US National Weather Service
National Centers for Environmental Prediction
Environmental Modeling Center

2018 HWRF Tutorial

HWRF & HYCOM modeling team
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HYCOM coupling

Next Generation HWRF
1. Introduction to HYCOM Coupling
2. HYCOM Hurricane Regional Domains
3. Initial and Boundary Conditions
5. Example of Forecast Performance between Two Ocean Couplings
6. Review of Present 3-Way Ocean Coupling
7. Future Plans for Improvement of TC Forecasting
8. 3-Way Coupling
9. Lessons Learned - Recommendations

Outline
Prototype of Pre-operational forecast system

One of ocean models chosen for ocean model impact study as a Hurricane Forecast Improvement Project (HFIP) initiative as a Model Impact Tiger Team (OMITT) initiative. Forecast skills have been demonstrated for the North Atlantic and Eastern North Pacific Hurricanes (Kim et al., 2014), since 2017; the Western North Pacific Typhoons (Kim et al., 2015), since 2012; and the North Indian Ocean Cyclones, since 2017.

Realistic and idealized configurations, along with diagnostic and graphic codes, exist in DTC SVN, but currently HYCOM coupling framework is not supported by DTC yet.
### 1. HYCOM Coupling

#### Differences of Ocean Models

<table>
<thead>
<tr>
<th>Lateral Boundary Values</th>
<th>Initialization</th>
<th>Mixing Physics</th>
<th>Dynamics &amp; Configurations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly GDEM3 Climatology + daily GDAS SST assimilation + Feature Model</td>
<td>Melleor-Yamada 2.5 closure</td>
<td>Mellor-Yamada 2.5 closure</td>
<td>Hydrostatic, free-surface, primitive equations on C grid</td>
</tr>
<tr>
<td>Adjusted T/S fields</td>
<td>Rectangular</td>
<td>KPP</td>
<td>1/12-degree</td>
</tr>
<tr>
<td>3 hourly 2D and 6 hourly 3D global RTOFS* forecasts</td>
<td>41 hybrid isopycnal-Z</td>
<td>Mercator</td>
<td></td>
</tr>
<tr>
<td>6 hourly NCODA-HYCOM global analysis</td>
<td>40 sigma</td>
<td>Rectangular</td>
<td></td>
</tr>
</tbody>
</table>

* RTOFS = Real-Time Ocean Forecast System producing 2-day nowcasts and 8-day forecasts each day.

HYCOM is the community model (but not HYCOM coupling), having NRL as the primary developer. Reference at https://hycom.org
Domains vs. All TC storms 1851-2006

2. HYCOM Hurricane Regional Domains
3. Initial and Boundary Conditions

- Sea surface temperature (SST)
- Precipitation
- Atmospheric pressure
- Heat fluxes – Sensible, Latent, Total, Radiation, and net shortwave radiation
- Wind stress

Exchange Variables

- GFS = Global Forecast System
- GSI = Gridpoint Statistical Interpolation
- DA = data assimilation
- CS/WS = cold/warm start
- ic = initial conditions
- bc = boundary conditions

Components and Data Flow

Pink Shade – Future plan
HYCOM for 2-way coupling to HWRF

IC/BC from real-time global RTOFS (Real-Time Ocean Forecast System) 

(1) IC/BC from real-time global RTOFS (Real-Time Ocean Forecast System)

(2) HYCOM-HYCOM* NCODA analysis and available for any 6-hr cycle.

(3) BC uses 5.25 day forecasts from daily RTOFS products: 3 hourly for barotropic and 6 hourly for baroclinic solutions


* NCODA: Navy Coupled Ocean Data Assimilation

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3. Initial and Boundary Conditions
Typically, $T$, $Q_L$, and $Q_S$ are explicitly related with ocean coupling.

Kim et al. (2014) Ocean Role Represented in Non-coupled vs. Coupled Configuration

<table>
<thead>
<tr>
<th>SST Coupling</th>
<th>SST Parameters</th>
<th>3D Coupling</th>
<th>1D Coupling</th>
<th>Non-coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
<td>3D circulations including advection</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>yes</td>
<td>Vertical mixing</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>no</td>
<td>Mixed-layer model only to include $T_S$ and $Q_S$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SST feedback: Ocean Coupling Changes the TC Thermodynamics Loop

Non-coupled vs. Coupled Configuration in Ocean Role Represented
Turbulent Heat Flux

Estimated at the surface boundary layer module, using Monin-Obukhov Similarity Approach,

\[ \text{Turbulent Heat Flux} \]
Turbulent Heat Flux

Stability parameter \( \zeta = z/L \), where \( L = -U^*/k \)

\[ \left( \frac{\partial}{\partial z} \right)^a \theta - \left( \frac{\partial}{\partial z} \right)^s \theta \right) \frac{\partial U}{\partial z} \theta = \frac{\partial}{\partial z} \left( \frac{\partial}{\partial z} \right)^m \nu \frac{\partial}{\partial z} \theta \]

where

\[ \frac{\partial}{\partial z} \left( \frac{\partial}{\partial z} \right)^m \nu \theta = \frac{k}{2} \eta \]

Stability parameter is related to the mean gradients related to the mean gradients for momentum/heat fluxes

Stability Function

5. Review of Present 2-Way Ocean Coupling
**6. Example of Forecast Performance:**

Hurricane Blanca (2015)

Comparisons of forecasting performance between HYCOM and POM coupling to HWRF for Hurricane Blanca (2015) during the height of El Niño conditions.

**Synopsis for Hurricane Blanca (May 31 – June 9, 2015):**

This is one of the HFIP (Hurricane Forecast Improvement Project) Ocean Model Impact Tiger Team (OMITT) activities.

COMISS Total Precipitable Water

CMISS Total Precipitable Water composite images for 00Z June 1 (A), 18Z June 3 (B), and 12Z June 6 (C).
HYCOM for H5Y5
POM for HCTL

OHC Analysis

HYCOM

OHC in warm pool for HCTL is too small.
OHC in warm pool for H5Y5 is similar to the
OHC in warm pool for

Blanca Initial OHC (Ocean Heat Content)

\[
\text{OHC} = \int_{26}^{\infty} \rho C_p \left[ T(z) \right] d z
\]

where \( C_p \) is the specific heat capacity of water (cal g\(^{-1}\) C\(^{-1}\)), \( \rho \) is water density (kg m\(^{-3}\)), and \( T \) is water temperature in degrees Celsius.

Example of Forecast Performance:

Hurricane Blanca (2015)
Example of Forecast Performance:
Hurricane Blanca (2015)
As function of radial distance (km) from the TC center, from lead time 0 (IC=2015/6/3 00Z) to 120 h for H5Y5 in (A) and HCTL in (B). Solid and dashed horizontal line represent the time for the 1st peak intensity (June 3 18Z) and the 2nd peak intensity (June 6 12Z). Sensible Heat Flux, $Q_s$: HYCOM coupling < 250 W/m$^2$ vs. POM coupling < 80 W/m$^2$; Latent Heat Flux, $Q_L$: HYCOM coupling < 1005 W/m$^2$ vs. POM coupling < 600 W/m$^2$. 6. Example: Hurricane Blanca (2015)
Superimposed Vmax on Qs (A and C) and Pmin on CAPE (B and D). Units for Vmax and Pmin are kt and hPa, respectively. Units for Qs and CAPE are W m$^{-2}$ and J kg$^{-1}$, respectively.

**Example of Forecast Performance:**

**Hurricane Blanca (2015)**

**18-h Forecast (IC=0000 UTC June 3, 2015)**

- **Null CAPE**
  - Negative Qs predominant – high SST cooling
  - Loose TC size
  - Weak winds

- **High CAPE (≥ 2.12 J kg$^{-1}$)**
  - Positive and high Qs (≤ 233.3 W m$^{-2}$)
  - Tight TC size
  - High winds

- **HYCOM coupling (H5Y5)**

- **POM coupling (HCTL)**
Comparisons of track (A) and Vmax (B) intensity forecasts between operational HWRF (HCL) and experimental HWRF (H5Y5): The vertical error bars in (A) denote 95% confidence interval.

**Example of Forecast Performance:** Hurricane Blanca (2015)

Homogeneous Forecast Verification for all 33 cases
For a coupled system, LETKF is planned to use for regional HYCOM. Currently GSI for HWRF and NCODA for HYCOM, in separate.

Data Assimilation in a Coupled Framework

1. HWRF:
   a) Surface stress modified by effects of sea state, directionality of wind and wave, and surface currents

2. WAVEWATCH III (WW3):
   a) Forced by sea-state dependent wind stress, including effects of growing/decaying waves and Coriolis-Stokes forcing

3. HYCOM:
   a) Ocean currents
       b) Turbulent mixing modulated by the Stokes drift (Langmuir)

   Forced by sea-state dependent wind stress, including effects of turbulent mixing and Coriolis-Stokes forcing

Future Plans for Improvement of TC forecasting

- 3-way coupling HWRF-HYCOM-WW3
- Future Plans for Improvement of TC forecasting
Processes in the Air-Sea Interface

8. 3-way Coupling

https://www.whoi.edu/science/AOPE/dep/CEBLAST/main.html
8-1. Improvement of Ocean Coupling

1. Relative winds to the ocean surface currents

\[ \nu(z) - \nu_s \text{ for TC} = \nu(z) - \nu^0 = \nu^0 \]

Where \( \nu^0 \) is the ocean surface currents.

\[ \nu^0 = U^0(z) - U^0(z) \]

should be: \( U^0(z) - U^0(z) \) should be winds relative to the sea surface currents (\( \nu^0 \)).

\[ U^0(z) + U^0(z) \]

should be winds relative to the sea surface currents (\( \nu^0 \)).

Latent Heat Flux:

\[ 0^\nu \Omega (v_L - s_L) s \sigma d \nu d = \sigma \]

Sensible Heat Flux:

\[ 0^\nu \Omega (v_b - s_b) v \sigma d \nu d = \sigma \]

Momentum Flux:

\[ 0^\nu \Omega (p_c - v_c) v d = \]

HWRF: Flux estimated using the Monin-Obukhov similarity theory.

1. Relative winds to the ocean surface currents

\[ \text{where } u(z) \text{ is the ocean surface currents.} \]

\[ \nu^0 = U^0(z) - U^0(z) \]

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Latent Heat Flux:

\[ 0^\nu \Omega (v_L - s_L) s \sigma d \nu d = \sigma \]

Sensible Heat Flux:

\[ 0^\nu \Omega (v_b - s_b) v \sigma d \nu d = \sigma \]

Momentum Flux:

\[ 0^\nu \Omega (p_c - v_c) v d = \]

HWRF: Flux estimated using the Monin-Obukhov similarity theory.
2. Enhance vertical mixing by including Langmuir circulations.

Via Langmuir number (La):

1. Options for the Langmuir number (La):

   - Takaya et al. (2010): \( \text{La} = \max \left( \frac{3 + \frac{3}{2} \frac{U_s t}{\epsilon} \sqrt{U^*}}{\frac{3}{2} \frac{U_s t}{\epsilon}} \right) \)
   - Smyth et al. (2002): \( \text{La} \leq 1.0 \), \( \text{La} = 1.0 + \frac{C_w U_s t}{U^* + \epsilon} \) \( \leq 5.0 \), \( C_w = 0.15 \) \( U_s t_{\text{max}} = \frac{0.6 - k_B d}{U^*} \)
     \( \text{La} = 1.0 + 0.098 \sqrt{\frac{3 + \frac{3}{2} \frac{U_s t}{\epsilon} \sqrt{U^*}}{\frac{3}{2} \frac{U_s t}{\epsilon}}} \)
     \( \text{La} = \max \left( \frac{3 + \frac{3}{2} \frac{U_s t}{\epsilon} \sqrt{U^*}}{\frac{3}{2} \frac{U_s t}{\epsilon}} \right) \)

Base vertical mixing scheme is KPP (K-Profile Parameterization) mixing.
Figure 1. Processes in the droplet evaporation layer.

\[
\frac{d\rho}{dt} + \nabla \cdot (\rho \mathbf{v}) = 0
\]

\[
\frac{dH}{dt} + \nabla \cdot (\rho c_p \mathbf{v} H) = \frac{d}{dt} \left[ \rho H \right]_{\text{int}} + \frac{d}{dt} \left[ \rho H \right]_{\text{latent}}
\]

Andreas et al. 2017

Figure 1. Results of a microphysical model [39] that predicts the temperature, radius, and salinity evolution of an individual spray droplet.
\[ Q_{\text{en}}, T = H_s, \text{int} + H_L, \text{int} + (\beta Q_s + \gamma Q_L) \]

\[ e.g.: Q_{\text{en}}, sp = \beta Q_s + \gamma Q_L = \rho_w C_w (\theta_s - T_{\text{eq}}, 100) \]

\[ V_{\text{en}} = \begin{cases} 6.84 \times 10^{-8} & \text{for} \ 0 \leq u^*, B \leq 0.1435 \text{ m/s} \\ 1.80 \times 10^{-5} & \text{for} \ 0.1435 \text{ m/s} \leq u^*, B \end{cases} \]

New wind function, \( V_{\text{en}} \):

\[ T_{\text{eq}, 100} = \text{the eq. temperature of droplets with 100 \mu m radius.} \]

\[ (p^* n)^u L_{\theta, 100} - \theta = \lambda \Delta \theta + \gamma \Delta \theta = \text{en}. \]

\[ \Delta \theta = \text{en}. \]

(\[ \Delta \lambda + \gamma \Delta \theta \]) + (\[ \Delta \theta H + \gamma \Delta \theta \]) = \text{en}. \]

8-3. Sea Spray
Better physics should result in better models.

But, there are more subtle reasons too:

Lessons Learned - Recommendations
1. Focus on best possible description of physical states for all models.

2. Deal with detuning of model due to "improved" physics in two ways:
   - Framework. Better physics makes for a better model. However, better model will almost always detune the model in a coupled framework.
   - Retune as possible, particularly when individual processes are documented to describe nature better (long term systematic approach).

3. We need to have a set of metrics for HWRF that reflects these mentioned above: Track and intensity verification alone will never work.

4. Coupled model makes further development of modeling system a little more complicated.

This is an unavoidable side effect of doing things physically better.

Kim et al. 24

9. Lessons Learned - Recommendations
Lessons learned

5. The key for coupled modeling is in the fluxes.

6. Developing a coupled model is a cyclic process:
   - First emphasis on getting the ocean right.
   - In the process, many issues with HWRF were revealed.
   - Not necessarily major issues, but critical for realistic coupling with a realistic ocean model.
   - Climatology based ocean model component appears less sensitive to these errors as ocean responses are suppressed to gain a more robust system.
   - Fixes and updates require a revisit to make sure that all ocean responses are realistic.

... and this will rinse and repeat...
Questions?