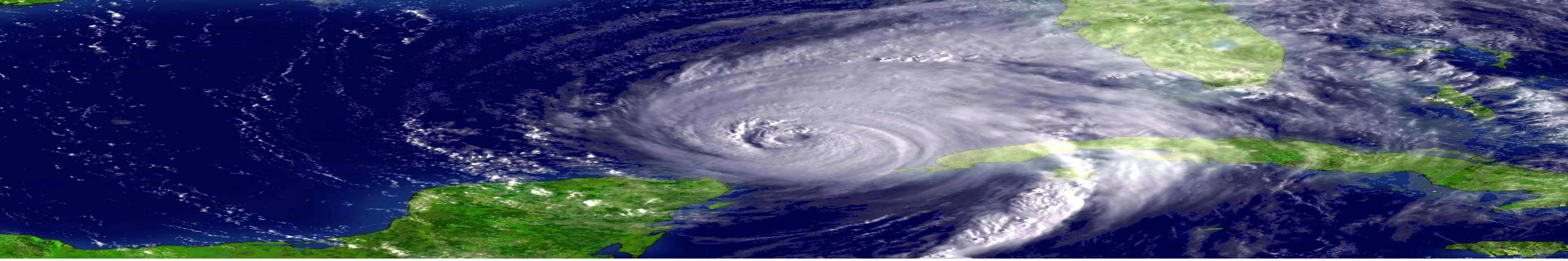

HWRF Ocean: The Princeton Ocean Model

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Graduate School of Oceanography
University of Rhode Island

THINK BIG WE DO

THE UNIVERSITY OF RHODE ISLAND

HWRF Tutorial
NCWCP, College Park, MD
25-27 January 2016

Why Couple a Fully 3-D Ocean Model to a Hurricane Model?

- To create accurate SST during hurricane model integration
- Evaporation (moisture flux) from sea surface provides heat energy to drive a hurricane
- Available energy decreases if storm-core SST decreases
- Uncoupled hurricane models with static SST neglect SST cooling during integration → high intensity bias
- One-dimensional (vertical-only) ocean models neglect upwelling and horizontal advection, both of which can impact SST during integration

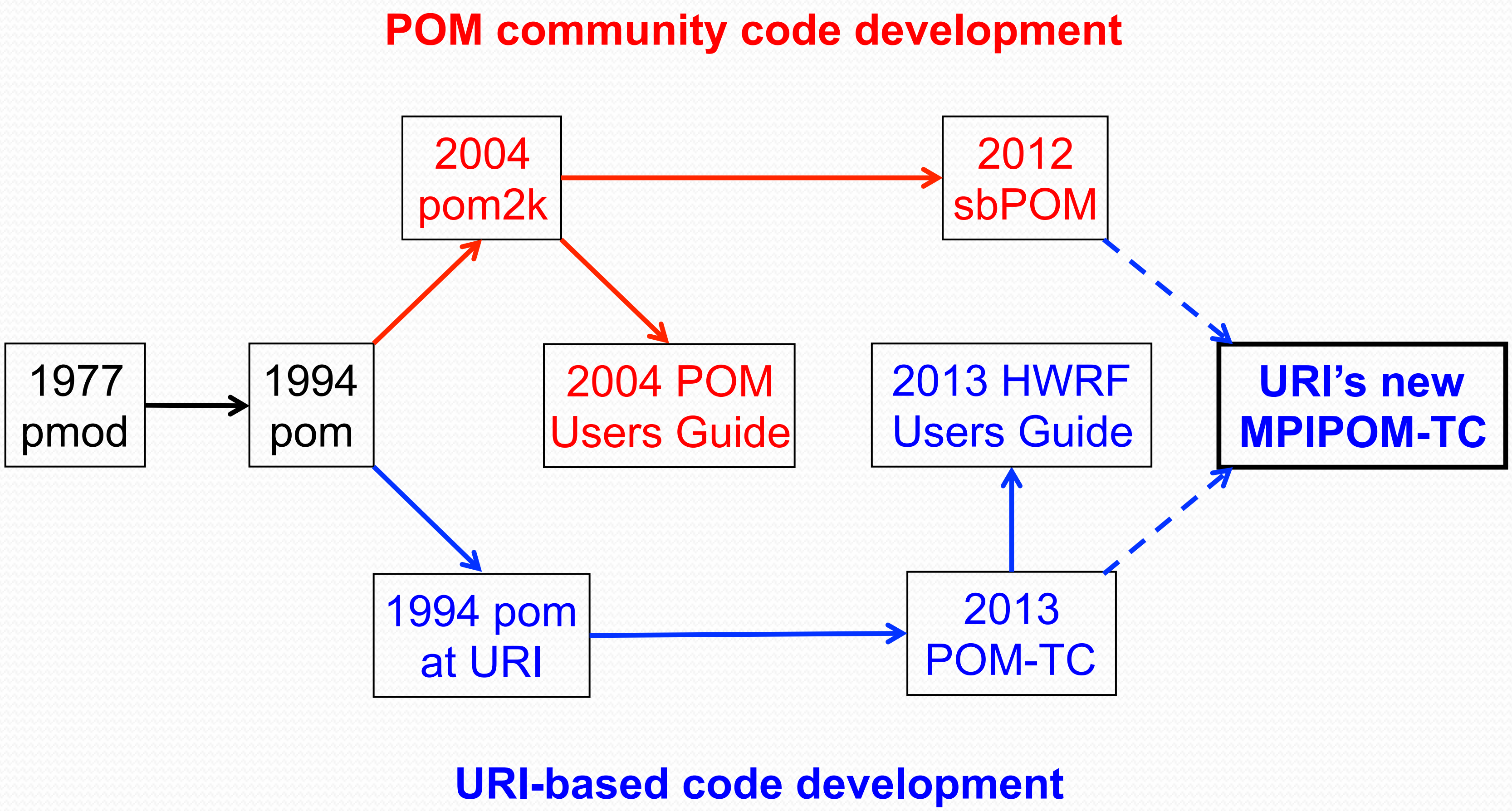
Early history of Princeton Ocean Model

- Three-dimensional, primitive equation, numerical ocean model (commonly known as POM)
- Originally developed by Alan Blumberg and George Mellor in the late 1970’s
- Uses Mellor-Yamada Level 2.5 turbulence closure model
- Initially used for coastal ocean circulation applications
- Open to the community during the 1990’s and 2000’s
- Many user-generated changes incorporated into “official” code version housed at Princeton University

Developing POM for Tropical Cyclones

- Available POM code version transferred to University of Rhode Island (URI) in 1994
- POM code changes made at URI specifically to address ocean response to hurricane wind forcing
- This POM version coupled to GFDL hurricane model at URI
- Coupled GFDL/POM model operational at NCEP in 2001
- Additional POM upgrades made at URI during 2000's (e.g. initialization) and implemented in operational GFDL/POM
- Same version of POM coupled to operational HWRF in 2007
- New version created in 2014: Message Passing Interface POM for tropical cyclones (MPIPOM-TC)

Developing a new MPIPOM-TC



POM community code development

1977 pmod

1994 pom

2004 pom2k

2004 POM Users Guide

2012 sbPOM

1994 pom at URI

2013 POM-TC

2013 HWRF Users Guide

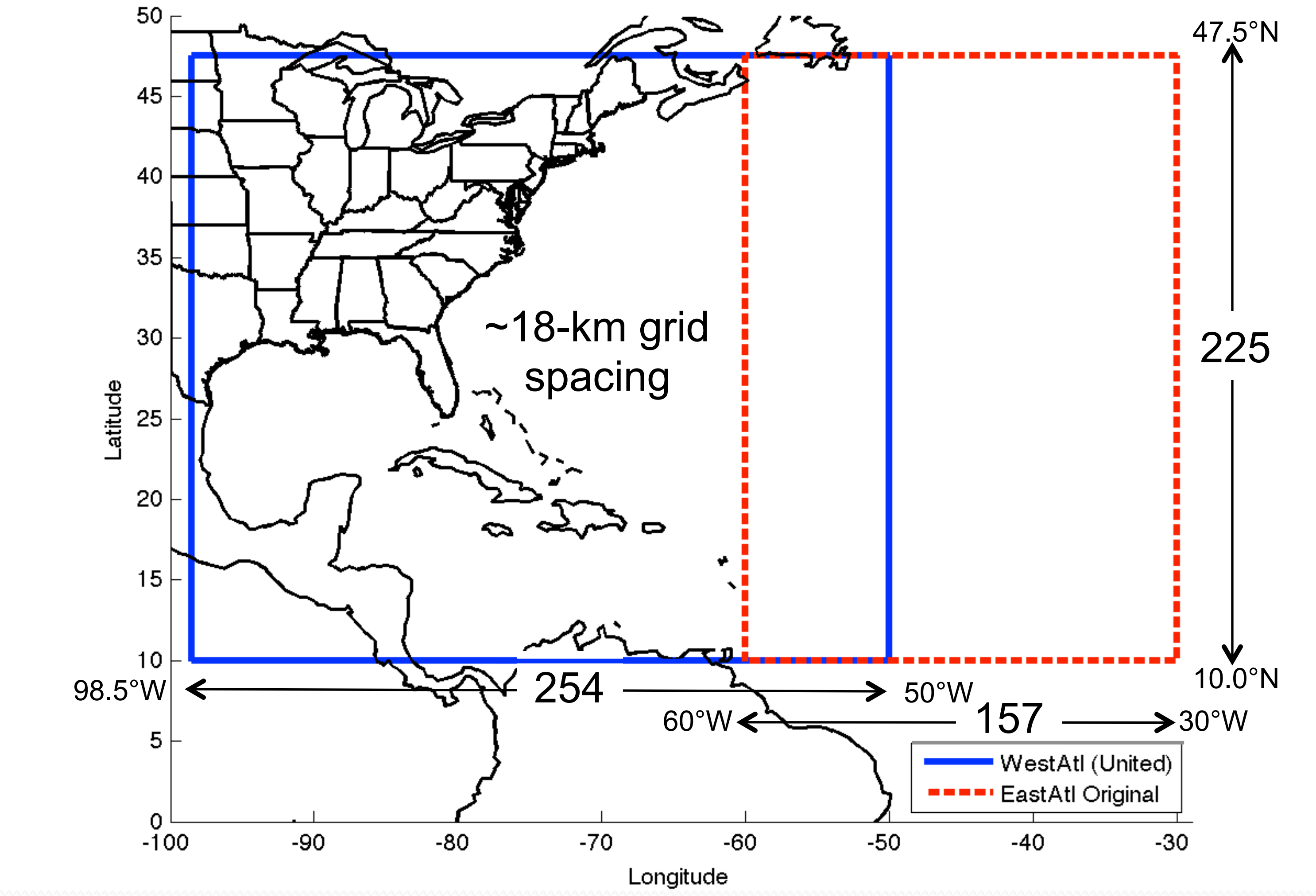
URI's new MPIPOM-TC

URI-based code development

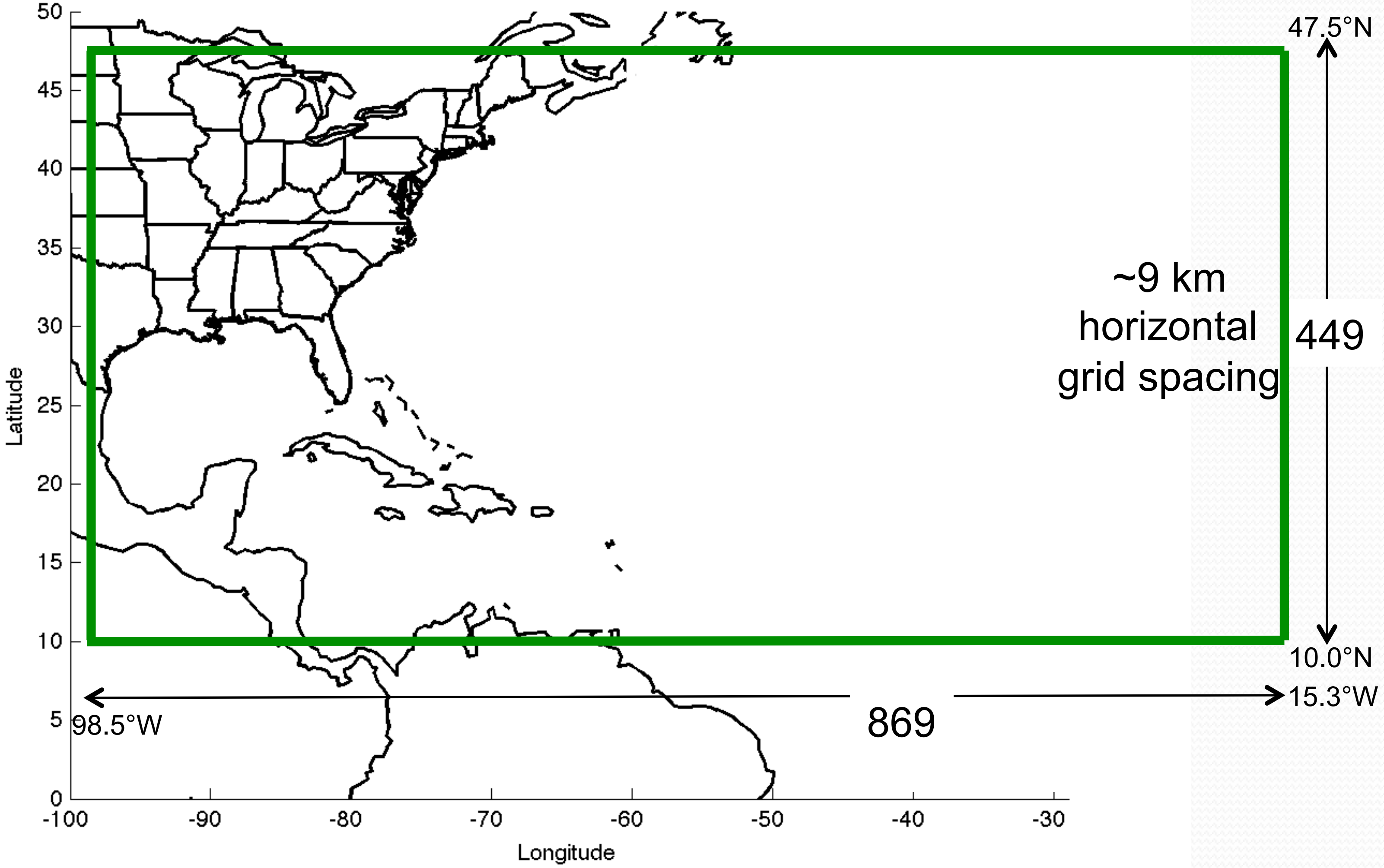
New Features in MPIPOM-TC

- MPIPOM-TC uses MPI software to run efficiently on multiple processors, allowing for both higher grid resolution and a larger ocean domain than POM-TC
- MPIPOM-TC accepts flexible initialization options
- MPIPOM-TC is an adaptation of sbPOM, which has community support and includes 18 years of physics updates and bug fixes
- MPIPOM-TC is a modernized code with NetCDF I/O
- MPIPOM-TC uses a single prognostic code in all worldwide HWRF ocean basins

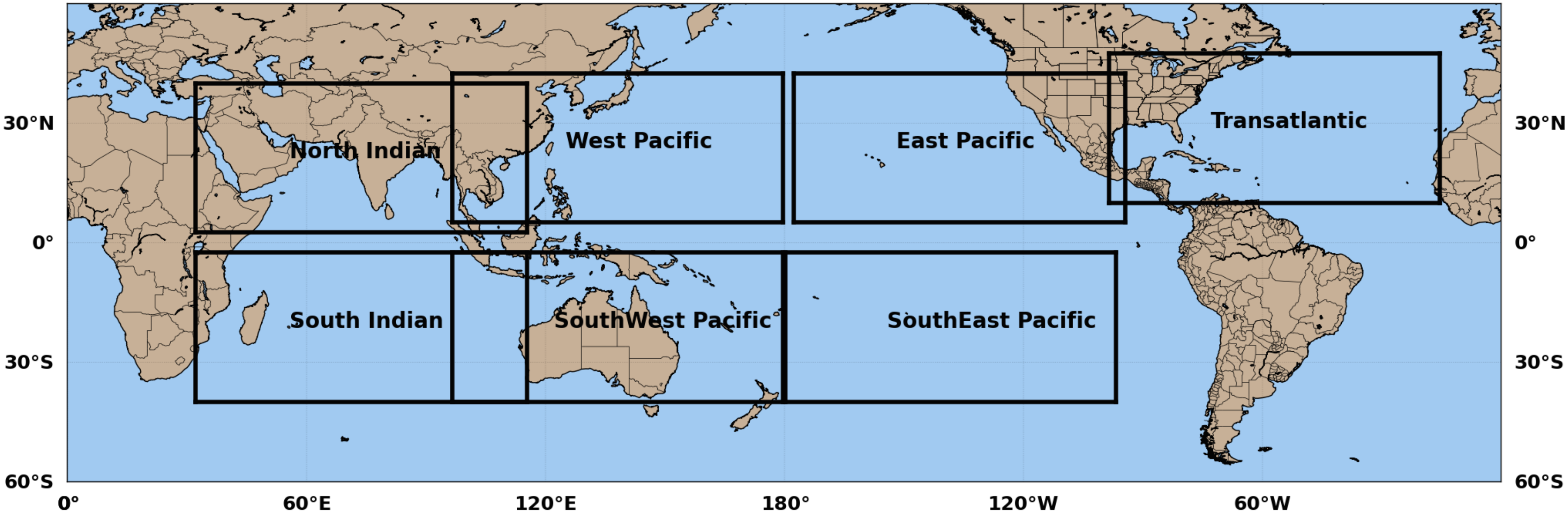
POM-TC Atlantic Domains: "United" and "East Atlantic"



MPIPOM-TC Transatlantic domain

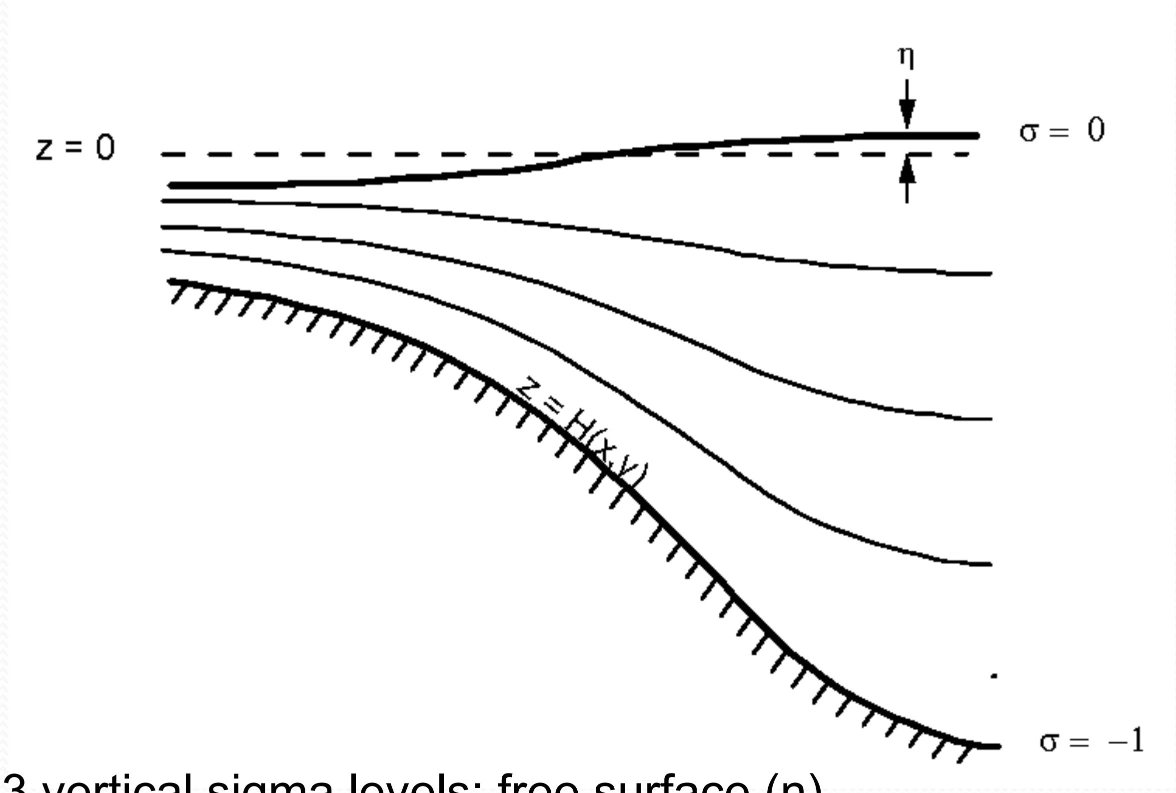


MPIPOM domains worldwide



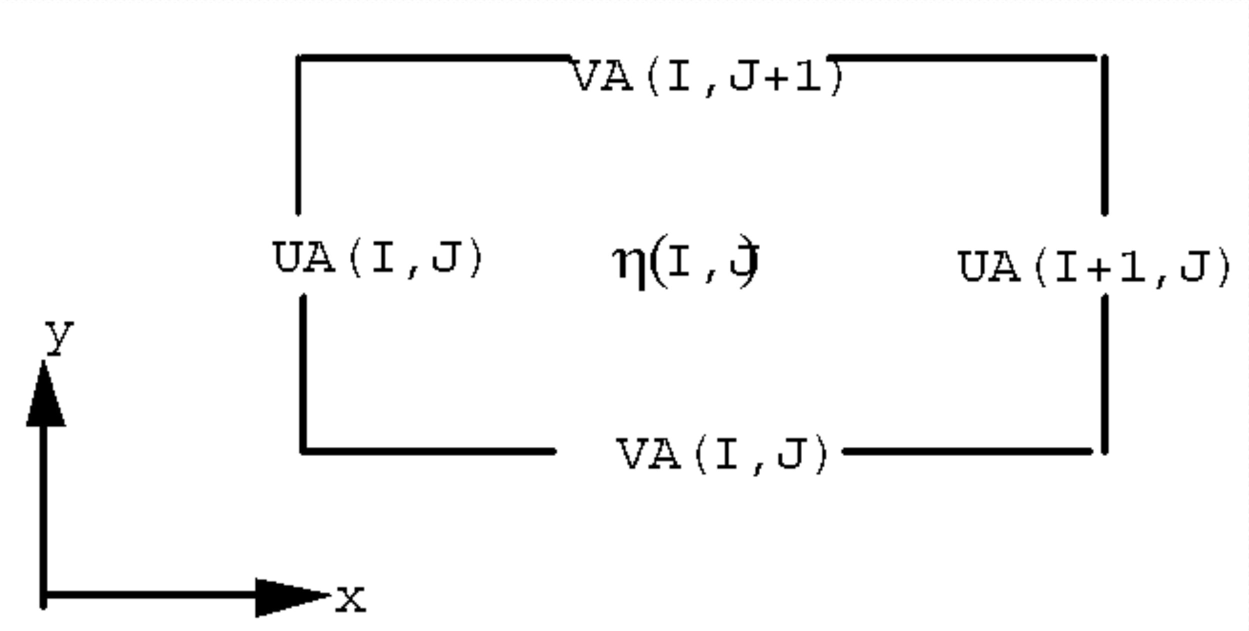
POM Numerical Design

Sigma Vertical Coordinate



- 23 vertical sigma levels; free surface (η)
- Level placement scaled based on ocean bathymetry
- Largest vertical spacing occurs where ocean depth is 5500 m
- Location of 23 half-sigma levels when ocean depth is 5500 m:
  5, 15, 25, 35, 45, 55, 65, 77.5, 92.5, 110, 135, 175, 250, 375, 550, 775, 1100, 1550, 2100, 2800, 3700, 4850, and 5500 m

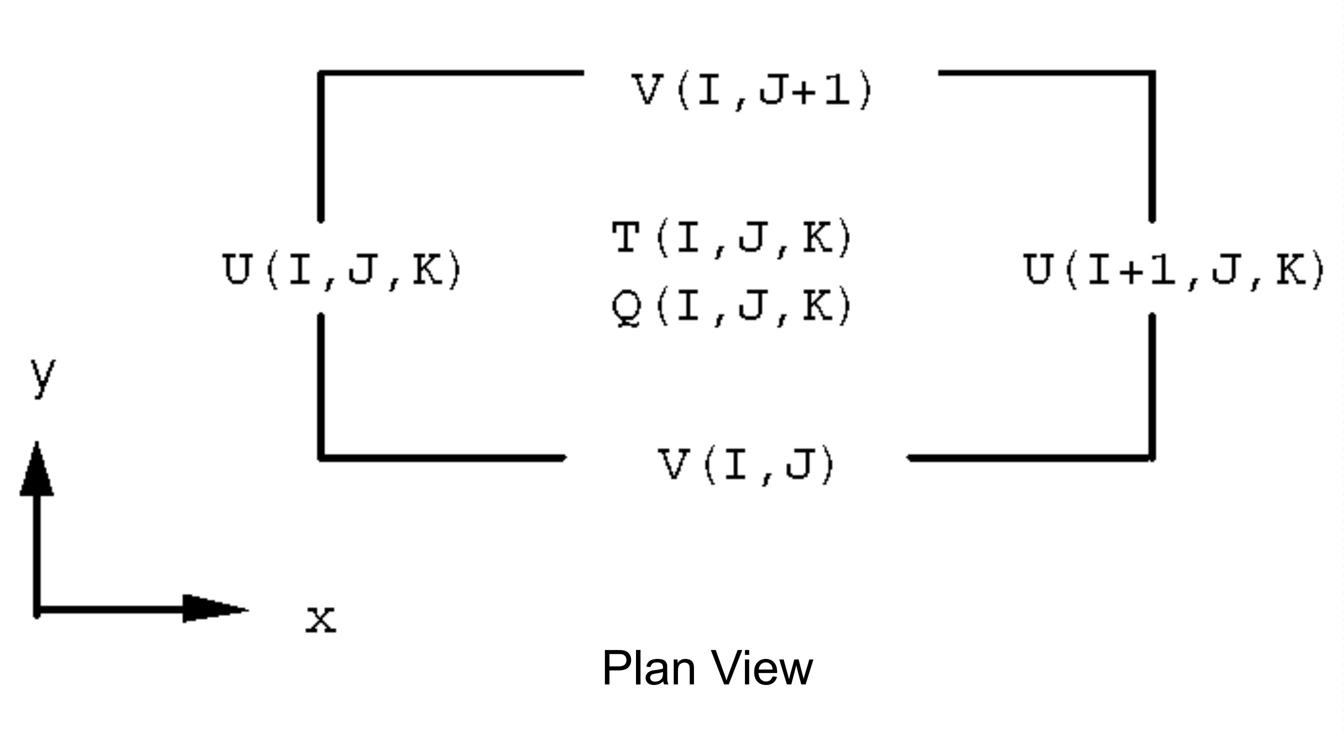
Arakawa-C Grid: External Mode



Plan View

- Horizontal spatial differencing occurs on staggered Arakawa-C grid
- 2-D variables “UA” and “VA” are calculated at shifted location from “η”

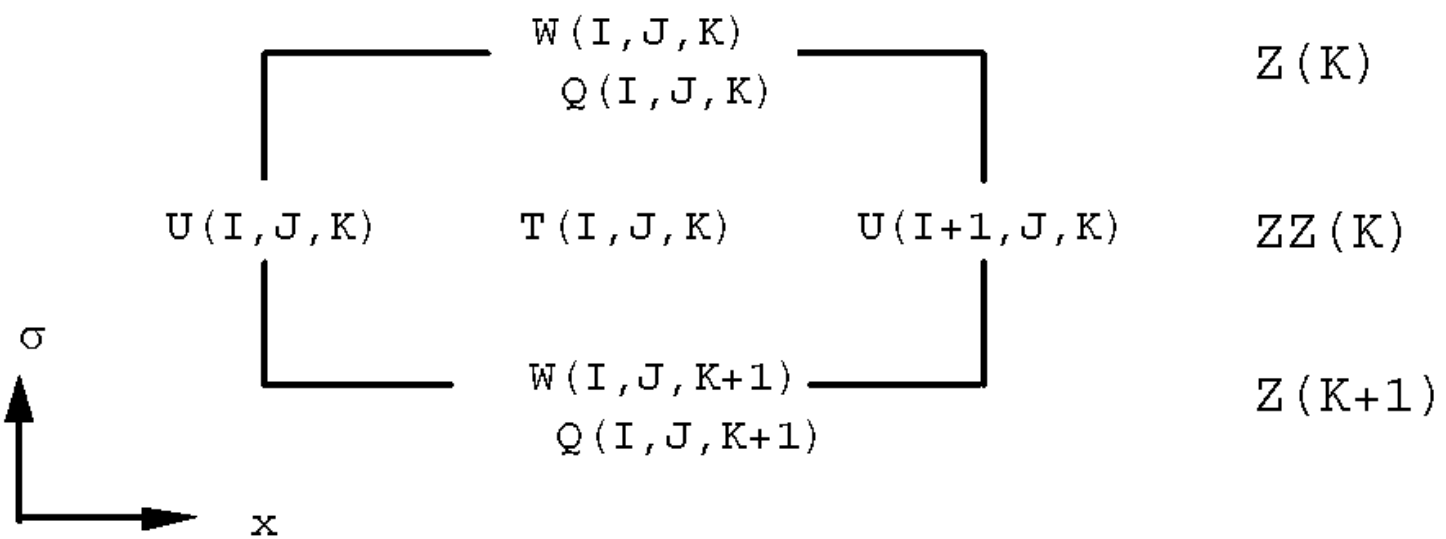
Arakawa-C Grid: Internal Mode



Plan View

- Horizontal spatial differencing occurs on staggered Arakawa-C grid
- 3-D variables “U” and “V” are calculated at shifted location from “T” and “Q”
- “T” here represents variables “T”, “S”, and “RHO”
- “Q” here represents variables “Km”, “Kh”, “Q2”, and “Q2l”

Vertical Grid: Internal Mode



Elevation View

- Vertical spatial differencing also occurs on staggered grid
- 3-D variables “W” and “Q” are calculated at shifted depth from “T” and “U”
- “T” here represents variables “T”, “S”, and “RHO”
- “Q” here represents variables “Km”, “Kh”, “Q2”, and “Q2l”

Time Stepping

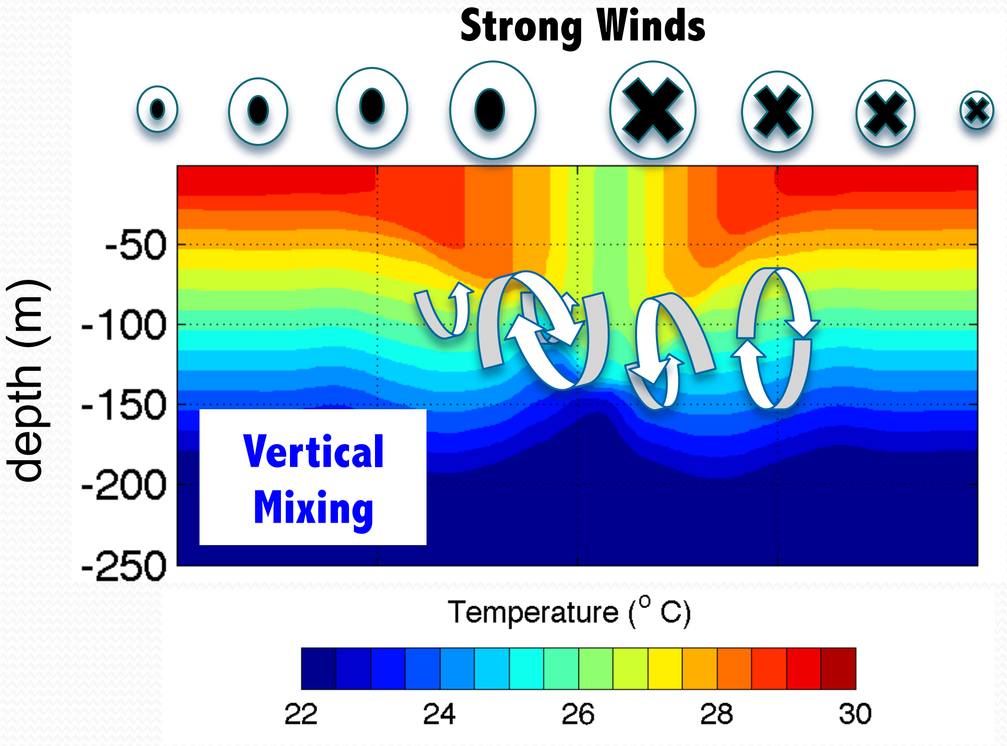
- POM has a split time step
- External (two-dimensional) mode uses short time step:
  - 22.5 seconds during pre-coupled initialization
  - 13.5 seconds during coupled integration
- Internal (three-dimensional) mode uses long time step:
  - 15 minutes during pre-coupled initialization
  - 9 minutes during coupled integration
- Horizontal time differencing is explicit
- Vertical time differencing is implicit

POM Physics

1-D processes

Hurricanes cool the ocean surface through:
(1) vertical (turbulent) mixing
(2) surface heat flux

Vertical mixing drives ~85% of sea surface temperature cooling



Vertical Mixing Parameterization

Turbulent flux terms are assumed proportional to the vertical shear of the mean variables, e.g.

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 turbulent mixing coefficient K is parameterized using either

(1) Mellor–Yamada level 2.5 turbulence closure model (M-Y scheme) or

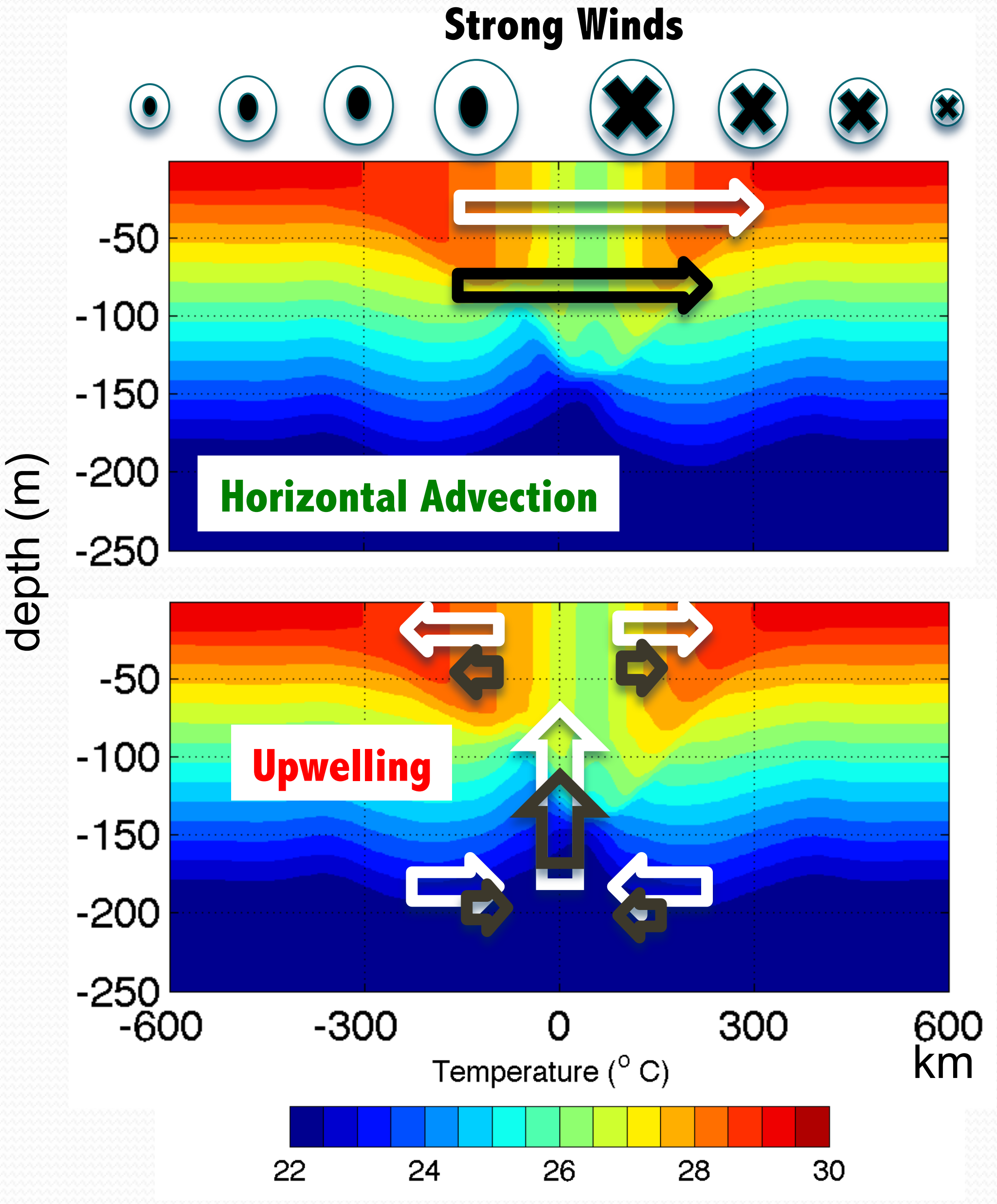
(2) K-Profile Parameterization (KPP scheme) *:*

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

h - mixing layer depth
W- turbulent velocity scale
G(z)- non-dimensional shape-function

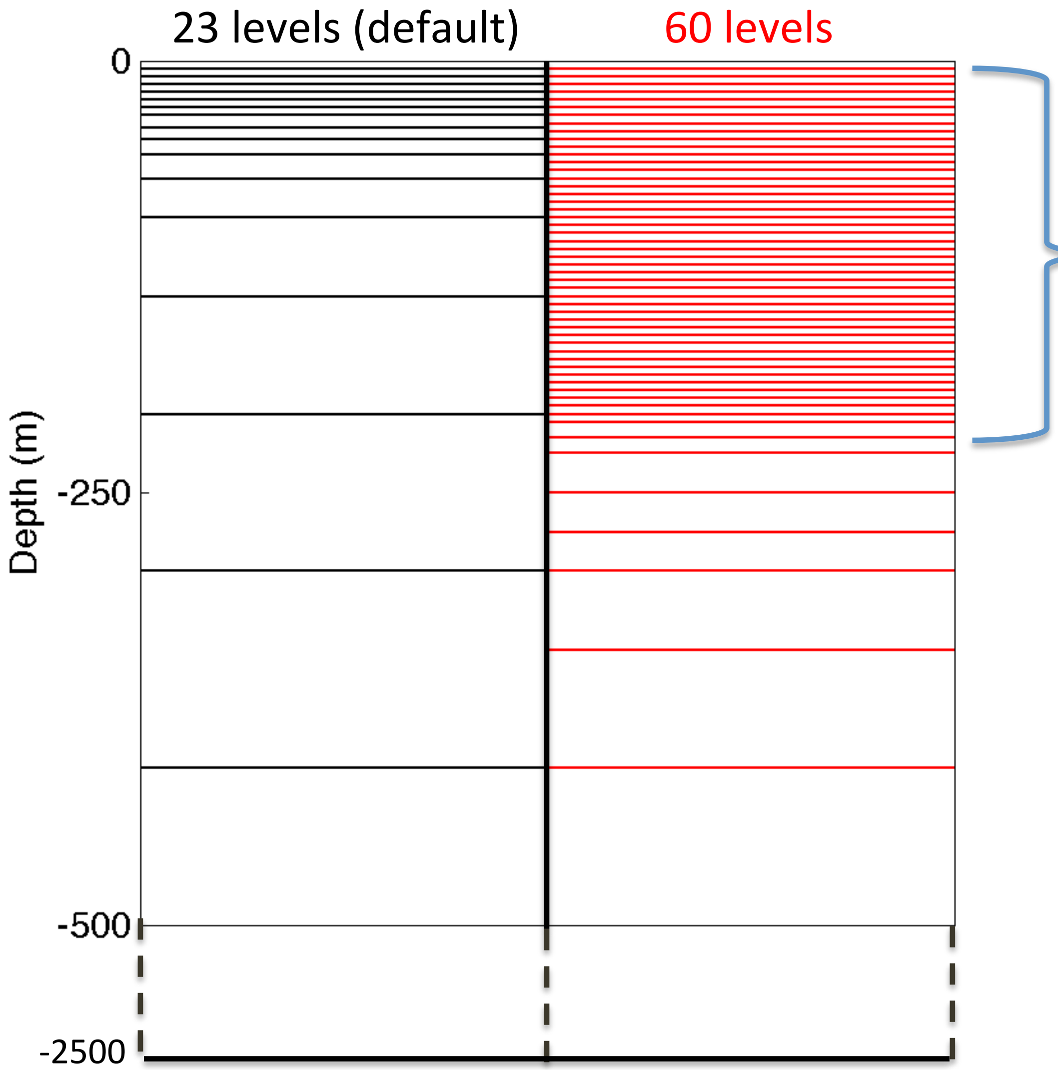
3-D processes

Hurricane induced upwelling and horizontal advection can enhance and/or modify surface cooling.



Impact of increased vertical resolution

- Higher resolution (60 level) sensitivity tests

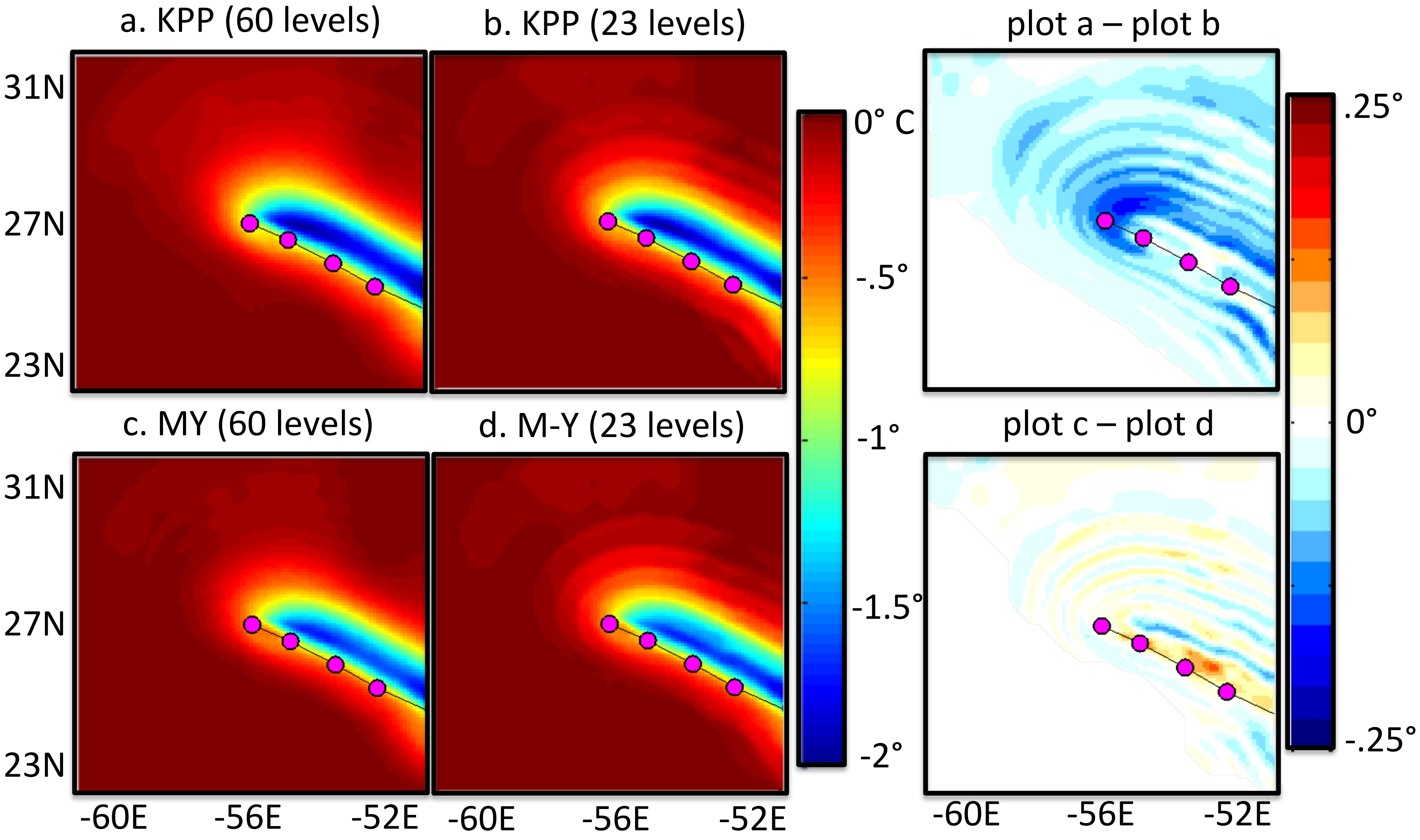


- 60 level MPIPOM maintains ~5 m resolution to mixing depth of ~200 m (for 2500 m ocean depth)

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

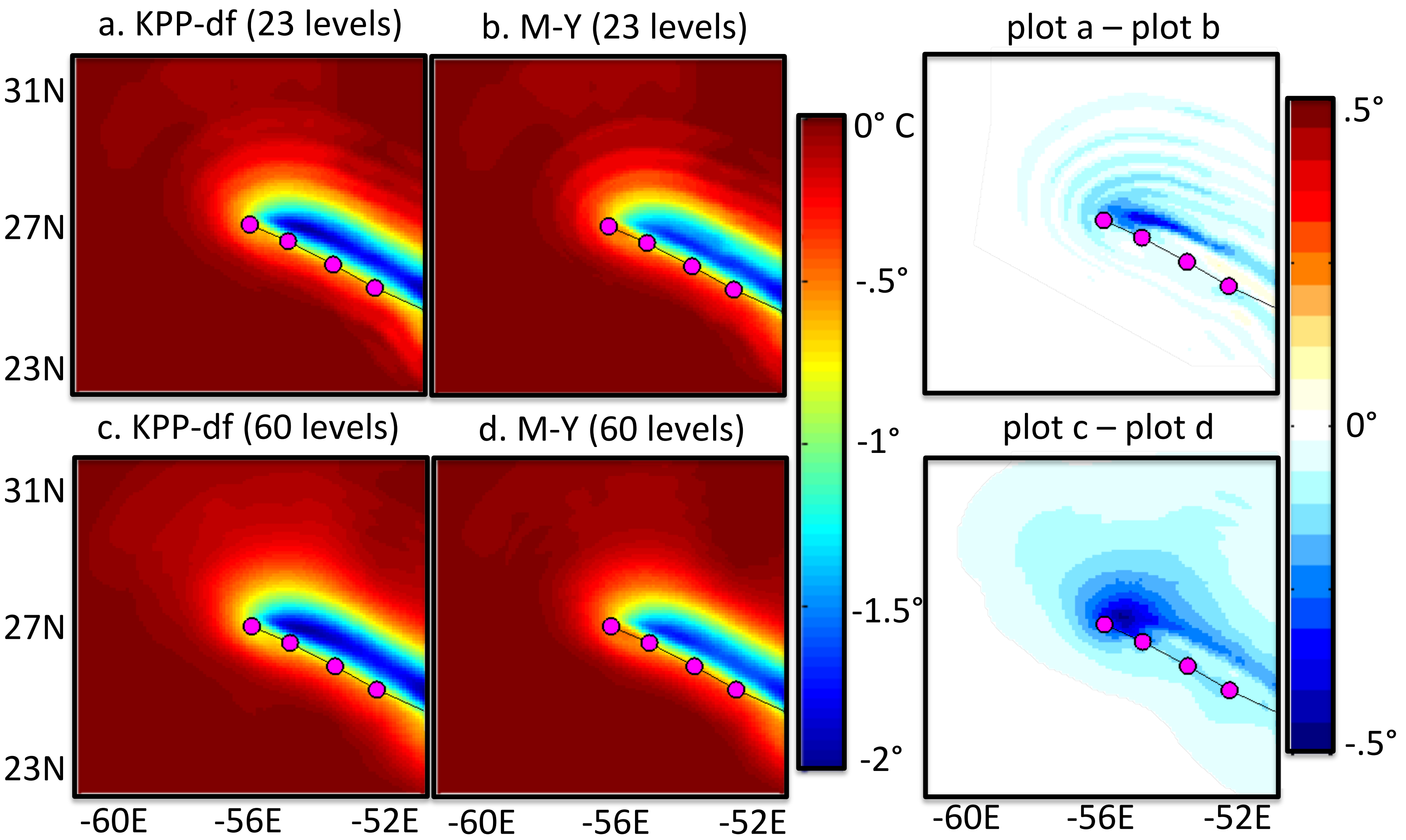
Hurricane Edouard 09/15 12Z, 2014

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

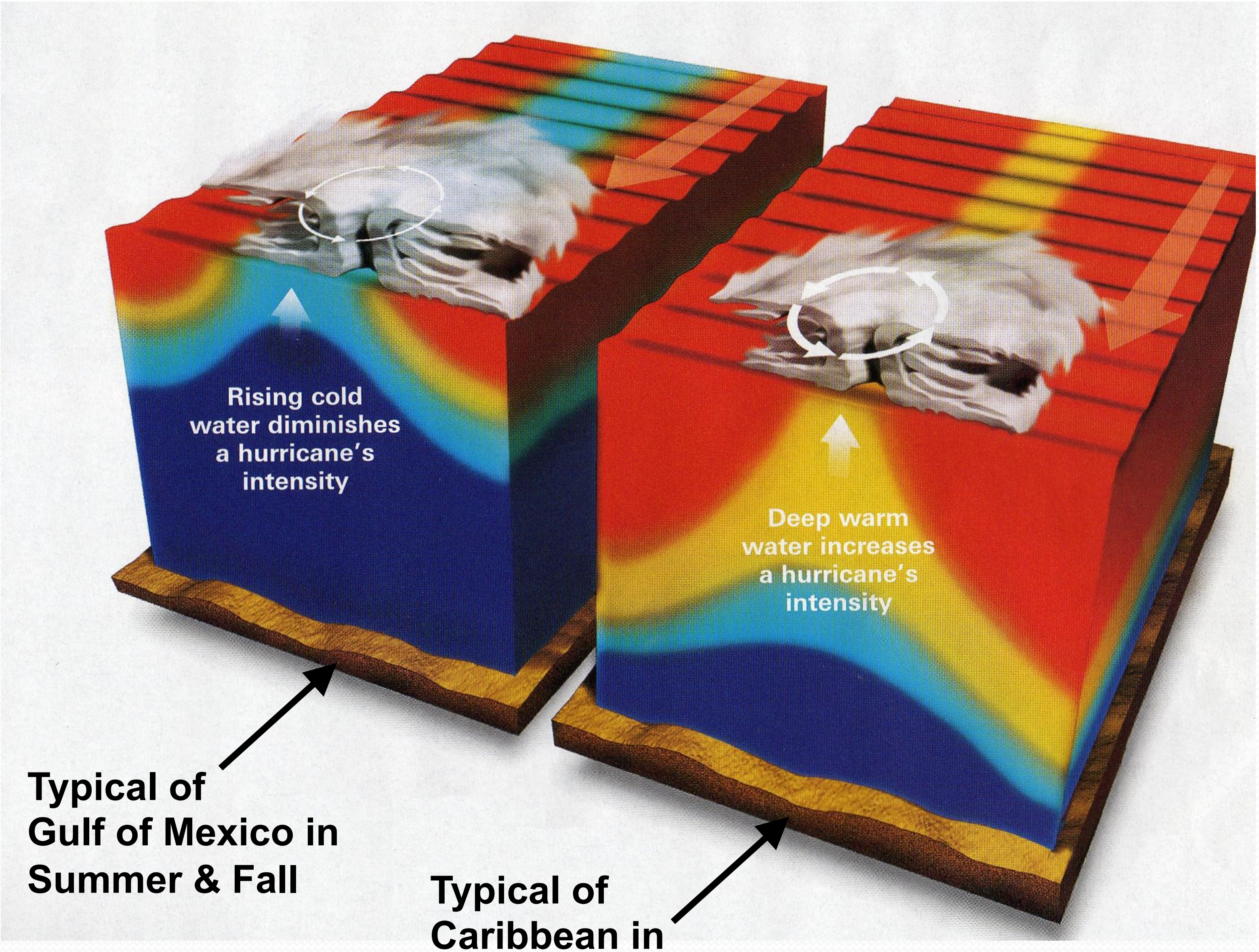


Hurricane Edouard 09/15 12Z, 2014

- 60 level noticeably smoother than 23 level
- KPP produces up to 0.5° C more cooling than M-Y



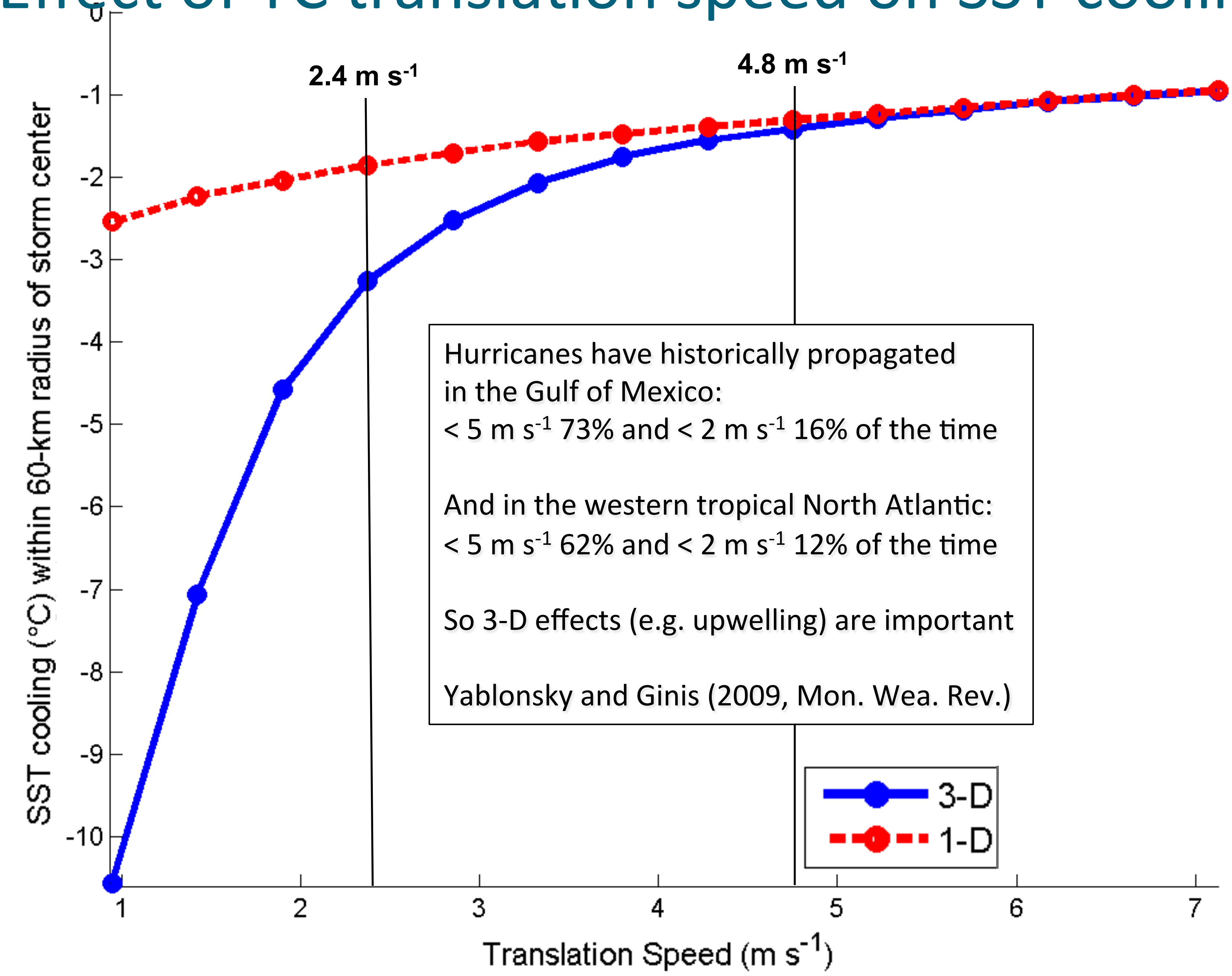
Effect of Ocean Stratification on SST cooling



Typical of Gulf of Mexico in Summer & Fall

Typical of Caribbean in Summer & Fall

Effect of TC translation speed on SST cooling

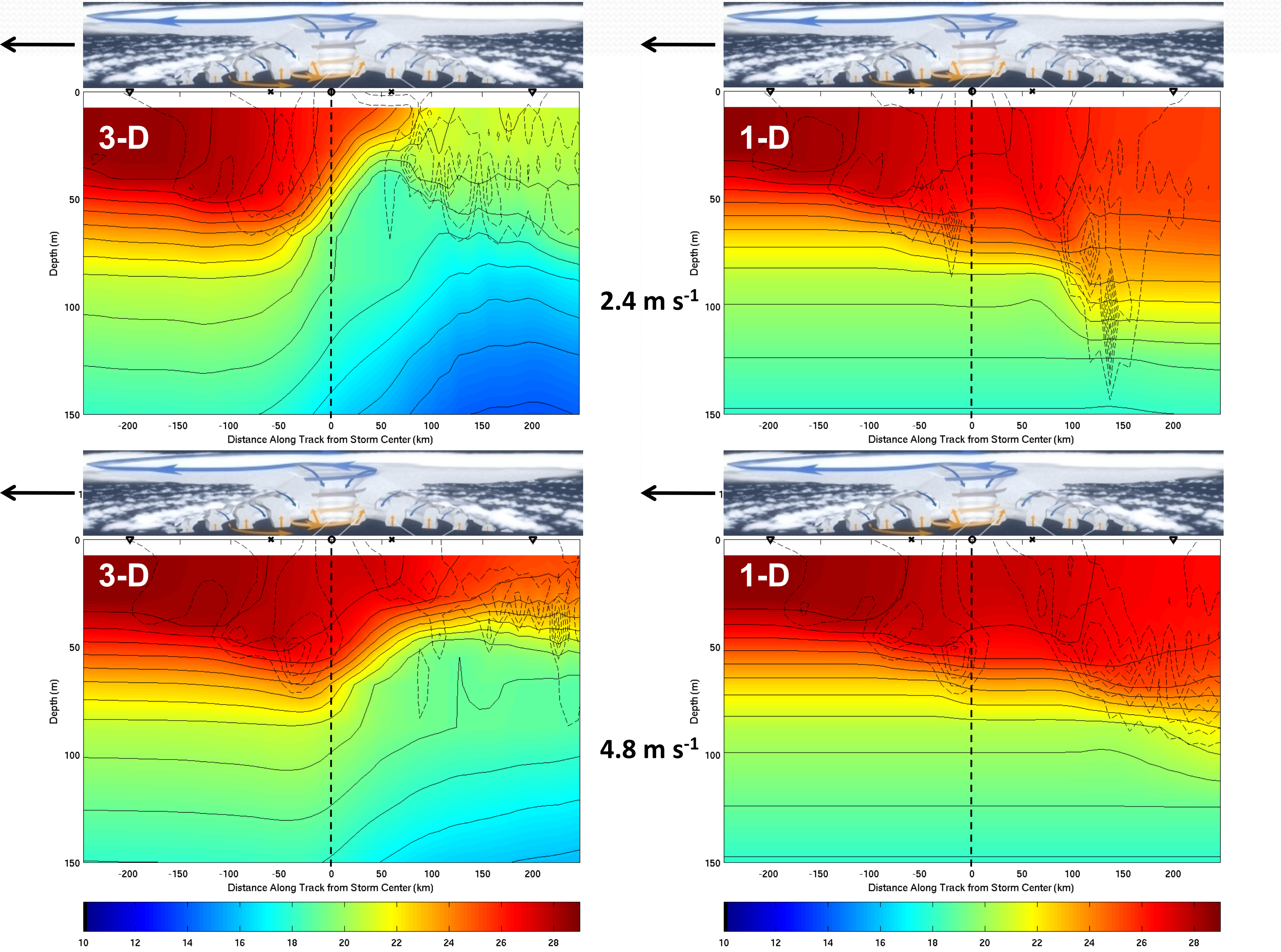


Hurricanes have historically propagated in the Gulf of Mexico:
< 5 m s^{-1} 73% and < 2 m s^{-1} 16% of the time

And in the western tropical North Atlantic:
< 5 m s^{-1} 62% and < 2 m s^{-1} 12% of the time

So 3-D effects (e.g. upwelling) are important

Yablonsky and Ginis (2009, Mon. Wea. Rev.)


3-D
1-D
2.4 m s^{-1}
4.8 m s^{-1}
3-D
1-D
Depth (m)
0
50
100
150
-200
-150
-100
-50
0
50
100
150
200
Distance Along Track from Storm Center (km)
10
12
14
16
18
20
22
24
26
28

POM Initialization

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)

* ***All of these ocean products are available in the public domain for real time tropical cyclone forecasting***

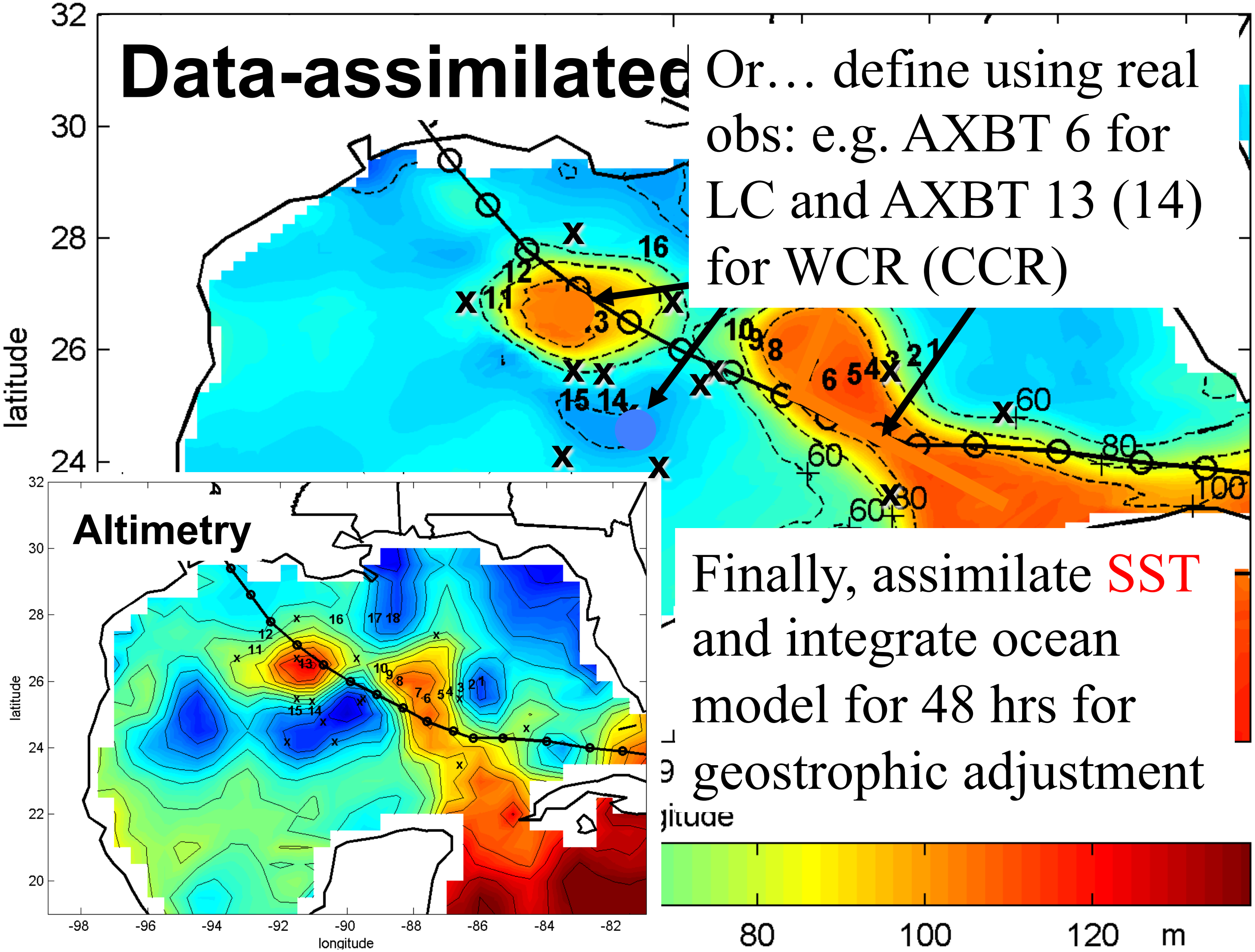
Feature-based (FB) initialization

- Prior to coupled model integration, POM is initialized with a realistic, 3-D temperature (T) and salinity (S) field

- This T & S field must then be used to generate realistic ocean currents via geostrophic adjustment

- The "spun-up" ocean must then incorporate the preexisting hurricane-generated cold wake by applying TC' s wind stress using the NHC hurricane message file

Feature-based Initialization

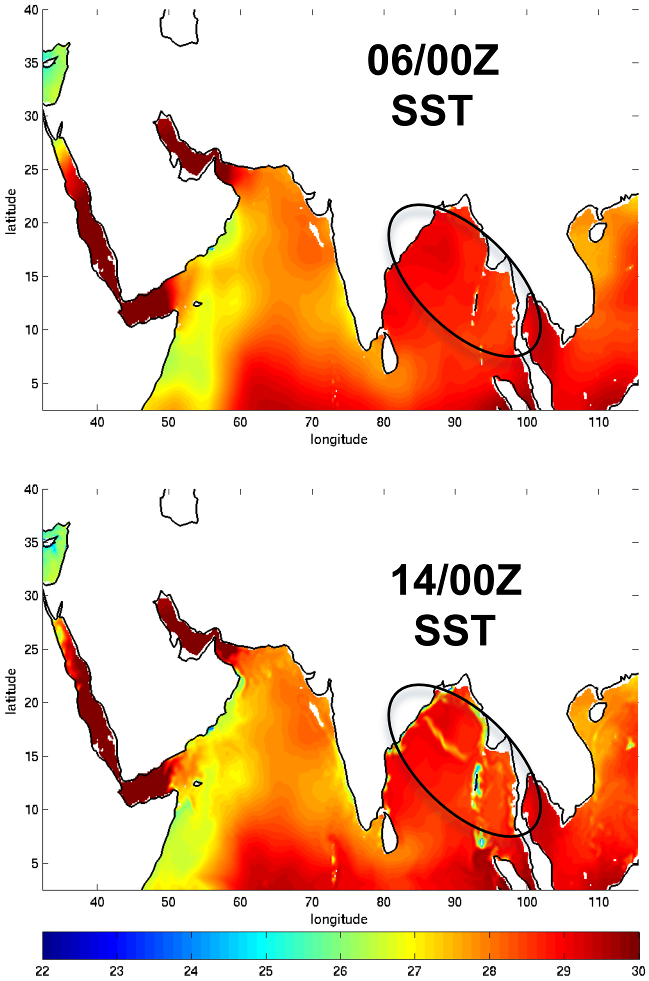


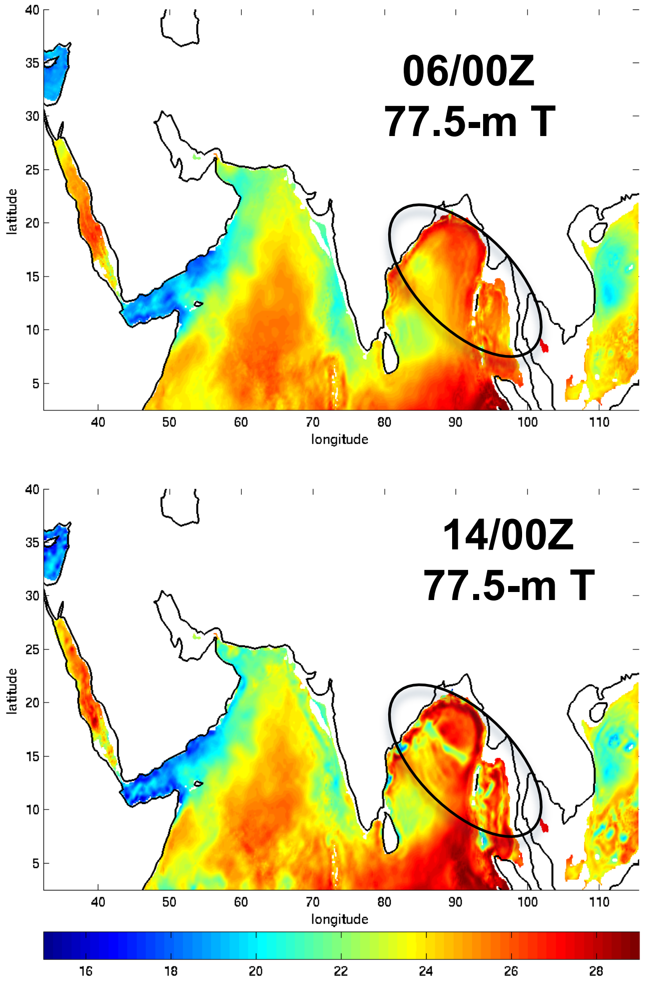
Or… define using real obs: e.g. AXBT 6 for LC and AXBT 13 (14) for WCR (CCR)

Finally, assimilate SST and integrate ocean model for 48 hrs for geostrophic adjustment

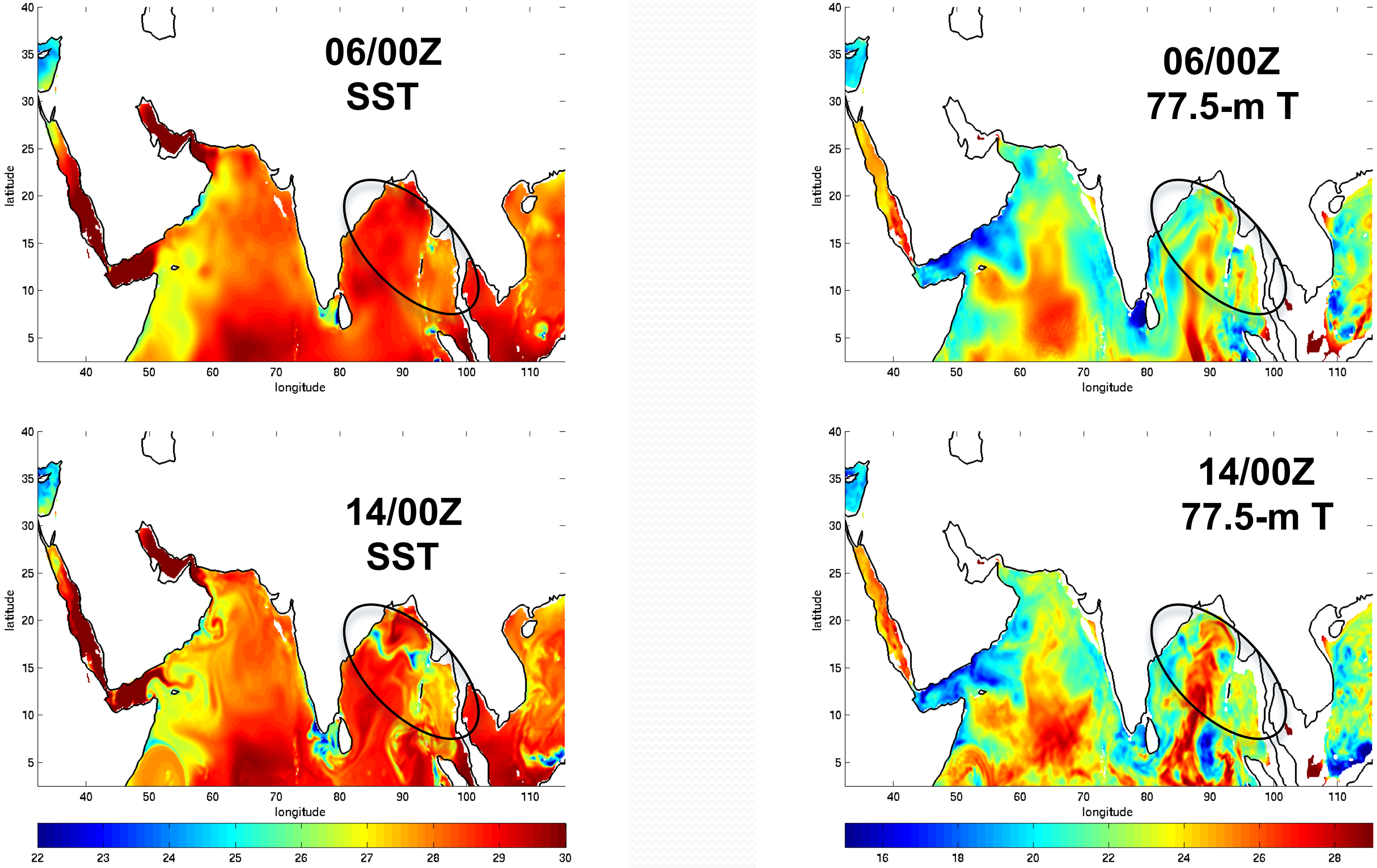
- Start with GDEM T/S
- Look at altimetry/obs
- Define LC & ring positions
- Use Caribbean water along LC axis & in WCR center
- Make CCR center colder than environ.
- Blend features w/ env. & sharpen fronts

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

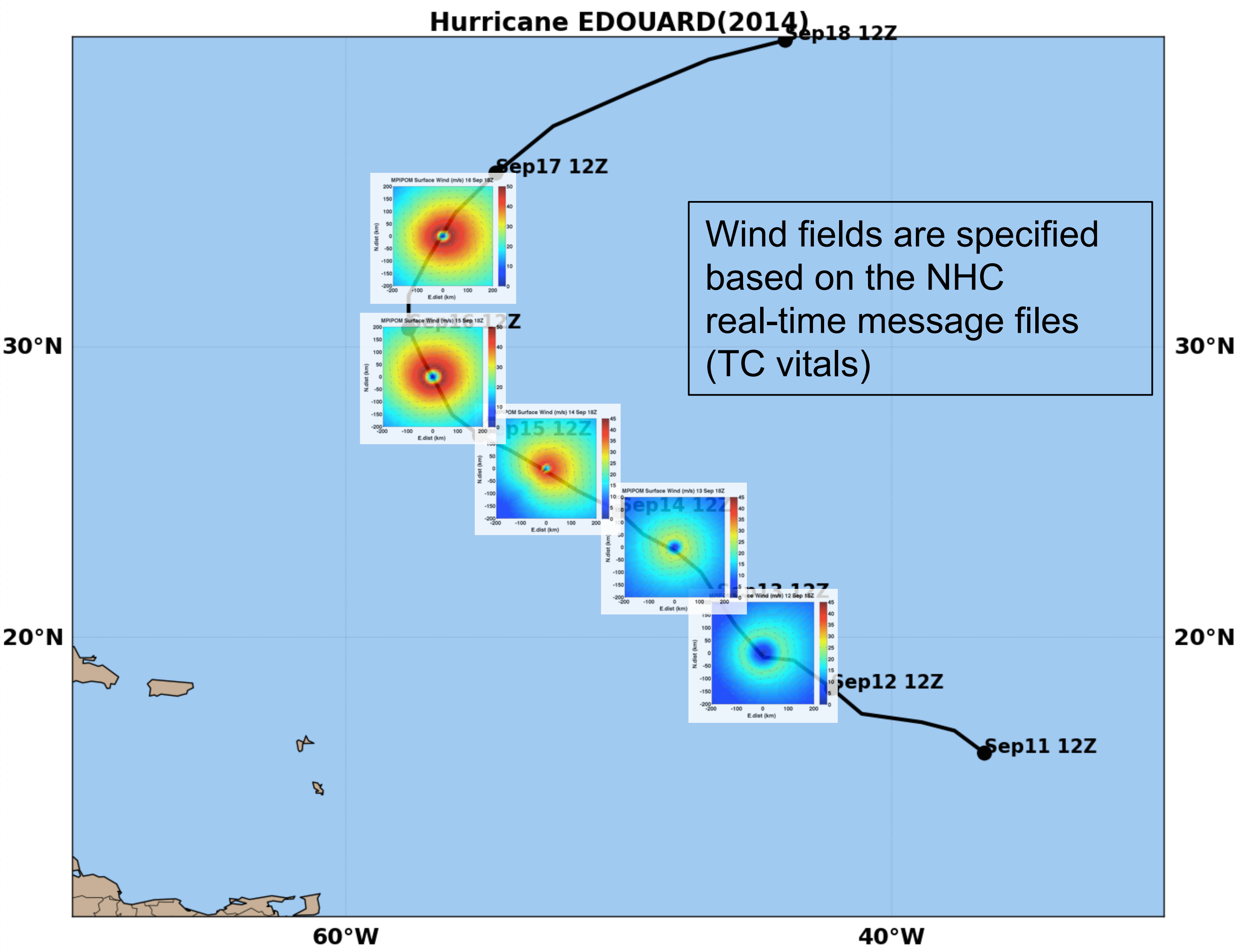




MPIPOM-TC North Indian Domain: Ocean Response to Cyclone Phailin with NCODA initialization: 2013100600-1400



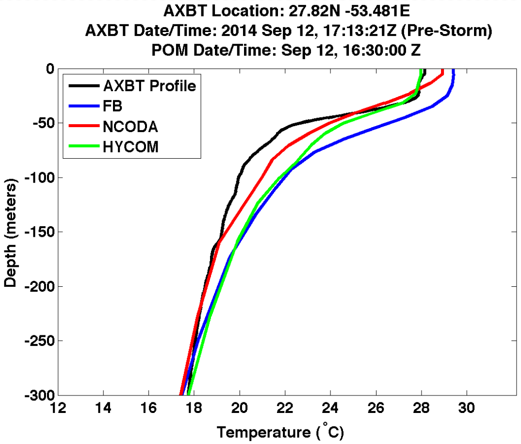
Evaluation of Ocean Initialization Options: Hurricane Edouard (2014)

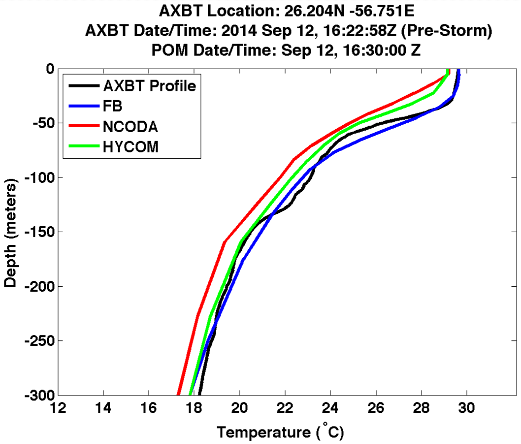


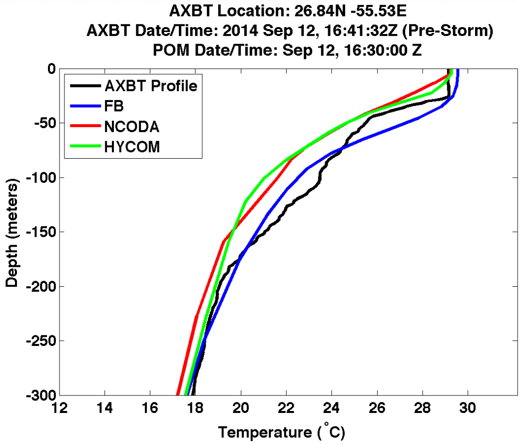
Wind fields are specified based on the NHC real-time message files (TC vitals)

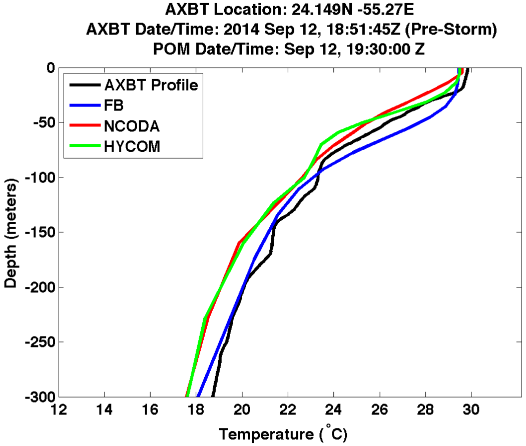
Evaluation of Ocean Initialization Options: Comparison with AXBTs

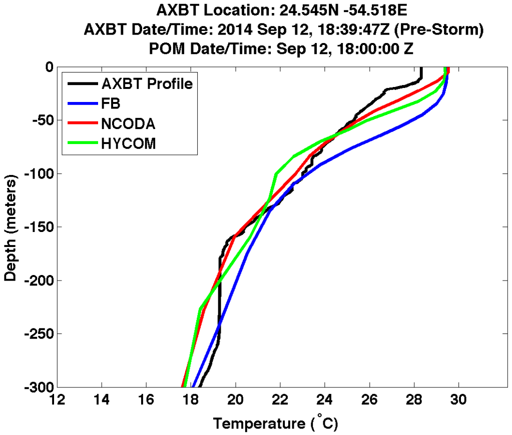
September 12, 2014 (pre-storm)

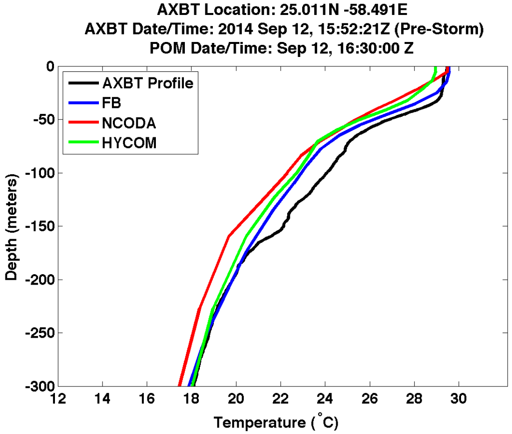

AXBT Location: 27.82N -53.481E
AXBT Date/Time: 2014 Sep 12, 17:13:21Z (Pre-Storm)
POM Date/Time: Sep 12, 16:30:00 Z


AXBT Location: 26.204N -56.751E
AXBT Date/Time: 2014 Sep 12, 16:22:58Z (Pre-Storm)
POM Date/Time: Sep 12, 16:30:00 Z


AXBT Location: 26.84N -55.53E
AXBT Date/Time: 2014 Sep 12, 16:41:32Z (Pre-Storm)
POM Date/Time: Sep 12, 16:30:00 Z

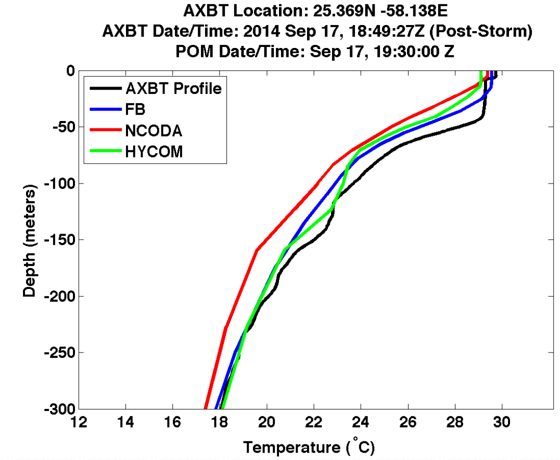

AXBT Location: 24.149N -55.27E
AXBT Date/Time: 2014 Sep 12, 18:51:45Z (Pre-Storm)
POM Date/Time: Sep 12, 19:30:00 Z


AXBT Location: 24.545N -54.518E
AXBT Date/Time: 2014 Sep 12, 18:39:47Z (Pre-Storm)
POM Date/Time: Sep 12, 18:00:00 Z


AXBT Location: 25.011N -58.491E
AXBT Date/Time: 2014 Sep 12, 15:52:21Z (Pre-Storm)
POM Date/Time: Sep 12, 16:30:00 Z

Evaluation of Ocean Initialization Options: Comparison with AXBTs

September 17, 2014 (post-storm)


AXBT Location: 25.369N -58.138E
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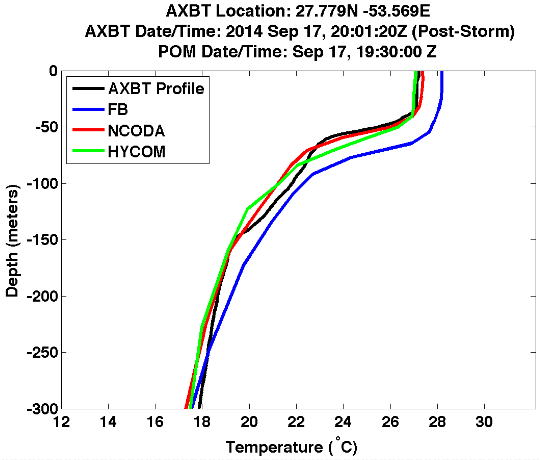
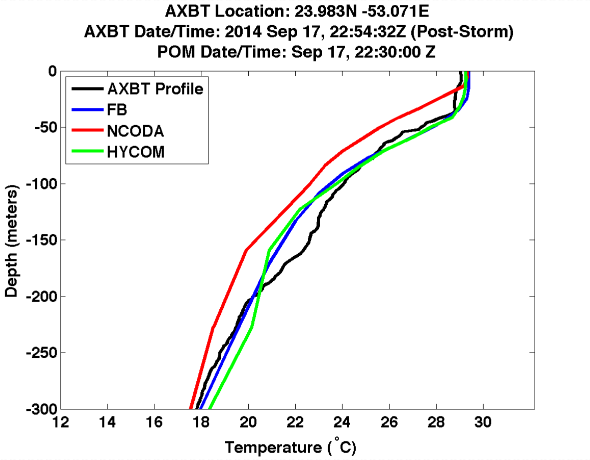
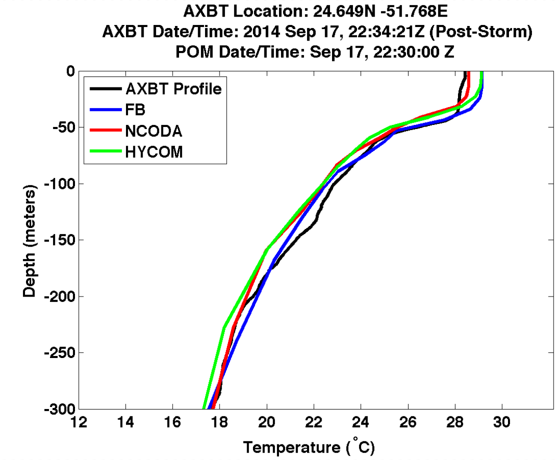
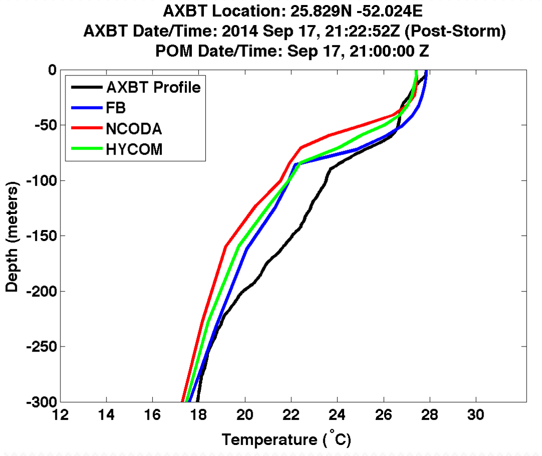
POM Date/Time: Sep 17, 19:30:00 Z


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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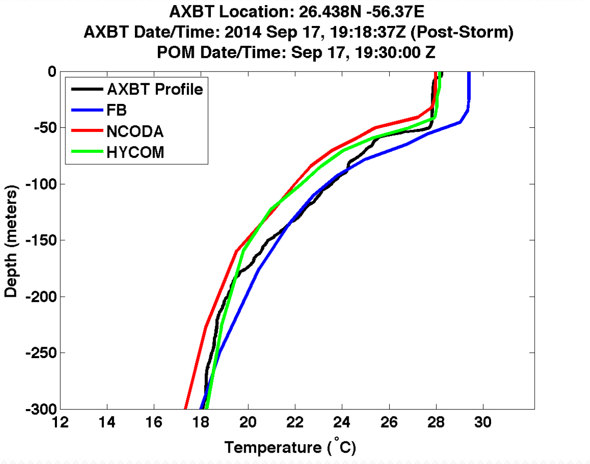
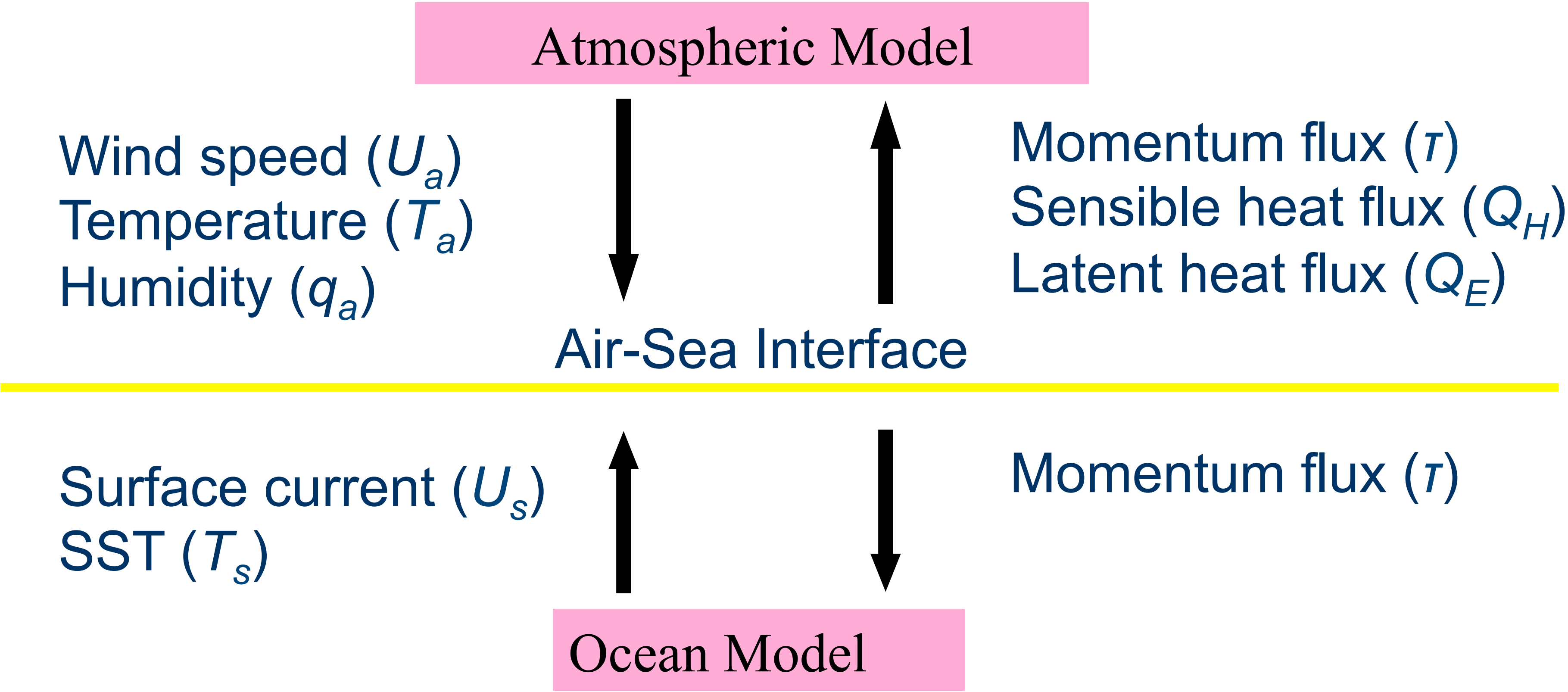
POM Date/Time: Sep 17, 21:00:00 Z


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

Atmosphere-Ocean Coupling



Atmospheric Model

Wind speed (U_a)
Temperature (T_a)
Humidity (q_a)

Momentum flux (τ)
Sensible heat flux (Q_H)
Latent heat flux (Q_E)

Air-Sea Interface

Surface current (U_s)
SST (T_s)

Momentum flux (τ)

Ocean Model

$$\tau = \rho_a C_D (U_a - U_s)(U_a - U_s) \qquad Q_H = C_H (U_a - U_s)(T_a - T_s)$$

$$Q_E = \frac{L_V}{C_P} C_E (U_a - U_s)(q_a - q_s)$$

Developing 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.

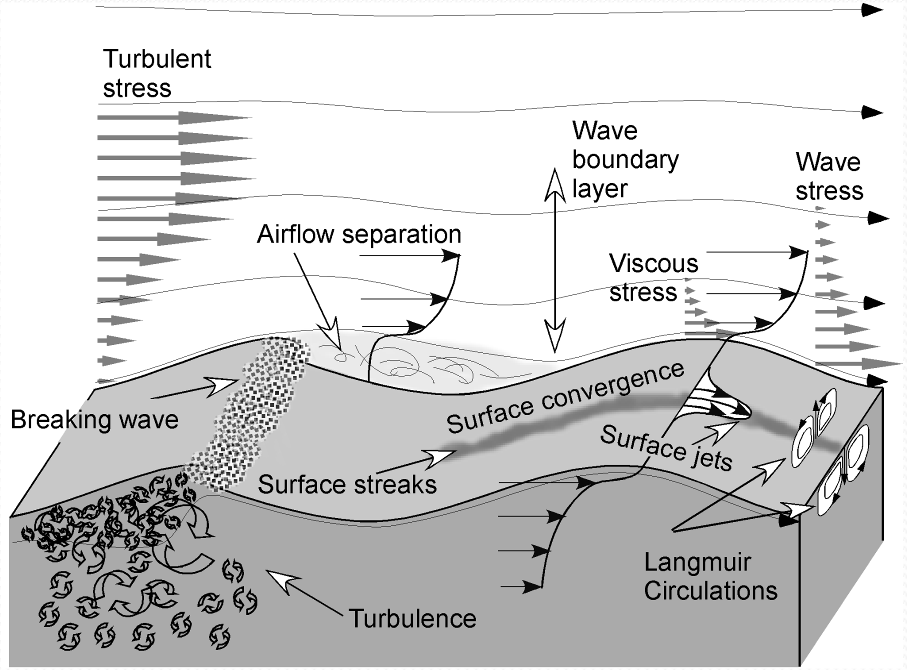
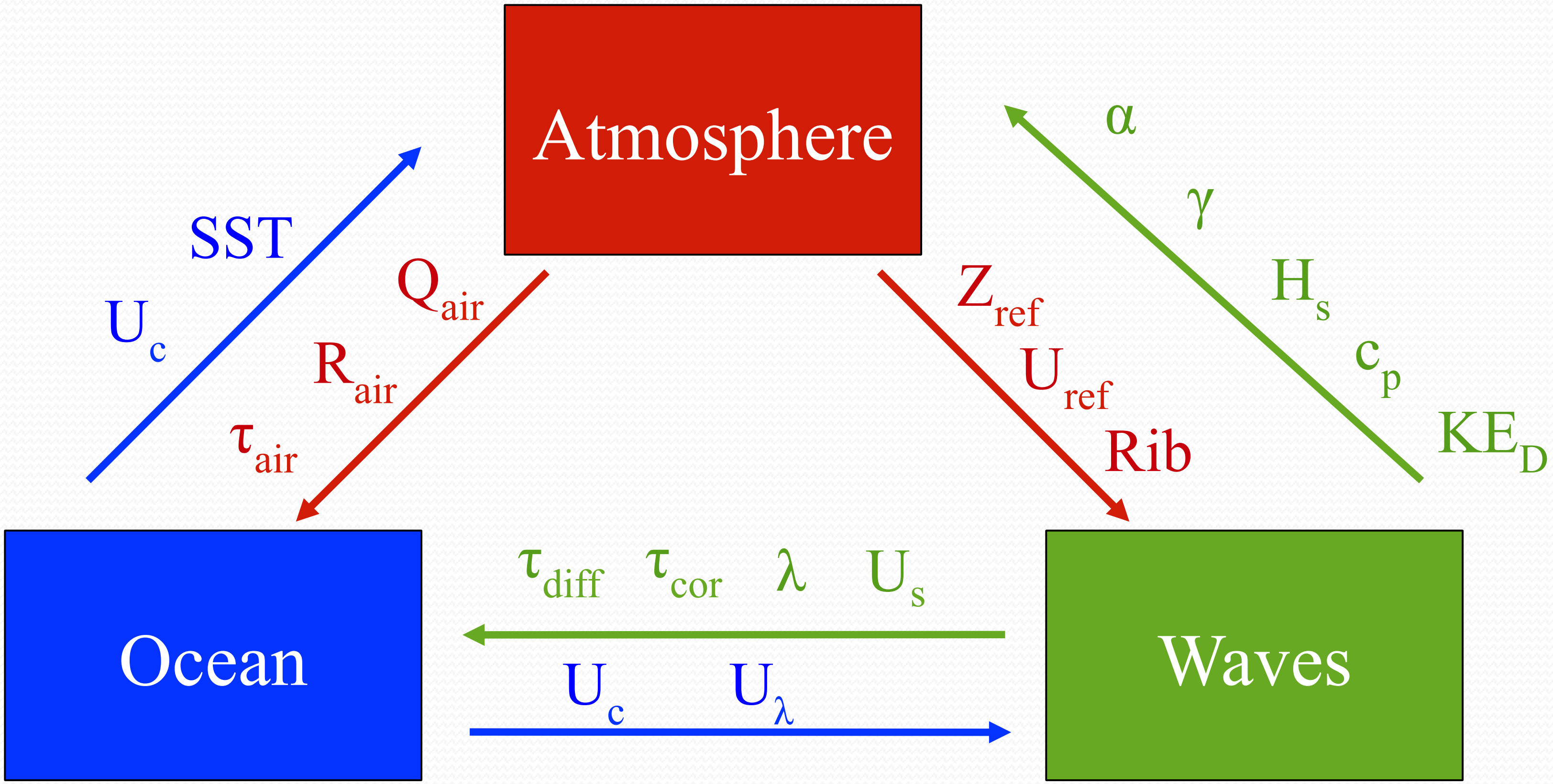
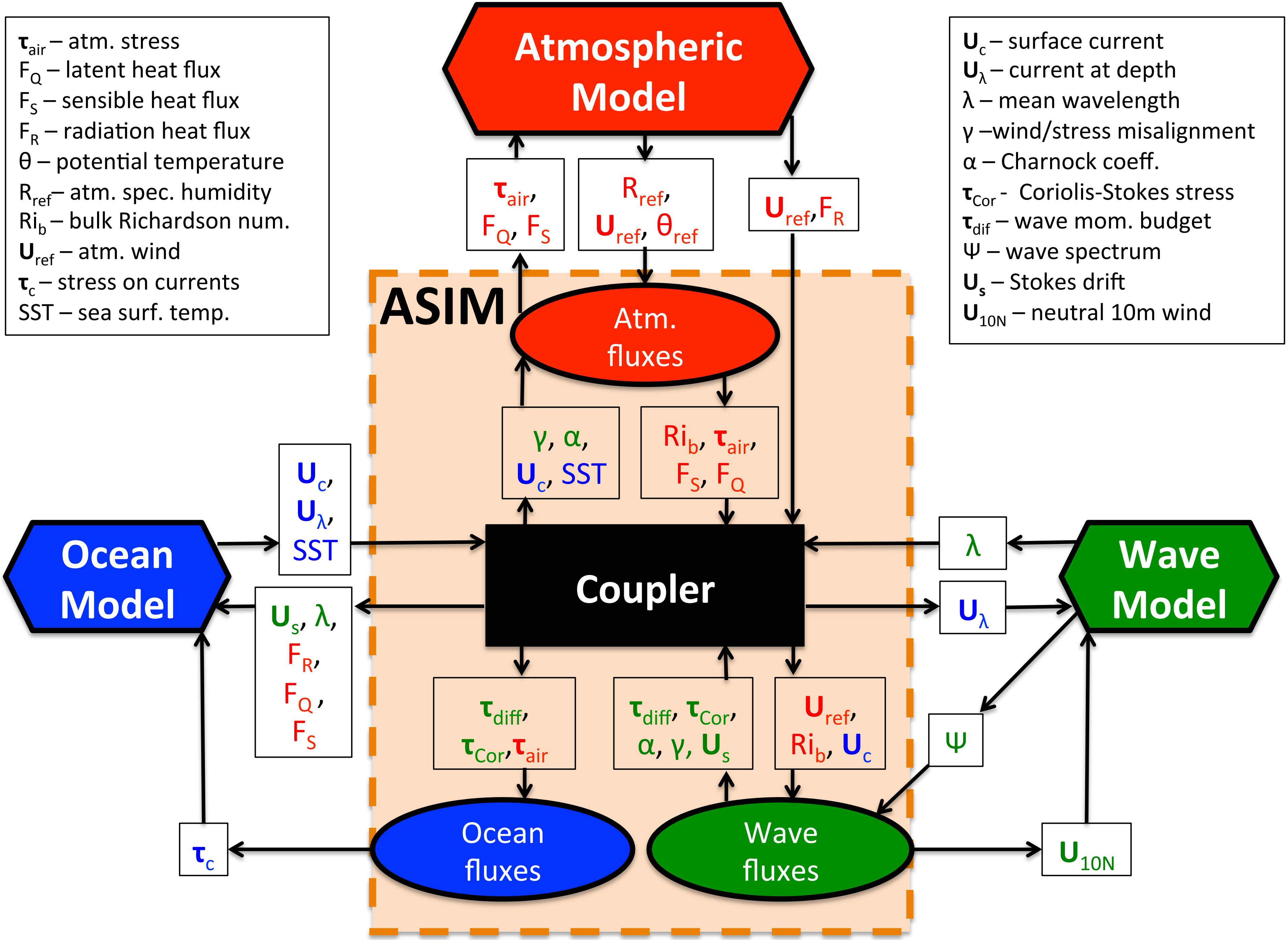


Image courtesy of Fabrice Veron

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**).

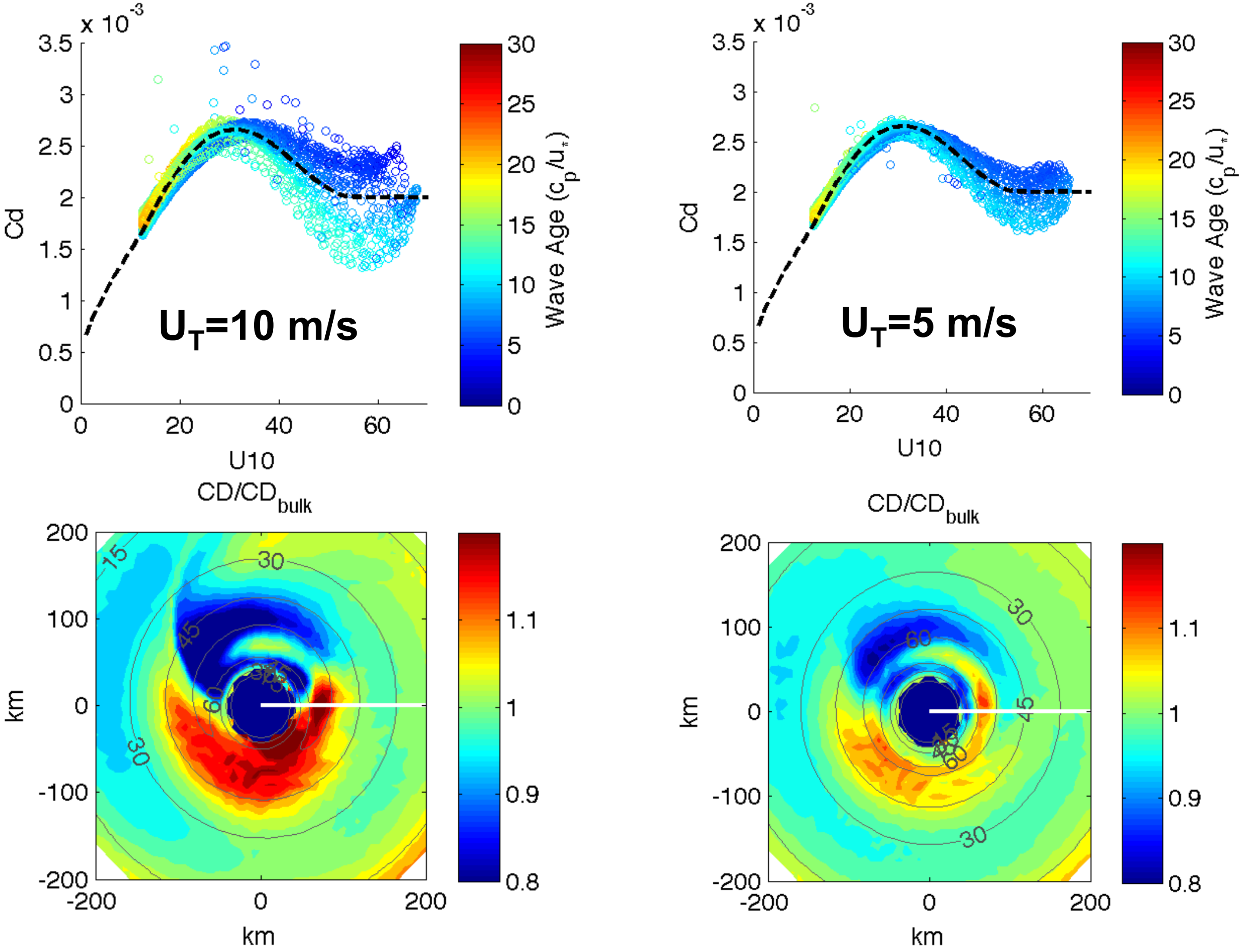


τ_{air} – atm. stress
F_Q – latent heat flux
F_S – sensible heat flux
F_R – radiation heat flux
θ – potential temperature
R_{ref} – atm. spec. humidity
Ri_b – bulk Richardson num.
U_{ref} – atm. wind
τ_c – stress on currents
SST – sea surf. temp.

U_c – surface current
U_λ – current at depth
λ – mean wavelength
γ –wind/stress misalignment
α – Charnock coeff.
τ_{Cor} - Coriolis-Stokes stress
τ_{dif} – wave mom. budget
Ψ – wave spectrum
U_s – Stokes drift
U_{10N} – neutral 10m wind

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

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



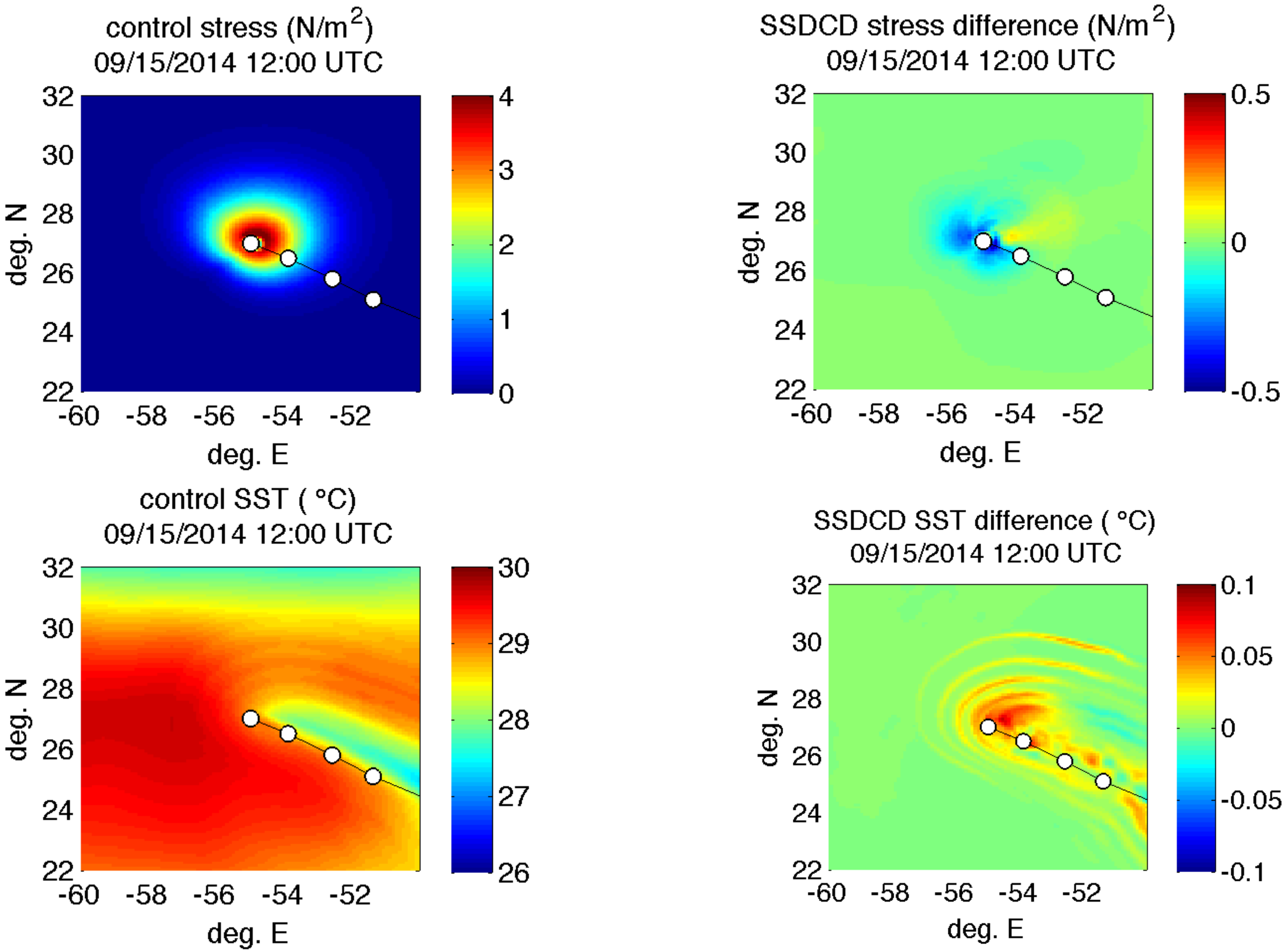
Wave dependent surface boundary conditions in the ocean model

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

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

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

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


control stress (N/m^2) 09/15/2014 12:00 UTC

SSDCD stress difference (N/m^2) 09/15/2014 12:00 UTC

control SST (°C) 09/15/2014 12:00 UTC

SSDCD SST difference (°C) 09/15/2014 12:00 UTC

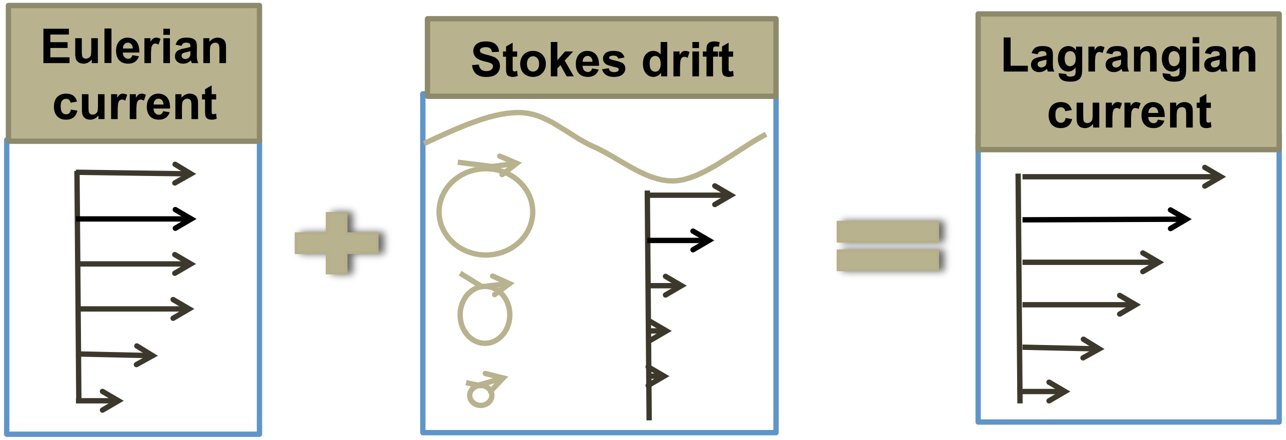
Langmuir turbulence modifications in KPP

1. Enhance K based on the Langmuir number

$$K(z) = \left[h w_* G(z) \right] \times F(La)$$

$$La = \sqrt{u_* / u_{St}}$$

2. Use the Lagrangian current in place of the Eulerian current in KPP



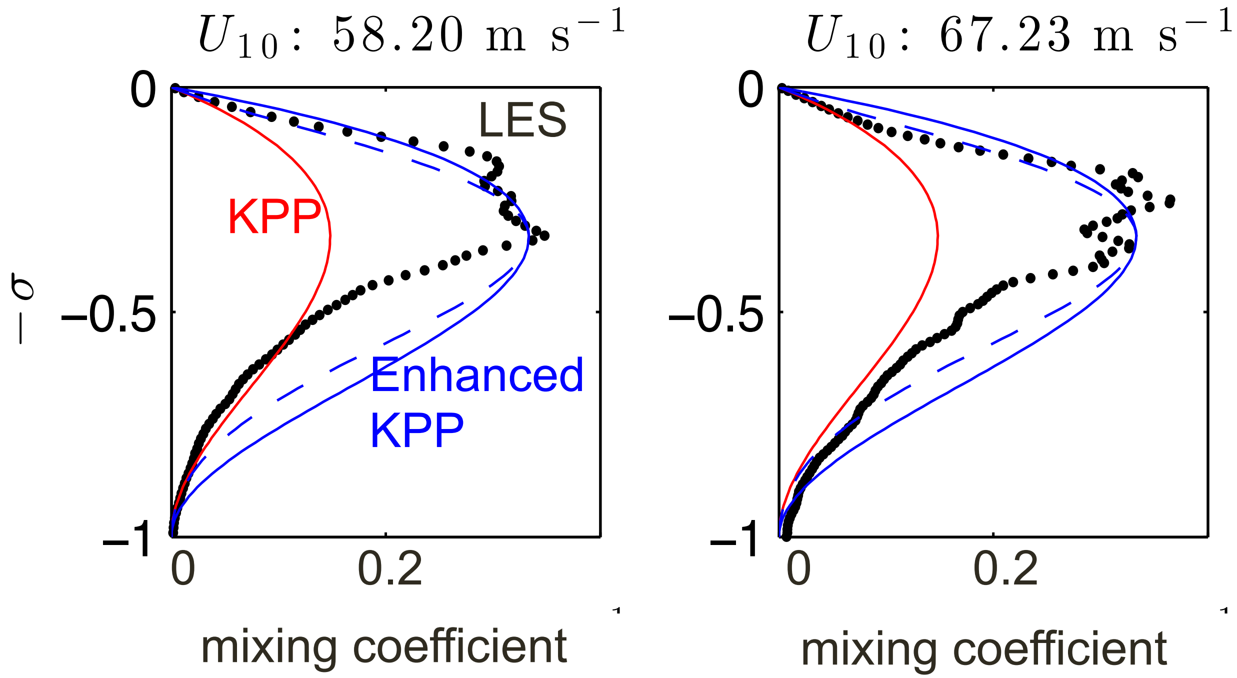
Eulerian current

Stokes drift

Lagrangian current

Langmuir turbulence modifications in KPP

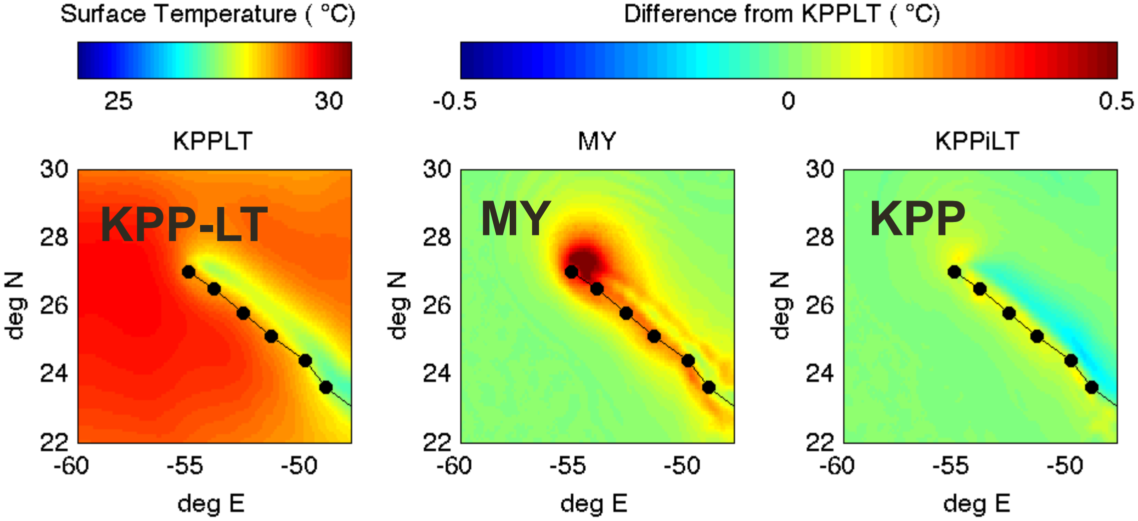
The enhancement factor needed in the KPP mixing coefficient is then found from the LES results



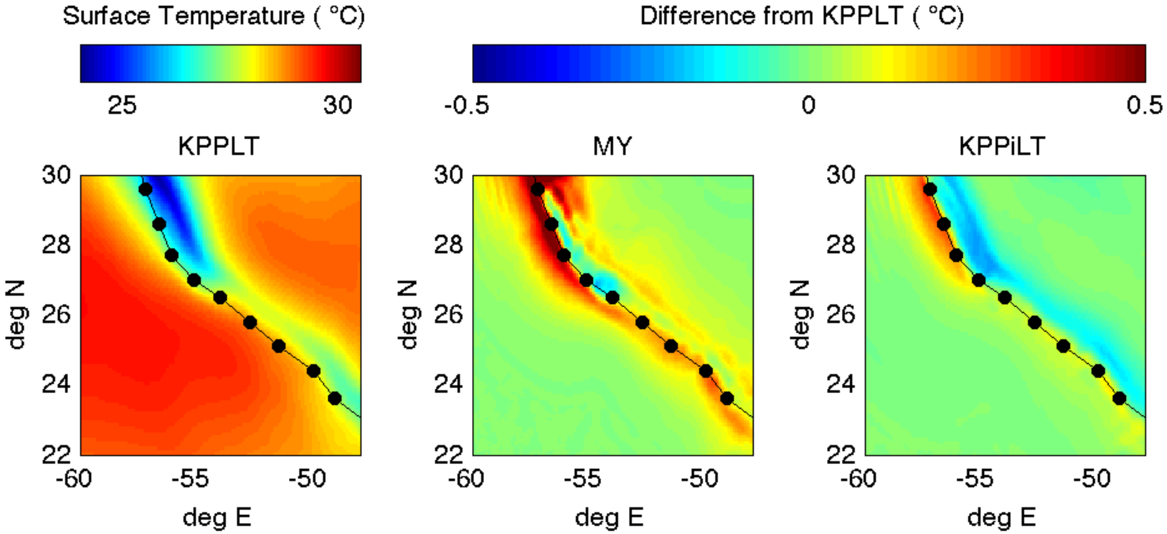
Left of hurricane

Right of hurricane

Langmuir impact on SST cooling (Hurricane Edouard): KPP-LT vs KPP and M-Y



September 15



September 16

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