Improved global tropical cyclone forecasts from NOAA: Lessons learned and path forward

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Rapid Progress in Hurricane Forecast Improvements

Key to Success: Community Engagement & Accelerated Research to Operations

Operational Hurricane Modeling System Development

- R&D: Public/Private Partnerships
- Enabling O2R and R2O Infrastructure
- NCEP/EMC
- HFIP/DTC

Transition to Operations: Implementation of Model Improvements

Continue the community modeling approach for accelerated transition of research to operations

Effective and accelerated path for transitioning advanced research into operations

International partnerships for accelerated model development & research
Significant improvements in Atlantic Track & Intensity Forecasts

Improvements of the order of 10-15% each year since 2012

What it takes to improve the models and reduce forecast errors???

- Resolution
- Physics
- Data Assimilation

Targeted research and development in all areas of hurricane modeling
Lives Saved

Only 36 casualties compared to >10000 deaths due to a similar storm in 1999

- **1999 Orissa Cyclone**
  - Deadliest storm since 1971
  - 155 mph winds and 8m (26 ft) storm surge at landfall
  - 10000 causalities, damages $5 Billion USD
  - Operational NWP at IMD based on 24-hr forecasts from NCEP QLM
  - Accurate 48-hr forecast lead time for tracks, no skill for intensity forecasts
  - Inadequate guidance on storm surge, rain & flood

Advanced modelling and forecast products given to India Meteorological Department in real-time through the life of Tropical Cyclone Phailin
A reflection on Collaborative Efforts between NWS and OAR and international collaborations for accomplishing rapid advancements in hurricane forecast improvements

**NWS:** Vijay Tallapragada; Qingfu Liu; William Lapenta; Richard Pasch; James Franklin; Simon Tao-Long Hsiao; Frederick Toepfer

**OAR:** Sundararaman Gopalakrishnan; Thiago Quirino & Frank Marks, Jr.
Advanced Research to Operations Transitions

Accurate representation of storm structure using advanced DA methods

Collection, transmission and assimilation of inner core hurricane observations using Tail Doppler Radar directly from NOAA’s P3 aircraft

HWRF is the only model in the world assimilating real-time hurricane inner core Tail Doppler Radar (TDR) data from NOAA’s P3 aircraft
New in 2015 for HWRF in Operations

➢ System & Resolution Enhancements
  ▪ Replace current partial HWRF python based scripts with complete Python based scripts for a unified system
  ▪ Increase the horizontal resolution of atmospheric model for all domains from 27/9/3 to 18/6/2 km.

➢ Initialization/Data Assimilation Improvements
  ▪ Upgrade and improve HWRF vortex initialization scheme in response to both GFS and HWRF resolution increases
  ▪ Upgrade Data Assimilation System with hybrid 40-member HWRF-based high-resolution ensembles and GSI system.

➢ Physics Advancements
  ▪ Upgrade Micro-physics process (Ferrier-Aligo); replace GFDL radiation with RRTMG scheme including sub-grid scale partial cloudiness; Upgrade surface physics and PBL, replace current GFDL slab model to more advanced NOAH LSM.

➢ First time in 2015….
  ➢ Self cycled HWRF ensembles based warm start for TDR DA
  ➢ Expand HWRF capabilities to all global (including WP/SH/IO) basins through 7-storm capability in operations to run year long
# HWRF Upgrade Plan for 2015 Implementation

## Multi-season Pre-Implementation T&E

<table>
<thead>
<tr>
<th>Description</th>
<th>GFS Upgrades</th>
<th>Model upgrades</th>
<th>Physics and DA upgrades</th>
<th>Combined</th>
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<tr>
<td>Control (H15Z)</td>
<td>Baseline (H15B)</td>
<td>NOAH LSM (H15W)</td>
<td>RRTMG/ PBL/ Surface Physics (H15W)</td>
<td>DA* (H15T)</td>
</tr>
<tr>
<td>Create a new control configuration of 2014 Operational HWRF run with newly upgraded GFS T1534 IC/BC</td>
<td>1. Resolution increase: 18/6/2km w/ same domain size; 2. Python scripts 3. New GFS T1534 4. Init improvement, GFS vortex filter</td>
<td>NOAH LSM (w/ Ch cap over land)</td>
<td>Separate species, w/o advection</td>
<td>Hybrid GSI/ HWRF- EPS based DA</td>
</tr>
<tr>
<td><strong>Cases</strong></td>
<td>Four-season 2011-2014 simulations in ATL/EPAC, cases (~2300)</td>
<td>Four-season 2011-2014 simulations in ATL/EPAC, cases (~2300)</td>
<td>Priority cases</td>
<td>Priority cases</td>
</tr>
<tr>
<td><strong>Priority cases</strong></td>
<td>Only TDR cases for 2011-2014</td>
<td>Four-season 2011-2014 simulations in ATL/EPAC, cases (~2300) WP/SH/IO 2013-2014 (~1200 cases)</td>
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<tr>
<td><strong>Platforms</strong></td>
<td>Jet/WCOSS</td>
<td>Jet</td>
<td>WCOSS</td>
<td>Jet/Zeus</td>
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<td>Jet/WCOSS/Zeus</td>
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</tbody>
</table>

*3x computer resources within the HWRF operational time window.*
2015 HWRF: Further improvements in the Hurricane Intensity Forecasts in All Basins

Retrospective forecasts for 1147 cases in the North Atlantic
881 cases in the Western North Pacific
The Threat

- 26 WPAC TCs ytd (+ 2 cross-over)
  - 26 TCs by 1NOV is climatological average
- Eastward shift of WPAC genesis area
  - Eight 40+ warning TCs
- 8 WPAC Super Typhoons
- IO at climatological avg (5)
- SHEM just below avg (25/27)
Real-time Operational Configuration for 2015 HWRF
Highlights of 2015 HWRF

Intensity Forecast Skill
2015 Atlantic Basin

Skill Relative to Decay-SHIFR5 (%)

Forecast period (h)

(Number of Cases)

OFCL
HWFI
GHMI
DSHP
LGEM
IVCN

197 177 154 130 91 63 44
12 24 36 48 72 96 120
Have the models improved in the past decade?
Improved Modeling of Hurricane Dynamics, Physics, and Air-Sea-Wave-Land Interactions

- Hurricane Katrina reminds us of critical and complex interactions between atmosphere, ocean, waves and land – all need to be accurately represented in numerical models for improving the forecast guidance

- NCEP Operational HWRF has demonstrated significant progress in improving the forecasts for high-impact events like Katrina

- Future efforts will continue with emphasis on high-resolution solutions for further improvements in hurricane intensity forecasts
High-Resolution HWRF Forecasts for Hurricane Andrew
New Products from 2015 HWRF

WPC QPF Issued on 00Z 16th June 2015 for TS Bill
Track error with JMA forecast

Intensity error

Bias
Verifying Rapid Intensification Forecasts from NCEP Operational HWRF

- Significant RI predictability skill first demonstrated in the Western North Pacific basin
- RI Skills are much lower in the Atlantic and Eastern Pacific basins

Conditions for triggering Rapid Intensification in HWRF Model

- Phase-Lock Mechanism for RI Onset
- High POD and Low FAR compared to other models

Structure of HWRF Model Storms at Extremely Strong Intensity Stage

- Development of Double Warm Core Structure for intense TCs
- Possible connections with warmer stratospheric air

Scientific Challenges for improved tropical cyclone RI forecasts

- HWRF is good at developing SEFs but not ERCs
- Role of advanced scale-aware physics for more accurate representation of physical processes for RI events
Improvement in RI Forecasts: North Atlantic and Eastern Pacific Basins

- **North Atlantic Basin**
  - **POD=4.8%**
  - **FAR=0.6%**

- **Eastern Pacific Basin**
  - **POD=44.4%**
  - **FAR=0.7%**
PDF Comparison of HWRF Predicted Intensity and Observed Intensity
PDF Comparison of HWRF Predicted 24h Intensity Changes and Observed 24h Intensity
Verification of RI in the HWRF model
Western North Pacific basins

POD = \frac{53}{53 + 184} = 22\%
FAR = \frac{44}{53 + 44} = 45\%

POD = \frac{4}{4 + 90} = 4\%
FAR = \frac{0}{4 + 0} = 0\%

POD increased to 36% with 2km 2015 HWRF
HWRF Forecasts for 2013-2014 Western Pacific STYs

For the six Super Typhoons (STYs) in 2013-2014 (17W USAGI, 26W FRANCISCO, 28W LEKIMA, 31W HAIYAN, 11W HALONG and 19W VONGFONG), HWRF track and intensity forecasts are the best, with close to zero intensity bias and significantly lower intensity errors.
HWRF in 2013 West Pac: Typhoon Soulik

Performance of Operational HWRF for Typhoon Soulik with accurate track, intensity, structure, rainfall and RI forecasts

- Formed: July 7, 2013
- Dissipated: July 15, 2013
- Highest winds 10-minute sustained: 185 km/h (115 mph), Lowest pressure: 925 mb
- Fatalities: 11 total
- Damage: USD $557 million
- Areas affected: Ishigaki Island, Batanes, Taiwan, Fujian, Zhejiang, Jiangxi, Guangdong

The most powerful storm of 2013: Super Typhoon Haiyan

Accurate track forecasts including from HWRF

Models showed intensification trend, but failed to match the RI magnitude despite impressive structure predictions from HWRF including distinct double warm core at peak intensity.
RI Forecasts for all storms in the WPAC Basin in 2013

HWRF captured RI for all 10 Super Typhoons of 2013

Typhoon Soulik (07W), Utor (11W), Usagi (17W), Pabuk (19W), Wutip (20W), Danas (23W), Nari (24W), Francisco (26W), Lekima (28W), Krosa (29W), and Haiyan (31W).
78-hr HWRF Forecast location and intensity valid at 00Z 28 March 2015 for Typhoon Maysak

Observed intensity: 140 kts
78-hr Predicted intensity: 120 kts
Real-time Forecasts from HWRF: 60hrs before pass over Chuuk State and 84hrs before reaching Category 5
78-hr HWRF Forecast location and intensity valid at 00Z 13 March 2015 for TC Pam

Observed intensity: 140 kts
72-hr Predicted intensity: 141 kts
High-Resolution Animations of Simulated Radar Reflectivity, IR Imagery and accumulated rain swath for Tropical Cyclone PAM

60-hrs before reaching category 5 of Tropical Cyclone PAM: HWRF (red), GFS (blue) and Best Track (Black)

_Tropical Cyclone PAM captured by the HWRF outer domain_
What Triggers RI in HWRF Model?

Phase-lock between warm core, storm strength and mid-level moisture at RI Onset

Of all ~100 real-time RI cases in the WPAC from HWRF we analyzed, the phase-lock mechanism is observed in all of them at the time of RI onset.

Phase-lock conditions are necessary but not sufficient for triggering the RI. Interactions with dry air, topography etc. could prevent the model to experience RI even after possessing the phase-lock conditions.

All idealized exps show a consistent structure at the onset of RI including a warm core at 500-300 hPa, a saturated core from surface to ~ 500 hPa, and sufficient tangential wind (> 18 ms^-1)
Phase-Lock not sufficient for RI: Influence of external factors: Land interaction

Phase-lock mechanism seen in non RI events as well – however, RI was not imminent for several cases due to “external” factors (here, it is land interaction for Typhoon Man-Yi 16W, 12Z Sept. 13, 2013)
Difficulties in RI Prediction: Role of initial intensity

HWRF fails to predict RI when the initial storm is >hurricane strength

Vertical cross-sections of (a) tangential wind (ms-1); (b) relative humidity (shaded %) and specific humidity (contours, g/kg) and (c) temperature anomaly (shaded, K) and absolute temperature (contours, K) for the mature state of Super Typhoon Usagi (17W) after 48-h into integration, initialized at 0000 UTC 19 September 2013.
Additional findings from HWRF on Rapid intensification

Triple eye-wall formation and subsequent eye-wall replacement for Typhoon Usagi (insufficient temporal frequency of output)

Asymmetric RI for H. Earl matching observed findings from NOAA P3 TDR

Phase-locking mechanism and Double warm core
Question: Is DWC a realistic phenomena?
Persistent double warm core structure for all STY cases during 2012-2015 seasons

Strong upper-level inflow above the typical outflow layer

Radial wind inflow (shaded, ms⁻¹)
**Hypotheses**

- **Hypothesis 1**: At high intensity ($V_{\text{max}} > 65$ ms$^{-1}$), the lower stratosphere can interact with TCs and produce a DWC structure, allowing TCs to further strengthen and maintain their high intensity.

- **Hypothesis 2**: The lower stratosphere can moderate the distribution of intense TCs and thus play a significant role in the TC-climate relationship.
Case study: DWC structure

3D cross section at 72-hour of Francisco initialized at 1200 UTC 17 July 2013,

Upper level inflow (UIL) is wide spread and is above the outflow (at 75hPa)
Case study: UIL-induced warming tendency

UIL could induce a substantial amount of warm advection from the lower stratosphere toward storm center;

\[ \text{adv} = -(u \frac{\partial \theta}{\partial r} + \omega \frac{\partial \theta}{\partial p}) \]
Low stratosphere: NATL/WPAC 2013

WPAC: more TCs with double warm core??? How about the higher MPI with colder outflow temperature? NATL: less TCs with no double warm core
The DWC structure may go outside the traditional framework of a TC with a single warm core.

Distribution of intense TCs should take into account the lower stratosphere beyond the outflow temperature;
Can we see DWC from AMSU data?

- 50 km resolution from ATMS AMSU data is too coarse to resolve the DWC;
- AMSU channels 5, 6, 7, 8 appear to be insufficient to resolve the gap between 2 warm cores;
Can we see DWC from AMSU data?

The same DWC structure vanishes, using the thinning method for 50-km resolution (Stern and Nolan 2012)

DWC visible in high resolution idealized and real-time simulations
Secondary Eyewalls and Eyewall Replacement Cycles: New research frontiers for TC intensity

SEs are a common feature of intense storms

Not in mesoscale simulations!

~6% in AHW

~30% in HWRF

Why?

Hawkins and Helveston (2008)
Precipitable Water (PW)

Secondary eyewall
Formation in the simulations
Observations

- Description of structures
- Evaluation of numerical simulations

Abarca and Corbosiero (2015)
WRF

Typhoon Sinlaku (2008)

model/observation- consistent dataset

Wu et al. (2012)
Supergradient flow during SEF

\[
\frac{u}{t} = \frac{u}{r} \frac{u}{u} \frac{w}{z} \frac{u'}{r} \frac{w'}{z} + \frac{v^2}{r} + f\nu + \frac{1}{r} \frac{p}{r} + F_u
\]
Edouard (2014)

Secondary eyewall observed in
✓ Nature
✓ HWRF 2015

Operational HWRF generates secondary eyewalls but they are rare, as in other mesoscale models (ARW or RAMs)
Typhoon Seminar

JMA, January 6, 2016

HWRF 2015 Real time: TC Intensity Vmax
Storm: SOUDELOR (13W) valid 2015073112

Tangential wind

Pressure (hPa)

Radial distance (km)

SOUDELOR 13w, z33, Azimuthally averaged, 2015073112, 96 h FCST
Tangential wind (contour), Min=-12,0586, Max=119,383 kts

HWRF SSMIS 91GHz: SOUDELOR 2015073112_f96

Storm Center: (19.2N, 223.4W)
Forecast Valid: 12004AUG2015
Intensity: 92kts

Reflectivity from the Guam radar on 8/03 0000 UTC
HWRF 2015
Edouard (2014)

Need to address what controls storm growth
Secondary eyewalls

It is now established that HWRF is capable of generating secondary eyewalls

Now assessing:

- How well HWRF captures secondary eyewall characteristics
  - Duration
  - Radial position
  - Azimuthal average kinematic structure of the storm
RMW ~ 2x!!

Hurricane Edouard: 10m Wind Speed (ms\(^{-1}\))

Valid: September 15\(^{th}\) 18Z

OBSERVATIONS

HWRF (t=0)
Does initial size matter?

HWRF 2015, Valid 15 Sept, 1800
HWRF 2015, Valid 15 Sept, 1800
Hurricane Edouard: Surface Latent Heat Flux (Wm$^{-2}$)

Valid: September 15th 18Z

OBSERVATIONS

HWRF (t=0)
Preferential treatment of heat fluxes
Advanced Research Findings from HWRF Model

Sudden weakening of Hurricane Guillermo (2015)

Rapid weakening and a new “hook” Feature triggering sudden demise

Vertical wind shear (VWS) and dry air intrusion weaken the storm by tilting the warm core

Downdrafts associated with dry intrusion generate a local warm core leading to formation of MSLP hook pattern

HWRF model is providing new opportunities to explore tropical cyclone dynamics and intensification
Rapid Weakening: New findings
Narrow wavenumber 1 asymmetry
Presence of hook feature in several storms……

VERy much so  somewhat

- Guillermo (2015 09E) – most cycles after 2015073000
- Maysak (2015 04W) - 2015041112
- Higos (2015 02W) - basically every cycle
- Amanda (2014 01E) - any cycle after 2014052312
- Vance (2014 21E) - there are hints of it in many cycles, but it gets worse after 2014110306
- Eduoard (2014 06L) - maybe, not a priority case, could be ET as well
- Fay (2014 07L) - cycles beginning with 2014101106, could be ET later
- Bertha (2014 03L) - 2014080400-2014080412 and maybe a few around those
- Hagupit (2014 22W) - 2014120306-2014120406 (after this forecasts took it over land)
- Tapah (2014 06W) - 2014042718-2014042900
- Faxai (2014 03W) - looks like a few cycles starting with 2014022218, but not as clear
- Ana (2014 02C) - 2014101700-2014101900 (before this land interaction with Hawaii)
- Francisco (2013 26W) - 201302200-201302418
- Lorenzo (2013 13L) – 201302118-201302218
- Jerry (2013 11L) – 2013092900-2013092906
- Gabrielle (2013 07L) – 2013091112
RW and SLP hooks by VWS and Dry Intrusion

- VWS and dry intrusion weaken the storm
- Downdrafts generate a local warm core => slp/hgt hooks
  - Dry intrusion related downdraft
  - Environmental VWS related downdraft
  - Compensational downdraft associated with strong convections in eyewall and rain bands
- VWS can also tilt storm warm core, resulting in slp/hgt contour hooks/curves
Physics Strategy: Parameterization development general direction

To improve HWRF performance, with regard to:
– Track and intensity guidance
– Physically based criteria
  » Rapid intensification
  » Secondary eyewalls
    • Formation, evolution and kinematic characteristics
      » Any other identified model bias
• Scale aware
  – To allow unified physics across model scales and applications

• Stochastic physics
  – To account for uncertainty, and variability in nature
Verification Issues

Model development strategies critically depend on verification results.

Observational uncertainty can be dealt with, but differences in various best track data can hurt evaluation procedures (and future model developments).
JTWC’s best track
JMA’s best track

**Track error with JGSM**

**Intensity error**

**Track error without JGSM**

**Intensity bias**
JTWC Vs JMA peak intensity difference

2013 Hurricane season

VMAX Difference of (JTWC-JMA) (kt)

SONAMU SHANSHAN YAGI LEEPI BEBINA RUMBA SOLIK CIMARON JEBI MANGKHUT UTOR TRAMI THIRTEEN KONG-REY TOKAJI MAN-YI USAGI EIGHTEEN PABUK WUTIP SEPAT FITOW DANA NARI WIPHA FRANCISCO TWEENTY-SEVEN LEKIMA KROSA THIRTY HAIYAN PODUL
JTWC Vs JMA peak intensity difference

2014 Hurricane season

VMAX Difference of (JTWC-JMA) (kt)

KAJIKI
FAXAI
FOUR
PEIPA
TAPAH
HAGIBIS
NEOGURI
RAMMASUN
MATMO
HALONG
NAKRI
FENGSHEN
FOURTEEN
KALMEGI
FUNG-WONG
KAMMURI
PHANFONG
VONGFONG
NURI
SINLAKU
HAGUPIT
JANGMI
JTWC Vs JMA peak intensity difference

2015 Hurricane season
JTWC Vs JMA peak intensity comparison during 2013-2015

JTWC = 1.7805*JMA - 32.545

JTWC=JMA
Track and intensity statistic plots of Western Pacific Basin (with GRAPEs) compared with JTWC best track data
Track and intensity statistic plots of Western Pacific Basin (with GRAPEs) compared with CMA’s best track data.
HFIP Experimental Regional Ensemble Prediction System in 2015

High-Resolution HWRF based Ensembles for Hurricane Forecasts at NATL
Advanced probabilistic guidance with representation of forecast uncertainty

- 20-member 3km HWRF ensembles driven by GEFS for IC/BC and stochastic convective and PBL perturbations
- High-resolution probabilistic products provide forecast uncertainty in track, intensity, structure (size) and rainfall, along with ensemble mean products
Planned HWRF Model improvements for 2016 hurricane season

- **Dynamic and Baseline Upgrades**
  - 2016 GFS upgrade for boundary and lateral boundary conditions
  - WRF-NMM dynamic core upgrade: V3.7.1a; Retaining non-hydrostatic state when nests move
  - Integration time step increase, 38+4/7s to 30s;
  - Support up to eight storms in operations

- **Physics upgrades**
  - PBL upgrades, align with latest GFS EDMF PBL scheme,
  - Microphysics upgrades, Adveccted Ferrier-Aligo or Thompson scheme;
  - Scale-aware convection scheme: Grell-Freitas scheme or GFS SAS;

- **Ocean/Wave Coupling**
  - ATMOS/Ocean/WAVE three-way coupling Intended to improve air-sea exchange coefficients and mixing in the oceanic upper layer
  - **Ocean model upgrades: MPIPOM or HYCOM for all ocean basins including WPAC**

- **Data Assimilation**
  - HWRF ensemble based background covariance for all basins for observations
  - Increment Adjustment Upgrade (IAU) to avoid initial spin up/down

- **Additional Products**
  - New grid for MAG and AWIPS;
  - Sustained wind swath
Forecast verification for WPAC with ocean coupling

HWRF: Operational HWRF for WPAC without ocean coupling
HPAR: HWRF for WPAC with ocean coupling

Chan-Hom 09W
Nangka 11W
Soudelor 13W
Goni 16W
Ettau 18W
Dujuan 21W
Mujigae 22W
Koppu 24W
Intensity Composite for Koppu 24W
New in 2016: Eight Storms Support Requested by NHC

NHC/CPHC storms have higher priority.

- 2016 upgrade: NHC/CPHC can use all eight slots,
- Storm Choices require a human (forecaster) decision if nstorms > 8.
# Test Plan and Upgrade Schedule: 2016 HWRF

<table>
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<tr>
<th>Sensitivity Tests</th>
<th>GFS Upgrade 2015 HWRF</th>
<th>Infrastructure Upgrades (Baseline)</th>
<th>Physics Test</th>
<th>Wave Model Test</th>
<th>Final 2016 HWRF Test</th>
<th>EMC/NCO Transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple</td>
<td>H16Z</td>
<td>H16B</td>
<td>H16P</td>
<td>H16W</td>
<td>H216 (EMC)</td>
<td>HWRF (NCO)</td>
</tr>
</tbody>
</table>

## Detail

**Old GFS Various HWRF sensitivity tests**
- New GFS Old HWRF with minimal bug fixes
- New GFS HWRF with infrastructure upgrades. Some physics and dynamics upgrades.

**All physics upgrades**
- Wave coupling included
- Final HWRF config

NCO runs parallel of fake storms to test dataflow. Customers verify. Repeat until approval.

## Cases

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<tbody>
<tr>
<td>WCOSS Jet/Theia</td>
<td>TO4 &amp; Jet</td>
<td>TO4 &amp; Jet</td>
<td>TO4 &amp; Jet</td>
<td>TO4 (NCO)</td>
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## Platform

<table>
<thead>
<tr>
<th>2015 June-Jan</th>
<th>2016 Jan-June</th>
<th>2016 Jan-Feb</th>
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<th>2016 Mar-June</th>
<th>2016 May</th>
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Typhoon Seminar

JMA, January 6, 2016

81/90
## Long-Term Plans for Hurricane Modeling at NCEP

<table>
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<th>Year</th>
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<td>2016</td>
<td>GFDL ——— HNMMB</td>
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<tr>
<td>2017</td>
<td>10-member HWRF/ HNMMB Ensembles</td>
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<tr>
<td>2018</td>
<td>NEMS Global Nests (NGGPS)</td>
</tr>
<tr>
<td>2019</td>
<td>HWRF Operational Model Continues Followed by Ensembles</td>
</tr>
<tr>
<td>2020</td>
<td>Basin-Scale HWRF/NMMB———Tropical NMMB Domain</td>
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**Hurricane Models take over Hurricane Wave Forecasts**

### Development, T&E and Implementation Plans for HNMMB (supported by HFIP and HIWPP)

- **2016**
  - June-Nov: uncoupled real-time demo
  - Nov: single-storm, coupled, no-DA ready
  - Nov-Dec: skill proven better than GFDL & comparable to HWRF
- **2017**
  - Jan-May: HNMMB pre-implementation test
  - Jun: HNMMB replaces GFDL operationally
Three-way coupled system development is in mature stage HYCOM for all global tropical storms:

- Climatology based MPIPOM has exposed the limitations in Eastern Pacific basin in 2015 with strong El-Nino conditions
- HYCOM with RTOFS initialization has been in the development
- OMITT helped improve the initialization and physics of HYCOM
- 2016 HWRF upgrades will include testing of HWRF-HYCOM (or HWRF-MPIPOM with RTOFS initial conditions)

One-way or two-way coupling with WaveWatchIII Hurricane Wave Model (multi2)

- Possible unification of hurricane wave model with HWRF for all tropical cyclones (UMAC recommendations)
- Two-way coupled system expected to enhance the representation of wave impacts on surface layer physics
- 2016 HWRF upgrades will include either of these options, with fully coupled system planned for 2017
High-Resolution HWRF Ensembles in 2018

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<td>2019</td>
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<tr>
<td>2020</td>
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HWRF Ensembles have been showing value during the past three years (HFIP Demo).

Surge in computing at NCEP operations allows us to plan for implementing high-resolution HWRF ensembles

Take advantage of ensemble DA, perturbations in physics and IC/BCs

Develop products that directly benefit NHC operations to improve deterministic forecasts

2016/2017: Continue HWRF ensemble HFIP Demo (multi-model regional ensembles); add HNMMB members to the mix

2016/2017: Develop advanced products for providing guidance on guidance and probabilistic forecasts

2018: 10-member HWRF/HNMMB ensemble implementation
Basin-Scale Multi-Storm HWRF/HNMMB in 2018

Large basin-scale domains that forecast multiple storms at the same time.
Need to show the value (cost vs. benefit)
Primary focus is for NATL/EPAC basins
Seven day forecasts including genesis.
Such large domains are needed for good wave forecasts
HNMMB could do a “tropical domain”: -60 to +60 latitude, cyclic in longitude; Covers all storms.

<table>
<thead>
<tr>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
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</thead>
<tbody>
<tr>
<td>Basin-Scale HWRF/NMMD—-Tropical NMMD Domain</td>
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</tbody>
</table>

2016: HWRF/HNMMB basin-scale parallel
2017: HWRF/HNMMB basin-scale operational (???)
2018:
   HNMMB basin-scale operational
   HNMMB tropical domain parallel
2019: HNMMB tropical domain operational
2020 onward: develop global nests to replace HNMMB tropical domain with the new non-hydrostatic dycore (NGGPS)
## Tropical Domain HNMMB in 2019

<table>
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<tr>
<th>Year</th>
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<td>Tropical NMNM Domain</td>
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</tr>
</tbody>
</table>

- **2017 Nov:** Full DA, basin-scale, system ready.
- **2018 Jun:** HNMMB with DA operational
  - Basin-scale, just like HWRF.
  - Upgrade at same time as HWRF.
- **2018 Nov:** “Tropical” domain ready
- **2019 Jun:** “Tropical” HNMMB model operational

### 2019 onward:
- Development switches to global nesting implementation.
- Three-way global coupling (wave/ocean/atmos)
- Target 2021 for parallel.
- Target 2022 for implementation.
- Follows the path of NGGPS for hurricanes.
- Assists in developing advanced modeling techniques for NGGPS hurricane components
Future Plans: Hurricane Physics

Align with HFIP and NGGPS Physics Strategy

Focus on improved air-sea interactions and inner core processes

Advanced scale-aware and stochastic physics with focus on multi-scale interactions
Future Plans: Hurricane Data Assimilation

Align with HFIP DA Strategy
Focus on inner core aircraft and all-sky radiance data assimilation
Advanced self-cycled HWRF EnKF-GSI Hybrid Data Assimilation System (HDAS)
Vortex relocation and initialization become part of Data Assimilation
Goals: Increase forecast accuracy at all lead times, especially during periods of rapid intensity changes; raise confidence levels for all forecast periods.

Kieu, Tallapragada and Hoggsett, 2014: Vertical structure of tropical cyclones at onset of the rapid intensification in the HWRF model Geophysical Research Letters; Volume 41, Issue 9, 16 May 2014, Pages: 3298–3306

Rosado: Ph.D. Dissertation on relationship of lightning and RI in HWRF model
Carter: MS Thesis on downstream impacts of RI for landfalling storms
Summary/Concluding Remarks

- HWRF has dismal RI predictability skills in the NATL and EPAC basins, getting better with time...
- HWRF has shown somewhat higher RI predictability in the WPAC basin
- A phase-lock mechanism is identified as a necessary condition for RI but not sufficient. Many external factors could inhibit model RI
- HWRF has better RI predictability when the initial storm intensity is weak. For storms with intensity > hurricane strength, HWRF fails to predict the RI
- HWRF captured very persistently DWC during the peak intensity for intense TCs (> 120 kt for longer than 12 h);
- HWRF real-time simulations show specific conditions for the DWC to take place;
- More observations/higher model resolution at upper level should be conducted to capture the existence of high level returning inflow.
- Possible solutions for improved RI: (a) increased resolution; (b) improved physics including scale aware features; (c) better initialization and DA and (d) high-resolution ensembles

Real-time and pre-implementation T&E HWRF products: http://www.emc.ncep.noaa.gov/HWRF