HWRF: Progress, Challenges & Plans for Improved Tropical Cyclone Forecasts

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Outline

- Hurricane Forecast Improvements from Operational HWRF Modeling System
  - Significant progress in the past three years
  - A success story driven by support from NOAA’s HFIP

- HWRF as a community modeling system for effective R2O
  - The only operational atmosphere-ocean coupled hurricane model available to the research community
  - Partnerships and collaborations between research and operations key for success

- HWRF as a unique high-resolution regional tropical cyclone model with global coverage
  - HWRF is now run in real-time for all tropical cyclones of the global tropical oceanic basins
  - Model of choice for NHC, JTWC and other operational agencies across the Asia Pacific and North Indian Ocean region

- Advanced experimental configurations of HWRF
  - 21-member high-resolution HWRF ensembles
  - Basin-Scale HWRF with multiple movable nests
  - HWRF-HyCOM-WAVEWATCH-III-NOAHLSM coupled modeling system

- Scientific Challenges for improved tropical cyclone forecasts
  - Data assimilation, initialization and improved use of observations
  - Advanced scale-aware physics for more accurate representation of physical processes

- Next generation model development efforts and plans for future
  - HWRF transitioning towards unified NMMB/NEMS infrastructure
  - Focus on representing Multi-Scale interactions in a global framework for high fidelity TC forecasts
High-Resolution Atmosphere-Ocean Coupled operational HWRF Modeling System: A Success Story Drafted by HFIP

- Starting in 2012, a high-resolution hurricane model operating at cloud-permitting 3km resolution implemented into NCEP operational system and has been upgraded annually for improved tropical cyclone predictions

- Multi-agency efforts supported by HFIP
  - **EMC**: Centralized model development, advanced nesting techniques, physics improvements, vortex initialization and data assimilation, operational tasking of NOAA P3 TDR missions, pre-implementation T&E and operational implementation
  - **HRD/AOML**: Model development, physics improvements, validation & diagnostics based on observations
  - **DTC/NCAR**: code management and community support, tutorials, visitor program, pre-implementation T&E, R2O
  - **ESRL**: Physics sensitivity tests and idealized capability
  - **URI**: Ocean and wave coupling, model diagnostics
  - **GFDL**: Physics, knowledge sharing, joint T&E
  - **NHC**: Diagnostics and evaluation of the HWRF pre-implementation tests and real-time forecasts; inputs for prioritized model development
  - **Academic Community**: Prioritized research on model/physics/data assimilation, model diagnostics

Three telescopic domains with storm following nests: 27km: 75x75°; 9km: ~12x12° and 3km: ~7.5x7.5°; 61L with 2hPa model top; Coupled to MPI POM in ATL & EPAC; Advanced vortex initialization and one-way hybrid regional En-Var DA system
2012 HWRF: Significant improvement in storm size forecasts from operational HWRF: the immediate impact of increasing horizontal resolution from 9km (HOPS) to 3km (H212)

Tallapragada et al. 2014: Evaluation of Storm Structure from the Operational HWRF Model during 2012 Implementation. MWR

2013 HWRF: Significant improvement in track and intensity forecasts from operational HWRF:

For Atlantic basin track, the HWRF is improved by ~5-15% and now appears competitive with the GFS. For intensity, the model reduces errors by ~15%, has demonstrated skill greater than that of the NHC official forecast and greater than that of the statistical models. These are remarkable results...

--James Franklin, NHC
Significant improvements in the Hurricane Track Forecasts for the Atlantic Basin: Approaching the NOAA HFIP 5-year Goals

Accelerated progress in improving the Hurricane Intensity Forecasts for the Atlantic Basin: Approaching the NOAA HFIP 5-year Goals
### Higher standards for operational implementation of annual upgrades:

*Multi-season Pre-Implementation T&E with Focus on R2O*

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<th><strong>Model upgrades</strong></th>
<th><strong>Physics upgrades</strong></th>
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| 1. 61 vertical levels 2hPa model top  
2. Expanded d02/d03  
3. Upgraded vortex initialization w/invest cycling  
| New nest motion  
NOAH LSM  
Separate species, w/ and w/out advection  
Radiation | Priority cases (~800)  
Priority cases (~800)  
Priority cases (~800)  
| Baseline + MPI-POM + new nest motion + Python scripts | Six-season 2008-2013 retrospectives ~2000 simulations in ATL/EPAC | Jet/WCOSS/Zeus |

*Systematic evaluation of each component of the upgrades is key for success.*  
*More than 10000 simulations on multiple platforms, three years in a row*
HWRF Storm Relocation and Vortex Initialization is the most complex part of the modeling system, designed to handle various storm conditions (weak, strong, sheared, developing, decaying ...) with lot of safeguards, to generate reasonable and accurate initial vortex. Previous cycle's 6-hr forecast is used as a first guess and the storm location, intensity, size and structure are adjusted to the tc vitals provided by the forecast agencies. For weaker storms (<16 m/s), GFS analysis is used as a first guess instead of cycled vortex.
HWRF One-Way Regional En-Var Hybrid Data Assimilation System

Effective use of aircraft reconnaissance (TDR & Dropsonde) data in Operational HWRF

Designed to assimilate NOAA P3 and other aircraft (AF, GH, GIV) reconnaissance observations (TDR and Dropsonde) along with clear-sky radiance data in the hurricane environment. Large-scale analysis is derived from GFS initial conditions. GFS ensembles provide background error covariance for regional hybrid analysis.
Ocean Coupling for better representation of air-sea interactions

HWRF Model is operationally coupled to POM, and has choice of coupling to HyCOM

Ocean Spin-Up and Loop Current/Ring initialization using altimetry observations

Subsurface (75-m) ocean temperature during Katrina & Rita

MPIPOM Domain Configurations for operational HWRF

Coupled HWRF-HYCOM System
Coupled hurricane modeling with regional ocean components (future HYCOM application, since 2009)

The Coupled System

Water Temperature Difference over a day (12 to 36 forecast hour for IC=00Z 2012/8/28)

- HWRF - HYCOM: max ~3.5°C
- HWRF Atm.: max ~0°C
- HWRF-POM: max ~1°C

Grid-to-grid interpolation / extrapolation

(additional WM? AM and WM? OM communications in progress)
Examples of Real-Time Forecasts from 2014 HWRF so far....

Advanced forecast products to aid forecaster needs

HWRF forecast for Arthur (01E) at 2014070118

HWRF forecast for JULIO (10E) & IESLLE (09E) at 2014080600
HFIP Multi-Model Regional Ensemble Prediction System

An aggressive approach for High-Resolution Navy/EMC/GFDL Ensembles for TC Forecasts

Setting stage for 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
- 10-member 3km COAMPS-TC ensembles driven by IC/BC perturbations based on GFS analysis & tcvitals
- 10-member 9km GFDL ensembles with vortex scale inner-core perturbations
- High-resolution probabilistic products provide forecast uncertainty in track, intensity, structure (size) and rainfall, along with ensemble mean products
HFIP Joint Multi-Center Regional Ensemble Prediction System

Real-Time Results for the developing storm in the Atlantic: 96L, IC: 2014082012

For more real-time products, visit the HWRF website at:

http://www.emc.ncep.noaa.gov/HWRF/ENSEMBLE/index.html
Operational HWRF as a Community Modeling System
Available to the research community through support from HFIP & DTC for accelerated R2O

Extended outreach through advanced HWRF model configurations including “idealized capability”; “basin-scale with multiple moveable nests”; a variety of sophisticated physics options and prioritized support for advanced model developers through DTC visitor program, T&E capability, tutorials and workshops.

More details by Christina Holt at 11.20 AM (SCI-PS238.03)
HWRF as a unique tropical cyclone model with global coverage

Run in real-time for all global tropical cyclones in support of NHC, JTWC and other international operational agencies across the Asia Pacific and North Indian Ocean regions

• With support from NOAA HFIP, HWRF model has now evolved as a unique high-resolution tropical cyclone forecast tool for all tropical oceanic basins, expanding the scope and reach to international TC research and forecast community

• 2012: For the first time, real-time support to JTWC for North West Pacific typhoon forecasts from HWRF. Collaborations with IMD, India and CWB/TTFRI, Taiwan

• 2013: Continued real-time support to JTWC for North West Pacific and North Indian Ocean basins. Extended collaborations with VietNam, Oman and China

• 2014: HWRF runs for all global tropical cyclones including Southern Hemisphere. Entered into bilateral agreements with Korea.

• First overseas HWRF Tutorial sponsored by HFIP, DTC, TTFRI, CWB and NCEP in May 2014.

• HWRF will be coupled to MPIPOM/HyCOM ocean models for all oceanic basins by August 2014.

International partnerships for accelerated model development & research
Performance of Operational HWRF for the Western Pacific basin

JTWC consensus model guidance includes experimental HWRF forecasts

- HWRF track forecasts outperformed all regional models; very close to GFS forecasts (ECMWF the best)
- HWRF intensity forecasts superior than all other models
- HWRF was able to forecast some of the most strongest storms of 2013 with high POD for Rapid Intensification
Verification of RI forecasts in WPAC basin 2013

HWRF as the most skillful real-time forecast model for RI predictions

Verification of RI in terms of category events shows superior RI forecast skill of the HWRF model as compared to other regional models at JTWC with high POD and very low FAR

Tallapragada and Kieu, 2014: Real-Time Forecasts of Typhoon Rapid Intensification in the North Western Pacific Basin with the NCEP Operational HWRF model. TCRR, in press.

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
What Triggers RI in HWRF Model?

A new concept of phase-lock between warm core, storm strength and mid-level moisture

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 may not be 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)

Fig. 1. Radius-height cross section of the relative humidity (shaded, unit %), the tangential wind (black contours at intervals of 3 ms⁻¹), and potential temperature anomalies with respect to the far-field environment (red contours at interval of 1°C, solid/dotted contours for positive/negative values) in an idealized experiment with the HWRF model (Kien et al. 2014).
HWRF Vortex Structures for Extremely Strong Super Typhoons

Unique double warm core structures exhibited by HWRF at very high intensity regime

Persistent double warm core at high intensity, which is seen only for strong storms >Cat3 strength. Captured quite frequently in model forecasts but not confirmed from observations.

Excellent opportunity to study intense storms forecasted in real-time.
Highly accurate and skillful track and intensity forecasts from operational HWRF for major typhoons in the North Western Pacific Basin. Rapid Intensification (RI) Forecast Skill from HWRF is about 0.36 POD – highest by any dynamical model operating in that region.
Globalization of NCEP Operational HWRF allowed the HWRF team to provide real-time forecast guidance for Southern Hemispheric Storms starting on Jan 14, 2014, in support of JTWC. All real-time products are accessible from http://www.emc.ncep.noaa.gov/gc_wmb/vxt/
“Performance metrics from 2012 confirmed HWRF added value to both track and intensity guidance available to JTWC forecasters, so we implemented its operational use in 2013. The model continues to perform very well, especially for intensity, where it outperformed other mesoscale models out to 72 hrs and was especially useful during the frequent rapid intensification events that occurred in the Western North Pacific this year”

--Bob Falvey, Director, JTWC

A preliminary analysis of the performance of various models indicate that the performance of NCEP HWRF model was very good. It was a very useful product in terms of track, intensity and landfall forecast guidance as well as rainfall. Its performance was better that that of IMD HWRF.

-- Dr. Mohapatra, Director, Cyclone Warning Division, IMD, India

Intensity errors are among the best with negative bias mostly associated with Phailin. Use of IMD best track gives even better statistics
Remarkable HWRF Real-Time Forecasts for Super Cyclone Phailin

HWRF was able to capture some complex TC interactions with NE Monsoon Flow for TC Madi

Rama Rao et al., 2014 Nat. Hazards, in press
Mohanty et al., 2014, submitted to BAMS
Challenges Ahead to Address the Next-Generation Forecast Needs

Increase forecast accuracy at all lead times, especially during periods of rapid intensity changes; raise confidence levels for all forecast periods.

Is HWRF capable of representing/predicting SEF/ERC?
Focus area for improvements: Much to do with getting more accurate initial vortex structure and environment (where observations and DA are critical)
Challenges Ahead: Non-linear Impact of Physics Improvements

Combination

Vertical Resolution + MP + Radiation + Ocean
Future Plans for Next-Generation Operational HWRF

Transition to NMM-B/NEMS Multi-Scale Global-to-local Modeling System

- NCEP/AOML Collaborative effort supported by OAR Sandy Supplemental High Impact Weather Prediction Project (HIWPP) and leveraged by NOAA’s HFIP support
- Take advantage of NMMB in NEMS infrastructure for developing next generation global-to-local-scale modeling system for tropical cyclone forecasting needs and for comprehensive solutions for landfalling storms
- Planned development, testing and evaluation leading to potential transition to operations in the next 3-5 years

Scientific advancements include:
- Scale aware and feature aware physics
- Advanced techniques for inner core data assimilation with use all available aircraft recon & satellite data
- High-resolution ensembles for prediction of RI/RW
- Enhanced land-air-sea-wave-hydrology coupled system

More details by Gopal at 11.00 AM (SCI-PS238.02)
Summary/Concluding Remarks

- HWRF has been performing consistently better than other regional models in all global tropical cyclone basins
- High-resolution ensembles are needed to provide more accurate guidance to the forecasters
- Focused development and T&E, collaboration among the best of the minds, sufficient computational resources and effective R2O strategies will enable us to reach or exceed the goals set by NOAA HFIP
- HWRF as a community modeling system for tropical cyclone research and forecasting provides a unique opportunity for researchers to make an impact that has far reaching benefits to the most vulnerable.
- Model physics and vortex initialization remain as major challenges for further improvements
- Next generation Hurricane Forecast System will include global-to-local scale predictions with emphasis on multi-scale interactions and improved forecasts for landfalling storms and downstream applications

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

Acknowledgements: HWRF team at EMC; EMC, DTC and HFIP Management; Collaborations with national and international operational and research agencies and academia