Next Generation HWRF

HYCOM coupling

Hyun-Sook Kim
HWRF & HYCOM modeling team

2018 HWRF Tutorial

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

Outline

1. Introduction to HYCOM Coupling
2. HYCOM Hurricane Regional Domains
3. Initial and Boundary Conditions
4. Non-Coupled vs. Coupled
5. Review of Present 2-way Ocean Coupling
6. Example of Forecast Performance between Two Ocean Model Couplings: Hurricane Blanca (2015)
7. Future Plans for Improvement of TC forecasting
8. 3-way Coupling
9. Lessons Learned - Recommendations

1. HYCOM Coupling

Prototype of Pre-operational forecast system

- One of ocean models chosen for ocean model impact study as a Hurricane Forecast Improvement Project (HFIP) initiative – Ocean Model Impact Tiger Team (OMITT)
- Forecast skills have been demonstrated for
  - the North Atlantic and Eastern North Pacific hurricanes (Kim et al., 2014), since 2009;
  - 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

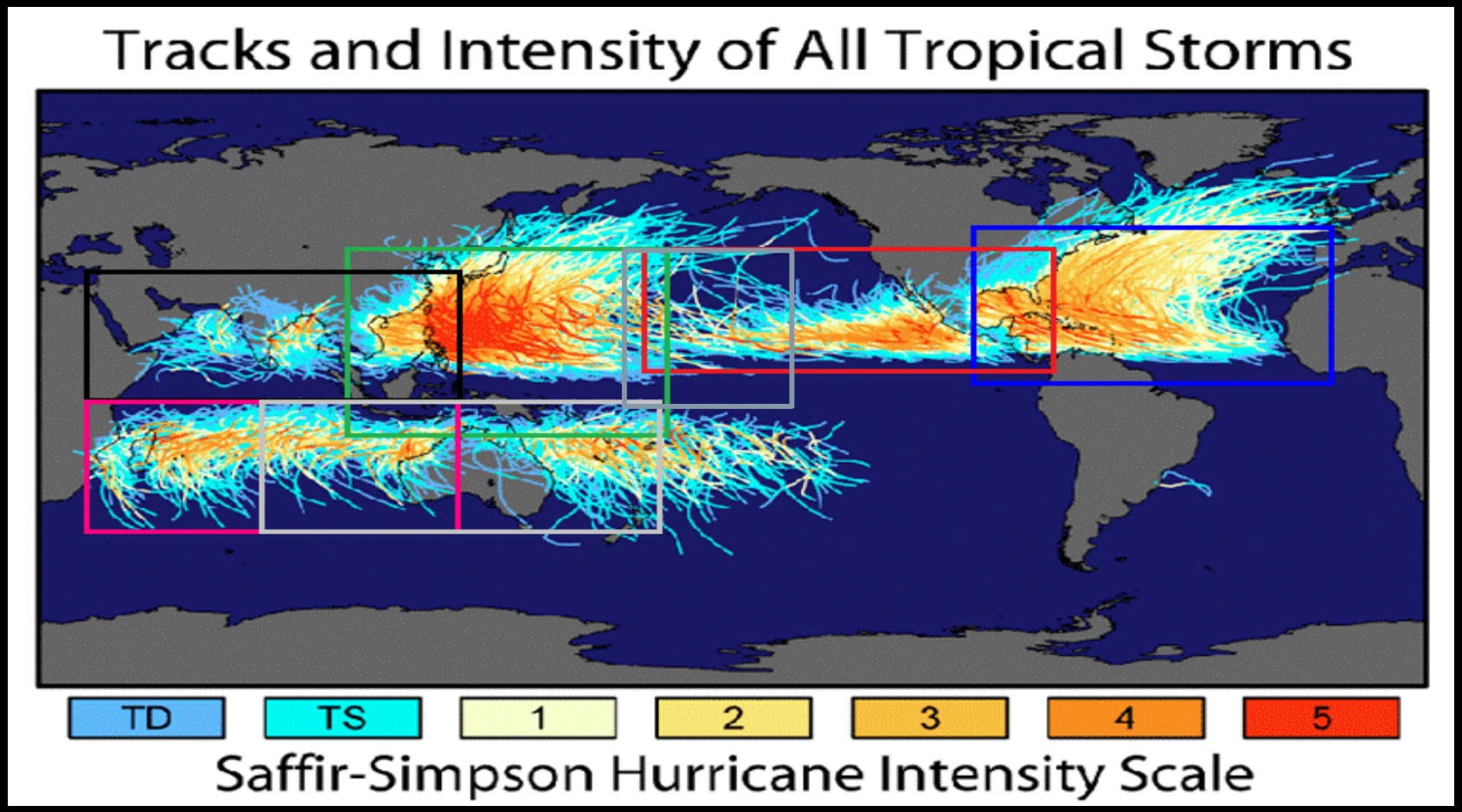
	POM	HYCOM
Dynamics & Configurations	Hydrostatic, free-surface, primitive equations on C grid	
	1/12-degree	
	Rectangular	Mercator
	40 sigma	41 hybrid isopycnal-Z
Mixing Physics	Mellor-Yamada 2.5 closure	KPP
Initialization	Monthly GDEM3 Climatology + daily GDAS SST assimilation + Feature Model	6 hourly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

*: 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*

2. HYCOM Hurricane Regional Domains

Domains *vs.* All TC storms 1851-2006

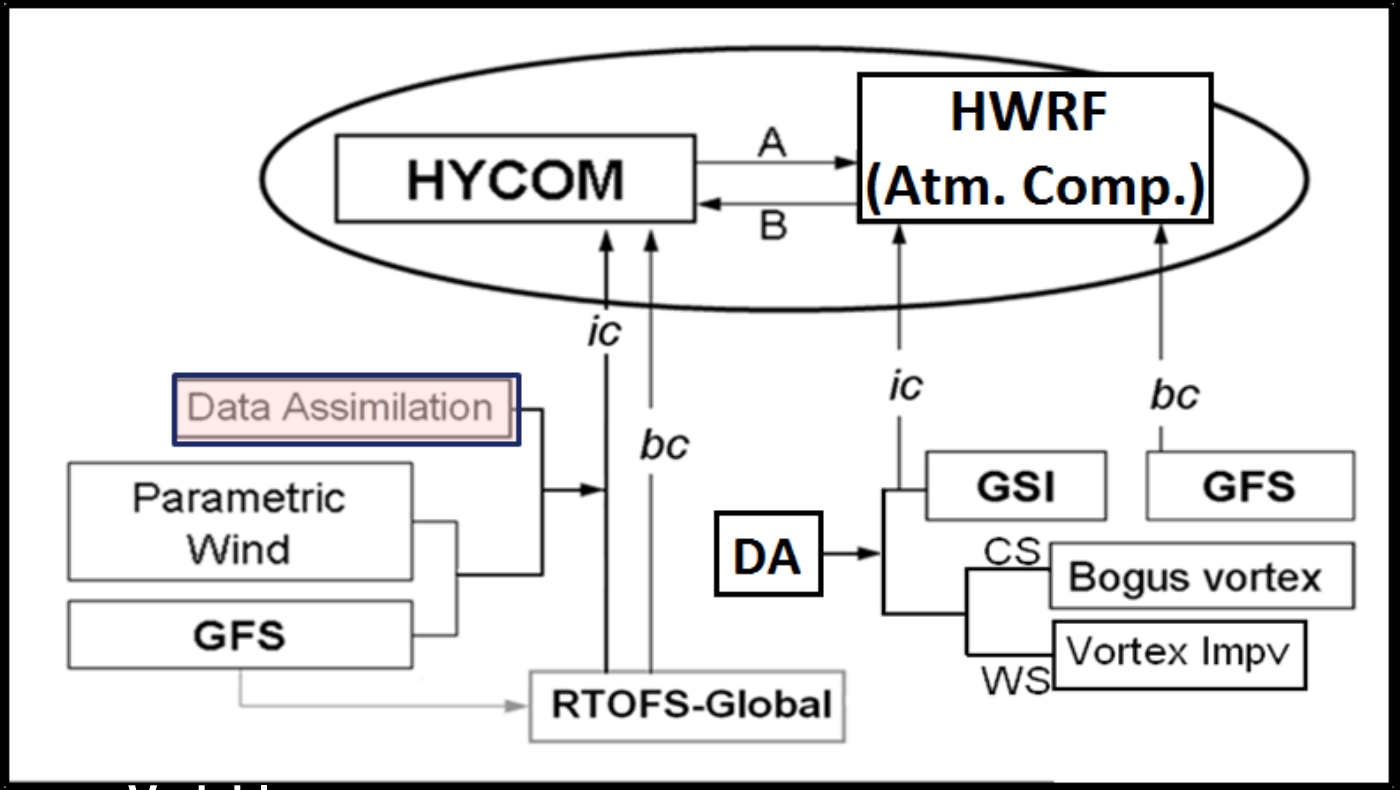


www.meted.ucar.edu, edited by Hyun-Sook Kim

- **NHC**: North Atlantic (blue), Eastern North Pacific (red), Central North Pacific (gray).
- **JTWC**: Western North Pacific (green), Eastern South Indian/Western South Pacific (light gray), North Indian (black), and South Indian (pink).

3. Initial and Boundary Conditions

Components and Data Flow



Pink Shade – future plan

Exchange Variables

A: sea surface temperature (SST)

B:

1. Precipitation
2. Atmospheric pressure
3. Heat fluxes – Sensible, latent, total radiation, and net shortwave radiation
4. Wind stress

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

3. Initial and Boundary Conditions

HYCOM for 2-way coupling to HWRF

1) IC/BC from real-time global RTOFS (Real-Time Ocean Forecast System) . RTOFS uses the same eddy-resolving HYCOM dynamics and physics solutions on 1/12-degree horizontal and 41 vertical layers.

2) IC uses NCODA*-HYCOM 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

4) **E**arth **S**ystem **M**odeling **F**ramework (**ESMF**) compliance: ready for coupling in **N**OAA **E**nvironmental **M**odeling **S**ystem (**NEMS**) framework.

* NCODA: Navy Coupled Ocean Data Assimilation

4. Ocean Role Represented in Non-coupled vs. Coupled Configuration

SST feedback: Ocean Coupling changes the TC thermodynamics loop

	Configuration	Sea surface parameters	SST cooling
1	Non-coupling	Fixed and persistent (T_s and q_s)	no
2	1D coupling	Mixed-layer model only to include vertical mixing	yes
3	3D coupling	3D circulations including advection	yes

Typically, T_s, Q_L, and Q_S are explicitly related with ocean coupling.

$$Q_L = \rho_a L_e C_l (q_s - q_a) U_{10}$$

$$Q_s = \rho_a C_p C_s (T_s - T_a) U_{10}$$

U_{10}=wind speed at 10 m
L_e=latent heat of evaporation
q_s/q_a=specific humidity at sea surface and 10 m
C_p=specific heat capacity of air
T_s/T_a=sea and air temperature
ρ_a = air density

5. Review of Present 2-way Ocean Coupling

Turbulent Heat Flux

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

Roughness lengths:

- The aerodynamic roughness (wind) = z_{om}
- The thermal roughness (heat & water vapor) = z_{oh}

In general, $z_{om} \neq z_{oh}$.

But, in HWRF

$z_{om} = z_{oh} = z_o$ is assumed.

The bulk formulae for exchange coefficients and assumption of C_s=C_L=C_h

$$C_d = \frac{k^2}{[\ln\left(\frac{z_r}{z_0}\right) - \Psi_m(\frac{z_r}{z_0})]^2} \qquad C_h = \frac{k^2}{[\ln(\frac{z_r}{z_0}) - \Psi_m(\frac{z_r}{z_0})][\ln(\frac{z_r}{z_0}) - \Psi_h(\frac{z_r}{z_0})]}$$

where

K = the von Karman coefficient (0.4),

Z_r = the reference level (the lowest numerical level),

$\Psi_{m/h}(\frac{z_r}{z_0})$ = non-dimensional stability function for momentum/heat fluxes related to the mean gradients

5. Review of Present 2-way Ocean Coupling

Turbulent Heat Flux

Stability Function:

$\Psi_{m/h}(\zeta)$ = non-dimensional stability function for momentum/heat fluxes related to the mean gradients

Stability parameter,

$\zeta = z/L$,

L = the MO length scale, depending on the surface momentum and buoyancy flux (B_s)

$$L = -U_*^3/kB_s,$$

where $U_*^2 = C_d U(z_r)^2$

$$B_s = C_h U(z_r) \frac{g}{\theta_{vs}} [\theta_{vs} - \theta_v(z_r)]$$

$\theta_{vs/v}$ = virtual temperature at sea surface (s) and reference level (z_r)

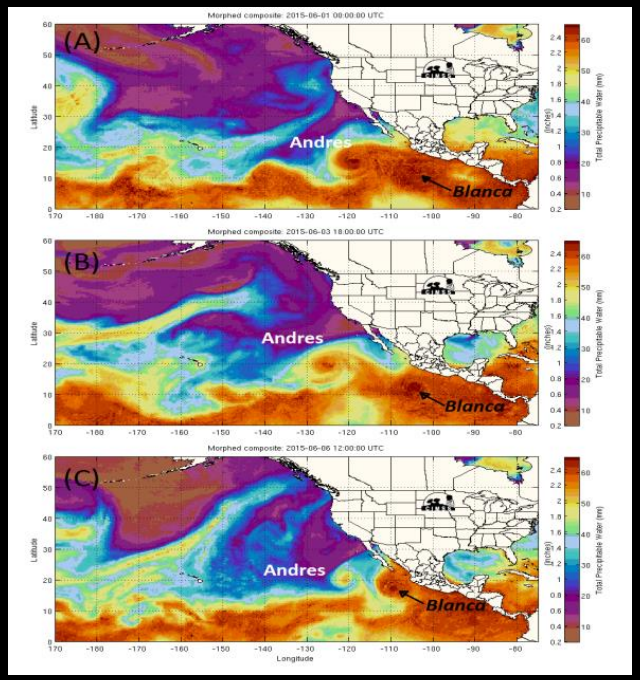
Kim et al. 10

6. Example of Forecast Performance: Hurricane Blanca (2015)

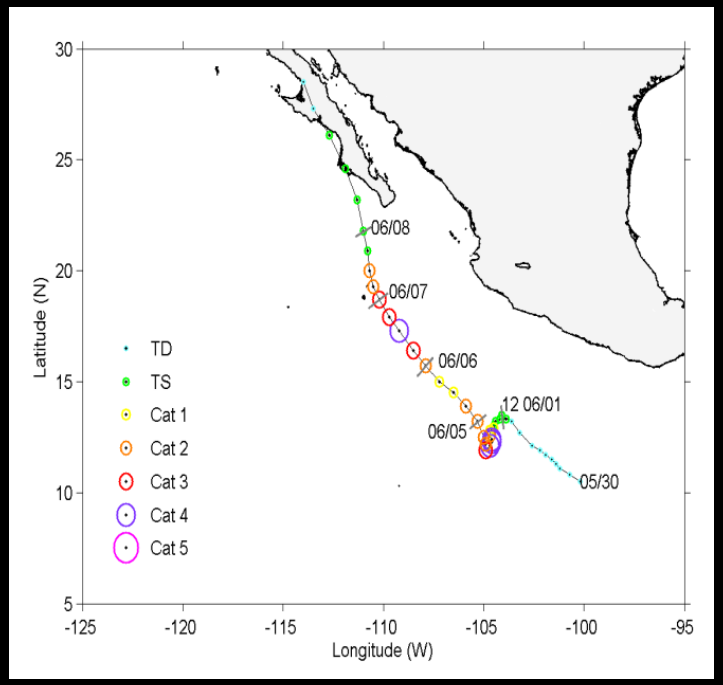
Comparisons of forecasting performance between HYCOM and POM coupling to HWRF for Hurricane Blanca (2015) during the height of El Niño conditions

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

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



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



NHC best track and observed intensity in the Saffir-Simpson wind scale.

Kim et al. 11

6. Example of Forecast Performance: Hurricane Blanca (2015)

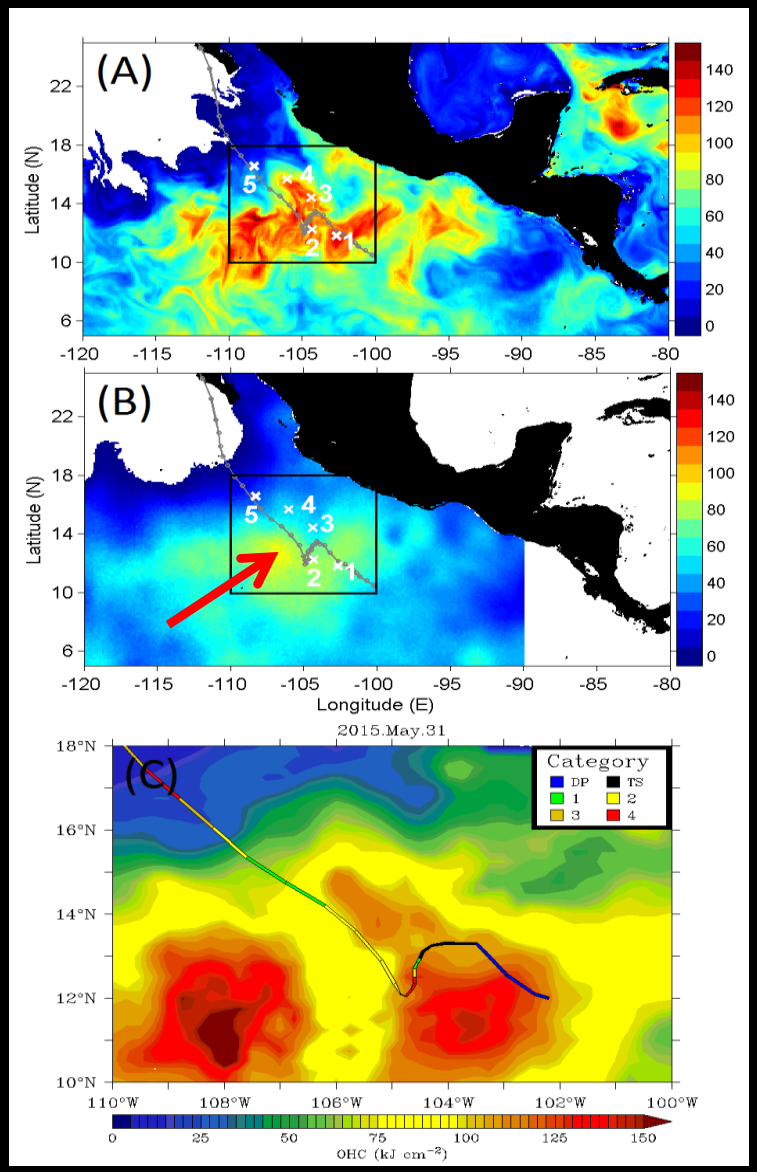
Blanca Initial OHC (Ocean Heat Content)

$$OHC = Cp \int_{0}^{z26} \rho(z)[T(z) - 26^{o}C]dz,$$

where *Cp* is the specific heat capacity of water (cal g^{-1} C^{-1}), ρ is water density (kgm^{-3}), and T is water temperature in degrees Celsius

HYCOM for H5Y5

POM for HCTL



OHC Analysis
http://www.rsmas.miami.edu/groups/upper-ocean-dynamics/research/ocean-heat-content/

OHC in warm pool for H5Y5 is similar to the OHC analysis.

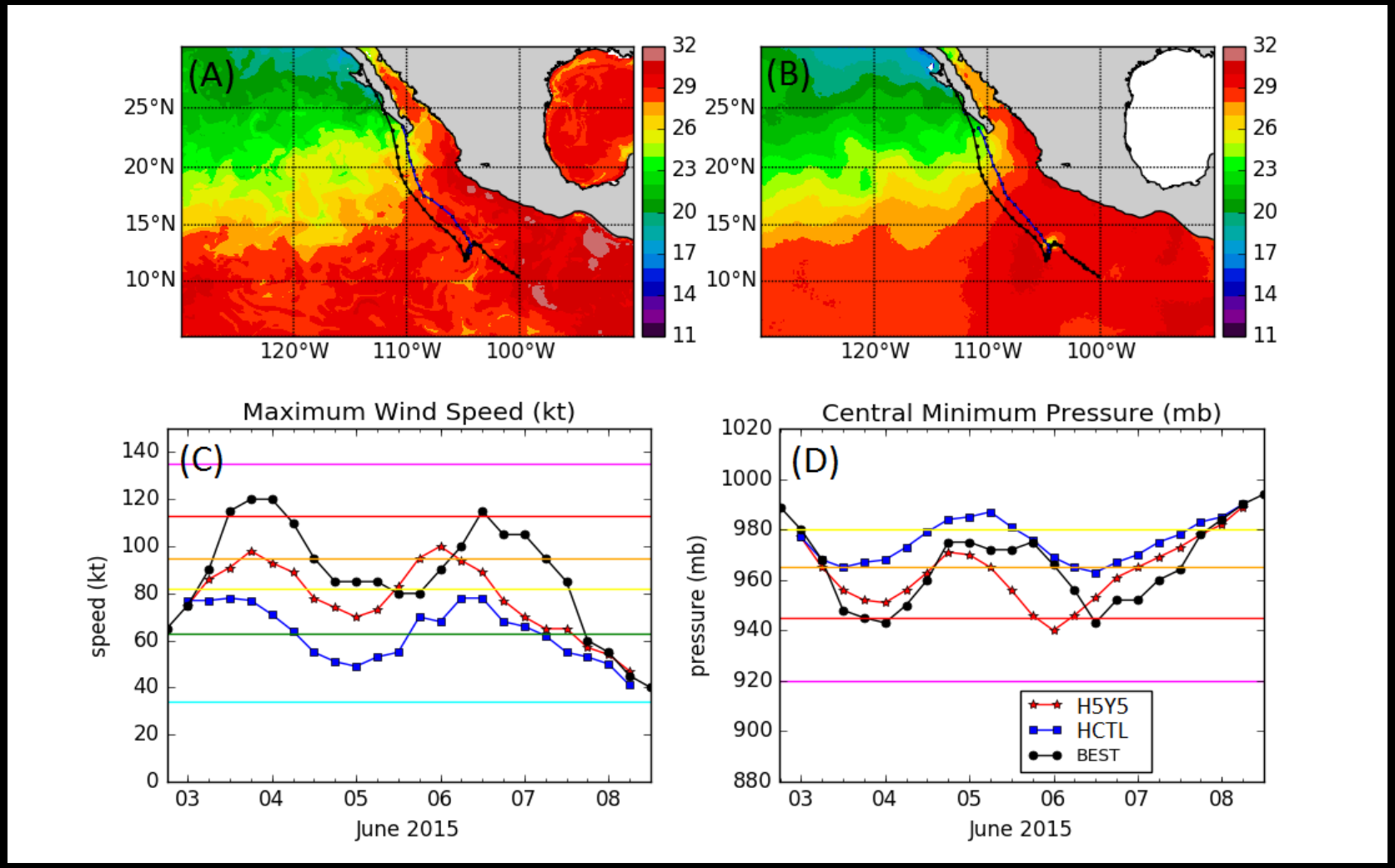
OHC in warm pool for HCTL is too small

Kim et al. 12

6. Example of Forecast Performance: Hurricane Blanca (2015)

BLANCA INITIAL SST AND FORECAST INTENSITY

H5Y5 SST **HCTL SST**



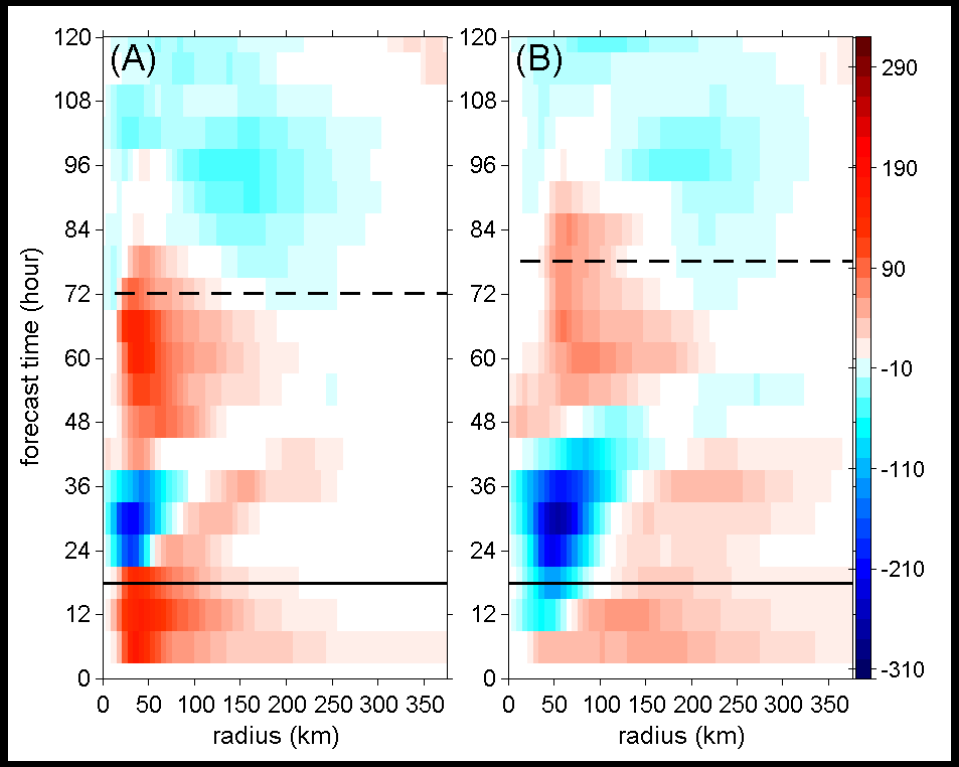
Kim et al. 13

6. Example: Hurricane Blanca (2015)

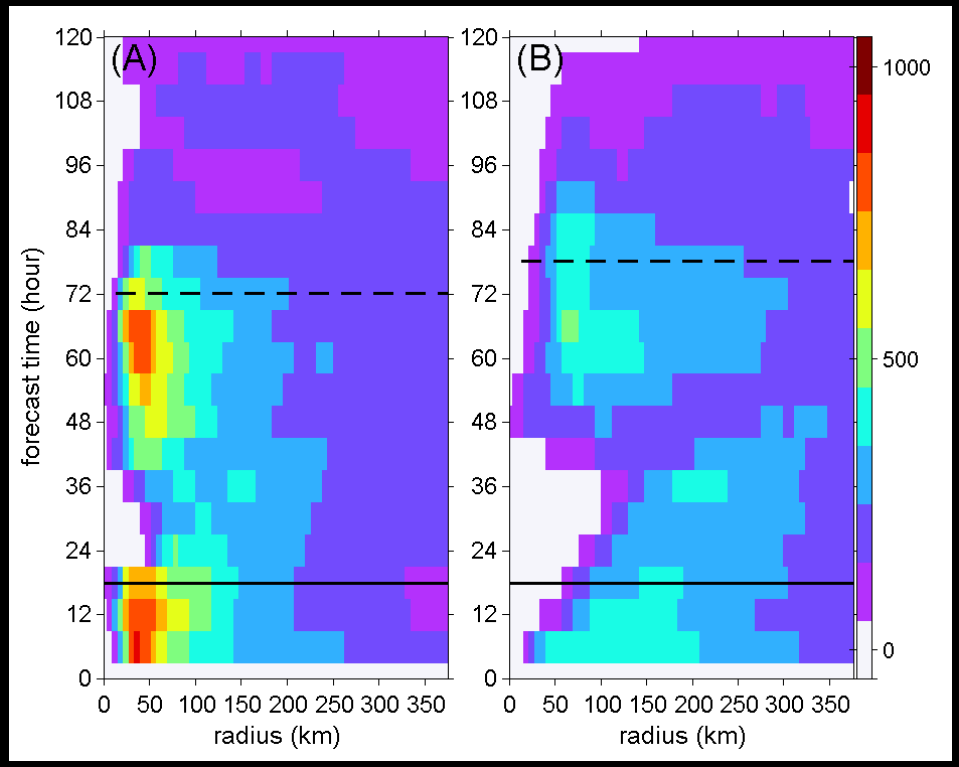
Turbulent Heat Flux

Hovemoller Diagrams of azimuthal average

Sensible Heat Flux, Q_s



Latent Heat Flux, Q_L



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 12 Z).

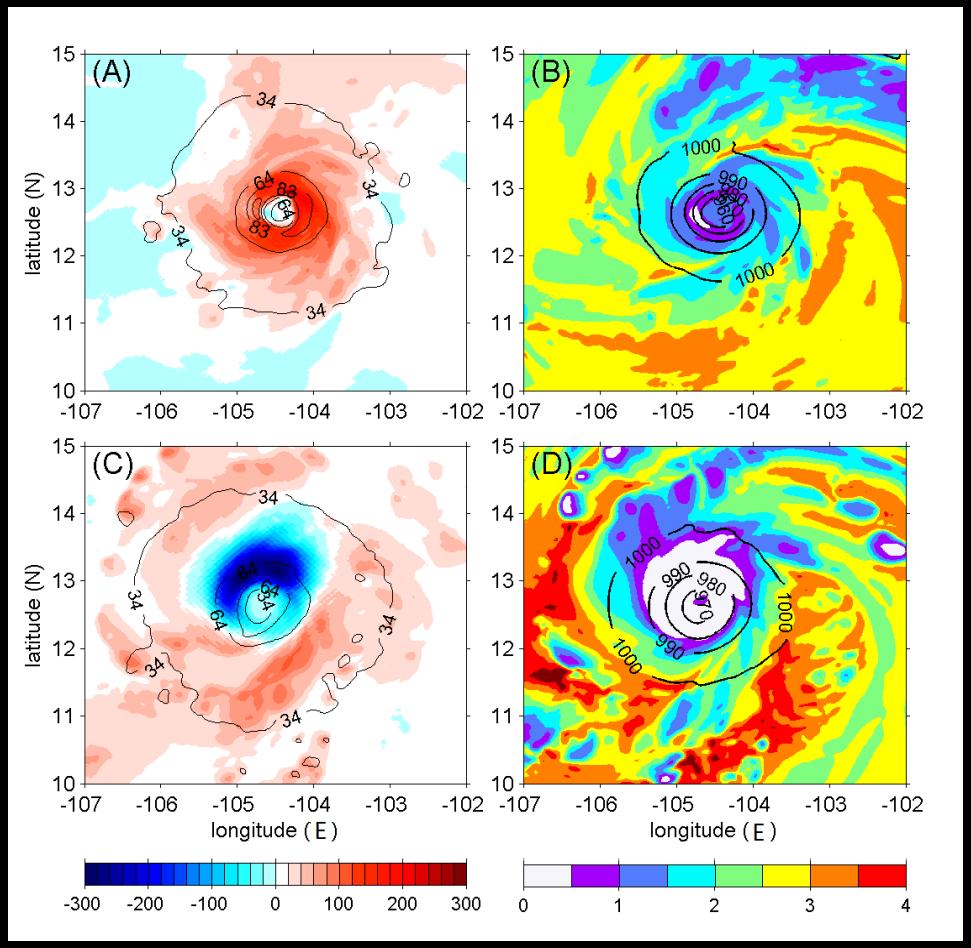
Q_S: HYCOM coupling < 250 W/m^2 vs. POM coupling < 80 W/m^2;
Q_L: HYCOM coupling < 1005 W/m^2 vs. POM coupling < 600 W/m^2.

Kim et al. 14

6. Example of Forecast Performance: Hurricane Blanca (2015)

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

Qs (Wm^{-2}) and CAPE ($kJ\ kg^{-1}$)



Superimposed Vmax on Qs (A and C) and Pmin on CAPE (B and D). Units for Vmax and Pmin are kt and hPa, respectively.

HYCOM coupling (H5Y5)

- High winds
- Tight TC size
- Positive and high Qs (≤ 233.3 Wm^{-2});
- High CAPE (≤ 2.12 Jkg^{-1})

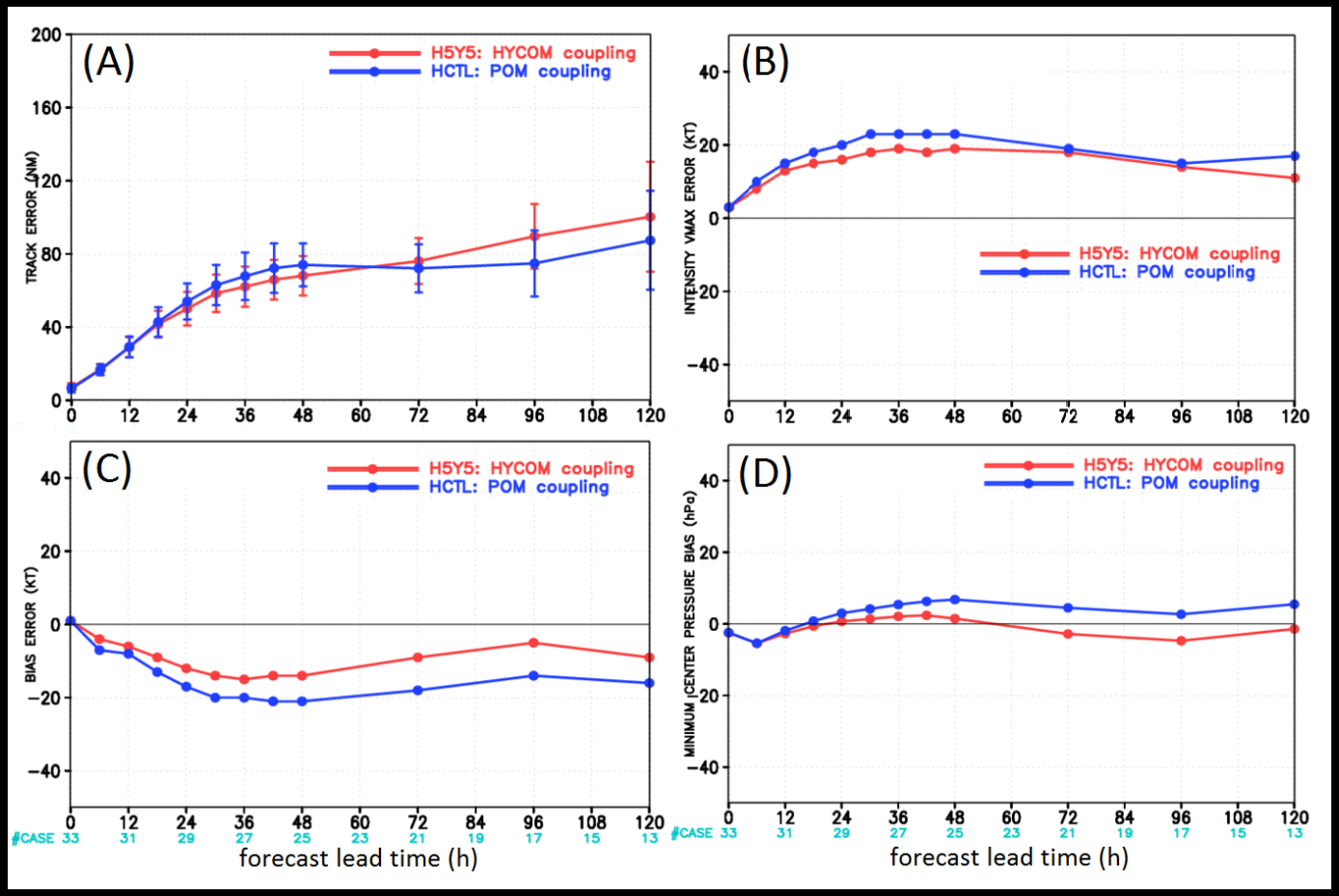
POM coupling (HCTL)

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

Kim et al. 15

6. Example of Forecast Performance: Hurricane Blanca (2015)

Homogeneous Forecast Verification for all 33 cases



Comparisons of track (A) and Vmax (B-C)/Pmin (D) intensity forecasts between operational HWRF (HCL) and experimental HWRF (H5Y5): The vertical error bars in (A) denote 95% confidence interval.

Kim et al. 16

7. Future Plans for Improvement of TC forecasting

- **3-way coupling HWRF-HYCOM-WW3**

  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 ocean currents
  3. HYCOM:
     a) Forced by sea-state dependent wind stress, modified by growing/decaying waves and Coriolis-Stokes forcing
     b) Turbulent mixing modulated by the Stokes drift (Langmuir turbulence)

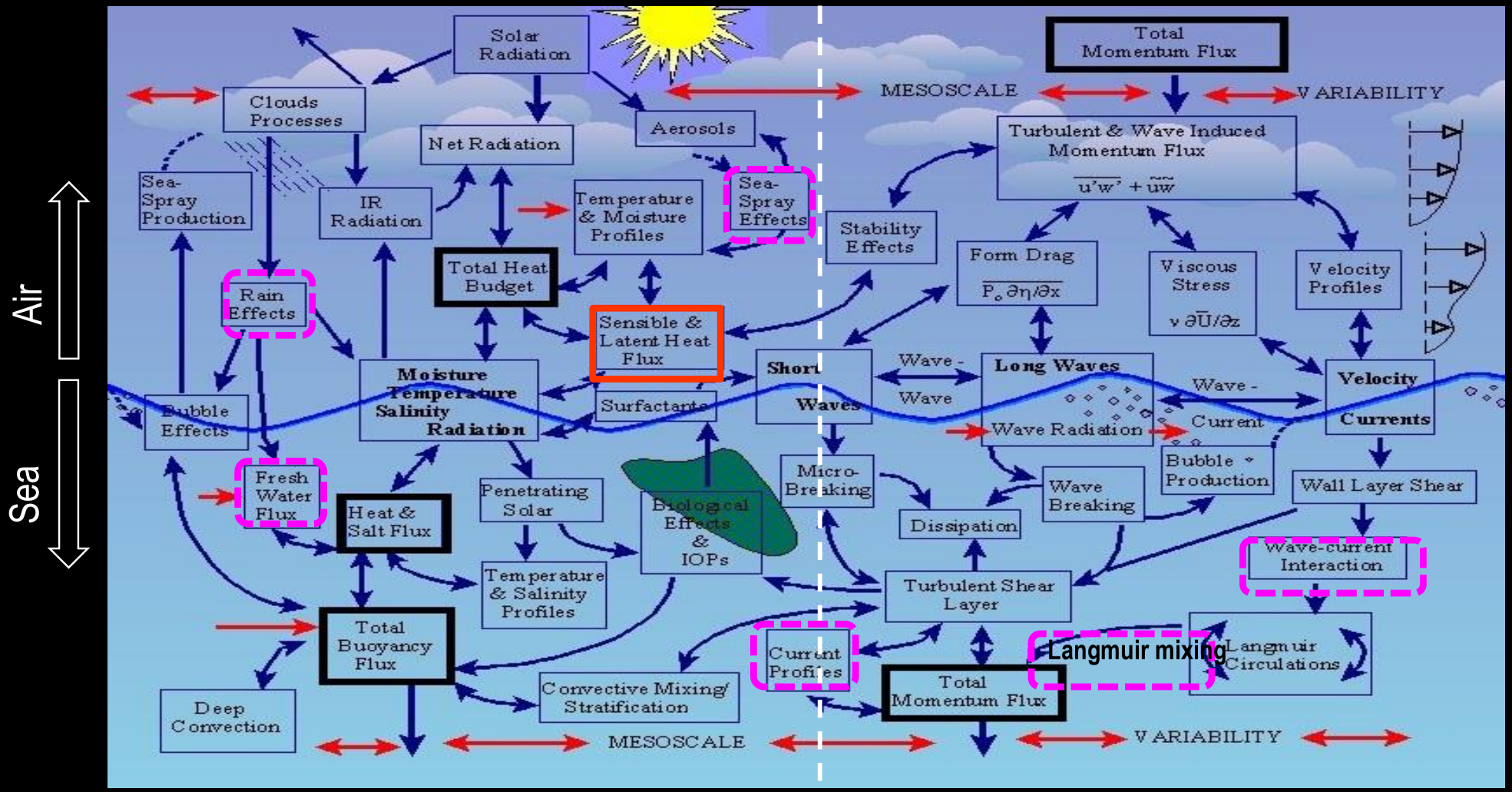
- **Data Assimilation in a coupled framework**

  Currently GSI for HWRF, and NCODA for HYCOM, in separate.
  For a coupled system, LETKF is planed to use for regional HYCOM.

Kim et al. 17

8. 3-way Coupling

Processes in the Air-Sea Interface



http://www.whoi.edu/science/AOPE/dept/CBLASTmain.html

Future planned testing and implementation

Kim et al. 18

8-1. Improvement of Ocean Coupling

1. Relative winds to the ocean surface currents

HWRF: Flux estimated using the Monin-Obukhov similarity theory

Momentum Flux: $\tau = \rho_a C_d U_{10}$

Latent Heat Flux: $Q_L = \rho_a L_e C_l (q_s - q_a) U_{10}$

Sensible Heat Flux: $Q_s = \rho_a C_p C_s (T_s - T_a) U_{10}$

U_{10} and $U(z_r)$ should be winds relative to the sea surface currents (U_s):

$U_{10}=U(z_r)$ should be:

- $U(z_r) - U_s$ *for TC*

Where Us is the ocean surface currents.

Kim et al. 19

8-2. 3-way coupling: HWRF-HYCOM-WW3

2. Enhance vertical mixing by including Langmuir circulations, via Langmuir number (La)

- Base vertical mixing scheme is KPP (K-Profile Parameterization) mixing
- Options for the Langmuir # (La):

1. McWilliams and Sullivan (2001); $La = \sqrt{1 + 0.08 * U_{st}^2/(U_*^2 + \varepsilon)}$
2. Smyth et al. (2002); 1.0 ≤ $La = \sqrt{1 + C_w * U_{st}^2/(U_*^2 + \varepsilon)}$ ≤5.0,

$$C_w = 0.15\left(\frac{U_*^3}{\max(U_*^3 + 0.6*(-k)Bd, \varepsilon)}\right)^2$$

3. Harcourt and D'Asaro (2008) & McWilliams and Sullivan (2001);

$$La = \sqrt{1 + 0.098 * \sqrt{U_{st}^2/(U_*^2 + \varepsilon)}}$$

4. Takaya et al. (2010); $La = \max\left(\left[\left(\frac{U_*}{U_{st}+\varepsilon}\right)^{\frac{1}{2}}\right]^{-0.667}, 1\right)$

8-3. Sea Spray

Andreas et al. 2014

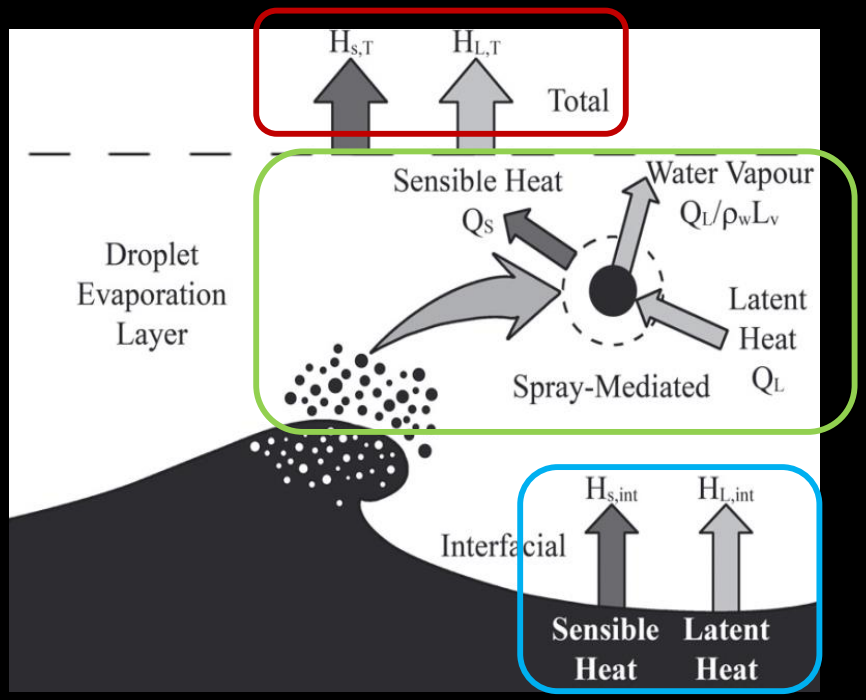


Figure 1. Processes in the droplet evaporation layer.

$$Q_{en,T} = \left(H_{s,int} + H_{L,int}\right) + \left(\beta\overline{Q_s} + \gamma\overline{Q_L}\right)$$

Andreas et al. 2017

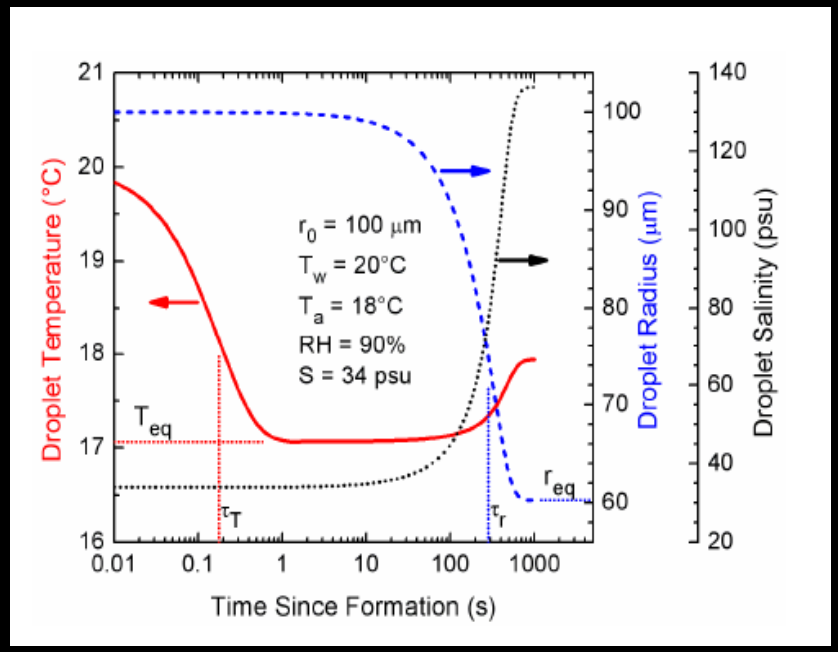


Figure 1. Results of a microphysical model [39] that predicts the temperature, radius, and salinity evolution of an individual spray droplet.

8-3. Sea Spray

Andreas et al. 2014

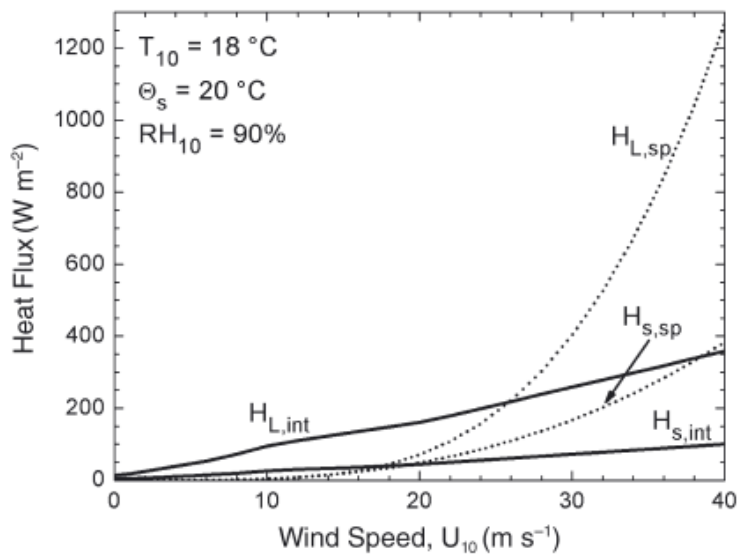


Figure 9. Calculations of the interfacial and spray latent and sensible heat fluxes from our new bulk flux algorithm for a range of 10 m wind speed, U_{10}. The sea-surface temperature (Θ_s) and 10 m values of air temperature (T_{10}) and relative humidity (RH_{10}) are fixed at the values indicated. The sea-surface salinity is 34 psu, and the barometric pressure is 1000 mb.

$$Q_{en,T} = \left(H_{s,int} + H_{L,int}\right) + \underbrace{\left(\beta\overline{Q_s} + \gamma\overline{Q_L}\right)}_{Q_{en,sp}}$$

e.g:

$$Q_{en,sp} = \beta\overline{Q_s} + \gamma\overline{Q_L} = \rho_w C_w(\theta_s - T_{eq,100})V_{en}(u_{*,B})$$

$T_{eq,100}$ = the eq. temperature of droplets with 100 μm radius.

New wind function, V_{en}:

$V_{en} = 6.84 \times 10^{-8}$ for $0 \leq u_{*,B} \leq 0.1435$ m/s

$V_{en} = 1.80 \times 10^{-5}\, u_{*,B}^{2.87}$ for 0.1435 m/s $\leq u_{*,B}$

Kim et al. 22

9. Lessons Learned - Recommendations

Better physics should result in better models

But, there are more subtle reasons too:

- Coupling forces you to take a closer look at details of the constituent models, in ways that are often complementary to the way the models are conventionally validated.

- This often leads to systematic improvement of the constituent models. That often has a positive impact on the component models, even if the impact on the actual coupling is found to be minimal.

9. Lessons Learned - Recommendations

1. Focus on best possible description of physical states for all models.
   - Better physics makes for a better model. However, better physics in a well tuned model will almost always detune the model in a coupled framework.

2. Deal with de-tuning of model due to “improved” physics in two ways, which makes most sense.
   - Deal with this as bias treatment in coupler (quick and dirty).
   - 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.

9. Lessons Learned - Recommendations

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

A weather model with a fixed or climatological SST is constrained in terms of systematic seasonal and climate shifts. But, in a coupled model, there is no constraint to the ocean state and also to the weather model. Hence, spurious drifts of the SST and mixed layer in general in the ocean will result in spurious drifts in the weather model, with a strong possibility of (nonlinear) feedback.

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 ad repeat…

Questions?