Regional Hurricane Model Advancements at NCEP/EMC:
FY2012 Implementation of High-Resolution 3km Triple-Nested HWRF

Vijay Tallapragada & HWRF Team

Environmental Modeling Center,
NCEP/NOAA/NWS, Camp Springs, MD 20746.
Outline

• Performance of current operational HWRF for 2011 season
• Unification of operational and research versions of HWRF in the community modeling framework (EMC/HRD/DTC)
• Development and evaluation of high-resolution tripled-nested HWRF through a major collaborative effort (EMC/HRD/GFDL/URI/NHC) - a success story inspired by support from HFIP
• Computational and scientific challenges towards implementing high-resolution HWRF at NCEP
• Planned FY2012 operational configuration
• Future developments 2012 and beyond
FY2011 HWRF Upgrades

FY2011 Operational HWRF Baseline Configuration

- WRF Repository (hosted by DTC)
- Extensive Testing (pre implementation)

02/2011: WRF V3.2+

HWRF operational configuration (2011)

Upgrades 2011

Extensive Testing (individual upgrades)

- Modified vortex initialization (storm size correction and balanced vortex)
- New GFS Deep Convection
- Modified Surface Physics, Radiation and Microphysics

- WRF V3.2*
- 04/2010

- WRF V3.1.1
- 07/2009

- WRF V3.1
- 04/2009

- WRF V3.0
- 04/2008

- WRF V2.2
- 12/2006

- WRF V2.1
- 08/2005

- WRF V2
- 05/2004

*Evaluation Completed

Regional Hurricane Model Development at EMC
Impact of upgraded vortex initialization scheme in 2011 HWRF

06-hour forecast wind speed bias (y axis) vs initial wind speed (x axis)

Reduced spin-up for weak storms and spin down for strong storms in 2011 season

1. Vortex size correction
   - Instead of matching only RMW but also matching outer radii such as ROCI or R34kt
2. Less use of the composite storms for weak storms
   - Preventing the rapid spin-up of weak storms
3. Matching the maximum 10m wind speed but not forcing the minimum SLP
   - With more balanced vortex, rapid spin-down of strong storm is much reduced

* Modified initialization significantly improved the intensity skill of HWRF model (especially 0-48hr)
**Performance of operational HWRF in 2011 Atlantic Season**

 HWRF and GFDL track forecasts less skillful than GFS

 HWRF exhibited much improved intensity forecast skill compared to GFDL at all forecast times (10-20% improvement)
Performance of operational HWRF in 2011 Eastern Pacific Season

HWRF and GFDL track errors comparable to GFS out to 72-hr fcst.

HWRF and GFDL have comparable intensity forecast skill except at 120-hr fcst.
Towards High-Resolution HWRF implementation in FY2012

- A major step towards improving intensity forecast skill and address rapid intensity
- Three atmospheric telescoping nested domains:
  - 27km outer domain 75x75 degree
  - 9km intermediate nest ~11x10 degree
  - 3km inner-most nest ~6x5 degree
- New centroid based nest motion algorithm
- Coupled with Princeton Ocean Model (POM) in the Atlantic and Eastern Pacific (1-D)
- Modified HWRF vortex initialization
- Changes to HWRF physics appropriate for 3 km with explicit convection in the third nest
- Upgraded tracker and new high-temporal resolution (every time step) track and intensity product
- New SSMI/S synthetic microwave imagery
- Extensive testing and evaluation starting with Stream 1.5 demo during 2011 season
- Six different configurations evaluated using HFIP computing resources on Jet (~10,000 runs)
High Resolution Research version of the HWRF system geared to compliment operations

- Improved resolution and improved understanding of forecast at about 3 km resolution
- Incorporate appropriate representation of physical processes in tropics for 3 km resolution based on observations
- Code management and community support through unified repository supported by DTC

DTC Supported Subversion based code management
Code evolution in a HWRF component

Community Development

Responsibilities
DTC
HWRF developers
Others

dev1

dev2

dev3
Operational Challenges:  

1. Code Optimization for Triple Nested HWRF System

- The bottleneck for the system to be implemented into operation is the run time: it took about 4 hours 15 minutes for 126 hours forecast on NCEP IBM CCS (5 sec. time step at 3 km resolution)

- Several possible ways explored to further reduce the model run time:
  - Extensive profiling of MPI usage – led to changes in NEST_TERRAIN code, *run time reduced by 100 minutes*
  - IO Servers configuration (identical results), *15 minutes*;
  - Adding one more node, *20 minutes*;
  - decreased physics call frequency, *30 minutes*;
  - separate buffering of stdout and stderr; *10 minutes*

- End Result: Triple Nested 3km HWRF system can run in about 80 minutes with four nodes (just 20 minutes more than current 9km operational HWRF)
2. Extending Vortex Initialization for triple nested HWRF

- New subroutine for the E-grid to E-grid interpolation
- Changes in 10m wind calculation consistent with model surface physics formulation
- Localized vertical interpolation and improved vertical mass adjustment
- New 30°x30° high-resolution (3 km) analysis domain with improved vortex size and structure correction
- Modified composite storm consistent with high-resolution model configuration
- Separate composite storm for medium and shallow storms
- Upgrade GSI in HWRF to latest community version V3.0

New and improved E-E interpolation algorithm

Improved vertical interpolation and mass adjustment
3. Physics upgrades suitable for higher resolution grid

- Upgrades to GFS PBL - vertical diffusivity reduced by 50%
- Surface physics based on HWRF 2010 formulation
- Addition of Shallow Convection Parameterization
- No CP at 3km resolution

Upgrades to Ferrier Microphysics consistent with higher resolution
- Increase max allowable ice concentration
- Increase NCW from 60 to 250 cm$^{-3}$
- Increase snow fall speeds for ice warmer than 0°C (realistic and consistent with Thomspn scheme)
2010-2011 – Atlantic basin

Table 1. Track improvement percentage w.r.t. HOPS (%)

<table>
<thead>
<tr>
<th>Time/</th>
<th>0</th>
<th>12</th>
<th>24</th>
<th>36</th>
<th>48</th>
<th>72</th>
<th>96</th>
<th>120</th>
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<td>HPHY</td>
<td>4</td>
<td>8</td>
<td>8</td>
<td>12</td>
<td>14</td>
<td>19</td>
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<td>14</td>
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Table 2. Intensity improvement percentage w.r.t. HOPS (%)

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<td>HPHY</td>
<td>-5</td>
<td>14</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>4</td>
<td>7</td>
<td>9</td>
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Oper. HWRF

2012 HWRF
Atlantic: 50-kt Radii verification

Oper. HWRF

2012 HWRF
Atlantic: 64-kt Radii verification

NE
- **Oper. HWRF**
- **2012 HWRF**

SE

NW

SW
2010-2011 – Eastern Pacific basin

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<td>15</td>
<td>20</td>
<td>18</td>
<td>17</td>
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Table 2. Intensity improvement percentage w.r.t. HOPS (%)

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<td>HB12</td>
<td>-10</td>
<td>10</td>
<td>-10</td>
<td>-4</td>
<td>-8</td>
<td>4</td>
<td>9</td>
<td>22</td>
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</table>

Oper. HWRF

2012 HWRF
EPAC: 34-kt verification
EPAC: 50-kt verification

**NE**
- **Oper. HWRF**
- **2012 HWRF**

**SE**

**NW**

**SW**
EPAC: 64-kt verification

Oper. HWRF

2012 HWRF
Atlantic basin

EPAC basin

3km HWRF Track Forecast Skill Comparable to Operational GFS for 2010-2011 seasons
New experimental products from operational HWRF

- Synthetic satellite imagery using a uniform RTM:
  - GOES-13 and GOES-11 Channel 2,3,4,6
  - Microwave 37 GHz and 85 GHz Vertical and Horizontal Polarization (replace AMSRE with SSM/I F17/F18/F20)

High Temporal Resolution HWRF
ATCF-style output at every time step (5 seconds) at 3km resolution
Are 6-hr outputs representative of the actual model forecast?
What is happening during development and RI within the model?
SSMI/S 37 GHz-H

SSMI/S 37 GHz-V

SSMI/S 37 GHz-Color Composite

HWRF Generated SSM/I S Microwave Imagery (new operational product)

-- Courtesy: Dave Zelinsky, NHC
max wind pdf oper. HWRF vs HWRF2012

2010 & 2011 atlantic cases

best track
HWRF 2012

Normalized Occurrence

10m wind max wind (m/s)
FY2012 and beyond...

- **HWRF Model (EMC, HRD)**
  - Multiple moving nests within a basin scale domain
  - Improved multi-scale interactions

- **HWRF Physics (URI, GFDL, ESRL, HRD)**
  - Surface fluxes, sea spray and wave coupling
  - Physics for high-resolution (convection, micro physics, PBL, LSM)

- **HWRF Diagnostics (HFIP, EMC, NHC, FSU, CIRA, HRD, UMBC/UMD)**
  - Hurricane model diagnostics, evaluation and verification
  - Develop a common and comprehensive diagnostics framework and tools to integrate model output with available observations for verification
  - Enhanced real-time product display and navigation

- **HWRF Ensembles**
  - Large Scale Flow, Structure and Physics Perturbations;
  - EnKF based perturbations in support of DA

- **Hybrid EnKF-GSI Data Assimilation for HWRF**
  - Real-time transmission of the P3 TDR data flow from aircraft to NCO/TOC/AOC and assimilation using advanced GSI and improved vortex initialization (model consistent 3-D balanced vortex)
  - Ensemble data assimilation - hybrid EnKF (Planned Demo for 2012 hurricane season (HFIP Stream 2))
  - Improved use of satellite radiance datasets, Model vertical levels and top consistent with NAM
Real-Time TDR radial velocity data assimilated in inner analysis domain

Positive improvements in track and intensity forecast skill using TDR data
HWRF Domain With Multiple Moving Nests

- Basin scale domain
- 7 days forecast
- SDA and cycling

- Regional ensembles/products
- Daily Tropical Outlook/genesis
- Computational Efficiency (27:9; about 2 h; 168 CPUs)
# Advancing the HWRF System FY2012 & Beyond

<table>
<thead>
<tr>
<th>Resolution/Infrastructure</th>
<th>2012</th>
<th>2013</th>
<th>2014*</th>
<th>2015*</th>
<th>2016*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triple nested HWRF (27/9/3 km)</td>
<td>Increased vertical resolution, higher model top</td>
<td>community R2O efforts (HFIP)</td>
<td>Upgrades to WRF infrastructure, Multiple moving domains, NEMS/ESMF/NMM-B, Other oceanic basins</td>
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<table>
<thead>
<tr>
<th>Physics</th>
<th>2012</th>
<th>2013</th>
<th>2014*</th>
<th>2015*</th>
<th>2016*</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBL, Shallow Convection &amp; Microphysics</td>
<td>Microphysics, Radiation, Surface Physics, Coupling to Waves and Land Surface, Physics for high-resolution</td>
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<tr>
<th>DA/ Vortex Initialization</th>
<th>2012</th>
<th>2013</th>
<th>2014*</th>
<th>2015*</th>
<th>2016*</th>
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<tbody>
<tr>
<td>Storm size correction, dynamic mass-wind consistency</td>
<td>Inner core DA (Doppler Radar, satellite)</td>
<td>Hybrid-EnKF DA, advanced vortex relocation procedure, improved GSI</td>
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<thead>
<tr>
<th>Ocean</th>
<th>2012</th>
<th>2013</th>
<th>2014*</th>
<th>2015*</th>
<th>2016*</th>
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<tr>
<td>HYCOM Coupling</td>
<td>Improved ocean data assimilation, physics and resolution, unified coupled system for ATL &amp; EPAC</td>
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<tr>
<th>Waves</th>
<th>2012</th>
<th>2013</th>
<th>2014*</th>
<th>2015*</th>
<th>2016*</th>
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<tr>
<td>One-way Wave Coupling</td>
<td>Two-way wave coupling, multi-grid surf zone physics, effects of sea spray</td>
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<tr>
<td>HWRF Ensembles, Coupling to Hydrological/ Surge/ Inundation models, diagnostics, product development</td>
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## Ongoing Work
- **2012 upgrades**
- **Planned developments**
- *Computer upgrade*
Real-time and pre-implementation T&E HWRF products:

http://www.emc.ncep.noaa.gov/gc_wmb/vxt/index.html

Thanks for your attention

Acknowledgements:

HWRF team at EMC, HRD and NHC

EMC and HFIP Management

Collaborations with NHC, DTC, HRD, GFDL, URI, CIRA and other HFIP partners

Questions?
Expanding the scope and applications of HWRF for world oceanic basins

Operational implementation of HWRF in India
http://www.imd.gov.in/section/nhac/dynamic/cyclone_fdp/CycloneFDP.htm
Benchmarking HWRF for Tropical Cyclones in the North Indian Ocean region

Average Track Errors (NM)


- HWRF
- JTWC: Navy Official
- GFDN
- AVNO: Oper. GFS

Chart showing track errors over forecast hours for different models.
Benchmarking HWRF for Tropical Cyclones in the North Indian Ocean region

Average Intensity Errors (kt)

- HWRF
- JTWC: Navy Official
- GFDN

Intensity Error (kt)

Forecast Hours: 00 12 24 36 48 72 86 14 120
#Cases: 64 64 62 60 48 35 27 12
HWRF: NCEP Operational HWRF For NIO Region

Storm: 100207 (GONU)

Forecasts: Beginning 2007080212 for AVNO model
Observed: Beginning 2007060212, every 12 hours

GFS T574
GFDN
HWRF Forecasts for Western Pacific Typhoons
Jangmi (19W), IC 2008092700
Typhoon Megi
Typhoon Megi
Simulated Satellite Model Forecasts

- **Forecast Verification**
  - Structure
    - IR (Dvorak)
    - Microwave
  - Microphysics
    - Satellite images dependent on modeled hydrometeors

- **Operations**
  - Composite images to allow forecast to easily compare model forecast with real storm
Coupling to Wave-Watch III

- NOAA/NCEP in-house wave model, based on WAM.
- Operational global and (nested) regional model.
- Specialized Atlantic and Pacific hurricane wave models with blended winds from GFS and GFDL model.
- WAVEWATCH III will be coupled to HWRF

Deep ocean model resolution dictated by GFS model

Higher coastal model resolution dictated by model economy

Highest model resolution in areas of special interest

Hurricane nests moving with storm(s) like GFDL and HWRF
Coupling to Land Surface Model

[Diagram showing the coupling between HWRF, POM, LSM, and Routing Model]

www.emc.ncep.noaa.gov/HWRF

Driving Forcing: Surface runoff and baseflow
Coupling to HYCOM

- New paradigm proposed by MMAB:
  - First assure that you have the most realistic ocean possible in a coupled HYCOM-HWRF system.
    - Use frozen HWRF and frozen RTOFS-Global (IC/BC).
    - Develop best possible coupled RTOFS nest.
      - Make GFS and HWRF fluxes compatible.
      - Add data assimilation to nested domain.
      - Validate and retune HYCOM using global TC data.
  - Then tune / modify HWRF for use with this ocean representation (optimizing track and intensity).
    Adjust fluxes / HYCOM tuning as needed while incrementally working on HWRF.

- Assuming that HWRF may fill present resources with third nest, no room for HYCOM in ops until 2014/15.

- 2012: MMAB sets up best possible RTOFS-HWRF.
  - Frozen HWRF, with bias correction in coupler.
  - Based on RTOFS-Global (not Atlantic).
  - Including data ocean data assimilation.
  - Focus on “global” ocean validation.

- 2013/2014:
  - Optimize HWRF for HYCOM.
    - Optimize HWRF for track and intensity, while
    - Assuring that ocean retains best behavior.
  - Possible addition of wave model to test system.

- 2015: Tentative implementation.
HWRF ensembles

- Mainly focused on better estimation of hurricane intensity forecasts from EPS.

**Single model, multi-initial condition ensembles.**

1) GEFS-based HWRF ensembles with three cumulus convection schemes: Simplified Arakawa-Schubert (SAS), Kain-Fritsh (KF), and Batts-Miller (BM); Each includes 21 members.

2) Error distribution-based model bias correction method was developed.

3) Intensity forecast skills are greatly improved by the bias correction method, compared to simple ensemble average method (See Figure).

**Multi-model, multi-physics ensembles.**

1) Ensemble members include GFDL, high resolution (27-9-3) HWRF, HWRF with various cumulus convection schemes, PBL schemes;

2) Mode analysis was developed using PDF kernel density estimation method

3) Results showed that the intensity forecast skills are further improved by using mode analysis, compared to the arithmetic ensemble mean.
HWRF Forecasts for Typhoon Jangmi (19W), IC 2008092700

85H Brightness Temperature [K] for 0hr

850mb vorticity \[ x 10^{-4} \text{ S}^{-1} \] for 0hr
SUMMARY

There has been lot of progress advancing the hurricane modeling capabilities at EMC, thanks to active collaboration between research and operations.

Improving intensity/structure forecasts are orders of magnitude more difficult than was for track forecasts.

Requires substantial effort between research and operational hurricane communities

With improved track, intensity and structure, it is possible to provide improved guidance on rainfall, storm surge, flooding and inundation.