, the POD went up from 1.2 in 2014 to 5.1 without much increase to the FAR. Improving RI forecasts is one of the highest priorities for HFIP and was recognized as the most challenging aspect of TC research. Much of the lack of improvement in the RI forecast skill is rooted in our lack of understanding of when and how RI

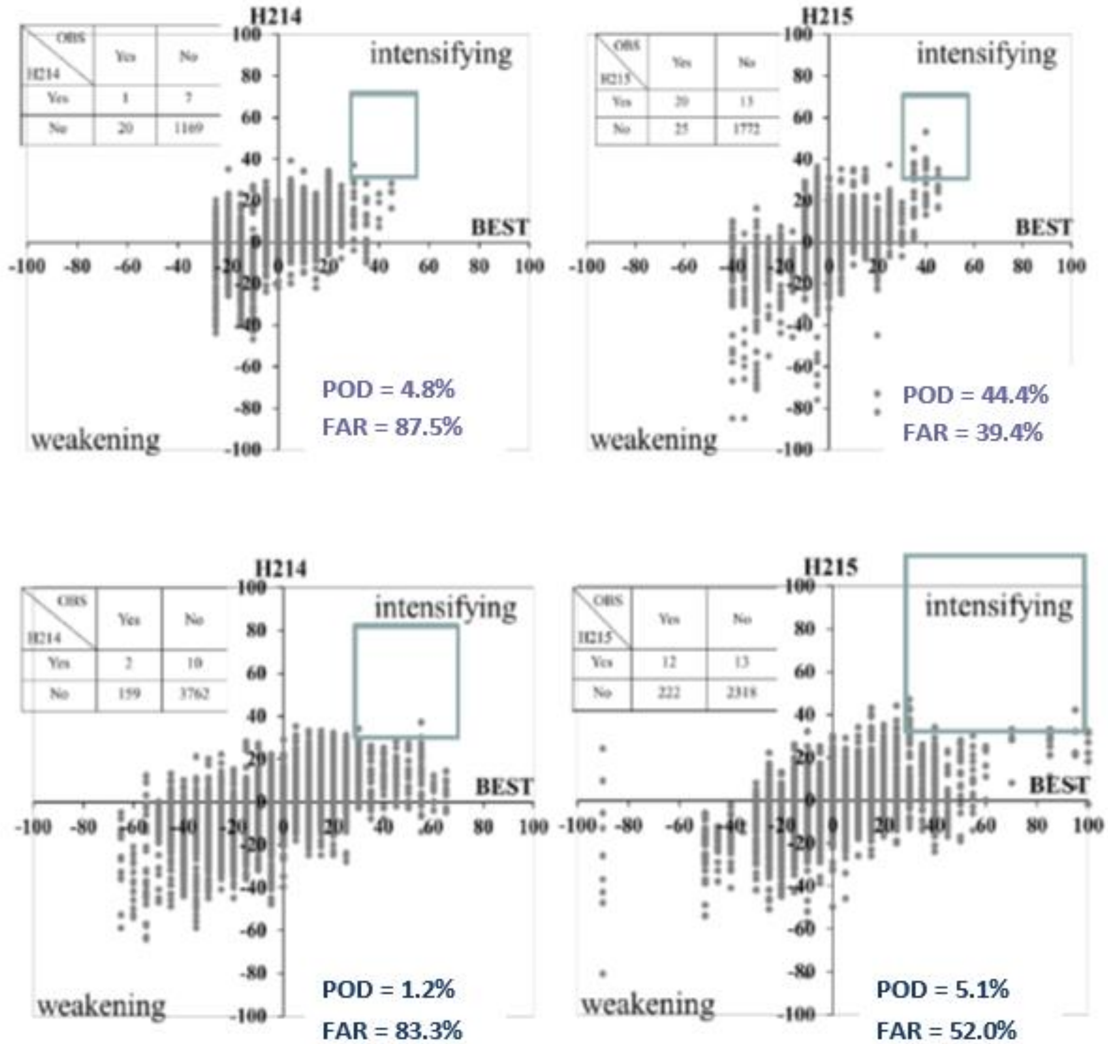

Figure 9: HWRF predicted 24-hour maximum 1-m wind speed changes (knots).
Real-time HWRF-predicted versus Observed 24-hour wind speed changes from 2014 version (left panels) and 2015 version (right panels) for the Atlantic (upper panels) and East Pacific (lower panels) basins. Points within the rectangles in the upper right quadrants are correctly predicted RIs. The corresponding contingency tables are shown in the upper left quadrants. Note: data represents storms after reaching 35 kts.

occurs in different environmental conditions and the historic inability of dynamical models to adequately predict not only the convection in the hurricane core, but also the large scale environmental factors such as shear and moisture that produce an RI event. The intensity forecast performance from the new operational HWRF model demonstrated its improved ability in representing and forecasting RI. Verification of the probability of detection (POD) and the false alarm rate (FAR) of RI forecasts for Atlantic and E-Pacific basins during 2015, shown in Figure 9, indicate improvements in the POD for the 2015 HWRF model compared to the 2014 version. Specifically, the POD index for RI forecasts (an increase >30 kt. intensity change in 24 hrs.) in the 2015 HWRF model is 44.4% compared to 4.8% in 2014 over the Atlantic basin. The FAR decreased substantially, as well. Similarly, in the Eastern North Pacific, the POD went up from 1.2 in 2014 to 5.1, with a decrease in the FAR. Note that the data used to develop Fig. 9 represents storms after reaching 35 knots. RI predictions made before maximum winds reached 35 knots are not included in the figure or the POD and FAR value calculations.

6. HWRF performance in other global basins

The cover picture shows the global coverage of the operational HWRF system on a particular day. In 2012, the HFIP began running real-time forecasts for the WPAC and in 2013 for the Indian Ocean. In 2014, HWRF runs were also extended into the southern Pacific and Indian Oceans. These runs were done in real time on the HFIP computers in Boulder, CO rather than operational computers. Forecasts were transmitted to the Joint Typhoon Warning Center[9] (JTWC) where they were used extensively in their forecasts. The transition of HWRF from Stream 2 to operations in 2015 was another success story for HFIP. This section briefly discusses the performance of HWRF in the other global basins.

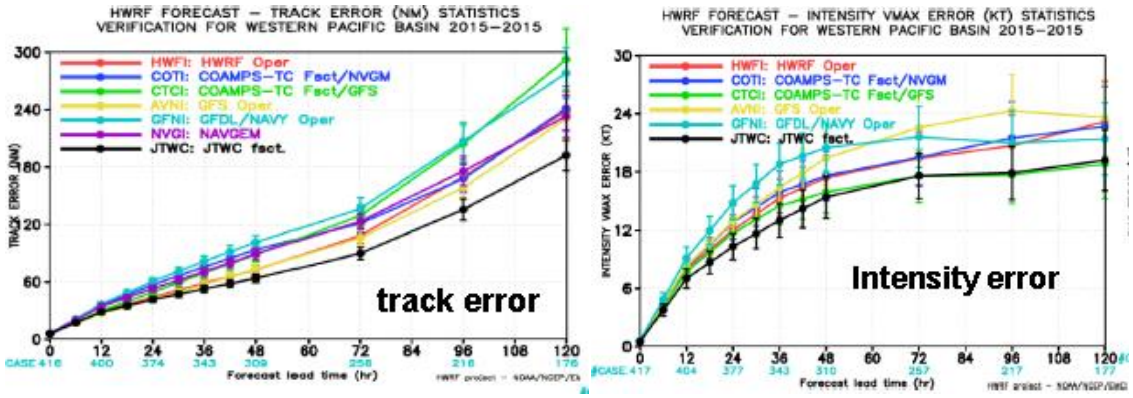

Figure 10: 2015 Seasonal track and intensity forecast skills for the West Pacific Basin. This figure illustrates (a) Track and (b) Intensity forecast skills over the West Pacific basin in the 2015 season.

Fig. 10 shows the performance for WPAC storms of HWRF compared to various other models. In this basin, both GFS and HWRF are top performers in terms of track until 72 hours followed by the NAVY models (NAVGEM and COAMPS-TC with NAVGEM boundary conditions). For intensity forecasting COAMPS-TC with GFS boundary conditions was the best, followed by HWRF and COAMPS-TC with NAVGEM boundary conditions. JTWC forecasters noted significant improvements between 2014 and 2015 HWRF forecasts for both track and intensity. However, it was also noted there was a positive bias for intensity forecasts. Lack of ocean coupling may be the reason for this bias. The HYCOM-HWRF coupled forecast will be run in the near future for that basin.

[9] https://metoc.ndbc.noaa.gov/JTWC/

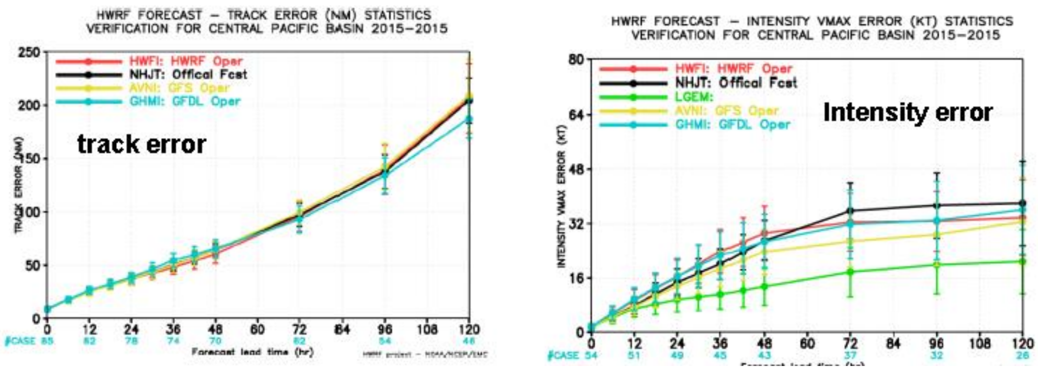

Figure 11: 2015 Seasonal track and intensity forecast skills for the Central Pacific Basin.
This figure depicts: (a) Track and (b) Intensity forecast skills over the Central Pacific basin in the 2015 season.

Fig. 11 shows the performance for Central Pacific storms of HWRF compared to various other models. In the Pacific basin, both HWRF and GFS performed as well as the official track forecast in terms of track error. Fig. 11 also shows the GFDL model has significantly less track error than official forecast results for 96-120 hours. HWRF intensity performance was better than official forecast performance at longer lead times between 48-120 hours. Nevertheless, LGEM was the best performing model with an intensity forecast error about half as large as the HWRF error. It also be noted that the number of samples in this basin were low.

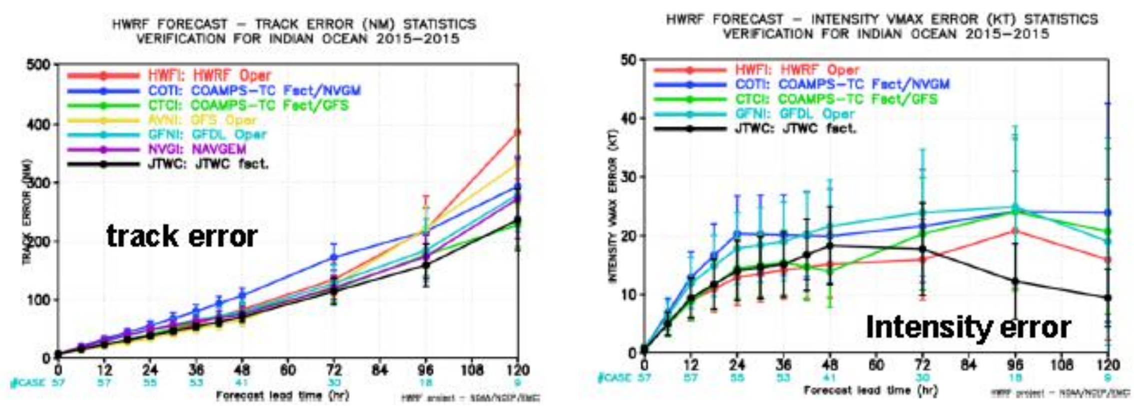

Figure 12: 2015 Seasonal track and intensity forecast skills for the Northern Indian Ocean.
This figure illustrates (a) Track and (b) Intensity forecast skills over the NIO basin in the 2015 season.

Fig. 12 shows the performance for North Indian Ocean storms of HWRF compared to various other models. Beyond 48 hours, HWRF tracks had some large errors reported in this basin. Nevertheless, HWRF was the best performing model for intensity guidance having nearly equaled or beaten the official JTWC forecast from 0 through 72 hours. The COAMPS-TC run with GFS boundary conditions had a similar intensity performance within that time. Note that COAMPS-TC run with GFS boundary conditions showed improvement in track guidance over that of COAMPS-TC with NAVGEM boundary conditions. NHC is considering this model configuration as an experimental candidate for real-time delivery for the upcoming hurricane season.

7. Important Stream 2 Results

a. Regional Multi-Model Ensembles

Since 2014, the HFIP began testing a multi-model regional ensemble. Three ensembles are used: the HWRF, COAMPS-TC and the GFDL Ensembles (described in more detail below).

The HWRF ensemble was the same system used for the HWRF ensemble last year with a few additional physics perturbations:

- 27-, 9-, 3-km horizontal grid spacing
- 20 members plus 1 control, the operational HWRF
- Initial Conditions (IC)/Boundary Conditions (BC) Perturbations were from the GEFS- and Ensemble Transform with the Rescaling (ETR) system to form ensemble members:
  - Stochastic boundary layer height perturbations in PBL scheme, -20% to +20%
  - Stochastic initial wind speed perturbations with zero mean and -3kts to +3kts
- Model Physics Perturbations (vortex scale):
  - Stochastic Convective Trigger in SAS, -50hPa to + 50hPa white noise
  - Stochastic Cd perturbation

Large-scale perturbations of the ensemble were derived from the GEFS to initially define each member. A stochastic convective triggers (initial wind and PBL height perturbations) were subsequently added within each member.

The COAMPS-TC ensemble was similar to that run in 2014, except that the size of the inner nest was increased to be consistent with the operational model, and the 2015 version of the model was used for the ensemble:

- 27-, 9-, 3-km. horizontal grid spacing (increased the size of the inner nest to match control) and this resolution is higher than the current operational COAMPS-TC.
- 1 control + 10 members with initial and boundary condition perturbations
- No physics perturbations (2015 version of COAMPS-TC has a new Cd formulation)
- No data assimilation
- Control forecast:
  - Initialized from the GFS analysis
  - Vortex initialized with a Rankine vortex based on TC vitals
- Ensemble members IC's perturbed about the control:
  - Synoptic perturbations drawn from static covariance (WRFVARcv3) for initial/BCs
  - Vortex IC's based on perturbed TC vitals

GFDL Ensembles**:**
For the last five hurricane seasons HFIP promoted running an ensemble of the operational GFDL model. HFIP uses the same model as the operational GFDL (which forms the control forecast for the ensemble, see Table 3). Working with NHC forecasters, GFDL scientists constructed an ensemble by modifying various parameters in the initial conditions, sea surface temperatures and surface fluxes used by the model. The *unbogussed* forecasts start from the GFS without modification to the vortex from what was in the GFS initially.

Table 3. Automated Tropical Cyclone Forecasting System (ATCF) ID Descriptions.

ATCF ID	2015 GFDL Ensemble Membership ↑(↓) = overall effect is increased (decreased) intensity relative to the Control	
GP00	**Control** forecast (configured similar to NCEP 2015 operational GFDL)	
GP01	**Unbogussed** forecast using the 2015 GFDL control model (**bogussed** for Invests)	
GP02	**Increase** NHC-observed V_{max} 10%, R34 25%, R50 40%, ROCI 25%	↑
GP03	**Decrease** NHC-observed V_{max} 10%, R34 25%, R50 40%, ROCI 25%	↓
GP04	**Increase** inner-core moisture by a max of 10%	↑
GP05	**Decrease** inner-core moisture by a max of 10%	↓
GP06	**Increase** SSTs by a max of 3°C within the initial extent of the TC	↑
GP07	**Decrease** SSTs by a max of 3°C within the initial extent of the TC	↓
GP08	Surface physics modification: ***GFDL 2011 operational formulation*** of C_D & C_H (surface drag and enthalpy exchange coefficients)	↑
GP09	Surface physics modification: ***HWRF 2014 operational formulation*** of C_H (surface enthalpy exchange coefficient)	↓
GP10	Physics modification: Effectively **increase** mean boundary layer depth	↑
GP11	Physics modification: Effectively **decrease** mean boundary layer depth	↓
GPMN	**Bias-uncorrected** ensemble mean: Average of uncorrected members computed at each lead time where the member availability is at least 4 members (40% threshold)	
GRMN	**Bias-corrected** ensemble mean: Average of linearly regressed members computed at each lead time where the member availability is at least 4 members (40% threshold)	

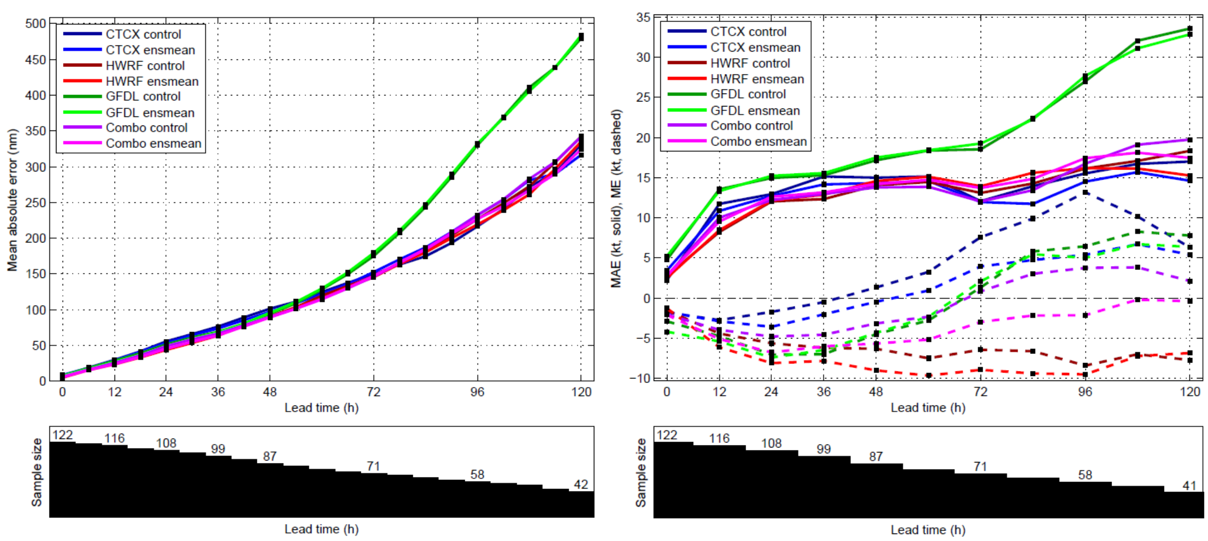

Figure 13: Multi-Model 2015 Season Mean Track, Intensity errors and bias.
This figure shows the mean (a) track & (b) intensity errors and bias from the multi-model regional ensembles. Blue curves are from COAMPS-TC members, pink from HWRF members and green from the GFDL members.

Fig. 13 provides an overview of the mean track and intensity from HFIP ensembles from the three models. While there were only 122 cases reflecting not many TCs in the 2015 Atlantic season, there were a much greater number of 2015 semi-real time cases run than in 2014. It was found that for individual model, ensemble mean of the tracks had accuracy similar to or somewhat better than the control. For intensity, the combination of COAMPS-TC and HWRF, outperformed the two individual models and consensus of COAMPS-TC and HWRF controls had superior accuracy and bias w.r.t. COAMPS-TC and HWRF ensemble mean. The combined ensemble (either two or three model) spread is not large enough, particularly for intensity at earlier lead times. However, the ensemble distinguished between low-uncertainty and high-uncertainty cases, for both track and intensity.

Based on the HFIP demo project, a one-day workshop was held at the annual HFIP meeting in Miami, Nov 17, 2015. Special attention was given to ensembles of high-resolution regional models (Navy, NCEP, and GFDL). Workshop topics included design and implementation of hurricane ensembles, ensemble post-processing techniques (weighted means, super-ensemble techniques), probabilistic forecasts, representation of uncertainty, use of ensembles in data assimilation, observation sensitivity experiments, and single model vs. multi-model ensembles etc. While NCEP operations continues its emphasis on the use of ensembles and HFIP also conducted a workshop dedicated to the subject five or so years ago, it should be noted that there is still a need for better, new ensemble techniques to improve deterministic forecasts. For the first time, this workshop covered state-of-the-art in the science and application of hurricane ensembles, and discussed the prioritized development of new applications for effective use of ensemble products for operational needs at NHC. The goal of this workshop was to encourage more community involvement and produce a set of recommendations for consideration by HFIP. Those findings are provided at:
http://www.hfip.org/events/annual_meeting_nov_2015/presentations/Wed_0845_Torn_EnsWs_Summary_HFIP_2015.pdf. Two key recommendations are:

- An urgent need for more investigation on how to improve model spread.
- Determine whether the deficiency in spread is conditional (i.e., only for hurricanes).
- Find ways to improve deterministic track and intensity forecasts and probabilistic genesis using high-resolution ensembles with better ways to display uncertainty information.
- Provide NHC with probabilistic intensity changes based on EPS guidance during the 2016 season.

b. Basin Scale HWRF developments

HWRF has become a valuable global hurricane forecasting system. As mentioned earlier, the HFIP’s eventual goal is to create regional models that can be nested within and interact with the global model. Specifically, high-resolution nests would be placed over each tropical cyclone in the global model, thereby accomplishing the track and intensity forecast goals through a unified global-to-regional scale modeling system. Although the operational HWRF system is showing exceptional skill in intensity forecasting, it should be noted that the current operational HWRF configuration is storm-centric and single-nested. This is not ideal for representing multi-scale interactions or for TC genesis forecast applications and is greatly limited in improving forecast skill beyond five days, which is a major goal of next generation efforts. Thus, the basin-scale HWRF was created under HFIP with: 1) A large outer domain that covers approximately one-fourth of the globe (eventually will cover the entire globe) and 2) Multiple moving multi-level nests at 1-3km. horizontal resolution to produce simultaneous tropical cyclone forecasts. The latter is especially important because tropical cyclones interact with the large-scale environment and with one another. The basin-scale HWRF system is a Stream 2 development and in 2015 it was transferred to the DTC.

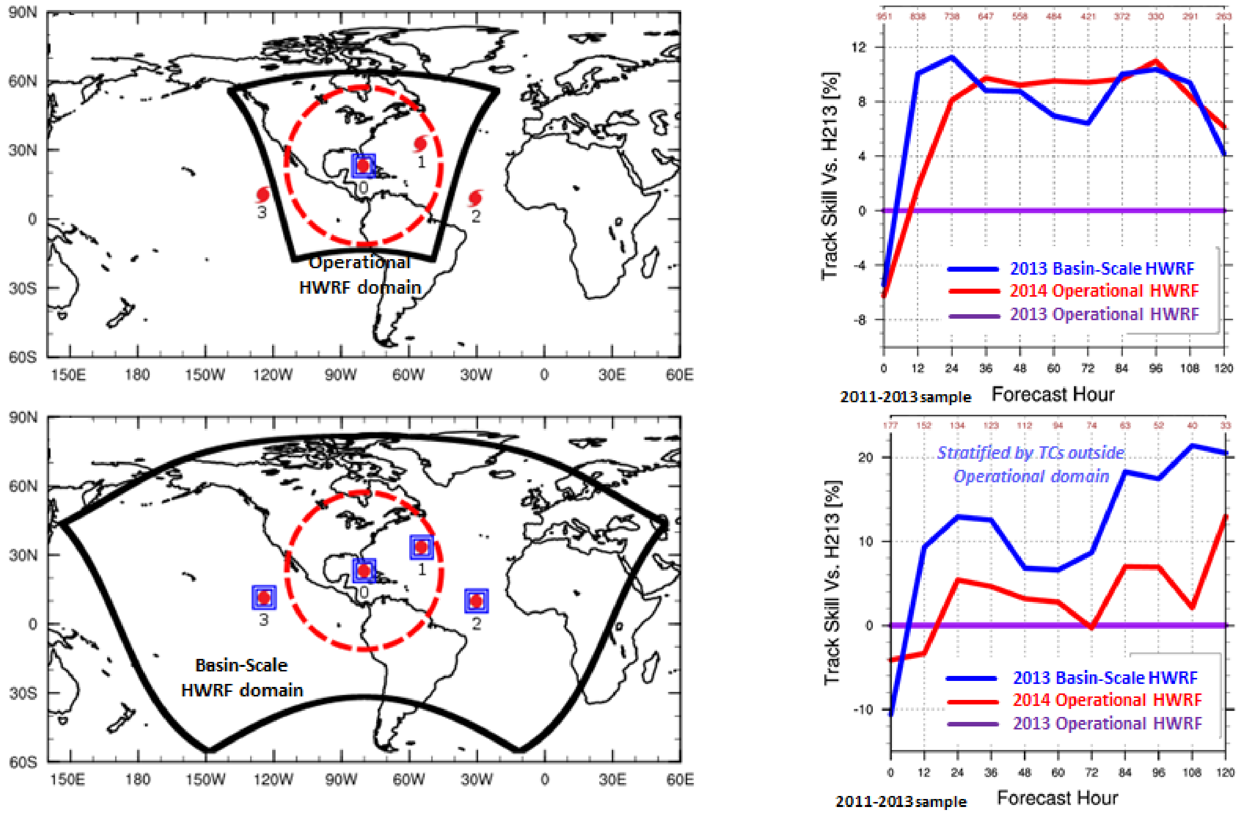

Figure 14: HWRF basin-scale example of far-field TC track forecast improvement.
Upper Left: A schematic showing how multiple TCs are simulated in the operational HWRF. Lower Left: As in Upper Left, except for the basin-scale HWRF. Upper Right: Track forecast skill verification for full TC sample in the Atlantic basin from 2011-2013. Lower Right: As in Upper Right, except stratified for 2+ far-field TCs.

At the same time, research was conducted at AOML in 2015 to identify scenarios for which the basin-scale HWRF improves TC forecasts. It's skillful when multiple TCs are active and far apart from one another ("far-field TCs"). Far-field TCs are defined as being more than 3500 km away another TC. In Figure 14, the red-dashed circle (centered on "TC 0") has a radius of 3500 km. and highlights two far-field TCs ("TC 2" and "TC 3"). Far-field TCs may be better represented in the basin-scale HWRF since they are simulated at high resolution (i.e., are nested) and are within the large outer domain (Fig. 14, lower left). On the other hand, the operational HWRF relies on the delivery of information from far-field TCs through the boundary conditions, where this information is distorted or lost (Fig. 14, upper left). For the full sample, track forecasts for the 2013 basin-scale HWRF and the 2014 operational HWRF exhibited similar skill and are both improvements over 2013 operational HWRF track forecasts (Fig. 14, upper right). The full sample was stratified so that only TC track forecasts with at least two far-field TCs were verified, which retained ~20% of the cases (Fig. 14, lower right). In this scenario, basin-scale HWRF track forecasts were 10-20% more skillful than operational HWRF track forecasts. Further research will investigate this TC-environment teleconnection to discover how TC information is passed over such long distances.

8. Data Assimilation Developments

In order to improve high resolution analyses and TC predictions for the Hurricane Weather Research and Forecasting (HWRF) model uses the dual resolution hybrid ensemble Kalman filter (EnKF)-variational data assimilation (DA) system. The EnKF/DA system is continuously cycled and grid-point statistical interpolation based. In this ensemble-variational (EnVar) hybrid system, a newly developed directed moving nest strategy was adopted to solve the issue of non-overlapped domains for cycled ensemble DA. In addition, both dual-resolution and Four-Dimensional ensemble-variational (4DEnVar) capabilities were implemented in the system. The performance of this system is investigated by conducting the end-to-end DA cycling and forecast experiments for hurricane Edouard (2014) and other cases during 2015 (Lu and Wang 2016). All operational observations in addition to the Tail Doppler Radar (TDR) data were assimilated. It was found that the dual resolution hybrid DA improves upon the coarser, single resolution hybrid DA; Vortex initialization and relocation in the control and relocation of the ensemble background on top of the DA improve the forecasts. Using 4DEnVar in the TDR-involved cycles improved the intensity forecasts for early lead times compared to 3DEnVar.

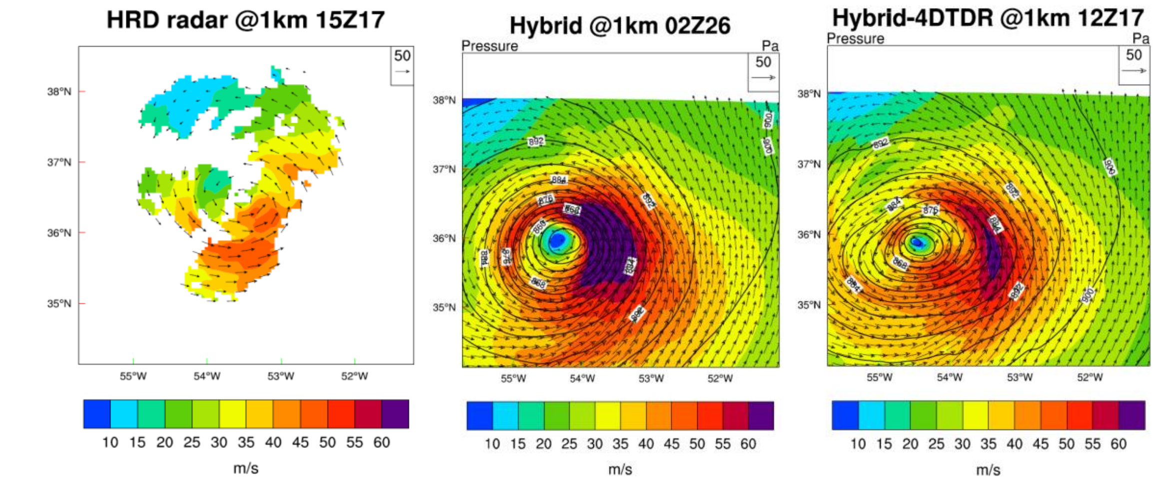

Figure 15: 1 km. Height Radar Wind and Pressure for HRD Wind and Hybrids.
In this figure, wind (shaded and vector) and pressure (contour) at 1km height for (a) HRD radar wind composite, (b) Hybrid, (c) Hybrid-279.

In Fig. 15 (left) the analyzed horizontal structure is shown after assimilating Doppler data from different experiments (valid at 12:00Z on Sep. 17th, 2014). During this time period, the storm was going through an eyewall replacement process while the temporal coverage of TDR data was very brief. The 3DEnVar analysis from "Hybrid", Fig. 15 (middle) showed a spuriously strong wind maximum in the east side of the storm center. In comparison, the 4DEnVar analysis from "Hybrid-4DTDR", Fig. 15 (right), greatly reduced the wind maximum and matched the HRD radar data analysis much better. This result indicated that 4DEnVar, with the capability to resolve the temporal evolution of the error covariances, was more effective than 3DEnVar in assimilating the inner core TDR data.

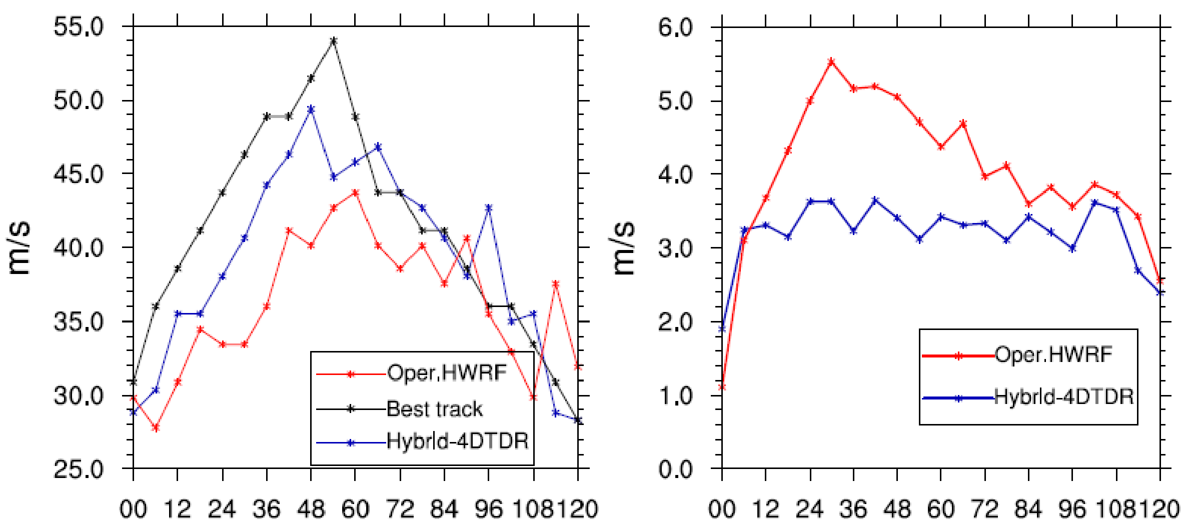

Figure 16: Operational HWRF vs. the New Hybrid System during Edouard (2014)
Left- An example of forecast from one cycle of Edouard by operational HWRF (red) and the new hybrid system (blue). Black dot is the best track position from NHC. Right -RMSE of Vmax forecast for the entire life cycle of Edouard (2014) by operational HWRF (red) and the new hybrid system (blue).

The experiment with Edouard (2014) also showed the potential of the new hybrid system, i.e., it improved intensity forecasts relative to the operational HWRF. For example, Fig. 16 shows that during the intensification period of Edouard (2014), the "spin-down" issue of the operational HWRF was largely alleviated. Improvement resulted from better analyzed structures of an intensifying storm. Research is on-going and tests will be conducted for more cases.

9. Physics Developments

In 2015, apart from routine model evaluations based on track and 10-m-wind estimates, TC structural metrics were used to identify model biases in addressing HWRF physics advancements. Interestingly, some of them came from DA efforts providing the synergies between various HFIP teams. Particular attention was being given to the reported large radius of maximum winds in Edouard (2014) and the mismatch of the vertical wind profiles between HWRF and those reported by observations.

Figure 17, shows for September 15th at 18:00Z the observed and simulated 10 m wind speed for Edouard (2014). HWRF 2015 model integrations are shown for the initial conditions, and 6Z, 12Z, 18Z, 24Z, 30Z, 36Z hours. It was shown that a large bias in the radius of maximum winds existed in the initial conditions and that it progressively got smaller as the integrations progressed, with the radius of maximum winds being comparable with observations at about 30 hours point of simulation. While in this case the large radius of maximum winds was shown to be an issue of model initialization and that the bias was ameliorated while model integration took place, an EMC-HRD collaboration consisting of a multi-storm study, based on 152 Doppler radar storm observations was conducted. Primary findings were reported at the American Meteorological Society 32nd Hurricane and Tropical Meteorology Conference in 04/2016.

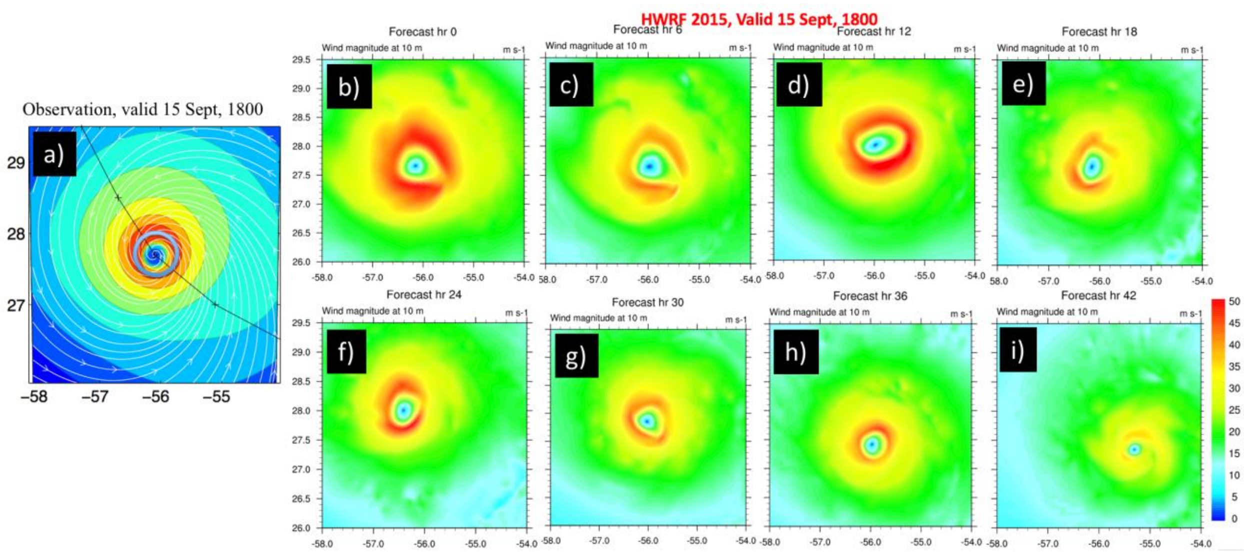

Figure 17: Observed and HWRF 2015 model simulated 10 m wind.
Valid time: 15th September 18:00Z. While all panels are valid at the same time, panels b-i represent HWRF integrations at b) initial conditions, c) 6 d) 12, e) 18, f) 24, g) 30, h) 36 and i) 42 forecast hour.

Observed and HWRF 2015 simulated vertical profiles of wind magnitude in the eyewall and the outer vortex for four different storm simulations are illustrated in Fig.18. This figure shows that HWRF tends to produce near-surface winds that are 10-20% too weak as compared to those in the upper part of the planetary boundary layer. While this is an issue of vortex initialization with large impacts on data assimilation (Tong et al. 2016), the bias persists during the model integration and should be addressed from the perspective of model physics. To address this issue, changes in the vertical structure of vertical diffusion and the surface exchange coefficient are being tested. Lowering the magnitude of the surface exchange of momentum shows some promise to ameliorate the problem (not shown) and thorough tests are being conducted at EMC to integrate such changes in HWRF 2016.

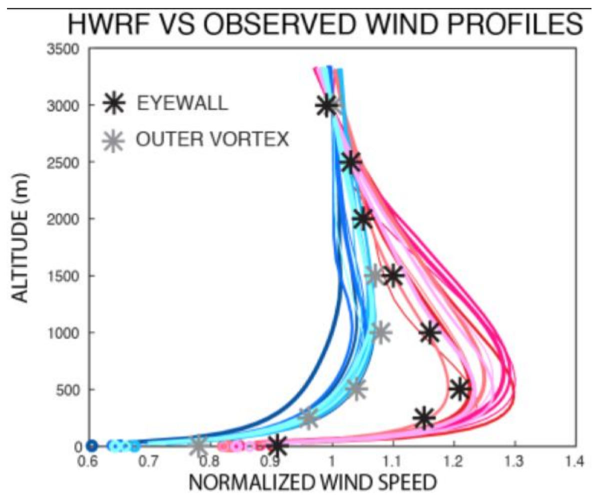

Figure 18: HWRF vs. Observed Wind Profiles.
Vertical wind profiles composited from observations (asterisks, Franklin et al. 2013) and from HWRF (at hour 48 of different simulated storms) both in the eyewall (pink lines) and in the outer vortex (blue lines).

10. Post Processing of Model Output

a. Post processing of model output

Post-processing of model output can be utilized to move closer to the HFIP goals in a couple of ways. Model diagnostics and verification are used to evaluate model upgrades, and to determine what proposed changes will help or hurt a modeling setup. Examples of these diagnostics are included in most of the sections above. Statistical post-processing can also be used to modify the forecast from a model or generate an independent forecast. Such statistical methods have historically been competitive with the best dynamical forecast models for tropical cyclone intensity prediction. In particular, the SHIPS, LGEM, and a blend of those applied to several dynamical models (SPICE/SPC3) have been improved over the past few years through HFIP and are among the top intensity models available to NHC forecasters. A probabilistic model called the Rapid Intensification Index (RII), provides beneficial information to forecasters about the likelihood of rapid intensification. Improvements to the statistical models in 2015 included a correction for the input model upper-level warm core, an improved historical database, and enhanced use of satellite data. Fig. 19 shows the improved performance of the 2015 SHIPS and

LGEM models relative to the 2014 version of each model after the aforementioned upgrades were implemented. This new version was run in parallel in 2015 and will be implemented operationally for the 2016 season.

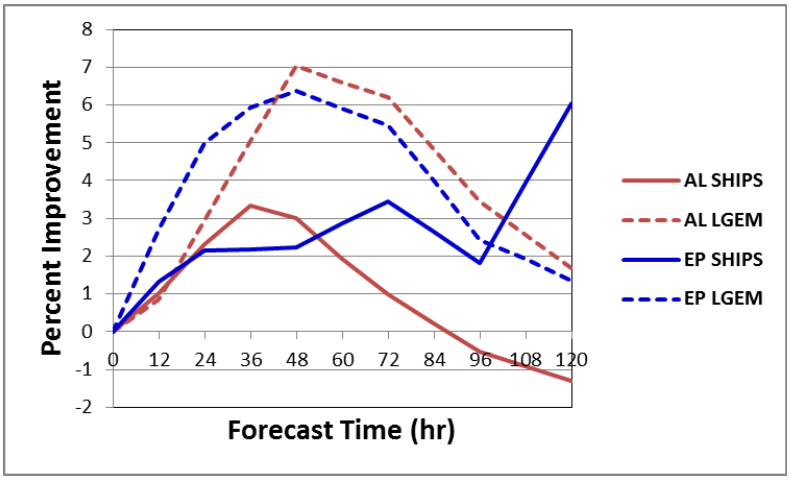

Figure 19: 5-Year sample SHIPS & LGEM models (2014 versions of each model, 2010-2014)

b. Dissemination and communication of model forecasts

Post processing is also used to improve understanding of current model forecasts. NHC forecasters use diagnostics to evaluate and compare forecasts from different models that may show very different forecasts for a storm. In addition, post-processing can be used to improve general public understanding of model forecasts. A perfect forecast of a hurricane provides little value if no one can act on that forecast.

Another statistical model used by the NHC is a wind speed probability model, which uses a Monte Carlo method to generate an ensemble of forecasts based on the current official forecast and historical forecast errors. This model was upgraded in 2015 with HFIP support, and provides emergency managers with a better way of visualizing the uncertainty of a forecast than the traditional “cone” graphic. To improve the use of this product NHC is developing a new product called the “time of arrival” graphic, which is intended to give emergency managers and the general public an indication of when storm preparations must be completed. Fig. 20 shows a prototype of this product that was demonstrated to several NHC partners.

HFIP continues to maintain a webpage for the purpose of demonstrating many of the experimental models discussed earlier in this report. This website is located at http://www.hfip.org/products/. A link is also available on the main HFIP website http://www.hfip.org. The products webpage allows forecasters at NHC to view experimental products side by side. It also allows modeling groups to compare their models, and is a very good demonstration tool for HFIP. Fig. 20 shows a screenshot from the hfip.org/products webpage. A sample of products available includes ensemble tracks and probabilities, deterministic model fields, and real-time experimental diagnostics.

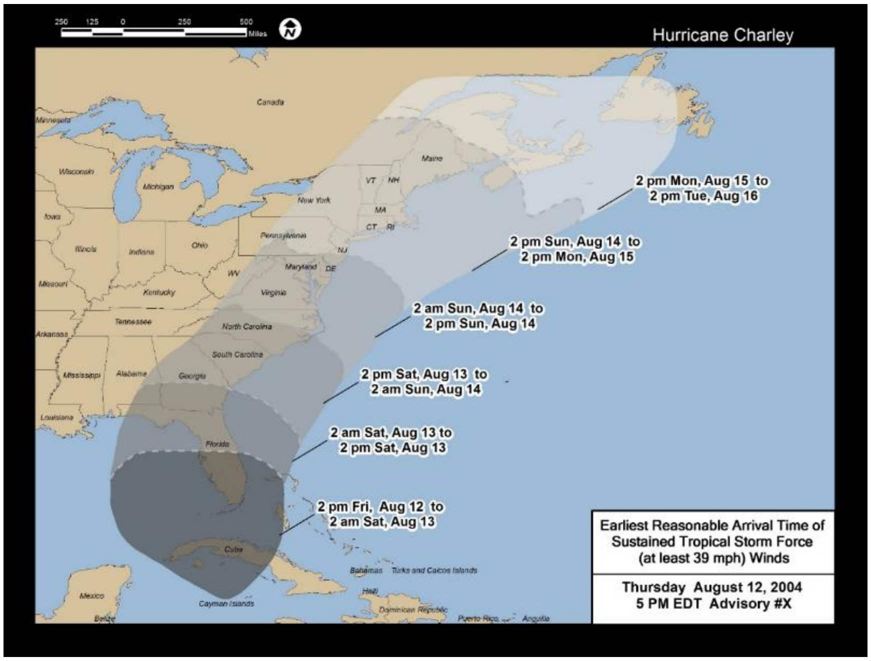

Figure 20: Time of Arrival Prototype.
The area in grey indicates locations where tropical storm force winds are possible during the next 5 days, with the darkness of grey showing how soon the winds will arrive. Darker colors indicate a sooner arrival.

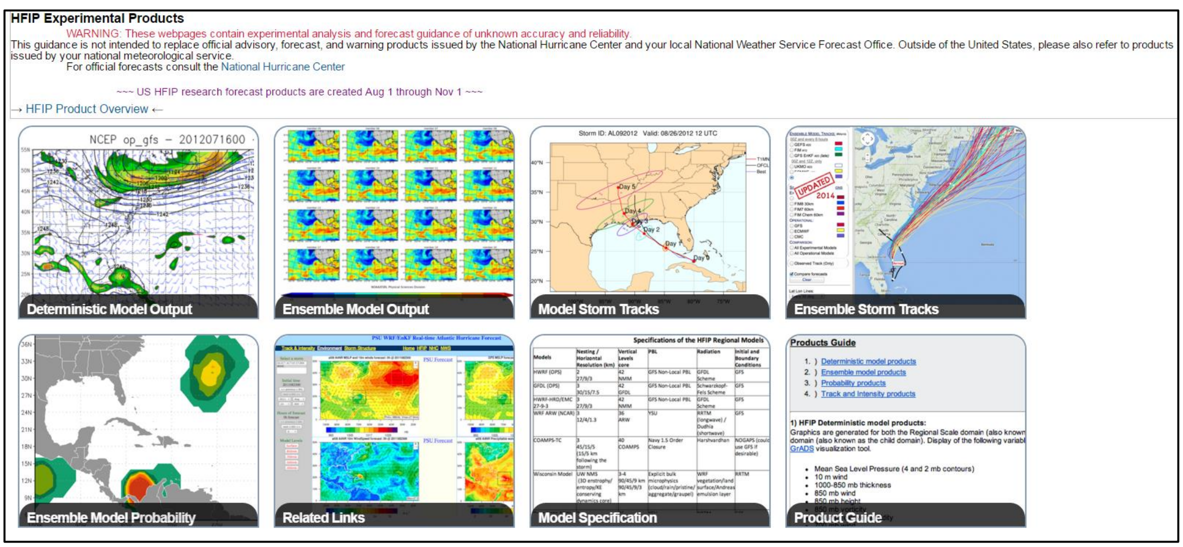

Figure 21: Screenshot of the HFIP products webpage.

11. NOAA Opportunity Announcement

The Table below provides the list of projects supported by HFIP during 2012-2016 and some R2O outcome:

Table 4. HFIP Supported Projects from 2012-2016 with some R2O results.

HFIP Round One (2012-14) Awards		
PI Name	**PI Institution**	**Project Title**
Xuguang Wang & M. Xue	University of Oklahoma	Improving High-Resolution Tropical Cyclone Prediction Using a Unified GSI-based Hybrid Ensemble-Variational Data Assimilation System for HWRF
T. Galarneau, T. Hamill & J. Whitaker (unfunded)	U Colorado - Boulder	HFIP Using Global Forecast System Reforecasts to Generate Tropical Cyclone Forecast Products
Jun Zhang, D. Nolan, and S. Lorsolo	University of Miami	Improving Sampling Strategies Through OSSEs for Optimal Assimilation of Airborne Doppler Radar Observations Using HRD's HEDAS
Xuejin Zhang, Kao-San Yeh & Da-Lin Zhang	University of Miami	Development of Multiple Moving Nests Within a Basin-Wide HWRF Modeling System
Aksoy, J. Chang & B. Klotz	University of Miami	Investigation of HWRF Model Error Associated with Surface-Layer and Boundary-Layer Parameterizations to Improve Vortex-Scale, Ensemble-Based Data Assimilation Using HEDAS
Fuqing Zhang, Y. Weng & X. Ge	The Pennsylvania State University	Real-time convection-permitting ensemble analysis and prediction of Atlantic hurricanes through assimilating airborne, radar and satellite observations
Ryan Torn	University of Albany	Evaluating Hurricane Intensity Predictability using the Advanced Hurricane WRF
T. Krishnamurti	Florida State University	Further Reduction in Intensity Forecast Errors for Hurricane by Extension of the Correlation Based Consensus (CBC) Method
Da-Lin Zhang	University of Maryland	Improving Hurricane Intensity Forecasts with Consistent Resolutions
Robert Fovell, K. L. Corbosiero, H. Su (JPL) & K-N Liou	UCLA	Influence of cloud-radiative processes on tropical cyclone storm structure
Z. S. Haddad & S. Hristova-Veleva	UCLA	Assimilation of precipitation observations into HWRFX without the pitfalls of microphysical representations
Isaac Ginis and R. Yablonsky	University of Rhode Island	Advancing NOAA's HWRF Prediction System through New and Enhanced Physics of the Air-Sea-Wave Coupling

HFIP Round Two (2014-16) Awards		
PI Name	**PI Institution**	**Project Title**
Xuguang Wang	University of Oklahoma	Advancing the assimilation of airborne hurricane observations using the GSI-based hybrid ensemble-variational data assimilation system for HWRF
Z. S. Haddad	UCLA	A holistic approach to represent the dependence of all-sky nearly-simultaneous radiances from microwave (LEO) to IR (geostationary) on atmospheric variables for assimilation into WRF
Jun Zhang **Hua Chen**	University of Miami	Addressing Deficiencies in Forecasting Tropical Cyclone Rapid Intensification in HWRF
Ryan Torn	University of Albany	Assessing the Predictability of Tropical Cyclone Intensity using HWRF
Isaac Ginnis	University of Rhode Island	Advancing NOAA's HWRF Prediction System through New and Enhanced Physics of the Air-Sea-Wave Coupling
Chris Rozoff	The Board of Regents of the University of Wisconsin System	Probabilistic Prediction of Hurricane Intensity with an Analog Ensemble
Mike Montgomery	Naval Postgraduate School (NRL MOU)	Improvement of short-term prediction of tropical cyclogenesis in the 0-5 day lead-time by incorporating and evaluating the HWRF-Genesis model within the marsupial framework and new Lagrangian flow technique
T. Krishnamurti	Florida State University	Research Towards Improvement of Hurricane Intensity Forecasts using the Multi-model Superensemble and a Suite of Mesoscale Models
Hakim	University of Washington	Intrinsic Hurricane Predictability
Zou	U. of Maryland	Improved Satellite Data Assimilation and Vortex Initialization for Hurricane Forecast Using HWRF
Pu	University of Utah	Improving vortex initialization in HWRF multiple-level nested domains with GSI hybrid data assimilation
Ping Zhu	Florida International University	Understanding the impact of sub-grid scale physics in HWRF on the predicted inner-core structure and intensity of tropical cyclones
Otkin	University of Wisconsin System	Using synthetic satellite brightness temperature to evaluate the ability of HWRF parameterization schemes to accurately simulate clouds and moisture in the tropical cyclone environment

List of R2O outcomes from the above projects:

1. Enhanced “hybrid” DA system for HWRF assimilating tail-Doppler radar data
2. New and more efficient ocean model (MPIPOM-TC) coupled to HWRF showed improved track and intensity forecast skill
3. Improved radiative and PBL parameterizations
4. Perturbation in ensemble physics has different effects than perturbations in initial conditions or environment
5. “Far” environment can affect warm-core HWRF analysis
6. Intensity forecast uncertainty due to oceanic perturbations can be larger but lagging atmosphere-only

7. Enthalpy and bulk drag coefficient ensemble perturbations are greater than those from microphysics
8. Increased vertical resolution implemented in 2014 HWRF improved track and intensity
9. Vortex “spin-down” in HWRF can be mitigated by Hybrid-DA or digital filter initialization (DFI) of analysis
10. Further improvements in vortex initialization and model clouds/moisture can be obtained using satellite retrieval products (microwave, sounders)
11. Further improved the HWRF air-sea-module
12. Low predictability (large σ) in HWRF is associated with conditions favoring intensification and small or asymmetric vortex when compared to analog runs
13. Scale-aware Cu-parameterization
14. Improved statistical techniques (e.g., corrected consensus), undergoing evaluation

12. Future Configuration of a Numerical Model Hurricane Forecast Guidance System to meet HFIP-NGGPS goals

It was already noted that the HWRF undergoes considerable testing when new techniques and technology are added to the system. This led to some significant improvements (Fig. 5). HWRF development for the remainder of the HFIP program, originally scheduled to be a 10 year program ending in 2019, is charted out here. The general strategy for the next 5 years is to gradually evolve the HWRF into the NOAA Environmental Modeling System (NEMS) framework, the infrastructure that was adopted for other models at EMC. In addition, HWRF will move from the EMC Non-hydrostatic Mesoscale Model (NMM) on the E-grid to NMM on the B-grid (NMMB) which is currently being used in other mesoscale models at EMC. At the same time, in collaboration with HRD, the HWRF system is evolving into a basin-scale (large domain) system where there are multiple moving double nests (one set per hurricane) where each set of nests interact with the large basin-scale domain. This allows for interactions between relatively close hurricanes via the larger scale domain. These interactions can occasionally have an important impact on hurricane track forecasts and perhaps a lesser impact on intensity. It also saves computer time since the basin-scale domain only has to be computed once for all of the hurricanes rather than separately for each hurricane. In addition HRD in partnership with EMC, ESRL and other NOAA partners is contributing to NGGPS via the development of a "generalized nesting framework" called NGGNF. This framework is ESMF based and it consists of a stand-alone, dynamical-core independent, grid-shape- and projection-independent nesting framework developed within NEMS. NGGNF will allow multiple atmospheric models or multiple instantiations of the same model (one serving as a parent and another serving as a high-resolution nest) to be coupled together for the purpose of nesting. The NGGNF internally provides all of the required horizontal interpolation, mass adjustment, and wind projection adjustment processes. NGGNF will provide a simple API that will enable atmospheric models to gain access to NGGNF's built-in nesting capabilities. The end goal is to provide the high-resolution (1-3 km) atmospheric nesting capabilities, which may be critical for hurricane predictions within NGGPS, (this powerful NEMS capacity may be extended over land as well). One example of nesting within the global framework is shown in Fig. 22.

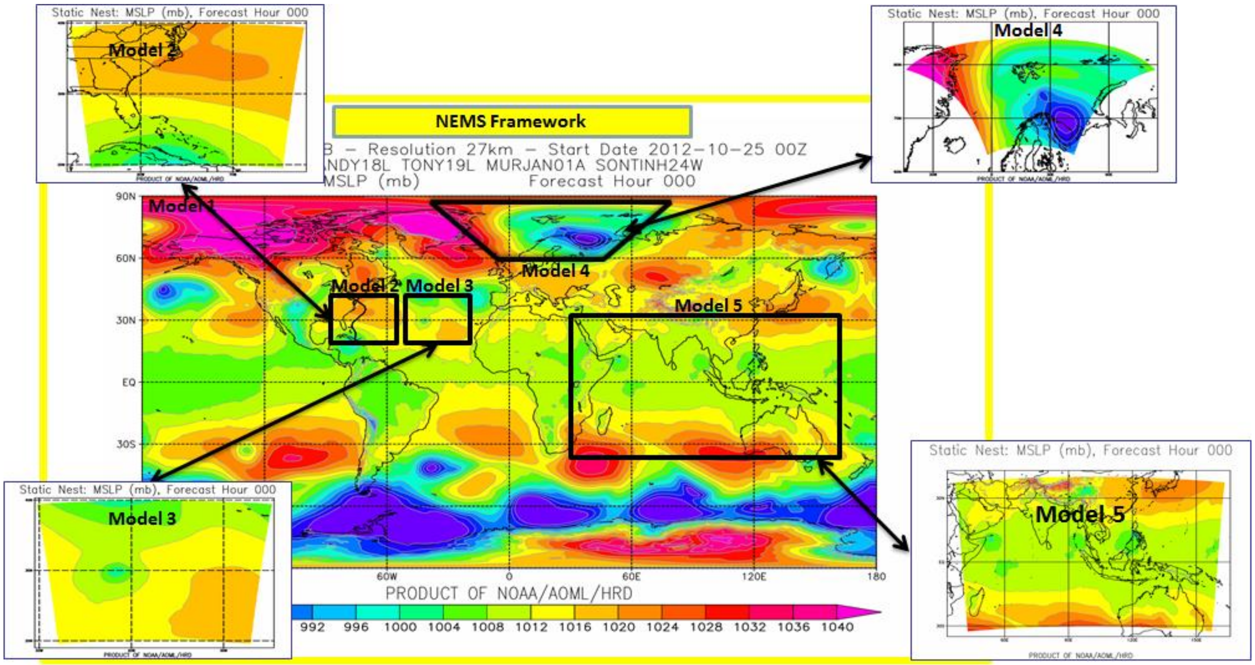

Figure 22: Experimental Global HWRF System in the NMMB NEMS Framework.
This figure is an example of the experimental global HWRF System in NMMB NEMS framework: A nest (eventually a moving nest) may be created on demand within the next generation global prediction system to track hurricanes.

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Appendix A: Model Acronyms

The following is a list of acronyms used to identify models in this document. Many of the acronyms follow the four-character naming convention in the Automated Tropical Cyclone Forecasting (ATCF) system. For example, 6-hour "early" (aka "interpolated") forecasts from "late" models are adjusted so that the previous 6-hour forecast matches the conditions at the beginning of the current forecast. Forecasts of those future conditions are denoted with an "I" at the end (12-hour interpolations are denoted with a "2").

Other conventions occasionally used in the model naming include the acronym "A" to denote advanced version, "D" to denote the addition of inland decay, "E" to denote ensemble, "H" to denote hurricane, "R" to denote research, "S" to denote statistical, "T" to denote track, "V" to denote Variable (ensemble of at least 2, for example), and beginning with an "I" to denote intensity.

3D-VAR:	Three-Dimensional VARiational approach
4DEnVAR:	Four-Dimensional Ensemble-VARiational
4D-VAR:	Four-Dimensional Ensemble-VARiational
ADCIRC:	Advanced Circulation Model for oceanic, coastal and estuarine waters
AEMI:	GEFS with 6-hour interpolation.
AOML:	Atlantic Oceanographic and Meteorology Laboratory
API:	Advanced Weather Research and Forecasting Model
ARW:	Pennsylvania State University Advanced Research WRF
CLIPER:	Climate and Persistence model.
COAMPS-TC:	Coupled Ocean/Atmosphere Mesoscale Prediction System-Tropical Cyclone model at the Fleet Numerical Meteorology and Oceanography Center.
DA:	Data Assimilation
Decay-SHIFOR5:	Decay Statistical Hurricane Intensity Forecast model.
DSHP:	Decay SHIPS.
DTC:	Developmental Testbed Center
ECMWF:	European Centre for Medium-range Weather Forecasts model.

EGRI:	United Kingdom Meteorological Office model, subjective tracker, with 6-hour interpolation.
EMXI:	ECMWF with 6-hour interpolation.
EnKF:	Ensemble Kalman Filter
EFS:	Experimental Forecast System (HFIP Stream 2, demonstration project)
ESRL:	Earth System Research Laboratory in Boulder, Colorado
ETR:	Ensemble Transform with Rescaling system
FAR:	False Alarm Rate
FSSE:	Florida State University Super Ensemble.
GDAS:	Global Data Assimilation System
GEFS:	National Centers for Environmental Prediction Global Ensemble Forecast System.
GFDI:	GFDL with 6-hour interpolation.
GFDL:	Geophysical Fluid Dynamics Laboratory model.
GFNI:	Navy version of GFDL with 6-hour interpolation.
GFS:	Global Forecast System.
GFSI:	GFS with 6-hour interpolation.
GHMI:	GFDL adjusted using a variable intensity offset correction that is a function of forecast time, with 6-hour interpolation.
GPMI:	GFDL ensemble mean (note all members of the ensemble include 6-hour interpolation).
GTMI:	Geophysical Fluid Dynamics Laboratory model's regional and dynamic ensemble.
GSI:	Grid-point Statistical Interpolation
HEVDAS:	Hurricane Ensemble Data Assimilation System
HRD:	Hurricane Research Division

HYCOM:	HYbrid Coordinate Ocean Model
HWFI:	HWRF with 6-hour interpolation.
HWRF:	Hurricane WRF.
HWRFI:	HWRF with 6-hour interpolation
JTWC:	Joint Typhoon Warning Center
LGEM:	Logistics Growth Equation Model.
NAVDAS:	NRL Atmospheric Variational Data Assimilation System
NAVDAS-AR:	NRL Atmospheric Variational Data Assimilation System-Accelerated Representer
NAVGEM:	Fleet Numerical Meteorology and Oceanography Center Navy Global Environmental Model (replaced NOGAPS February, 2013).
NCEP:	National Centers for Environmental Prediction
NEMS:	NOAA Environmental Modeling System.
NGGNF:	Next Generation Generalized Nesting Framework
NGGPS:	Next Generation Global Prediction System
NGPI:	NOGAPS with 6-hour interpolation.
NHC:	National Hurricane Center
NMMB:	NMM on the B-grid.
NRL:	Naval Research Laboratory (U.S.)
OFCL:	Official National Hurricane Center Forecast.
PBL:	Planetary Boundary Layer
POD:	Probability of Detection
RI:	Rapid Intensification (an increase of 30 knots in 24 hours).
RII:	Rapid Intensification Index

RW:	Rapid weakening (a decrease of 25 knots in 24 hours).
SAB:	NOAA Science Advisory Board
SHIPS:	Statistical Hurricane Intensity Prediction System.
SPC3:	Six member weighted SPICE ensemble using output from GFS, HWRF, and GFDL as input for DSHP and LGEM. The ensemble weights vary with forecast lead time.
SPICE:	Statistical Prediction of Intensity from a Consensus Ensemble.
STTP:	Stochastic Total Tendency Perturbation scheme
TDR:	Tail Doppler radar
TVCE:	Variable Consensus of AVNI, EGRI, EMXI, NGPI, GHMI, GFNI, HWFI Model Track Forecasts
UKMI:	United Kingdom Meteorological Office model, automated tracker, with 6-hour interpolation.
UTC:	Universal Time Coordinated, Greenwich Mean Time (GMT), or Zulu Time Zone (Z). There is no time difference between all of these time zones.
WRF:	Weather Research and Forecasting model. It is a regional system with options for the dynamic core, physics, initialization, post processing and verification. Variations include the Hurricane WRF (HWRF), PSU Advanced Research WRF (ARW), and NCAR Advanced Hurricane WRF (AHW).