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HURRICANE FORECAST IMPROVEMENT PROJECT

2016 HFIP R&D Activities Summary: Recent Results and Operational Implementation

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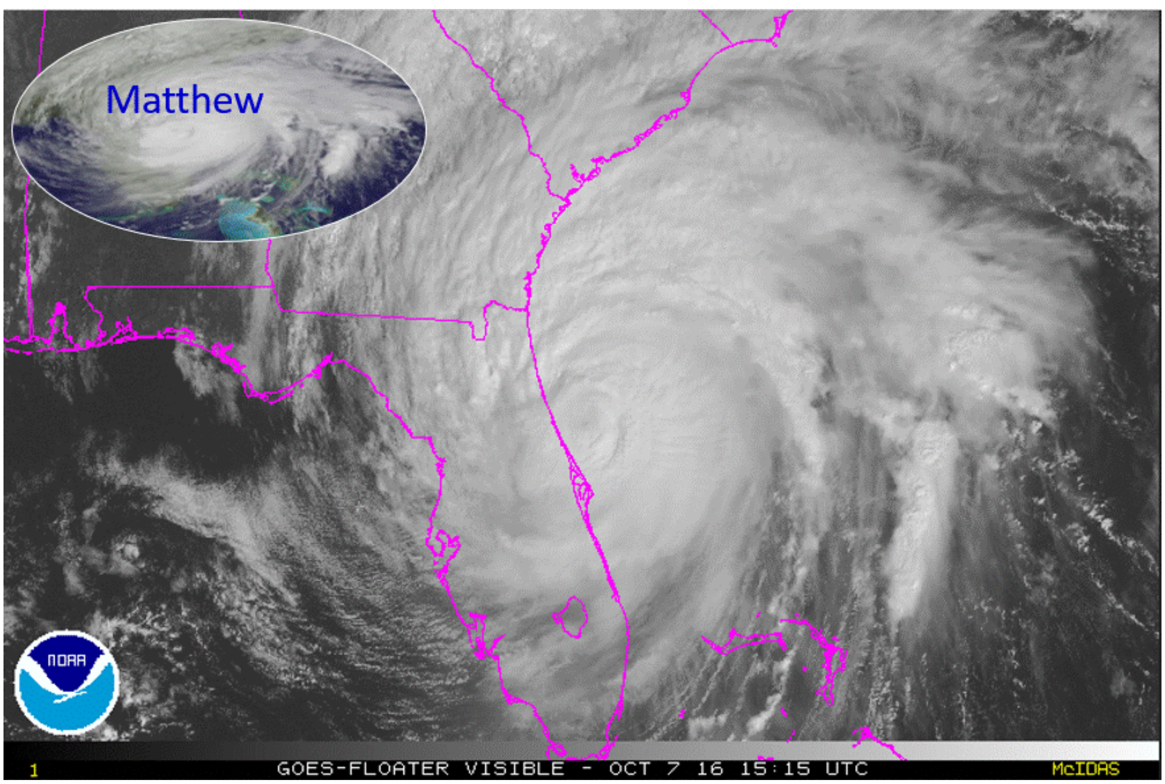

Images on cover page are of Hurricane Matthew[1] (AL14)
NOAA/GOES and NASA/GSFC GOES 1515 UTC October 7, 2016

[1] Large image is GOES with states outlined and small image is NOAA GOES-13/NASA GSFC GOES Project

2016 HFIP R&D Activities Summary: Recent Results and Operational Implementation

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Executive Summary

This report describes the activities and results of the Hurricane Forecast Improvement Project (HFIP) in 2016. It should be generally noted that 2016, unlike 2015, was a representative season for the Atlantic due to more tropical cyclone (TC) activity and rapid intensification (RI) events. In the Atlantic basin 4 of 16 storms in 2016 had RI vs. only 2 of 12 storms in 2015 had RI. The major developmental focus in 2016 was on the Hurricane Weather Research and Forecast (HWRF) regional model and regional ensembles for track and intensity predictions. 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 Research and Development High Performance Computing Center (RDHPC) in Boulder, CO (also referred to as *Jet*). This report outlines HFIP, how it is organized, its goals, its models, and shows results from both operational model development (Stream-1) and experimental model development (Stream-2).

Stream 1.0 Results and Accomplishments

- Hurricane Weather Research and Forecast model (HWRF) 2016 implementation consisted of physics advancements, continued improvements to the initialization package, system enhancements and improved products (sections 8 and 9). Over the eastern North Pacific (EPAC), Real-time Ocean Forecast System (RTOFS) initialization was used for providing more realistic ocean initial conditions. For the first time, some simulations from HWRF showed that the model may be able to reproduce complex eyewall replacement cycles, key for further improving structure and intensity predictions (Fig. 22).
- Significant upgrades to HWRF resulted in further improvements in model intensity guidance in 2016 nearly over all basins. HWRF was the best performing deterministic model for intensity forecasts over the EPAC basin, beating the official forecasts at 48 hours and beyond (Fig. 9a). The model showed increased skill with forecast time and was a top performer at days 4 and 5 over the North Atlantic basin (Fig. 6a). However, the model was too strong on weak storms and too weak on strong storms (Fig. 7a) in that basin.
- Coupled Ocean/Atmosphere Mesoscale Prediction System-Tropical Cyclone (COAMPS-TC) provided some improved intensity guidance especially at days 4-5 in the North Atlantic Basin (Fig. 6a).
- In the western North Pacific basin (WPAC), HWRF and operational GFS models were top performers in predicting TC tracks from 12 hours through 72 hour forecast periods (Fig. 12a). HWRF outperformed the official Joint Typhoon Warning Center (JTWC) intensity forecasts for days 2-3, but trailed official guidance skill beyond that time (Fig. 12b), which was likely due to high track errors associated with more complex TC tracks in that part of the globe in 2016. The expansion of HWRF for all global TCs ensures forecasters at the 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 forecast cycle.

- HWRF continued to show some significant promise for detecting rapid intensification (RI) especially over the WPAC basin (Fig. 10, lower right panel). However, due to relative lack of RI events in the Atlantic basin over recent years, some caution is advised in looking at improvements to RI predictions.
- HFIP working closely with Office of Coastal Survey (OCS) on the hurricane storm surge models implemented the Hurricane Storm-surge On-demand Forecast System (HSOFS). This capacity will provide NHC forecasters with a unique opportunity to initiate ADCIRC runs on-demand near or at landfall.
- The Global Forecast System (GFS), which serves as the backbone for track advancements, continues to progress under parallel development at EMC. The model continues to provide excellent guidance superior to most other models, is comparable to the European Centre for Medium-range Weather Forecasts model (ECMWF) guidance. For the EPAC basin, HWRF and GFS individually reached HFIP's 5-yr track skill goal (Fig. 3b).

Stream 1.0 Challenges

- Predicting RI in TCs continues to pose challenges to the forecasters both over Atlantic and EPAC basins (Fig. 11). Some sustained HFIP research is recommended in this area.
- Large divergence between deterministic and ensemble forecasts and/or lack in track spread between ensemble members from GFS and ECMWF models continue to pose forecast challenges that need to be addressed by HFIP research (Fig. 4).
- It appears that while HFIP 5-year forecast intensity error goals have been reached, improvements seem to be leveling off (Fig. 8). Sustained HFIP research and developments may be necessary for further improvements, especially, in improving the forecasts of 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 (Section 13).

Stream 2.0 Results and Accomplishments

- Developed by NHC using improved model consensus techniques, the HFIP Corrected Consensus Approach (HCCA) model provided best track guidance and superior performance to other NHC consensus models (Fig 2).
- In partnership between the Environmental Modeling Center (EMC) and the Atlantic Oceanographic and Meteorological Laboratory (AOML) Hurricane Research Division (HRD), under a Hurricane Sandy Supplemental sponsored effort, a new hurricane forecasting system called Hurricane in a Multi-scale Ocean coupled Non-Hydrostatic model (HMON) was developed and is expected to replace the operational Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model in 2017 (Fig. 15).
- A 41-member, multi-model regional ensemble system consisting of HWRF (20 members), COAMPS-TC model (10 members) and GFDL model (11 members) was run on the HFIP Jet System in real-time. New products from these ensembles demonstrate the potential for providing guidance on guidance (Fig.5 and Fig.17).

- Supported by HFIP research, the Basin-Scale HWRF was transitioned to the Development Testbed Center[2] (DTC) in 2015 and is evolving to provide a unique capability for the community since then. Some of the results from TCs' Matthew and Nicole from this system (Fig. 18) are starting to demonstrate that multiple, two-way interactive, high-resolution moving nests may be a viable option for accomplishing the track and intensity forecast goals in the unified Next Generation Prediction System (NGGPS; section 13).

Future configuration of the Hurricane Forecast System

Based on seven 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 deterministic model and ensembles with 4D Hybrid Data Assimilation	NGGPS chose the Finite Volume Cubed Sphere (FV3) dynamic core with advanced physics and higher resolution (~9km 128levels) and 30-member ensembles at ~25 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, HMON, 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), HFIP Corrected Consensus Approach model (HCCA), and others.

[2] 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 longer somewhat from last year and 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.

For FY16, the HFIP budget was $14.5M reduced from the original $23M funding levels in the first 5 years (2009-2014) of HFIP, with $4M dedicated to enhancing the Research and Development High Performance Computer System (RDHPCS) available to the Program. HPC funding was used for operations and maintenance, and to increase computing power of the Jet system established in Boulder, Colorado since FY2009. The $2M hardware procurement in FY16 was the final incremental annual expansion which resulted in a machine with 45,000 processors and 4.4 Petabytes of storage. About $6M of the $14M is part of the base funding for Atlantic Ocean and Meteorology Laboratory (AOML) in Miami. The remaining $4.5M was distributed to: 1) NOAA operational centers: Environmental Modeling Center (EMC) and National Hurricane Center (NHC) at NCEP for hurricane model development and operational improvements, 2) the National Center for Atmospheric Research (NCAR) primarily for maintaining HWRF code repository and community support, 3) the Naval Research Laboratory in Monterey (NRL) to contribute improvements of the HFIP regional multi-model ensemble system and Automated Tropical Cyclone Forecasting (ATCF) upgrades for NHC, and 4) seven universities for mission-oriented research: University of Wisconsin, Pennsylvania State University, Colorado State University, Florida State University, University of Wisconsin, Florida International University, and University of Oklahoma (awarded through a NOAA Federal Funding Opportunity).

2. The Hurricane Forecast Improvement Project

The 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)[3] for RI[4] to 90% at Day 1 decreasing linearly

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[3] 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).

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. Due to 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 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. Nevertheless, most of the operational HWRF advancements, including the high-resolution nests and appropriate physics originated from Stream 2 work.

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. Modeling systems currently in use by HFIP are outlined below.

a. The Regional Model

Although HWRF and GFDL are primary regional models under Stream 1, COAMPS-TC and experimental configurations of HWRF (e.g., Basin Scale HWRF) 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

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[4] 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.

and 11 perturbed members from GFDL were run for the 2016 season. COAMPS-TC deterministic model guidance was available in real-time to the NHC in 2016. Specifications of regional models used by HFIP in 2016 are shown in Table 2.

Table 2. Specifics of the HWRF and other regional models used by HFIP in 2016

Models	Domains/ Horizontal Resolution (Res) in km	Vert. Levels/ Top Core	Initialization	Sea-surface Temp. (SST)	Physics Schemes					
					Cumulus Parameterization	Micro-physics	PBL	Land Surface	Radiation	Initial and Boundary Conditions
HWRF (OPS) H216	3 18/6/2 km (6/2 following the storm)	61L /2 hPa NMM	Improved GSI DA & Vortex Initialization (INI) Hybrid TDR DA	MPIP OM	Scale-aware scheme (SAS) for 18/6/2 km nests	Ferrier -Aligo	GFS Non-Local PBL	NOAH LSM	RRTMG	GFS Hi-Res
HWRF Basin-Scale HB216	3 18/6/2 km (6/2 following the storm)	61L /2 hPa NMM	Improved Vortex INI	GFS (static) RT	SAS for 18/6/2 km nests	Ferrier -Aligo	GFS Non-Local PBL	NOAH LSM	RRTMG	GFS Hi-Res
GFDL (WP, HFIP version)	3 55/18/6 km (18/6 following the storm)	42L GFDL	GFDL Synthetic Bogus Vortex	MPIP OM	SAS	Ferrier	GFS Non-Local PBL	GFDL Slab Model	Schwarzkopf-Fels (LW) / Lacis-Hansen (SW)	GFS
GFDL (Ens.) 11 members	3 55/18/6 km (18/6 following the storm)	42L GFDL	GFDL Synthetic Bogus Vortex with inner core perturbation	MPIP OM	SAS	Ferrier	GFS Non-Local PBL	GFDL Slab Model	Schwarzkopf-Fels (LW) / Lacis-Hansen (SW)	GFS
HYCOM-Coupled HWRF	3 27/9/3 km (9/3 following the storm)	61L NMM	Vortex INI	3D HYCOM	SAS	Ferrier	GFS Non-Local PBL	GFDL Slab Model	GFDL Scheme	GFS
HWRF-HRD/EMC Basin Scale	3 27/9/3 km (9/3 following each storm)	61L NMM	Vortex INI	GFS (static)	SAS	Ferrier	GFS Non-Local PBL	GFDL Slab Model	GFDL Scheme	GFS
HWRF-HRD (HEDAS)	2 9/3 km (3km following the storm)	61L NMM	EnKF; 1-hour cycling; storm-relative obs processing	GFS (static)	SAS	Ferrier	GFS Non-Local PBL	GFDL Slab Model	GFDL Scheme	GFS
COAMPS-TC© (HFIP RT ver.) 11-member Ens. Fully-Coupled (NCOM)	3 36/12/4 km (12/4 km following the storm)	40L COAMPS	Balanced vortex INI (4D-VAR, EnKF options)	NCODA with parametric SST (1D)	Kain Fritsch on 36 and 12 km meshes	Explicit µ-physics -5 class bulk scheme	Navy 1.5 Order Closure	Slab with the NOAH LSM as an option	Fu-Liou	GFS
COAMPS-TC© (OPS) Coupled (NCOM)	3 45/15/5 km (15/5 km after the storm)	40L COAMPS	No Cycling or Cycling:3D-Var (NAVDAS), 4D-Var, EnKF DART)		Kain Fritsch on 45 and 15 km meshes	Explicit µ-physics -5 class bulk scheme	Navy 1.5 Order Closure	Slab with the NOAH LSM as an option	Fu-Liou	COTC (NAVGEM ICs BCs) & CTCX (GFS ICs BCs)

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 Experimental Forecast System (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 the 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. In 2016, Global Data Assimilation System was upgraded to 4D-Hybrid En-Var system with more frequent (hourly) assimilation cycles.

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 then adjusted towards observation 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 6-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[5] (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 6-hour HWRF ensembles (self-cycled since 2016) when tail Doppler radar (TDR) observations are available, and when TDR is unavailable it uses the 6-hour GDAS ensemble.

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

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

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; Aksoy et al, 2012).

c. The HWRF Community Code Repository and User Support

Research to Operations (R2O) was one of the initial goals of the WRF program, and is supported by HFIP in developing a repository for a community-based hurricane modeling system which ensures the same code base can be used for research and in operations. During 2009-2016, both the Environmental Modeling Center[6] (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 3.8a. The 3.8a version 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. At this time (2016) there are more than 1300 registered HWRF users world-wide. Support provided by the DTC in 2015-2016 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 eastern North 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).

4. Meeting 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 (Franklin, 2009, 2010).

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

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.

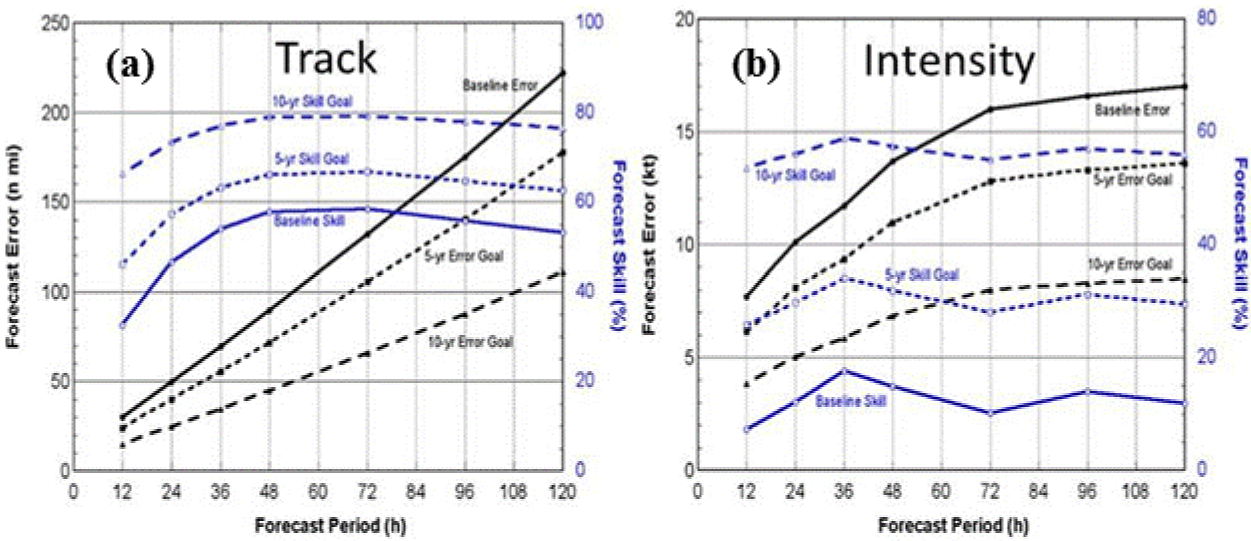

Figure 1: HFIP (a) Track and (b) Intensity Error Baseline and Goals. Baseline errors (black lines) were determined from an average of the top-flight operational models during the period 2006-2008. The HFIP expressed goals (dashed lines) are to reduce this error by 20% in 5 years and 50% within 10 years. 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, 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 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) OFCL (NHC’s official forecast) is virtually on top of 5-year HFIP goals followed by GFS and HWRF. In the eastern North-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. Both HWRF and GFS are virtually on top of 5-year HFIP goals. However, TCs like Joaquin (2015) and Hermine (2016) continue to pose challenges to track forecasting and genesis forecasting. Sustained HFIP research and developments may be necessary for further improvements in tracks of outlier events. It is also expected that the 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 13).

c. Reaching 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 was successful in having produced the best intensity guidance for 2015 (Fig. 6b reported in 2015) and 2016 at days 4 and 5 (Fig.6a) in the Atlantic basin. Additionally, HWRF was the best performing deterministic model for intensity forecasting in the EPAC for days 3-5 (Fig. 9a). Results from Atlantic (AL), EPAC, Central Pacific (CPAC), Western Pacific (WPAC) basins and the Southern Hemisphere (SH) from the HWRF model for intensity forecasts are presented in this report. Early results suggest that output from individual HFIP models can also 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 (G2R) 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 this section are considered met when the model guidance provided to NHC by NCEP[7] reaches those goals. Since 2016 represents the seventh 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 2016. This includes the NCEP's GFS and the HWRF operational regional models. While the GFS, which serves as the backbone for track advancements, continues to progress under parallel development at EMC, this report focuses on the HWRF system which is primarily supported by HFIP.

a. Track Guidance

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

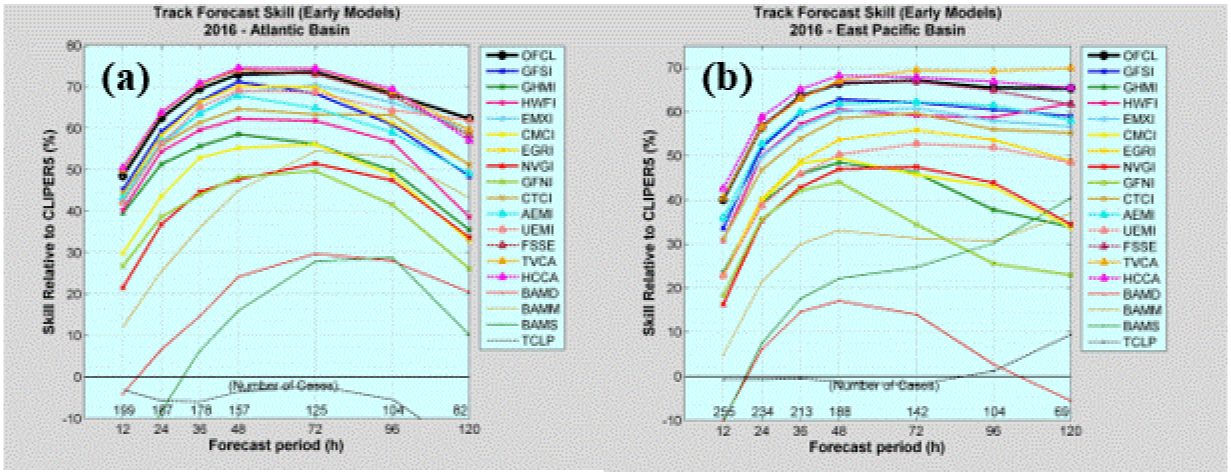

Figure 2: 2016 Track forecast skills for (a) AL and (b) EPAC basins.

In the 2016 season, over the Atlantic basin (Fig. 2a) official forecasts were very skillful, near the best performing consensus aids. Amongst consensus aids, HCCA, TVCA and FSSE were close to one another. GFSI and EGRI were the best individual models in short range, whereas, EMXI was better at longer lead times. The UK Met ensemble mean (UEMI) was very skillful and as good or better than GFSI, EMXI and EGRI. The strong performance of the UK met office models, EGRI and UEMI, was boosted by their correct predictions of Hurricane Matthew moving parallel to and just offshore of the Florida east coast. AEMI, CTCI and HWRI were the next best models. Evolution of TC Hermine in the Atlantic was a forecasting challenge during 2016. Early and wrong location of genesis for TC Hermine resulted in false alarms from both GFS as well as the downstream models such as the HWRF model. In the EPAC basin (Fig. 2b), the official forecasts were again very skillful and were near the consensus aids. Among the consensus models, HCCA had the lowest errors, and it was the only aid that beat the official forecast at all time periods. GFSI and AEMI were the next best models with EMXI, HWFI, and CTCI not far behind. EGRI and UEMI were fair performers, while GHMI, GFNI, NVGI, and CMCI lagged behind.

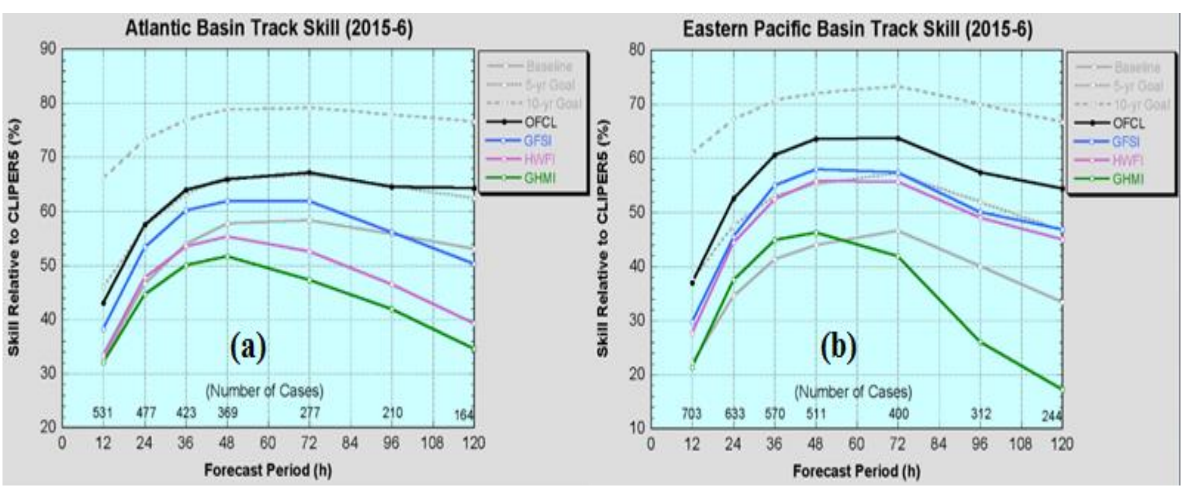

Figure 3: 2015-2016 Seasonal track forecast skills over (a) AL and (b) EPAC basins.

The two-year sample for the Atlantic basin (Fig. 3a) showed that the 5-year HFIP goal was reached and reflected by the OFCL forecast. OFCL is virtually on top of the 5-yr HFIP goal. Both GFS and HWRF lagged behind in these goals. On the contrary, in the EPAC basin (Fig. 3b), for the 2-year sample, OFCL was well above the HFIP 5-year goal and nearly about halfway along in achieving the 10-year goal. Whereas, deterministic models, HWRF and GFS ran neck to neck, and individually reached HFIP's 5-yr track tracking skill goals in the EPAC basin (Fig. 3b).

b. A Note on Ensemble Forecast System for Track Guidance

In the 2016 season, ensemble mean provided some very useful information especially for track guidance. While UK Met ensemble mean (UEMI) was very skillful and as good or better than GFSI, EMXI and EGRI, AEMI was competitive with GFSI and HWRI in both Atlantic and EPAC basins (Fig. 2). However, spread or lack in spread of ensemble tracks continues to be an elusive forecasting problem. Often the mean track for ensemble members diverges significantly from observations as well as deterministic forecast. A classic example was Joaquin from 2015 and Hurricane Matthew and Nichole for 2016. What constitutes good track spread in ensemble

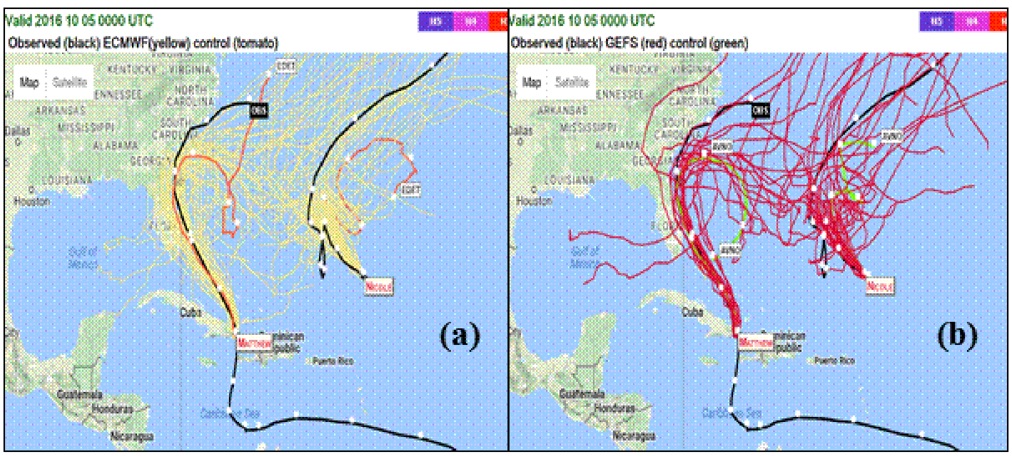

Figure 4: Ensemble predictions from 20161005 00Z ECMWF and GFS ensembles' cycles.

members remains a challenging area of active research in forecasting. Figure 4 shows Hurricanes Matthew and Nichole in the AL basin from the ECMWF ensemble system and GEFS. Predictions from the 20161005 00Z cycle from ECMWF (4a) and GFS ensembles (4b) illustrate track spread of ensemble members. Clearly, both the deterministic and a large number of members from both models exhibited looping motion with very few members falling in the manifold of the observed track at longer lead time; illustrating the need for research on track spread of ensemble members.

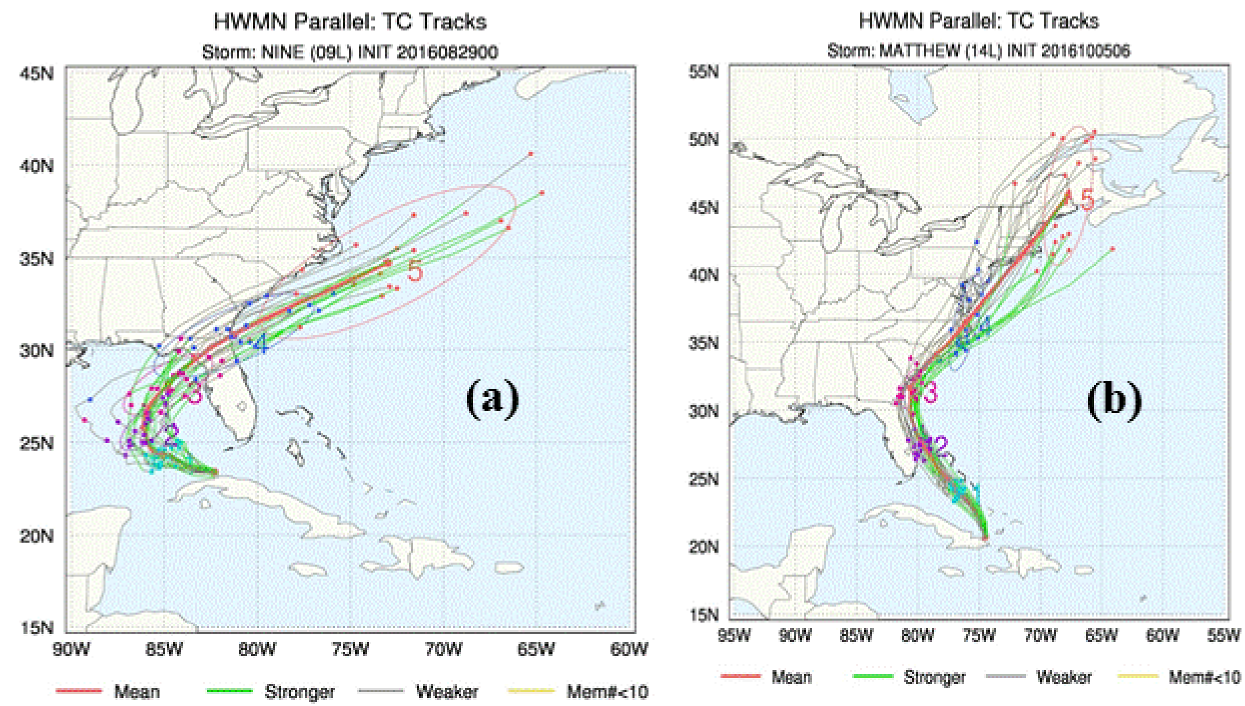

Figure 5: Ensemble forecast tracks for (a) Hermine (20160829, 00Z cycle) and (b) Matthew (20161005, 06Z cycle) from HWRF ensembles (Stream 2).

High-resolution forecasts from HWRF may be useful to better understand the problems associated with track spread, i.e. how meaningful they may be when they may be linked with intensity and/or landfall. Ensemble means for both Hurricanes Hermine (09L) and Matthew (14L) using HWRF ensembles (parallel stream 2 activity) are shown with ensemble members track spread in Fig 5a and Fig 5b, respectively, to demonstrate the usefulness of these stream 2 products. In the case of Hermine as well as Matthew the mean of HWRF ensembles was close to the observed track. The weaker members are clustered left of the mean and stronger members are to the right, most likely due to environmental shear in Hermine (Fig. 5a) and due to land interactions in Matthew (Fig. 5b). The products are available in real-time and may be useful for further research (http://www.emc.ncep.noaa.gov/HWRF/HWRFEPS/index.php).

c. Intensity Guidance: HWRF Guidance for AL and EPAC basins

1) Atlantic (AL) Basin

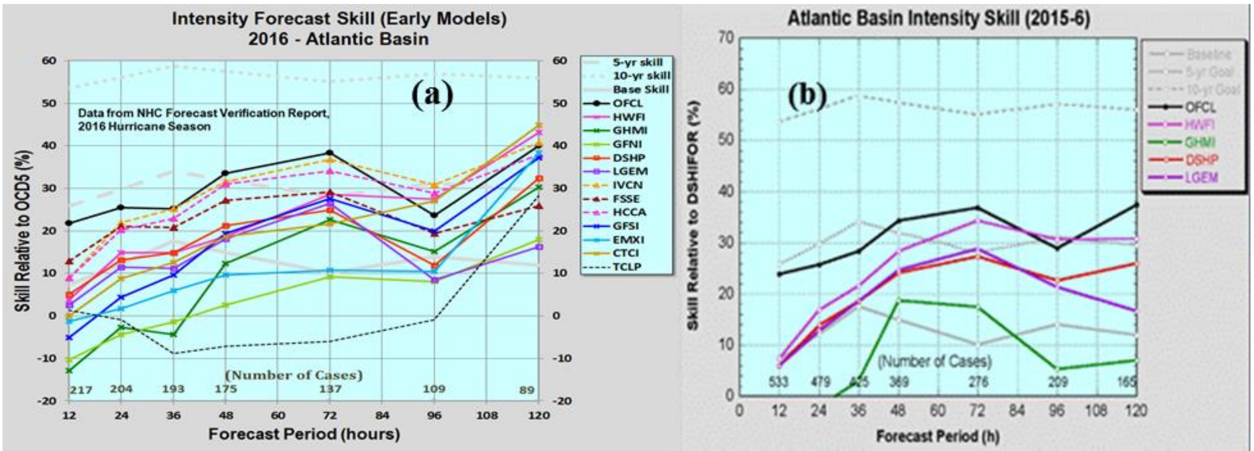

Figure 6: Hurricane intensity forecast skills for the AL basin (a) 2016 and (b) 2015-2016.

In the 2016 season, in the Atlantic basin (Fig. 6a) HWFI, CTCI, IVCN, and HCCA showed increased skill with forecast time and were the best models at days 4 and 5. For some HWRF forecasts of Matthew when it was over the Caribbean, the eyewall unrealistically collapsed. This is expected to have an effect on the model-predicted intensity and subsequently on the skills for the 2016 season. Nevertheless, official intensity forecasts were very skillful, near the best performing consensus aids. Among the consensus aids, IVCN was a little better than HCCA and FSSE. LGEM was skillful but not as good as consensus aids or HWFI and CTCI. GFSI was competitive at the 48-hour forecast period and beyond. GFNI, GHMI, and EMXI trailed. The two-year sample for the Atlantic basin (Fig. 6b), where more sample data sets were available, shows that the 5-year HFIP goal was basically met by OFCL in the Atlantic basin. Figure 6b clearly shows HWRF is the top performing model combining 2015-2016 especially after 36 hours. It is noteworthy to point out that the dynamical model (HWRF) is starting to consistently outperform its statistical counterparts. Nevertheless, caution is advised due to the relative lack of RI events in recent years. RI events were 40 percent more common during the baseline period than during the last two years. During the baseline period, the ratio of RI events to total forecasts was 54:705 (7.7 percent). Same ratio for 2015-16 was 29:536 (5.4 percent). When there are few RI events, OFCL errors go down. When storms are unusually weak, SHIFOR errors can actually go up. Also in 2016, HWRF showed some biases (Fig. 7) where forecasters noticed that the model was too strong on weak storms and too weak on strong storms (Fig. 7a) in that basin. However, unstratified statistics that are used to evaluate model performances (Fig. 7b) showed very small but noticeable bias that leveled out at 1-2 knots after 48- hours emphasizing the need for a careful analysis of stratified samples (e.g. Gopalakrishnan, et al., 2012) at every stage of HWRF advancements. It should also be mentioned that some biases were noted in 2012 related to size predictions in the HWRF system. For the first-time, in 2012, flight level data collected during HRD field campaign was used as the basis to correct model biases especially in modeled eddy diffusivities (Gopalakrishnan, et al., 2013).

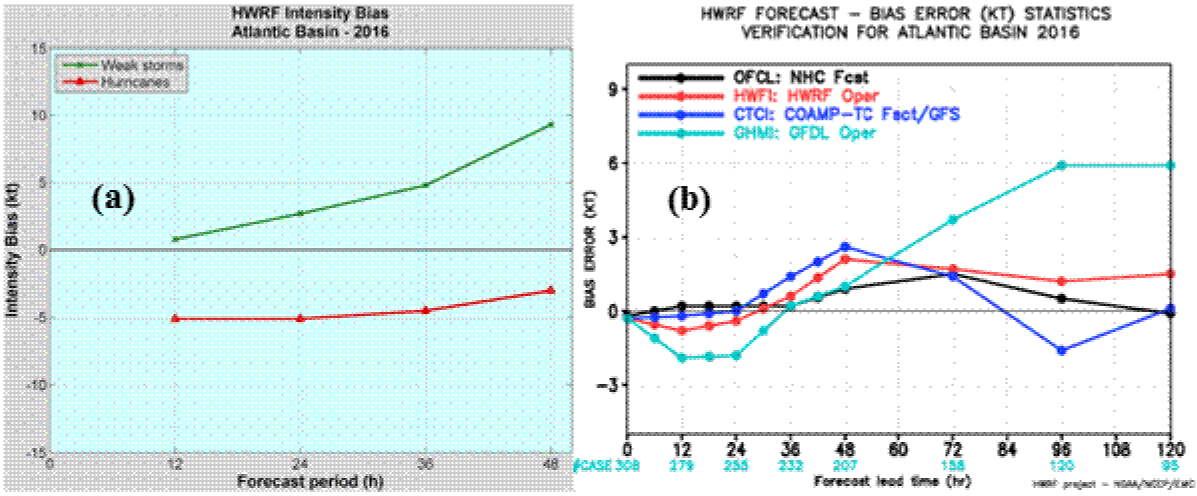

Figure 7: 2016 HWRF AL Basin Intensity (a) Bias and (b) Bias Error without stratification.

Those HWRF system changes have not only led to steep-step improvements in structure predictions but also had significant positive impacts on intensity predictions. Careful re-examination of stratified samples, evaluation of the HWRF system against available observations of composites, and the use of idealized HWRF framework to understand the origin of these biases are recommended.

Figure 8 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, research results that include 2016 retrospective samples, show HFIP has reached its 5-year intensity error goals. However, intensity forecast error improvements seem to be leveling off in the Atlantic basin (Fig. 8). Sustained HFIP research and developments, especially focused on forecast failures and RI events, is recommended for further improvements in intensity predictions. 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 (section 13).

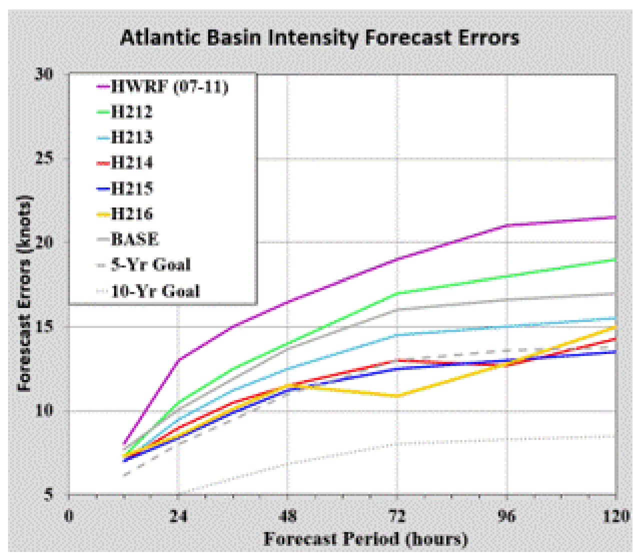

Figure 8: 2011-2016 HWRF Intensity Forecast Error improvement for the AL basin. Improvements in forecast intensity error for the Atlantic Basin from 2011 to 2016 are shown. Seasons for which models were run are depicted on each line. Note that some samples (years) are not homogeneous between models.

2) East Pacific (EPAC) Basin

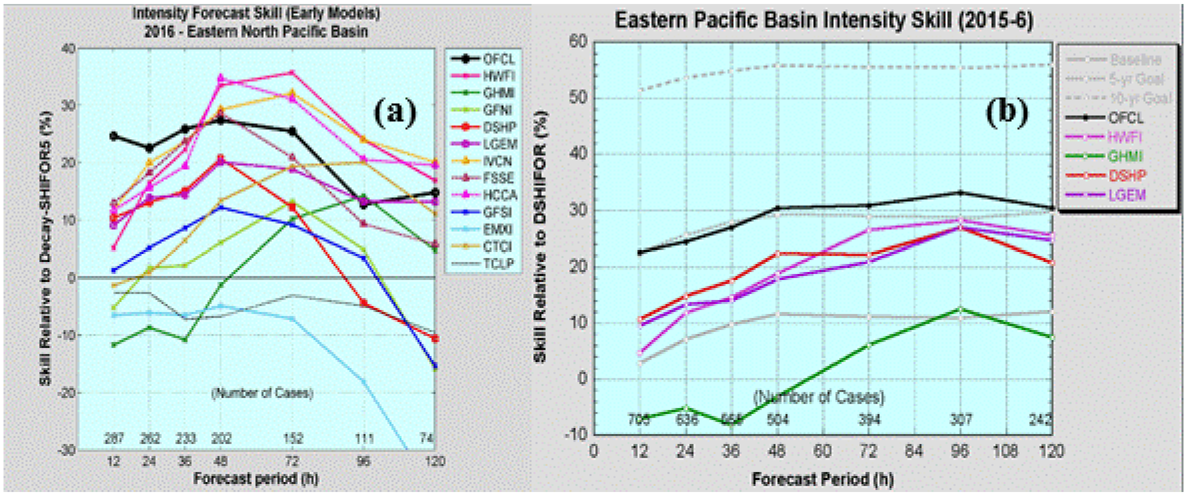

Figure 9: EPAC Basin Intensity Forecast skills for (a) 2016 and (b) 2015-2016.

In the 2016 season, over the EPAC (Fig. 9a) HWRF was the best deterministic model for intensity skill. In general, official forecasts outperformed the models through 36 h, but were beaten by HWFI and consensus aids (HCCA, and IVCN) at 48 h and beyond. FSSE was not as good as IVCN or HCCA. LGEM was competitive, but DSHP trailed for the longer leads. CTCI showed increased skill with time and was among the best models at days 4 and 5. GHMI, GFNI, and GFSI had little skill and were not competitive. EMXI was not skillful. Fig. 9b shows in the 2-yr sample, OFCL was right at the 5-yr goal (and well above the individual guidance). HWRF was competitive with DSHP. It should be noted that while the RI event ratio for baseline period was 7.7 percent, the RI event ratio for 2015-16 was 12.4 percent.

Improving RI (increase >30 kt intensity change in 24 hours) 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 accurately predict not only convection in the hurricane core, but also large scale environmental factors such as shear and moisture that produce an RI event (Chen and Gopalakrishnan, 2015). Nevertheless, in contrast to the state of RI predictions at the beginning of the HFIP, some progress is being made with HWRF in this front, as well. Figure 10 shows RI verifications over different basins for 2015 and 2016. While HWRF verification of the probability of detection (POD) remained within about 0.6 percent difference between 2015 and 2016, the false alarm rate (FAR) of RI forecasts remain high over the Atlantic (AL) basin. In the EPAC, POD increased from 1.2 in 2014 to 5.3 in 2015 to 8.2 in 2016. This was a noteworthy increase of 2.9 percent in POD from 2015 to 2016 but FAR also increased. Solid improvements in both POD and FAR were observed in the WPAC. Specifically, the POD increased from 16.8% in 2015 to 20.3% in 2016, an increase of 3.5 percent. Additionally, HWRF's 2016 FAR decreased from 76.6% in 2015 to 67.7% in 2016, a decrease of about 9 percent. Given the complexities involved in RI predictions, these numbers, especially over the Western Pacific are of notable positive significance.

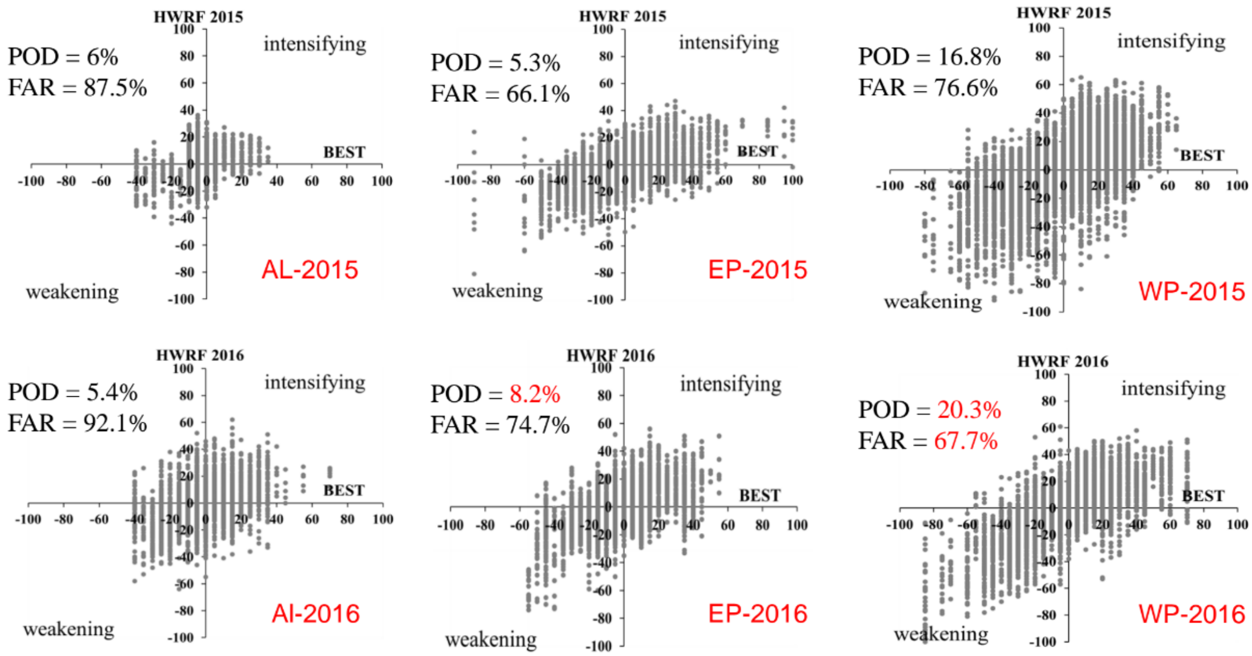

Figure 10: HWRF predicted 24-hour maximum 1 m wind speed changes (knots). Real-time HWRF-predicted versus Observed 24-hour wind speed changes from 2015 version (upper panels) and 2016 version (lower panels) for the Atlantic (left panels), East Pacific (mid panels), and West Pacific basins (right panels). 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.

Although RI/RW predictions began to show promise with HWRF model improvements (Fig. 8 and Fig. 6), there were some notable model forecast failures that posed significant

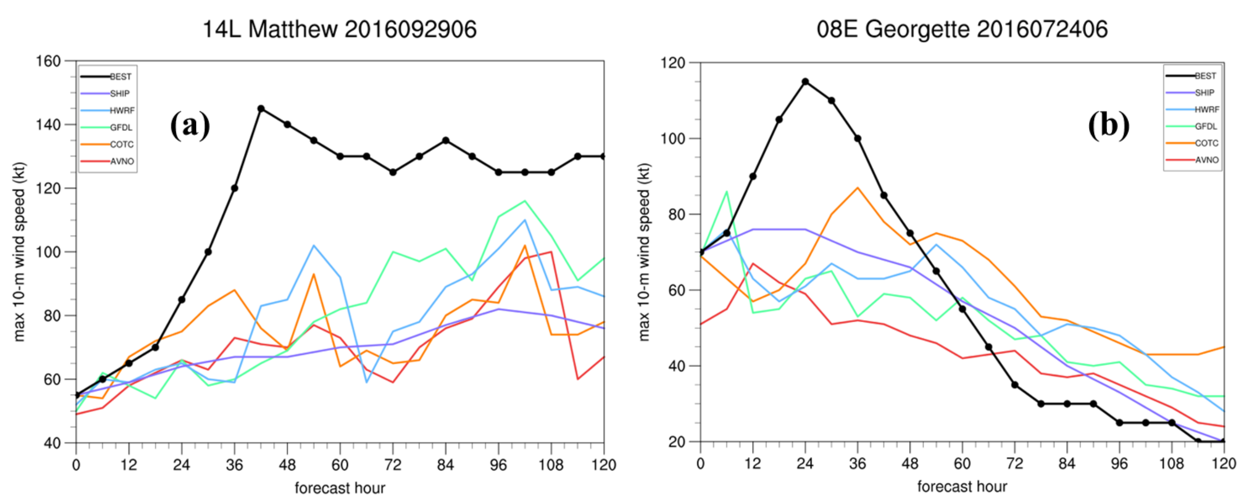

Figure 11: Model performance during RI of Hurricanes' (a) Matthew and (b) Georgette.

challenges to forecasters in 2016 (Fig. 11). As seen in Figure 11a, no models, including HWRF, were able to predict the rapid intensification of Hurricane Matthew, 2016, which began at about 18:00 Z (GMT) through 36 hours on September 29, 2016. Hurricane Georgette is another typical

example of the challenge facing numerical modelers and forecasters in accurately predicting RI (Fig. 11b). All models failed to predict Hurricane Georgette's RI. Sustained research using retrospective cases is recommended especially for Atlantic and East Pacific basins.

6. HWRF performance in other global basins

In 2012, the HFIP began running real-time forecasts for the WPAC and in 2013 for the Indian Ocean (IO). In 2014, HWRF runs were also extended into the IO and southern Pacific (SPAC). These runs were done in real time on HFIP computers in Boulder, CO rather than operational computers. Forecasts were transmitted to the Joint Typhoon Warning Center[8] (JTWC) where they were used extensively in their forecasts. The transition of HWRF from Stream 2 to operations in 2015 was another HFIP success story. This section briefly discusses the performance of HWRF in the other global basins.

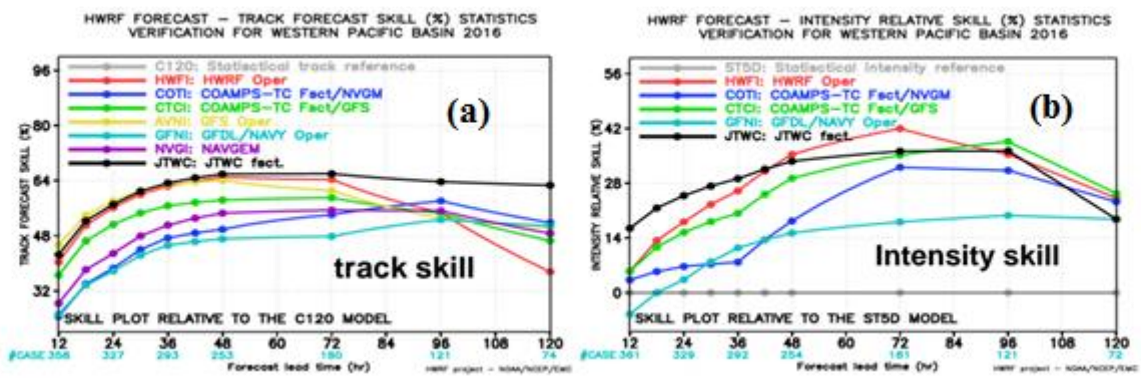

Figure 12: 2016 Seasonal (a) Track and (b) Intensity forecast skills for the West Pacific Basin

During the 2016 season, in the WPAC basin, HWRF and operational GFS models were top performers in skills predicting storm track most accurately from 12 hours through 72 hour forecast periods (Fig. 12a). COAMPS-TC and NAVGEM tracking skills trailed through this forecast time frame. Nevertheless, COAMPS-TC/NAVGEM, NAVGEM, and GFDL/Navy operational models showed improved performance at longer lead times while HWRF trailed at those times. For intensity skill (Fig. 12b), HWRF, COAMPS-TC/GFS, and COAMPS-TC/NAVGEM were competitive at the 12-hour forecast period but HWRF outperformed all other models through 18h-84h forecast periods. In fact, HWRF outperformed the official Joint Typhoon Warning Center (JTWC) intensity forecast during that time (Fig. 12b). COAMPS-TC/GFS was the best performing model at longer lead time (Fig. 12b). HWRF skills were fairly competitive with COAMPS-TC/ GFS through 96h-120h prediction time frames (Fig. 12b). Tropical cyclone RI remains a forecasting challenge and a top forecast improvement priority. Nearly 50 percent of WPAC tropical cyclones reaching tropical storm strength or greater will have RI.

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

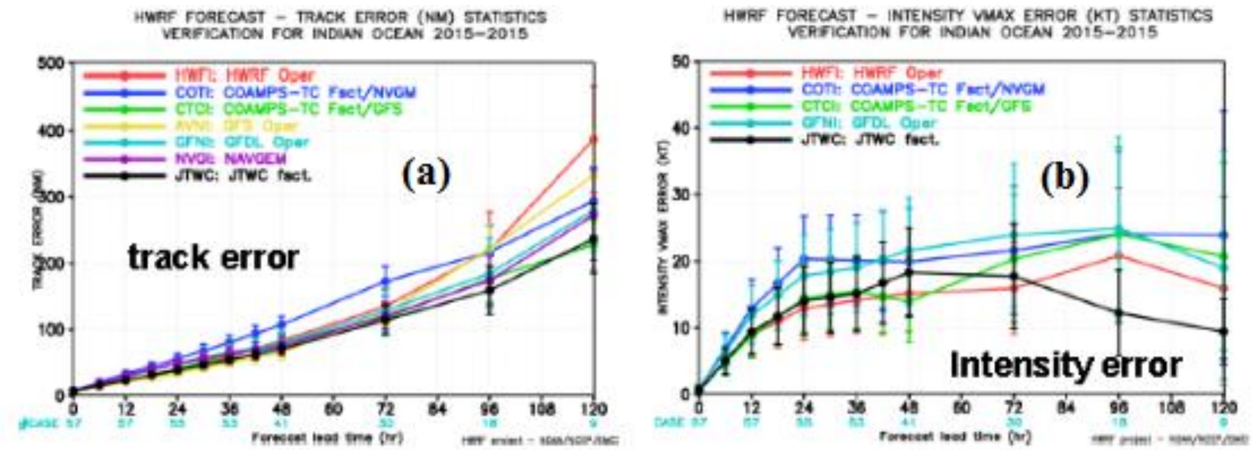

Figure 13: 2016 Seasonal forecast (a) Track and (b) Intensity error for the North Indian basin

Fig. 13 shows HWRF performance for North Indian Ocean (NIO) storms compared to various other models, including JTWC observed error for track (Fig. 13a) and intensity (Fig. 13b). All models were competitive through the first 24 hours in predicting track with COAMPS-TC/NAVGEM trailing through during 12h-84h forecast periods. Fig. 13a shows operational GFS as the best performer, having the least track errors throughout the first 48 hours. NAVGEM, Operational GFS, COMPS-TC/GFS, and HWRF remained competitive through the 72-hour forecast period. After the 72-hour forecast period, COAMPS-TC/GFS, NAVGEM, and Operational GFDL were better performers in track. All other models trailed noticeably in accuracy after the 96-hour forecast period. For intensity predictions, while HWRF and COAMPS-TC/GFS remained competitive from the 12-hour to 48-hour, the clear leader was the operational HWRF model throughout the entire 12h-120h forecast (Fig. 13b). It is noteworthy that COAMPS-TC/GFS slightly outperformed HWRF at the 48-hour forecast period after which all other models sharply trailed HWRF as shown in Fig. 13b shortly after the 48h forecast period through remaining forecast time frames.

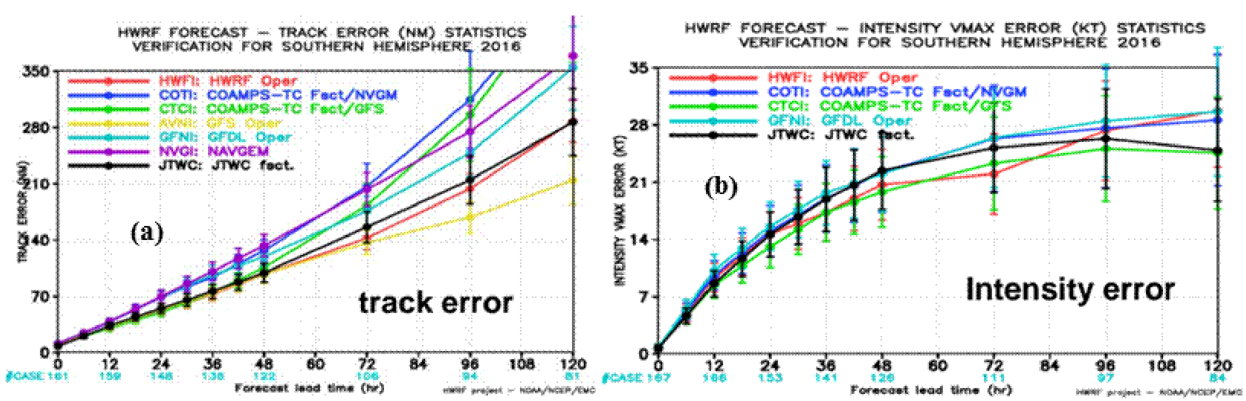

Figure 14: 2016 Seasonal forecast skills of (a) Track and (b) Intensity in the S. Hemisphere

In the southern hemisphere (SH), track errors were the least for GFS and HWRF models. In fact, in the southern hemisphere, both GFS and HWRF operational models outperformed the JTWC track guidance beyond 48-hours (Fig. 14a). SH intensity prediction was very competitive for the early forecast periods (12h-24h) with HWRF and COAMPS/GFS performing better than JTWC

guidance after 24-hours through 84-hours. Beyond the 84-hour period COAMPS/GFS was the best intensity model (Fig. 14b). However, it should be noted that intensity errors are still very large in this area suggesting need for more research and case studies.

7. Important Stream 2 Results

a. HMON developments

The HMON (Hurricanes in a Multi-scale Ocean-coupled Non-hydrostatic) is a new hurricane model for NWS/NCEP operations, and is an important step towards implementing a long-term strategy at NCEP/EMC for multiple static, moving, one-way and two-way interactive nests globally. HMON is also coupled to other (ocean, wave, land, surge, inundation, etc.) models using NOAA's Environmental Modeling System (NEMS) infrastructure. Developed initially as a collaborative effort between NOAA's Environmental Modeling Center (EMC) and Hurricane Research Division (HRD) as a component of High Impact Weather Prediction Project (HIWPP), HMON was originally referred to as HNMMB (Hurricanes in a Non-hydrostatic Multiscale Model on B-grid). HMON's development has been supported by HFIP and NGGPS (Next Generation Global Prediction System) projects.

The HMON model is based on the NMMB dynamic core which is currently being used in other NCEP's operational systems namely, the NAM (North American Mesoscale Model) and the SREF (Short Range Ensemble Forecast) model. The HMON model was built using shared infrastructure with unified model development within the NOAA Environmental Modeling System (NEMS). The NMMB dynamic core is much faster and more scalable than other contemporary dynamic cores deployed for modeling Hurricanes at NCEP. Use of NEMS also paves the way for future use of CCPP (Common Community Physics Package) style physics packages.

The objective for HMON/HNMMB development is to provide high-resolution intensity forecast guidance to NHC along with HWRF (and to replace the legacy GFDL hurricane model). Robust retrospective testing and evaluation in the past year has demonstrated that the HMON model has shown superior results over GFDL and different characteristics than HWRF (Fig. 15) for both North Atlantic and North Eastern Pacific basins.

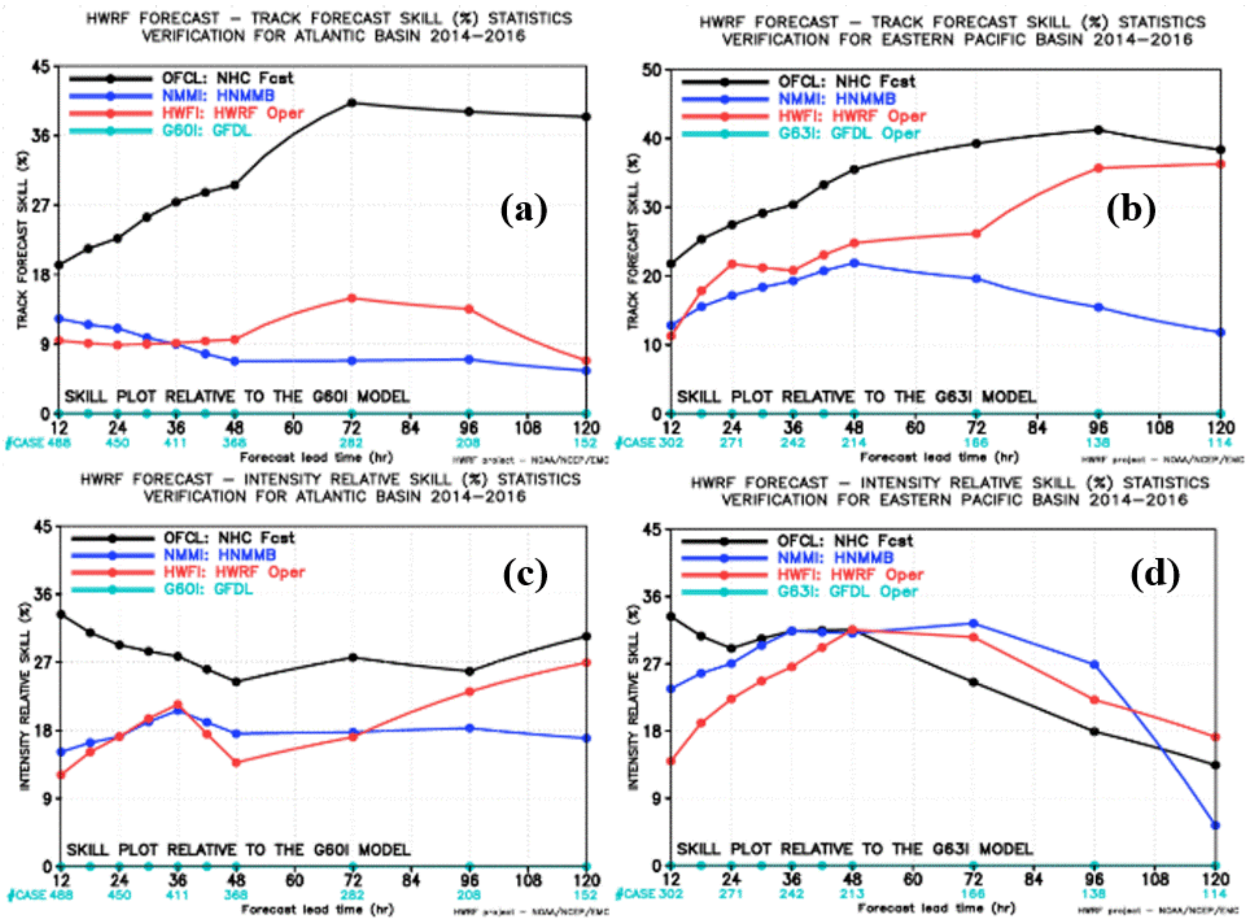

Figure 15: Skill (a, b) track and (c, d) intensity plots for 2014-2016 relative to GFDL's Model. Seasonal plots are shown with GFDL (cyan), HMON (blue), HWRF (red), and official results (black) for Forecast Track Skills in (a) EPAC, (b) AL basin, and Intensity Skills in (c) AL and (d) EPAC basins.

b. Regional Multi-Model Ensembles

Since 2014, the HFIP began testing a multi-model regional ensemble. Three ensembles were used: the HWRF, COAMPS-TC and the GFDL Ensembles (described in more detail below). The GFDL ensemble system is the same as what was reported in 2015. In reviewing success stories, since HWRF ensembles and COAMPS-TC ensembles outperformed GFDL ensembles for this year, we are only reporting some salient findings from these two model ensembles.

The HWRF based ensemble real time parallel used the 2016 operational HWRF model with the following highlights;

- Reduced resolution in horizontal (3/9/27 km vs. 2/6/18 km) and vertical (L43 vs. L61)
- 20 member GEFS with IC/BC perturbations (large scale)
- 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 Planetary Boundary Layer (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, -50 hPa to + 50 hPa white noise
- Stochastic Cd perturbation

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

In 2016 COAMPS-TC used the same configuration as the 2015 real-time ensemble. This configuration was similar to that run in 2014, except that the size of the inner nest was increased to be consistent with the operational model; basic ensemble configuration follows:

- 3/9/27 km horizontal resolution including increased size of the inner nest to match control
- 1 unperturbed control + 10 perturbed members with IC/BC perturbations
- No physics perturbations (2015 version of COAMPS-TC with a new Cd formulation)
- No data assimilation
- Control forecast:
  - Initialized from the GFS analysis (GFS deterministic used as the parent model)
  - Vortex initialized with a Rankine vortex based on TC vitals
- Ensemble members' ICs perturbed about the control:
  - Synoptic perturbations drawn from static covariance (WRFVARcv3) for initial/BCs
  - Vortex IC's based on perturbed TC vitals

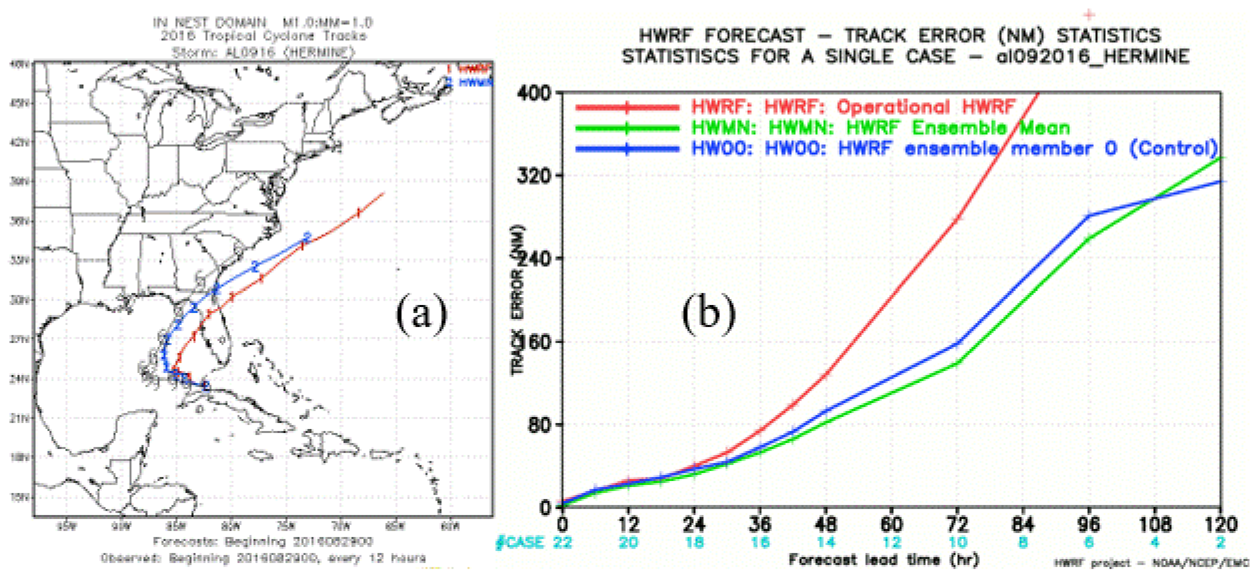

Figure 16: (a) Track forecast for 00Z cycle on August 29, 2016 and (b) Track errors from all cycles for TC Hermine. In Fig. 16a, the red line indicates the operational track and the blue line indicates the mean from HWRF ensembles. Fig 16b shows track error for Hermine from HWRF (red) and the HWRF ensemble mean (green).

The regional multi-model ensemble under stream 2 was run successfully in near real-time during 2016. Figure 16, for example, shows (a) Track forecast for 00Z cycle on August 29, 2016 and (b) Track errors from all cycles of TC Hermine. Clearly HWRF ensembles outperformed the deterministic run for this challenging case demonstrating the need for sustained R&D for ensembles under stream 2. Some of the products from ensembles may also be very useful for

providing additional model guidance for the forecasters. For instance, Fig. 17 provides an example of the 24-hour-intensity-change probability obtained from COAMPS-TC ensembles for a forecast cycle and the multi-model depiction of the same case. Guidance on guidance is an active area of HFIP research. One of the HFIP tiger team efforts in 2016-2017 is to focus on providing more information on the high-resolution ensembles simply beyond routine the error statistics.

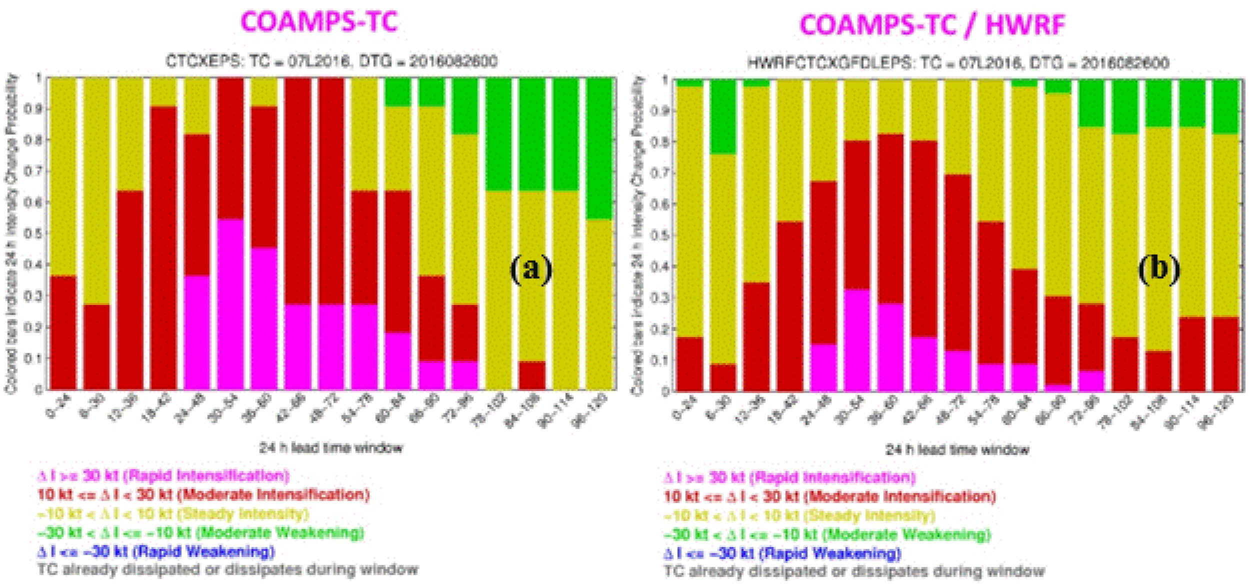

Figure 17: 24-hour intensity-change-probability for (a) COAMPS-TC and (b) multi-model ensembles

c. Basin Scale HWRF developments

HWRF has become a valuable tropical cyclone forecasting system over the entire globe. 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 track and intensity forecast goals through a unified G2R scale modeling system. Although the operational HWRF system is showing improved 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 1-3 km. horizontal resolution to produce simultaneous tropical cyclone forecasts (Fig. 18). 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.

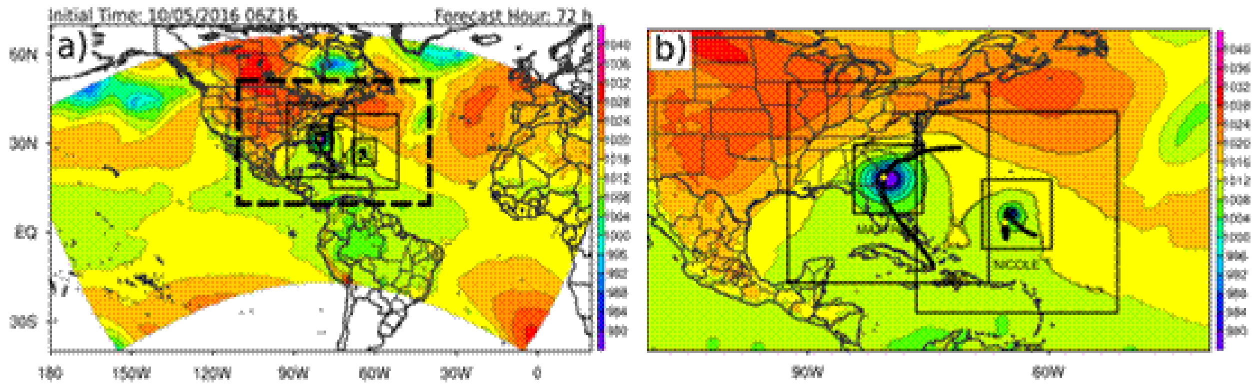

Figure 18: High resolution nests for (a) Matthew and (b) Nicole from Basin-Scale HWRF. Mean sea level pressure (hPa) from the HWRF Basin-Scale (a) for the entire outer domain and the western AL basin, represented by the dashed box. High-resolution nests (b) for Matthew and Nicole initialized 06Z 05 October 2016.

The 2016 version of HWRF-B (HB16) ran in real-time (4x daily) for the 2016 Atlantic and East Pacific hurricane seasons. HB16 track forecasts were improved up to 15% compared with the 2016 operational HWRF (H216). Impressively, HB16 track forecast errors were comparable to those from the GFS at long lead times (Fig. 19). For example, during the 2016 season, as Matthew (cover picture) approached the United States, it interacted with nearby Hurricane Nicole, creating a very complex forecast scenario. Nevertheless, HB16 excelled for these critical forecasts, capturing a realistic interaction between the two tropical cyclones (Fig. 19). GFS, on the other hand, continually looped Matthew back to the southeast United States, when, in reality, the storm tracked northeast out to sea. One reason for the improved forecasts is that, unlike the GFS, HB16 simulated Matthew and Nicole with high-resolution simultaneously within the same environment. Multiple moving multi-level nests at 2 km within HWRF-B better captured the vortex-environment interaction of both tropical cyclones and resulted in the better track forecasts of Matthew and Nicole. HB16 forecasts for the 2016 hurricane season can be accessed online at: https://storm.aoml.noaa.gov/basin. Currently, HWRF-B has been coupled with an ocean model and retrospective forecasts are underway.

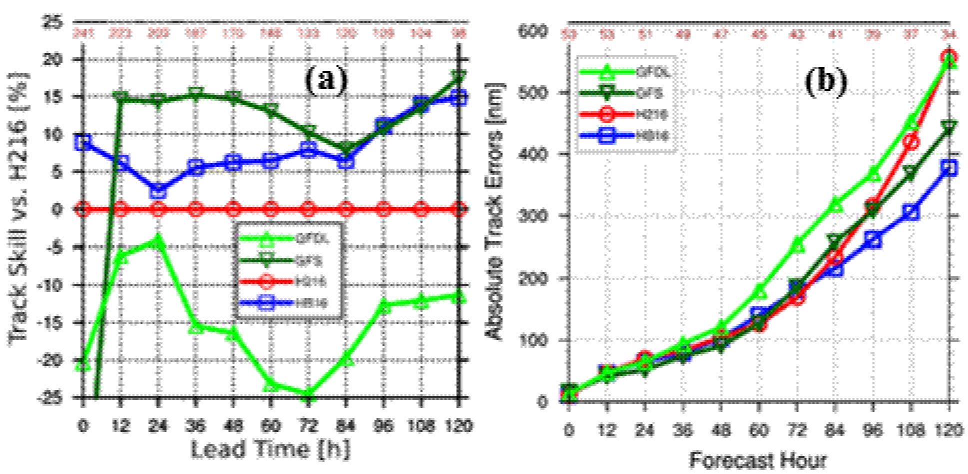

Figure 19: Track skill (a) of HB16, GFDL and GFS vs. (b) H216 in the AL basin

Track skill of HB16, GFDL, and GFS versus H216 for the Atlantic basin in 2016 is shown (Fig. 19a), and absolute track errors (Fig. 19b) are shown from HB16, H216, GFS, and GFDL for Hurricane Nicole (AL152016). In summary, HFIP has succeeded in creating the moving multi-level nest framework. HWRF-B has proved the concept that this nesting framework may be utilized in a real-time. With further testing and evaluation, the moving multi-level nest framework will help build a pathway for seamless prediction of tropical cyclones in the Next Generation Global Prediction System (NGGPS). “HWRF-B can serve as an effective bridge between the current operational HWRF system and these next-generation global model efforts at NCEP” (Alaka, et al. 2017).

8. 2016 HWRF Upgrades and Developments

Hurricane Weather Research and Forecast model (HWRF) 2016 implementation consisted of physics advancements, continued improvements to initialization package, system enhancements and improved products. System and resolution enhancements consisted of testing and evaluation (T&E) with the new 2016 4D-Hybrid GDAS/GFS initial boundary (IC)/boundary conditions (BC), dynamic core upgrades, smaller time steps (dt=30 s vs. 38/4/7 s), increased nested domain sizes, and more products (MAG and AWIPS-2). Initialization and data assimilation improvements included GSI upgrades with new data sets for GSI (CrIS, SSMI/S, and METOP-B changes), and DA turned on for all EPAC storms. Physics advancements implemented in 2016 included the 2016 version GFS planetary boundary layer (PBL), upgrade to SAS physics convection in all domains, updated momentum and enthalpy exchange coefficients (Cd/Ch), and improved vertical wind profile in the surface and boundary layer. For the first time in 2016, implementation occurred on NOAA’s Weather and Climate Operational Supercomputing System (WCOSS), RTOFS was used in physics advancement for initialization of EPAC storms for more realistic ICs and improved RI forecasts. The major developmental highlights are provided below.

a. Data Assimilation Developments

Several needs in 2016 were identified and emphasized for future development; reducing forecast spin-down was of particular interest. These needs included: (1) replacing vortex initialization with inner-core DA; (2) continue assessing the relative benefits of 4DEnvar, hourly 3DEnVar, and Incremental Analysis Updates (IAU); (3) testing of cycling and updating hydrometeors; and (4) testing of new observation types such as HDOB and GOES-R Atmospheric Motion Vectors (AMVs). The need for more interaction between modeling and DA teams has also been emphasized as critical to future success.

HWRF DA also underwent substantial development in preparation for the 2017 release. Major additions are planned for data being assimilated in addition to advancements to the DA system itself. Future upgrades will be based on findings from a large amount of testing undertaken from June 2016 into early 2017. As part of HWRF DA advancements, the most significant upgrade [that started in 2016] to the data assimilation system is the addition of an ensemble Kalman filter to supply flow-dependent covariance to the GSI hybrid system (see Fig. 20). This upgrade will allow for more faithful representation of hurricane inner-core error structures during assimilation. With use of more appropriate error covariance, inner-core observations such as those from reconnaissance aircraft should have a more positive impact on tropical cyclone

forecasts. The new system also sets a foundation of other future important data assimilation advancements.

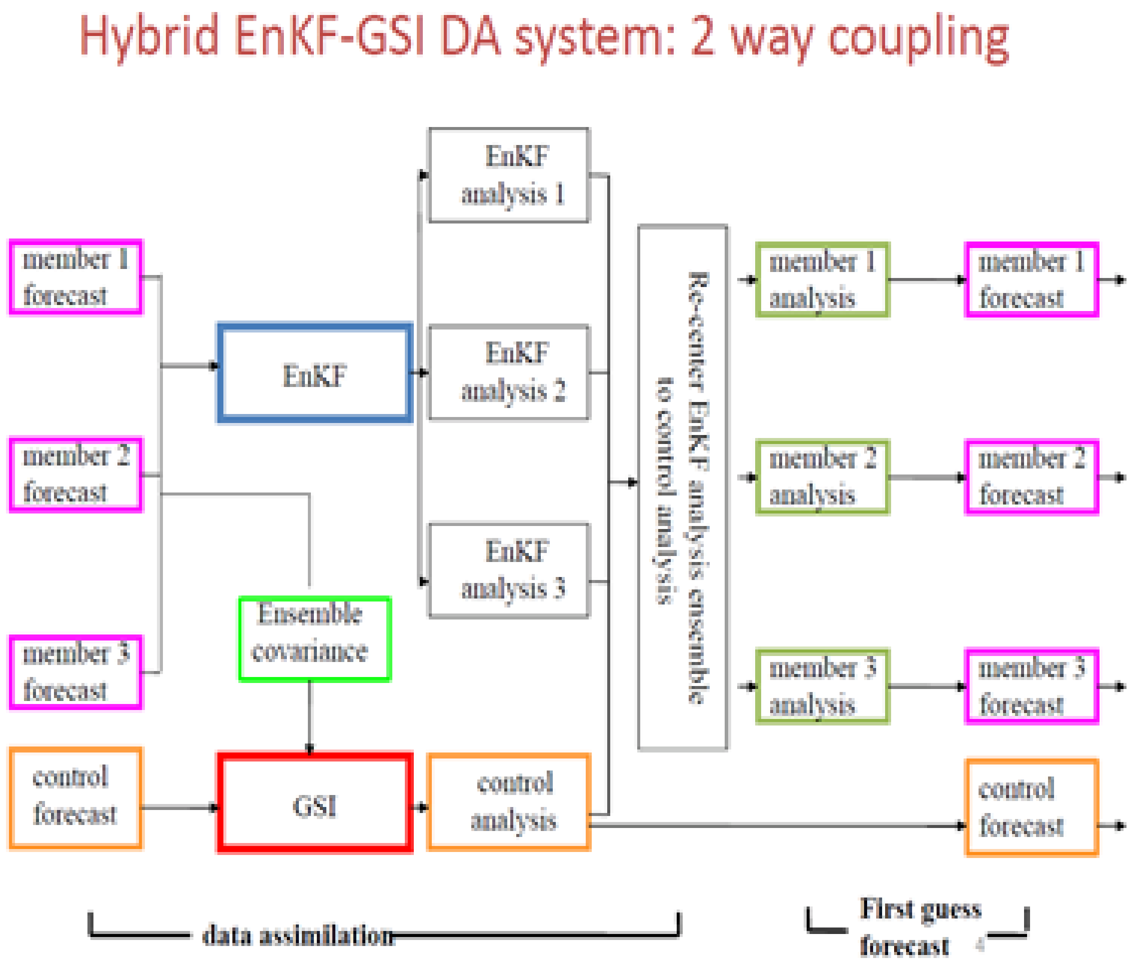

Figure 20: Two-way Coupling in the Hybrid EnKF-GSI DA system.

Another planned system upgrade is to increase the intensity threshold at which blending is used. Blending is a method in HWRF wherein the GSI analysis increments are eliminated in the inner-core region in favor of the first-guess provided by a vortex initialization procedure. The motivation for blending is that the GSI analysis can cause extreme spin-down in the forecast of hurricanes, and major hurricanes in particular. The problem is that blending on average reduces track and intensity skill, so it is desirable to use it sparingly. In H216, blending was used for all TCs with a maximum intensity > 50 kt, but extensive testing revealed that a threshold of 64 kt produces better results without a risk of spin-down.

Finally, a significant improvement is planned for the data being assimilated. Specifically, starting in 2017 all flight-level observations will be assimilated into HWRF. This addition was shown to produce a significant forecast intensity improvement during 2016 retrospective tests, and considering the large number of NOAA and USAF reconnaissance flights, there should be a substantial benefit to operational forecasts. In addition, three new types of Atmospheric Motion

Vectors (AMVs) will also be assimilated. These include vectors derived from clear-air water vapor, short-wave infrared and visible sources.

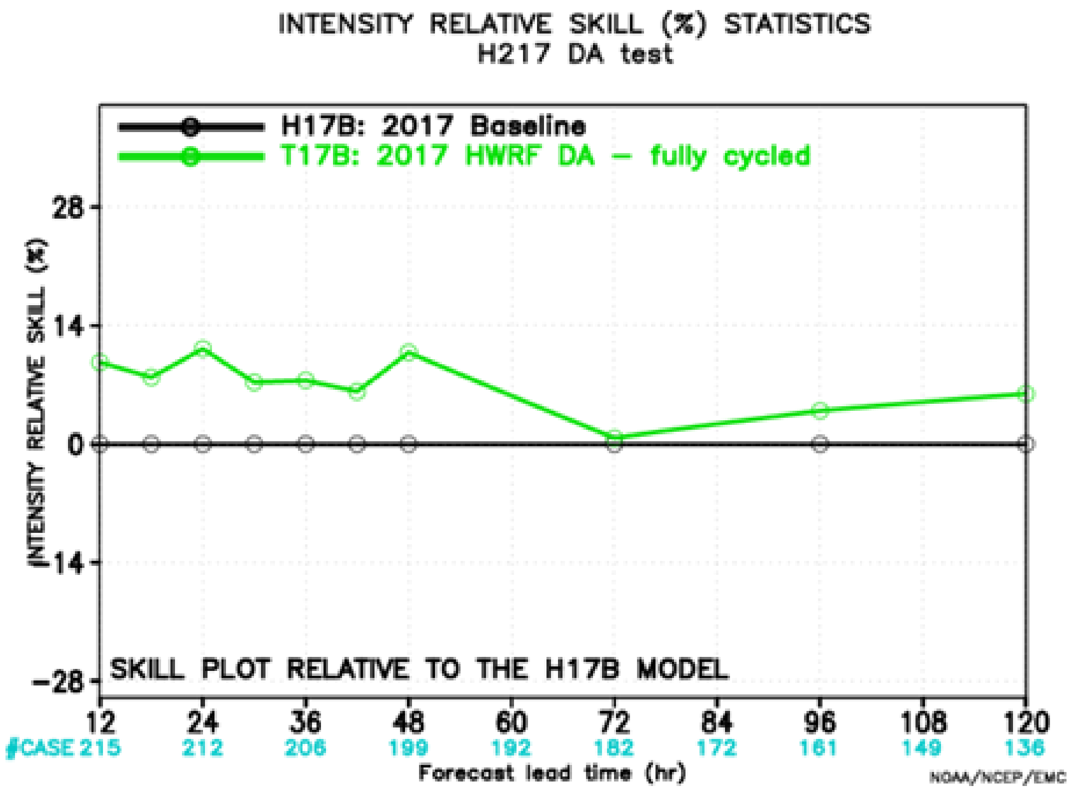

Figure 21: HWRF Intensity Skill improvement by DA upgrades from 2016 retrospective runs.

Improvement of skills is shown in intensity resulting from data assimilation upgrades (T17B) with respect to the baseline (H17B) with about a 10 percent increase in skills using HWRF DA (T17B) over the baseline (H17B) as shown from 12h-48h forecast periods and about a 3 percent increase over the baseline during post-72 hour forecast periods (Fig. 21).

9. Physics Developments

In 2016, the physics team worked several qualitative model biases. It was identified that HWRF is indeed able to generate secondary eyewalls in forecast mode, although with substantial variability from cycle to cycle. There are indications that the PBL and microphysics parameterizations can be targeted to improve secondary eyewall formation (SEF) forecasts in the model (Fig.22). It was reported that the large bias on HWRF radius of maximum wind previously identified persist, and while it is not clear to what extent that is a physics problem, it is hoped that this bias will be addressed by 2017.

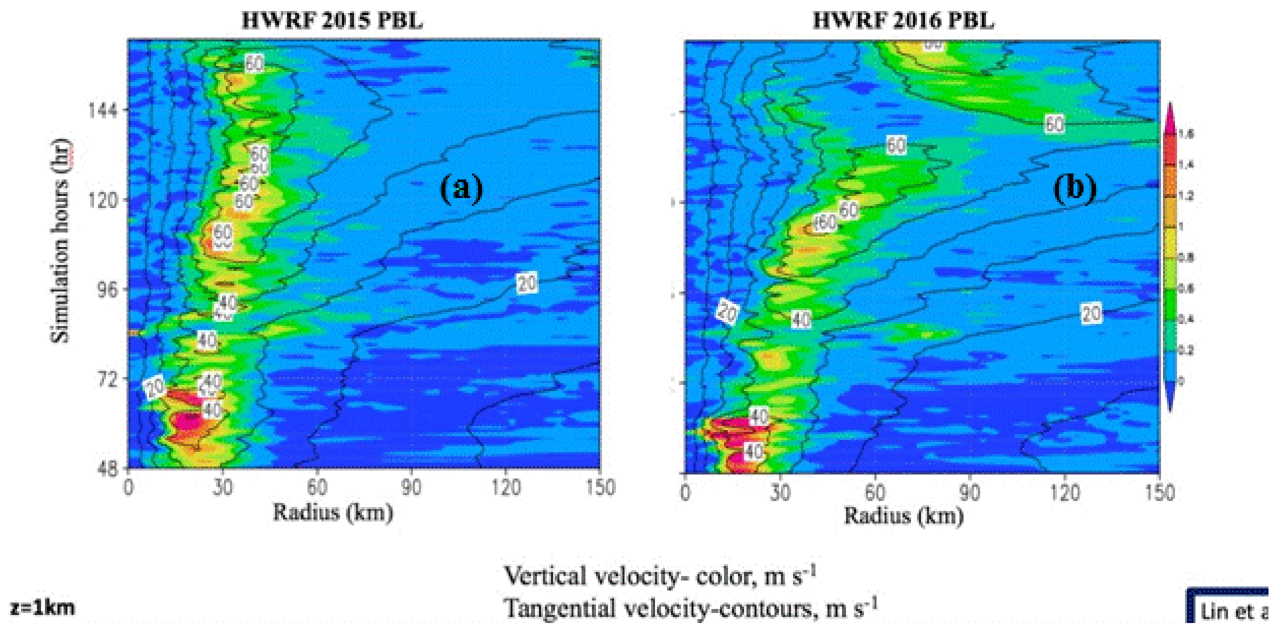

Figure 22: Hovemoller diagram of (a) vertical and (b) tangential velocity for Matthew (2016). There has been Steep-step progress with storm structure predictions. Hovemoller Diagram of vertical velocity (shaded) and contours of tangential velocity indicating that the 2016 version of HWRF is able to capture eyewall replacement cycles (ERCs).

Model development priorities include addressing identified model biases and, in the longer term, priorities for physics betterment include to continue incorporating SAS physics, alignment with global models, transition to either higher moment microphysics or include advection of species and adopt stochastic approaches. Model biases include: rapid intensification (physics that will enable increased probability of detection and decreased false alarm rates remain a priority); secondary eyewalls (lack of them or rarity of them in operational cycles), radius of maximum wind (there is a large bias); too warm and too humid inner core bias.

The Ocean Model Impact Tiger Team (OMITT) quantitatively evaluates the importance of ocean coupling in TC prediction models, and also evaluates air-sea flux and ocean physics parameterizations in these models with the overarching goal of improving intensity forecasts. OMITT documented the importance of realistically initializing the ocean model. The exceptionally warm upper ocean in the EPAC due to El Niño contributed to an unusual number of very strong storms, and initialization of the ocean model by realistic analyses vs. climatology partly corrected low bias in predicted intensity in both operational POM-HWRF and

experimental HYCOM-HWRF. Improved intensity prediction for Hurricane Gonzalo (2014) was also realized in North Atlantic HYCOM-HWRF forecasts when the ocean model was initialized from a data-assimilative analysis vs. an unconstrained ocean analysis. Sensitivity of year-to-year differences in upper-ocean heat content was documented for Hurricane Edouard (2014) by initializing the ocean model from climatology vs. fields on September 13 for five different years from 2010-2014. These different ocean conditions produced a large spread in predicted intensity (Fig. 23). The addition of 3-D ocean coupling to the COAMPS-TC model improved both track and intensity forecasts.

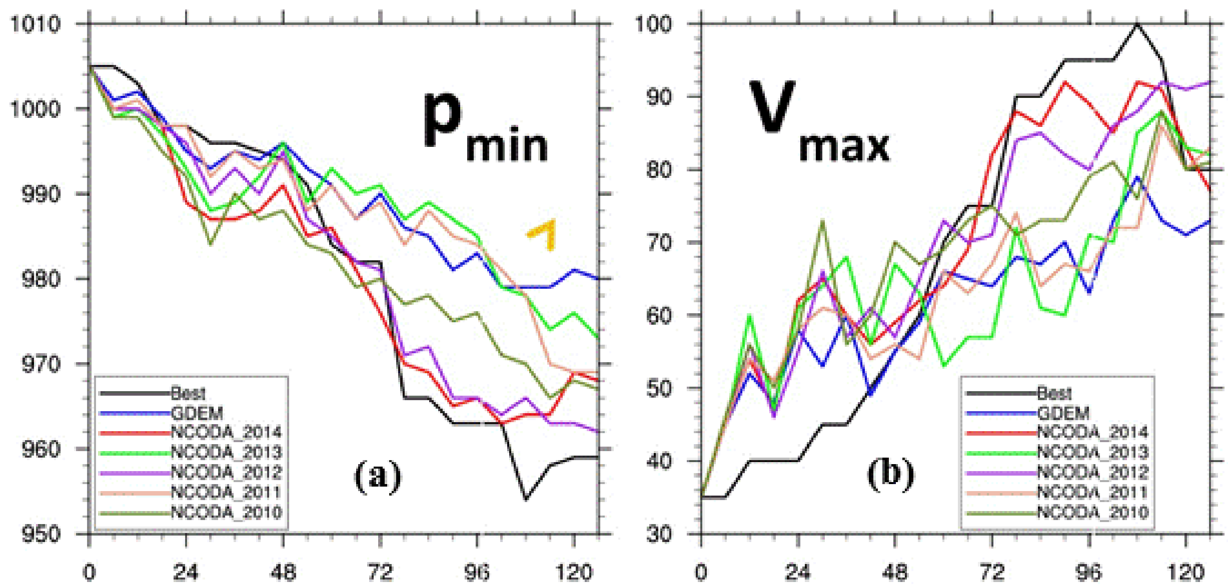

Figure 23: Hurricane Edouard (a) P_{min} and (b) V_{max} forecasts (2010-2014). Hurricane Edouard intensity forecasts both initialized September 13 with fields from five different years (2010-2014) plus climatology.

The importance of ocean observations for reducing errors and biases in ocean analyses used for model initialization has been documented using Observing System Simulation Experiments. The existing operational observing system provides substantial error and bias reduction while rapid-response airborne profile surveys conducted ahead of storms provide additional error and bias reduction. Also, COAMPS-TC forecasts of Hurricane Matthew (2016) demonstrated that 24-hour SST response forecasts were substantially improved by the assimilation of in-storm AXBT deployments performed by the USNA TROPIC project. Work is also ongoing to collect and analyze observations to evaluate and improve the representation of physical processes governing ocean coupling in models, particularly in the Gulf of Mexico for Hurricane Isaac (2012) and for the upcoming 2017 season with the deployment of repeat-profiling EM-APEX floats, and also in the western Pacific using time series of ocean profiles from a Kuroshio Extension Observatory buoy that was struck by typhoons. Finally, work is ongoing to further develop and improve ocean coupling in the HWRF model and the new HMON model at EMC, and to further develop and evaluate ocean coupling in the COAMPS-TC model at NRL-Monterey.

10. Societal Impacts

In this section three types of products that impact society are presented and they are: 1) Storm Inundation, 2) Storm Surge Watch Warning, and 3) Arrival of Tropical Storm Force Winds (ATSFW). The NWS's National Hurricane Center (NHC) has been developing products to help increase public understanding and response to storm surge. The NHC has used social science research techniques to guide development of new products and to engage stakeholders in the process.

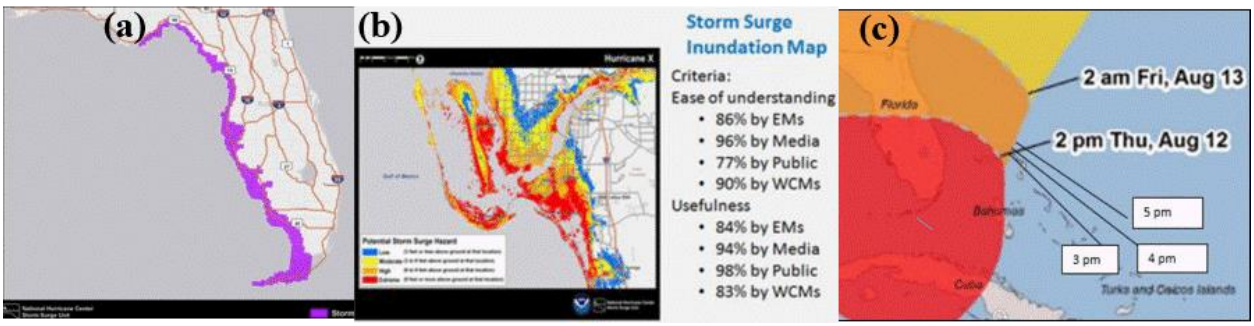

Figure 24: Storm Surge Watch/Warning, Inundation and arrival of Tropical Storm Force Winds forecast products

a. Storm Surge Watch/Warning and Inundation

In support of the effort to increase public response to storm surge, the NWS Office of Planning and Programming for Service Delivery (OPPSD) developed an experimental Storm Surge Watch/Warning product (Fig. 24a) that is anticipated to be completed in 2017. The Eastern Research Group (ERG) helped the NWS evaluate early prototypes of these products. A storm inundation forecast graphical product (Fig. 24b) was made operational in the Summer of 2016. Time of arrival products have now been produced in real time on an experimental basis.

b. Time of Arrival (TOA) for Tropical Storm Force Winds

Phase 1 research and development (R&D) for an ATSFW forecast graphic (Fig. 24c) based on probabilistic data of track, wind speed, wind radii, and other information was completed in late 2016. There are several variations of this graphic (not pictured) which depict different color schemes, labeling options, titles, and confidence depictions that social scientists have tested with potential users.

Stake holder opinions from community groups and decision-makers from local, state, school/ university, regional officials and planners are taken into consideration during R&D for all three product types.

Once specific graphics are approved, the NHC would issue the graphic along with each advisory as a TC approaches to enable emergency managers (EMs) and other officials make more informed preparedness, evacuation decisions and to communicate this information to other community decision makers. The graphic would also be available for use on broadcast media, websites, and social media (See Section 11 for further discussion of TOA graphics efforts).

11. Post Processing of Model Output

a. NHC product research and developments

The Post-Processing And Verification (PPAV) team effort in 2016 focused on new product development, improvements to NHC's Guidance Suite, Wind Speed Probability (WSP) model, and model diagnostics. Significant progress was made in each of these areas. For more than a decade NHC has been providing uncertainty information regarding their deterministic tropical cyclone forecasts through their WSP model products. These products include the probability of 34, 50 and 64 kt winds out to 5 days. Feedback from EMs indicated that probabilistic information on the arrival of 34 kt winds would also be very useful for mitigation planning. A prototype TOA product was developed (Fig. 25), which will be demonstrated in real-time during the 2017 season. Fig. 25 below is an example of the prototype, which shows the most likely time of arrival and the 0-120 h cumulative probability of gale-force winds.

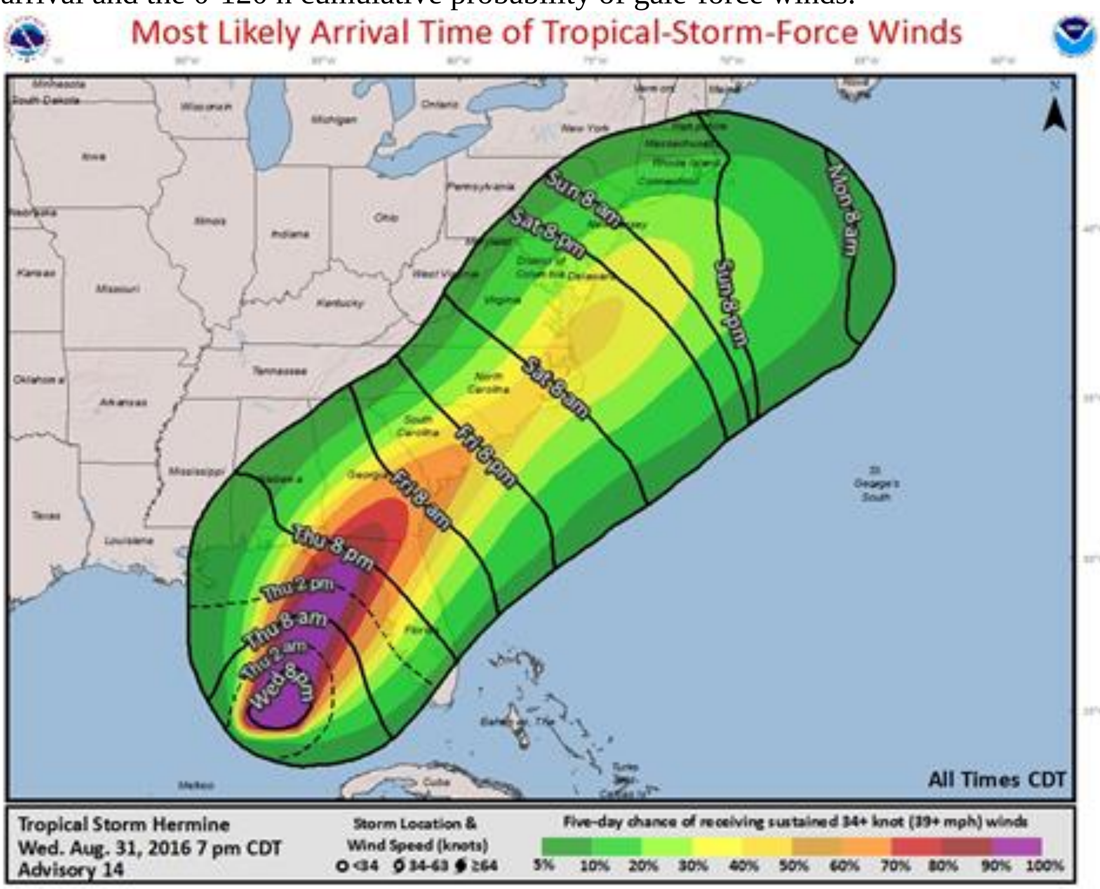

Figure 25: Prototype of Tropical-Storm-Force Winds Arrival for Hermine (2016).

A companion product that shows the earliest reasonable time of arrival based on the 10th percentile from the WSP model will also be provided on NHC's web page for public comment. NHC also redeveloped the entire tropical cyclone graphics suite of products for the 2017 hurricane season. The new graphics use a common set of maps, projections, and plotting routines, that help migrate NHC away from legacy NAWIPS/GEMPAK functionality. These new graphics will also be featured on the Central Pacific Hurricane Center (CPHC) webpage, marking the first time that both centers will issue a common set of baselined graphics. NHC runs

several post-processing applications including statistical intensity forecast models, in the NHC Guidance Suite. Improvements to the NHC Guidance Suite included new satellite databases, refinements to the RI index, and improved model consensus techniques like the HFIP Corrected Consensus Approach (HCCA). Those developments were transitioned to operations for the 2017 season.

NHC's Automated Tropical Cyclone Forecasting (ATCF) system is the primary tool for the Hurricane Specialist Unit. The ATCF is separate from the National Weather Service (NWS) Advanced Weather Interactive Processing System second generation (AWIPS2). Work has begun on migration of some ATCF capabilities to the AWIPS2 system. Accomplishments include database import/export capabilities and preliminary design of a new Graphical User Interface (GUI).

Because the ATCF is an operational system, the ability to use it to develop new product capabilities is limited. An HFIP experimental products web page is maintained at the Developmental Test Center (DTC) to enable new product capabilities to be evaluated. The DTC also continues to support the HFIP real-time web page (hfip.org/products) to facilitate the evaluation of new models and products.

The Hurricane Weather Research and Forecast (HWRF) model is updated annually. An important consideration is how these upgrades impact NHC's track and intensity forecasts. However, the validation of the model using only forecast center positions and maximum surface wind provides little information regarding the sources of errors. New diagnostic techniques were developed to better compare HWRF model fields to products determined from aircraft data. Methods to identify and analyze forecast outliers continue to be developed. This comparison continues to provide more guidance on how to improve the HWRF model.

b. HFIP product research and developments: Experimental ensemble products

During the 2016 season, the HFIP Ensemble Products Tiger Team developed an ensemble-based probabilistic RI product based on varied ensemble prediction systems (EPS) that have participated in HFIP. This includes the HWRF ensemble, GFDL ensemble, COAMPS-TC ensemble (Section 7b), and the SPICE statistical model (Table 1). These probabilities are compared to the statistical SHIPS RI product, which has been used operationally by NHC forecasters. For this product, multiple RI definitions are employed, which include a 30-knot change in 24 h, a 55-knot change in 48 h, and a 65-knot change in 72h. At the beginning of this process, there was no infrastructure to transmit the probabilities into the NHC system and validate the probabilities. To address, this, we extended the ATCF e-deck format, so that RI probabilities could be included in these files and hence could be ingested into the NHC forecaster suite. In addition, a real-time web page was created to visualize the output (https://ral.ucar.edu/projects/hfip/d2016/ensRI/). Moreover, the MET-TC tools were extended to include probabilistic forecast validation based on e-deck inputs (these improvements will be included in the next release of this software).

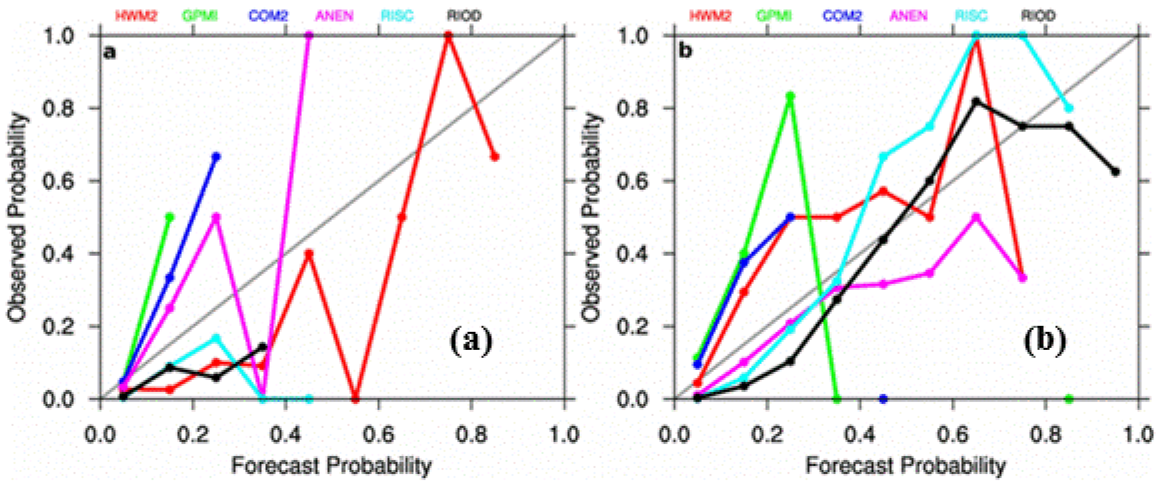

Figure 26: Reliability diagrams for 30 kt probability change/24 h in TC maximum wind speed. Atlantic (a) and EPAC (b) basins forecasts during 2013-2015 seasons. HWM2 denotes HWRF ensemble, GPMI is the GFDL ensemble, COM2 is the COAMPS-TC ensemble, ANEN denotes the HWRF analog ensemble, RISC is the SPICE model, and RIOD is the operational SHIPS RI product.

Prior to the start of the 2016 season, the HFIP team validated retrospective ensemble-based probabilities from 2013-2015 seasons. Fig. 26 shows the reliability diagram for Atlantic and Eastern Pacific 24 h RI probabilities from various models. Ideally, each model's curve should fall along the black 1:1 line. Models below/above that line mean that the probabilities are higher/lower, respectively than how frequently RI actually takes place. Note that because RI is a relatively infrequent occurrence, it is difficult to obtain a large enough sample to properly validate this quantity. As a consequence, the real-time forecast verification is not shown, as RI was relatively infrequent during 2016. In the Atlantic Basin for 2013-2015, HWRF and SPICE models generally have probabilities higher than observed, while the COAMPS-TC and GFDL ensembles are lower because RI takes place less frequently. While the COAMPS-TC and GFDL ensembles behave similarly in the Eastern Pacific, the HWRF and SPICE have more consistent probabilities in this particular basin. During the 2017 season, it is planned to extend these probabilities to other intensity change thresholds and explore the possibility of multi-model ensemble probabilities.

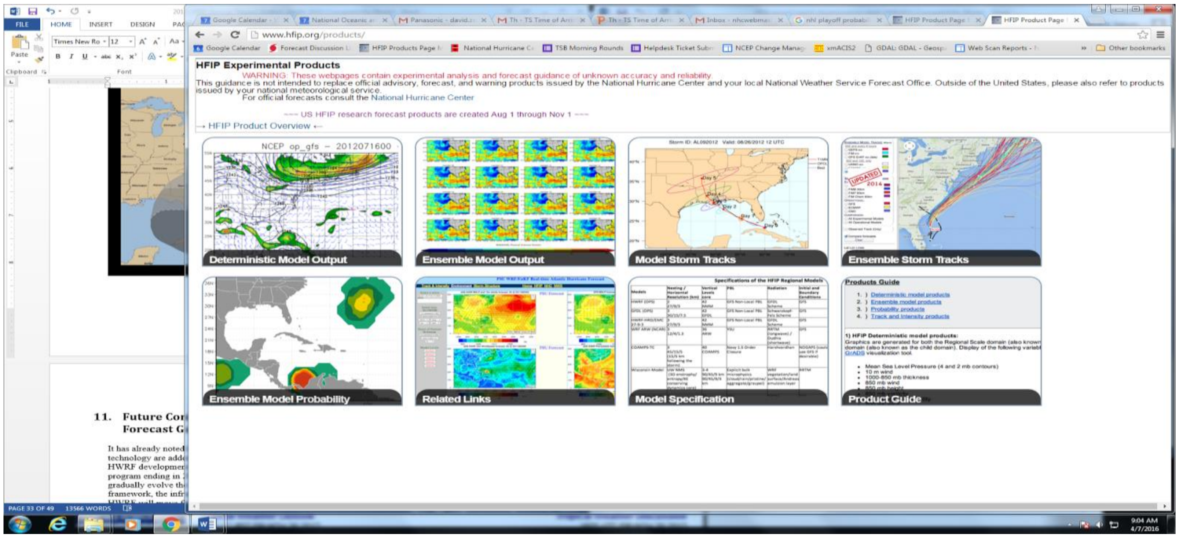

Figure 27: Screenshot of the HFIP products webpage.

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. 27 shows a screenshot from the hfip.org/products webpage. The sample of products available includes ensemble tracks and probabilities, deterministic model fields, and real-time experimental diagnostics.

12. NOAA Announcement of Federal Funding Opportunity (FFO)

The following Tables (3 and 4) provide lists of projects supported by HFIP during 2012-2016 and some R2O outcome:

Table 3. 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 Super-ensemble 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 subgrid 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

Table 4. HFIP Supported Projects from 2016-2018.

HFIP Collaborative Awards Round III (2016-2018)		
PI Name	**PI Institution**	**Project Title**
Xuguang Wang	University of Oklahoma	Further Advancement of HWRF Self-consistent Ensemble-variational Hybrid Data Assimilation System to Improve High Resolution Hurricane Vortex Initialization
Chanh Kieu	Indiana University	Characteristics of Hurricane Intensity Error Growth and Predictability Limit in the HWRF Model
Ryan Torn	University of Albany	Evaluating Methods of Parameterizing Model Error in the HWRF Ensemble Prediction System
Ping Zhu	Florida International University	Improving HWRF's Ability to Predict Rapid Change in Tropical Cyclone Intensity Governed by Internal Physical Processes
Christopher Rozoff	University of Wisconsin	Probabilistic Prediction of Tropical Cyclone Track, Intensity, and Structure with an Analog Ensemble

List of R2O outcomes from the above projects[9]:

1. Vortex "spin-down" in HWRF can be mitigated by inner-core hybrid-DA or digital filter initialization (DFI) of analysis and possibly new turbulent mixing physics
2. Further improvements in vortex initialization and model clouds/moisture can be obtained using satellite retrieval products (microwave, sounders)
3. Extended new air-sea-module to all basins in HWRF
4. Short horizontal mixing lengths intensify vortex faster than that with longer mixing lengths
5. Largest HWRF forecast errors associated with shallower and weaker model convection
6. Analog Ensemble technique can improve HWRF biases
7. Developed corrected bias consensus
8. Improved boundary layer vertical diffusivity improves track and intensity HWRF forecast skill including RI

[9] American Meteorological Association (AMS) Poster Presentation on *Hurricane Forecast Improvement Project Awards: Summary of research-to-operations (R2O) Gaines at the NWS.*

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

As illustrated in the previous sections, HWRF has evolved into a valuable tropical cyclone forecasting system providing track, intensity and RI guidance over all global basins. 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-vortex scale modeling system. In fact, by creating the basin-scale HWRF, HFIP has already demonstrated the feasibility of operating high resolution, two-way interactive moving nests that may be seamlessly integrated into a larger scale model (section 7c).
In late 2016, GFDL's Finite Volume Cubed Sphere (FV3) model was selected as the next dynamical core for NOAA's Global Forecasting System (i.e., fvGFS). At the same time through a set of recent initiatives, NOAA is reducing complexity in the NCEP production suite, organizing development around the FV3 core and within the NEMS framework.

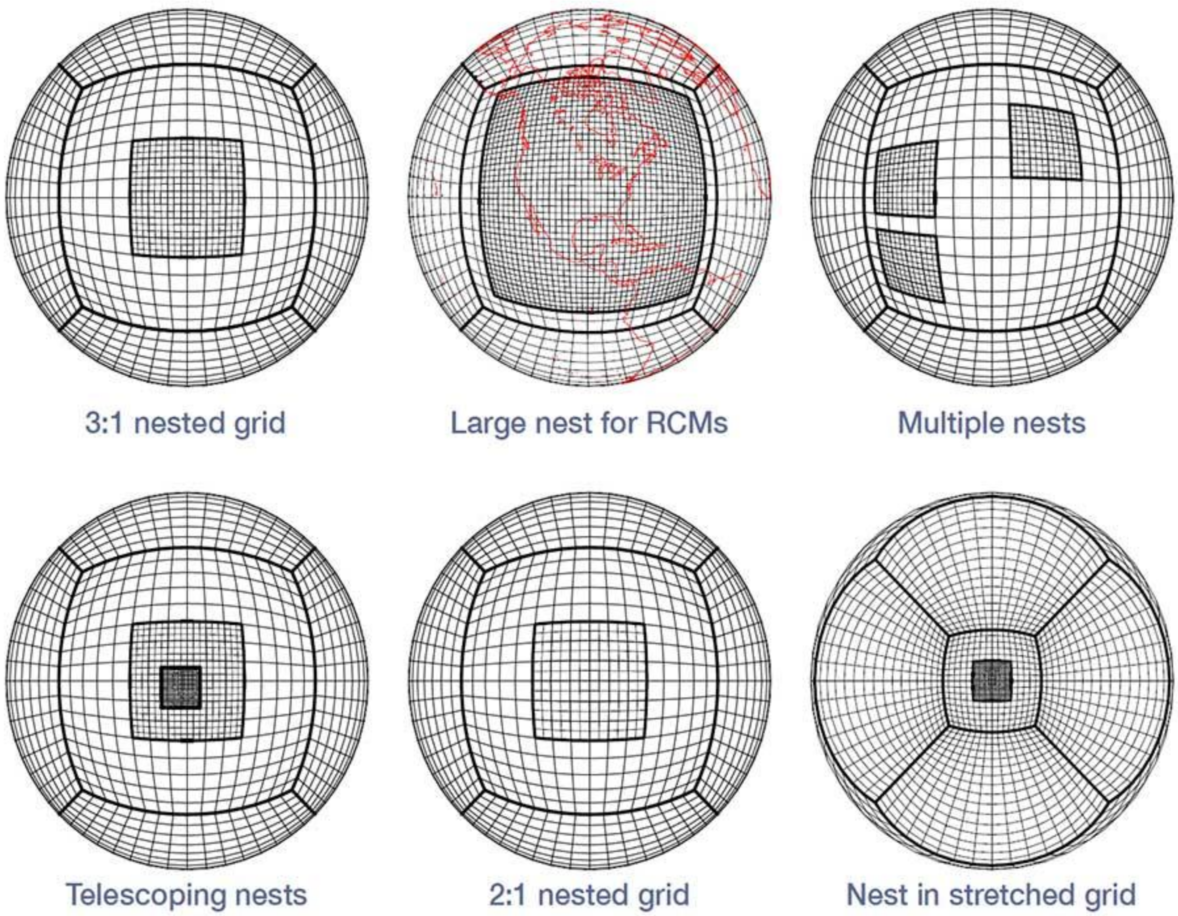

Figure 28: Examples of advancements in Nested Grid Capabilities.

Since FV3 is a proven cloud-resolving model, the strategy may be to continue incremental operational advancements in HWRF and HMON (e.g. Basin Scale) under HFIP and, in parallel, transition the next-generation hurricane developments to FV3. Although the FV3 model itself is

fully tested and cloud resolving, certain aspects of its nesting capability prevent its use in critical situations. In particular: the hurricane intensity and structure forecasting problem requires both a large domain as well as very high resolution of 1-2 km to resolve convective scale motions in the eyewall region. Subsequently, hurricane forecast applications require storm following, telescopic nests at about 1-2 km resolution that can be located anywhere in the globe and should be capable of following the tropical storms for several days. In addition, two-way interactive nests are essential for improving accuracy of forecasts. This is different from the requirements for severe weather, where one way static nesting may be sufficient given the shorter timescales involved in the forecast (5-7 days for hurricanes -vs- 1-2 days for severe storms). The hurricane forecast requirements cannot be fulfilled by the current static nesting and stretching capability of the FV3 model (Fig. 28). In addition, the nature of FV3's 'cubed sphere' domain and the embedded FMS infrastructure may pose a significant technical challenge to unrestricted nest movement internal to FV3. With these limitations in mind, developers from the HWRF, HMON, and FV3 teams met at GFDL to discuss a high-resolution nesting strategy for hurricanes and severe weather within fvGFS in the NGGPS era, and also to advance a regional version of FV3 for unification in operations. The workshop proposed the two-pronged approach shown in Fig. 29 (an outcome from the workshop).

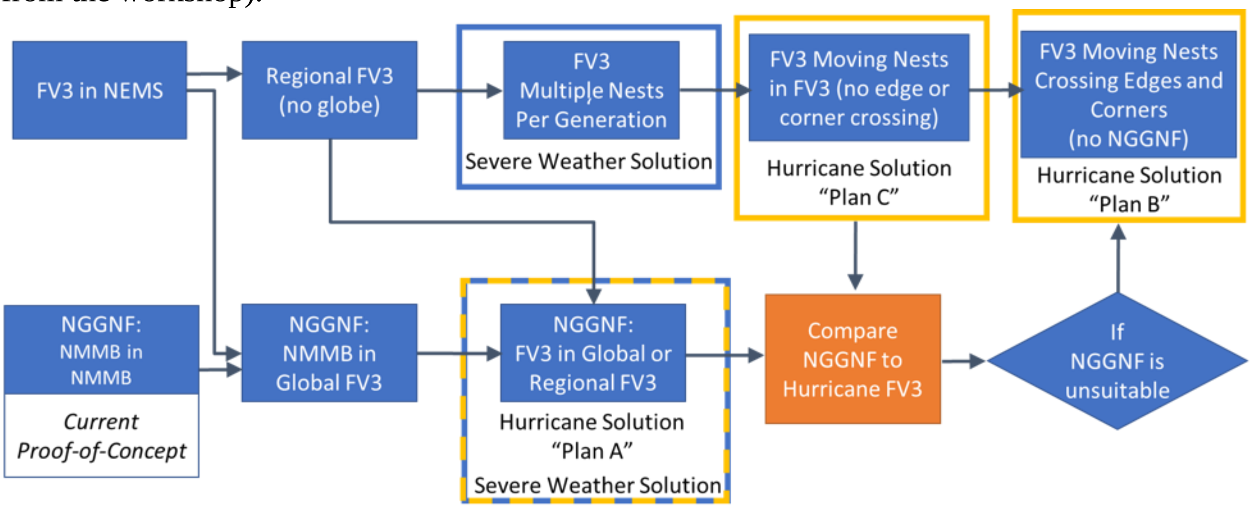

Figure 29: Proposed development and decision flowchart in the Dec. 2016 nesting workshop

A development and decision flowchart (Fig. 29) was proposed at the EMC-AOML-GFDL nesting workshop held in December 2016. The Next Generation Generalized Nesting Framework (NGGNF) is a standalone and ESMF-based framework that is grid-shape-, projection- and dynamical-core-independent that is under development within the NEMS framework. It "couples" nests multiple atmospheric models or multiple instances of the same model. As NGGNF operates independently of any dynamical core or grid composition, it is suggested as the primary avenue of development for moving nested hurricane applications ("Plan A" in Fig. 29). This approach assumes the concurrent development of particular features of the FV3-based model (i.e., NEMS compatibility and a regional version), and is also contingent to the ability of the NGGNF system to sufficiently reproduce native solutions. The NGGNF is a high risk but high gain pathway. The parallel approach ("Plan C" in Fig. 29) develops nesting for hurricane application internally to fvGFS, utilizing the current two-way static-nested dynamical core. It is a realistic and attainable choice within two years, with fully movable nesting capability attainable

within three years (“Plan B” in Fig. 29; subject to the technical caveats mentioned above). However, plan B and C have a critical dependence on FMS infrastructure that embeds the FV3 model. In 2017, it is expected that further developments will be made related to moving nests in FV3. Further progress will be reported in the next report.

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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.

ACRONYM:	**TITLE with Acronym and DESCRIPTION (optional):**
3D-VAR:	Three-Dimensional VARiational approach (3D-VAR)
4DEnVAR:	Four-Dimensional Ensemble-VARiational (4DEnVAR)
4D-VAR:	Four-Dimensional Ensemble-VARiational (4D-VAR)
ADCIRC:	Advanced Circulation model for oceanic, coastal and estuarine waters (ADCIRC)
AEMI:	GEFS with 6-hour interpolation (AEMI)
AOML:	Atlantic Oceanographic and Meteorology Laboratory (AOML)
API:	Advanced Weather Research and Forecasting Model (API)
AVNI:	GFS with 6-hour interpolation (AVNI)
AHW:	Advanced Hurricane Weather (AHW) Weather Research and Forecasting (WRF) Model under the National Center for Atmospheric Research.
AHWI:	AHW with 6-hour interpolation (AHWI)
AMVs:	Atmospheric Motion Vectors (AMVs)
APSI:	ARW with 6-hour interpolation (APSI)
ARW:	Advanced Research for Weather (ARW) at Pennsylvania State University, Weather Research and Forecast (WRF) model
ATCF:	Automated Tropical Cyclone Forecasting System (ATCF)

ACRONYM:	TITLE with Acronym and DESCRIPTION (optional):
ATSFW:	Arrival of Tropical Storm Force Winds (ATSFW) product
AWIPS:	Advanced Weather Interactive Processing System (AWIPS)
BAMM:	Medium-Layer Beta and Advection Model Track Forecast
BAMO:	Regression coefficient on the phase of the AMO or βAMO ~ flat on $R_{Poisson}$)
BAMS:	Shallow-Layer Beta and Advection Model Track Forecast
BC:	Boundary Condition (BC)
BSC:	Barcelona Supercomputing Center (BSC)
CMC:	Canadian Meteorological Centre model
CMCI:	CMC with 6-hour interpolation (CMC)
CLIPER:	Climate and Persistence model (CLIPER)
CLIPER5:	Climate and Persistence model-five (CLIPER5)
COAMPS-TC:	Coupled Ocean/Atmosphere Mesoscale Prediction System-Tropical Cyclone (COAMPS-TC) at Fleet Numerical Meteorology and Oceanography Center
COTC:	U.S. Navy COAMPS-TC Model Forecast (COTC)
COTI:	COAMPS-TC with 6-hour interpolation (COTI)
CPC:	Climate Prediction Center (CPC)
CPHC:	Central Pacific Hurricane Center (CPHC)
CTCI:	Previous experimental COAMPS-TC Forecast Interpolated ahead 6-hours
CTCX:	Experimental U.S. Navy COAMPS-TC Model Forecast (CTCX)
CXTI:	Experimental COAMPS-TC Forecast Interpolated Ahead 6 hours (CXTI)
DA:	Data Assimilation (DA) or Data Analysis (DA)

ACRONYM:	TITLE with Acronym and DESCRIPTION (optional):
DART:	Data Assimilation Research Testbed (DART)
Decay-SHIFOR5:	Decay Statistical Hurricane Intensity Forecast model (Decay-SHIFOR5)
DFI:	Digital Filter Initialization (DFI)
DSHP:	Decay SHIPS (DSHP)
DTC:	Developmental Testbed Center (DTC)
ECMWF:	European Centre for Medium-range Weather Forecasts model (ECMWF)
DWF:	Double Warm Core
EFS:	Experimental Forecast System (EFS), HFIP Stream 2, demo project
EGRI:	United Kingdom Meteorological Office model, subjective tracker, with 6-hour interpolation (EGRI)
EMC:	Environmental Modeling Center (EMC)
EMS:	Emergency Managers (EMs)
EMXI:	ECMWF Forecast Interpolated Ahead 6 hours (EMXI)
EnKF:	Ensemble Kalman Filter (EnKF)
ERG:	Eastern Research Group, Inc. (ERG)
ESMF:	Earth System Modeling Framework (ESMF)
ERC:	Eyewall Replacement Cycle (ERC)
ESPC:	Earth System Prediction Capability (ESPC)
ESMF:	Earth System Model Framework (ESMF)
ESRL:	Earth System Research Laboratory (ESRL)
F-A:	Ferrier-Aligo (F-A) microphysics scheme
FAR:	False Alarm rate (FAR)
Far-Field:	Tropical cyclones that are more than 3,500 km apart (Far-Field)

ACRONYM:	TITLE with Acronym and DESCRIPTION (optional):
FSSE:	Florida State University Super-Ensemble (FSSE)
FV3:	Finite Volume Cubed-Sphere Dynamical Core (FV3)
G01I:	GFDL ensemble member 01 with 6-hour interpolation (G01I) where in general, G##I denotes GFDL ensemble member ## with 6-hour interpolation.
GDAS:	Global Data Assimilation System (GDAS)
GEFS:	National Centers for Environmental Prediction Global Ensemble Forecast System (GEFS)
GFDI:	Geophysical Fluid Dynamics Laboratory model with 6-hour interpolation (GFDI)
GFDL:	Geophysical Fluid Dynamics Laboratory (GFDL) model
GFNI:	Navy version of GFDL with 6-hour interpolation (GFNI)
GFS:	Global Forecast System (GFS)
GFSA:	GFS Analysis (GFSA)
GFSI:	Early GFS with 6-hour interpolation (GFSI)
GFS IC/BC:	Global Forecast System Initial Condition/Boundary Conditions (GFS IC/BC)
GHMI:	GFDL adjusted using a variable intensity offset correction that is a function of forecast time, with 6-hour interpolation (GHMI)
GMT:	Greenwich Mean Time (GMT), Universal Time Coordinated (UTC), or Zulu Time Zone (Z). There is no time difference between all of these time zones.
GMTB:	Global Modeling Test Bed (GMTB)
GOES-R:	Geostationary Operational Environmental Satellite-R (GOES-R) series
GPMN:	GFDL Ensemble Mean (GPMN)
GPMI:	GFDL Ensemble Mean including 6-hour interpolation (GPMI)
GSD:	Global Systems Division (GSD)

ACRONYM:	**TITLE with Acronym and DESCRIPTION (optional):**
GSI:	Grid-point Statistical Interpolation (GSI)
H3WI:	NOAA's Hurricane research Division (H3WI) model
HDOBS:	High Density Observations (HDOBS) from aircraft
HEVDAS:	Hurricane Ensemble Data Assimilation System (HEVDAS)
HFIP:	Hurricane Forecast Improvement Program (HFIP)
HCCA:	HFIP Corrected Consensus Approach model (HCCA)
HIRWG:	Hurricane Intensity Research Working Group (HIRWG)
HIWPP:	High Impact Weather Prediction Project (HIWPP)
HEDAS:	Hurricane Ensemble Data Assimilation System (HEDAS)
HMON:	Hurricanes in a Multi-scale Ocean coupled Non-hydrostatic (HMON) model or Hurricane Non-hydrostatic Multi-scale Model on B-grid (NMMB)
HNMMB:	Hurricane Non-hydrostatic Multi-scale Model on B-grid (HNMMB)
HPC:	Hydro-meteorological Prediction Center (HPC)
HRD:	Hurricane Research Division (HRD)
HSOFS:	Hurricane Storm-surge On-Demand Forecast System (HSOFS)
HWFI:	HWRF with 6-hour interpolation (HWFI)
HWRF:	Hurricane Weather Research & Forecasting (HWRF)
HWRFI:	HWRF with 6-hour interpolation (HWRFI)
HYCOM:	Hybrid Coordinate Ocean Model (HYCOM)
IAU:	Incremental Analysis Updates (IAU)
IC:	Initial conditions (IC)
ICON:	National Hurricane Center Intensity Consensus (ICON)

ACRONYM:	TITLE with Acronym and DESCRIPTION (optional):
IV15:	Intensity forecast ensemble including 2012 stream 1.5 forecasts (IV15)
IVCN:	Intensity Variable "ConNsensus" model
JEDI:	Joint Effort for Data assimilation Integration (JEDI)
JTWC:	Joint Typhoon Warning Center (JTWC)
LBAR:	Limited Area Barotropic Model Track Forecast
LEO:	Low Earth Orbiting satellite sounder (LEO)
LGEM:	Logistics Growth Equation Model (LGEM)
NAVDAS:	NRL Atmospheric Variational Data Assimilation System (NAVDAS)
NAVDAS-AR:	NRL Atmospheric Variational Data Assimilation System-Accelerated Representer (NAVDAS-AR)
NAVGEM:	Fleet Numerical Meteorology and Oceanography Center Navy Global Environmental Model (NAVGEM), replaced NOGAPS February, 2013.
NCAR:	National Center for Atmospheric Research (NCAR)
NCEP:	National Centers for Environmental Prediction (NCEP)
NCO:	NCEP Central Operations (NCO)
NCODA:	Navy Coupled Ocean Data Assimilation (NCODA) system
NCOM:	Navy Coastal Ocean Model (NCOM)
NEMS:	NOAA Environmental Modeling System (NEMS)
NESDIS:	NOAA Earth System Research Laboratory (NESDIS)
NGGNF:	Next Generation Generalized Nesting Framework (NGGNF)
NGGPS:	Next Generation Global Prediction System (NGGPS)
NGPI:	NOGAPS with 6-hour interpolation (NGPI)
NGXI:	Experimental NOGAPS with 6-hour interpolation (NGXI)

ACRONYM:	**TITLE with Acronym and DESCRIPTION (optional):**
NHC:	National Hurricane Center (NHC)
NMM:	Environmental Modeling Center Non-hydrostatic Mesoscale Model (NMM)
NMMB:	Non-hydrostatic Multi-scale Model on the B-grid (NMMB)
NOGAPS:	Navy Operational Global Atmospheric Prediction System (NOGAPS), replaced by NAVGEM February 2013 at Fleet Numerical Meteorology and Oceanography Center.
NPS:	Naval Postgraduate School (NPS)
NRL:	U.S. Naval Research Laboratory (NRL)
NUOPC:	National Unified Operational Prediction Capability (NUOPC)
NVGI:	Previous NAVGEM Forecast Interpolated Ahead 6-hours
OA:	Opportunity Announcement (OA)
OAR:	Oceanographic and Meteorological Laboratory (OAR)
OCS:	Office of Coastal Survey (OCS)
OCD5:	Operational CLP5 and DSHF Blended intensity forecast: Simplest Statistical model for intensity (also called Decay-SHIFOR5)
OFCL:	Official National Hurricane Center Forecast (OFCL). The NHC uses a variety of models as guidance in preparation of their own forecast. The NHC issues its official forecast every six hours at 5 A.M., 11 A.M., 5 P.M., and 11 P.M. Eastern Daylight Time (0900, 1300, 1700, 2100 UTC).
OMITT:	Ocean Model Impact Tiger Team (OMITT)
OSE:	Ocean Observing System (OSE)
OSSE:	Ocean observing System Simulation Experiment (OSSE)
OSTP:	Office of Science and Technology Policy (OSTP)
OU:	Oklahoma University (OU)

ACRONYM:	**TITLE with Acronym and DESCRIPTION (optional):**
PAC:	Procurement, Acquisition, and Construction (PAC)
PI:	Physics Interoperability(PI) working group or Principal Investigator
PACOM:	Pacific Command (PACOM) in the United States
PBL:	Planetary Boundary Layer (PBL)
PO:	Program Office (PO)
POD:	Probability of Detection (POD)
POM:	Princeton Ocean Model (POM)
PPAV:	Post-Processing And Verification (PPAV) development
PSU:	Pennsylvania State University (PSU)
RDHPCS:	Research and Development High Performance Computer System (RDHPCS)
RI:	Rapid Intensification RI), An increase in 30 Knots/24 hours
RII:	Rapid Intensification Index (RII)
R_{MAX}:	Maximum Radius ($R_{MAX)}$
RSMAS:	Rosenstiel School of Marine and Atmospheric Science, Univ. of Miami (RSMAS)
RTOFS:	Real-Time Ocean Forecast System (RTOFS)
RW:	Rapid Weakening (RW)
SAB:	NOAA Science Advisory Board (SAB)
SAS:	Simplified Arakawa-Schubert (SAS) scheme (Pan & Wu, 1995)
SHIPS:	Statistical Hurricane Intensity Prediction System(SHIPS), a statistical-dynamical model based on statistical relationships between storm behavior and environmental conditions estimated from dynamical model forecasts as well as on climatology and persistence factors.

ACRONYM:	**TITLE with Acronym and DESCRIPTION (optional):**
SOO:	Science and Operations Officer (SOO) program
SPC3:	Six-member weighted SPICE ensemble using output from GFS, HWRF, and GFDL(SPC3) as input for DSHP and LGEM. The ensemble weights vary with forecast lead time.
SPICE:	Statistical Prediction of Intensity from a Consensus Ensemble (SPICE)
SST:	Sea Surface Temperature (SST)
STAR:	Center for Satellite Applications and Research (STAR)
STTP:	Stochastic Total Tendency Perturbation (STTP) scheme
TCLP:	Trajectory Climatology and Persistence Forecast (Track and intensity)
TCMT:	Tropical Cyclone Modeling Team (TCMT)
TDR:	Tail Doppler Radar (TDR)
TFLOPS:	Terra (x10^{15} FLoating points Operations Per Second (TFLOPS), used in performance measurement
TV15:	Track forecast ensemble including 2012 stream 1.5 forecasts (TV15)
TVCA:	Track Variable Consensus (TVCA) of at least two of AVNI, EGRI, EMXI, NGPI, GHMI, HWFI forecasts.
TVCE:	Variable Consensus (TVCE) of AVNI, EGRI, EMXI, NGPI, GHMI, GFNI, HWFI Model Track Forecasts
TVCI:	Variable Consensus (TVCE) of AVNI, EGRI, EMXI, NGPI, GHMI, GFNI, HWFI Model Track Forecasts (Interpolated 6-hours)
TVCN:	National Hurricane Center Track Variable Consensus (TVCN)
UEMI:	UKMET MOGREPS-G Ensemble Mean (Interpolated 6-hours)
UKMI:	United Kingdom Meteorological Office model, automated tracker, with 6-hour interpolation (UKMI)
UTC:	Universal Time Coordinated (UTC), Greenwich Mean Time (GMT), or Zulu Time Zone (Z). There is no time difference between all of these time zones.

ACRONYM:	TITLE with Acronym and DESCRIPTION (optional):
UWNI:	UW-NMS with 6-hour interpolation (UWNI)
UW-NMS:	University of Wisconsin Non-hydrostatic Modeling System (UW-NMS)
WCM:	Warning Coordination Meteorologist
WRF:	Weather Research and Forecasting (WRF) 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).
WW3:	Wave Watch 3 (WW3)
YSU:	Yonsei University physics scheme used in the WRF model
ZULU:	Zulu Time Zone (Z), Universal Time Coordinated (UTC) or Greenwich Mean Time (GMT). There is no time difference between all of these time zones.