Ocean, Waves and Sea Spray in HWRF

Efforts, Progress and Future

Hyun-Sook Kim
Hyun.sook.kim@noaa.gov

Behalf of
Hendrik L. Tolman
Chief, Marine Modeling and Analysis Branch
NOAA/NWS/NCEP/EMC

Hendrik.Tolman@noaa.gov

Hurricane modeling team at EMC

- V. Tallapragada and team (7 + leveraging EMC ≈ 5).
- Original GFDL hurricane model coupled to POM ocean model in operations since 2005.
  - Main justification is to improve intensity forecast.

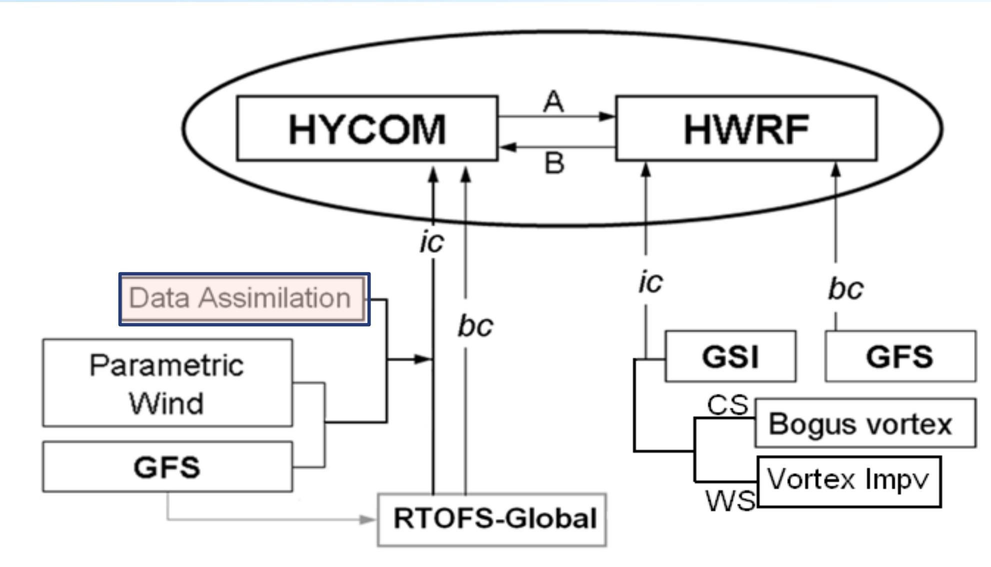
- Now in HWRF hurricane model.
  - Presently with POM model coupling from GFDL since 2007.
  - Moving to HYCOM coupling.

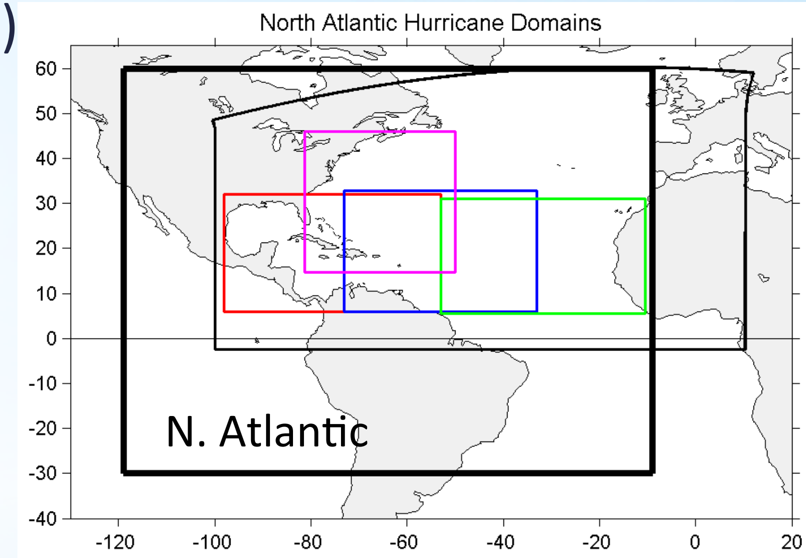
- In Progress and Future:
  - 3-way coupling - Add wave coupling in collaboration with URI and U. Miami.
  - **N**OAA **E**nvironmental **M**odeling **S**ystem (**NEMS**) framework – **E**arth **S**ystem **M**odeling **F**ramework (**ESMF**) compliance in collaboration with NLR and U. Miami

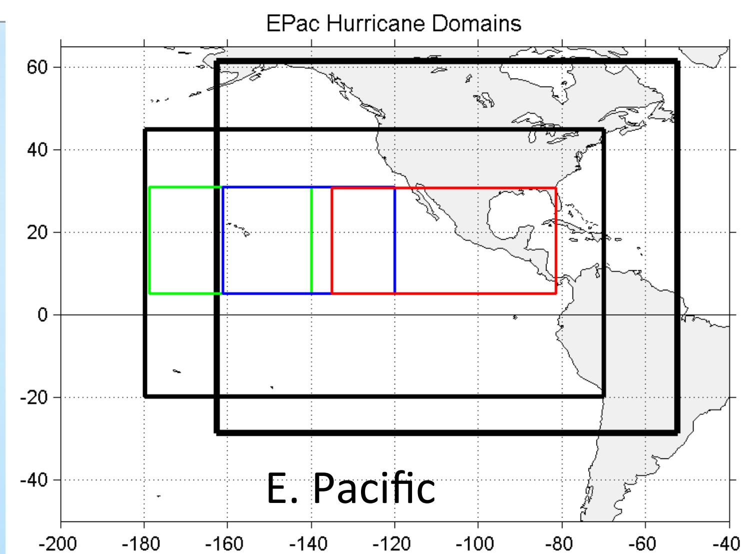
HWRF-HYCOM

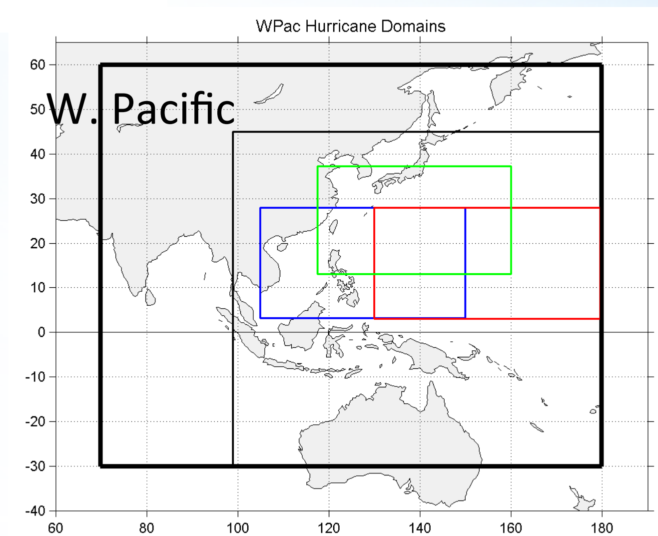
2-way coupling

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









Current:

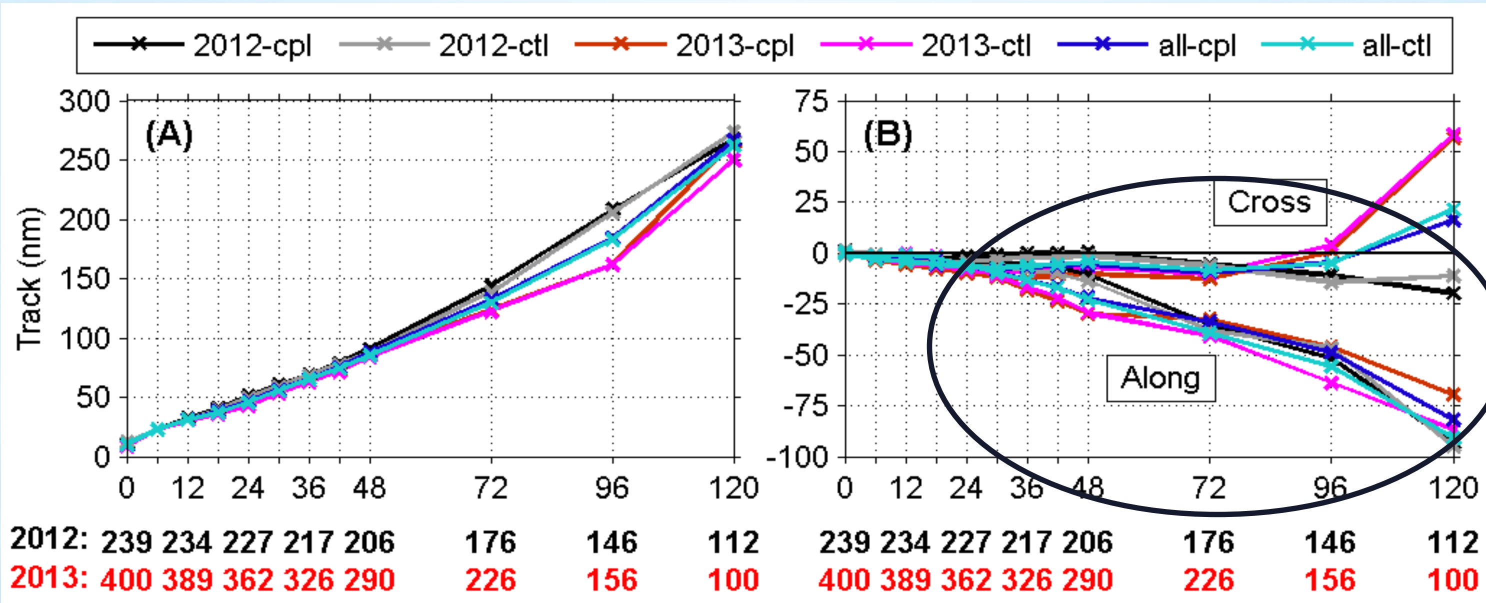
Future - basin

HWRF parent

Typhoon Forecasts for the 2012 and 2013 season HWRF-HYCOM (cpl) vs. HWRF (ctl)

2-way coupling

Track Verification (639 cases)



Absolute Mean Error

Component Mean Error

- The differences in TC track between Coupled (**cpl**) and persistent SST (**ctl**) forecasts are very small.
- Analysis of the individual components suggests that the tracks have a southwestward bias, but having ocean coupled corrects this bias. cf. southward bias (Khain and Ginis, 1991) or northward bias (Bender et al. 1993) for a westward moving storm.

Typhoon Forecasts for the 2012 and 2013 seasons
HWRF-HYCOM (cpl) vs. HWRF (ctl)

2-way coupling

Intensity verification (639 cases)

- HWRF-HYCOM (**cpl**) shows smaller error especially later forecast hours, cf non-coupled (**ctl**).
- Mostly, negative bias in Vmax, and positive Pmin.

➡ ***HWRF – highly tuned (2012 runs)***

Pmin-Vmax relationship:

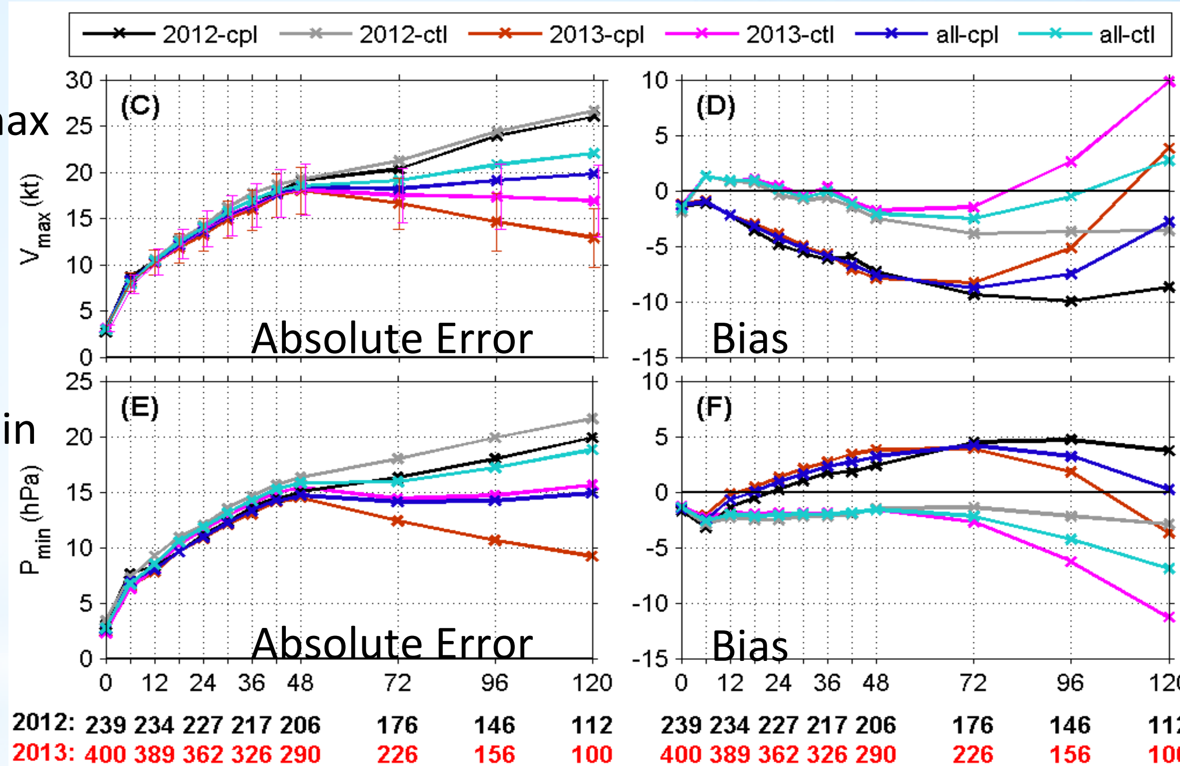
- Skillful Pmin simulations at Vmax range between 25 and 100 kt. Under-prediction of Pmin for both lower and high Vmax.

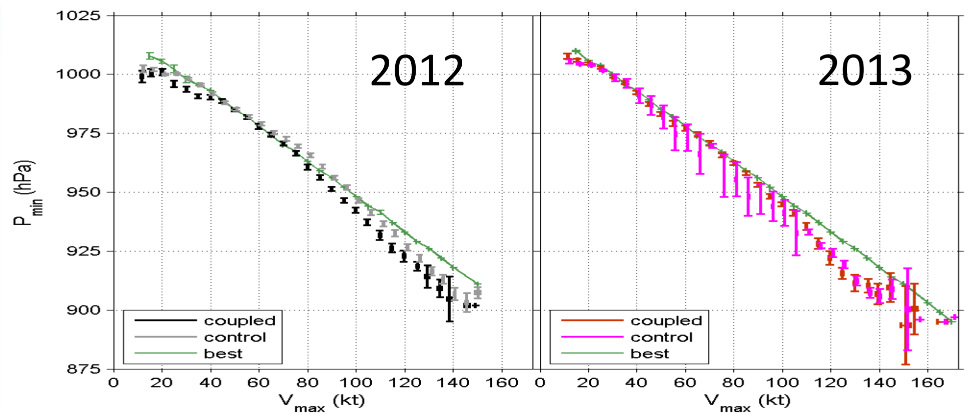
Seasonal Performance:

- HWRF better for 2012 and
- HWRF-HYCOM better for 2013

Vmax

Pmin





Vmax. vs. Pmin

SST Analysis

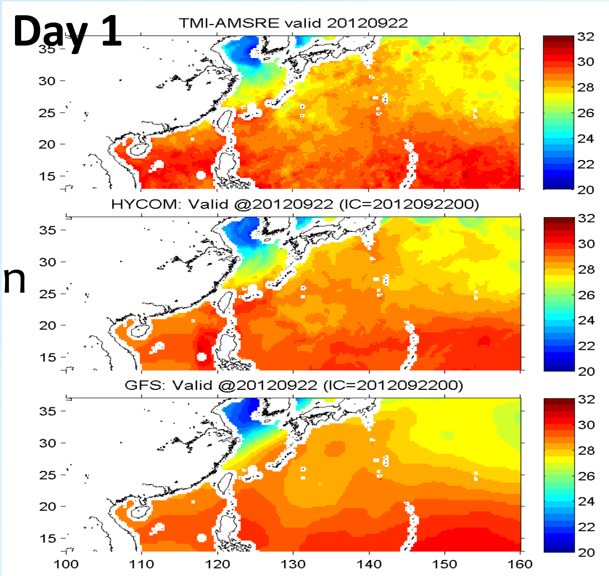
2-way coupling

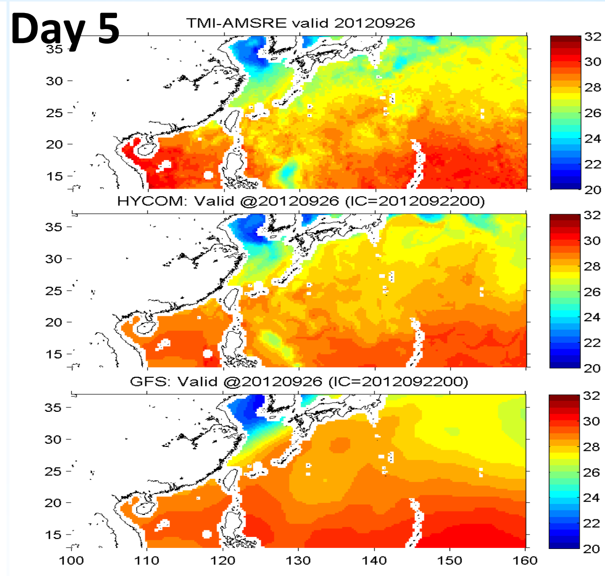
Comparison against daily TMI & AMSRE OI SST

Obs.

HYCOM in cpl

GFS in ctl





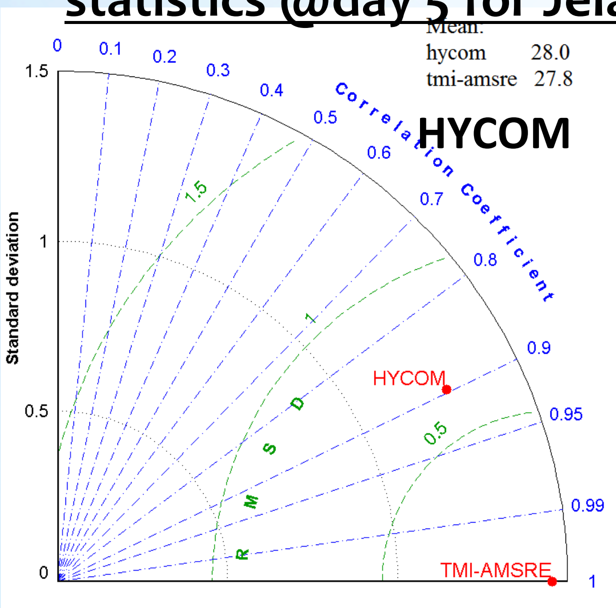
HYCOM SST

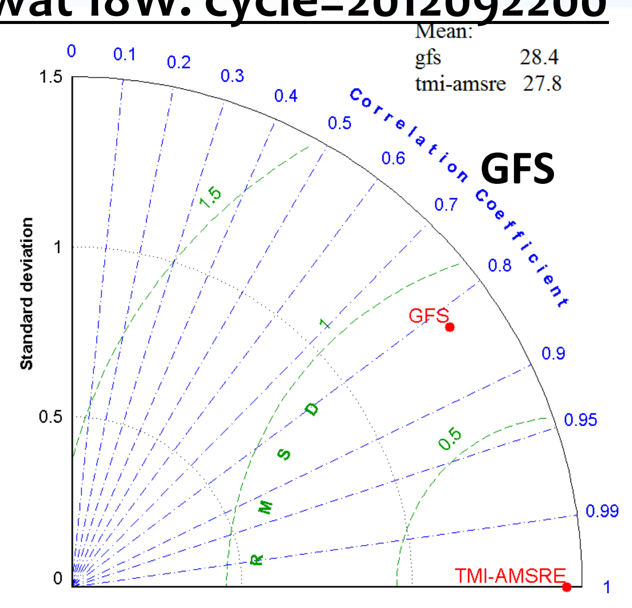
- Similar cold wake (~26°C) at a similar degree of cooling (~3°C)
- Mesoscale variability

GFS SST

- No change in GFS SST
- No cold wake and no cooling
- No Mesoscale variability

statistics @day 5 for Jelawat 18W: cycle=2012092200



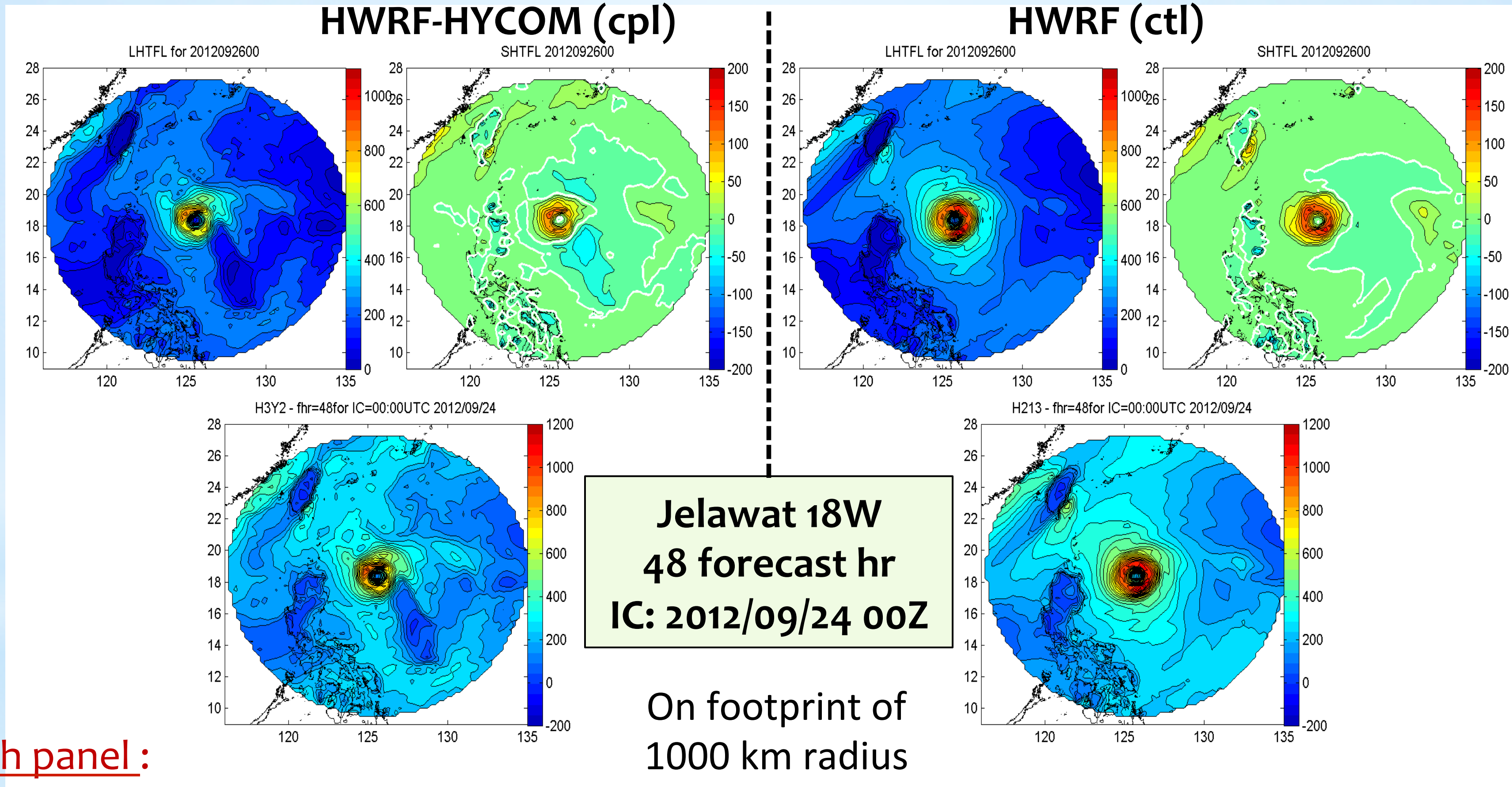


HYCOM SST

- Similar magnitude of mean
- Higher correlation coefficient (0.899)
- Lower RMSD (0.6) and STD (0.5).

Analysis of Storm size , Wind pattern, and Heat flux

2-way coupling



Each panel :

Latent Heat (top left) 0~1100; **Sensible Heat** (top right) -200~200; LH+SH (bottom) -200~1200

HWRF-HYCOM cf. HWRF:

- Size - Smaller by ~5%
- Wind Pattern – Asymmetric
  - ➔ SST feedback plays significant.
- Magnitude – Smaller by 25% (LHT), 14% (SHT) and 26% (combined).

Preliminary Conclusion

(coupled) HWRF-HYCOM compared to (non-coupled) HWRF:

1. Smaller storm size on average, and Contracting with time (less than 5%).
2. Asymmetric wind pattern.
3. (Slower translation speed.)
4. Lower surface enthalpy (less than 26%).
5. HYCOM SST cooler than GFS.
6. Meso-scale dominant.

Maximum Potential Intensity (MPI)

Emanuel (2003)

$$V_{\max}^2 \propto \frac{(T_1 - T_2)}{C_d T_2} F_h$$

T_1 = *SST*;
T_2 = outflow temperature;
C_d = drag coefficient;
and
F_h = (*LHT+SHT*) the surface flux of enthalpy.

- *T1*, *LHT*, *SHT*, *Cd* and (*Ch)* are either explicitly or implicitly related with SST.
- Coupling w/ an ocean model results in the SST feedback.
- The simulations are done w/o optimal tuning for coupling. Results are textbook example.

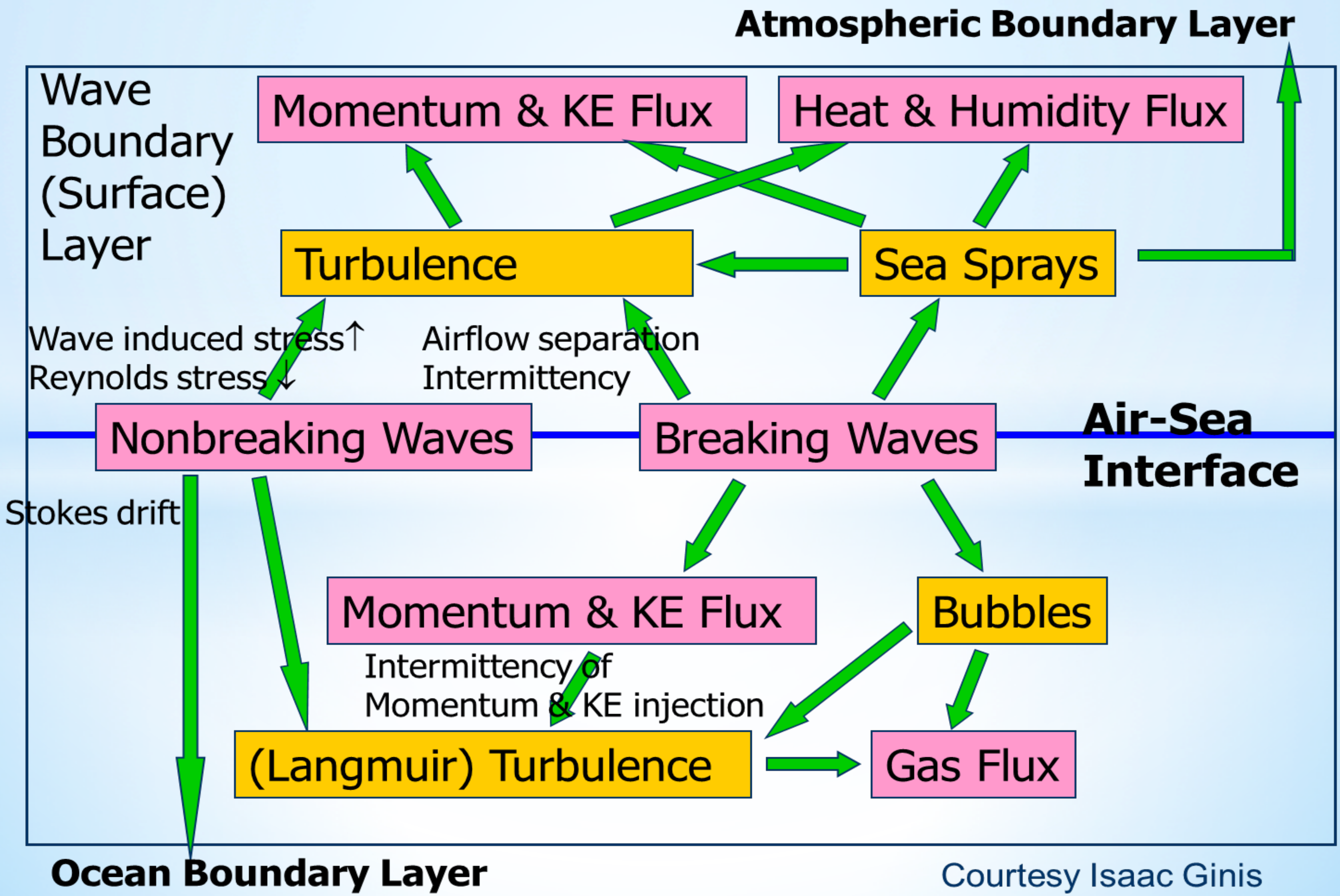
Hence, re-considered are:

1. Sub-grid parameterization in both the atmospheric and oceanic components;

2. Optimizing air-sea flux parameters to two-way coupling system, e.g. Cd & Ch.

Or, employing three-way coupling.

HWRF-POM/HYCOM-WaveWatchIII Coupling



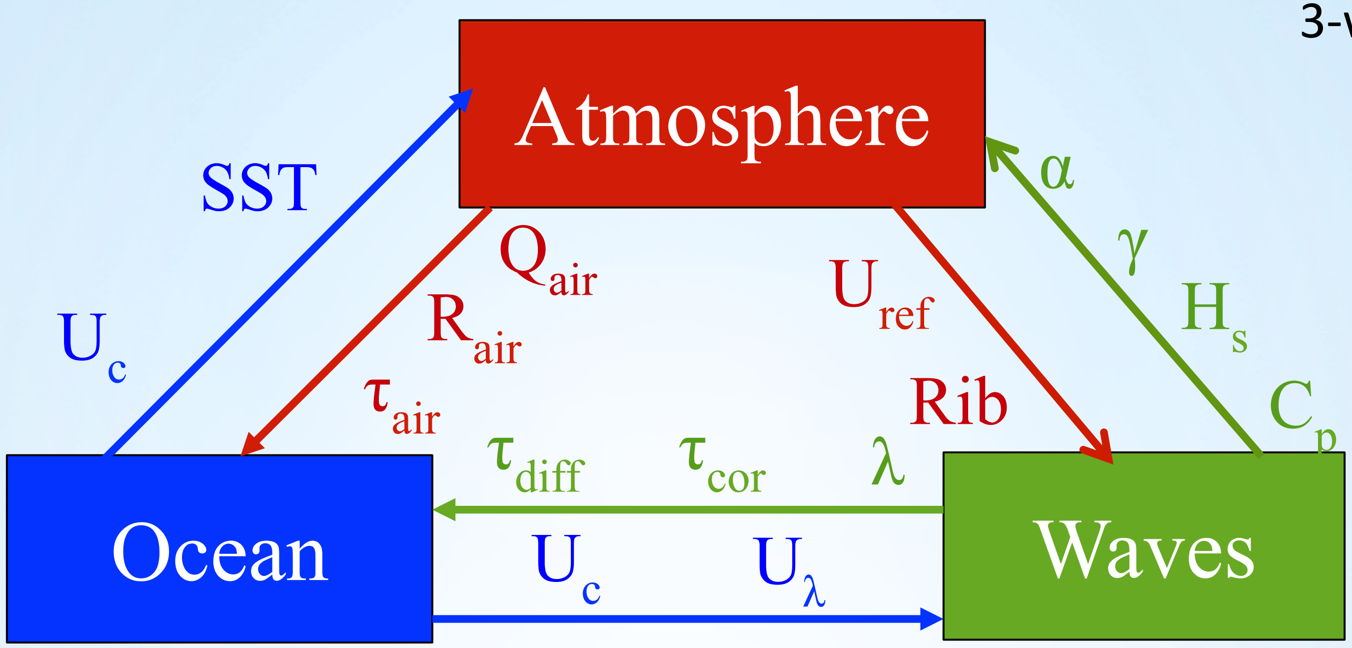
Courtesy Isaac Ginis

HWRF three-way coupled Air-Sea Interface Module (ASIM)

ASIM implemented in HWRF includes the following physical processes affected by surface waves:

- **Hurricane model**
  - surface stress includes effects of **sea state**, **directionality of wind** and **waves**, **sea spray**, and **surface currents.**
- **Wave model**
  - forced by **sea state-dependent wind stress.**
  - includes effects of **ocean currents.**
- **Ocean model**
  - forced by **sea state-dependent wind stress**, modified by **growing or decaying wave fields** and **Coriolis-Stokes forcing**..
  - turbulent mixing is modulated by the Stokes drift (**Langmuir turbulence**)

URI
3-way coupling



α - Charnock coefficient	γ - Misalignment (wind angle - stress angle)
λ - Mean wavelength	Hs – significant wave height
Cp – wave age	SST – Sea surface temperature
$\boldsymbol{\tau}_{Coriolis\text{-}Stokes}$ - Coriolis-Stokes stress	$\boldsymbol{\tau}_{diff}$ - Surface wave momentum budget
$\boldsymbol{\tau}_{air}$ - Wind Stress at wave height	$\mathbf{U}_{ref}$ - wind vector at reference height
$\mathbf{U}_{\lambda}$- wind vector at reference height	$\mathbf{U}_{c}$ - current vector
Q_{air} – Heat Flux	R_{air} – air moisture

Effects of surface waves on ocean currents and turbulence

URI
3-way coupling

$$\frac{\partial}{\partial t}U_{c\alpha} + \frac{\partial}{\partial x_\beta}\left(U_{c\alpha}U_{c\beta}\right) + \frac{\partial}{\partial z}\left(WU_{c\alpha}\right) - \varepsilon_{\alpha\beta z} f U_{c\beta} = -\frac{1}{\rho}\frac{\partial P}{\partial x_\alpha} + \frac{\partial \bar{\tau}_{t\alpha}}{\partial z}$$

Turbulence closure(modified by wave effects)

$$\bar{\tau}_{t\alpha} = \tau_{air\alpha} - \frac{\partial}{\partial t}M_\alpha - \frac{\partial}{\partial x_\beta}MF_{\alpha\beta} - \tau_{s\alpha} \quad at \quad z = \hat{\eta}$$

ASIM momentum flux budget

$$M_\alpha = \int_{-\infty}^{\hat{\eta}} u_{s\alpha}\, dz \qquad MF_{\alpha\beta} = \int_{-\infty}^{\hat{\eta}} S_{\alpha\beta}\, dz \qquad \tau_{s\alpha} = -\int_{-\infty}^{\hat{\eta}} \varepsilon_{\alpha\beta z} f u_{s\beta}\, dz$$

(green oval): Langmuir turbulence effect – will be included in the turbulence closure model (in collaboration with Kukulka, U. Delaware)

(red oval): wave-dependent momentum flux budget terms (Fan et al. 2010)
S - wave spectrum

(yellow oval): Coriolis-Stokes forcing term (Polton et al. 2005)
f - Coriolis parameter

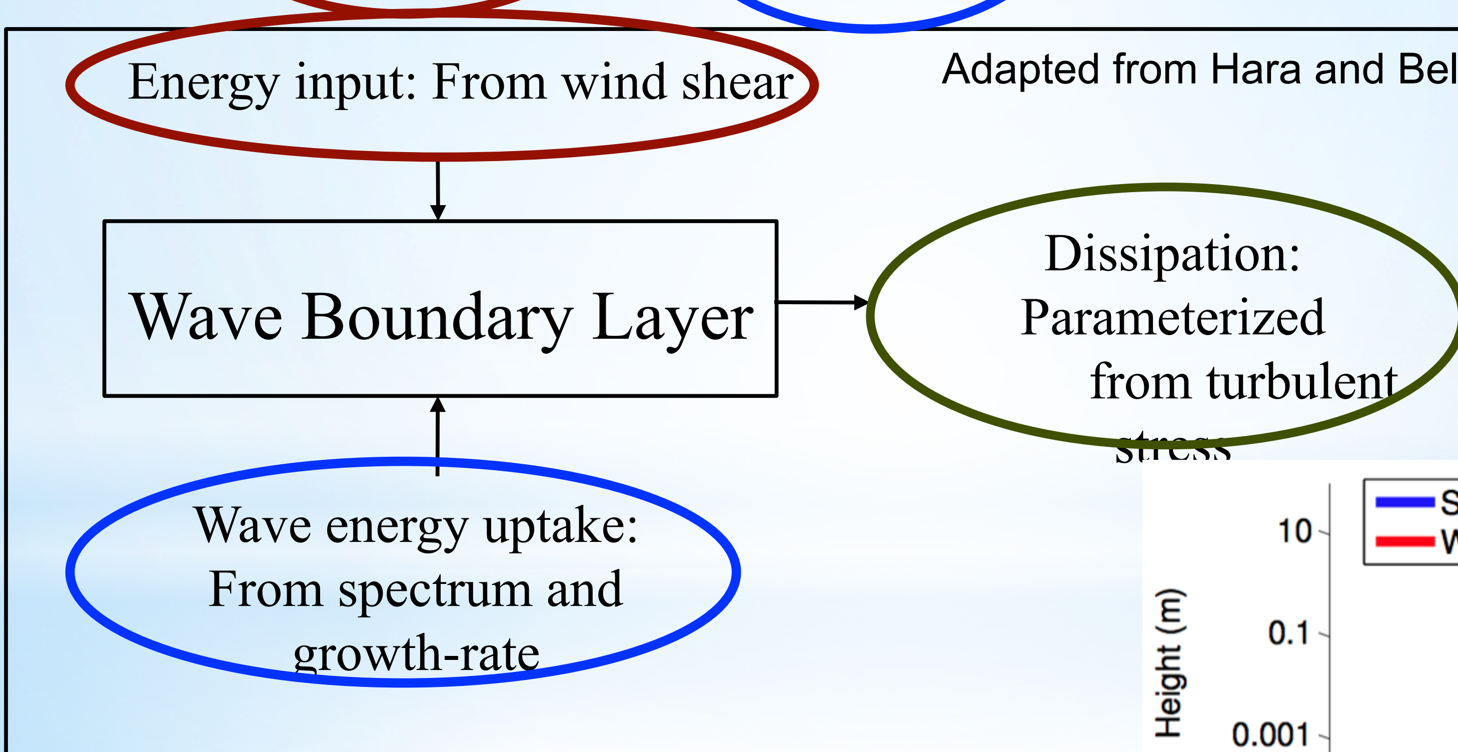
Wind profile in Wave Boundary Layer (WBL)

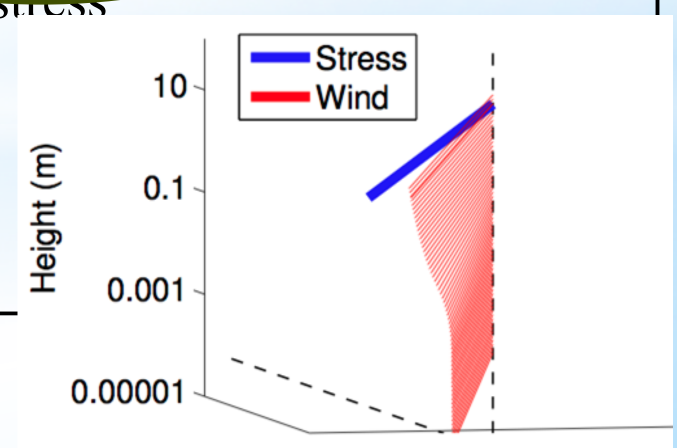
URI
3-way coupling

Wind shear is not aligned with wind stress. Wind profile is explicitly solved, and the misalignment angle (γ) is determined.

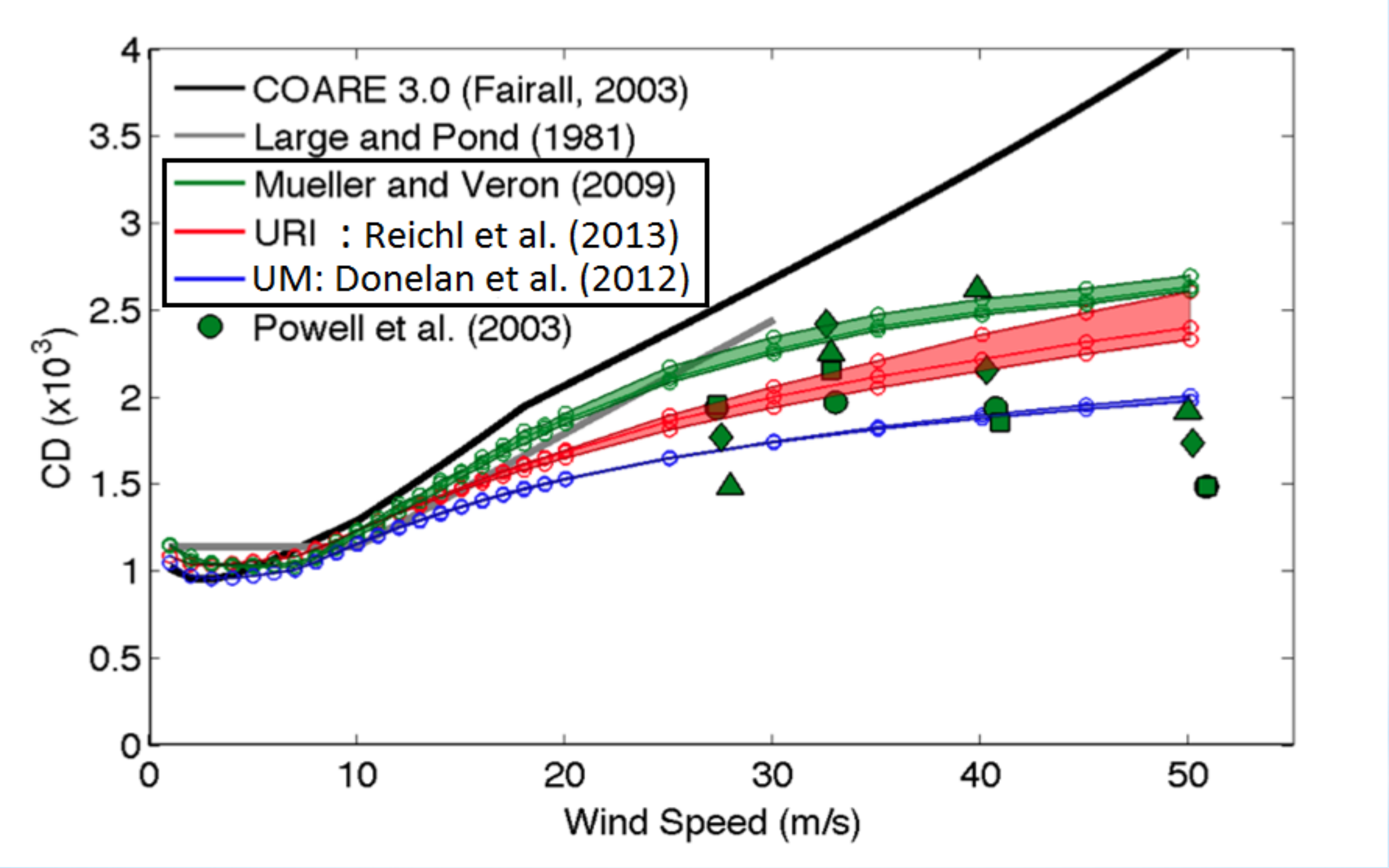
$$\frac{d}{dz}(\vec{u}\cdot\vec{\tau}_{tot}) + \frac{d(\Pi+\Pi')}{dz} - \rho_a\epsilon = 0$$

RHG method
(Reichl et al. 2013)





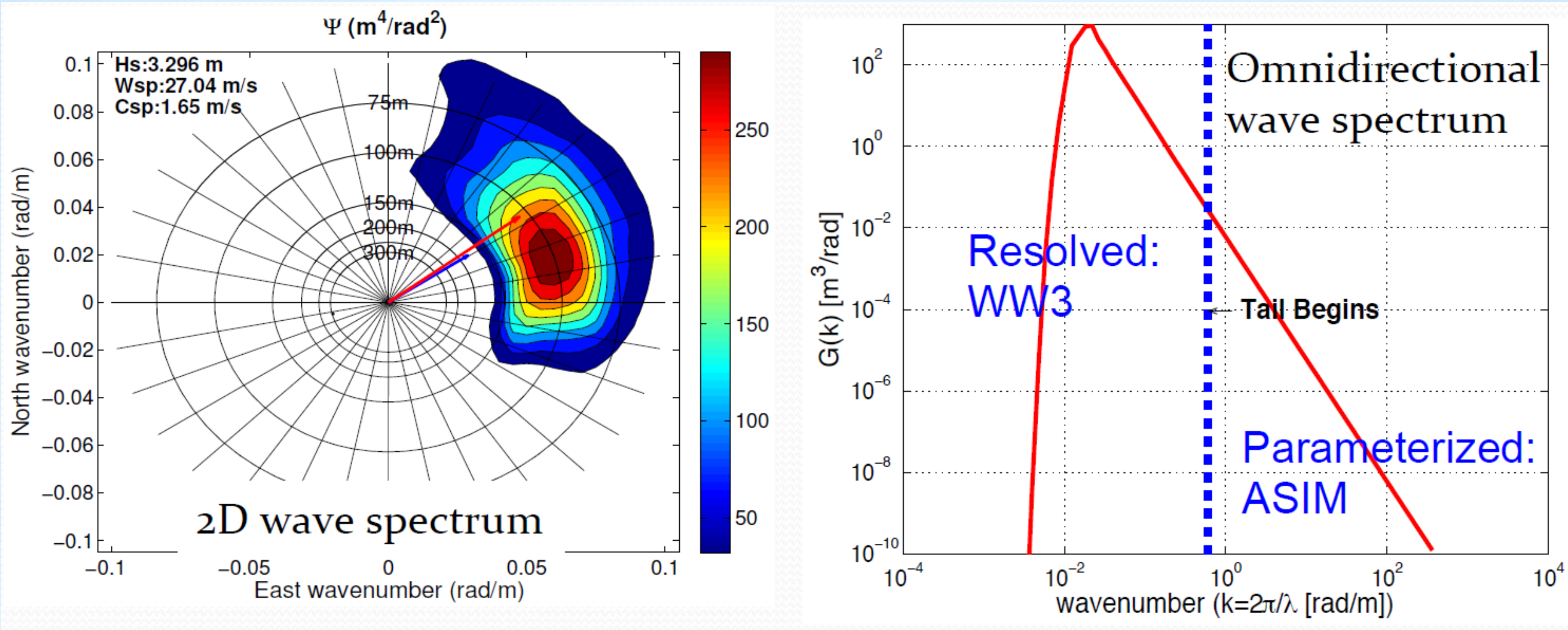
Cd vs. Wind
for different ASIM parameterization options



ASIM includes three sea-state dependent Cd parameterization options tested here using an empirically-driven wave spectrum from the Joint North Sea Wave Project (Elfounhaily et al. 1997).

Sea state dependent Cd

URI
3-way coupling

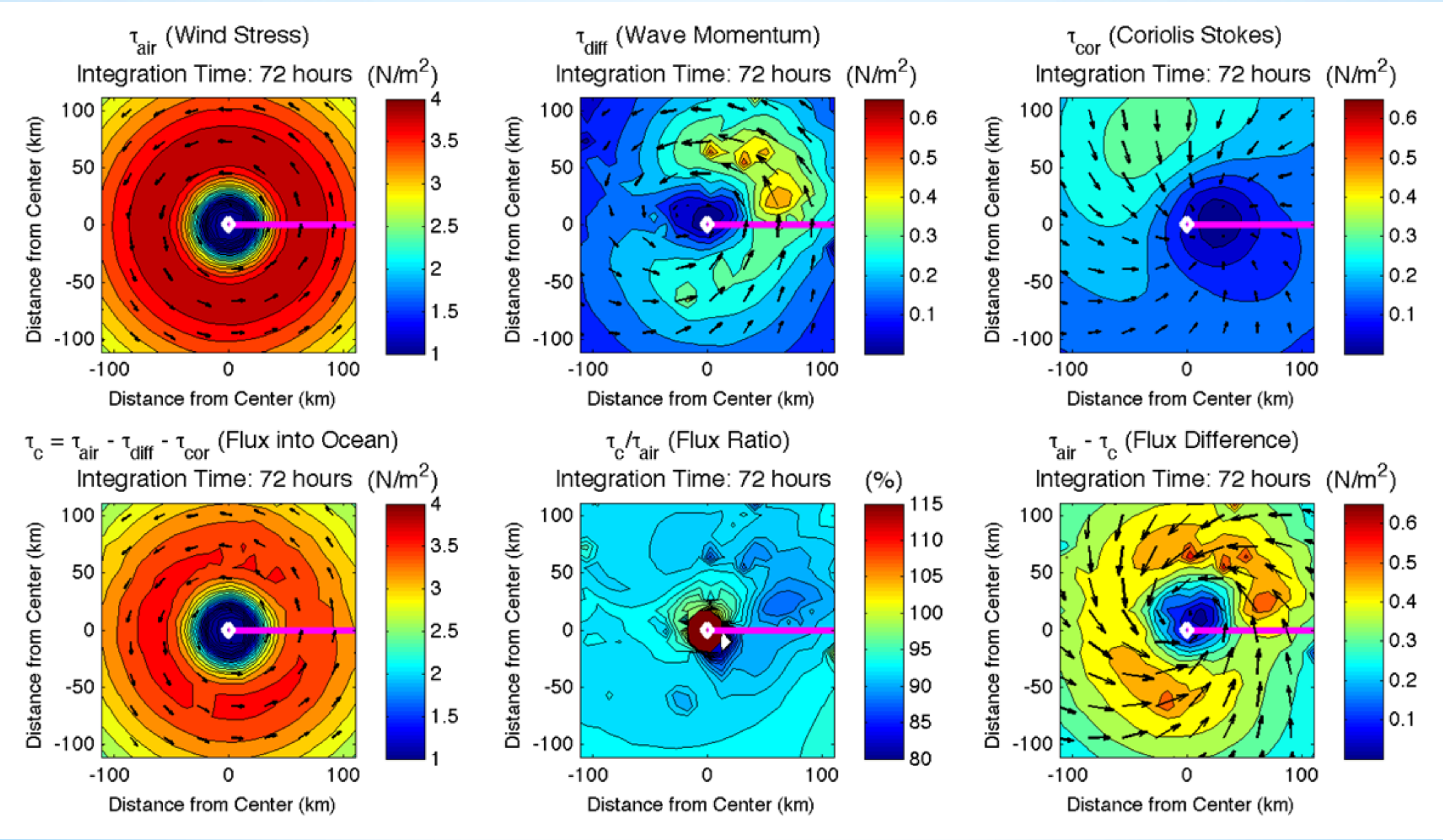


Ψ - Wave spectrum

- Form drag is obtained by integrating the 2D wave spectrum times growth rate over all wavenumbers and directions.
- The short wave spectral tail and growth rate are parameterized in ASIM using different theoretical and empirical methods.

ASIM momentum flux budget terms In idealized hurricane

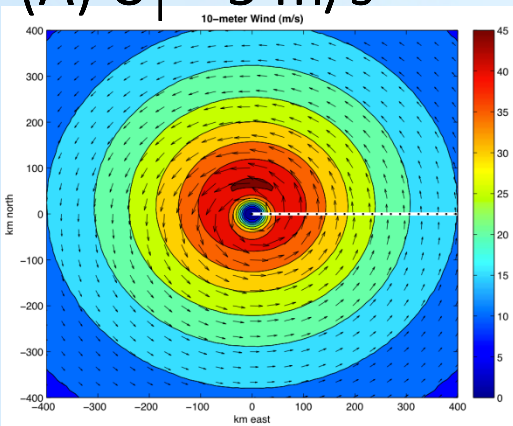
URI
3-way coupling



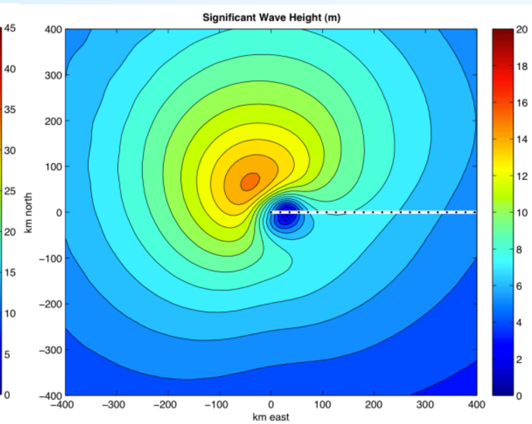
Investigation of sea-state dependent Cd
Idealized hurricane

URI
3-way coupling

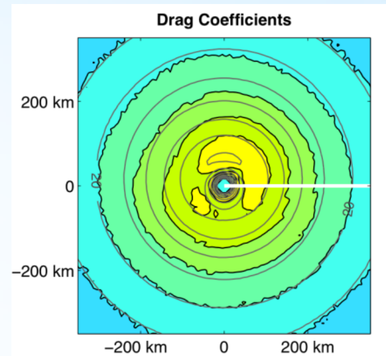
(A) U_T = 5 m/s



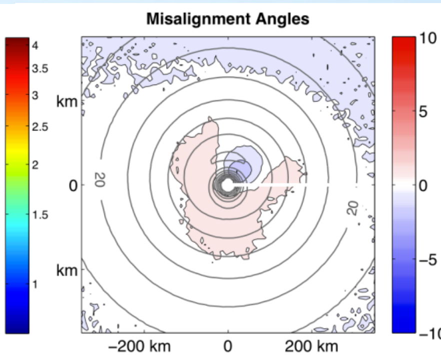
Wind speed (m/s)



Hs (m)

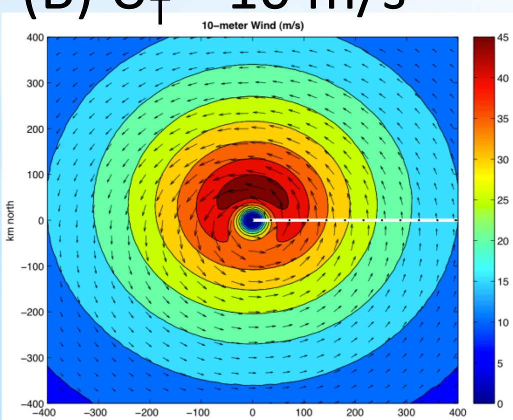


Cd (E-03)

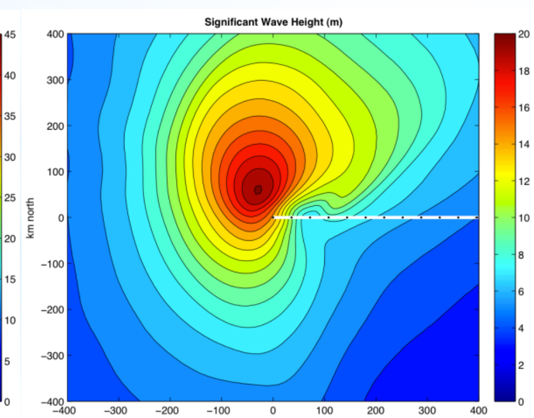


Misalignment btwn sfc stress and wind shear

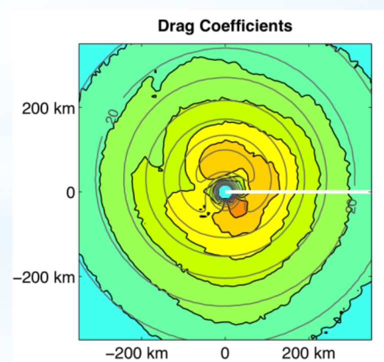
(B) U_T = 10 m/s



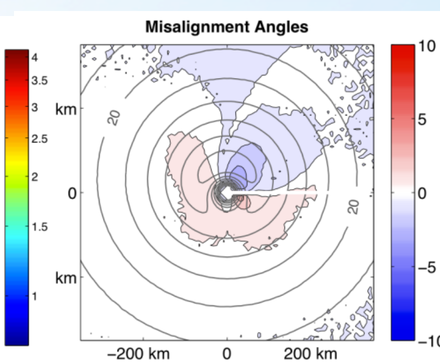
Wind speed (m/s)



Hs (m)



Cd (xE-03)

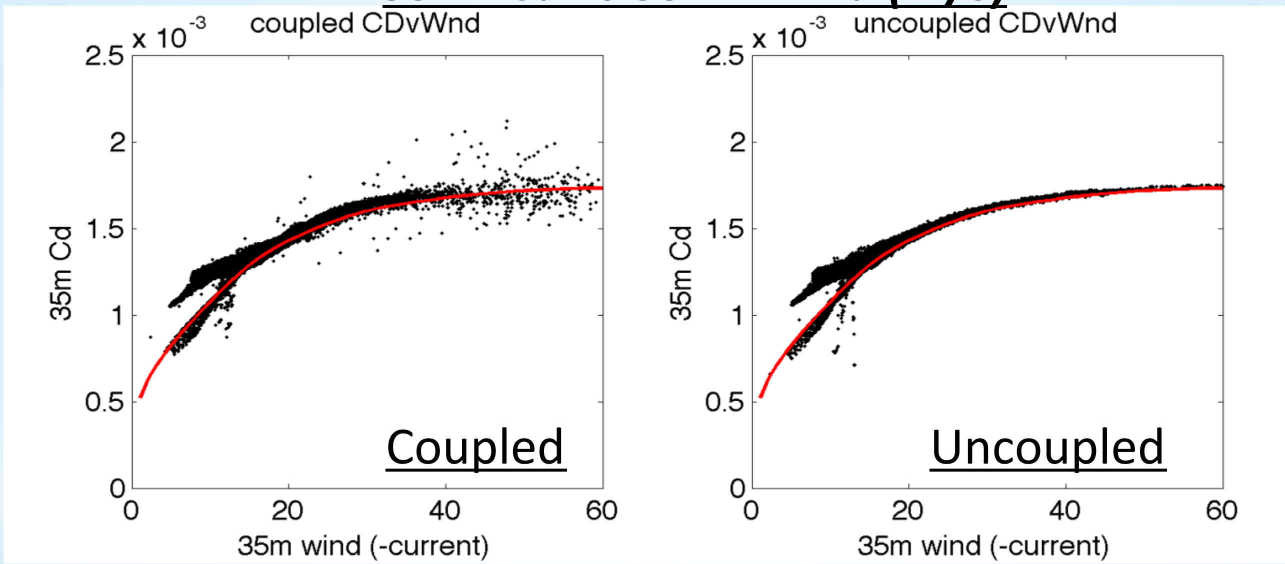


Misalignment btwn sfc stress and wind shear

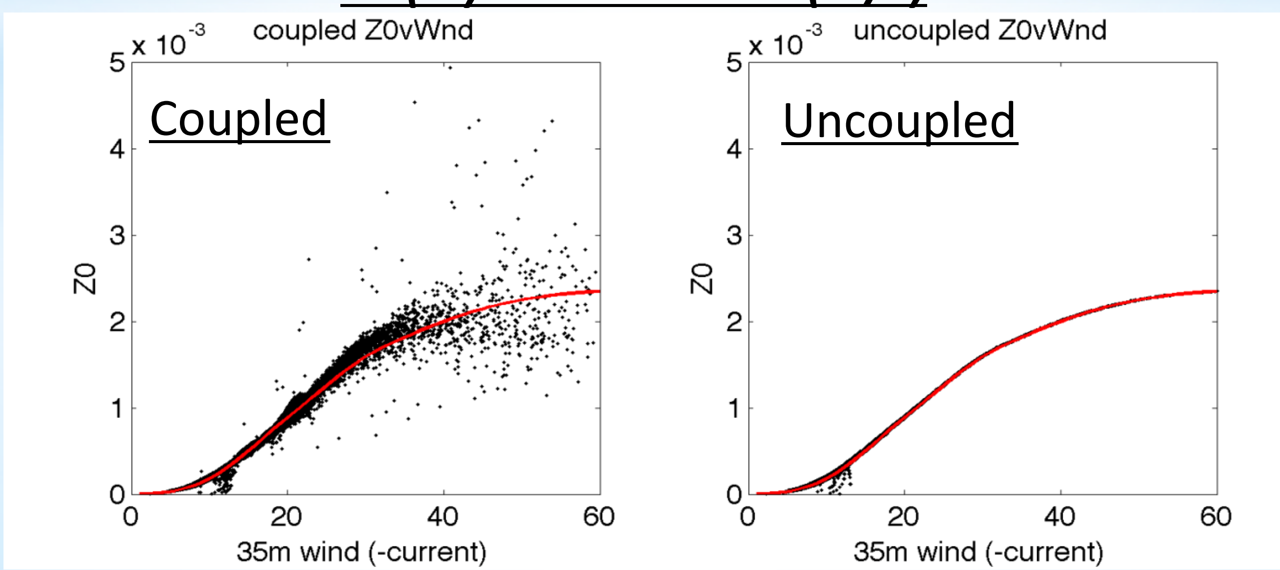
Results: GFDL-POM-WW3

URI
3-way coupling

35-m Cd vs 35-m Wind (m/s)

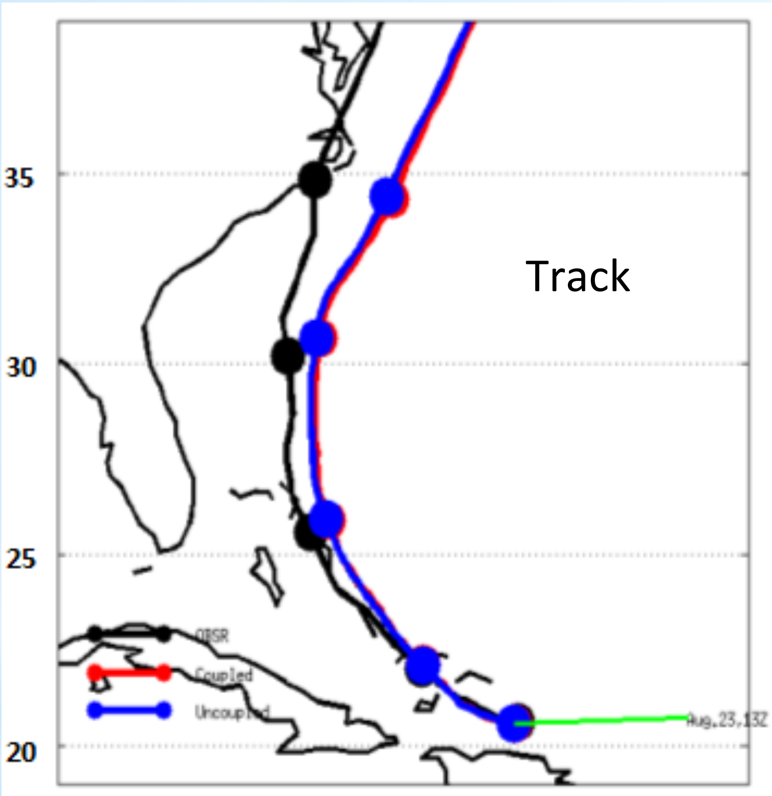


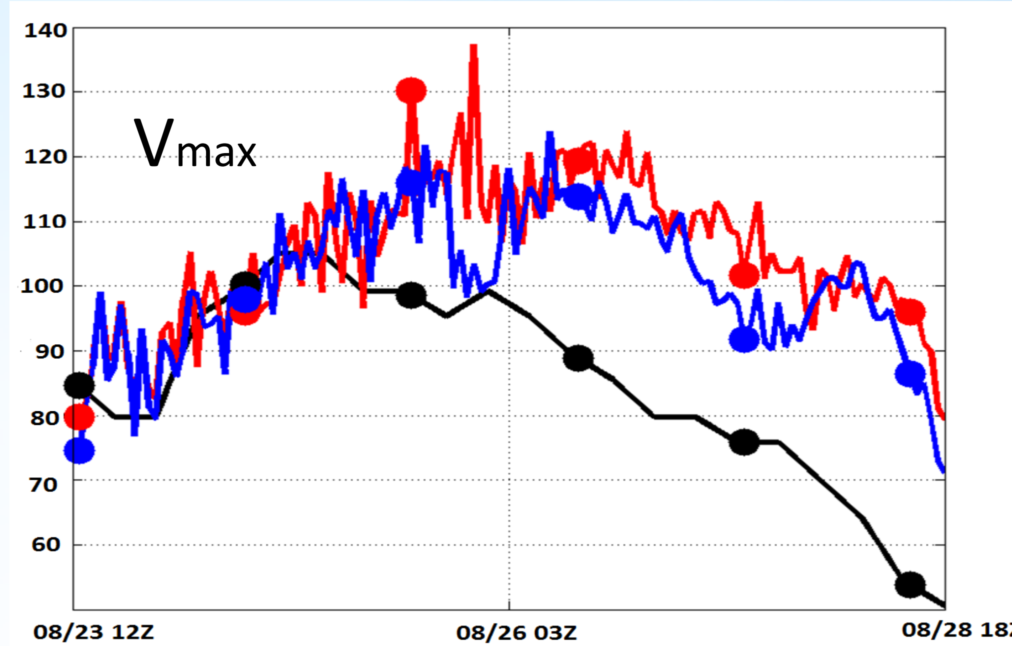
Z0 (m) vs 35-m Wind (m/s)

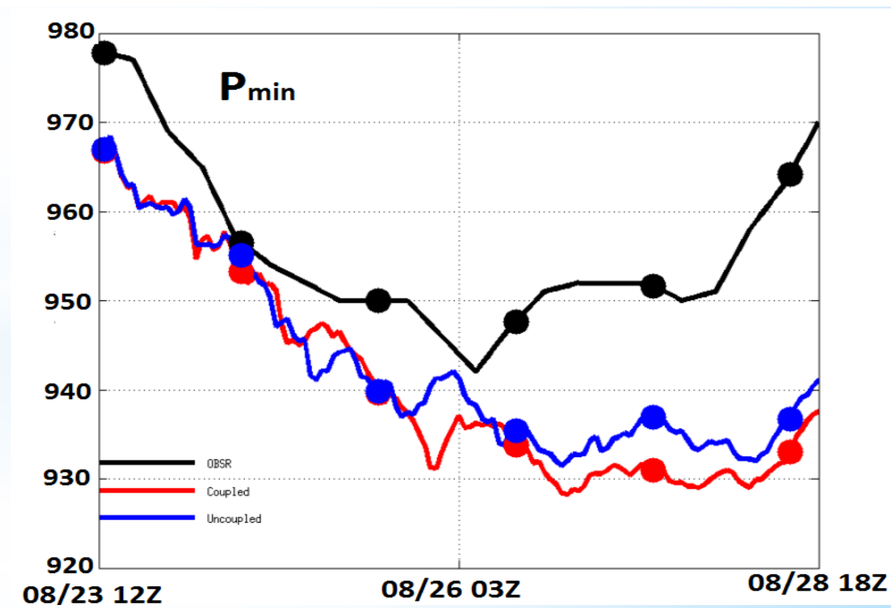


Results: GFDL-POM-WW3

Hurricane Irene (IC=08/23/2011 12Z)







Obs.
Coupled
Uncoupled

For coupled HWRF (2-way):

1. Focus on best possible description of physical states for all models.
   - ➔ Better physics makes for a better model. But …, better physics in a well tuned model will almost always detune the model.
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 this, track and intensity 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.

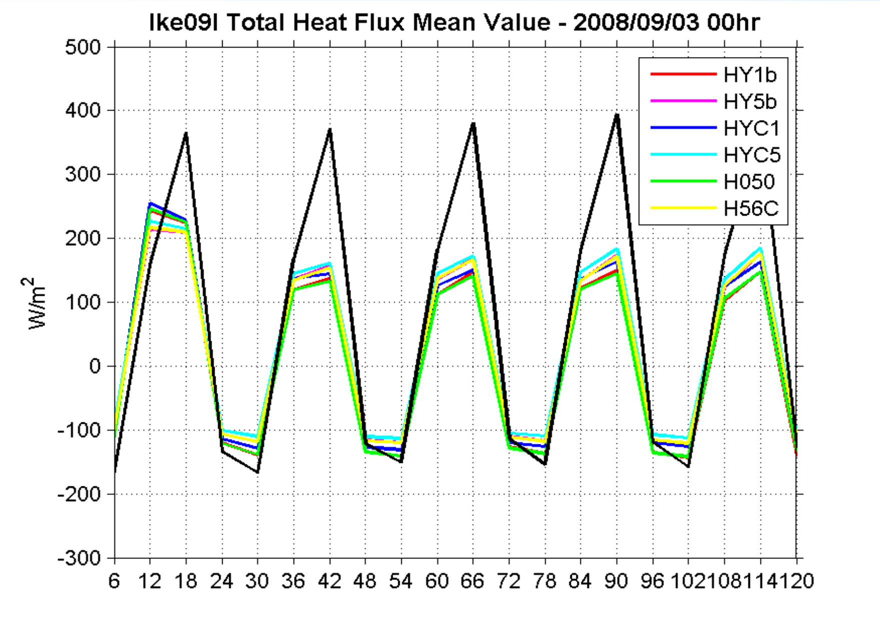
5. The key for this kind of coupled modeling is in the fluxes.
    - A weather model with a fixed or climatological SST is constrained in terms of systematic seasonal – climate shifts. But, In a coupled model, there is no constraint to the ocean state.
    - Hence, spurious drifts of the SST and mixed layer in general in the ocean will result in spurious drifts in the weather model, with a strong possibility of (nonlinear) feedback

6. Developing this coupled model is a cyclic process:
    - First emphasis on getting the ocean right,
    - In the process, we found many issues with HWRF.
        - Not necessarily major issues for HWRF, but critical for realistic coupling with a realistic ocean model.
        - POM appears less sensitive to these errors as ocean responses are suppressed to gain a more robust system.
    - Fixes and updates in the HWRF model require a revisit to make sure that all ocean responses are realistic.
    - … and this will never stop…

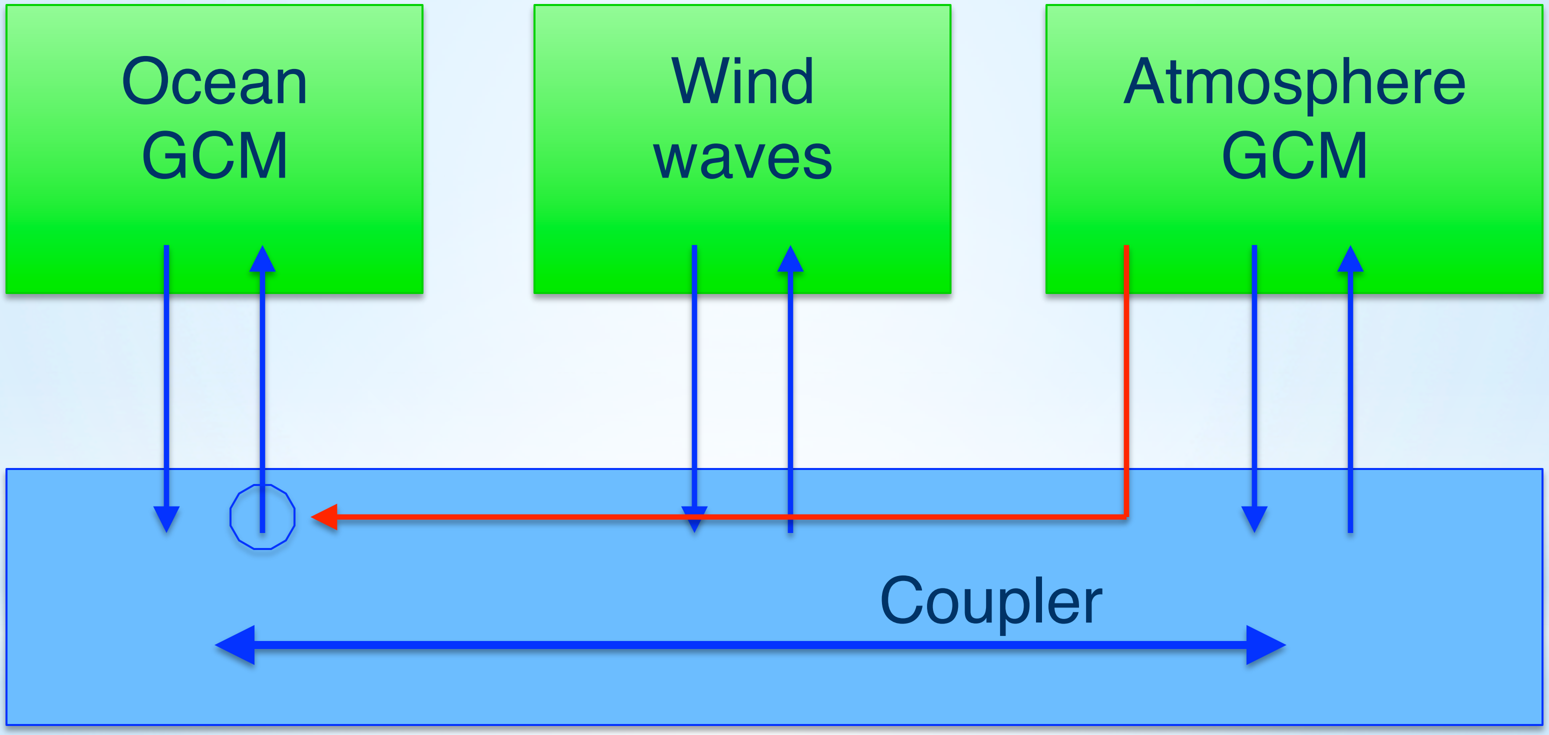
Coupling HWRF weather model to HYCOM ocean model.

- Regional ocean model nested in basin scale ocean model.
- Basin scale ocean model set up to work well with GFS fluxes.
- HWRF fluxes are systematically different from GFS fluxes resulting in SST drift issues:
  - No drift in RTOFS ← GFS.
  - Drift in RTOFS ↔ HWRF.
  - Short term fix in coupler.
    - Successful.
    - Eventually, correct the HWRF fluxes (since 2012)
  - Long term NWS issue
    - Will require collaboration.

    e.g. wind stress



Courtesy Hyun-Sook Kim and Jamese Sims



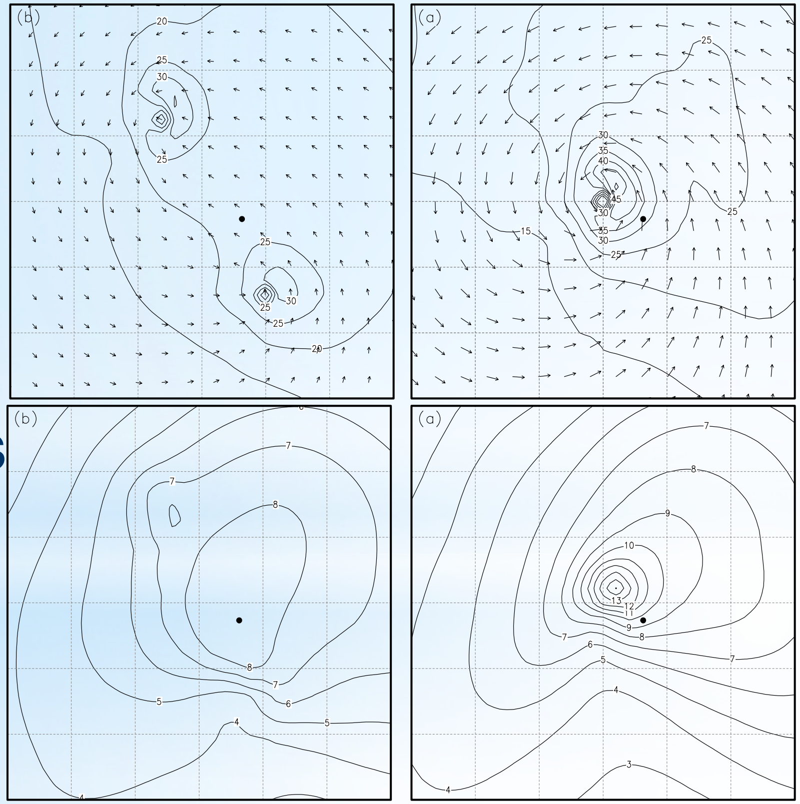
Needed modification in coupler for HWRF-HYCOM coupling (and any other ocean).
Coupler needs to know which atmosphere and ocean models are used.

Winds / waves example

Unresolved in time | Resolved in time

wind

waves

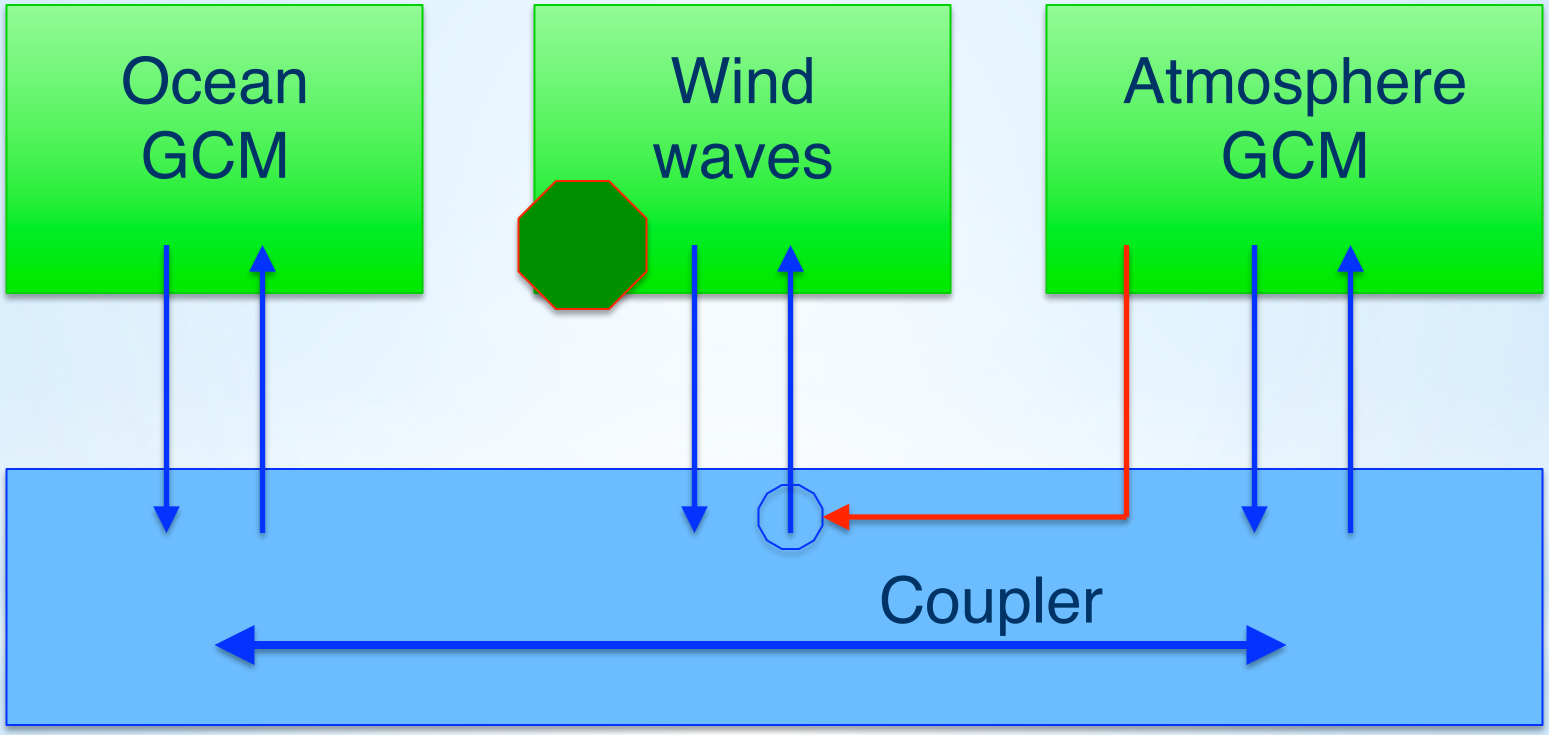


So, coupling gives you better resolution of parameters in time, and therefore gives a better wave model.

- This, and not coupling physics is the reason why the coupled wave-weather model at ECMWF gives improved wave prediction.

However, if you go to high spatial resolution coupled modeling, time scales of coupling also become smaller, and …….

- Waves in a traditional model become higher and higher and less and less reliable, but ….
- If wind fields are smoothed before passing them on to the wave model, wave model behavior remains reliable.



Coupler needs to know scales in atmosphere used for waves.

Or wave model physics need to be modified to account for wind scales resolved.

Generic coupler needs both.

As mentioned before:

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 complimentary to the way the models are conventionally validated.
  - ECMWF wave-atmosphere coupling.
- This often leads to systematic improvement of the constituent models, that often has a positive impact on the constituent models, even if the impact on the actual coupling is found to be minimal.
  - HYCOM - HWRF coupling.

Future: Challenge for HWRF

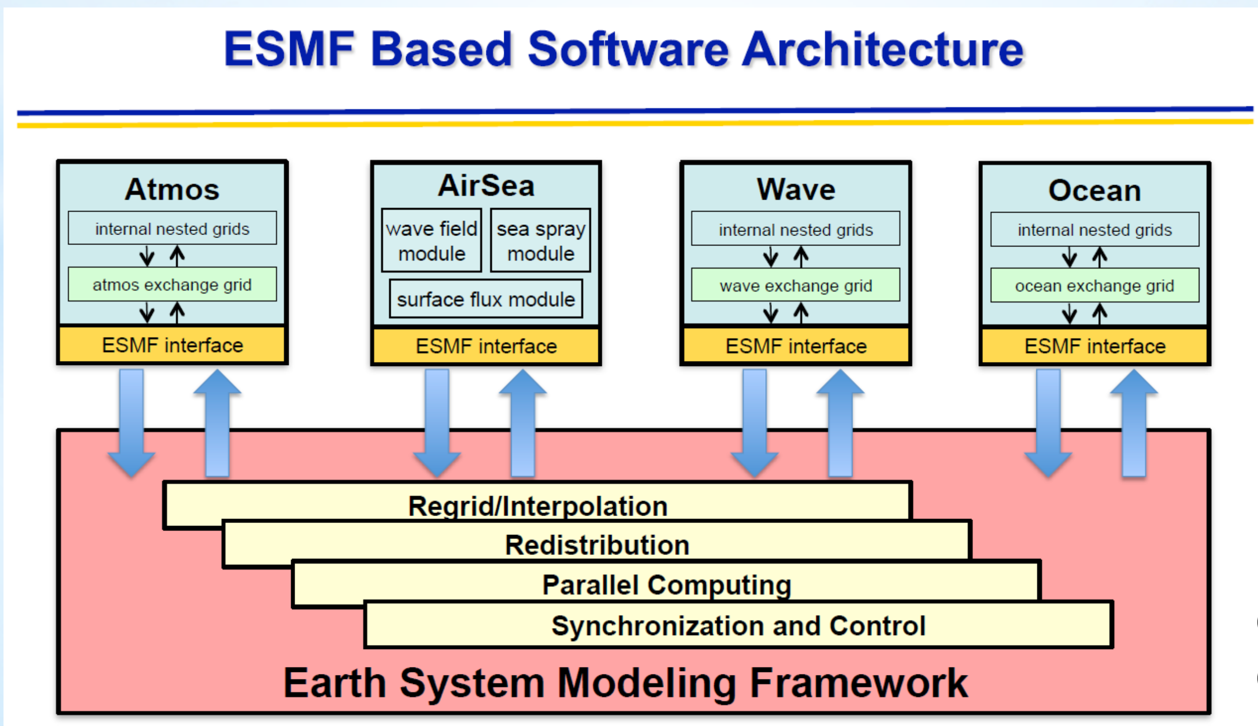
NOAA Environmental Modeling System (NEMS) team at EMC

Mark Iredell and team (4 + EMC + OAR + Navy + …).

Earth System Modeling Framework (ESMF): USA federal coupling standard

This is the basic framework / architecture.

Either core of the model, or wrapper around existing software.



Courtesy of Chen (2013)