Hurricane Forecast Improvement Project Annual Conference Executive Notes
January 11-12th, 2017
National Hurricane Center, Miami, FL

The Hurricane Forecast Improvement Project (HFIP) held at the National Hurricane Center (NHC) the second week of January 2017 had 73 participants (see last page) and 33 presentations. Vijay Tallapragada, Frank Marks, and Ed Rappaport shared opening remarks along with welcoming everyone aboard. Everyone was reminded of the meeting's purpose to develop a multiple year strategy on how to improve hurricane forecast numerical guidance and in achieving HFIP's overall goals.

HFIP 5-Year Goals

HFIP's 5 year goals were stated to have been completed, especially regarding intensity however, there were concerns raised about how to make further gains (NHC 2016 Forecast Preliminary Verification, James Franklin).

HFIP Priorities

In 2017, the HFIP Program Office focus is on (1) Scale-aware model physics, vortex initialization and DA, (2) Leverage Next Generation Global Prediction System (NGGPS) to maintain cross NOAA and community involvement, and (3) Implement an operational partnership for multi-model ensembles in all basins. In addition to continue to improving products for forecasters, goals for evolving hurricane forecast prediction were noted to include an emphasis on providing Global to Local (G2L) forecasts using multi-scale interactions, improving forecasts for land-falling storms/downstream applications, improving post-landfall precipitation forecasts, and to further develop nesting technology (F. Toepfer). In 2016, Dr. Vijay Tallapragada noted that G2L scale modeling and coupled Earth system modeling are in progress to be unified to transform NWP at National Centers for Environmental Prediction (NCEP).

Issues in 2016

General issues outlined early on in the conference were: rapid intensification (RI) failure (e.g., was *Matthew*), strong high bias prediction for Hurricane Weather Research and Forecasting (HWRF) weak storms, genesis prediction failures (*Hermine* and *Nicole*), and the Global Forecast System (GFS) Ensemble was under-dispersive and under predicted genesis, more in Eastern Pacific (EPAC) than the Atlantic (ATL), worse than European Countries (EC) and United Kingdom (UK) and the 5-day forecast was worse than the 2-day forecast. Additionally, single model ensembles were noted as not producing enough diversity and it was emphasized that model diversity must be maintained. In terms of HWRF performance, RI Probability of Detection (POD): False Alarm Rate (FAR) statistics appeared to show skewed distribution between best track intensity change and model; perhaps the cumulative distribution function (CDF) needs to be plotted in order to see median shift. It was also noted that 2016 GFDL Jet-based real-time runs could not continue in all basins (V. Tallapragada). In 2016, some noted major problems with HWRF appeared to be: inappropriate parameterization of in-cloud

turbulence generated by latent heating, radiative cooling, and evaporative cooling in the eyewall and rainbands. Since in-cloud turbulent mixing is directly linked to micro-physics, it can substantially affect the performance of microphysics and the radial transport/distribution of solid-phase hydrometeors, which was shown to be critical to TC inner-core structure change and intensification including RI (Ping Zhu-FIU; S. Gopalakrishnan, R. Black, & Frank Marks-AOML; Vijay Tallapragada-NCEP; & Jun Zhang, Xujing Zhang-NOAA).

Tracking Improvements

In 2016, the HFIP Corrected Consensus Approach (HCCA) model provided best track guidance and provided superior performance to the NHC consensus models. The HWRF Basin-scale (HB16) provided comparable forecast guidance for track to H216; slightly better in the ATL basin and nearly identical in the East Pacific (EPAC). HWRF upgrades at the Environmental Modeling Center (EMC) in vertical resolution (from 61 to 75 levels) have increased track forecasts greatly, especially out to 4-days and 5-days (A. Mehra). The Joint Typhoon Warning Center (JTWC) discovered big speed in errors in track, especially with Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). In the future, Ocean Model Impact Tiger Team (OMITT) plans to analyze Navy Coupled Ocean Data Assimilation (NCODA) assimilation impact on COMPS-Tropical Cyclone (TC) track and intensity study. DTC provided initial results in the Atlantic (ATL) basin showing promising results in both track & intensity (K. Newman). It was discovered that as compared with Geophysical Fluid Dynamics Laboratory model (GFDL), Hurricane Non-hydrostatic Multi-scale Model on B-grid (HNMMB) consistently showed improved performance for intensity and tracking skill for the North Atlantic basin (based on 2014-16 seasons). In terms of operational modeling in 2016, Avichal Mehra noted that land parameterizations were upgraded with higher resolution and land surface climatology. Improved track errors (new terrain and initialization) for COAMPS-TC (2016 version-NRL) were achieved as noted by Dr. J. Doyle, Dr. J. Moskaitis, et al. The Basin-scale HWRF Modeling system started using the NOAH Land Surface Model in 2016 (X. Zhang et al).

Intensity Improvements and Discoveries

Using the fully coupled Navy Coastal Ocean Model (NCOM), it was discovered when surface drag was changed, intensity prediction improved. HCCA provided the largest coefficients of intensity for HWRF and COAMPS-TC. HWRF Ensemble 2016 resultant findings revealed most low-spread deficient cases from 2014-2016 were characterized by intensification, and what caused low-variance in the ensemble spread appeared to be internal physics vs. environment. HWRF upgrades at EMC via increased vertical levels have significantly helped intensity forecasts over 24-hours (A. Mehra). HWRF performance indicates that the Eyewall Replacement Cycle (ERC) prediction appeared to improve. HWRF outperformed JTWC operations up to Day-3 in terms of intensity skill. HWRF Basin-scale (HB16) provided comparable forecast guidance for intensity to H216; slightly better in the ATL and nearly identical in the EPAC. In 2017, the plan for the Analog Ensemble (AnEn) is to develop intensity/intensity change with the track forecast system and HWRF reforecast data. In 2018, the plan is to develop structure based upon the *AnEn* system, with real-time testing. The NHC noted that HWRF-RI is a priority and HWRF weak storm over prediction needs to be addressed. The JTWC noted that RI is a high priority and is becoming an issue. In the future, research needs to

be conducted on the *Mathew* RI issue using test cases (e.g., *Hua* with the EMC). It was noted that in HWRF 2016, turbulent mixing is parameterized separately by the diagnosed PBL height. Above the PBL, the eddy exchange coefficient is calculated by equation, which was originally developed to represent the clear-sky free atmosphere diffusion. In the eyewall and rainbands, there is no physical interface that separates the turbulence generated by the surface processes and cloud processes (Ping Zhu, S. Gopalakrishnan, V. Tallapragada, J. Zhang. Et al). It was also discovered that intensities are better predicted by including reduced drag coefficients and sea-state dependent coupling process (A. Mehra, B. Reichl, et al). Dr. Frank Marks added that a NHC priority associated with RI is satellite DA. Other priorities were: HNMMB Guidance verification, HWRF weak storm over-prediction, GFS genesis/ensemble issues, and upgrades to statistical models (e.g., HCCA).

Model Initialization and Vortex Prediction Improvements (Spin Up/Down)

In 2016, progress made relative to spin-down, the data assimilation (DA)/Ensemble Team identified model spin-down issues using hybrid DA and in the future, plan to: (1) Replace CAtchment-based Hydrological Model Data Assimilation (CAHMDA-VI) with DA, (2) Continue Hybrid-DA pre-implementation system tests, spin-down issues, research and development (R&D) on HWRF Hybrid-DA (4DEnVar, hourly 3DEnVar, IAU) including hydrometers and HDOB, dropsondes, Geostationary Operational Environmental Satellite-R Series (GOES-R), and testing beyond single case-study; and (3) Need to get DA and Model Teams working together consistently. The HWRF DA testing and plan strategic priority for DA is to add inner-core dropsondes to improve forecasting spin-down, bias, and allow for greater data usage. Vortex relocation/initialization was integrated with 6-hourly hybrid DA in 2016 which improved TC analysis and later forecasts. High resolution analysis was produced through dual resolution hybrid DA improved structure analysis (Vmax) and intensity in terms of Mean Sea Level Pressure (MSLP) (Xuguang Wang). The Ensemble Products Tiger Team provided an extension of ATCF e-deck format to intensity change probabilities; expansion of MET-TC software to validate RO probabilities. In as far as model initialization improvements, The OMITT's Real-Time Ocean Forecast System (RTOFS) initialization showed improved guidance over Princeton Ocean Model (POM) initialization and the HWRF Basin-Scale was developed in an operational HWRF framework using MPI POM-TC initialization with RTOFS. In 2016 HWRF used RTOFS initialization for EPAC storms that improved RI forecasts. In terms of operational modeling the 2016 baseline integrated a new composite vortex to improve initialization (Zhan Zhang, Avichal Mehra, et al, HWRF Performance verification). HWRF/Hurricane Research Division (HRD) developed basin-scale MPI POM-TC initialization w/RTOFS, and improved Vortex Initialization (improved GSI DA). In recapping the 2016 HFIP Annual Workshop, Frank Marks noted GFS under-predicted genesis (more in EPAC than ATL; worse than EC and UK. 5-day; worse than 2-day). The DA Initialization/Ensemble development team used hybrid DA to identify model issues responsible for spin-down.

FIU, AOML, NCEP, reported from 2016 data results that a "*top-down*" pathway for prediction exists to Secondary Eyewall Formation (SEF) triggered by the penetrative downdraft resulting from the fall-out of lofted solid-phase hydrometeors at the far radii from the primary eyewall. Radial transport and distribution of solid-phase hydrometeors were shown to be one of the keys that can substantially affect the TC inner-core structure in HWRF simulations. Although the causing reason may vary from case to case, the incorrect radial transport of solid-phase

hydrometeors and the resultant distribution were noted as one of the culprits for HWRF not to simulate the observed SEF/ERC. In the eyewall and rain bands there was no physical interface that separated the turbulence generated by the surface processes and cloud processes.

The OMITT plans to evaluate observations using the Ocean Observing System (OSE)/Ocean Observing System Simulation Experiment (OSSE) to improve initialization. In recapping of the 2016 HFIP Annual Workshop, Dr. Frank Marks noted that the physics team needs to run more idealized runs in 2017. Dr. Marks added that the DA Team needed to be added in all physics evaluations to ascertain impacts on DA. In 2017 NRL's version of the COAMPS-TC effort will strive to improve spin-down and intensity error using a new vortex initialization with new C_D parameters (Doyle, Moskaitis, et al, NRL). In 2017 through 2018 The COAMPS-TC real-time Ensemble effort plans to use perturbed physical parameterization or other approaches to improve intensity forecast distribution (Moskaitis, Doyle, et al). Future efforts will use hybrid DA to identify HWRF model issues to improve intensity forecasts (e.g., spin-down for strong hurricanes). In 2017 The Ensemble Products Tiger Team plans to integrate Multi-system RI probabilities (<= 30 kt/24 hrs; 30 kt/24 hrs; etc.). The High Resolution Physics Tiger Team Report indicated that future efforts planned are RI/RW and storm structure (secondary eyewalls' & RMW). Jason Sippel and the EMC HWRF Team noted future DA and testing plans for 2016-2017 include integration of RI/RW, storm structure, and in 2017 to replace vortex initialization with self-consistent DA of something derived from TCVitals. Indiana University reported on the predictability limit of the HWRF Model efforts. More specifically, to determine intensity growth rate during RI and discover how the growth rate depends upon environmental factors and model perturbations. Christopher Rozoff noted that in 2017-2018 plans are to develop a structure based Analog Ensemble (AnEn) system.

Multi-Model Coupling

Improvements to Multi-model coupling in 2016 consisted of: (1) The OMITT coupled HNMMB to the HYbrid Coordinate Ocean Model (HYCOM) and Princeton Ocean Model (POM), and with HWRF-POM-Wave Watch III (WW3) coupling tests showed small improvements through fluxes, (2) Basin-scale HWRF completed *one-way* ocean coupling, (3) National Earth System Prediction Capability (ESPC) Coupled Earth system modeling to transform NWP at NCEP, (4) Full ocean coupling with the Navy Coastal Ocean Model (NCOM) improved model verification (fully coupled), and (5) At EMC in the 3-Way coupled atmosphere-wave-ocean (AWO) model, discovered that sea-state is dependent upon air-sea fluxes.

In the future, Basin-scale HWRF plans to retrospectively test ocean coupling over a 3-year period starting spring 2017 for potential research to operations (R2O). The EMC plans to conduct a full 3-year impact investigation of different mixing schemes for ocean coupling, and determine how HWRF upgrades impact maximum radius (R_{MAX}) bias. NHC plans to upgrade to statistical dynamic models, e.g., HFIP Corrected Consensus Approach (HCCA) model. In 2017, GFDL is retiring and being replaced by HNMMB, now named HMON and the 10-member HWRF/HNMMB to happen in 2018-2019. In 2019-2020, The NOAA Environmental Modeling System (NEMS) Global nests (NGGPS) is to be implemented (A. Mehra). From FY17 to FY22, there will be an effort to transition the Climate Forecast System (CFS) into the Finite Volume Cubed-Sphere Dynamical Core (FV3) - based Global Forecast System Analysis (GFSA) model

coupled to many Earth system components and strongly coupled DA (EMC, etc.) using National Unified Operational Prediction Capability (NUOPC) as a mediator. NUOPC is using parallel efforts to develop a Unified Global Coupled System and explore the scientific value of coupling systems for weather and sub-seasonal forecasts (V. Tallapragada). Another effort noted in the future is to implement Aerosol Forecast Capability (NGAC) into GFS and to implement the Whole Atmosphere Model (WAM).

Model and Ensemble Comparisons, Multi-Model and Operational Partnerships

In terms of model comparisons, the Experimental U.S. Navy COAMPS-TC Model Forecast using GFS initial conditions (CTCX) proved better than the U.S. Navy COAMPS-TC Model Forecast using NAVGEM initial conditions (COTC) and CTCX compared very well to HWRF performance where HWRF performed slightly better. The Coupled Multi Model High Resolution Ensemble (NOAA/Navy) and air-ocean coupling looked to be promising by NRL's COAMP-TC 2016 version effort. The JTWC used dynamical guidance consensus for wind radii with resultant findings that revealed global models have a slight high bias other than EC. Regional models are better (Sampson et al 2017, Wea. & Forecasting). In 2016 the JTWC noted that Global models improved significantly but still have uneven performance. The Ensemble Tiger Team discovered different models showed definite preferences for intensity change probability. More specifically, HWRF was uniform across intensity changes, GFDL was good for rapid weakening, and COAMPS was good in the middle of PDF. As noted earlier under issues, the GFS ensemble in 2016 was reported as under-dispersive. The Hurricane Nonhydrostatic Multi-scale Model on B grid (HNMMB)[1] runs uses HFIP resources; COAMPS-TC ensemble uses GFS and UKMet as parent models; 7d fcsts; 34 kt dynamic swath. Also, Ryan Torn (Univ. of Albany) reported that the real-time ensemble-based probabilities were submitted to the DTRC for the Demo project. The OMITT reported in 2016 they conducted HYCOM Impact analyses for HNMMB Testing and Evaluation (T&E), transitioned COAMPS-TC coupled to 3D ocean model NCOM (5 km), and is now operational at FNMOC for all ocean basins. NCEP/EMC noted 3-way (AWO) coupling was initiated in 2016 including sea-state dependent air-sea fluxes.

In the future, the NGGPS effort plans to explore Global Ensemble Forecast System (GEFS) needs using stochastic physics vs. number of members via a hurricane case study. NHC plans to continue the Ensemble Products Tiger Team. The NGGPS/FV3 effort plans to transform operational models for seamless forecasts of weather, hurricanes, subseasonal and seasonal climate. In 2017, it has been requested for HFIP to coordinate the Ensemble Products Tiger Team to evaluate/compare the Analog Ensemble (AnEn) with other models, and conduct real-time testing. The COAMPS-TC real time (RT) Ensemble effort during FY17-FY19 plans to continue contributing to the HFIP Multi-Model Ensemble effort (J. Moskaitis, J. Doyle, et al). NRL's COAMPS-TC 2016 version effort plans to in 2017 couple up with NCOM and 3 km ensemble with HFIP, WATL, EPAC, and WPAC11 members; and in 2018 to include ocean-wave coupling. The PPAV Team intends in the future to transfer the latest version of community tracker (GFDL tracker) to the HWRF group with the operational FY16 HWRF upgrade and to the DTC for community release. Also planned is to continue to maintain and provide support for the GFDL community TC Tracker (David Zelinsky, Mark DeMaria). The NCEP/EMC future plan is to conduct a full 3-year study to investigate impact of different mixing schemes for ocean

[1] HFIP Annual Conference-JTWC 2016 Review: *TC Activity Fcst Challenges & Dev. Priorities*, Brain Strahl

coupling. NEMS future plans include: (a) Basin-scale with multi-nesting configuration in NEMS with genesis adaptability, (b) Potential migration from NMMB to FV3-based Next Generation Global Prediction System (NGGPS) dycore under NEMS, (c) Redo retrospective runs with 2017 GFS data (plus ocean coupling plus other upgrades) to assess these improvements for final statistics before operational implementation (EMC), and (d) Check impact(s) on NHC consensus model tracks and intensity forecasts before operational implementation (NHC)

It was noted by Frank Marks that in 2017, the Ensemble Team needs NHC and JTWC to be involved in identifying ensemble products that improves forecast guidance, and questioned if this could be addressed by having a workshop. Dr. Marks recommended a bi-weekly presentation on this work in the next month to get feedback from NHC. Dr. Marks added the model team needs more evaluation of HNMMB to satisfy NHC, and asked if this should include physics and DA team evaluations. Dr. Marks also noted a transition plan is needed for Basin-scale HWRF working with the EMC. The Post-Processing And Verification (PPAV) Team needs to develop evaluation/ verification focused on weak storm/non-developing over prediction (e.g., Basin-scale HWRF), to upgrade to statistical dynamic models (e.g., HCCA), and to work with the Ensemble Team to provide NHC timely products to evaluate the multi-model ensemble for guidance.

DTC Activities

Testing and training activities with the DTC consisted of providing HWRF support/training. DTC also supported physics testing using Thompson microphysics evaluation - mixed - time step issues as well *Grill-Freitas* (G-F) cumulus evaluation in HWRF. Future DTC efforts noted were: (1) Ascertain impact on DA by adding a *DA Team* for all physics evaluations, (2) Integrate DTC physics development evaluation with EMC approach to physics evaluation as Dr. Sergio Abarca outlined, (3) Continue R2O potential through testing and evaluation (T&E) i.e, Physics advancement-Thompson and/or G-F schemes, and TC physics migration to NCEP's unified modeling system, and (4) Continue unified code management/maintenance and user/developer support (public release and active HWRF developers/HFIP Principle Investigators). It was noted that HWRF performance needs to be evaluated and verified focusing on weak storm over prediction and non-development over prediction themes. Christopher Rozoff noted that in 2017-2018 plans are to conduct real-time testing.

Code Development

Improvements to code development were noted that the HWRF code repository supports multi-storm capability and idealized HWRF upgrades.

AWIPS 2 Plans

Migration efforts in 2016 were: The JTWC contributed to Automated Tropical Cyclone Forecasting System (ATCF)-Advanced Weather Interactive Processing System II (AWIPS-2) transition development, and ATCF maintained core code, upgraded to 64-bit capability, and dedicated a full-time employee NCEP Central Operations (NCO) contractor to help support the ATCF to AWIPS migration effort (HFIP helped). Mark DeMaria emphasized ATCF is and has been a critical workhouse for NHC & JTWC for over 2 decades. In 2017 as an operational priority, to develop A/B deck import/export functions, continue development of the primary GUI for AWIPS2 capable of displaying track/intensity guidance from A/B decks, and acquire another contractor to support the ATCF to AWIPS2 migration effort to the Ops floor (B. Strahl). In 2018-2019 to provide potential capabilities in the AWIPS2 baseline, and provide JTWC support to accelerate development and incorporate DoD requirements. HCCA plans to test the impact of additional input models (e.g., GFDL to HNMMB, and evaluate techniques to stratify and match training forecasts based on current forecast characteristics). A future operational priority in operational modeling is to replace the operational hurricane wave model with the HWRF system (A. Mehra).

Product Issues and Improvements

Product improvements in 2016 were characterized advancements in TC-ensemble forecast system design and products. HWRF Basin-scale implemented a new web page and products (including real-time products generation), and ran HWRF Basin-scale in real-time for FY16 season. Multi-Model Regional Ensemble efforts resulted in development of *Wind Probability* and *Intensity Change* products. HWRF product developments were associated with MSG and AWIPS2. HWRF noted a large flux in intensity forecasts, initial spin up/down, track forecasts impacted by LBC, and over-forecast of intensity for INVEST storms. *Mathew* was used to study Secondary Eyewall development and spin-down in HWRF. It was noted by Dr. Ryan Torn that in 2016 development of real-time web page to plot probabilities was accomplished. Dr. Vijay Tallapragada added that the HFIP Webpage had 42,000 views with 9,000 unique users. In terms of operational modeling and a HWRF performance review in 2016 at NCEP, two new product developments were *MAG* and *AWIPS2*. New products for the COAMPS-TC RT Ensemble in 2016 consisted of: *Real-time (RT) 24h Intensity Change Probability*, *RT RI Probability*, *RT 10-member Wind Threshold Exceedance Probability*, *RT Track colored by Forecast Intensity*, and *Performance Statistics for ATL & EPAC* (Ensemble Mean Error vs. Ensemble Spread and Ensemble Control vs. Ensemble Mean). Also in 2016, the Basin-scale HWRF product website was re-designed and operated *RT HB16* (4 cycles daily). HWRF web product delivery was near real-time, and HB16 resolution was increased to 18-6-2 km. Timing of products were on par with HWRF (Products-HB16, HB15, GFS). In terms of ensemble development, Dr. Xuguang Wang reported advancement was made on TC ensemble forecast system design and product development. The PPAV Team Report (D. Zelinsky, M. DeMaria, et al) noted 2016 and future efforts would be to continue to develop NHC Graphical products (*new time of arrival 34 kt. winds*; updated TC graphical suite including pre-genesis modifications). Also in 2016, developments were Fix-position (F-deck) display and database editing tool (fix types are aircraft, analysis, microwave, radar, sat and scatterometer). The ESRL/GSD PPAV Team maintained the products webpage, made HFIP products page available on HFIP.org with GFS, HWRF & GFDL models, and made new links to HWRF-NNMB, NUOPC, etc.) on related links. The AOML

PPAV Team made diagnostic tools available for researchers thru contributed codes for evaluating future hurricanes. The ATCF update reported in 2016 that several NHC/CPHC text products transitioned to mixed-case (B. Samson, M. DeMaria, et al). In 2016 the JTWC employed HNMMB model runs using HFIP resources and the COAMPS-TC ensemble including GFS and UKMet as parent models producing *7-day forecasts* and *34 kt. Dynamical swath products* (Brian Strahl).

During FY17-FY18, the COAMPS-TC RT effort noted to continue product development; interfacing with forecasters at JTWC and NHC. The PPAV Team report noted in 2017 to continue Ensemble product development (Repeat Tiger Team Demo at NHC). The NCAR PPAV Team will continue to provide HFIP website support, database support and the HFIP display & Diagnostic system. The CIRA PPAV Team future effort is to develop a modern *common wind speed* and *p-surge probabilities framework* by June 30, 2017, and to develop *satellite databases for enhancement to SHIPS/RII/LGEM* (30Jun2017) to improve statistical models using consensus versions w/multiple-model and enhanced satellite data inputs. The ATCF update stated that in FY17, the primary graphic user interface (GUI) within AWIPS2 is under development to display track/intensity from A/B decks; and in FY18-FY19 the plan is to continue to be a HFIP contractor, with possible JTWC support to accelerate development and incorporate Department of Defense (DoD) requirements, and possible implementation of initial capabilities in the AWIPS2-baseline. Dr. Frank Marks noted that a NHC priority in 2016 and the future is to: work with the Tiger Team is to continue to develop products useful for forecast guidance. HFIP future priorities will be to: continue HFIP Webpage for graphics with PPAV Team inputs to sharpen relevant graphics, generate new ensemble products, to use HFIP supported projects to develop ensemble techniques supporting deterministic forecasts (pending budget availability and prioritization); develop more products, and provide additional evaluation of hi-res HFIP RT regional multi-model ensembles (V. Tallapragada). In the PPAV report it was stated that in 2017 the NHC Team is to provide *storm surge inundation data* vs. evacuation data product using 3 historical cases (30Sep2017), develop probabilistic surge ensemble products [*experimental probabilistic extratropical storm surge (PETSS)* model into AWIPS2]; and to continue in-house testing. It is planned in 2018 for PETSS to become operational.

Data Assimilation Improvements

Improvements in Data Assimilation (DA) for 2016 were characterized by the DA/Ensemble Team in the development of a new fully cycled GSI-hybrid DA system for HWRF, and advanced assimilation of existing or new observations using hybrid or EnKF. HWRF DA was reported to be undergoing dramatic advancements by Jason Sippel and the EMC HWRF Team. HWRF also improved vertical wind profile in the surface and PBL. In terms of operational modeling plans, Avichal Mehra reported in 2016 that HWRF increased vertical resolution to 75 levels to the 10-Hectopascal top with adjusted domain sizes (do2: 256x472, do3: 256x472 & H216:288x576); and assimilation of additional data (some GPS data, AMVs, & some radiances). In 2016 Basin-scale HWRF improved GSI DA resulting in improved Vortex Initialization. The DA Initialization/ Ensemble development team reported a new fully cycled self-consistent GSI hybrid DA system for HWRF was implemented and used hybrid DA to identify model issues responsible for spin-down. Basin-scale HWRF used Hybrid TDR DA and improved GSA DA Ops HWRF-H216) and in targeting the R2O transition in 2016, created a new development branch and completed ocean initialization merging; resulting in improved efficiency on the

completed multi-storm coupler. HWRF improved DA for all EPAC storms in FY16 and used new data sets for GSI (CrIS, SSMI/S, METOP-B changes). The OMITT reported to have completed development and evaluation of an optimal target ocean observation tool in NCODA. In 2016 GFDL's nested FV-GFS development effort supported 3 km resolution nesting with 95 vertical levels. Xuguang Wang noted in 2016 that the hybrid provided largest positive impact of the airborne radar data (TDR).

Futuristic endeavors reflect NGGPS plans to participate in the Joint Effort for Data Assimilation Integration (JEDI) DA effort. Future Basin-scale HWRF plans are to form an *Operational Implementation Transition Plan* and test on operational machine configuration and scalability. Additionally, in future activities Dr. Xuguang Wang (Univ. of Oklahoma) reported the HWRF self-consistent Ensemble Variation Hybrid DA System vortex initialization effort further extended capability of the fully-cycled, self-consistent GSI-based Hybrid DA system for HWRF to include 4D-IAU capability. Designed and conducted extensive experiments to investigate the best DA configuration (e.g., 4DEnVar vs. Hourly w/out IAU; full vs. dual res hybrid DA). Dr. Wang added plans are to extend the hybrid DA system to update hydrometeors, if additional funding is available. Additional plans are to systematically explore the impact of aircraft data on the analysis, deterministic and ensemble forecasts of the TCs by using the best configuration of the newly extended hybrid DA system for HWRF. Lucas Harris and the GFDL FV3 Team reported that higher-resolution land model inputs will be integrated. In FY17 HWRF planned upgrades include High Density Observations (HDOBS) DA (Jason Sippel's presentation). Fully cycled EnKF 2-way hybrid DA when TDR data available (Warm Start for ATL and EPAC). In the future, more data will be used that should lead to forecast intensity improvements. Long term plans are to allow for greater data usage, continue to develop the 4D-Hybrid w/IAU., assimilate new data like GOES-R AMVs, cloudy radiances, inner-core dropsondes, and coupled atmospheric-ocean DA. Dr. Frank Marks noted the DA Team needs to work with model teams to solve the spin-down issue and focus should be with the operational HWRF system.

The COAMPS-TC effort by NRL reported plans in 2017 are to integrate ocean DA with NODA and in 2018 to integrate 4D-Var/EnKF, satellite DA, and ocean waves coupled DA. Also in 2018, NGGPS will prioritize satellite DA and ocean-waves-coupled DA. The Ensemble Development Team reported plans in 2017 are to integrate systematic pre-implementation tests of the hybrid DA system, replace VI with DA, and continue R&D on HWRF hybrid DA. The best DA-Configurations (4DEnVar, hourly 3DEnVar, IAU, blending or not) were recommended for consideration. Also, recommended was to further develop HWRF hybrid DA to include hydrometeors and to use hybrid DA to research spin-down issues for strong hurricanes (meaning to coordinate between DA and physics). Advancement of assimilation of existing or new obs using hybrid or EnKF is also planned. In 2018, the NGGPS/FV3 effort plans to adapt GSI to FV3, and include GOES-R JPSS DA, NCEP coupled hybrid DA Model Ensemble (Atmos-Aerosols, Land using Inline Noah Land Model, Wave using WW3, and Sea-Ice-Ocean). In 2019, Vijay Tallapragada noted coupled DA development and scientific evaluation (JEDI-2019) will be pursued. Also plans are to continue development of ensemble capabilities in NEMS and have DA on the FV3 Grid. The OMITT reported plans are to continue R&D on air-sea stress and targeting ocean and wave observations, implement DA to the HYCOM ocean component, and to implement coupled DA.

Physics Improvements

In 2016, improvements to physics were characterized by the Model Physics Team: (1) Ensured observations were consistent with model physics upgrades, (2) Utilized understanding of storm structure and observations to evaluate model improvements, and (3) *Incorporated scale-aware physics*, and (4) Maintained alignment with global models. NGGPC emphasized improved representation of the physical processes at all spatial and temporal scales. NGGPS noted that the Finite Volume Cubed-Sphere Dynamical Core (FV3) was approved as the interoperable physics driver (IPD) package. NGGPS emphasized improved representation of physical processes at all spatial/temporal scales, and unified *G2L scale modeling*. Multi-Model Regional Ensemble efforts ran the HWRF ensemble with results being the same as FY15 plus larger D02 and D03 and *scale-aware convection* in D03. The COAMPS-TC effort ran comparable cases to HWRF but it was not clear how much overlap existed. The Global Forecast System Initial Condition/Boundary Conditions (GFS IC/BC) improved performance. NCEP noted that in 2016 performance verification, HWRF upgraded to the scale-aware Simplified Arakawa-Schubert (SAS) convective scheme. The Basin-scale HWRF Modeling system in 2016 used the scale-aware SAS convective Ferrier-Aligo scheme in high resolution. EMC continued to use scale-aware physics and plans to do so in the future (Sergio Abarca). The DTC is testing scale-aware physics and aerosol-aware physics in HWRF using the Grell-Freitas (G-F) scheme. The High-Resolution Physics Tiger Team reported plans to maintain performing global model alignment and implemented the G-F Convective scheme in HWRF (Grell & Bao, NGGPS) i.e. Scale-aware/Aerosol-aware (G-F, 2014) (Sergio Abarca, EMC). GFDL reported that FV3 supports grid stretching and 2-way grid 3 km nesting (Lucas Harris, GFDL FV3 Team). DTC noted in the future that R2O can be potentially achieved through T&E physics advancement (Thompson and/or G-F schemes), and support migration of TC physics into future unified modeling system at NCEP.

In the future, operational modeling plans are to update the Ferrier-Aligo (F-A) microphysics, PBL/EDMF and scale-aware SAS schemes (DTC, Sergio). It was further noted by Dr. Abarca that part of the physics strategy is to maintain alignment with global models. The Model Physics Team plans to: (1) Adopt stochastic approaches, (2) Address identified model biases RI/ Rapid Weakening (RW), size, microphysics, ERC, R_{MAX}, structure, air-sea interface, (3) Provide a framework supporting realistic physics scheme development for model upgrades to evolve beyond model evaluation by 3 numbers (e.g., PBL scheme changes led to improved ERC), and (4) Continue incorporating scale-aware physics, maintaining alignment with global models. The NGGPS effort will continue to develop the FV3 based GFS in operations quarter (Q3) FY18, FV3 GEFS in FY19, and become NEMS compliant spectral GFS in FY17. In 2018, *COAMPS*-TC will prioritize Planetary Boundary Layer (PBL) fluxes, microphysics 4D-Var/EnKF, and the stochastic physics ensemble. In terms of HWRF Performance, it was expressed there is need to research the *Mathew* RI issue using test cases (e.g., *Hua* with the EMC) and how the Hurricane Ensemble Data Assimilation System (HEDAS) performed as well with this issue. It was also noted that HFIP needs to focus attention to the *Mathew* RI issue (initialization and physics). COAMPS-TC plans to use stochastic physics in 2018. The High Resolution Physics Tiger Team reported plans to continue to incorporate scale-aware physics, integrate microphysics higher moment (or species advection), and adopt stochastic approaches (Sergio Abarca). In the future GFDL plans to use nested FV-GFS development and to use scale-aware SAS or Univ. of

Wisconsin (UW)-GFDL convection, Thompson, Ferrier, or M-G Microphysics in collaboration with Univ. of Oklahoma-CAPS and EMC), Yonsei University (YSU), Eddy-Diffusivity/Mass-Flux (EDMF), or Mellor-Yamada (MY)-Type PBL schemes (Luca Harris, GFDL FV3 Team). In recapping of the 2016 HFIP Annual Workshop, Dr. Frank Marks noted that the physics team needs more work on the model bias in 2017.

Model Resolution Improvements

Model resolution improvements in 2016 were described as *Basin-scale HWRF* operated HB16 in real-time with increased resolution to 18-6-2 km. Also, HWRF upgraded/increased vertical coverage from 61 to 75 levels affecting nest sizes, PBL changes led to improvements, and microphysics adjusted to remove high reflectivity bias in ice, initialization and from new data sets. HWRF also increased the size of nested domains with smaller time steps, upgraded to WRF3.7.1a; and underwent Testing and Evaluation (T&E) with the new 2016 4D-Hybrid GDAS/GFS/BC.

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Acronyms

AOML	Atlantic Oceanographic and Meteorology Laboratory
ATL	Atlantic basin
ATCF	Automated Tropical Cyclone Forecasting System
AWIPS	*Advanced Weather Interactive Processing System*
AWO	Atmosphere-Wave-Ocean model
BC	Boundary Conditions
CFS	Climate Forecast System
COAMPS	Coupled Ocean/Atmosphere Mesoscale Prediction System
DA	Data Assimilation
DTC	Developmental Testbed Center
EPAC	East Pacific basin
ERC	Eyewall Replacement Cycle
EMC	Environmental Modeling Center

[2] Speaker(s)

Acronyms (Continued):

F-A	*Ferrier-Aligo* microphysics scheme
F-Deck	Fix-position deck
FV3	Finite Volume Cubed-Sphere Dynamical Core
G2L	Global to Local
G-F	*Grill-Freitas* physics scheme
GFDL	Geophysical Fluid Dynamics Laboratory
GFS	Global Forecast System
GOES-R	Geostationary Operational Environmental Satellite-R Series
GSI	Gridpoint Statistical Interpolation
GUI	Graphics User Interface
HCCA	HFIP Corrected Consensus Approach
HEDAS	Hurricane Ensemble Data Assimilation System
HFIP	Hurricane Forecast Improvement Project
HNMMB	Hurricane Non-hydrostatic Multi-scale Model on B grid
HWRF	Hurricane Weather Research and Forecasting
HYCOM	HYbrid Coordinate Ocean Model
IAU	Incremental Analysis Update
IC	Initial Condition
IPD	Interoperable Physics Driver
JEDI	Joint Effort for Data Assimilation Integration
JTWC	Joint Typhoon Warning Center
NCO	NCEP Central Operations
NEMS	NOAA Environmental Modeling System
NHC	National Hurricane Center
NGGPS	Next Generation Global Prediction System
NUOPC	National Unified Operational Prediction Capability
OMITT	Ocean Model Impact Tiger Team
PPAV	Post Processing And Verification
PBL	Planetary Boundary Layer
POM	Princeton Ocean Model
R^2O	Research To Operations
R_{MAX}	Maximum Radius
R&D	Research and Development
RI	Rapid Intensification
RTOFS	Real-Time Ocean Forecast System
RW	Rapid Weakening
SAS	Simplified Arakawa-Schubert scheme (Pan & Wu, 1995)
SEF	Secondary Eyewall Formation
T&E	Testing and Evaluation
TC	Tropical Cyclone
TCVitals	Tropical Cyclone Vitals
WPAC	West Pacific basin
WW3	Wave Watch III