THE UNIVERSITY OF RHODE ISLAND
GRADUATE SCHOOL OF OCEANOGRAPHY

Improving NOAA's HWRF Prediction System through New Advancements in the Ocean Model Component and Air-Sea-Wave Coupling

Isaac Ginis, Biju Thomas, Brandon Reichl
Tetsu Hara, and Austen Blair
University of Rhode Island

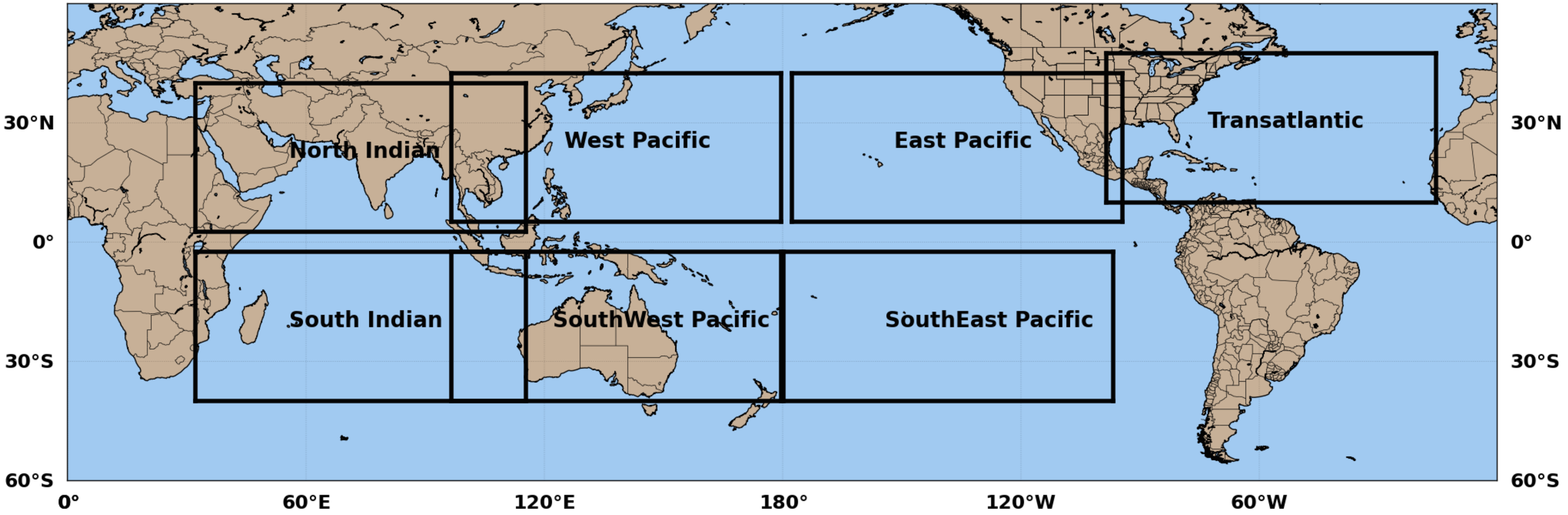
HFIP funded project

Special thanks to our collaborators at EMC, GFDL, DTC, and University of Delaware

Outline

- Global expansion of HWRF-MPIPOM coupling
- Implementation of flexible ocean initialization
- Increased vertical resolution and implementation of KPP mixing scheme
- 2015 C_d formulation in HWRF
- Developing physics modules for HWRF air-sea-wave coupling

Expanding HWRF-MPIPOM ocean coupling capabilities to all ocean basins

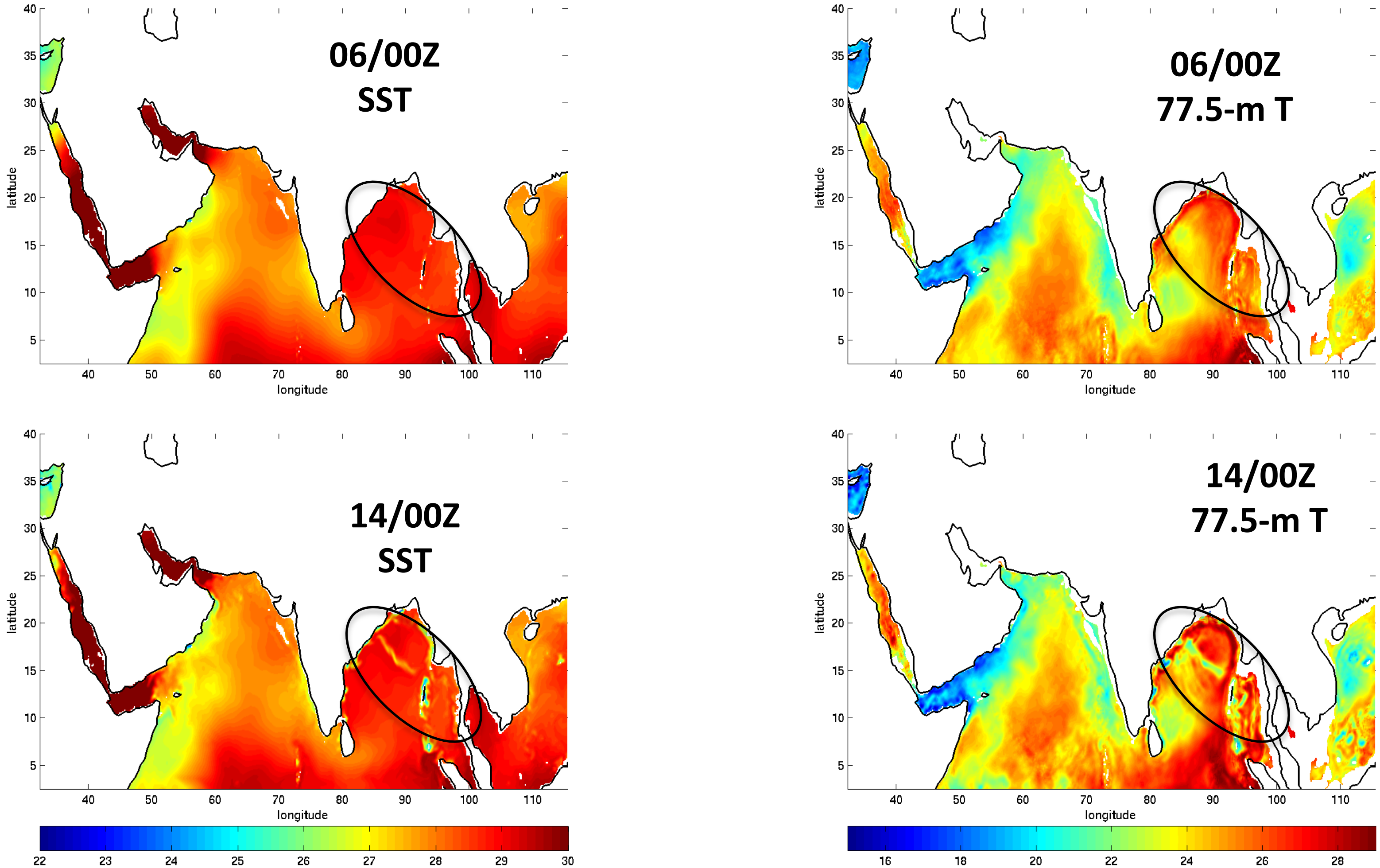


MPIPOM-TC is Message Passing Interface Princeton Ocean Model for Tropical Cyclones, created at the University of Rhode Island.

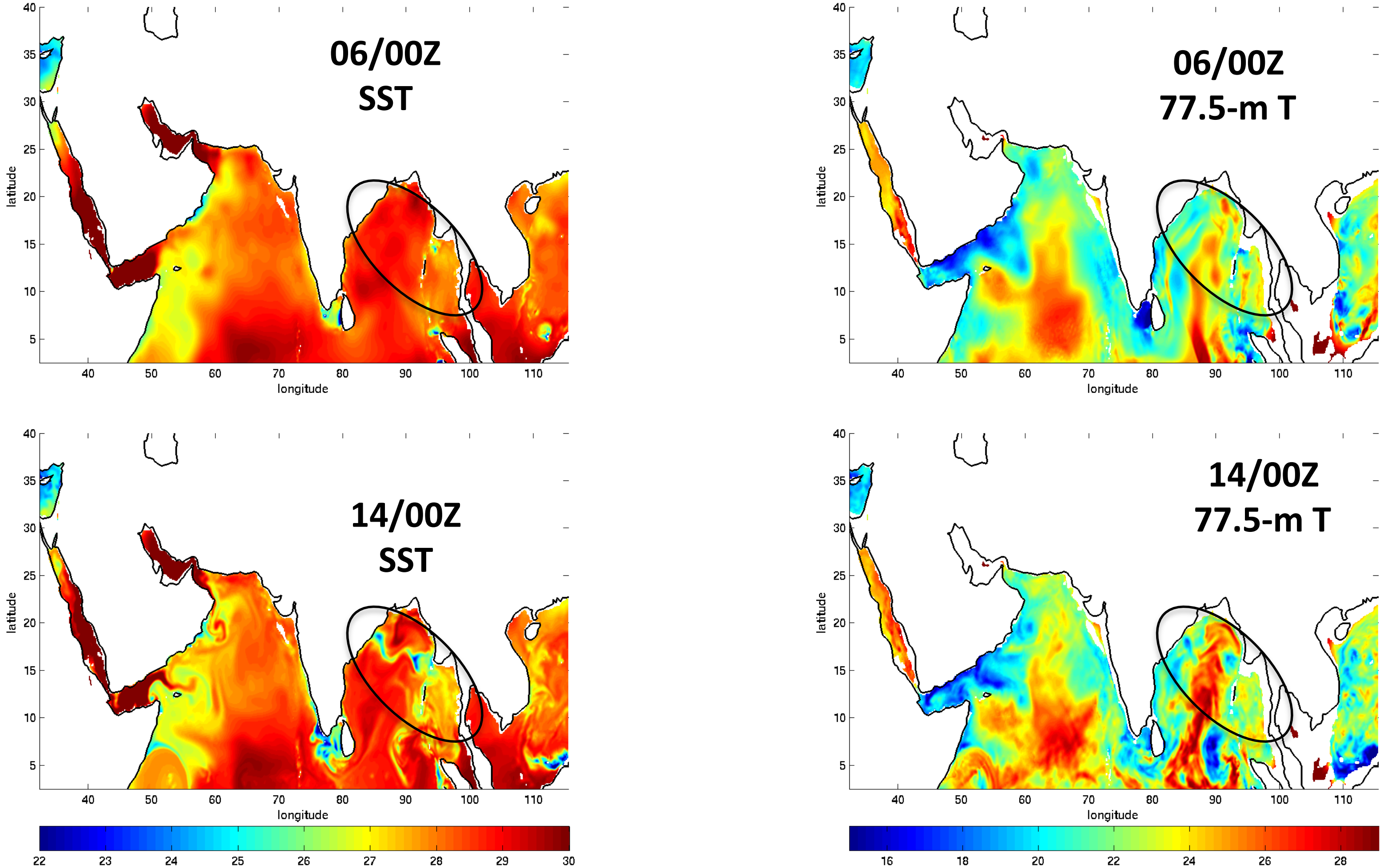
MPIPOM Flexible Initialization Options

1. Feature-based modifications to GDEM monthly temperature (*T*) and salinity (*S*) climatology with assimilated daily GFS SST (FB)
2. Navy Ocean Data Assimilation daily *T* and *S* fields (NCODA)
3. HYbrid Coordinate Ocean Model global daily product (HYCOM)
4. NCEP Global Real-Time Ocean Forecast System (RTOFS)

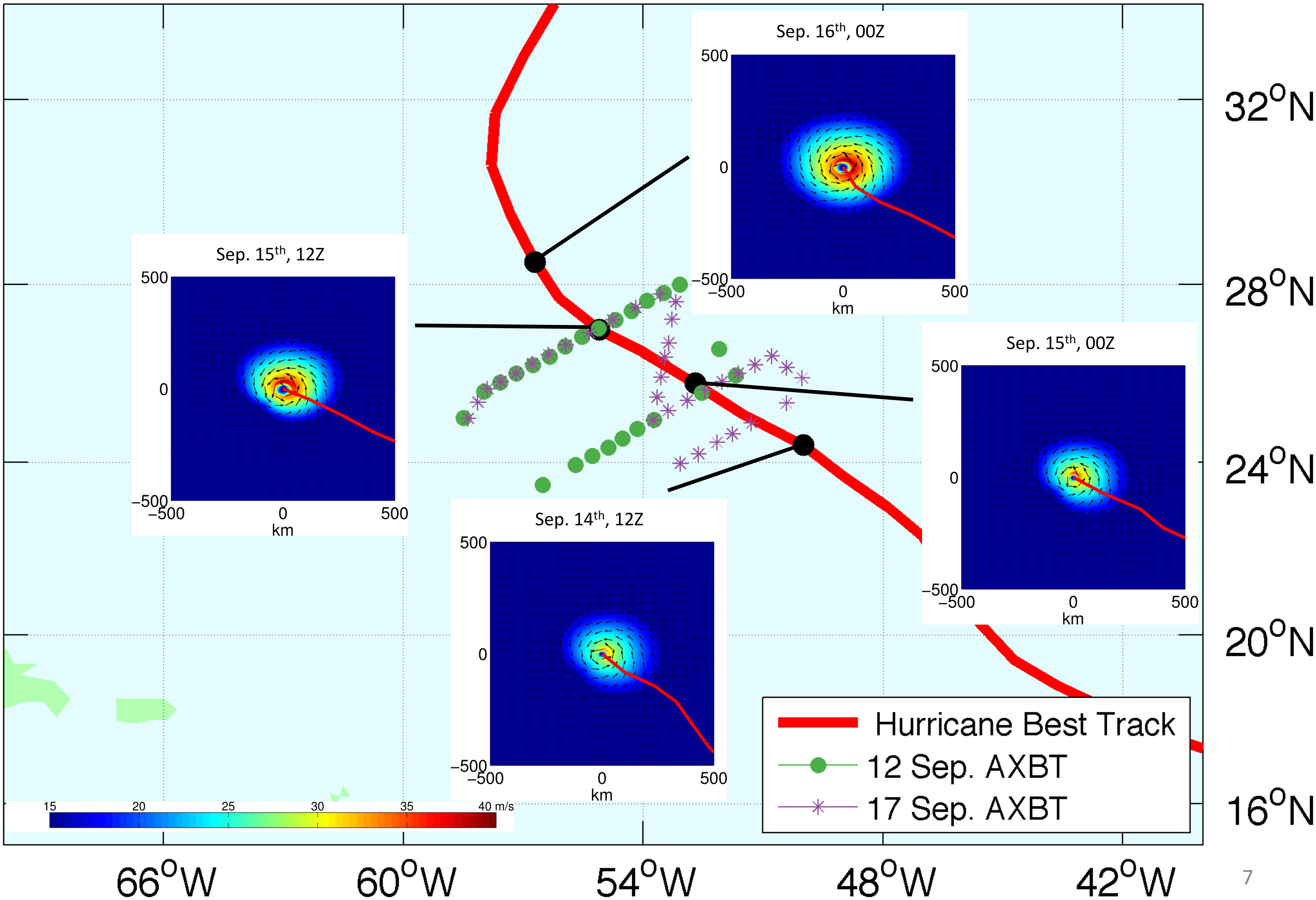
MPIPOM North Indian Domain: Ocean Response to Cyclone Phailin with FB initialization: 2013100600-1400



MPIPOM North Indian Domain: Ocean Response to Cyclone Phailin with NCODA initialization: 2013100600-1400

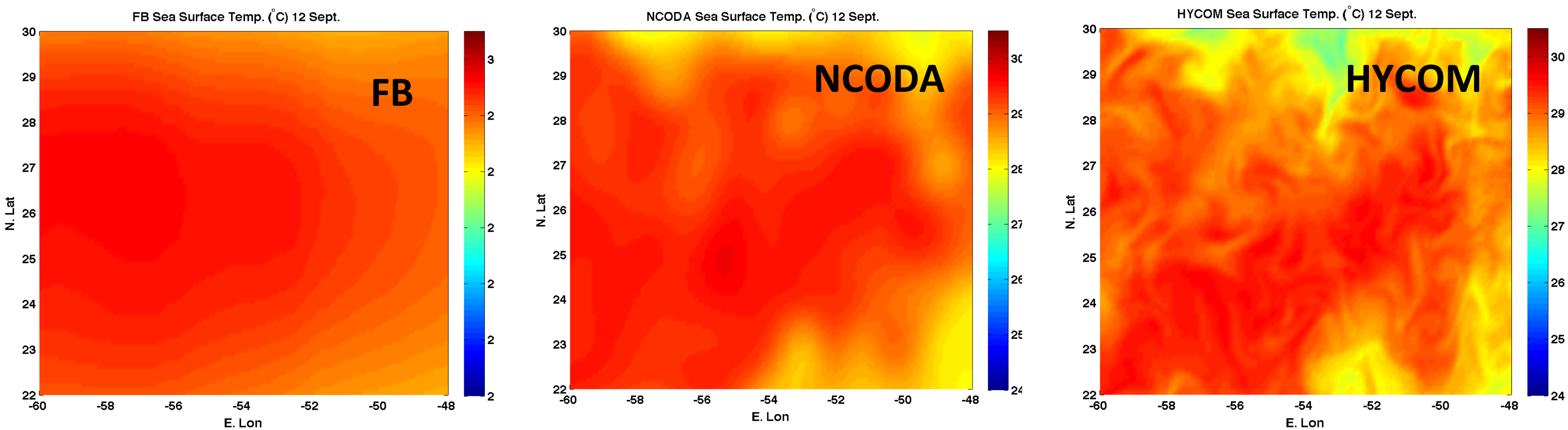


Case study: Hurricane Edouard (2014), TCVitals-based Winds

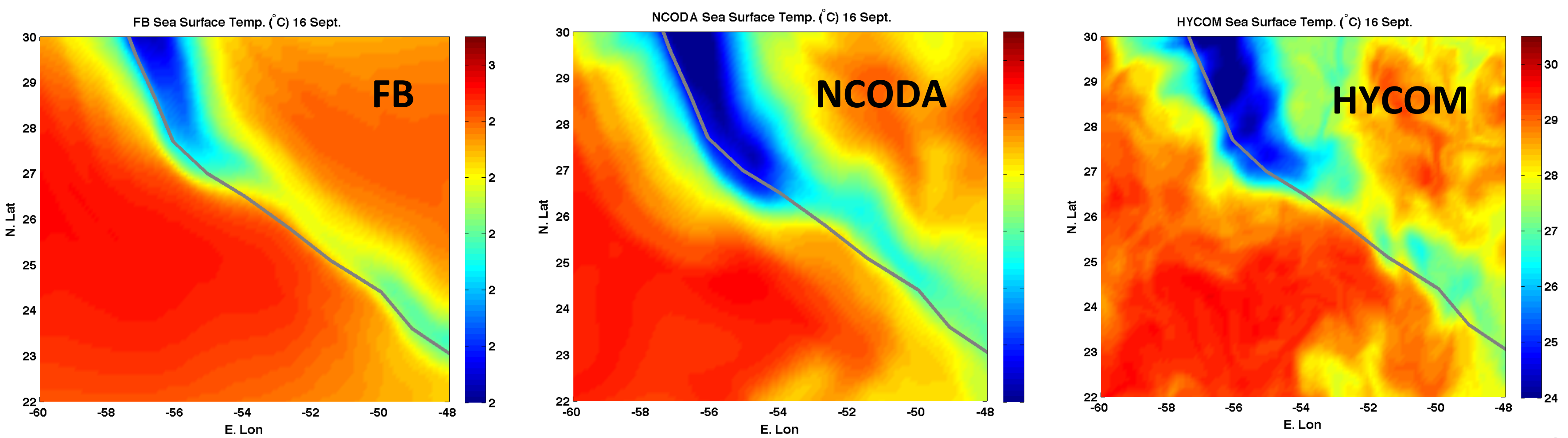


Evaluation of Ocean Initialization Options: Sea Surface Temperature

September 12, 2014 (pre-storm)

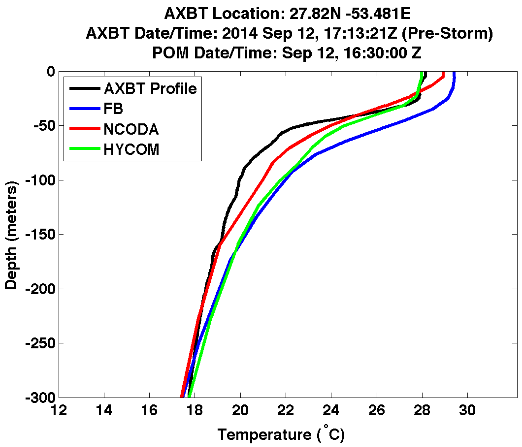


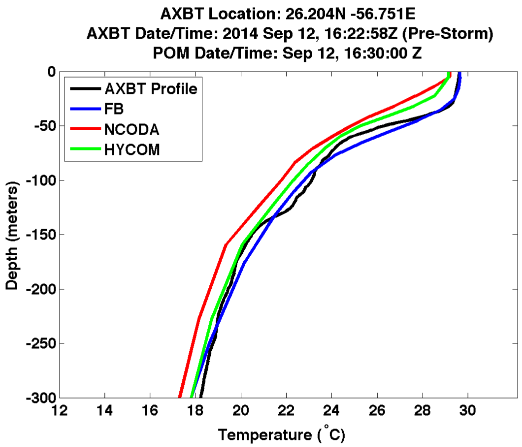
September 16, 2014

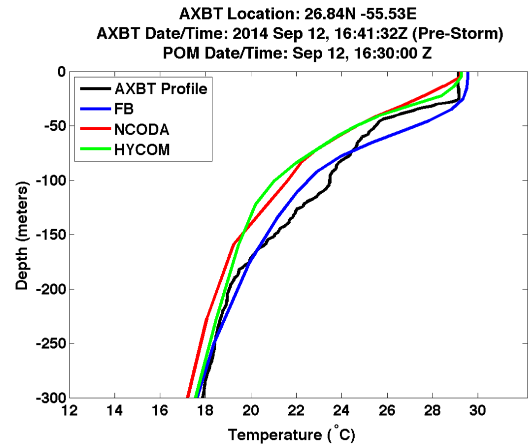


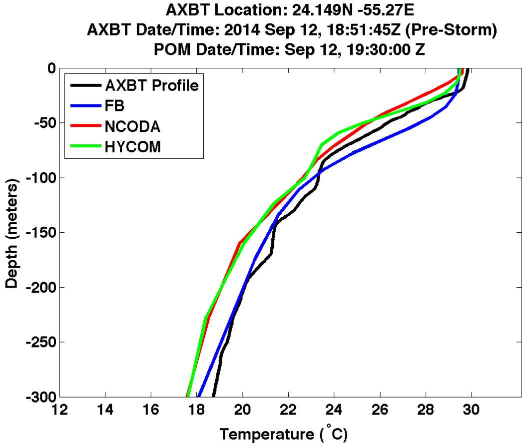
Evaluation of Ocean Initialization Options: Comparison with AXBTs

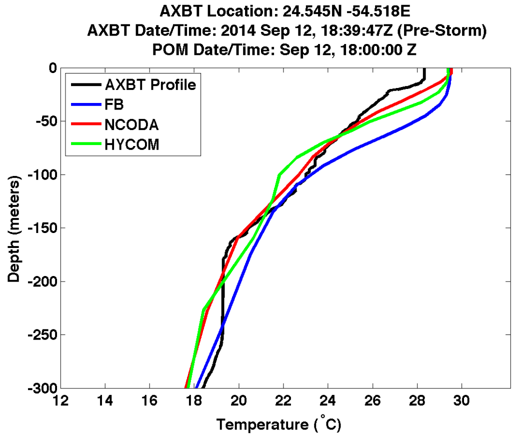
September 12, 2014 (pre-storm)

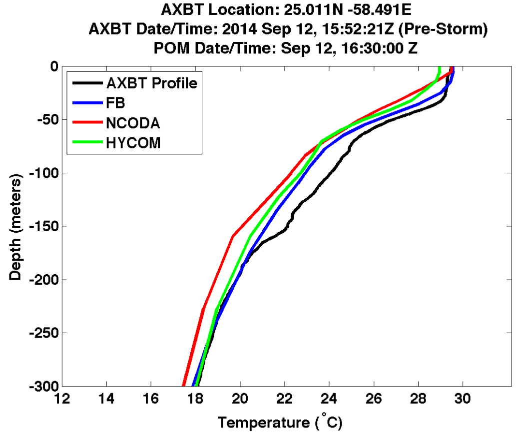








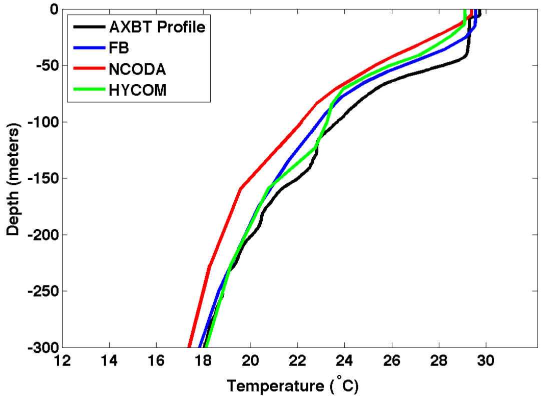




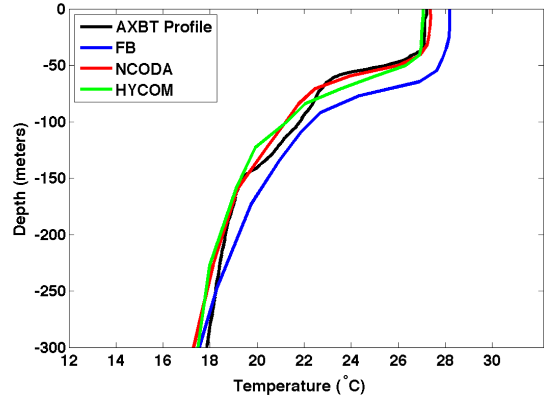
Evaluation of Ocean Initialization Options: Comparison with AXBTs

September 17, 2014 (post-storm)

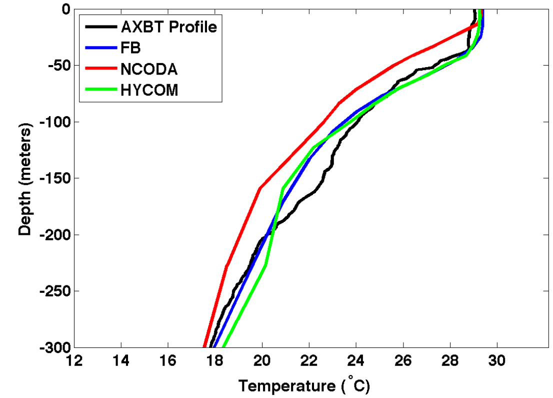
AXBT Location: 25.369N -58.138E
AXBT Date/Time: 2014 Sep 17, 18:49:27Z (Post-Storm)
POM Date/Time: Sep 17, 19:30:00 Z



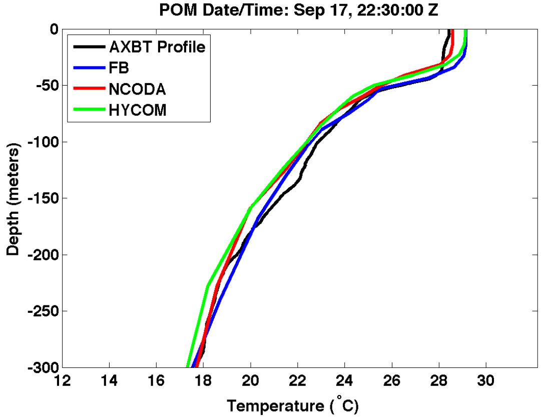
AXBT Location: 27.779N -53.569E
AXBT Date/Time: 2014 Sep 17, 20:01:20Z (Post-Storm)
POM Date/Time: Sep 17, 19:30:00 Z



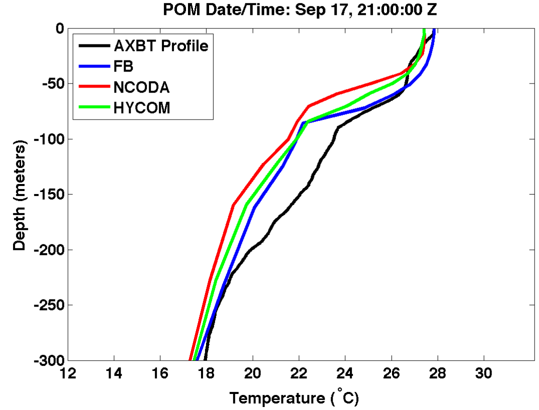
AXBT Location: 23.983N -53.071E
AXBT Date/Time: 2014 Sep 17, 22:54:32Z (Post-Storm)
POM Date/Time: Sep 17, 22:30:00 Z



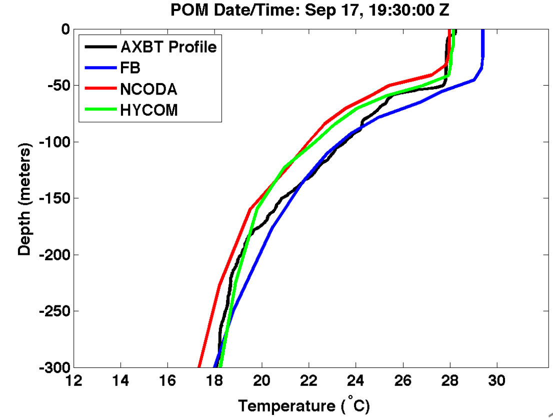
AXBT Location: 24.649N -51.768E
AXBT Date/Time: 2014 Sep 17, 22:34:21Z (Post-Storm)
POM Date/Time: Sep 17, 22:30:00 Z



AXBT Location: 25.829N -52.024E
AXBT Date/Time: 2014 Sep 17, 21:22:52Z (Post-Storm)
POM Date/Time: Sep 17, 21:00:00 Z

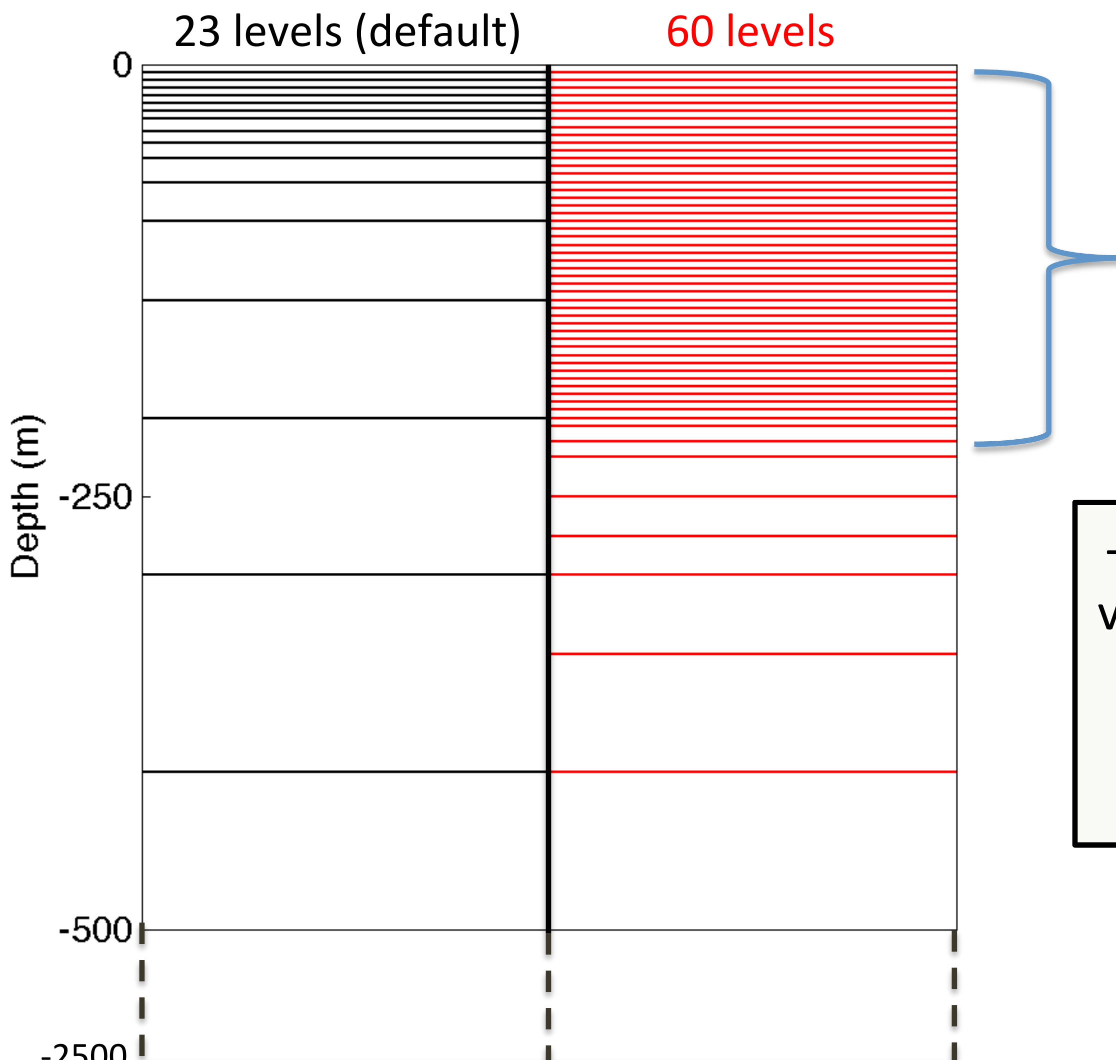


AXBT Location: 26.438N -56.37E
AXBT Date/Time: 2014 Sep 17, 19:18:37Z (Post-Storm)
POM Date/Time: Sep 17, 19:30:00 Z



MPIPOM: Increased number of sigma levels

- New higher resolution (60 level) MPIPOM implemented to test sensitivity to upper ocean vertical resolution



- 60 level MPIPOM maintains ~5 m resolution to mixing depth of ~200 m (for 2500 m ocean depth)

- 23 level MPIPOM has vertical level resolution of ~50 m at 200 m depth (for 2500 m ocean depth)

MPIPOM physics upgrade: KPP mixing parameterization (KPP-df)

- Vertical turbulent mixing is parameterized from the shear.

Momentum

$$\overline{w'u'}(z) = -K\left(\frac{\partial \overline{u}}{\partial z}\right)$$

Temperature

$$\overline{w'\theta'}(z) = -K\left(\frac{\partial \overline{\theta}}{\partial z}\right)$$

- The K-Parameter Profile (KPP) model is used to determine K.

$$K(z) = hWG(z)$$

h - Mixing layer depth
W - Turbulent velocity scale
G (z) - Non-dimensional shape-function

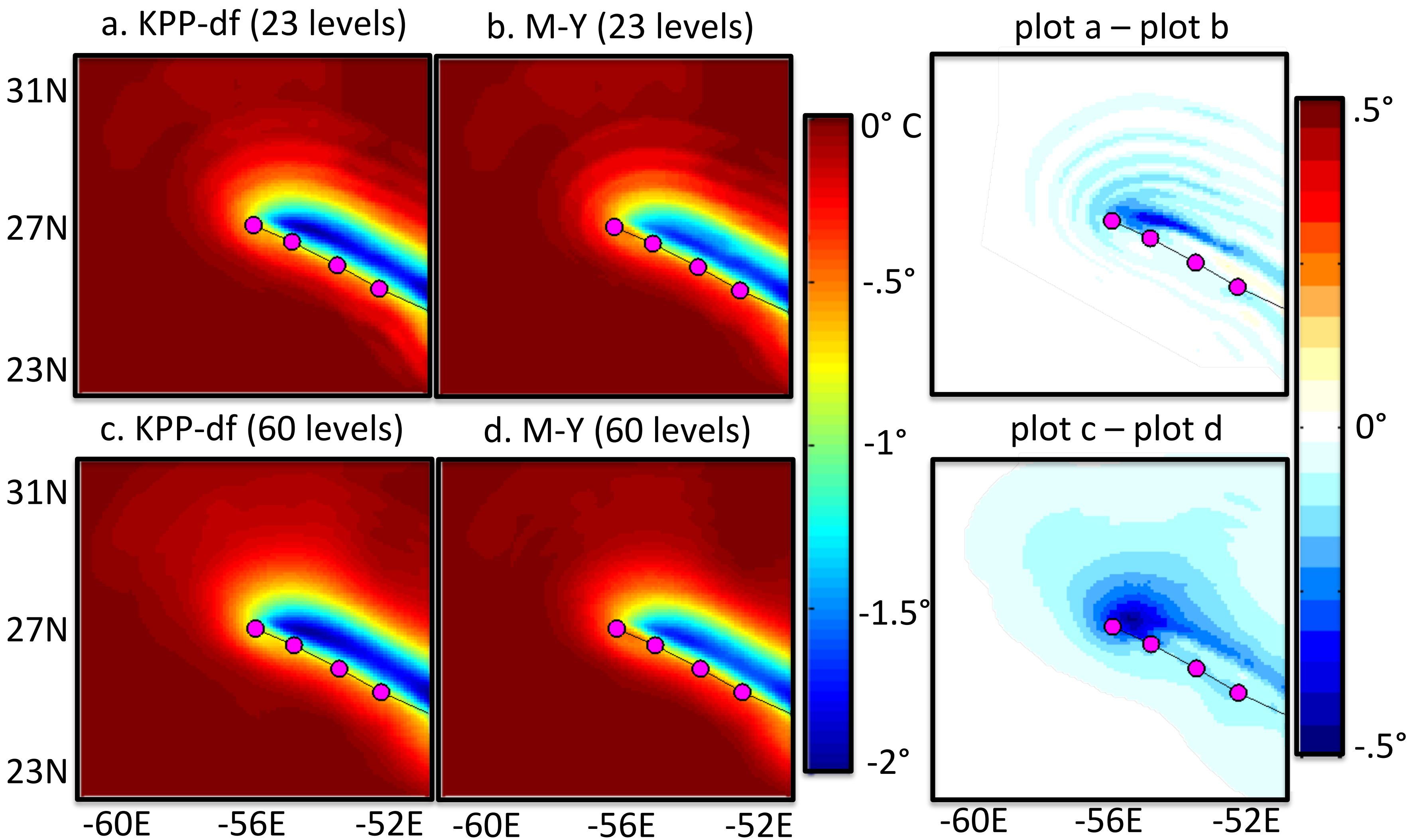
- *h* is determined from bulk Richardson number criteria ($Ri_c = 0.3$)

$$Ri_b(z) = \frac{(B^r - B(z))|z|}{(U^r - U(z))^2 + (V^r - V(z))^2 + V_t^2(z)} < Ri_c$$

B - Buoyancy
U/V - currents (X/Y)
V_t - unresolved turbulent shear

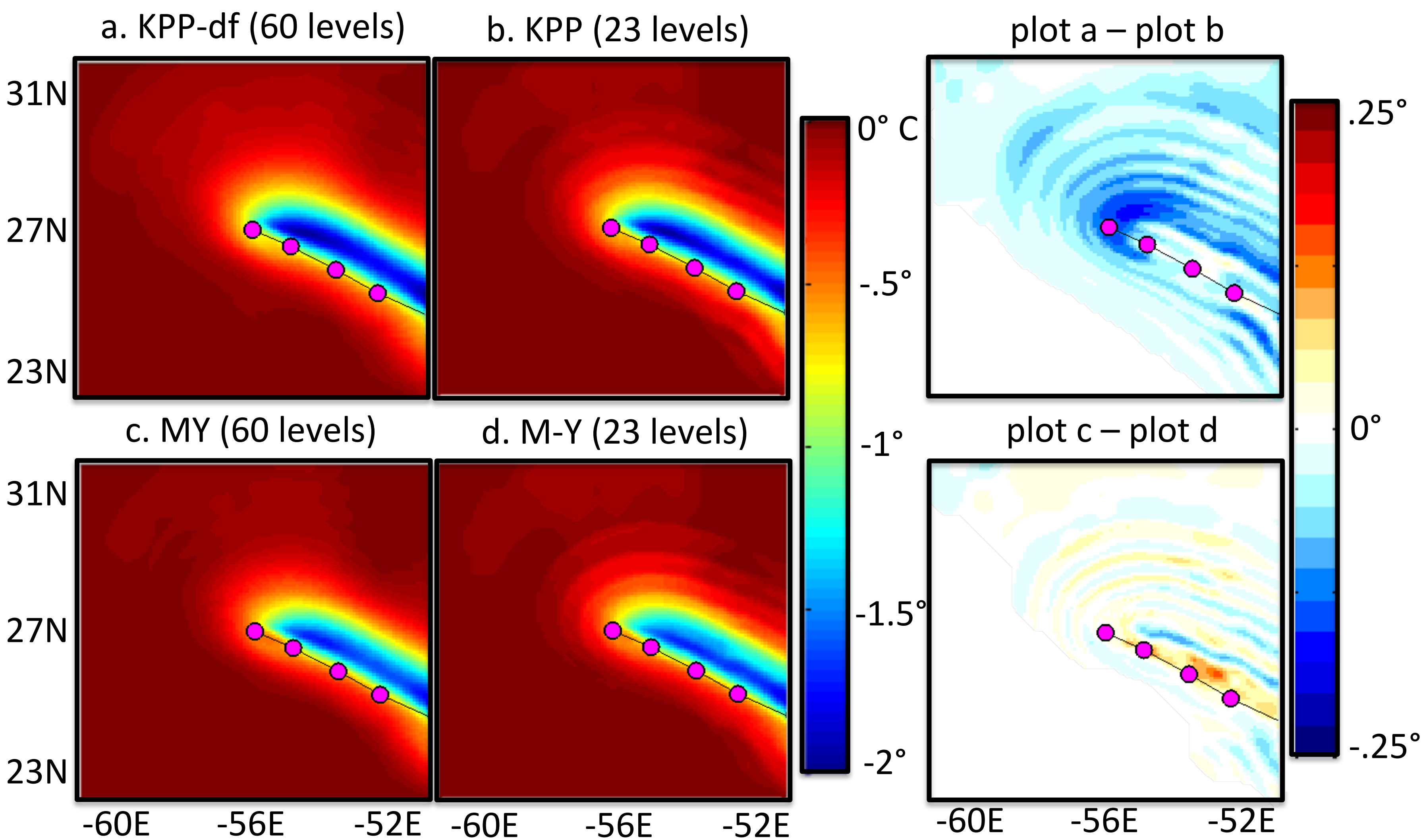
Hurricane Edouard 09/15 12Z: KPP vs. M-Y

- 60 level noticeably smoother than 23 level
- KPP-df (Ri_c=0.3) produces up to 0.5° C more cooling than M-Y



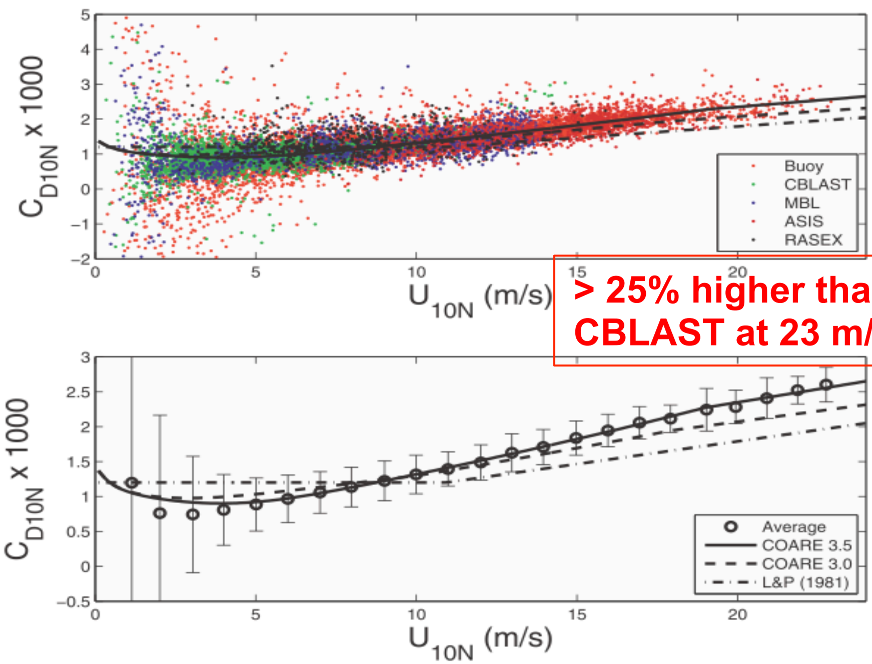
Hurricane Edouard 09/15 12Z: Sensitivity to Resolution

- KPP: less cooling for 60 levels by up to 0.2°
- M-Y: Impact of increased vertical resolution is small



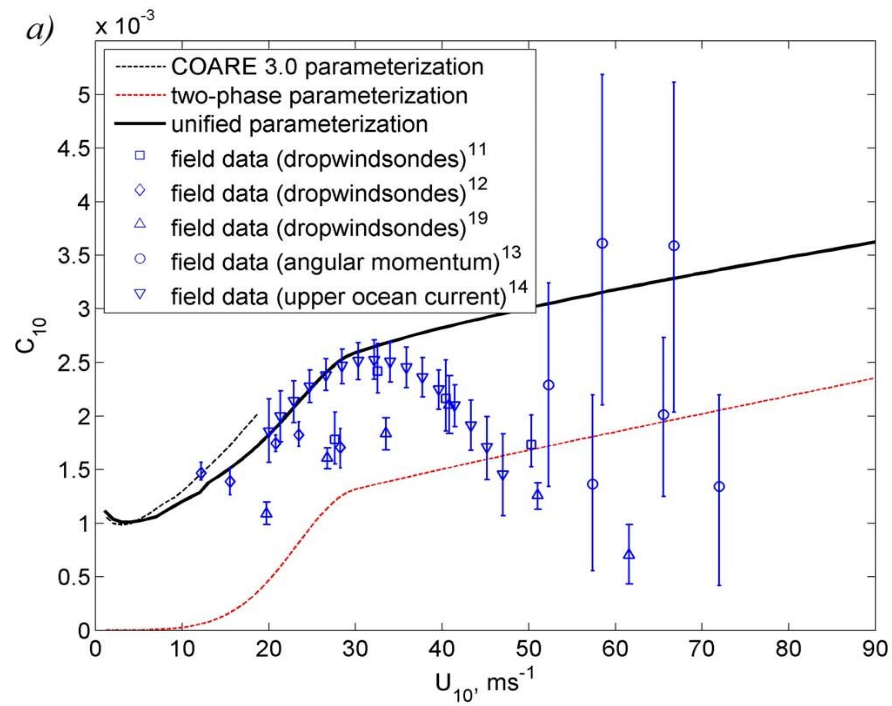
The 2015 HWRF surface physics upgrade: C_d formulation is based on direct measurements and theoretical analysis at high winds

Edson et al, 2013

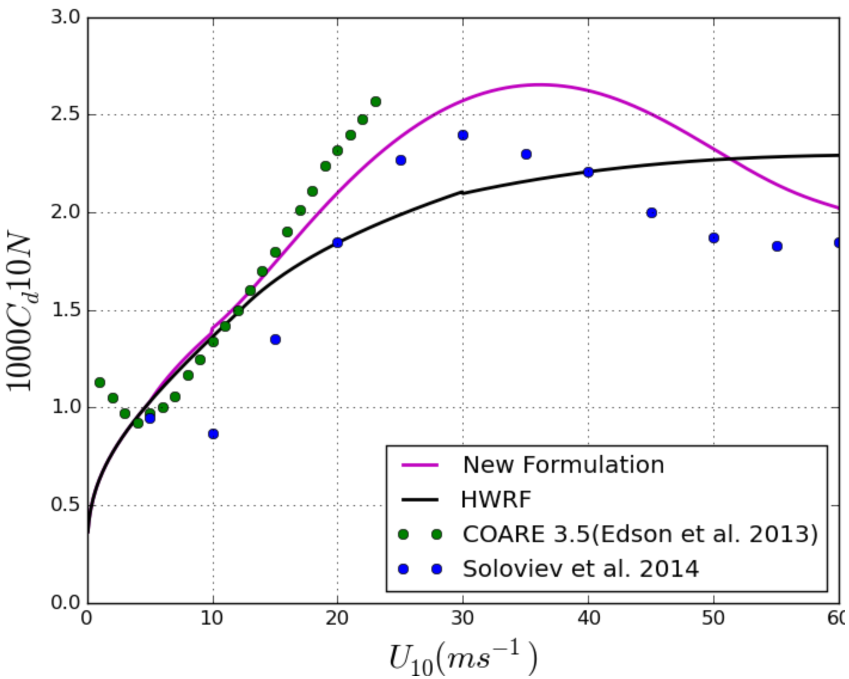


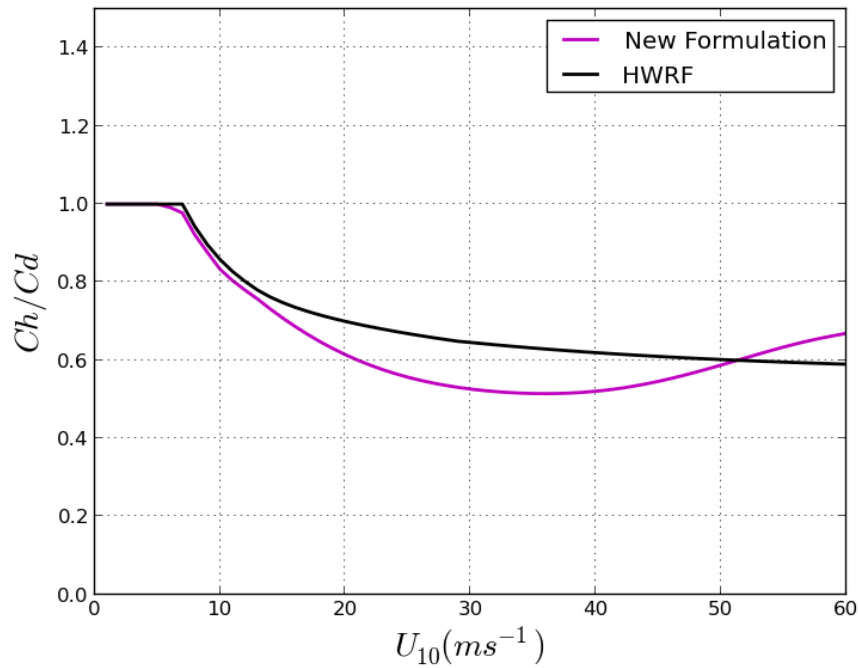
> 25% higher than CBLAST at 23 m/s

Soloviev et al, 2014



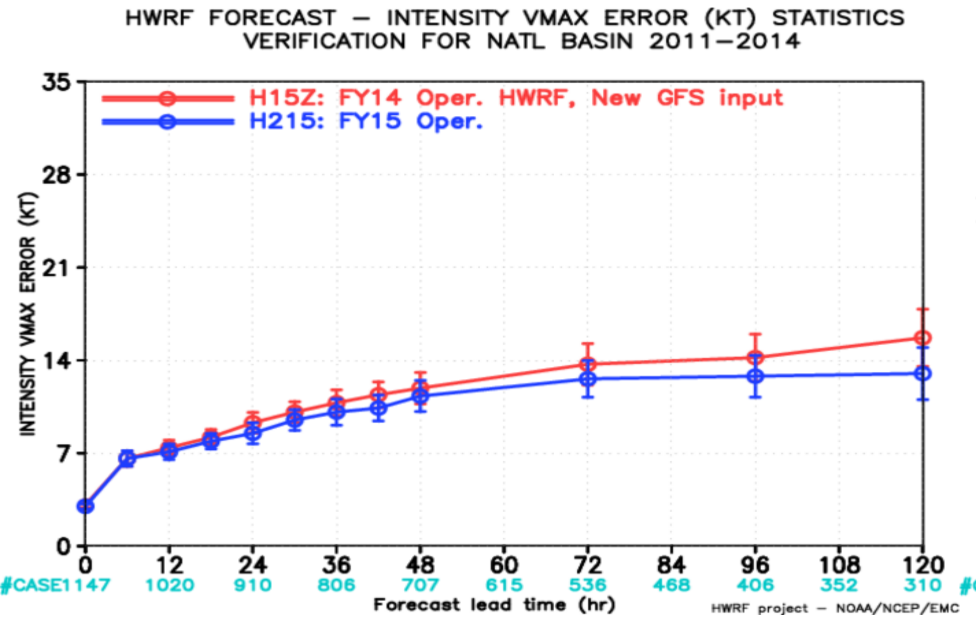
New C_d formulation implemented in 2015 Operational HWRF

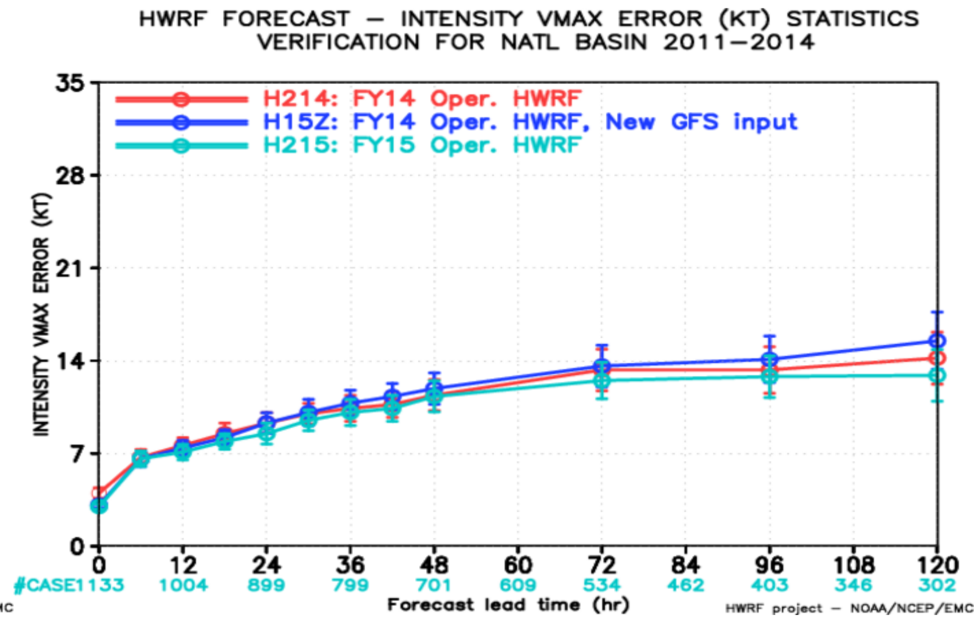


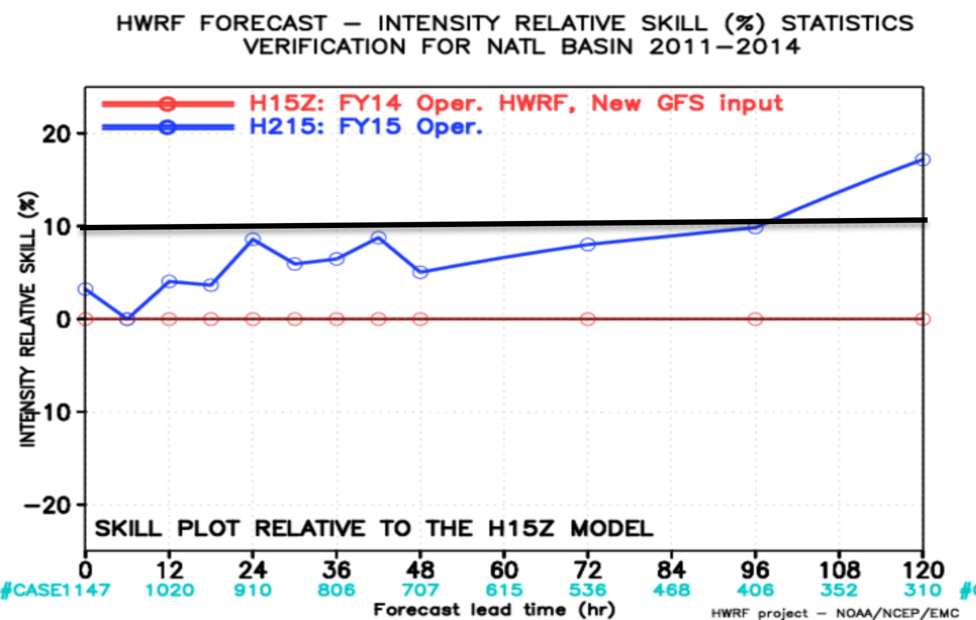


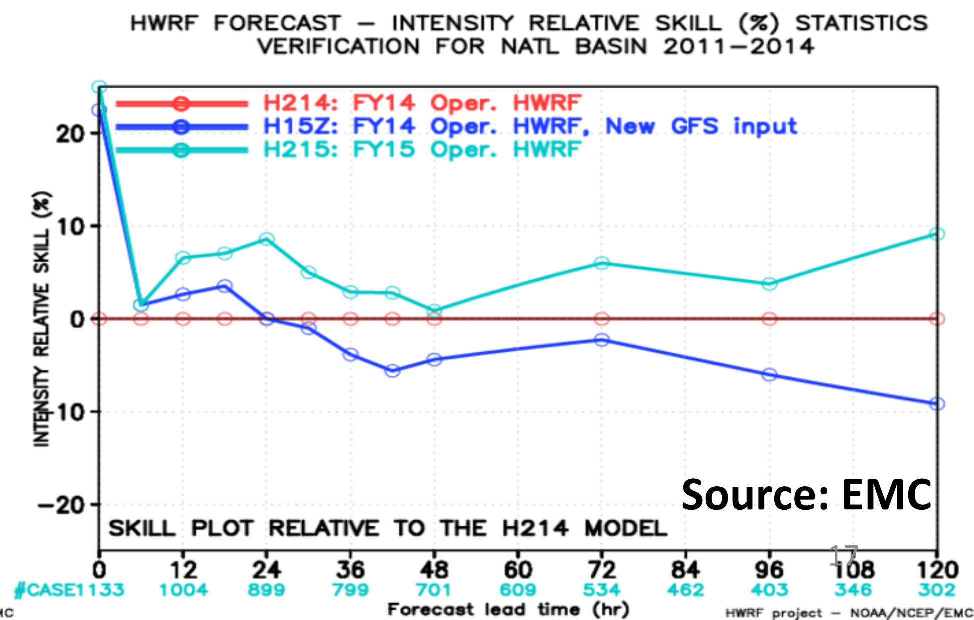
Impact of Physics, Resolution & New GFS, (H215 vs H15Z & H214)

NATL Intensity Error Forecasts 2011-2014









Developing HWRF air-sea interface module (ASIM) with explicit wave coupling

Motivation: air-sea fluxes and turbulent mixing above/below sea surface are significantly modified by surface waves in high wind conditions.

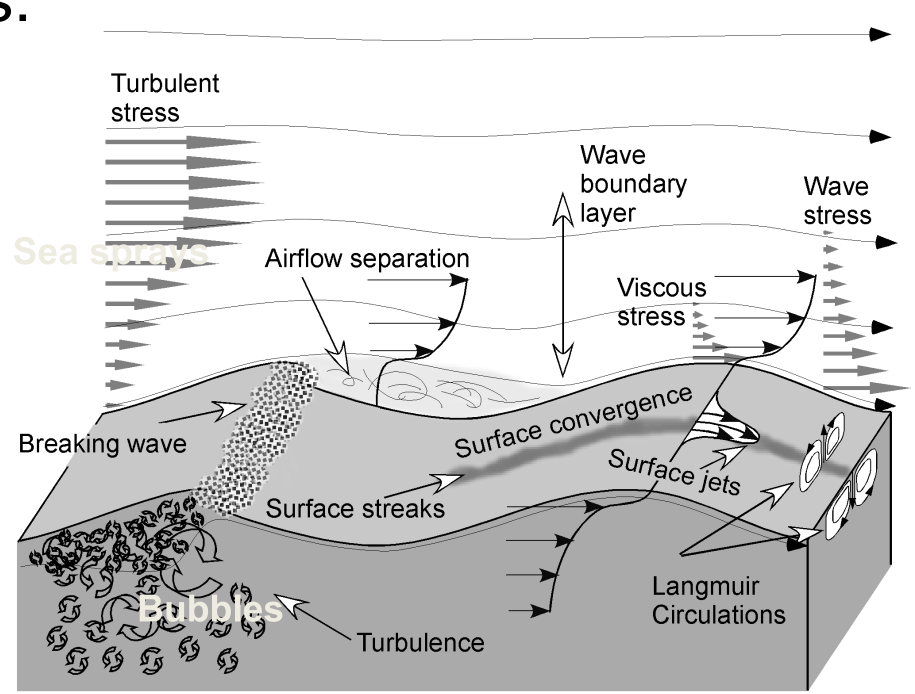
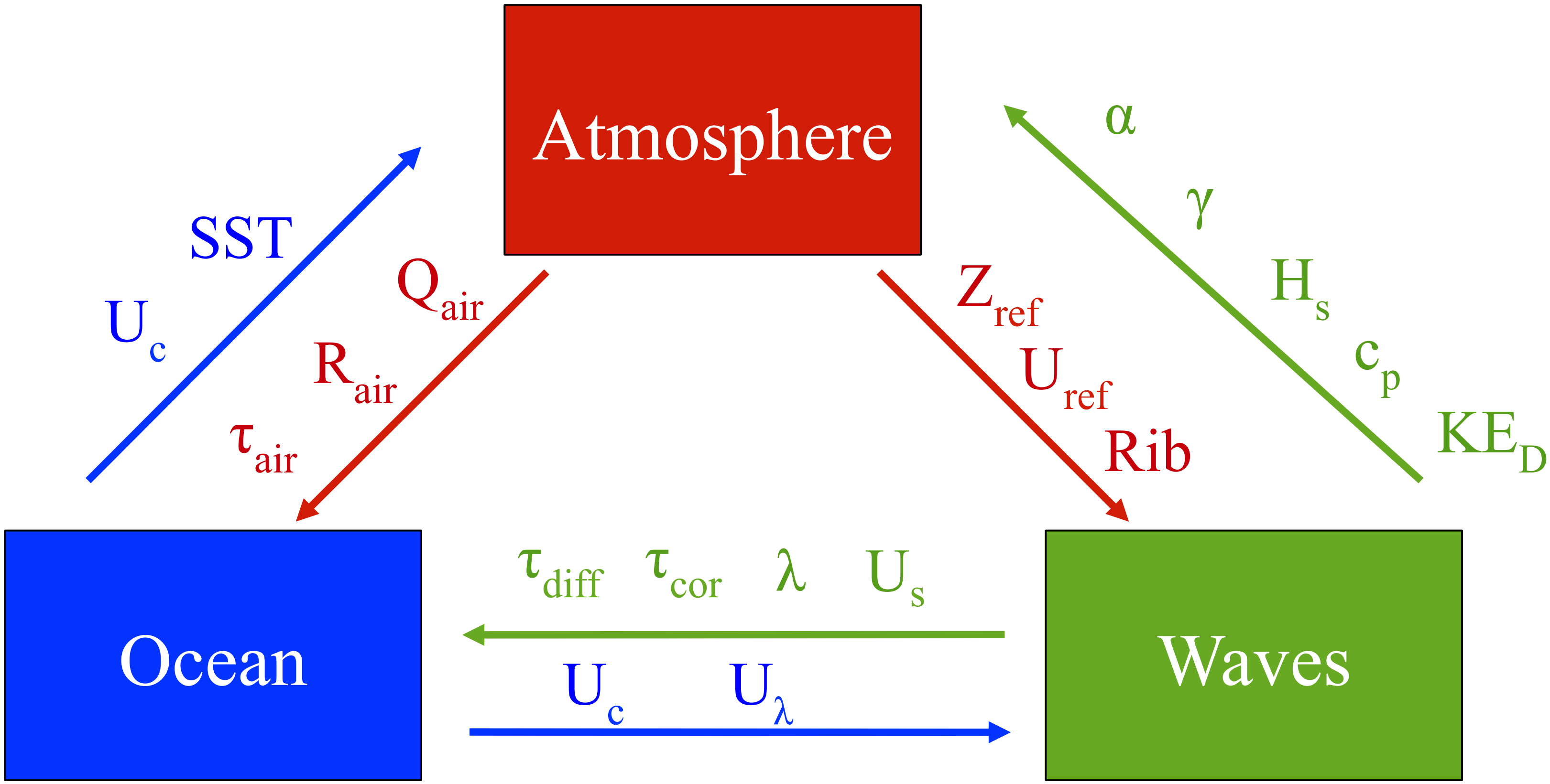
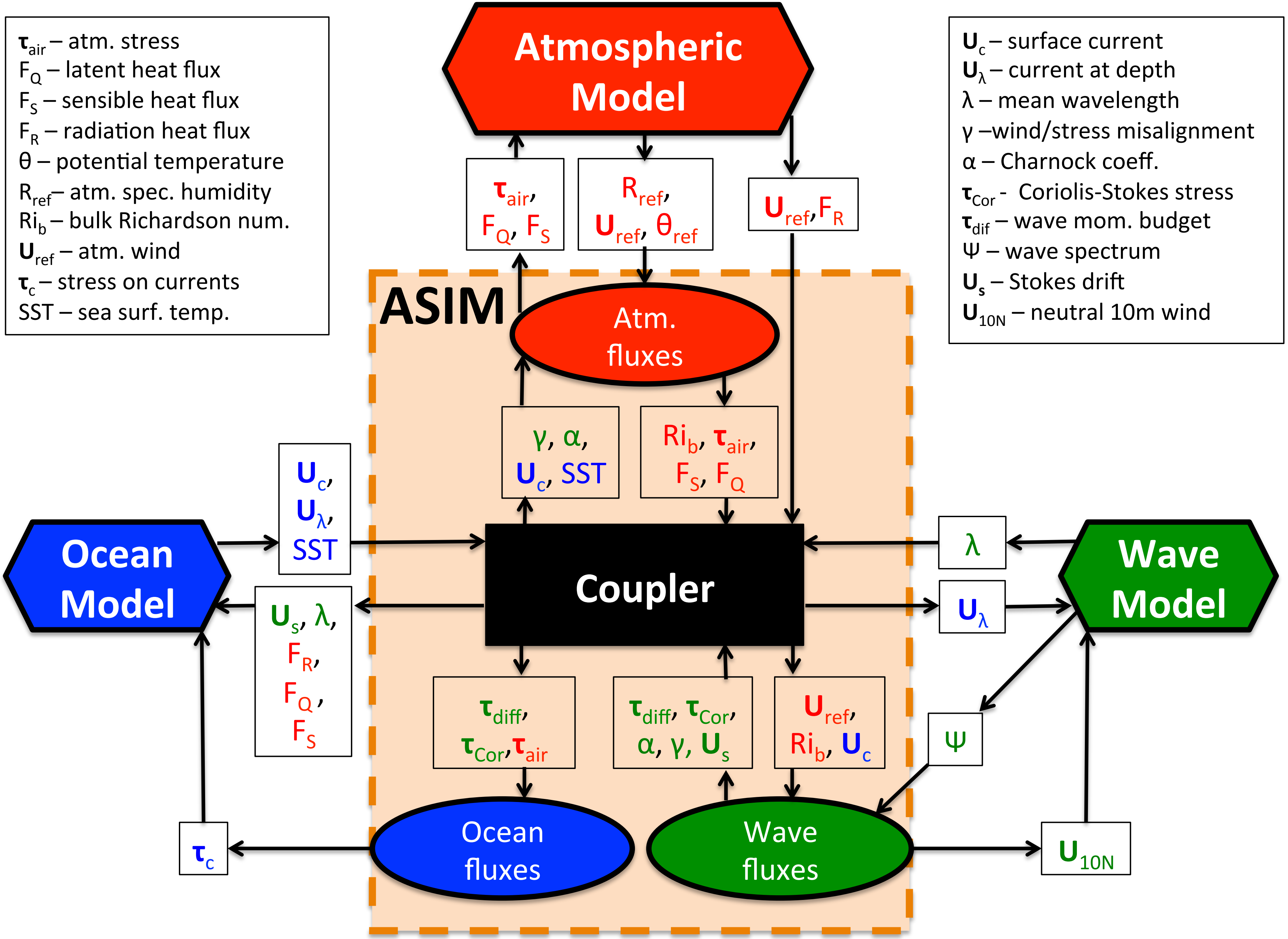


Image courtesy of Fabrice Veron

Wave-dependent physics in HWRF



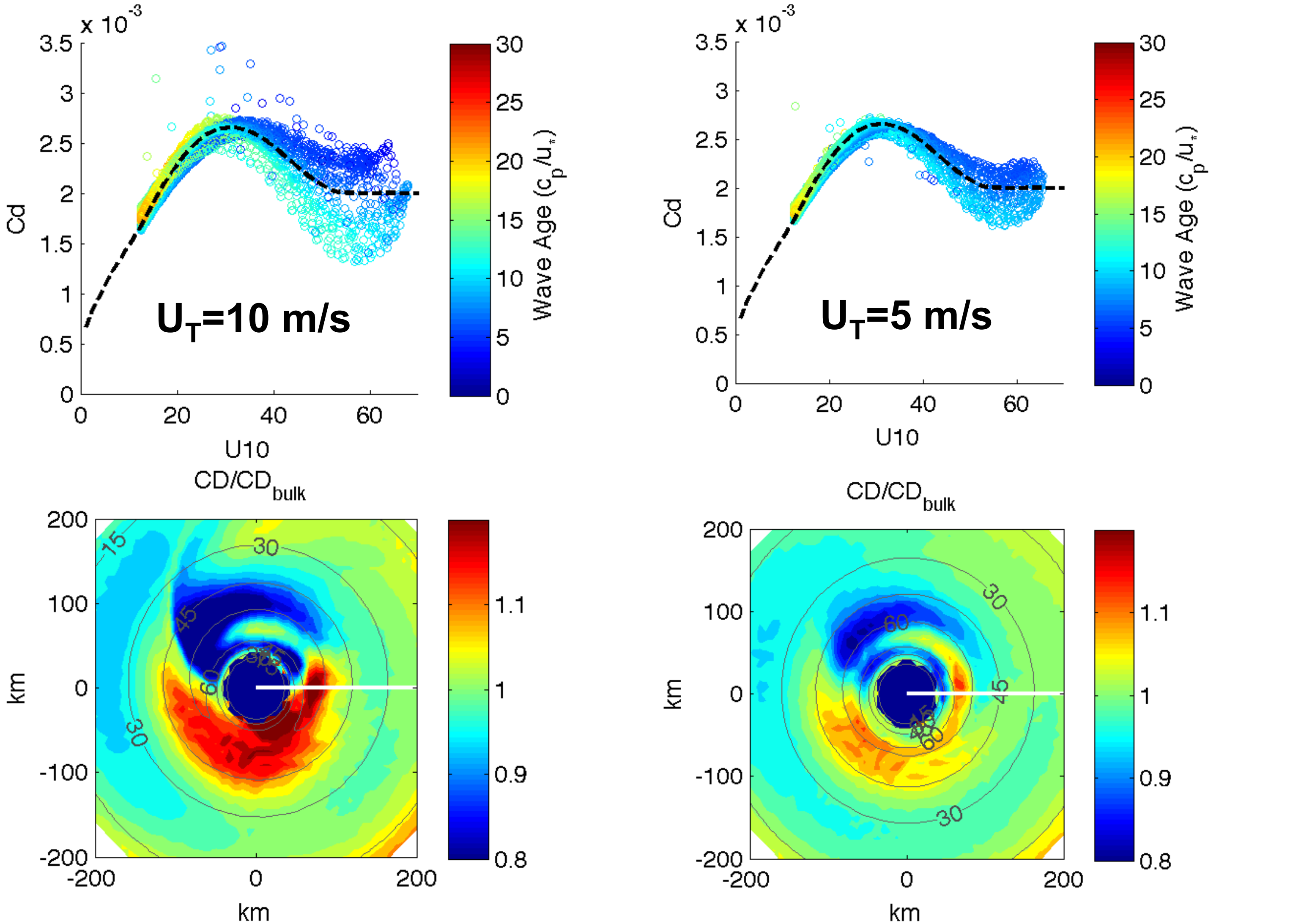
- **Atmospheric model:** air-sea fluxes depend on **sea state**
- **Wave model:** forced by **sea state** dependent wind forcing
- **Ocean model:** forced by **sea state** dependent wind stress modified by **growing or decaying wave fields** and **Coriolis-Stokes effect.** Turbulent mixing is modified by the Stokes drift (**Langmiur turbulence**).



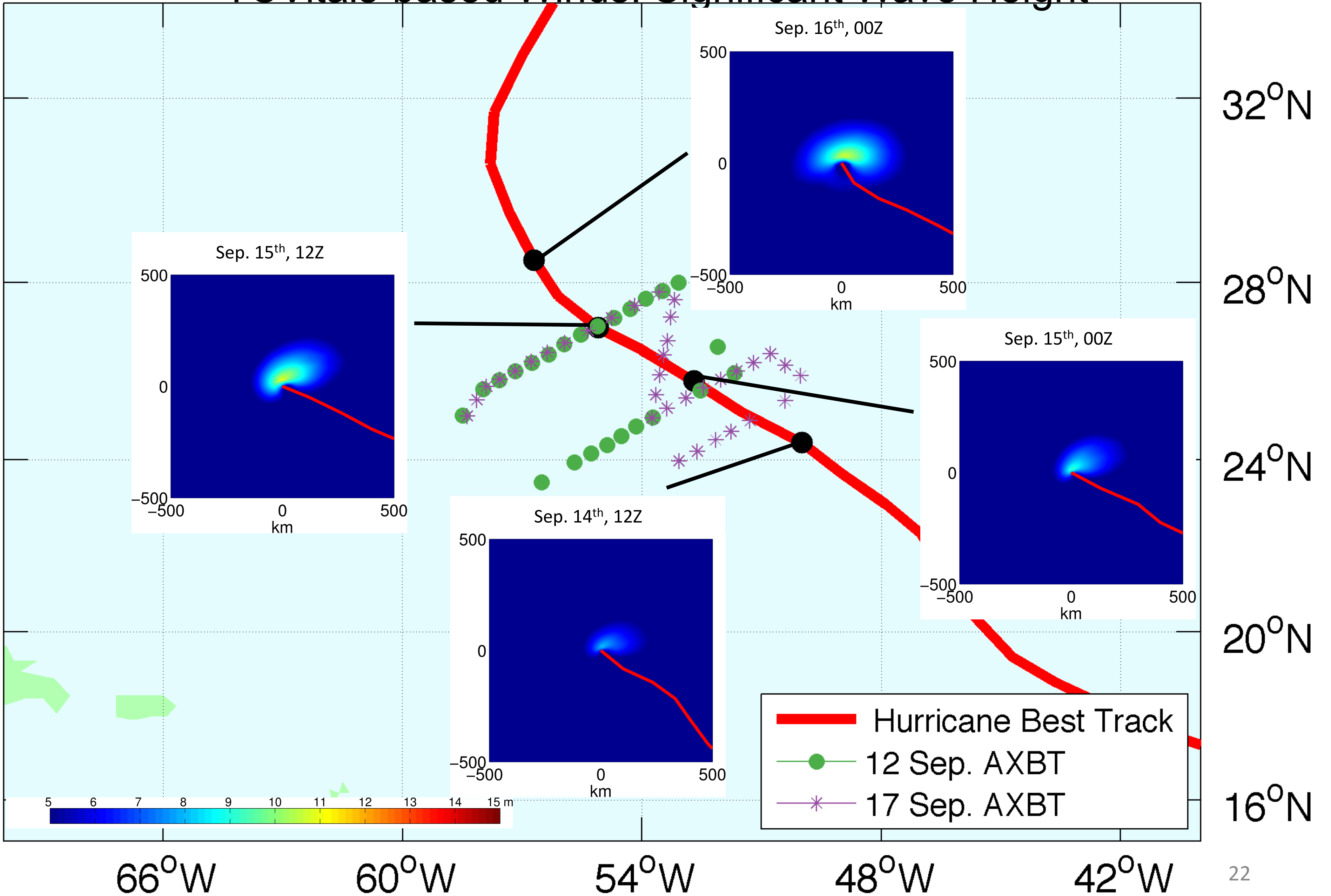
τair – atm. stress
FQ – latent heat flux
FS – sensible heat flux
FR – radiation heat flux
θ – potential temperature
Rref – atm. spec. humidity
Rib – bulk Richardson num.
Uref – atm. wind
τc – stress on currents
SST – sea surf. temp.
Atmospheric Model
τair, FQ, FS
Rref, Uref, θref
Uref, FR
Uc – surface current
Uλ – current at depth
λ – mean wavelength
γ –wind/stress misalignment
α – Charnock coeff.
τCor - Coriolis-Stokes stress
τdif – wave mom. budget
Ψ – wave spectrum
Us – Stokes drift
U10N – neutral 10m wind
ASIM
Atm. fluxes
γ, α, Uc, SST
Rib, τair, FS, FQ
Uc, Uλ, SST
Ocean Model
Coupler
λ
Uλ
Wave Model
Us, λ, FR, FQ, FS
τdiff, τCor, τair
τdiff, τCor, α, γ, Us
Uref, Rib, Uc
Ψ
τc
Ocean fluxes
Wave fluxes
U10N

Examples of sea state dependent C_d in WW3-MPIPOM coupled model (wind is prescribed)

RMS= 70 km, U_{10max}= 65 m/s



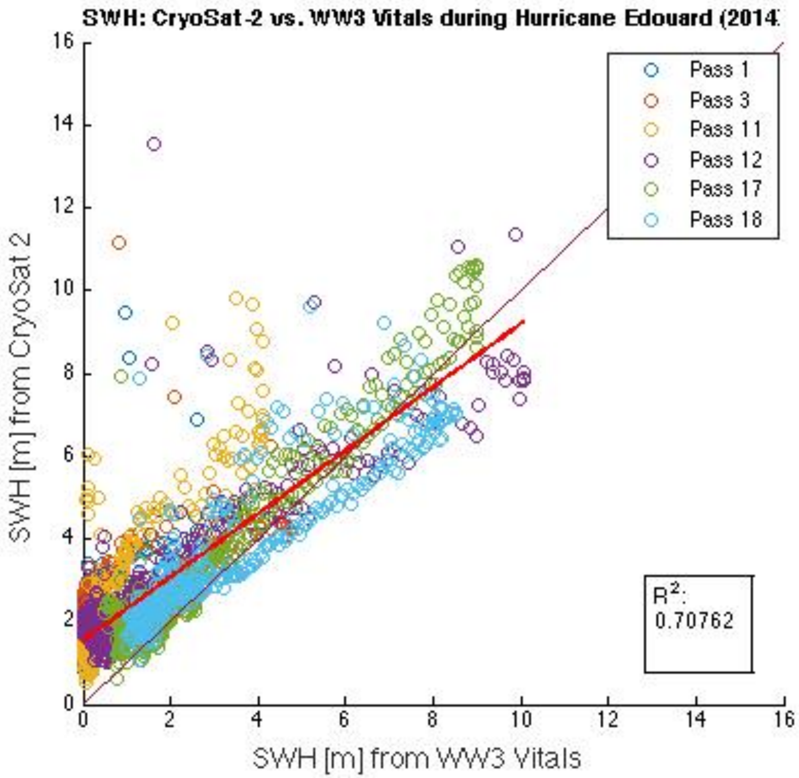
Hurricane Edouard, Coupled WW3-MPIPOM forced by TCVitals-based Winds: Significant Wave Height

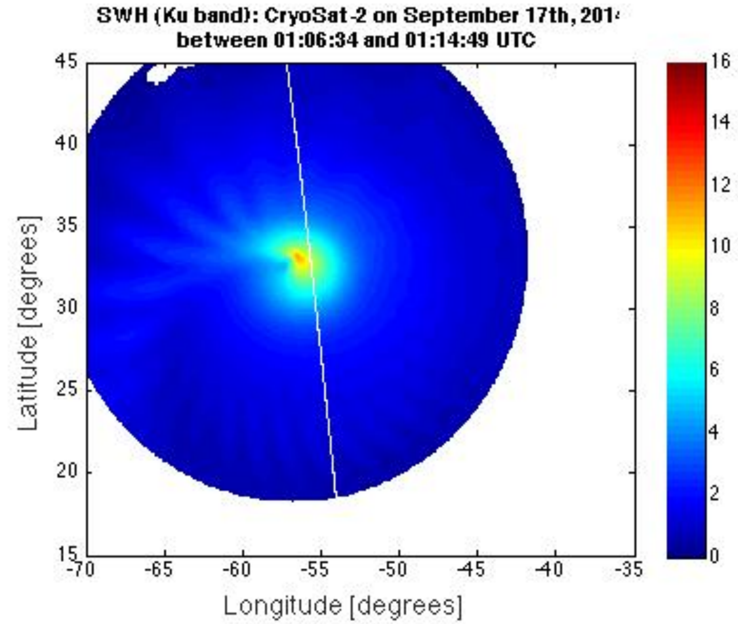


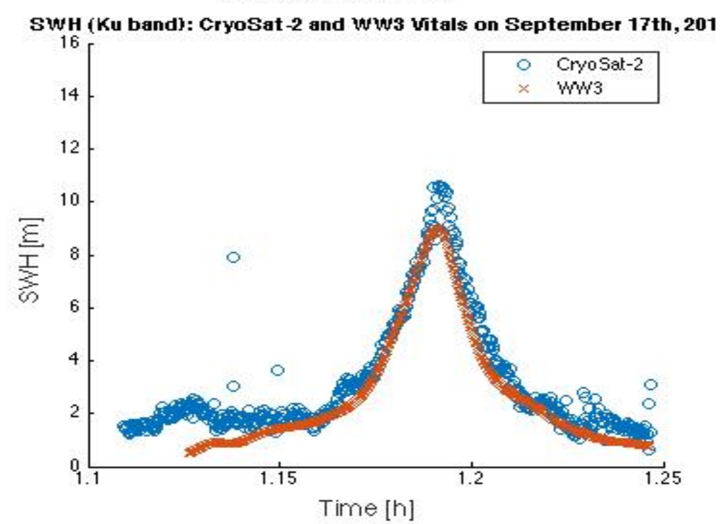
Hurricane Edouard, Coupled WW3-MPIPOM forced by TCVitals-based Winds

Significant wave height is compared to satellite observations (CryoSat-2)

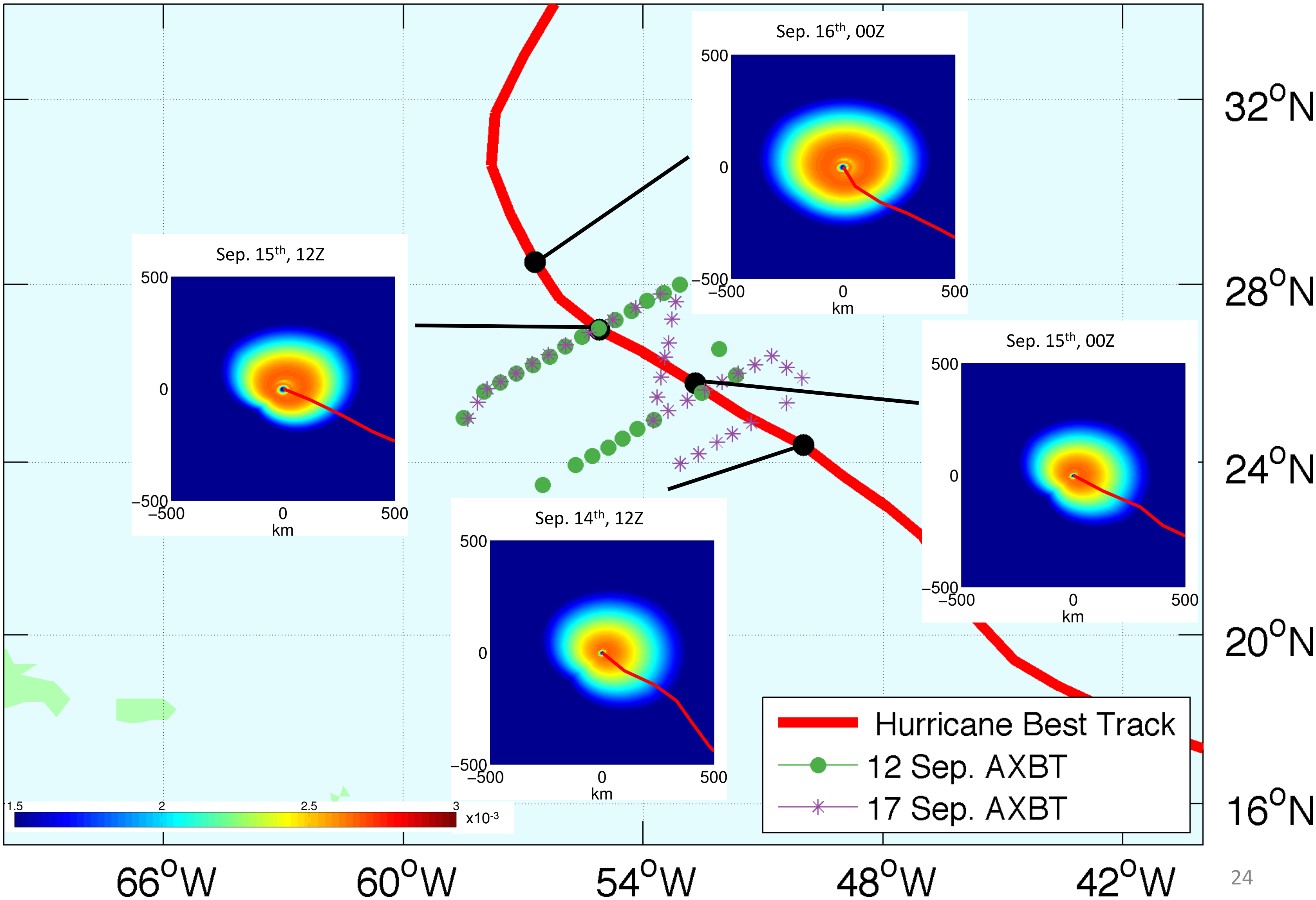
All satellite passes



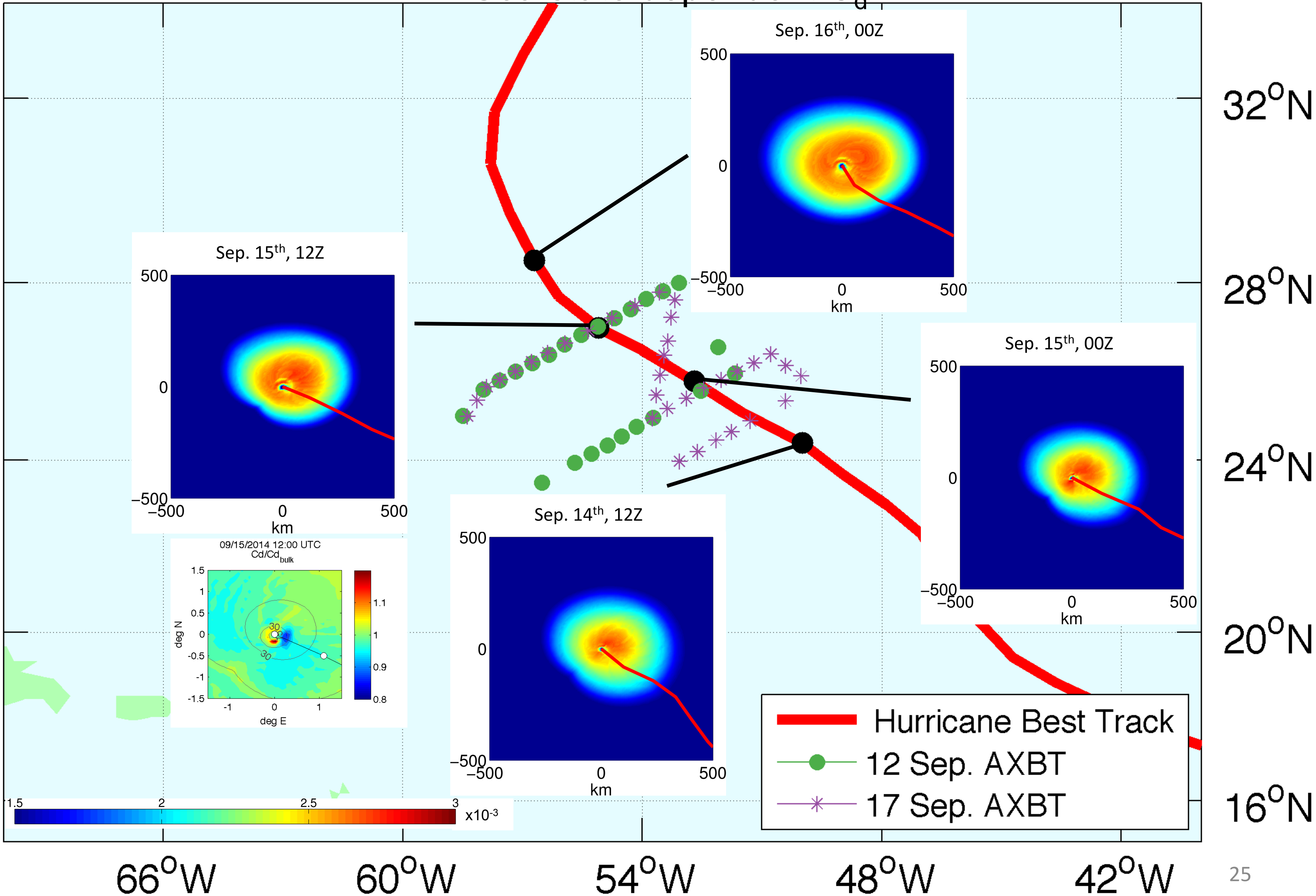




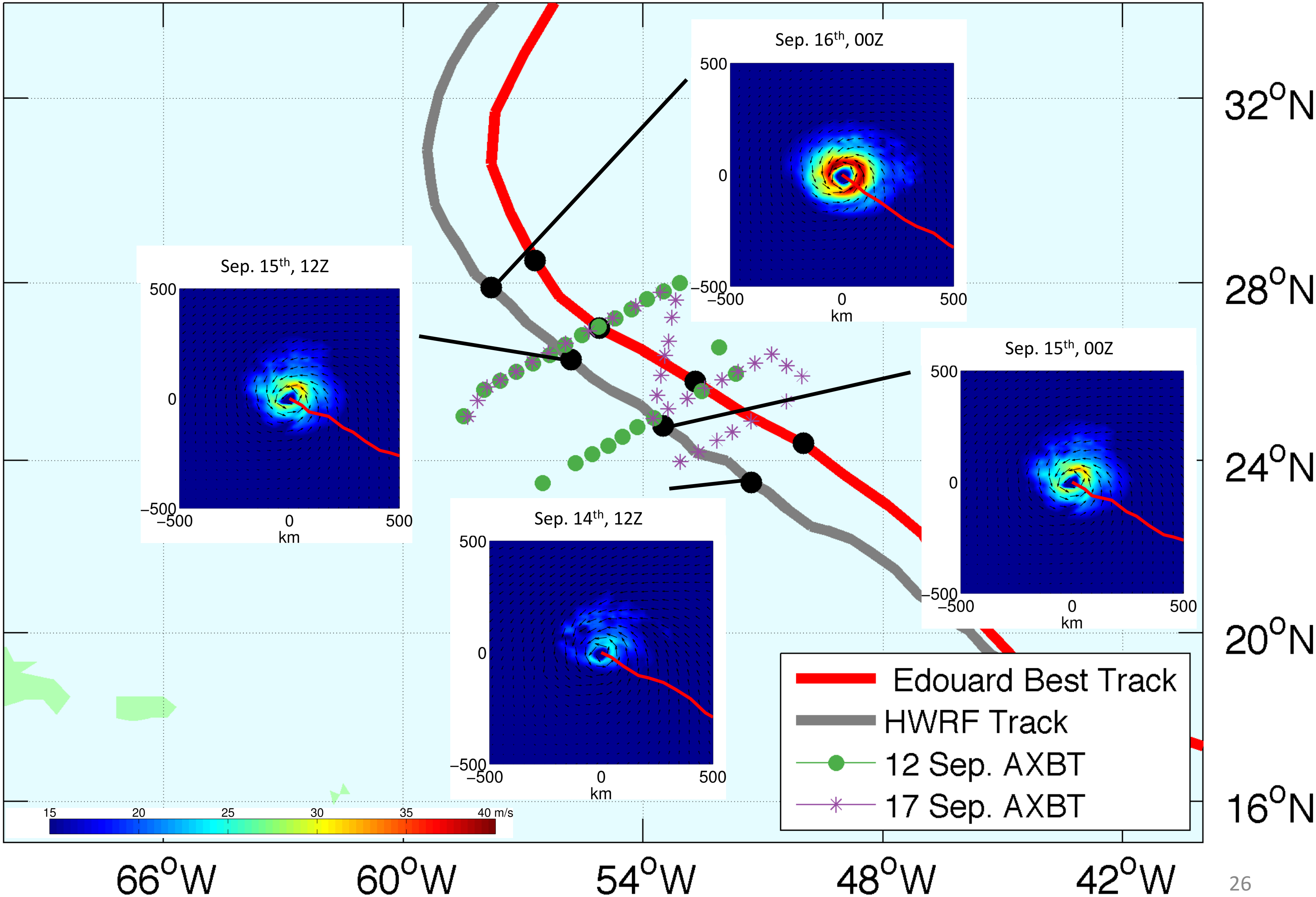
Hurricane Edouard, MPIPOM forced by TCVitals-based Winds: C_d Bulk



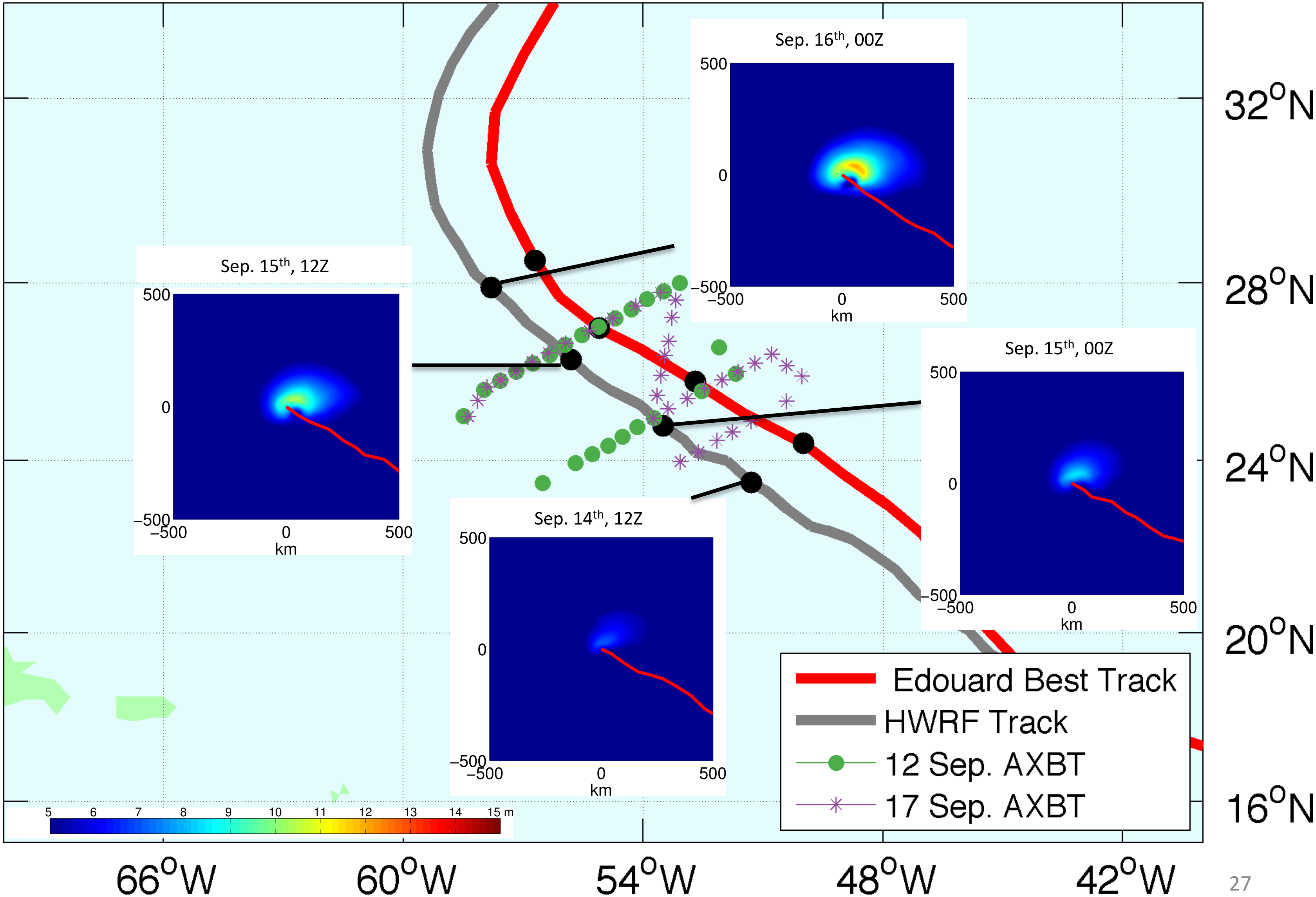
Hurricane Edouard, Coupled WW3-MPIPOM forced by TCVitals-based Winds: Sea state dependent C_d



Hurricane Edouard: HWRF forecast U_{10} winds



Hurricane Edouard, Coupled HWRF-WW3: Significant Wave Height



Wave dependent surface boundary conditions in the ocean model

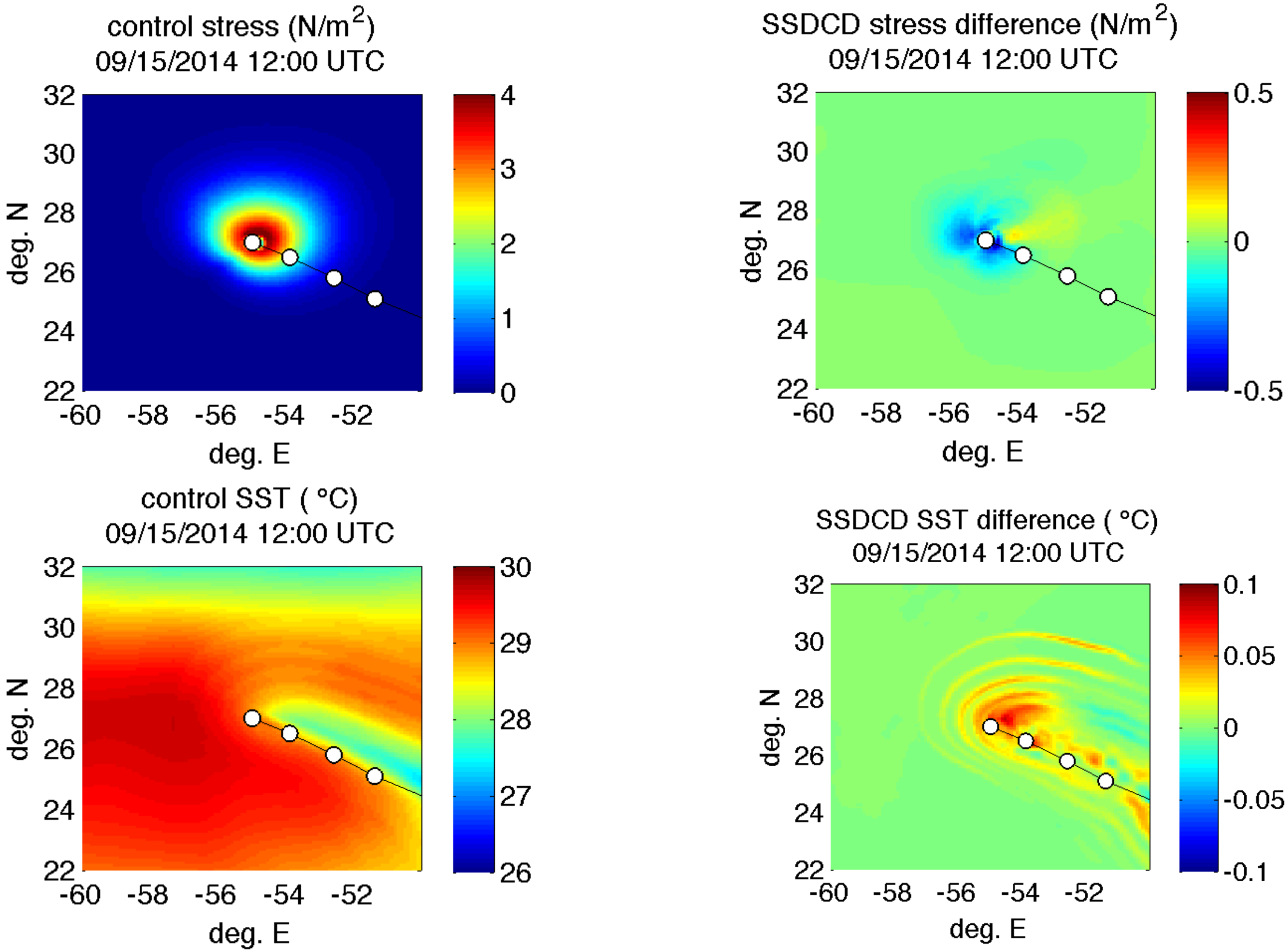
$$\bar{\tau}_{t\alpha} = \underbrace{\tau_{air\alpha}}_{\text{Wind stress}} \underbrace{- \frac{\partial}{\partial t} M_{\alpha} - \frac{\partial}{\partial x_{\beta}} MF_{\alpha\beta}}_{\text{Wave momentum budget}} \underbrace{- \tau_{s\alpha}}_{\text{Coriolis-Stokes}} \quad at \quad z = \hat{\eta}$$

Wind stress   Wave momentum budget   Coriolis-Stokes

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

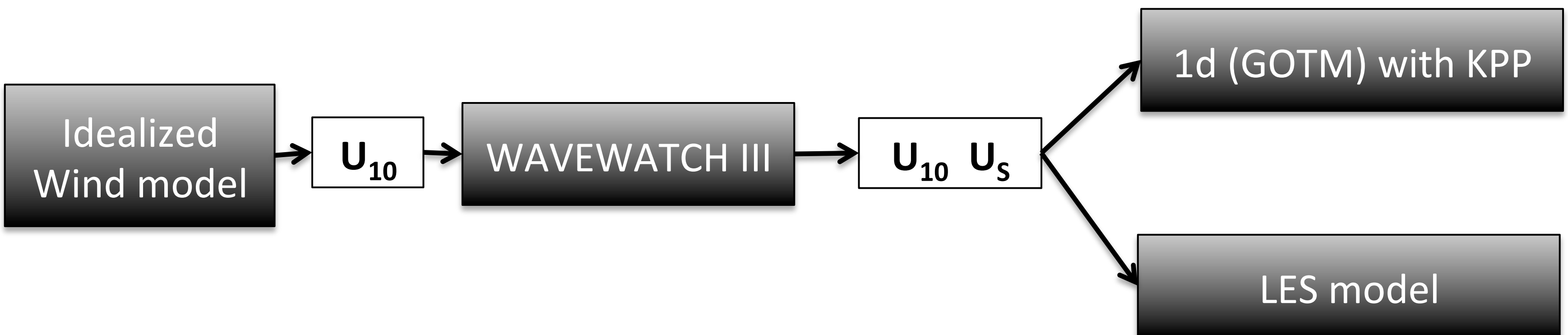
$u_{s\alpha}$: Stokes drift $S_{\alpha\beta}$:Radiation stress

Hurricane Edouard, Coupled WW3-MPIPOM: Effect of wave dependent surface boundary conditions



Modification of KPP mixing to include wave dependent Langmuir turbulence

Experiment Design

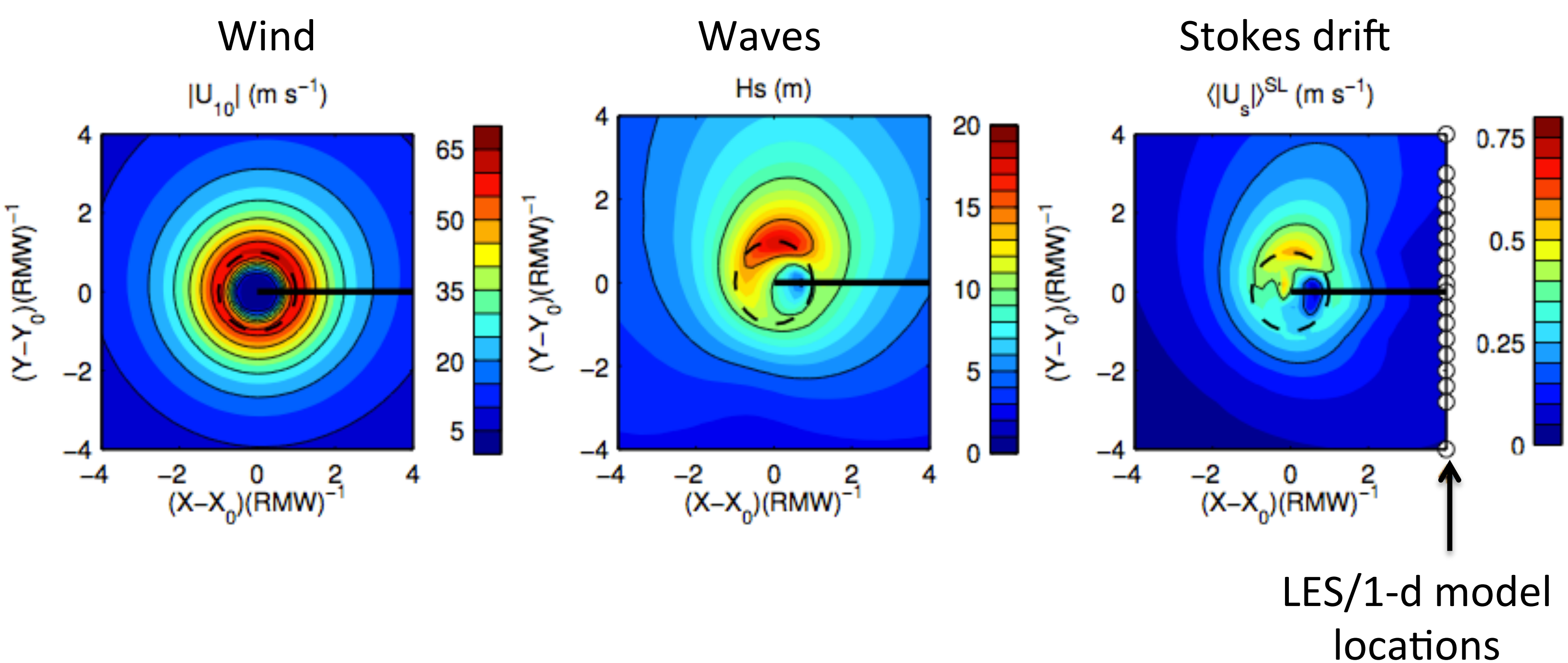


U_{10} – 10 meter wind vector
U_S – Stokes drift vector profile

The mean profile of the LES results and the 1-d column model w/ KPP results can be compared to evaluate performance of KPP

WAVEWATCH III simulation

- Idealized hurricane, 5 m/s translation speed, 50 km RMW, 65 m/s max wind



The wind field and Stokes drift are used to force LES model and 1-d model with KPP mixing model.

Large Eddy Simulation (LES) Model

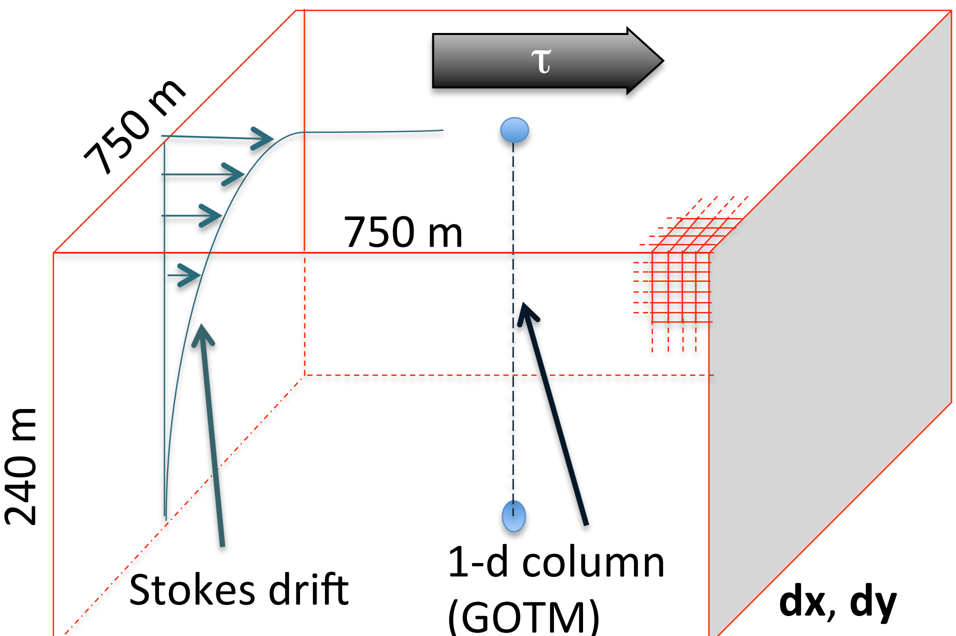
Momentum equation

$$\frac{D\mathbf{u}}{Dt} + f\hat{\mathbf{z}}\times(\mathbf{u}+\mathbf{u}_S) = -\nabla\pi - g\hat{\mathbf{z}}\left(\frac{\rho}{\rho_0}\right) + \mathbf{u}_S\times(\nabla\times\mathbf{u}) + SGS$$

Coriolis — pressure — buoyancy — CL-vortex force

- $\mathbf{u}$ – ocean current
- f – Coriolis parameter
- $\mathbf{u}_S$ – Stokes drift
- π – generalized pressure
- g – gravitational acceleration
- ρ – density
- SGS – Subgrid processes

LES domain

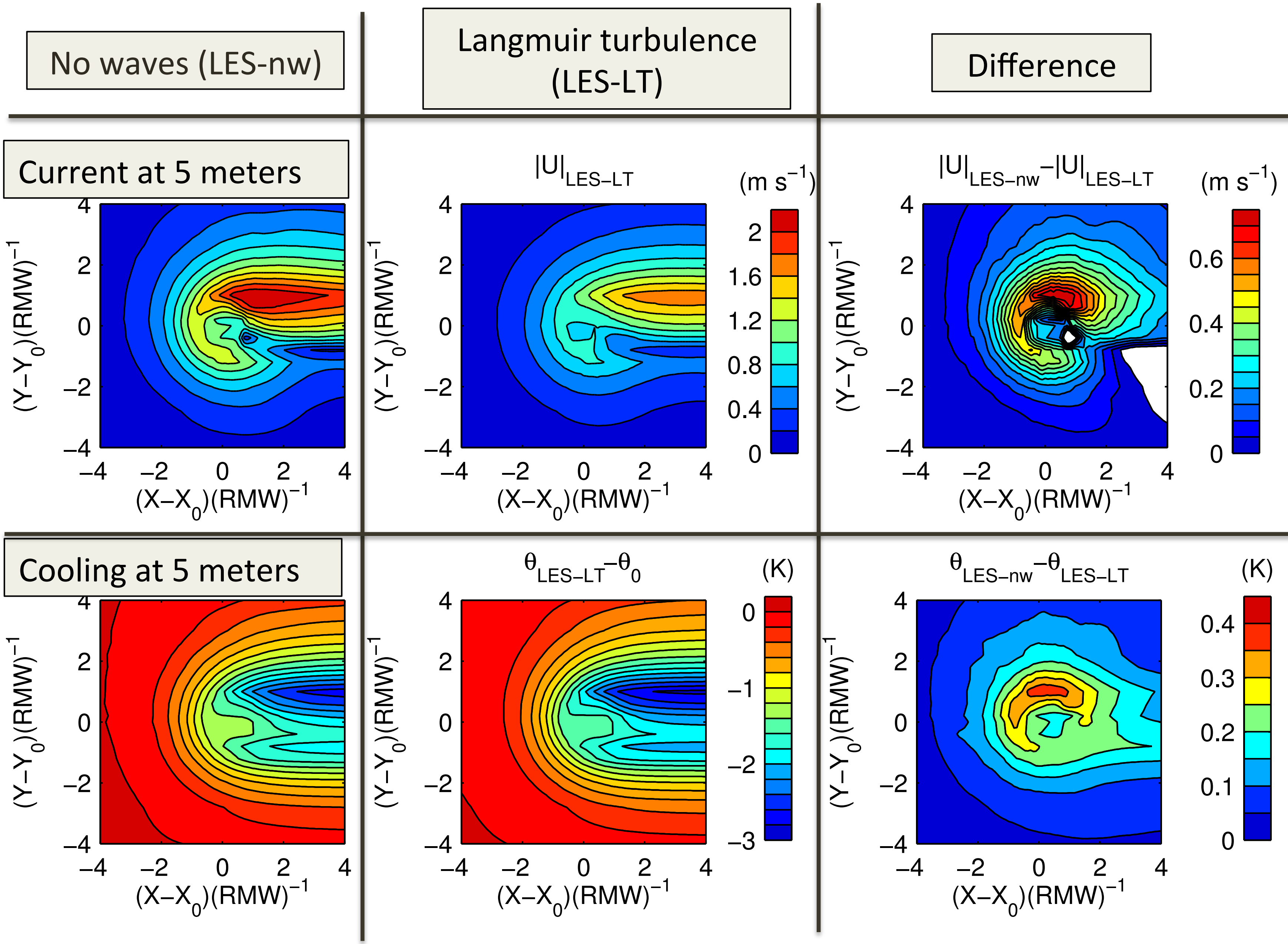


dx, dy	~3 m
dz	~1 m

Methodology for KPP wave-dependent tuning

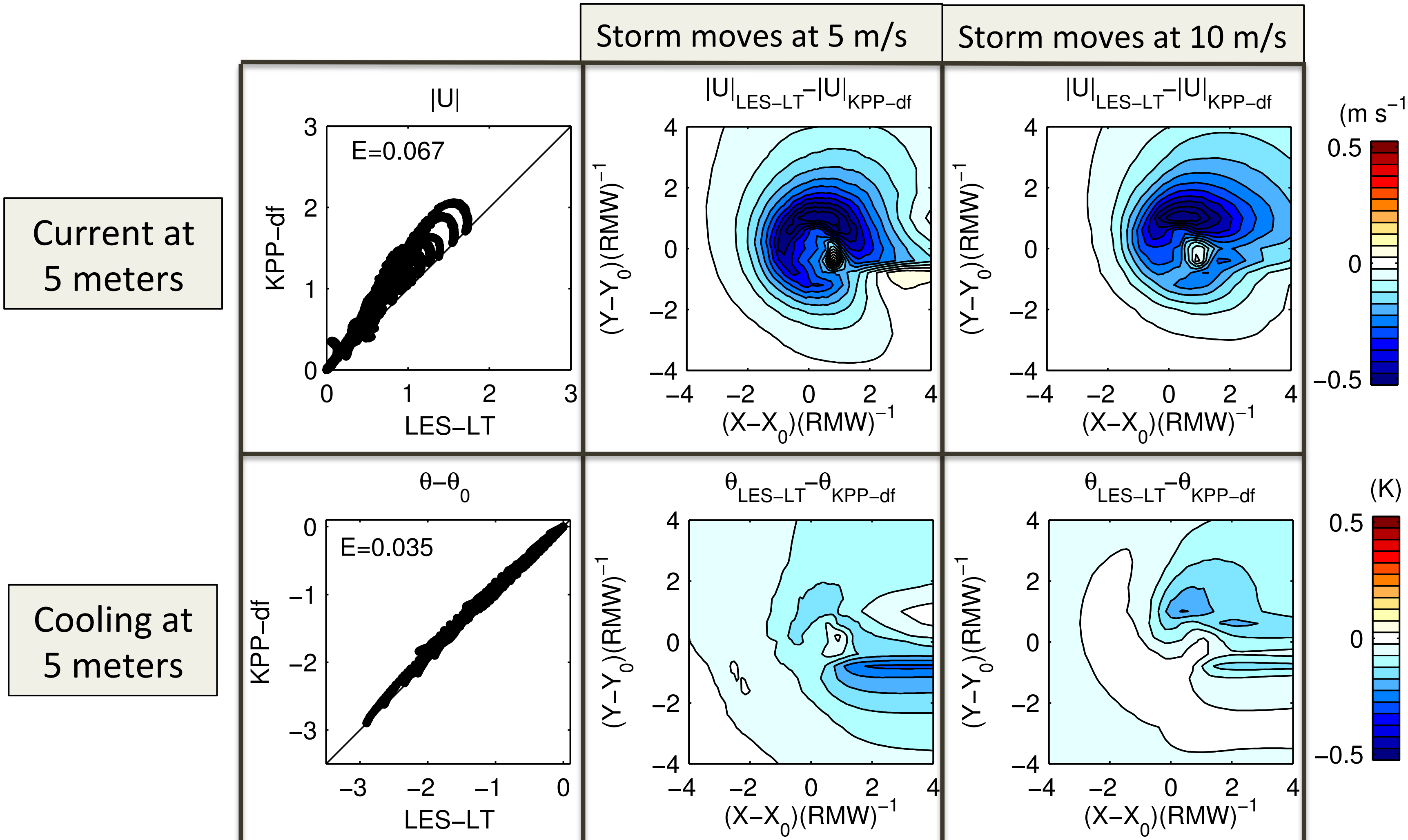
1. Run LES without Stokes drift (LES-nw)
2. Tune KPP using LES without Stokes drift
3. Run LES with Stokes drift (LES-LT)
4. Add LT effect to retuned KPP and compare to LES with Stokes drift

LES simulations



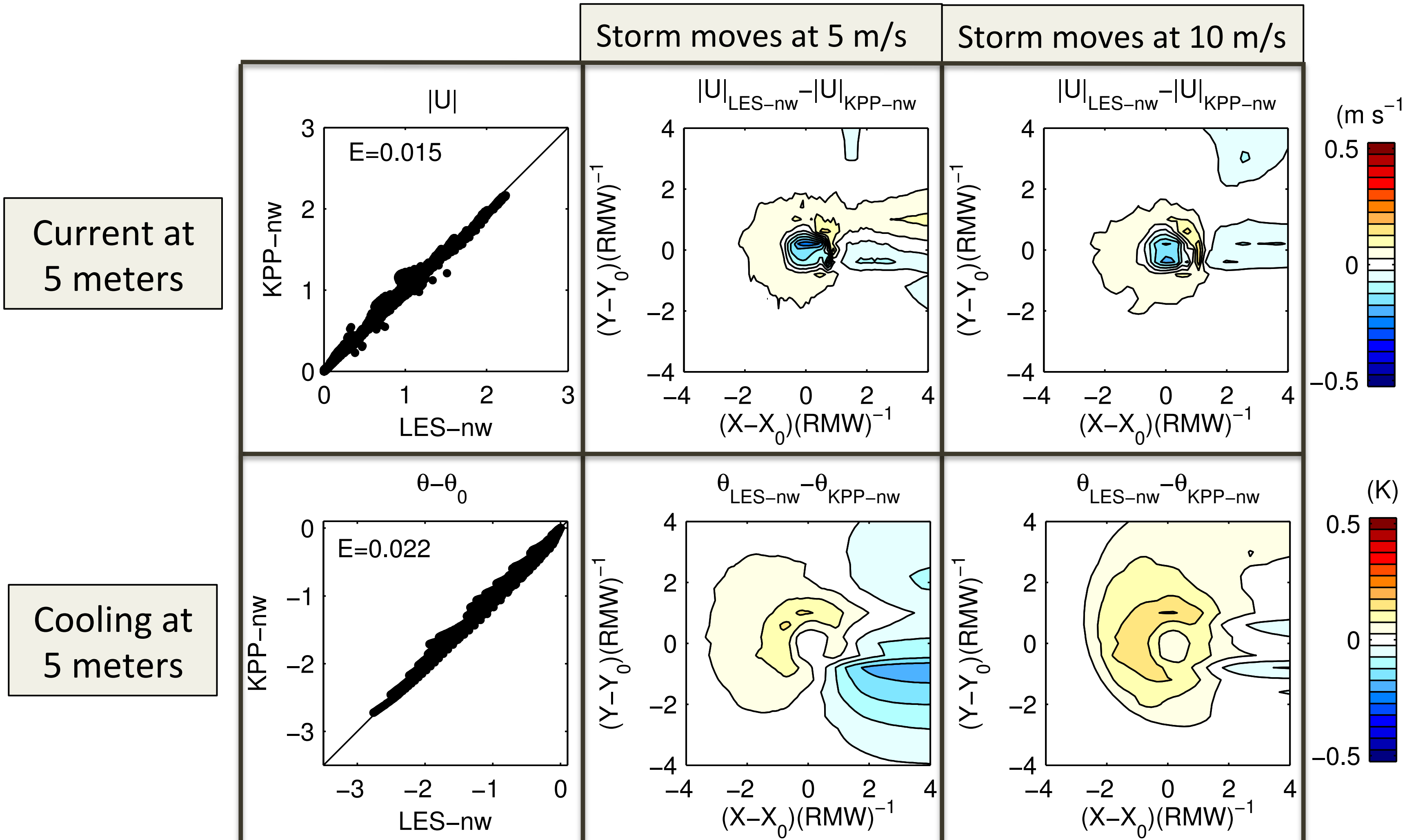
KPP-df vs LES-LT

- KPP-df does a reasonable job predicting the sea surface temperature, but does not do well predicting the current.



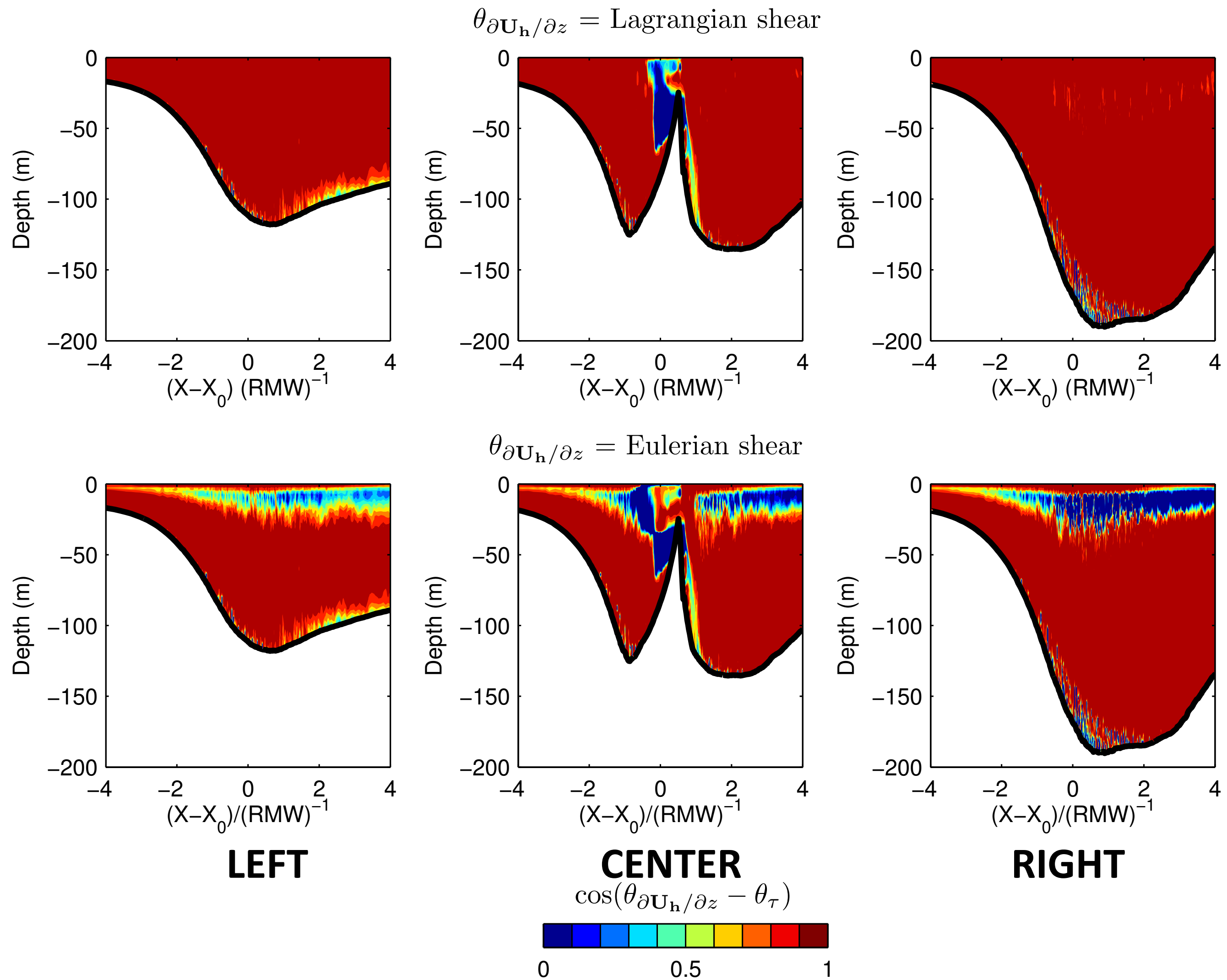
KPP-nw vs LES-nw

- First we remove the implicit wave (Langmuir turbulence) effect from KPP-df by retuning the critical Richardson number (0.235) against LES-nw.

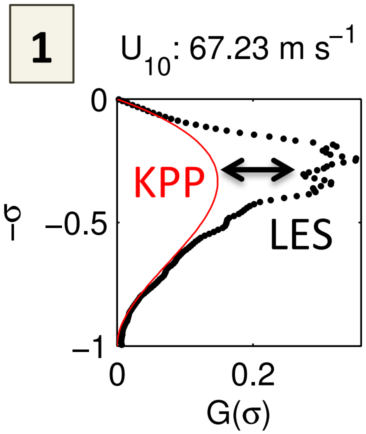


KPP modification, Lagrangian shear (KPP-Lag)

- Using the Lagrangian current (Eulerian + Stokes drift) in place of the Eulerian current in the KPP model.



KPP-LT: Enhancing turbulent velocity scale in KPP based on LES

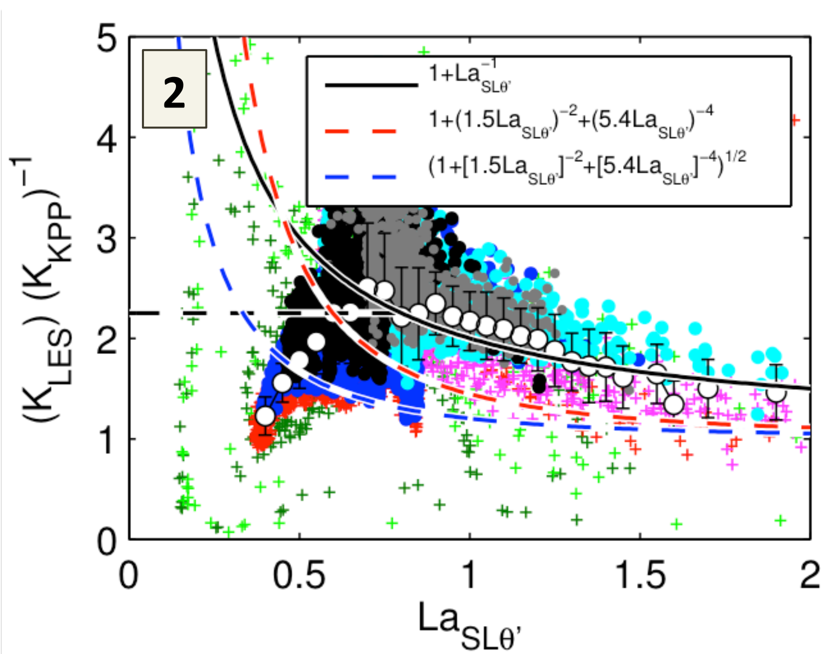


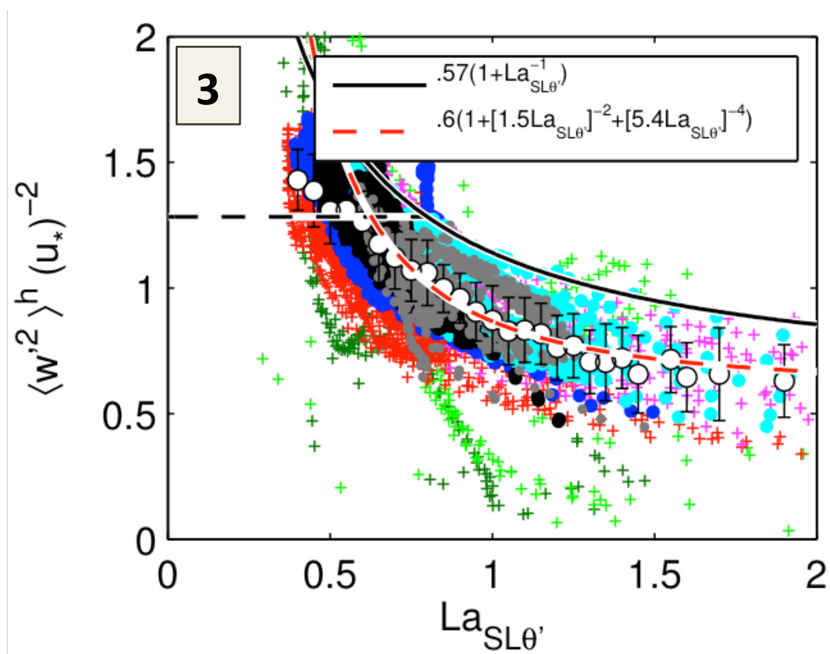
- The enhancement to the KPP mixing coefficient is derived from LES results (fig 1).

- The KPP enhancement is then derived a function of (projected) Langmuir number (fig 2).

$$La_{SL\theta'} = \sqrt{\frac{u_*}{\langle|\mathbf{u}_s|\rangle_{SL}} \frac{1}{\cos(\theta_{waves} - \theta_{Shear})}}$$

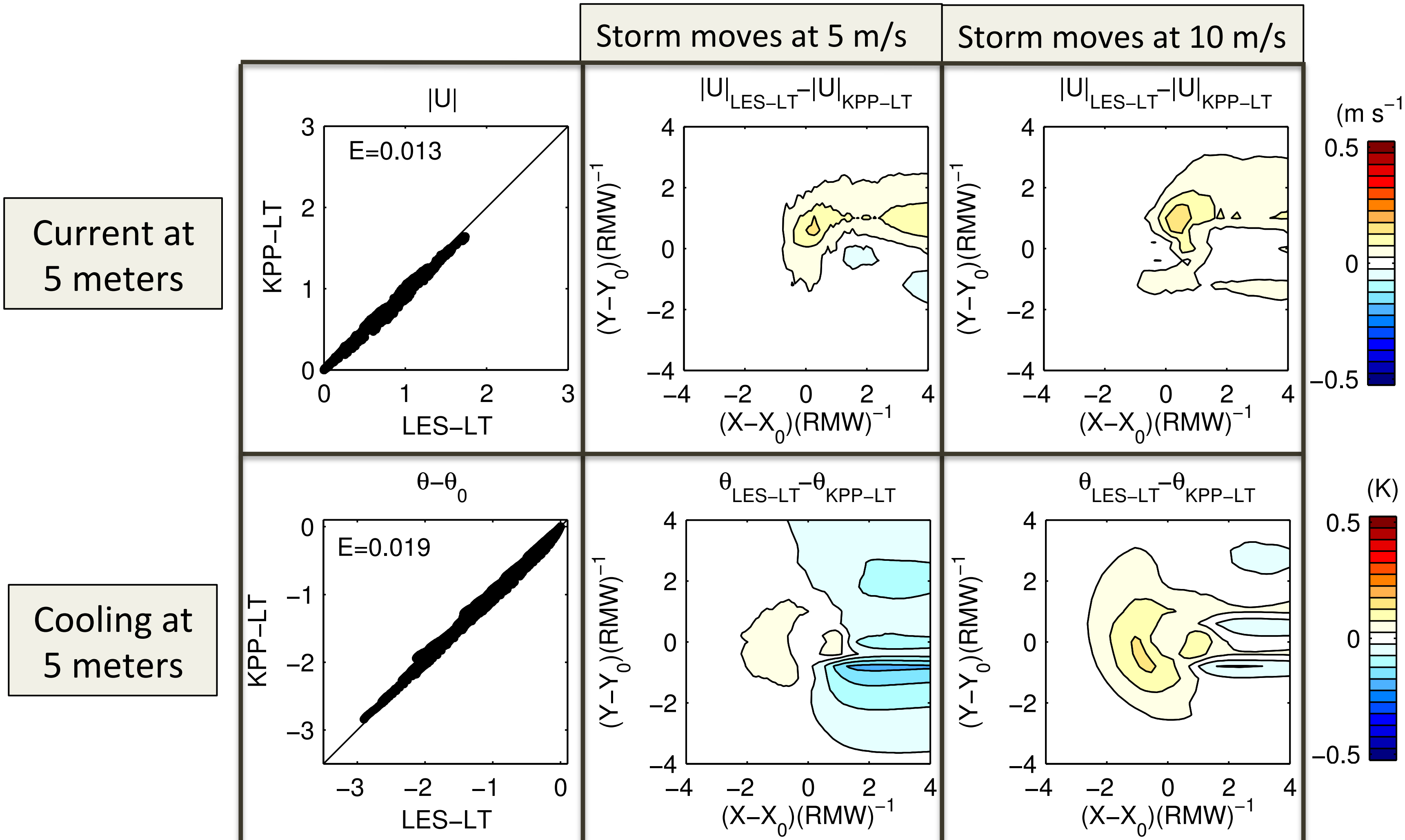
- This new relationship is compared to $\langle w'^2 \rangle$ scaling (fig 3).





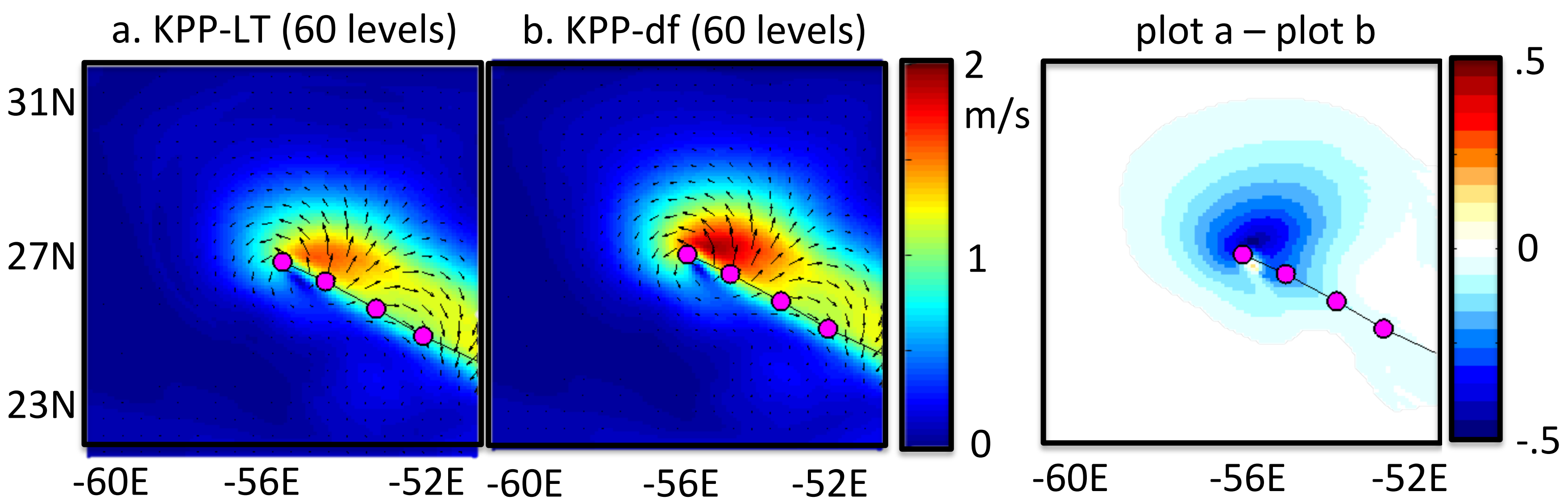
KPP-LT vs LES-LT

- Using the Lagrangian current and the enhancement to the turbulent velocity scale together provide a good match to LES-LT results.



Coupled WW3-MPIPOM with KPP-LT vs. KPP-df mixing

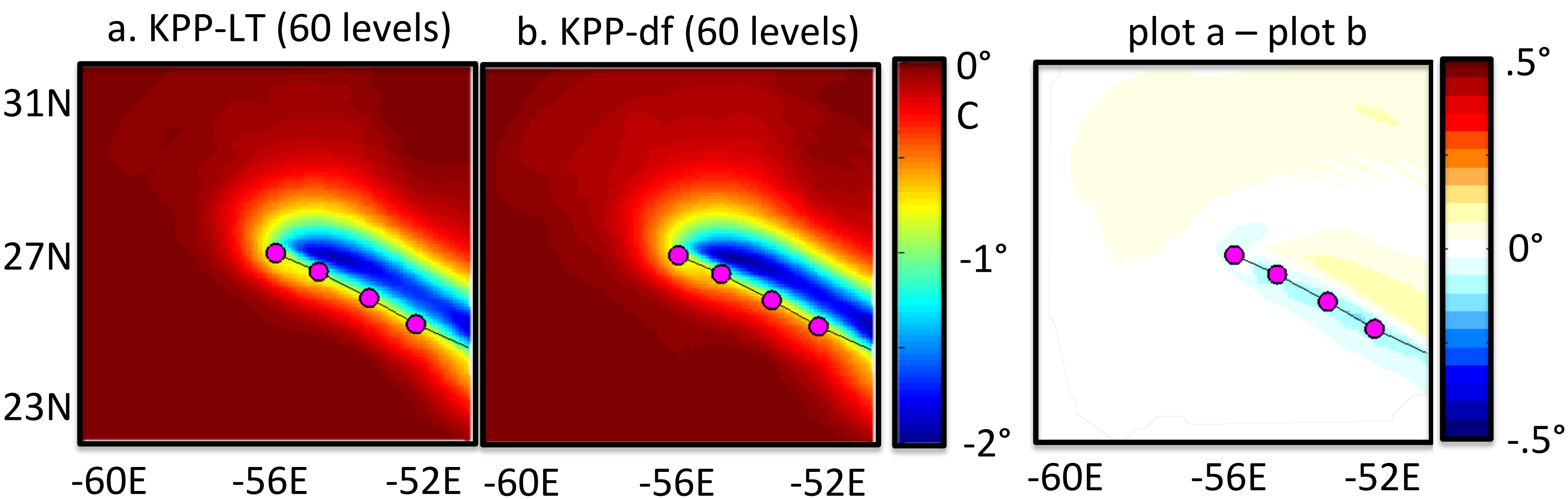
Hurricane Edouard 09/15 12Z: Currents



- KPP-LT has ~0.5 m/s lower surface current magnitude than KPP-df

Coupled WW3-MPIPOM with KPP-LT vs. KPP-df mixing

Hurricane Edouard 09/15 12Z: Sea Surface Temperature



- KPP-LT and KPP-df produce simular surface cooling.

Summary

- MPIPOM is updated with new capabilities: computational domain is designed to be relocatable to regions around the world with flexible initial condition modules.
- Vertical resolution is increased in the upper ocean and KPP mixing scheme is implemented.
- Evaluation of different initialization conditions and ocean response is conducted against AXTB measurements in Hurricane Edouard (2014).
- A new drag coefficient formulation is implemented in the 2015 operational HWRF.
- The HWRF air-sea-wave coupling framework and wave-dependent physics modules are being developed and tested. The near-real time evaluation will begin later this year.

Publications 2014-15

- Reichl, B. G., T. Hara, and I. Ginis, 2014: Sea state dependence of the wind stress over the ocean under hurricane winds. *J. Geophys. Res. Oceans,* **119,** 30-51.
- Rabe, T. J., T. Kukulka, I. Ginis, T. Hara, B. G. Reichl, E. A. D'Asaro, R. R. Harcourt, and P. Sullivan, 2015: Langmuir turbulence under hurricane Gustav (2008). *Journal of Physical Oceanography*, **45**, 657–677.
- Reichl, B. G, D. Wang, T. Hara, I. Ginis,, T. Kukulka, 2015: Langmuir turbulence parameterization in tropical cyclone conditions, *Journal of Physical Oceanography,* in review.
- Yablonsky, R. M., I. Ginis, B. Thomas, 2015: Ocean modeling with flexible initialization for improved coupled tropical cyclone-ocean prediction, *Environmental Modelling & Software*, **67**, 26-30.
- Yablonsky, R. M., I. Ginis, B. Thomas, V. Tallapragada, D. Sheinin, and L. Bernardet, 2015: Description and analysis of the ocean component of NOAA's operational Hurricane Weather Research and Forecasting (HWRF) Model. J. Atmos. Oceanic Technol., 32, 144–163.