Improving the HWRF model physics using observations and model diagnostics

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Many thanks to my colleagues!


Acknowledge the support from HFIP
Acknowledge HRD and EMC HWRF modeling team members
Outline

• Motivation and objectives

• Model diagnostics using observations

• Observation-based model physics upgrade in HWRF

• Future work
Why is hurricane intensity so hard to be predicted?

- Model initialization
- Model resolution
- Model physics

- Environmental control
- Microphysics

- Air-sea interaction
- Boundary layer physics
Objectives

• Increase usefulness of observations in high resolution (e.g. regional) hurricane modeling systems.

• Develop advanced model diagnostic techniques to support model improvements and identification and analyses of sources of model errors.
Develop advanced model diagnostics to identify model deficiency and errors through comparison with observations
The experimental version HWRF

Tracks of Hurricane Bill (2009)

- Best Track
- Simulated track

Wind speed in knots

Hours after Aug. 16 0000 UTC
### Rapid Intensification (Hits and Misses)

<table>
<thead>
<tr>
<th>Best Track/Model</th>
<th>Hits</th>
<th>Misses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>17</td>
<td>--</td>
</tr>
<tr>
<td>HWRF-x (hwrf) low res</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>HWRF-x (hwrf) high res</td>
<td>13</td>
<td>4</td>
</tr>
<tr>
<td>HWRF-x (gfdl) low res</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>HWRF-x (gfdl) high res</td>
<td>13</td>
<td>4</td>
</tr>
</tbody>
</table>

### Rapid Intensification (False Alarms and Correct Rejections)

<table>
<thead>
<tr>
<th>Best Track/Model</th>
<th>False Alarms</th>
<th>Correct Rejections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>--</td>
<td>38</td>
</tr>
<tr>
<td>HWRF-x (hwrf) low res</td>
<td>1</td>
<td>37</td>
</tr>
<tr>
<td>HWRF-x (hwrf) high res</td>
<td>7</td>
<td>31</td>
</tr>
<tr>
<td>HWRF-x (gfdl) low res</td>
<td>1</td>
<td>37</td>
</tr>
<tr>
<td>HWRF-x (gfdl) high res</td>
<td>8</td>
<td>30</td>
</tr>
</tbody>
</table>

A total of 9 Storms, 69 Cases

2005 Storms: Emily, Katrina, Ophelia, Phillipe, Rita, Wilma

2007 Storms: Ingrid, Humberto, Karen
HWRFx runs selected for analysis

### HWRF initialization 27-9 km

<table>
<thead>
<tr>
<th>Initialization Time</th>
<th>Hit or Miss</th>
<th>Time period in simulation</th>
<th>Intensity range during SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>07_13_00</td>
<td>Hit</td>
<td>58 h – 77 h</td>
<td>95 – 105 kt</td>
</tr>
<tr>
<td>07_14_00</td>
<td>Hit</td>
<td>55 h – 72 h</td>
<td>92 – 102 kt</td>
</tr>
<tr>
<td>07_15_00</td>
<td>Hit</td>
<td>17 h – 38 h</td>
<td>105 – 115 kt</td>
</tr>
<tr>
<td>8_24_00</td>
<td>Hit</td>
<td>67 h – 85 h</td>
<td>104 – 113 kt</td>
</tr>
<tr>
<td>8_26_00</td>
<td>Hit</td>
<td>32 – 46 h</td>
<td>105 – 115 kt</td>
</tr>
<tr>
<td>8_27_00</td>
<td>Hit</td>
<td>12 – 28 h</td>
<td>105 – 115 kt</td>
</tr>
<tr>
<td>10_19_00</td>
<td>Hit</td>
<td>33h – 49 h</td>
<td>100 – 110 kt</td>
</tr>
<tr>
<td>10_20_00</td>
<td>Hit</td>
<td>12h – 32 h</td>
<td>125 – 135 kt</td>
</tr>
</tbody>
</table>

### HWRF initialization 9-3 km

<table>
<thead>
<tr>
<th>Initialization Time</th>
<th>Hit or Miss</th>
<th>Time period in simulation</th>
<th>Intensity range during SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>07_13_00</td>
<td>Hit</td>
<td>76 h – 96 h</td>
<td>125 – 135 kt</td>
</tr>
<tr>
<td>07_14_00</td>
<td>Hit</td>
<td>45 h – 61 h</td>
<td>108 – 118 kt</td>
</tr>
<tr>
<td>07_15_00</td>
<td>Hit</td>
<td>12 h – 40 h</td>
<td>125 – 135 kt</td>
</tr>
<tr>
<td>07_16_00</td>
<td>Hit</td>
<td>13 h – 37 h</td>
<td>110 – 120 kt</td>
</tr>
<tr>
<td>8_24_00</td>
<td>Hit</td>
<td>59 h – 73 h</td>
<td>105 – 113 kt</td>
</tr>
<tr>
<td>8_26_00</td>
<td>Hit</td>
<td>26 – 38 h</td>
<td>106 – 117 kt</td>
</tr>
<tr>
<td>10_19_00</td>
<td>Hit</td>
<td>31h – 38 h</td>
<td>122 – 132 kt</td>
</tr>
<tr>
<td>10_20_00</td>
<td>Hit</td>
<td>12h – 28 h</td>
<td>140 – 150 kt</td>
</tr>
</tbody>
</table>
Surface layer structure diagnostics

Zhang, Cione, Uhlhorn and Rogers, 2010

The simulated surface layer is too warm and too moist compared to observations.
1975-2007 TCBD individual buoy and C-Man observations

Cione, Kalina, Zhang and Uhlhorn, 2012
Simulated boundary layer is too deep compared to observations!
Compositing Dropsonde data
Zhang, Rogers, Nolan and Marks, 2011 MWR

A total of 2231 dropsonde data from 13 hurricanes have been analyzed, and 794 of them are used in the final analysis.
Identify deficiency of the surface layer and boundary layer schemes
Why is the simulated surface layer so warm and moist?

\[ C_{E10N} = \frac{\langle w'q' \rangle}{U_{10N}(q_{sat}-q_{10N})} \]

Feedback to Young Kwon and Bob Tuleya when they visited HRD in 2010
The Coupled Boundary Layer Air-sea Transfer Experiment (CBLAST)

Black et al. 2007 BAMS
Drennan et al. 2007 JAS
French et al. 2007 JAS
Zhang et al. 2008 GRL
Zhang et al. 2009 JAS
Zhang 2010 a,b QJ, JAS
Why is the simulated boundary layer so deep?

MRF type PBL schemes are too diffusive!

Working with Gopal and Frank to identify the problem
Data

We use the flight-level data that were collected using the low-level eyewall penetrations of Hurricanes Allen (1980), Hugo (1989) and David (1979).

Allen, Aug. 6, 1980

Hugo, Aug. 15, 1989

(Marks 1985 MRW) (Marks et al. 2008 MWR)
Hurricane Hugo flight

Run # 3 includes Eyewall Vorticity Maxima (EVM)
Methodology

1. Vertical and horizontal momentum fluxes:

\[ \dot{\tau} = \rho \left( -w'v'_t \hat{i} - w'v'_r \hat{j} \right) \quad \text{and} \quad F_h = -\rho \left( v'_t v'_r \right) \]

2. Turbulent kinetic energy:

\[ e = \frac{1}{2} \left( v'_r^2 + v'_l^2 + w^2 \right) \]

3. Vertical eddy diffusivity:

1) definition: \[ K = |\dot{\tau}| \left( \frac{\partial V}{\partial z} \right)^{-1} \]
2) Hanna (1969) method: \[ K_1 = c_l \sigma_w \quad l = \sigma^3_w / \epsilon \]
3) TKE-closure method: \[ K_2 = c_2 e^2 / \epsilon \]

4. Horizontal eddy diffusivity:

\[ F_h = \rho K_h S_h \quad S_h = (\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}) \quad S_h = \left( \frac{\partial v}{\partial r} - \frac{v}{r} \right) \cos 2\lambda + \left( \frac{\partial v}{\partial r} - \frac{v}{r} \right) \sin 2\lambda \]

\[
D_h^2 = \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)^2 + \left( \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \right)^2 \\
D_h^2 = 2 \left( \frac{\partial v}{\partial r} \right)^2 + 2 \left( \frac{v}{r} \right)^2 + \left( \frac{\partial v}{\partial r} - \frac{v}{r} \right)^2
\]

\[ D_h^2 = 2 \left( \frac{\partial v}{\partial r} \right)^2 + 2 \left( \frac{v}{r} \right)^2 + \left( \frac{\partial v}{\partial r} - \frac{v}{r} \right)^2 \]
Work with model developers to improve model physics based on observations
Implementation of observation-based physics in hurricane models

Thanks to Young Kwon and Bob Tuleya who modified the surface layer scheme code in HWRF to be consistent with observations!
Use observations to improve PBL physics in operational hurricane models

Before modification (operational HWRF)

After modification  (HWRF 2012)

Thanks to Gopal who modified the GFS boundary layer scheme code to lower Km and match with observations!
Impacts of the modified physics on the simulated storm structure and intensity forecast
Sensitivity of axisymmetric radial wind to vertical diffusivity

(Gopalakrishnan et al. 2012 JAS, in submission)

- depth of inflow layer more consistent with dropsonde composites
- peak radial inflow stronger with more accurate Km
- more prevalent role of BL dynamics in spin up process

The purple line is the inflow layer depth from the composite analysis using hundreds of dropsonde data (Zhang et al. 2011b MWR, on the characteristic height scales of the hurricane boundary layer).
EMC verification of the 2012 version HWRF model with new surface layer and boundary layer physics and high horizontal resolution (3km)

87% of total retrospective runs from 2010-2011 seasons show 10-25% reduction in track errors and 5-15% reduction in intensity errors

37 Storms
2010: Alex, Two, Bonnie, Colin, Five, Danielle, Earl, Fiona, Gaston, Hermine, Igor, Karl, Matthew, Nicole, Otto, Paul Richard, Shary, Tomas

2011: Arlene, Bret, Cindy, Don, Emily, Franklin, Gert, Harvey, Irene, Ten, Lee, Katia, Maria, Nate, Philippe, Rina, Sean
Summary

1. HRD’s aircraft observation data are unique for model diagnostics in terms of hurricane structure;

2. Observations also provide baseline for physics development and improvement in hurricane models;

3. Model deficiency can be identified through model diagnostics of TC structures based on observations;

4. Feedback to model developers leads to model improvements;

5. HFIP provides a bridge for model developers and observation scientists to work closely, which is promising.
Future work

1. Evaluate the surface layer and boundary layer structure in hurricane simulations with the 2012 version operational HWRF;

2. Further improve the parameterization of vertical eddy diffusivity in HWRF;

3. Evaluate the horizontal eddy diffusivity in HWRF;

4. Evaluate the vortex-scale and convective scale structures in HWRF simulations.
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NOAA Hurricane Research Division

NOAA/OMAO
Aircraft Operations Center