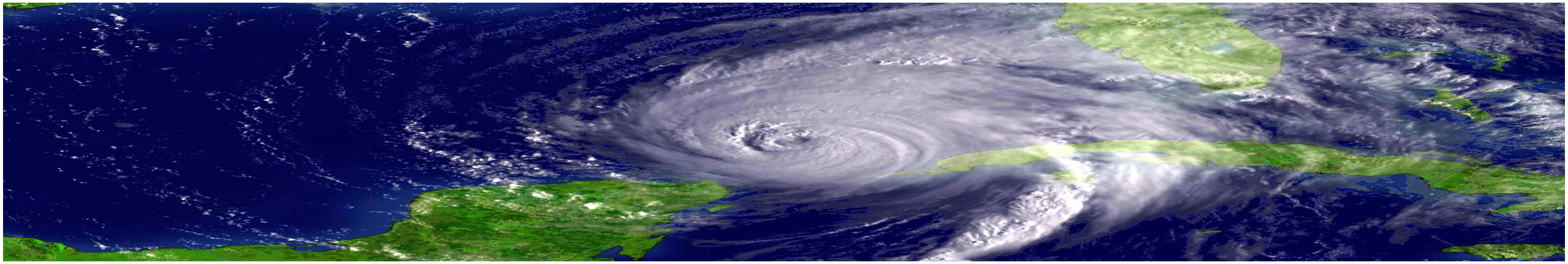

HWRF Ocean: The Princeton Ocean Model

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THINK BIG WE DO™

THE UNIVERSITY OF RHODE ISLAND

Why Couple a 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

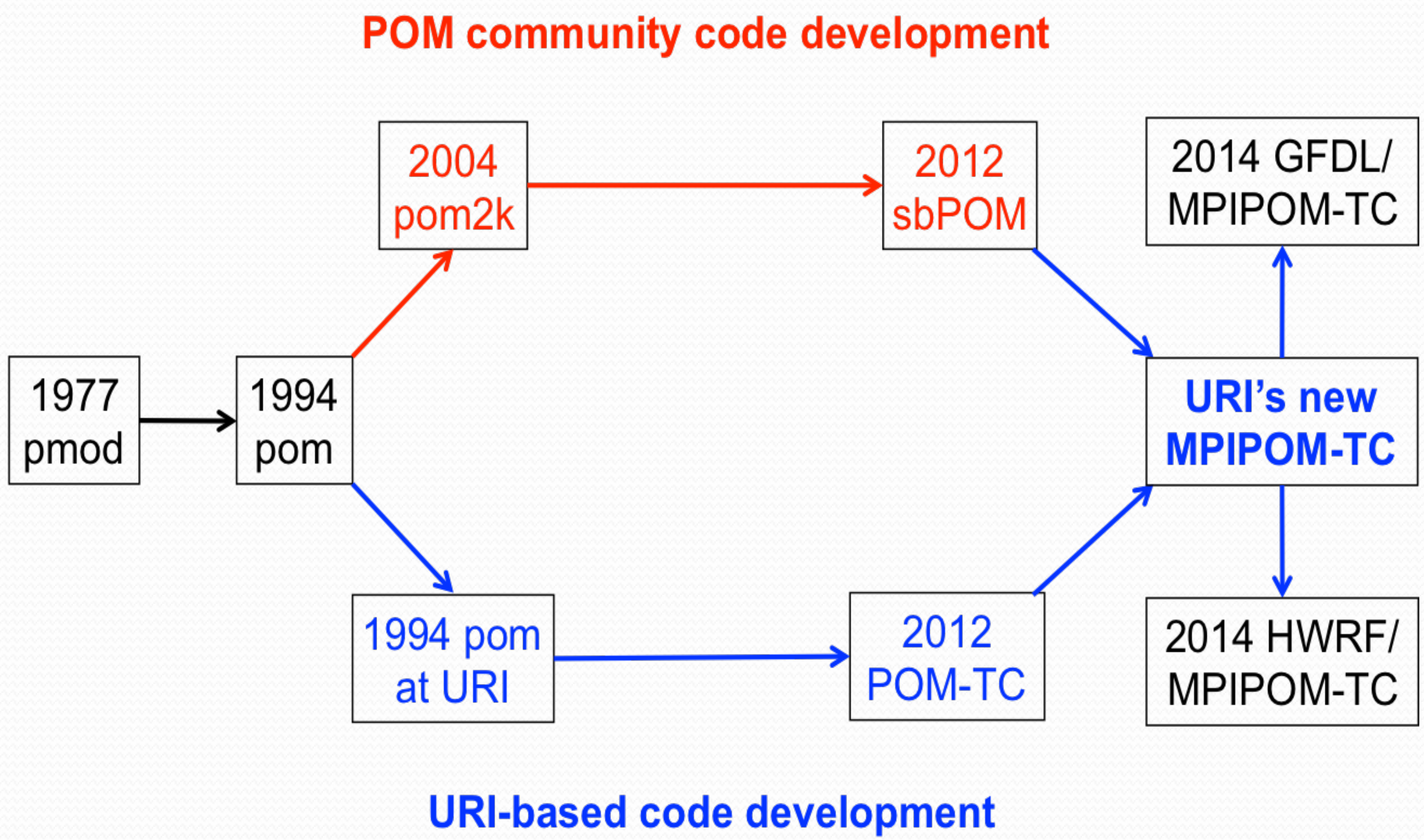
Early history of Princeton Ocean Model

- Three-dimensional, primitive equation, numerical ocean model (commonly known as POM)
- Originally developed by Alan Blumberg and George Mellor in the late 1970's
- Initially used for coastal ocean circulation applications
- Open to the community during the 1990' s and 2000' s
- https://en.wikipedia.org/wiki/Princeton_ocean_model

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 NWS 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)

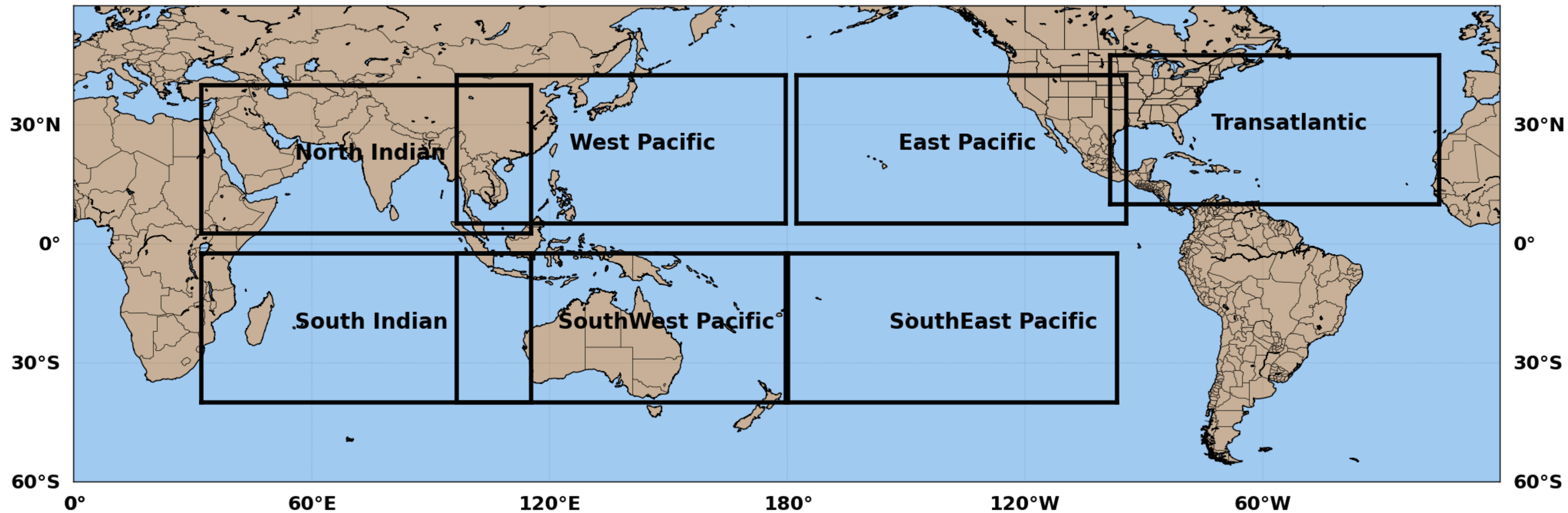
Developing MPIPOM-TC



MPIPOM-TC Features

- 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

MPIPOM Domains Worldwide

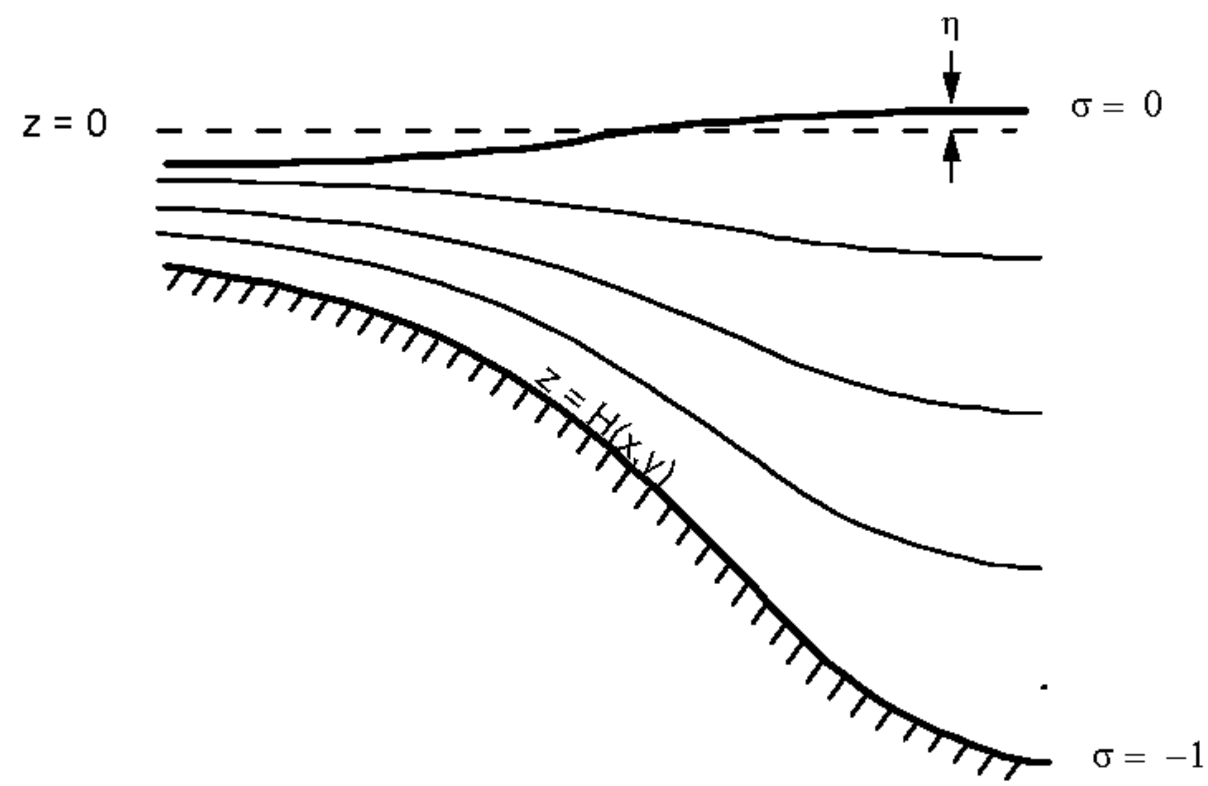


All domains are set to the same size covering 83.2° (37.5°) of longitude (latitude) with a horizontal grid spacing of 1/12°.

By default, HWRF runs coupled in all ocean basins except Southern Hemisphere. DTC will provide instructions on how to run coupled in all basins.

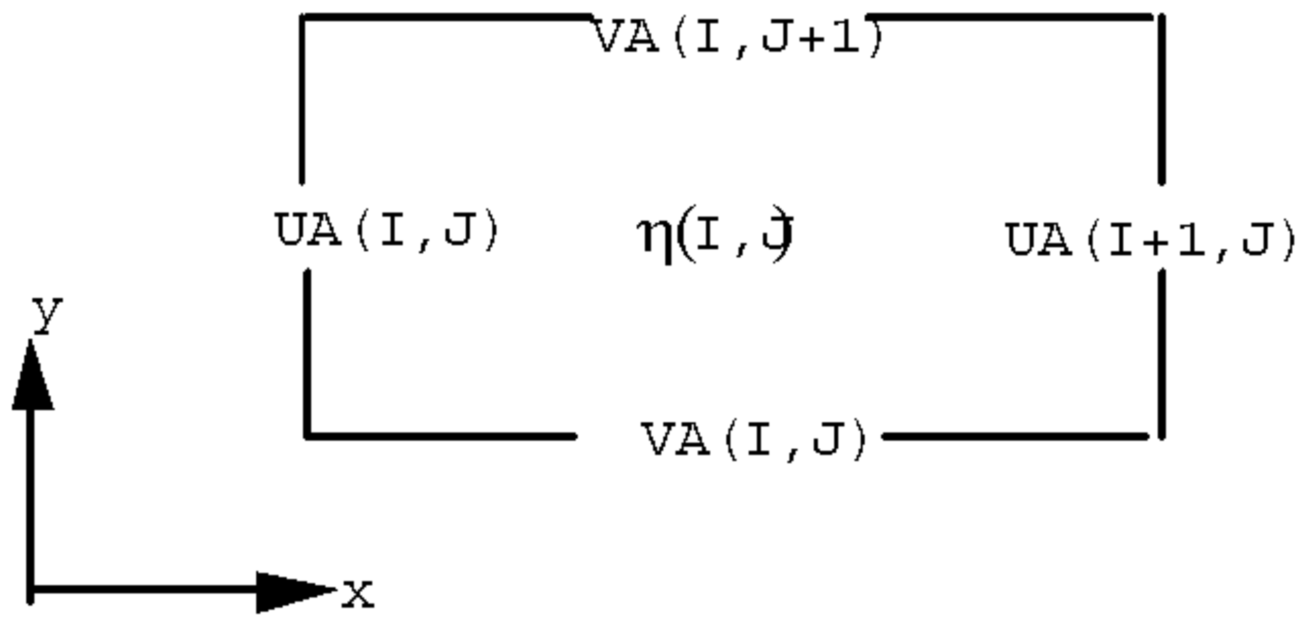
POM Numerical Design

Sigma Vertical Coordinate



- 40 vertical sigma levels; free surface (η)
- Level placement scaled based on ocean bathymetry
- Largest vertical spacing occurs where ocean depth is 5500 m

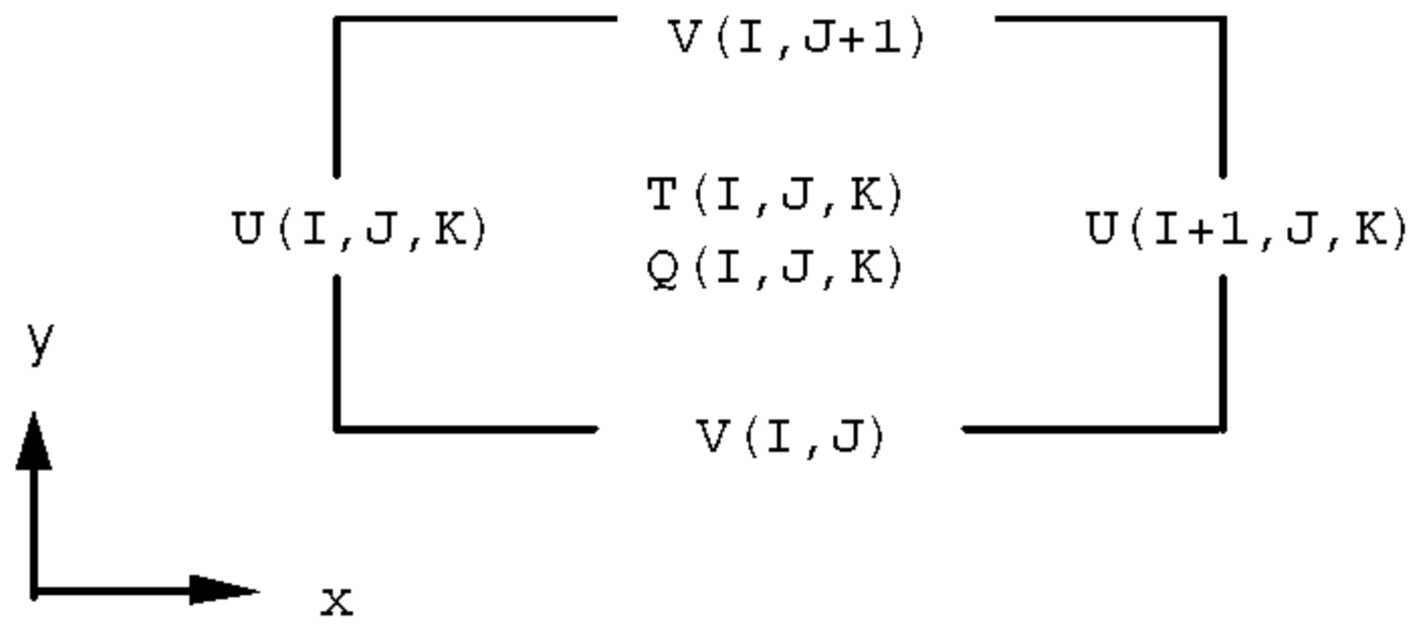
Arakawa-C Grid: External Mode



Plan View

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

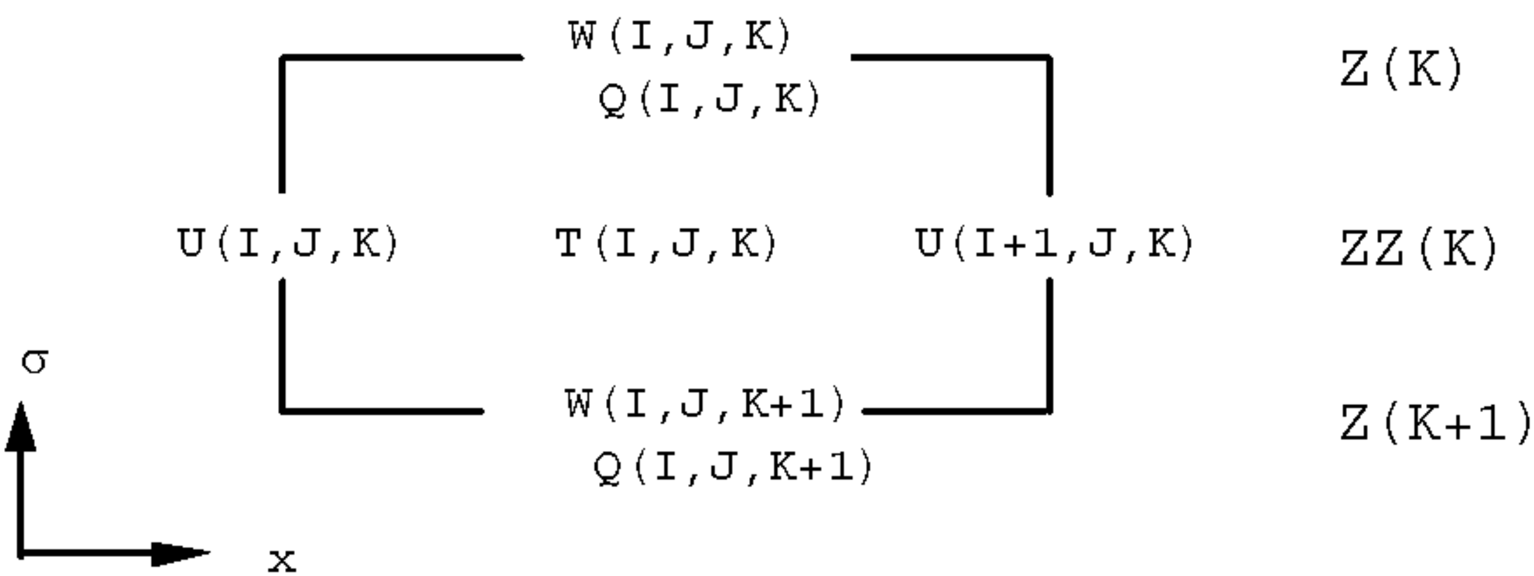
Arakawa-C Grid: Internal Mode



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"

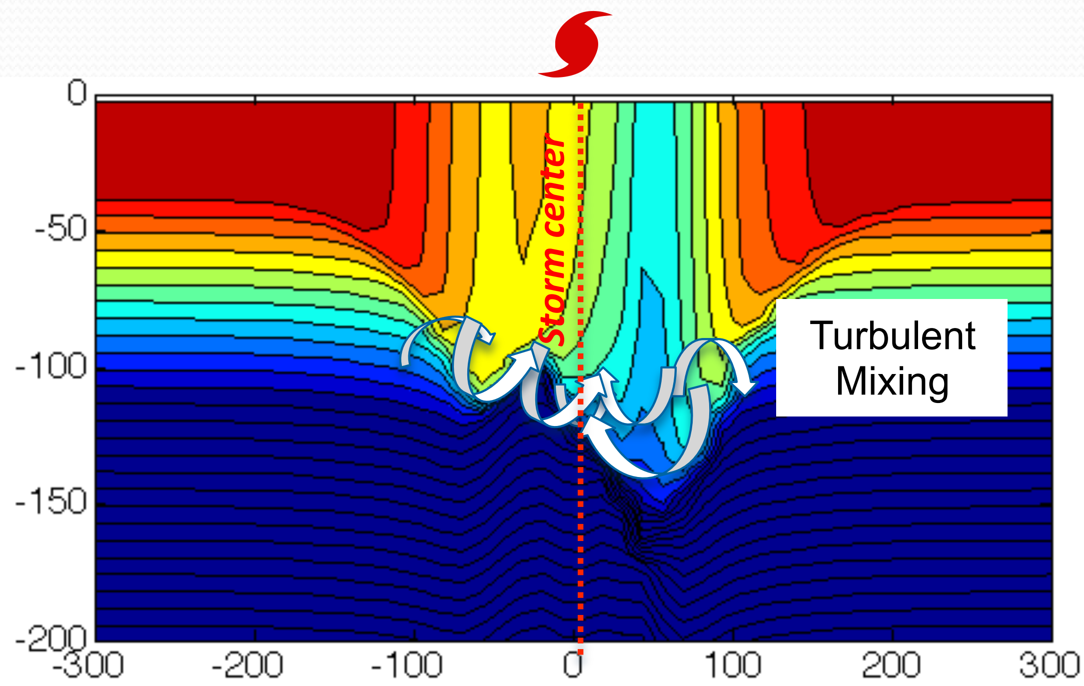
Time Stepping

- 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

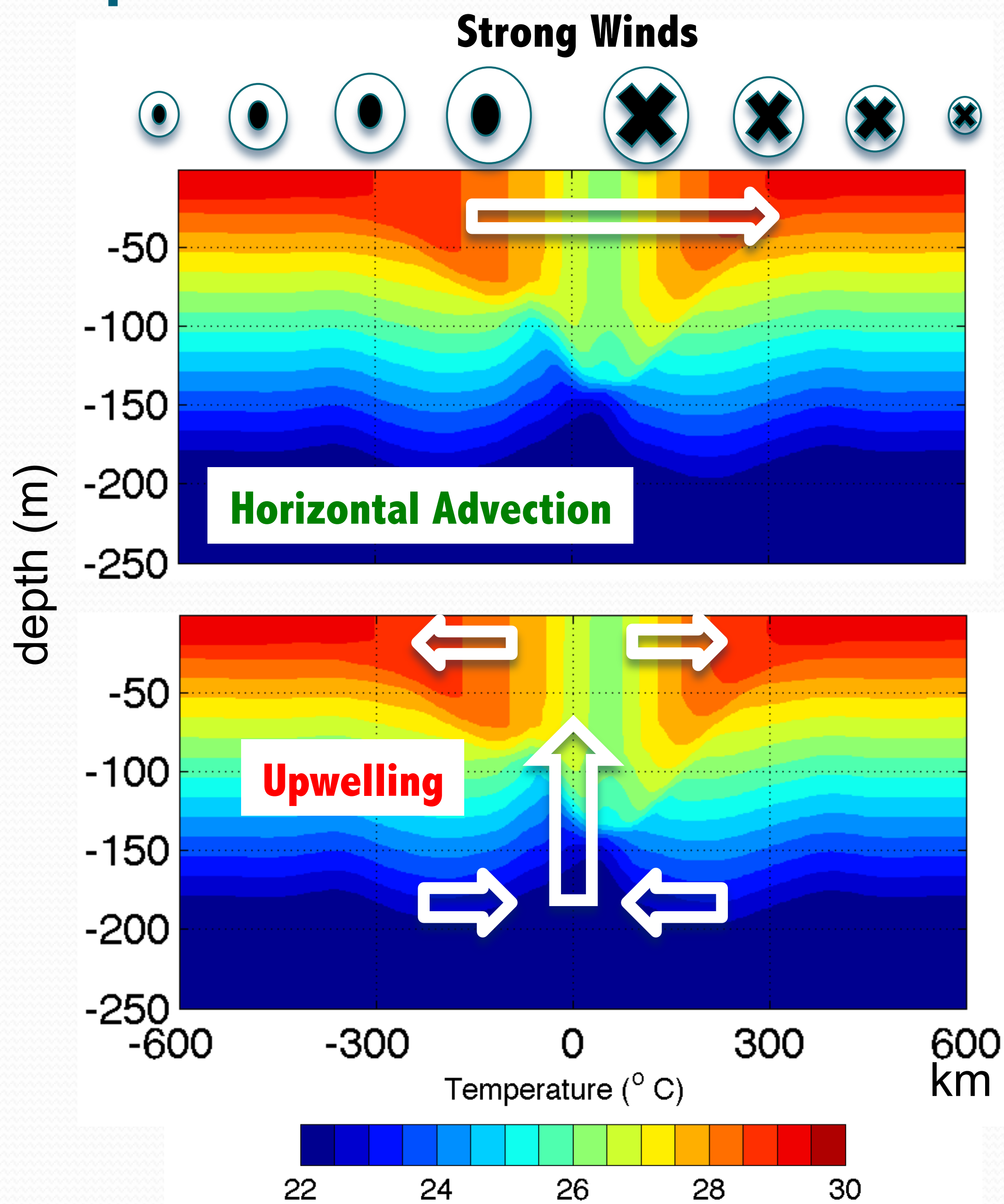
(2) K-Profile Parameterization (KPP scheme) *:*

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

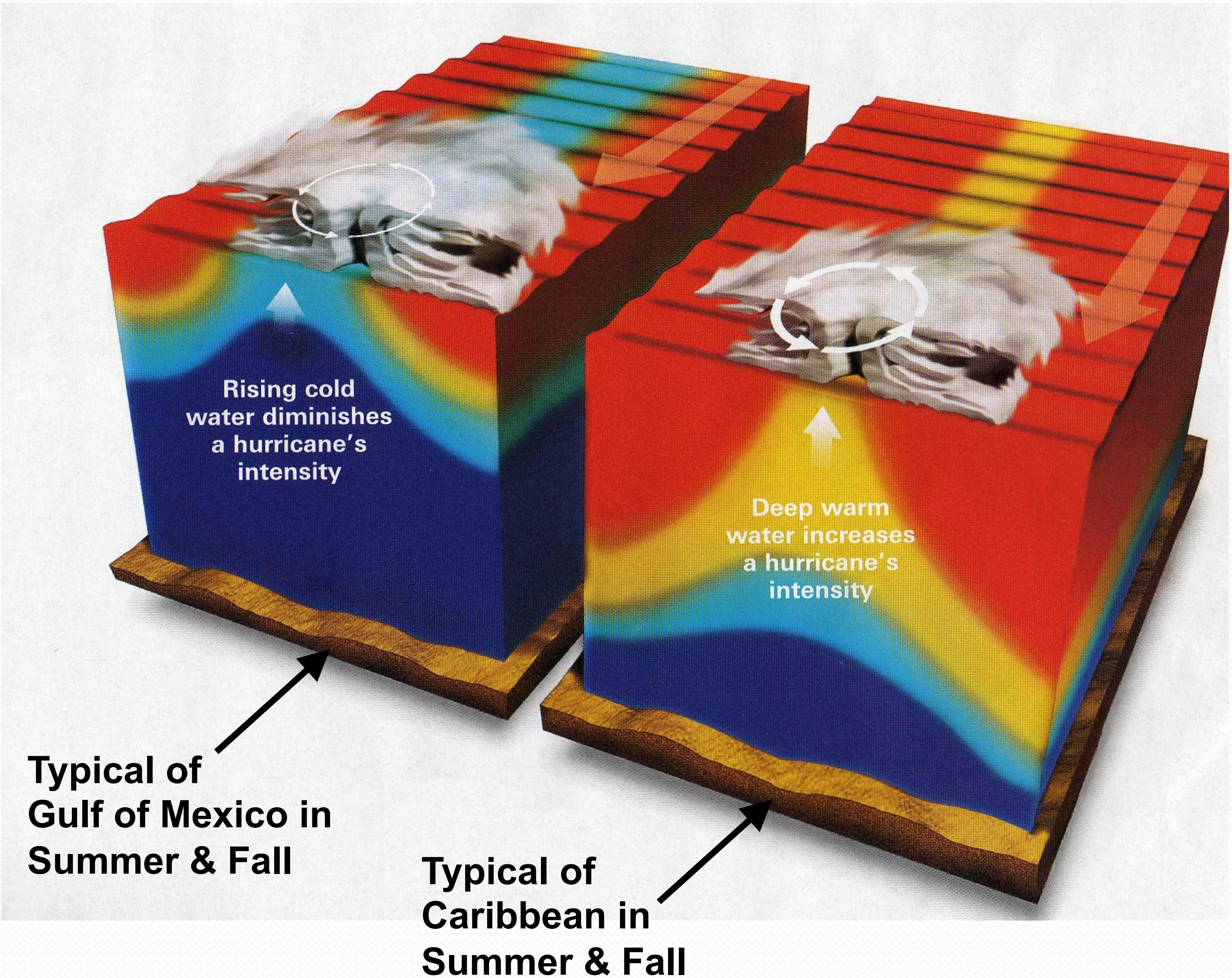
h - mixing layer depth
W- turbulent velocity scale
G(z)- non-dimensional shape-function

3-D processes

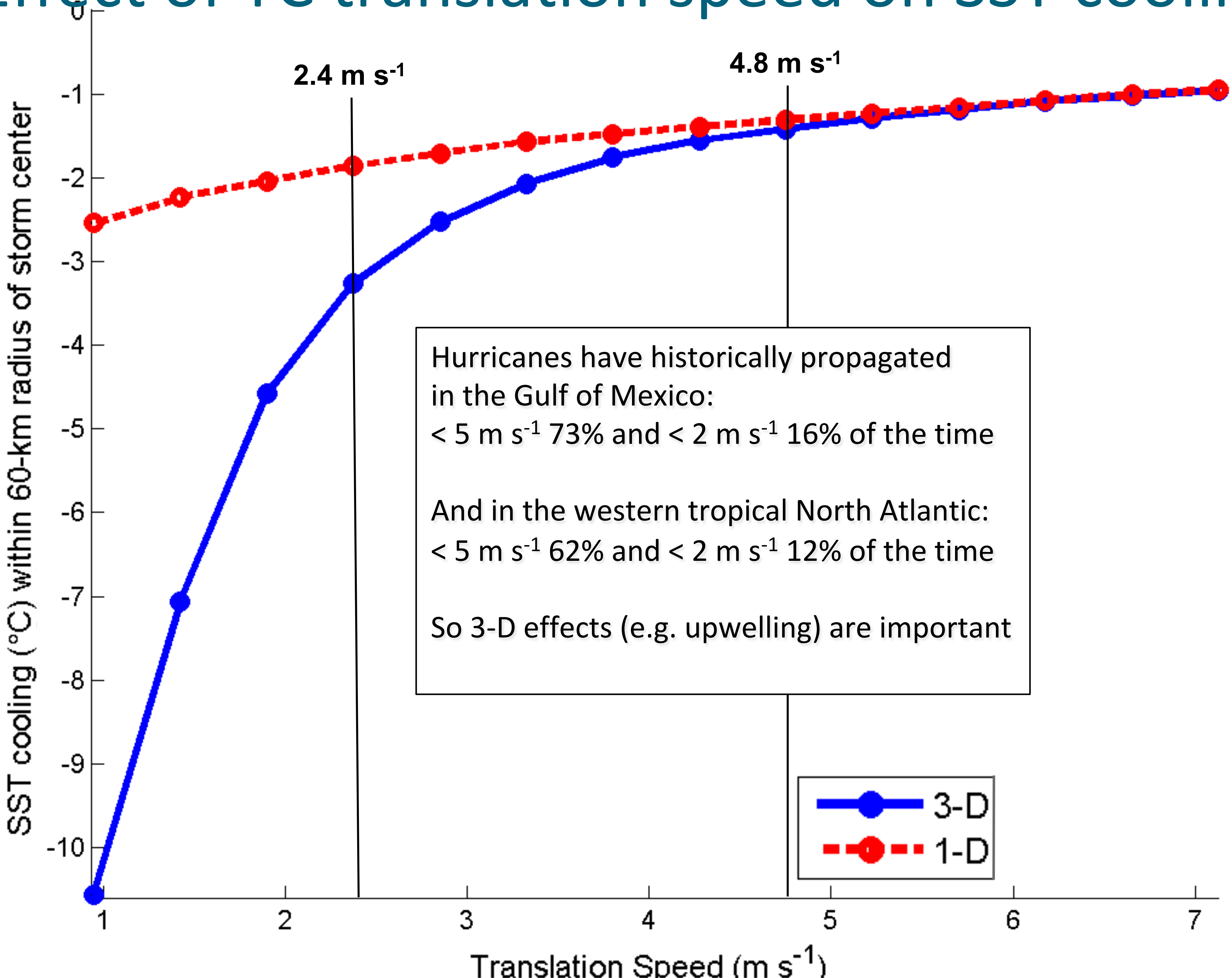
Hurricane induced upwelling and horizontal advection can enhance and/or modify surface cooling.



Effect of Ocean Stratification on SST cooling



Effect of TC translation speed on SST cooling

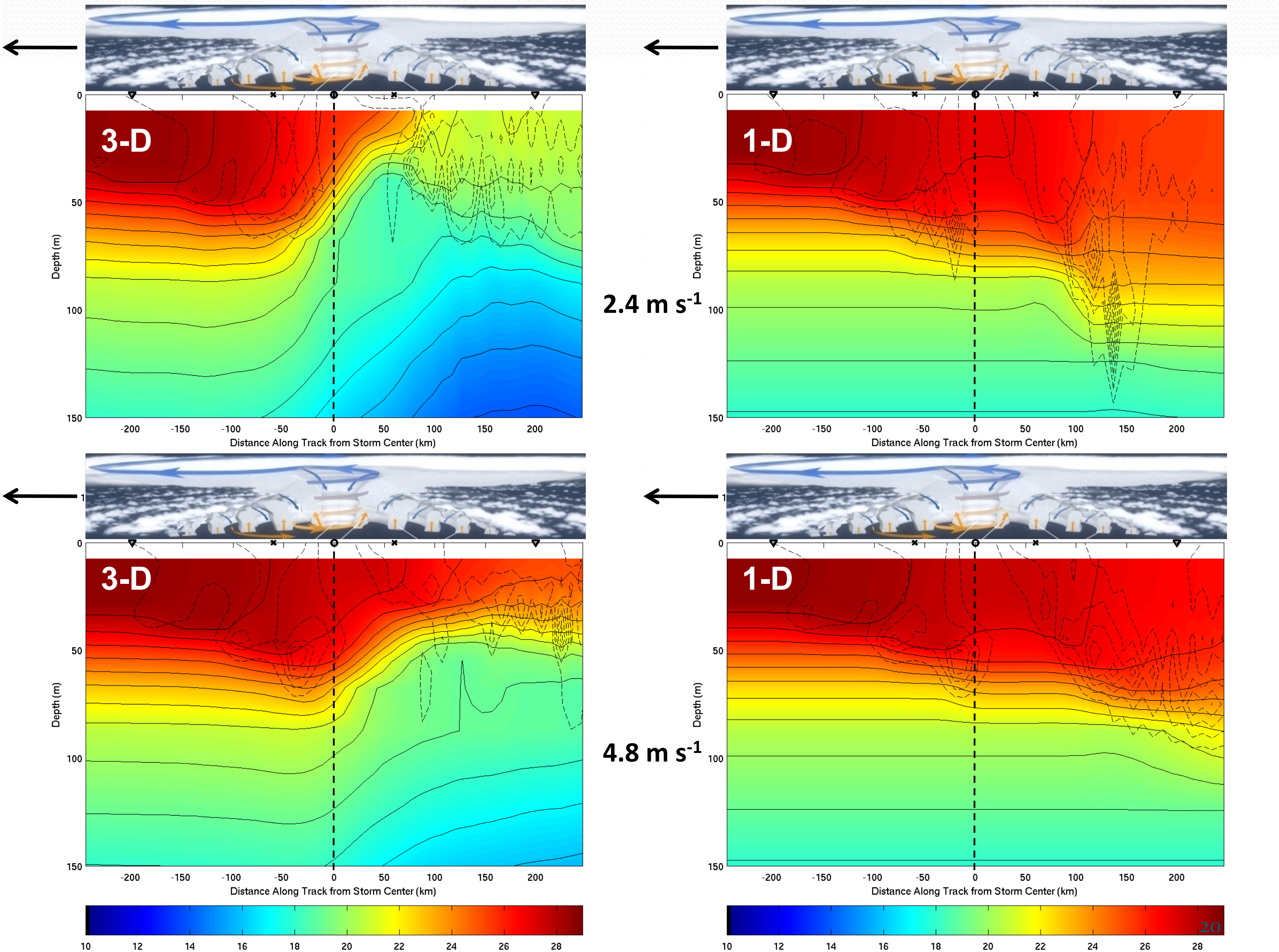


Hurricanes have historically propagated in the Gulf of Mexico:
< 5 m s^{-1} 73% and < 2 m s^{-1} 16% of the time

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)


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

POM Initialization

Flexible Initialization Options

1. Feature-based modifications to U.S. Navy's Generalized Digital Environmental Model (GDEM) monthly temperature (*T*) and salinity (*S*) climatology with assimilated daily SST (FB) used in NATL.

2. Global Real-Time Ocean Forecast System (RTOFS) used in EPAC & CPAC.

Feature-based (FB) initialization

- The basic premise of the FB procedure is that major oceanic fronts and eddies in the western North Atlantic Ocean are poorly represented by GDEM climatology.

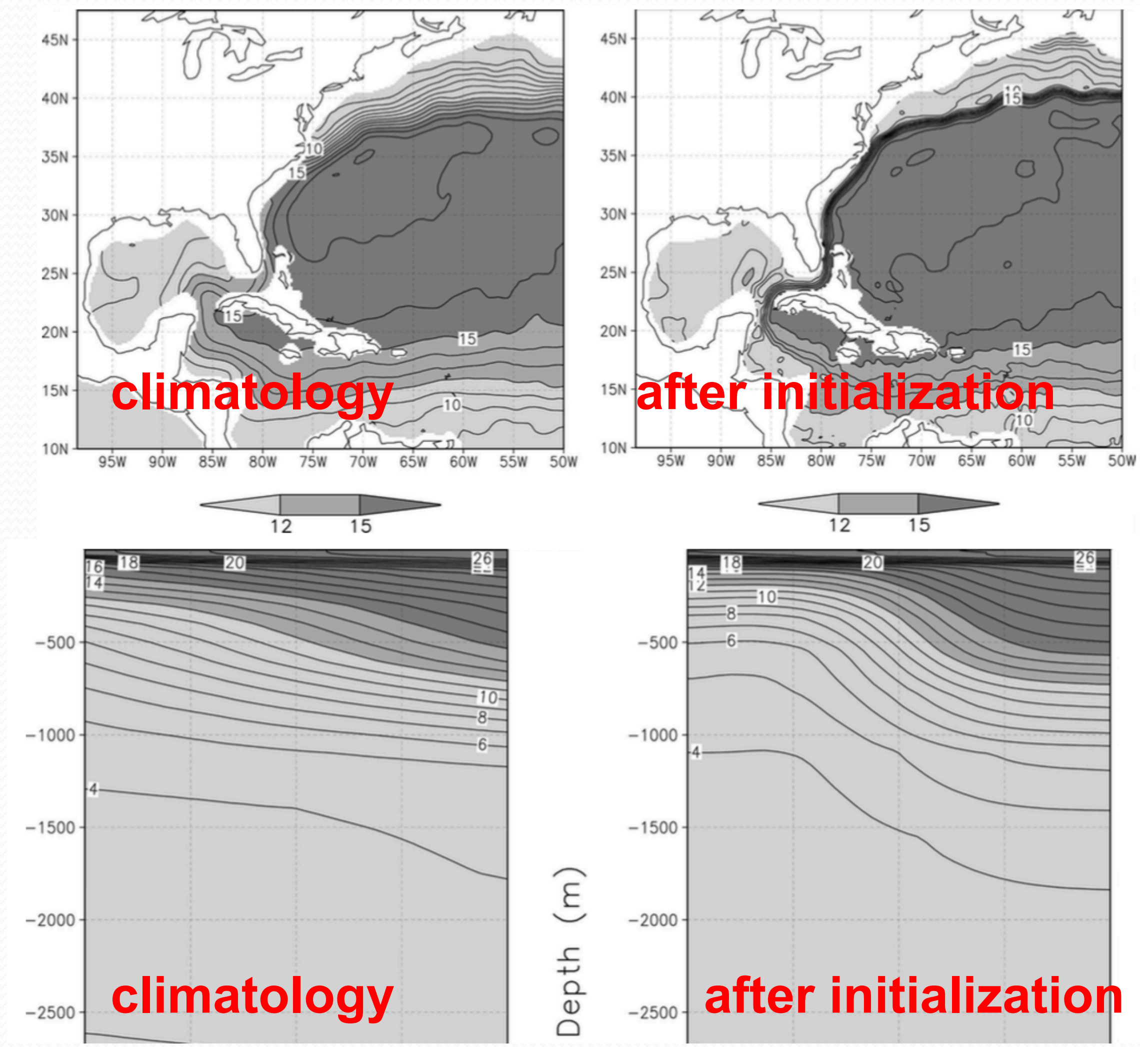
- By defining the spatial structure of these fronts and eddies using observations gathered from field experiments, cross-frontal "sharpening" of GDEM T & S fields is performed to increase the horizontal density gradients across the fronts.

- Algorithms are incorporated to initialize the Gulf Stream and Loop Current with prescribed paths and to insert eddies into the Gulf of Mexico based on guidance from near-real-time observations, such as satellite altimetry.

Feature-based Initialization: Gulf Stream

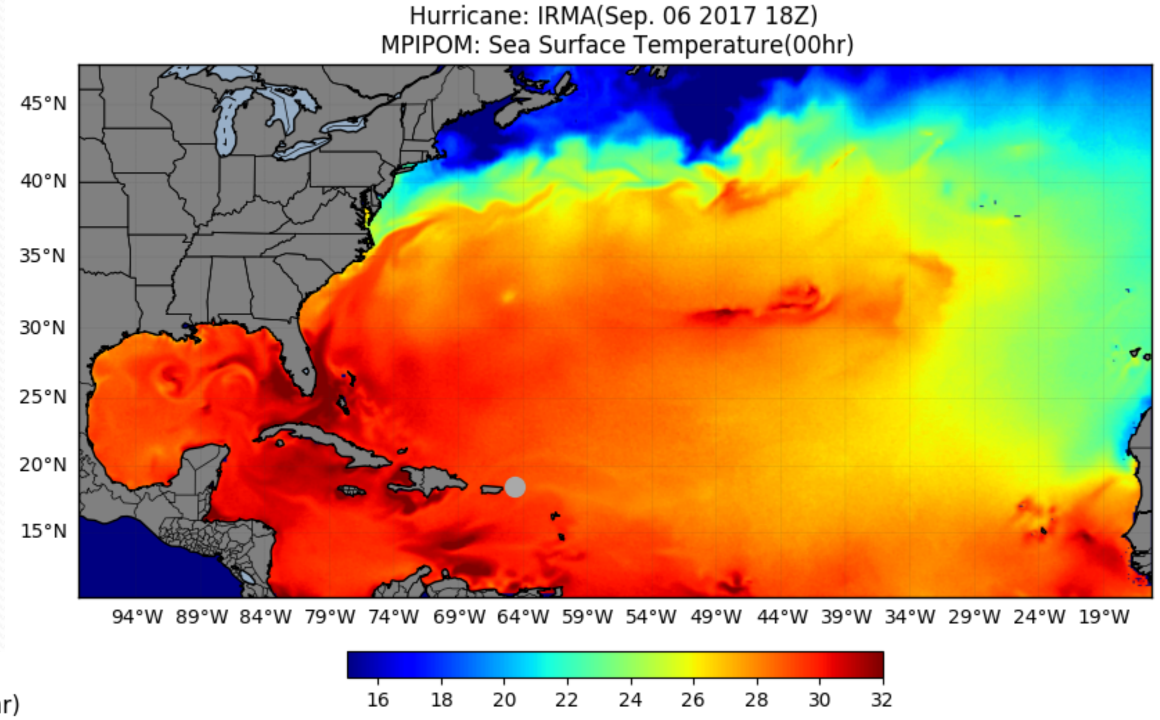
Temperature at 400 m

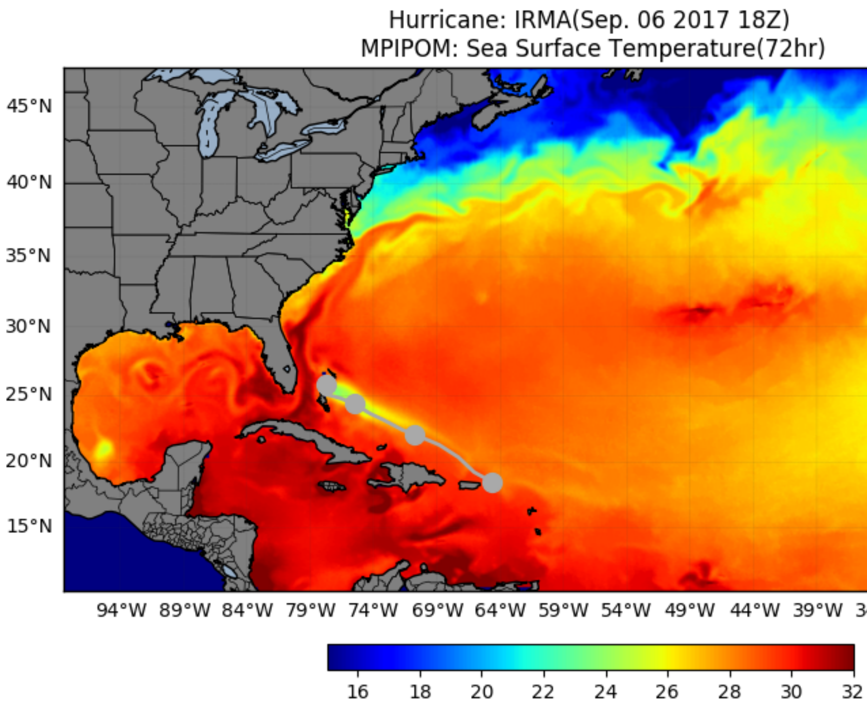
Gulf Stream cross-section



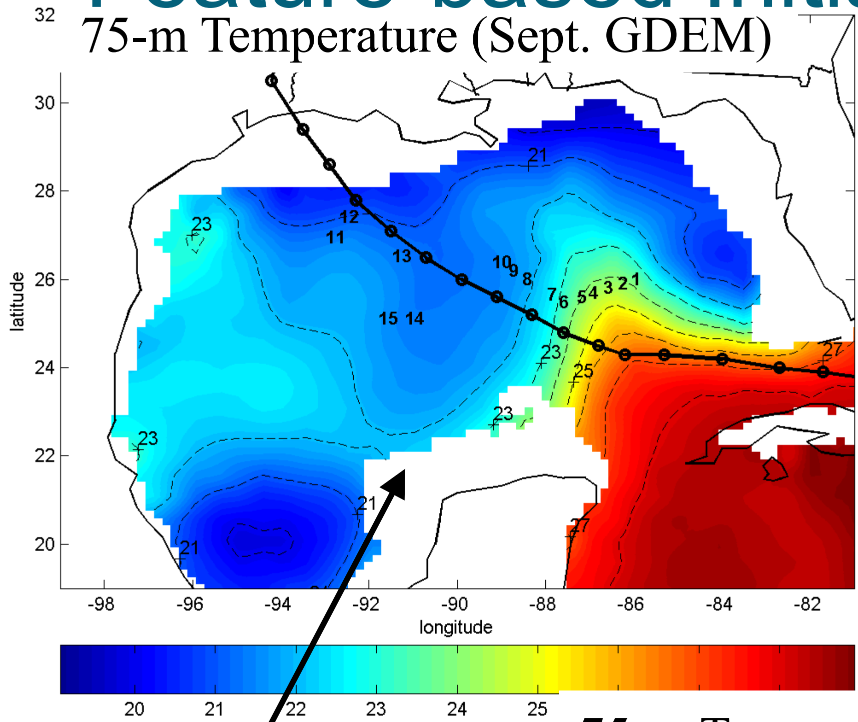
Falkovich, A., I. Ginis, and S. Lord, 2005

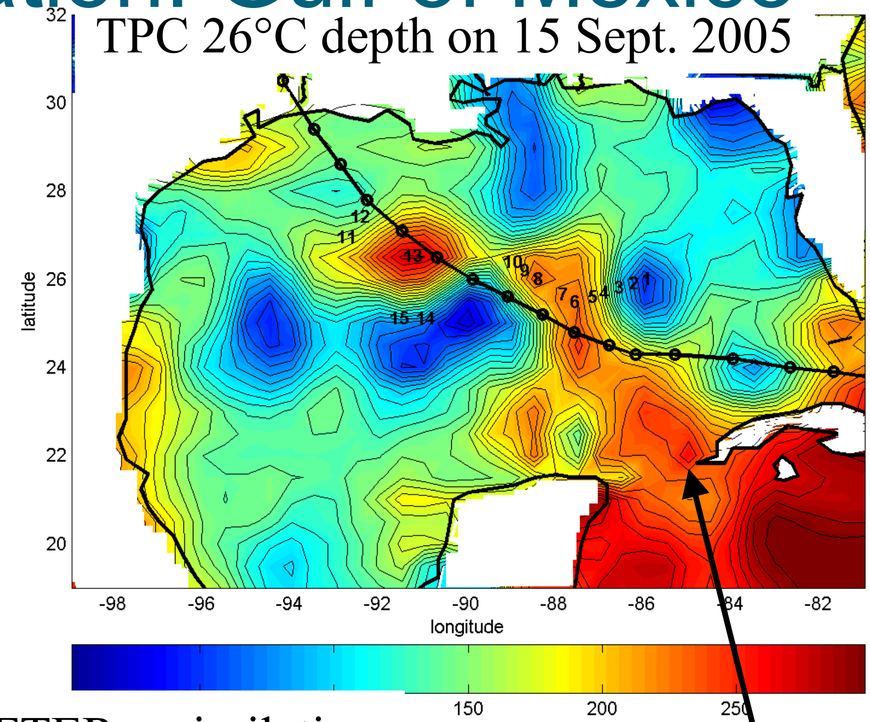
Feature-based Initialization: Hurricane Irma





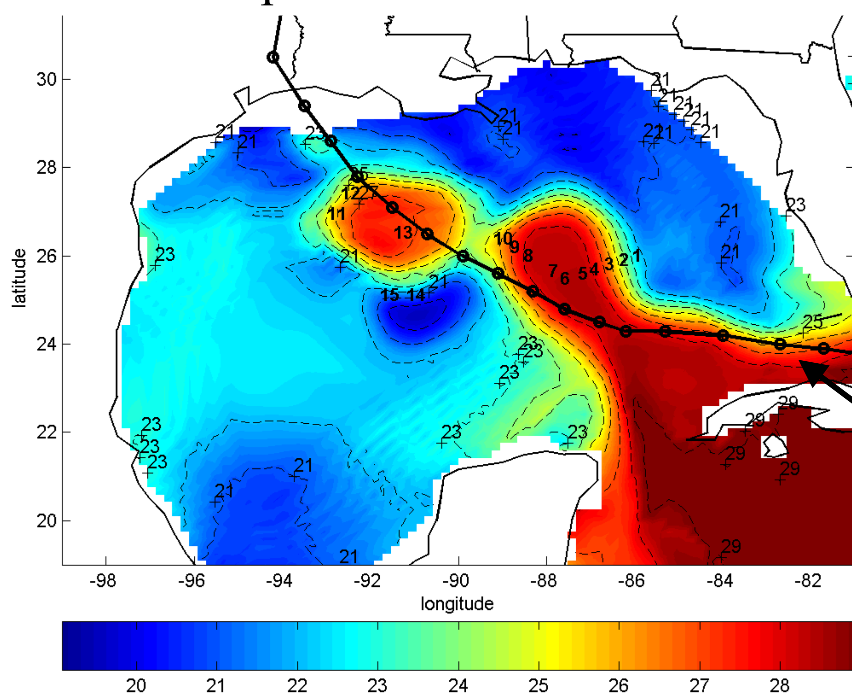
Feature-based Initialization: Gulf of Mexico





(1) Start with monthly climatology

(2) Adjust LC position & add warm- and cold-core eddies info derived from altimetry



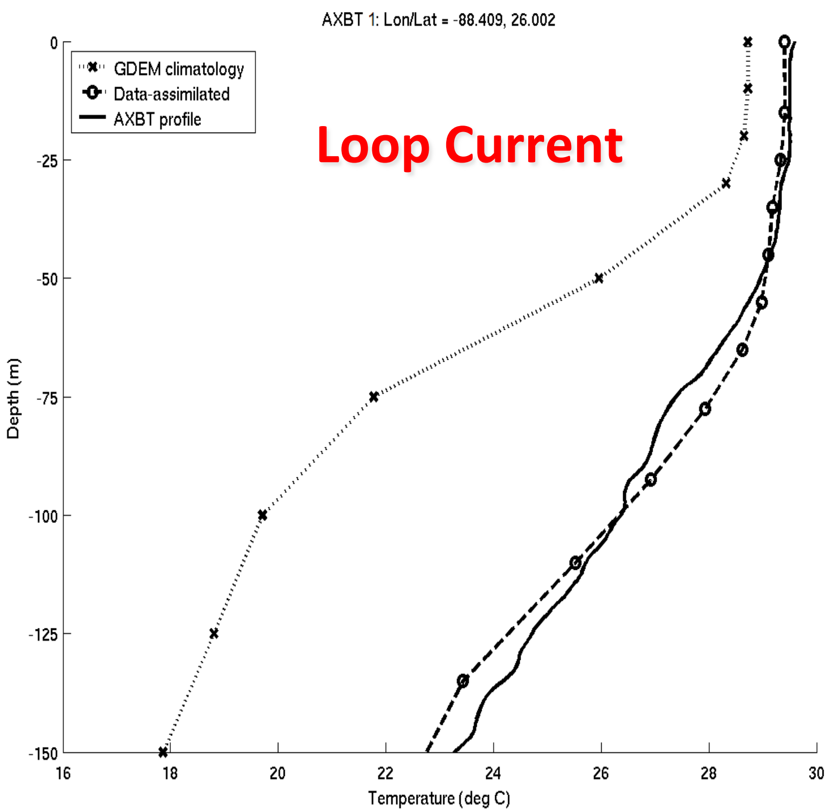
(3) Assimilate SST analysis

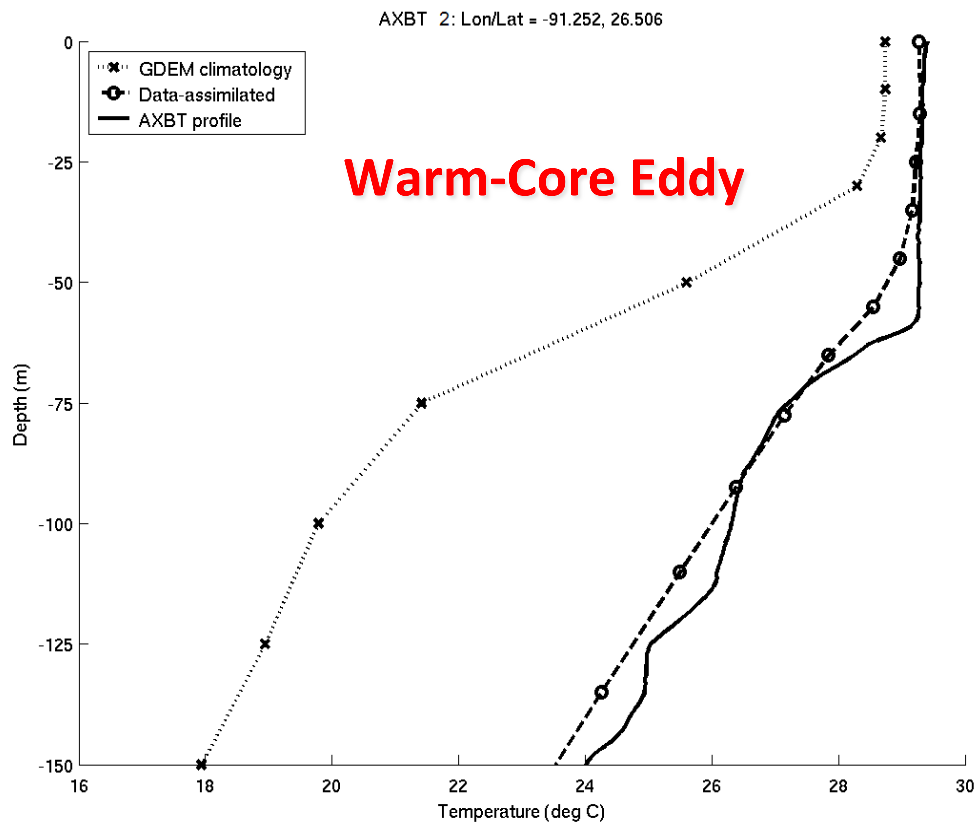
(4) Spin-up ocean currents

Future Hurricane Rita track

Yablonsky and Ginis (2008)

Feature-based Initialization: Examples of improved vertical temperature in Loop Current and warm-core eddy

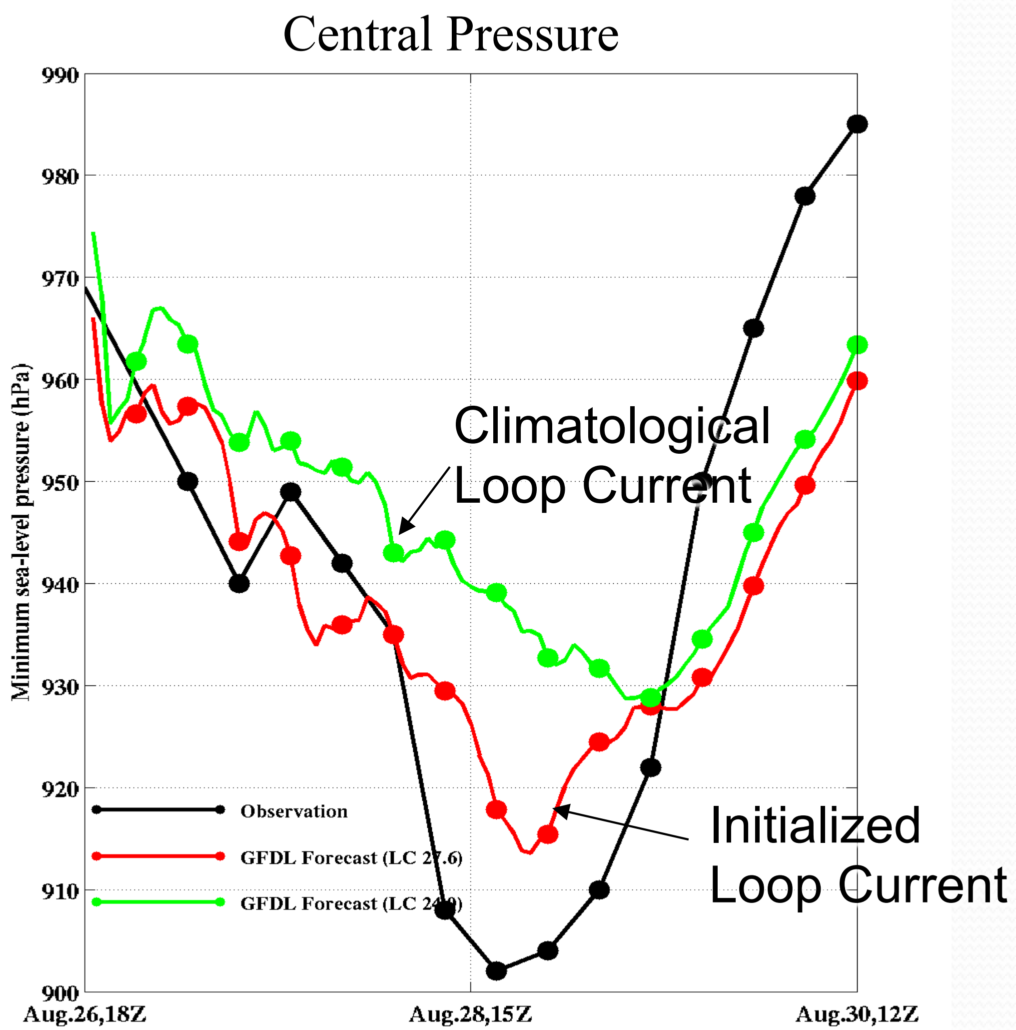




Yablonsky and Ginis (2008)

Effect of Loop Current on Hurricane Katrina Intensity

GFDL forecast Initialized Aug. 26, 18Z



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

$$\tau = \rho_a C_D (U_a - U_s)(U_a - U_s)$$

$$Q_H = C_H (U_a - U_s)(T_a - T_s)$$

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

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.

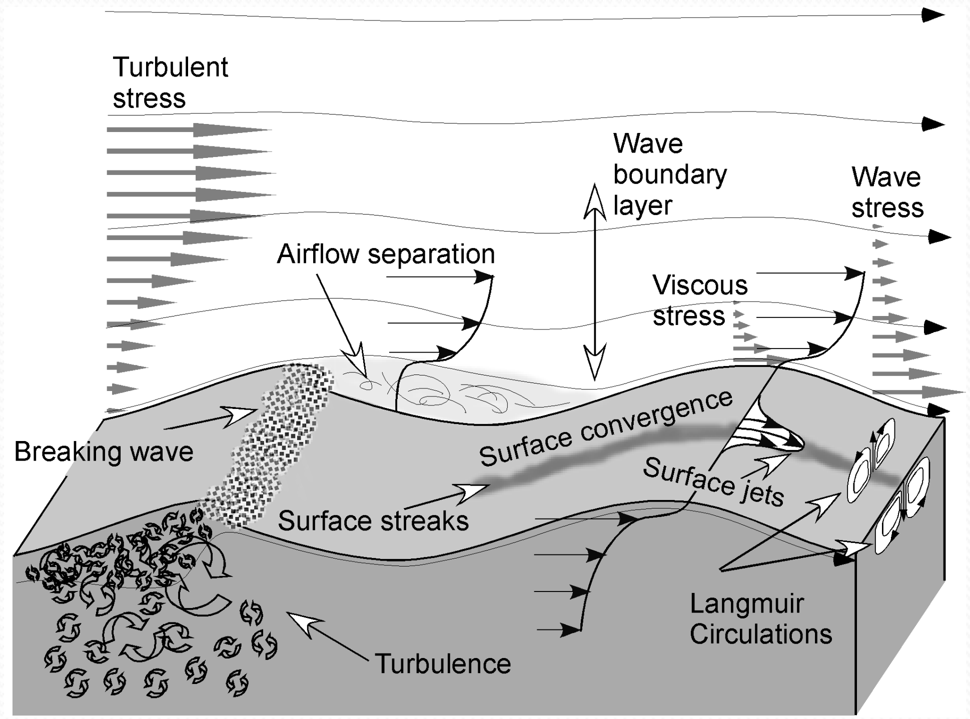
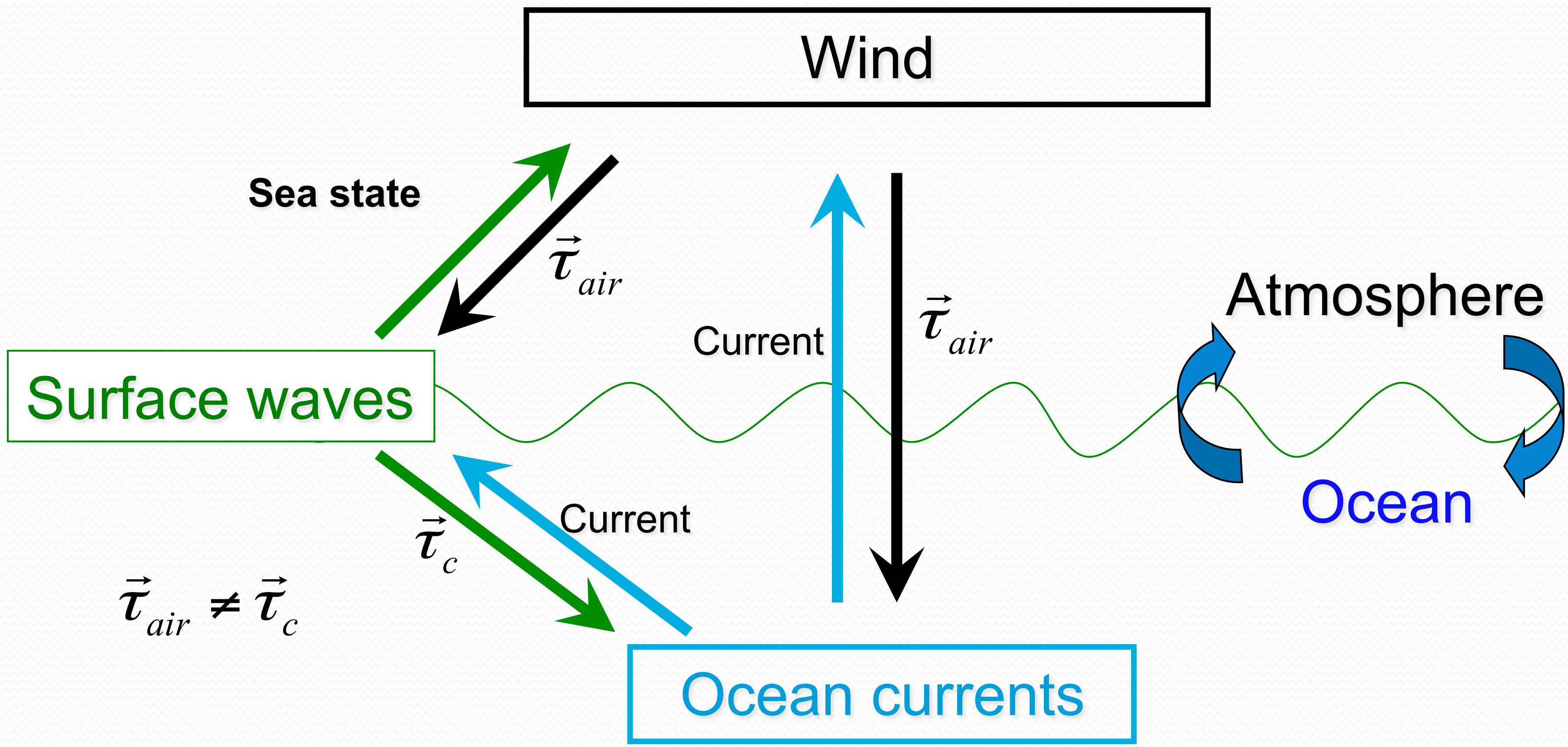


Image courtesy of Fabrice Veron

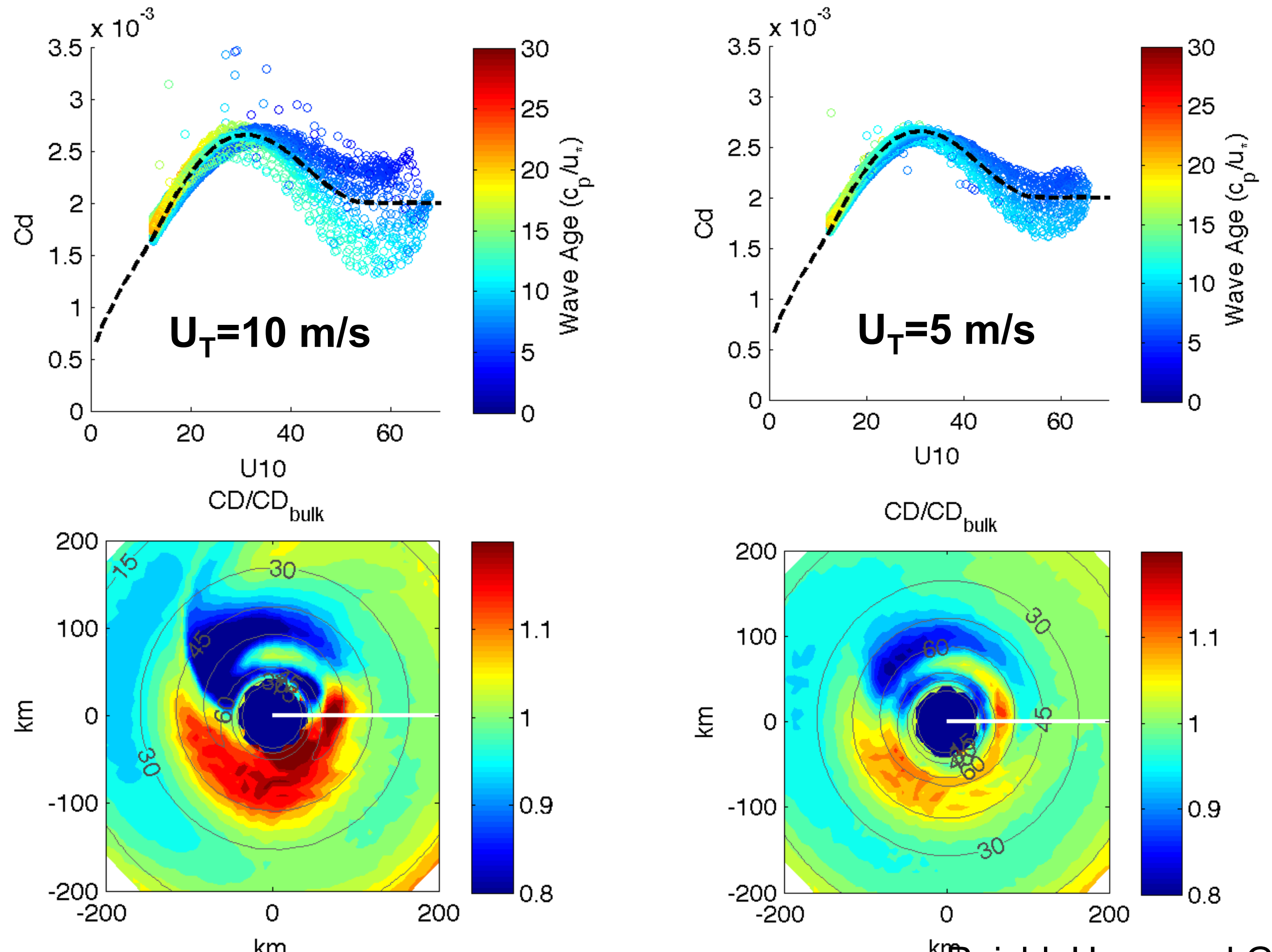
Wind-Wave-Current Interaction In Hurricanes



Fan, Y., I. Ginis, and T. Hara, 2010

Sea State Dependent Drag Coefficient in WW3-MPIPOM coupled model

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



Reichl, Hara, and Ginis, 2014

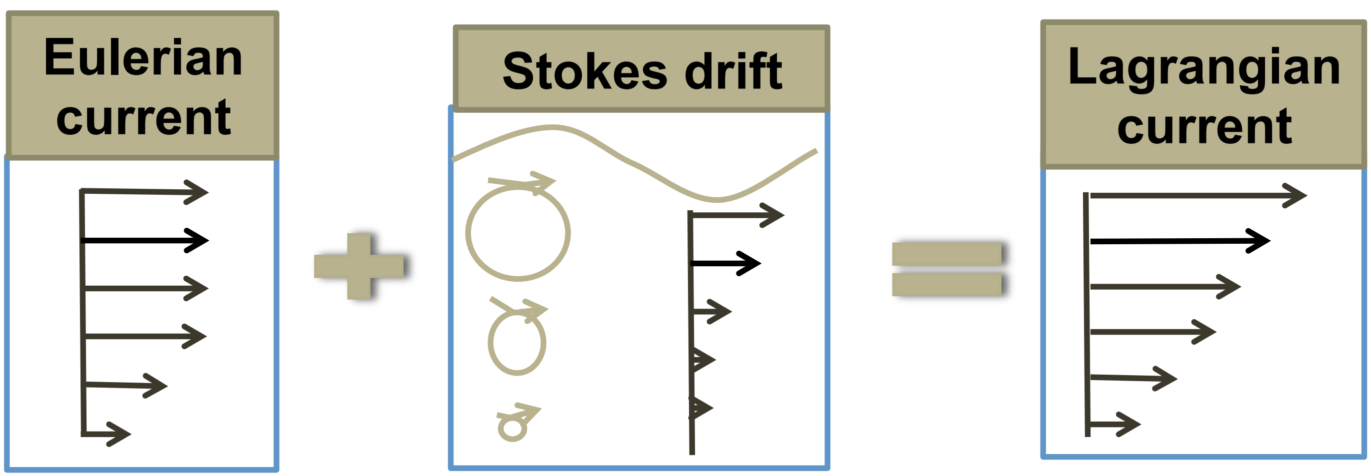
Sea State Dependent Langmuir turbulence in KPP

1. Sea state enhancement of K based on the Langmuir number

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

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

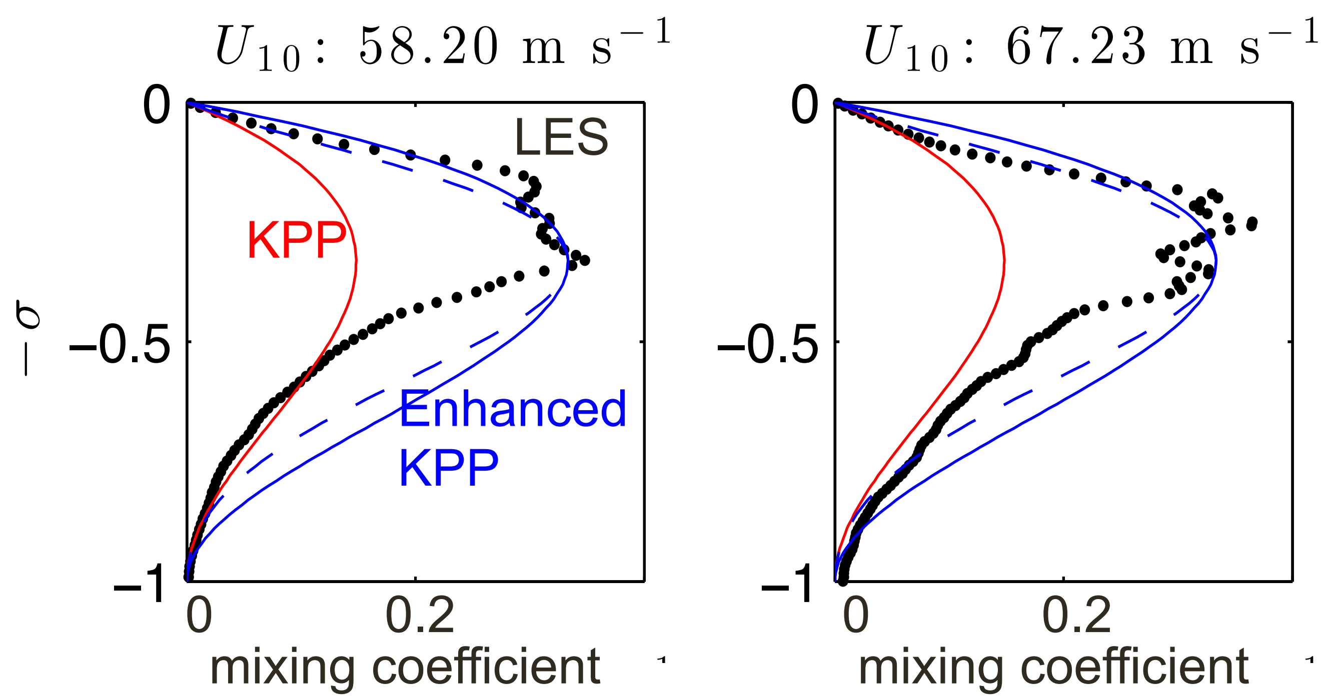
2. Use the Lagrangian current in place of the Eulerian current in KPP



Reichl et al, 2016

Sea State Dependent Langmuir turbulence in KPP

The enhancement factor needed in the KPP mixing coefficient is found by running a Large Eddy Simulation (LES) model



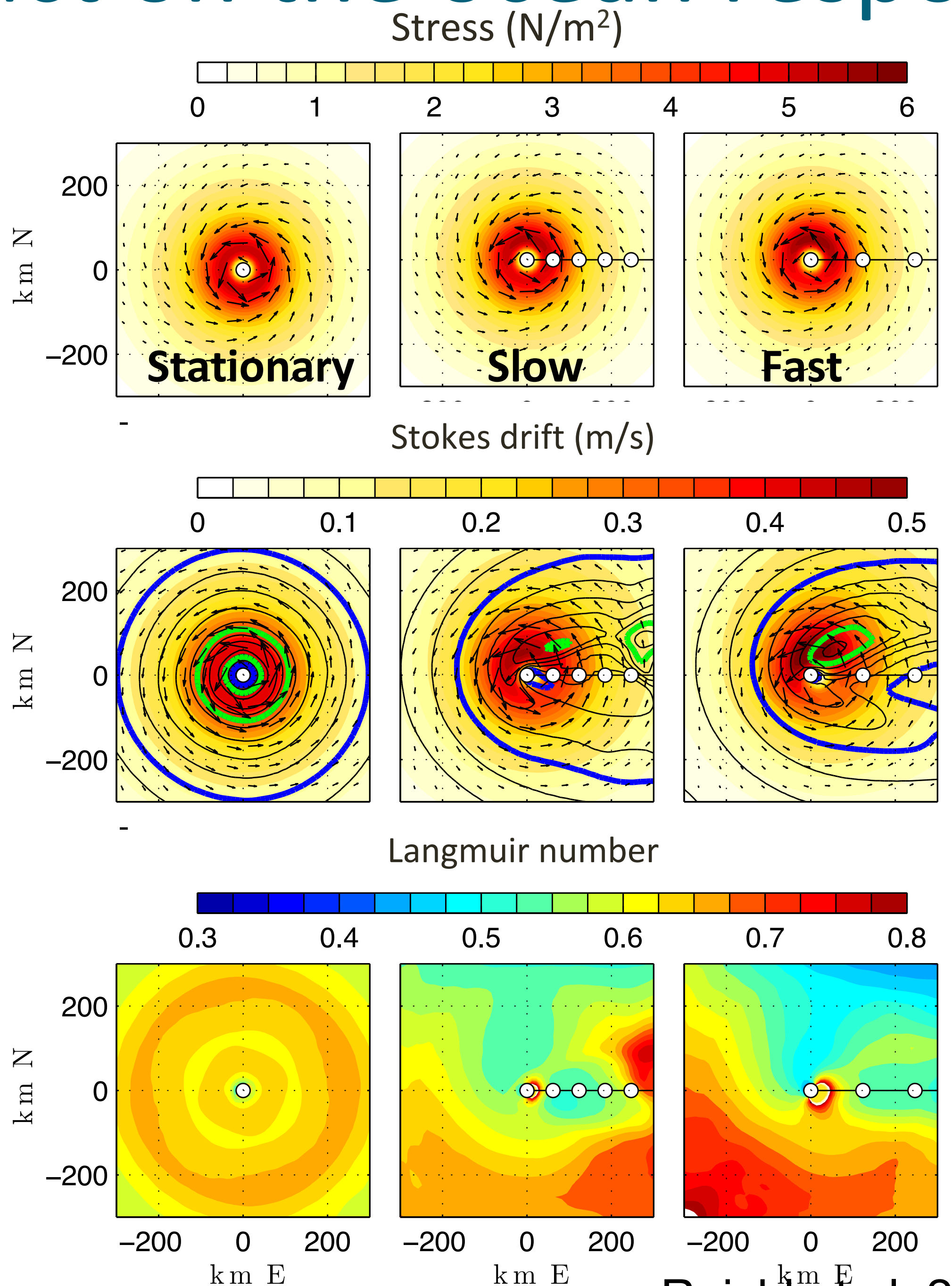
Reichl et al, 2016

Langmuir impact on the ocean response

An ideal hurricane is translated westward.

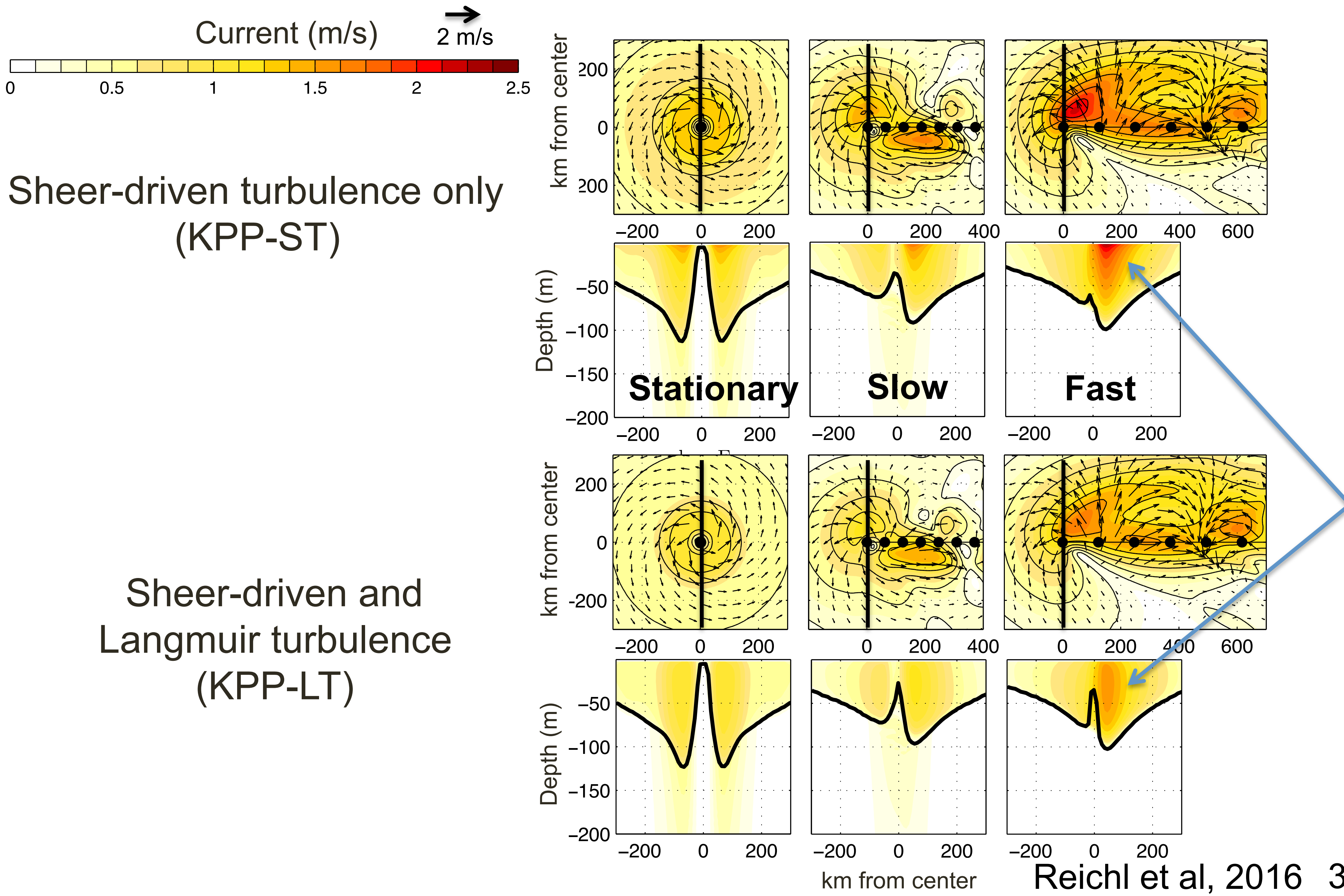
Three translation speeds:
0 (stationary),
2.7 (slow), and 5.8 (fast) m/s.

Initial temperature profile:
Mixed Layer Depth: 20m
dT/dz=-.1°C/m



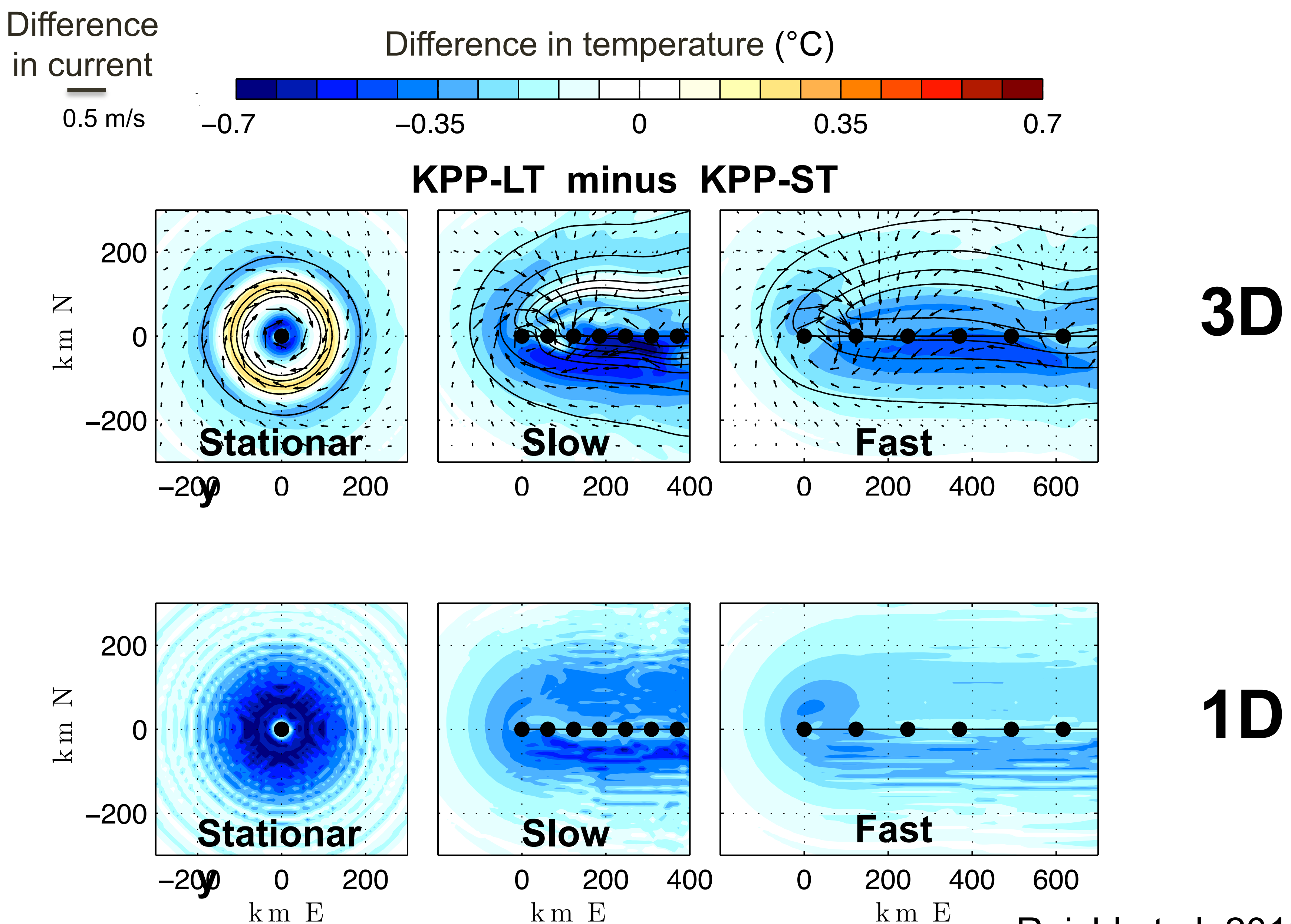
Reichl et al, 2016

Langmuir impact on the ocean response



Reichl et al, 2016

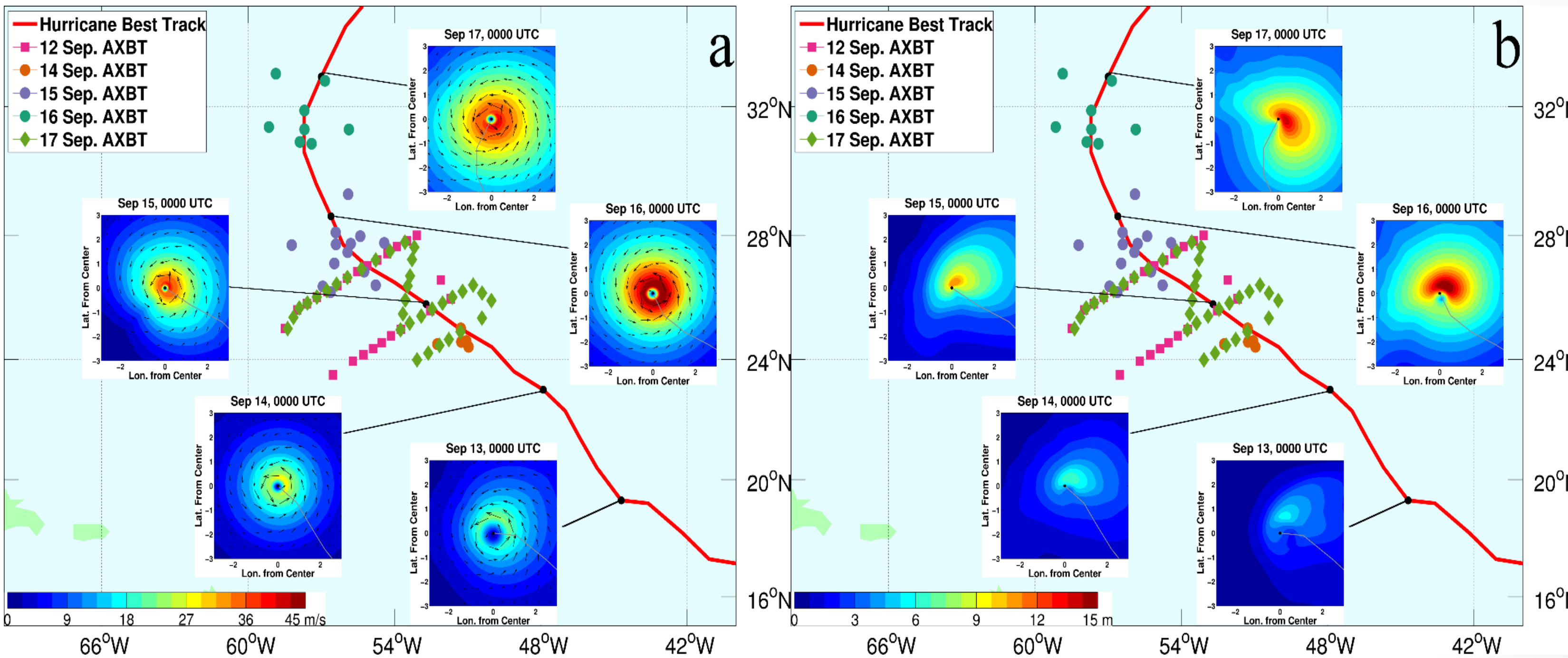
Langmuir impact on the ocean response



Reichl et al. 2016

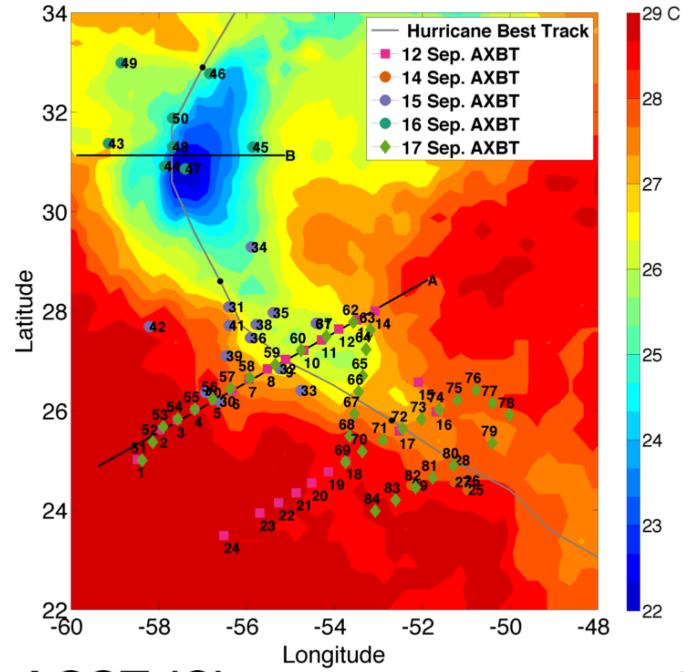
Coupled WW3-MPIPOM Modeling of Hurricane Edouard (2014)

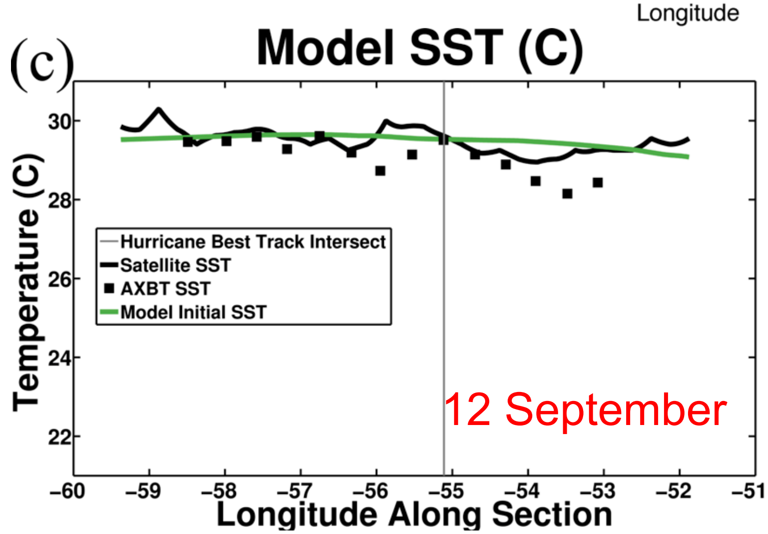
Model wind fields based on TC vitals   Modeled significant wave heights

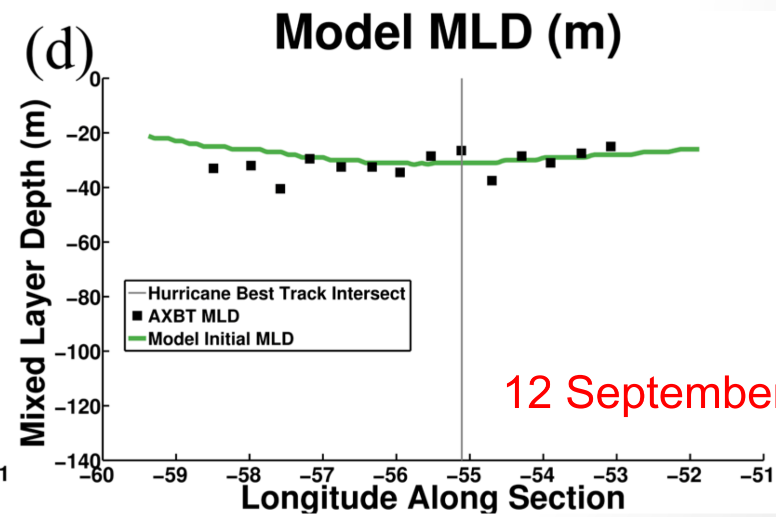


Blair et al. 2017

Coupled WW3-MPIPOM Modeling of Hurricane Edouard (2014)

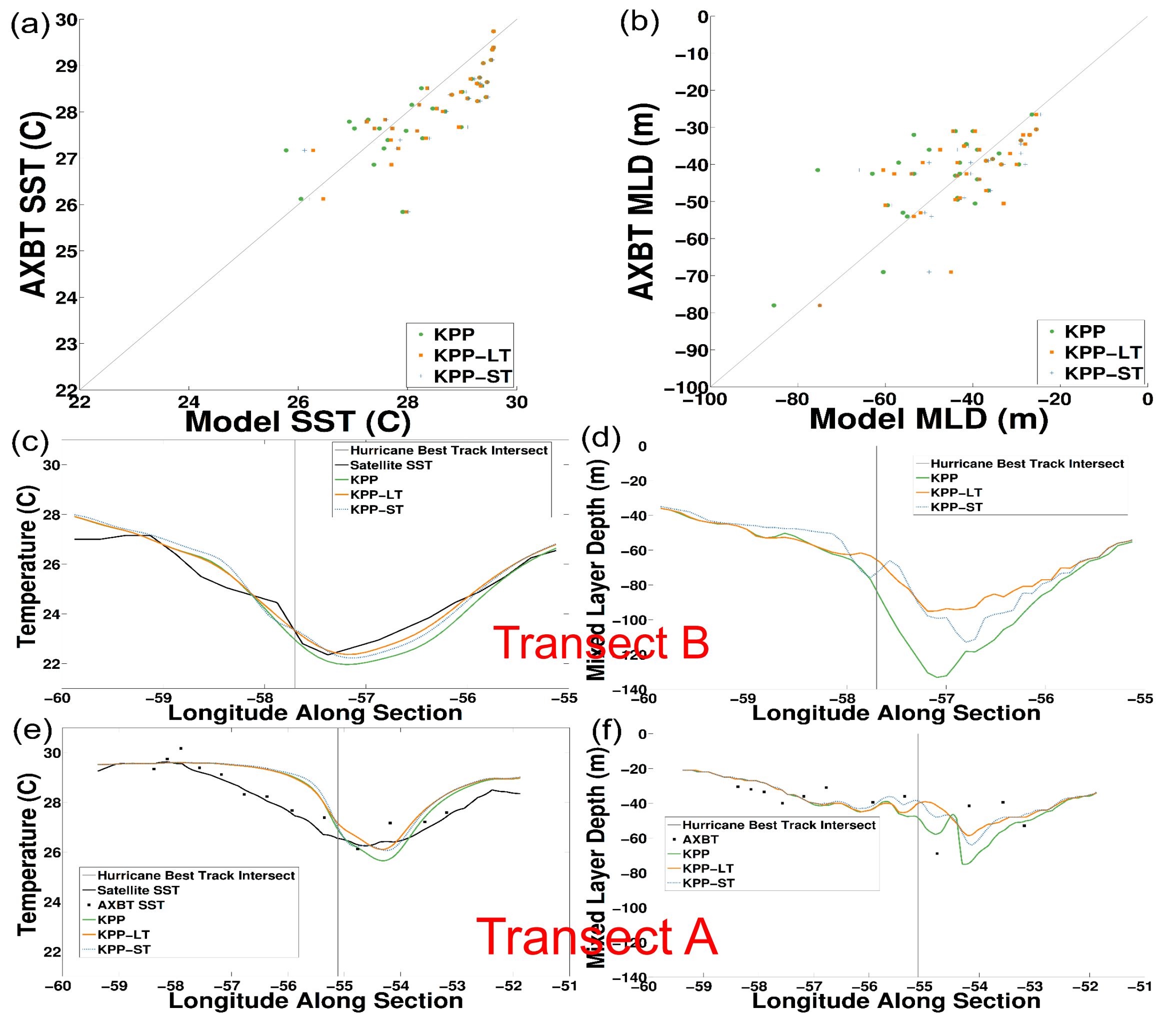






Blair et al. 2017

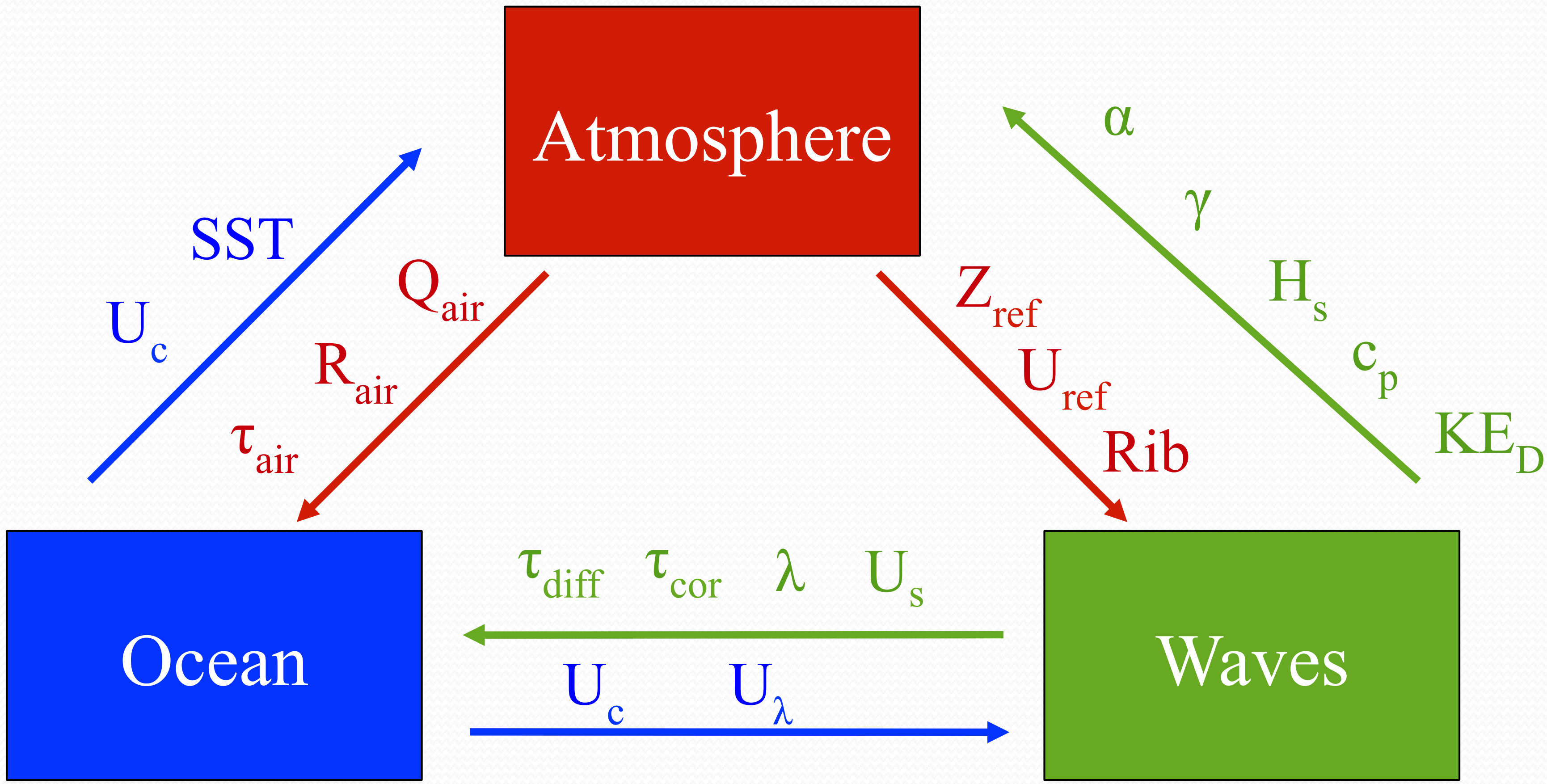
Coupled WW3-MPIPOM Modeling of Hurricane Edouard (2014)



Comparisons between model and observations of SST and mixed layer depth after the storm, on September 17th,1800 UTC.

Blair et al. 2017

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**).

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