Diagnostics for the ocean model component of coupled hurricane models

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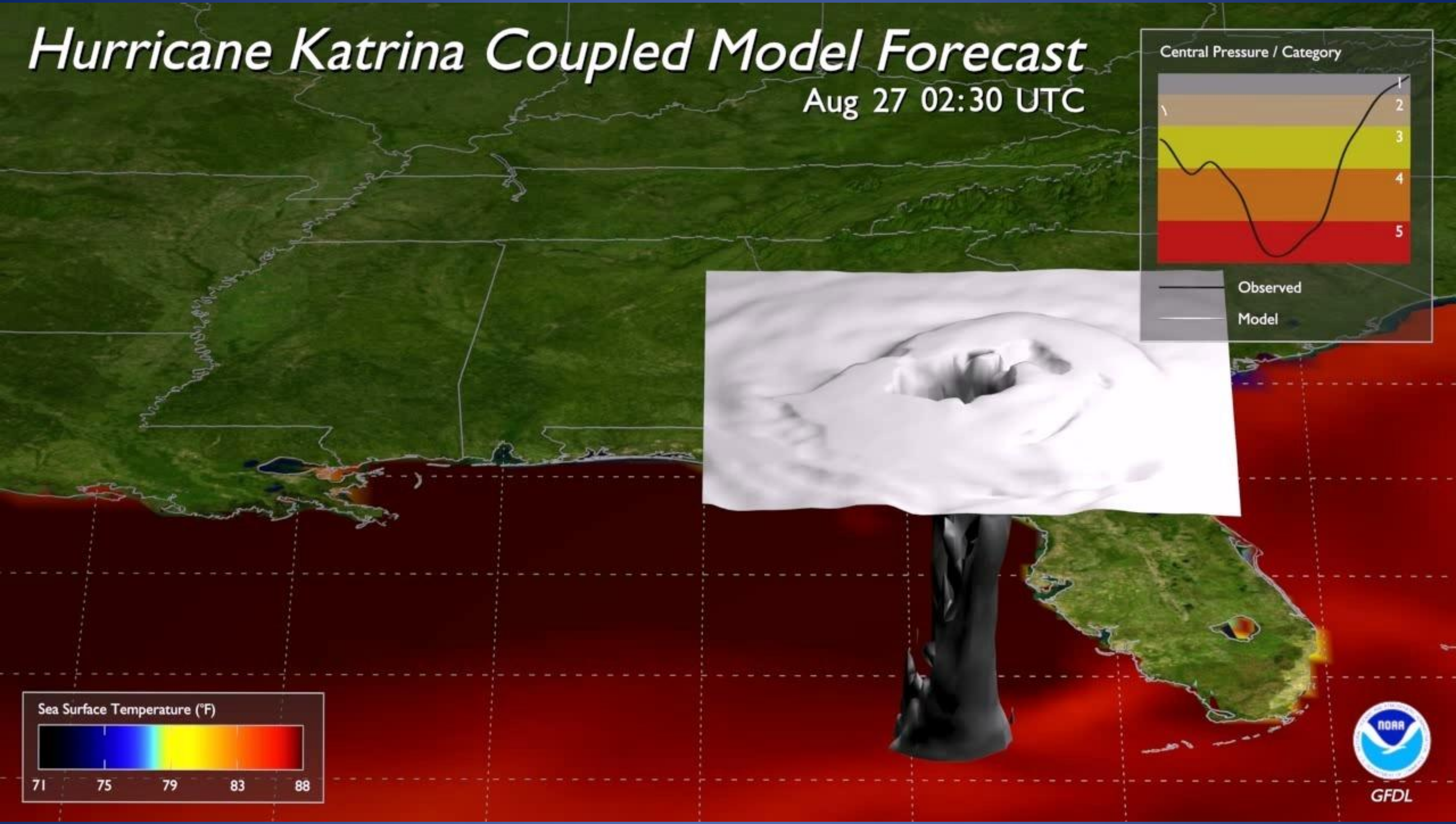
National Hurricane Center, Miami, FL
5 May 2009



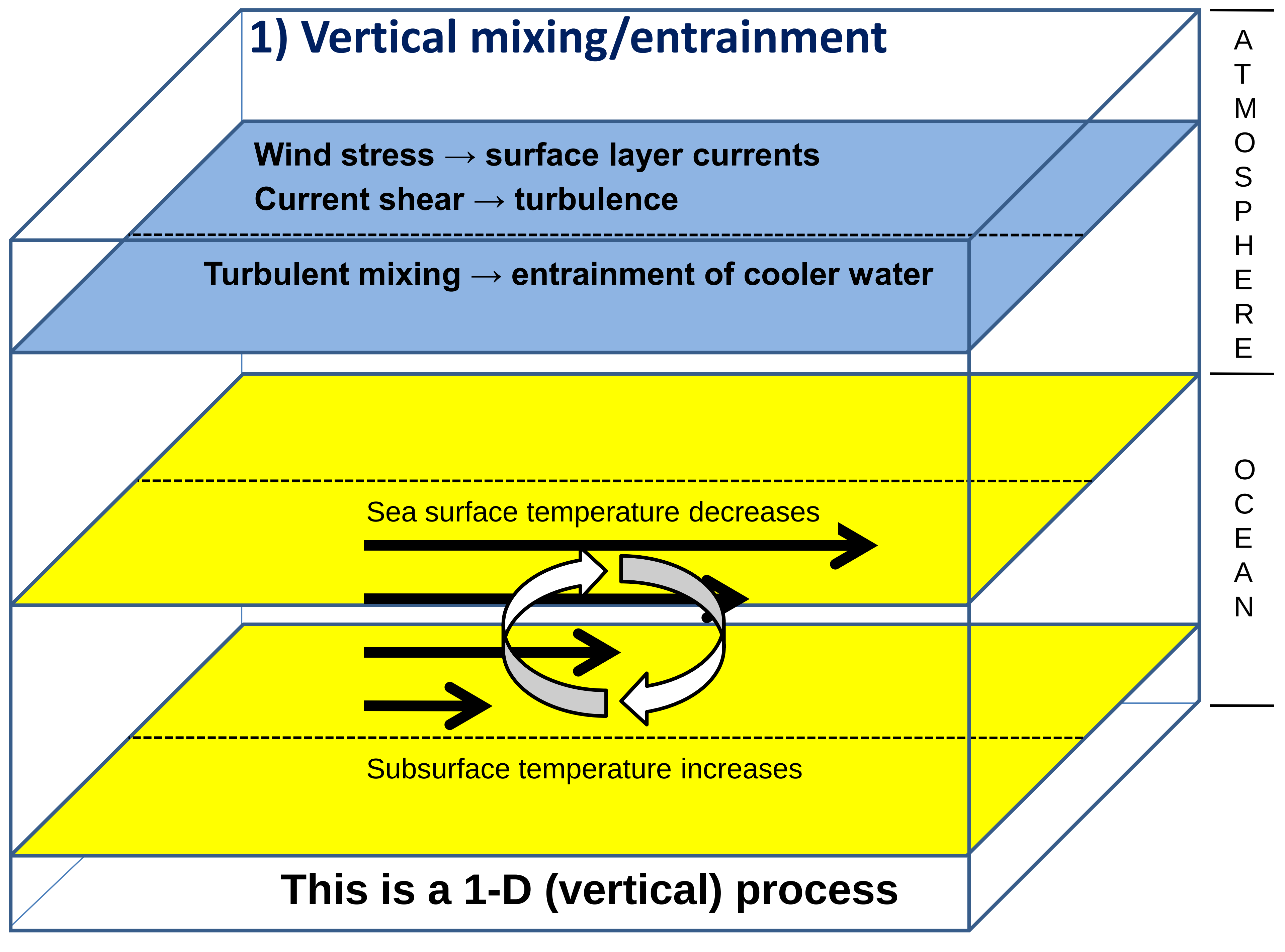
GFDL/POM Coupled Hurricane-Ocean Model (Operational)

Storm-core SST reduction

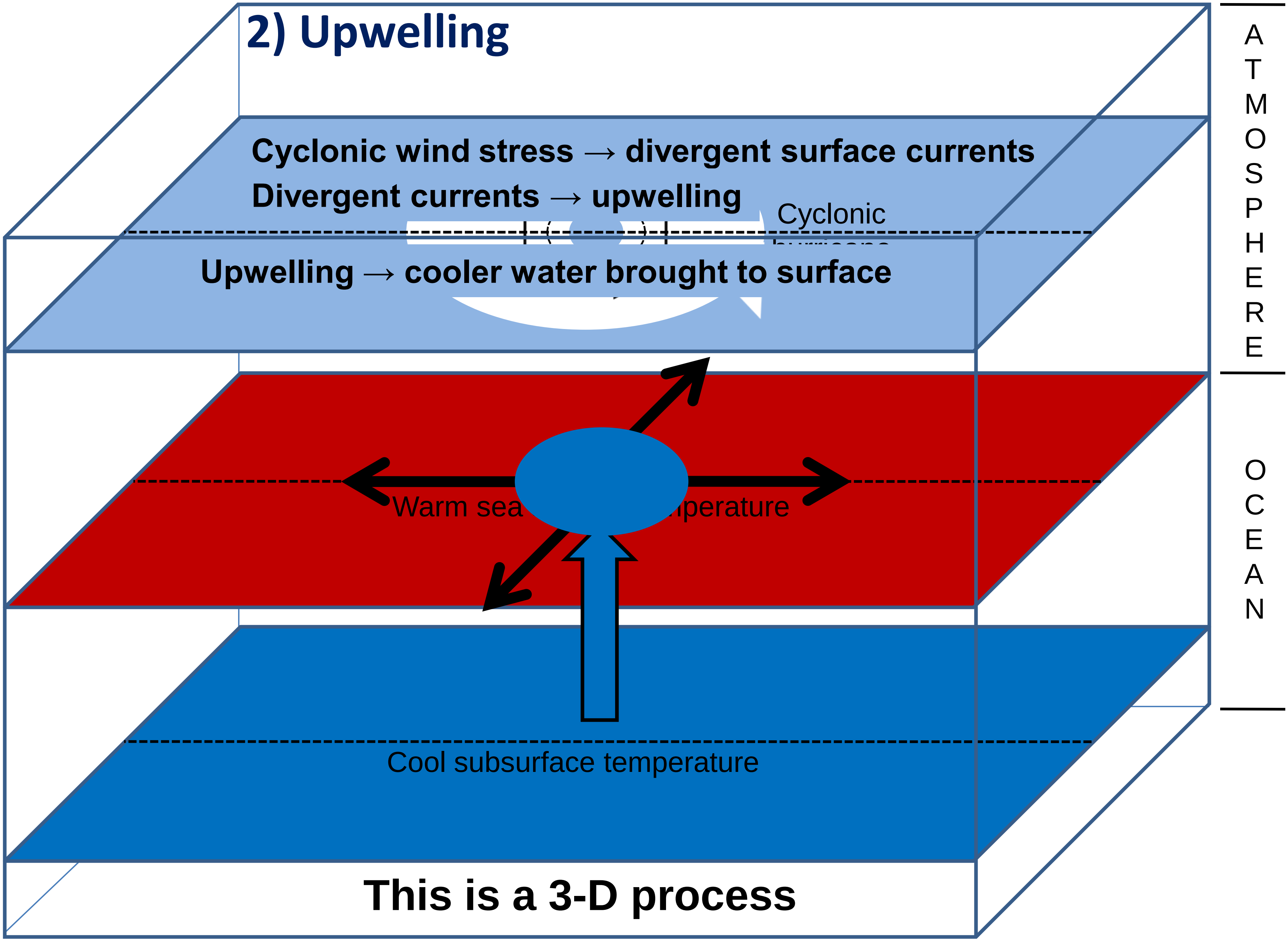
- Evaporation from sea surface provides heat energy to drive the hurricane

- Energy decreases if ***storm-core SST*** decreases

- SST can decrease in the hurricane's core by:
  1) **Vertical mixing/entrainment**
  2) **Upwelling**
  3) ~~**Horizontal advection of a surface cold pool**~~ **Later…**
  4) ~~**Heat flux to the atmosphere**~~ **Small by comparison**

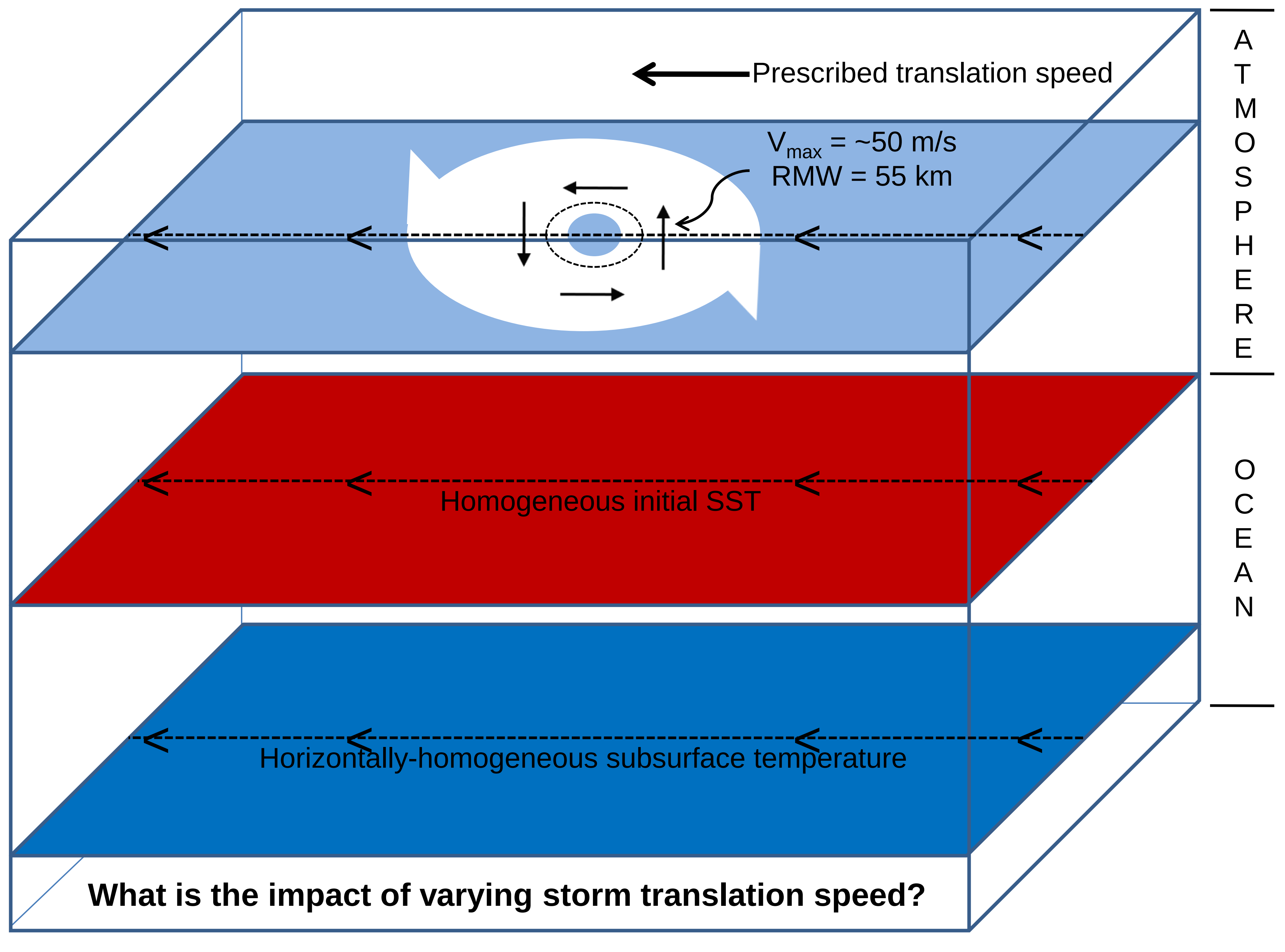


1) Vertical mixing/entrainment
Wind stress → surface layer currents
Current shear → turbulence
Turbulent mixing → entrainment of cooler water
Sea surface temperature decreases
Subsurface temperature increases
This is a 1-D (vertical) process
ATMOSPHERE
OCEAN

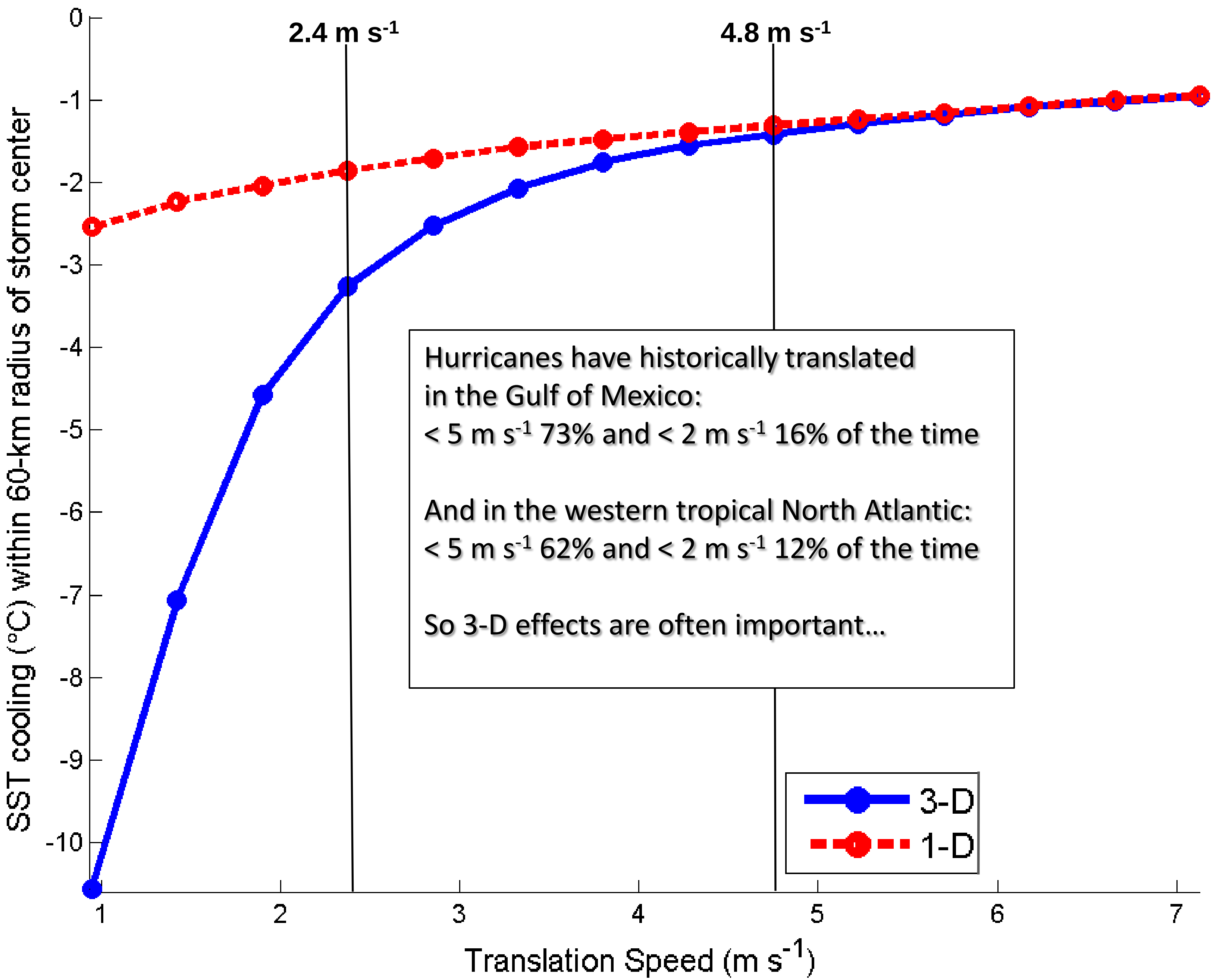

2) Upwelling
Cyclonic wind stress → divergent surface currents
Divergent currents → upwelling
Cyclonic
Upwelling → cooler water brought to surface
Warm sea
Cool subsurface temperature
This is a 3-D process
ATMOSPHERE
OCEAN

Are 1-D Ocean Models Sufficient?

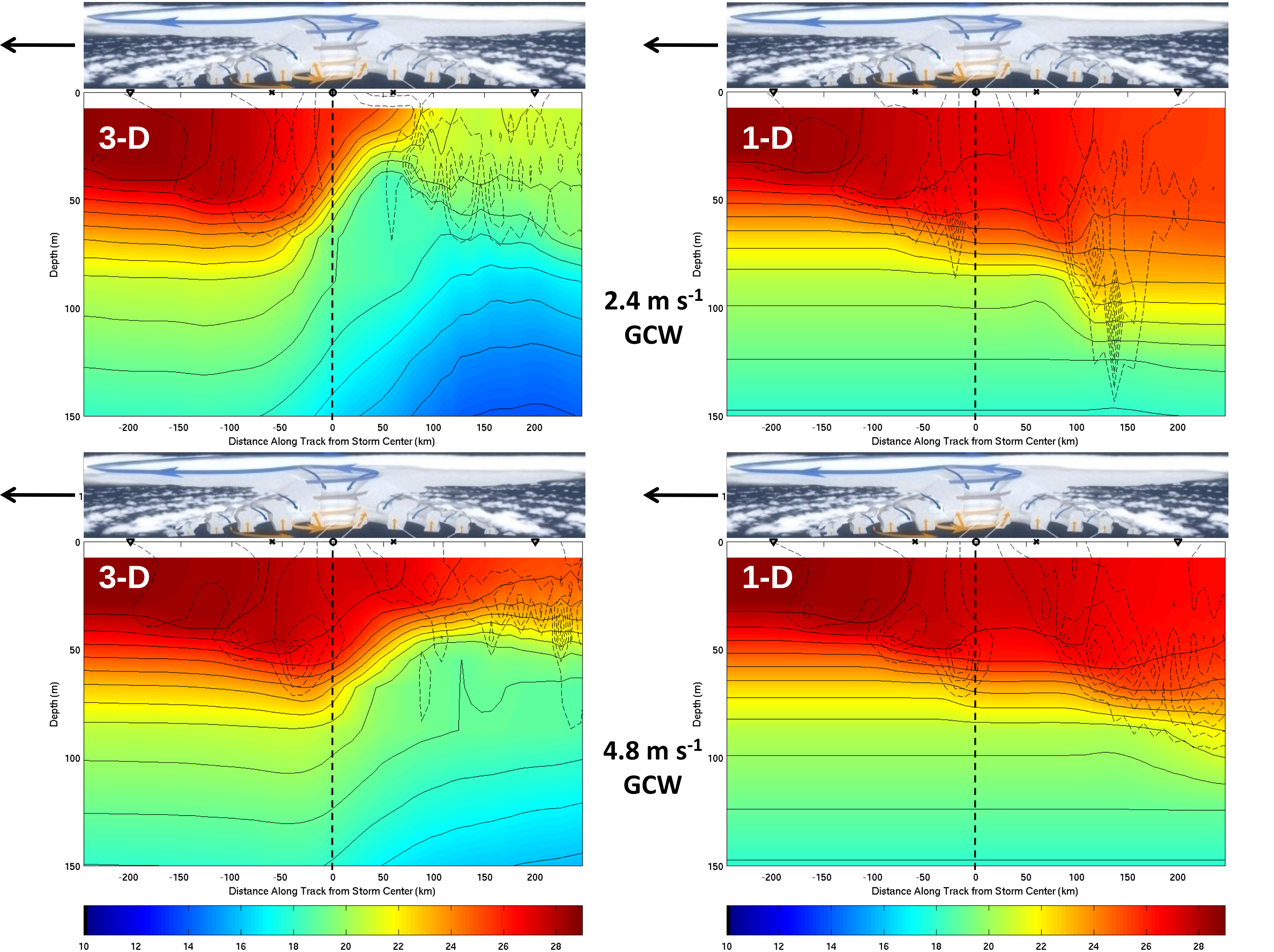
- **Vertical mixing/entrainment** is assumed to be the dominant mechanism for storm-core SST reduction
- **Upwelling** is neglected in coupled hurricane-ocean models that use a 1-D (vertical) ocean component
- **Is vertical mixing/entrainment >> upwelling?**

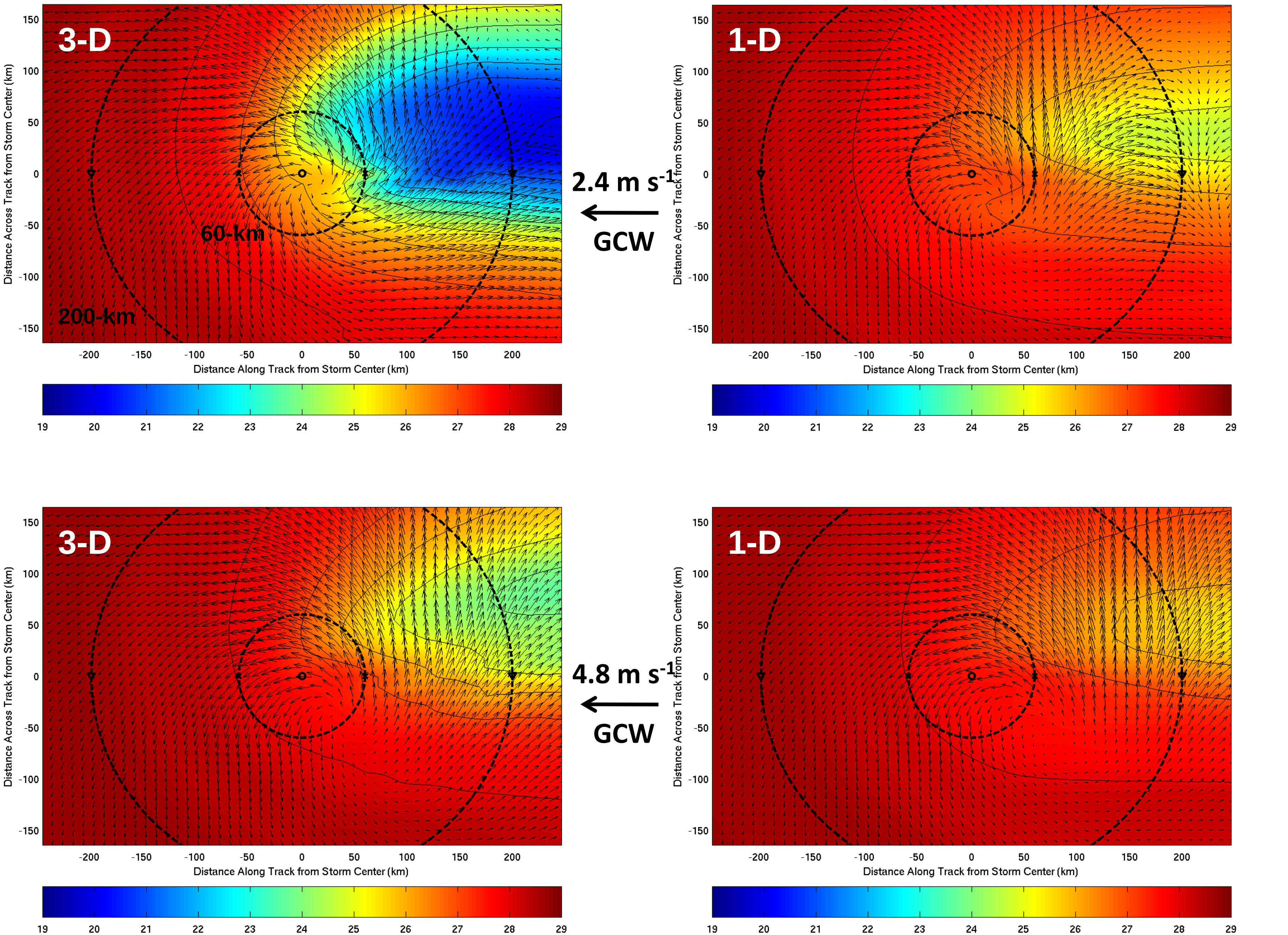


Prescribed translation speed
V_{max} = ~50 m/s
RMW = 55 km
ATMOSPHERE
Homogeneous initial SST
OCEAN
Horizontally-homogeneous subsurface temperature
What is the impact of varying storm translation speed?



2.4 m s-1
4.8 m s-1
Hurricanes have historically translated
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 are often important…
3-D
1-D
SST cooling (°C) within 60-km radius of storm center
Translation Speed (m s-1)
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
1
2
3
4
5
6
7


3-D
1-D
3-D
1-D
2.4 m s-1
GCW
4.8 m s-1
GCW
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


3-D
1-D
3-D
1-D
60-km
200-km
2.4 m s-1
GCW
4.8 m s-1
GCW
Distance Along Track from Storm Center (km)
Distance Across Track from Storm Center (km)

Validating Storm-Core SST During Coupled Model Forecast

- Accurate wind field, including size, shape, & magnitude are required for producing an accurate ocean response, which feeds back to the hurricane via the *storm-core SST*

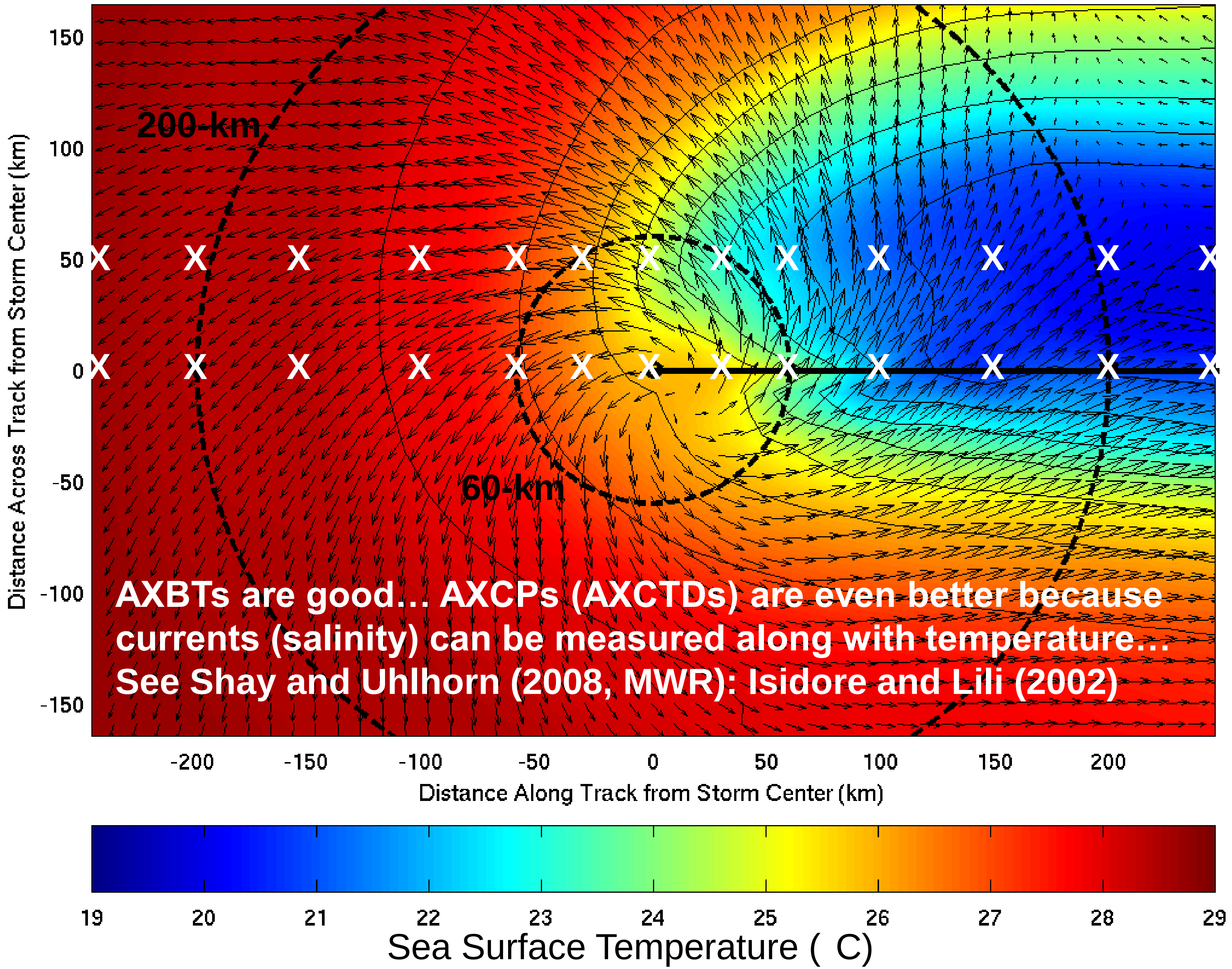
- *Thus the wind field must be validated as part of the ocean model validation*

- What is the "storm core" radius over which heat flux to the atmosphere is significant for intensity change?
  - Storm-dependent (e.g. Eyewall; Rmax; 2*Rmax; 34-kt radius)?
  - Fixed value (60-km; 90-km; 100-km; 150-km; 200-km; 250-km)?
  - All of these values (& others) appear in the literature and/or are used as diagnostics for coupled models… open question?

Validating Ocean Response

- Location/magnitude of hurricane-induced currents
  - Strongest surface currents to the right of storm track
  - Inertial oscillation in current field
- Location & magnitude of hurricane cold wake
  - Displaced to the right of the storm track where surface current shear & vertical mixing are maximized
  - Increased symmetric component of cooling for slow-moving storms due to high impact of upwelling
- Also validate salinity & biochemical parameters?

Where do we want measurements?

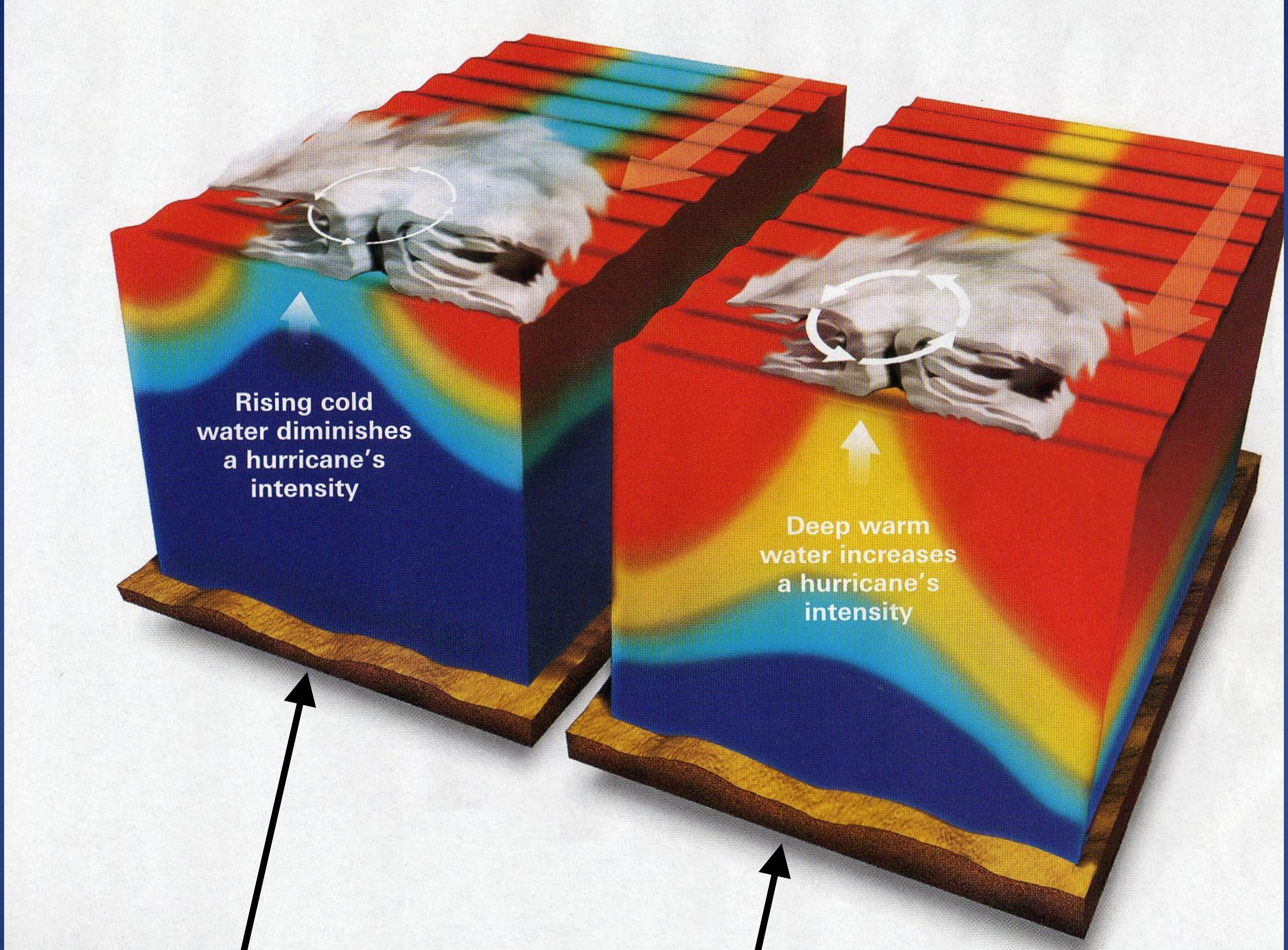


Requirements for model validation

- Future track of hurricane core is key region for validation of initial conditions
- In regions with weak horizontal variability (e.g. the Sargasso Sea), a few *in situ* measurements (e.g. floats and drifters) with low spatial resolution are sufficient to validate initial field
- In regions of strong mesoscale variability (e.g. Gulf of Mexico), targeted high spatial resolution measurements are required…

Validating Ocean Initial Condition

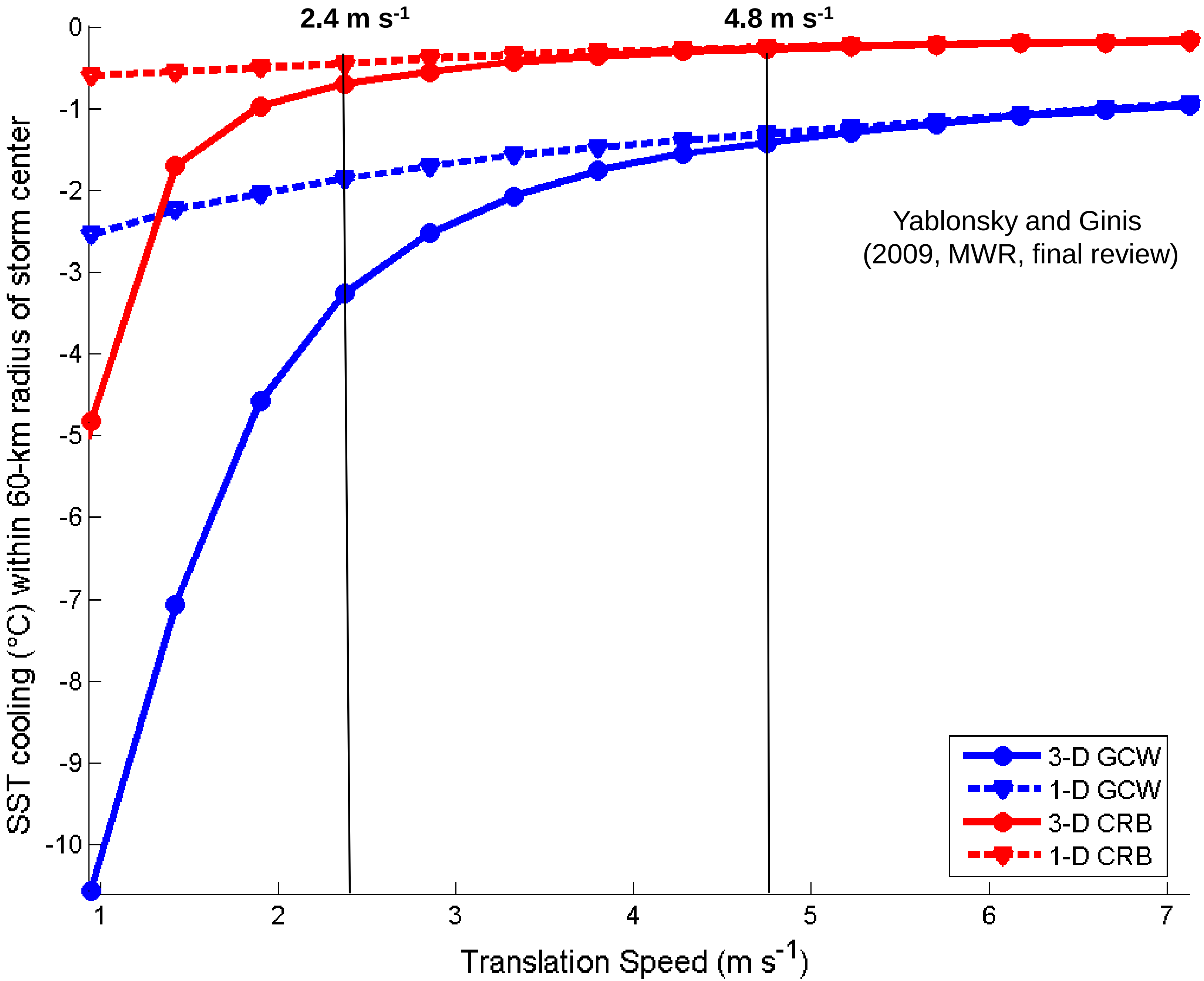
- Validate the temperature (T), salinity (S), and current (U,V) fields at the beginning of the coupled hurricane model forecast
- For the subsequent impact on hurricane intensity, the key parameters to validate are:
  - Sea surface temperature (SST)
  - Depth of the upper oceanic mixed layer (OML)
  - Vertical temperature (& salinity?) gradient (i.e. slope) in the upper thermocline directly below the OML



Typical of Gulf of Mexico Common Waters in September

Typical of Caribbean Waters in September

… but temperature is just one component of the density field … salinity may also be important


2.4 m s-1
4.8 m s-1
Yablonsky and Ginis
(2009, MWR, final review)
3-D GCW
1-D GCW
3-D CRB
1-D CRB
SST cooling (°C) within 60-km radius of storm center
Translation Speed (m s-1)
0
-1
-2
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-7
-8
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-10
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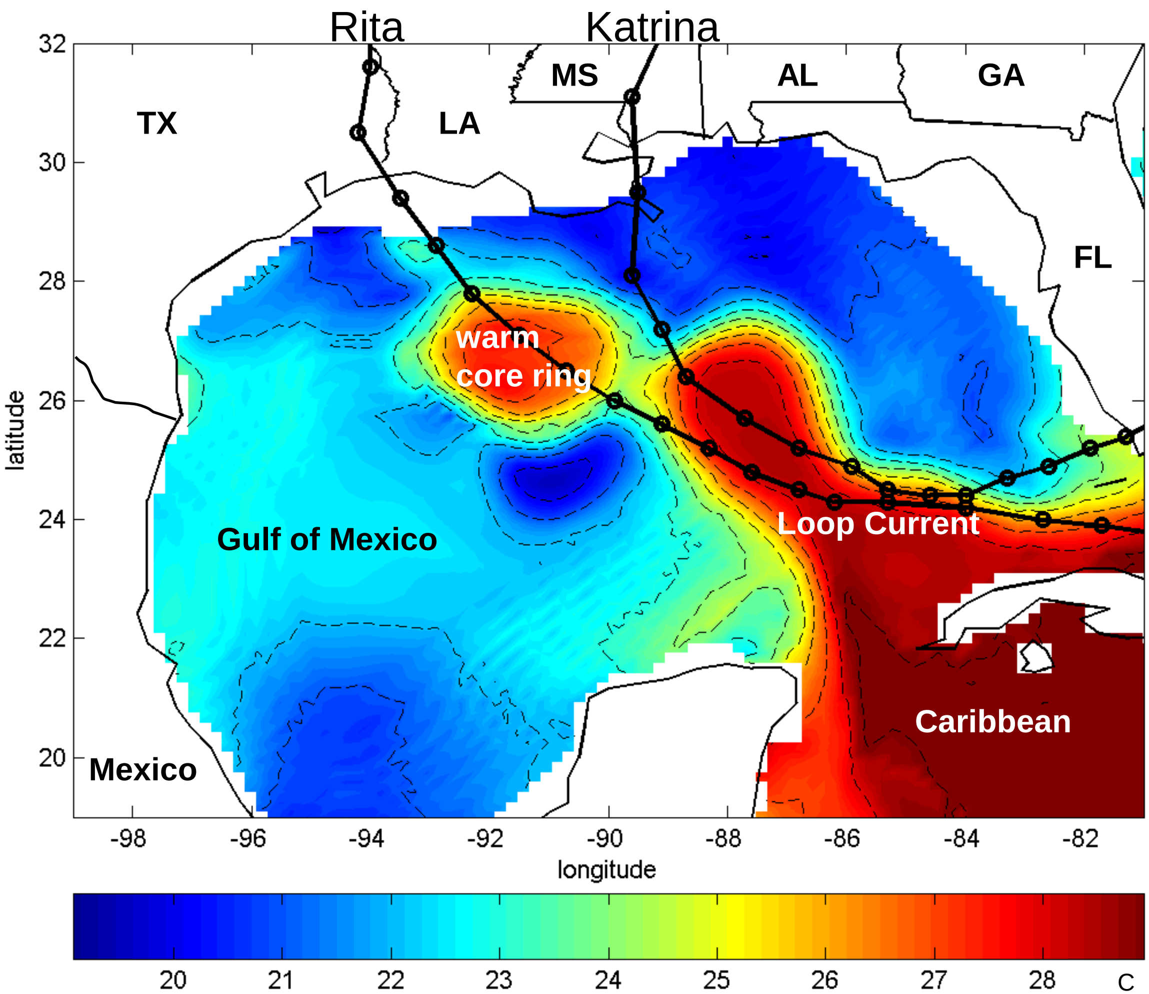
6
7

Mesoscale Oceanic Features in the GoM



Subsurface (75-m) ocean temperature during Katrina & Rita

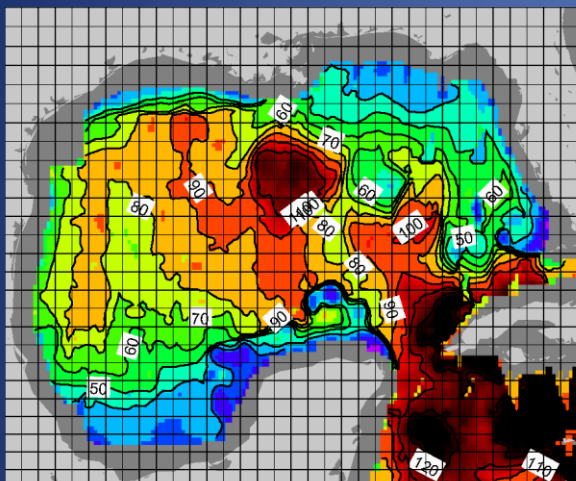
Warm Loop Current water and a warm core ring extend far into the Gulf of Mexico from the Caribbean…

Representing Mesoscale Features

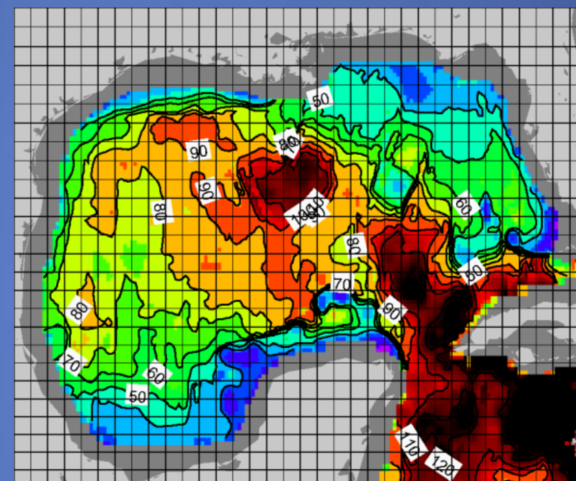
- In Atlantic Basin, main mesoscale oceanic features are the Gulf Stream (SE US coast) and the Loop Current and associated warm- and cold-core rings (Gulf of Mexico)
- During hurricane season, the Gulf Stream position can generally be observed from SST data, but…
- Loop Current and rings are typically indiscernible from SST
- For the Gulf of Mexico, sea surface height based on satellite altimetry is key for determining and validating the shape and location of the Loop Current and rings

Validating Mesoscale Features in Ocean Model in GoM

- More available satellites… more accurate validation?

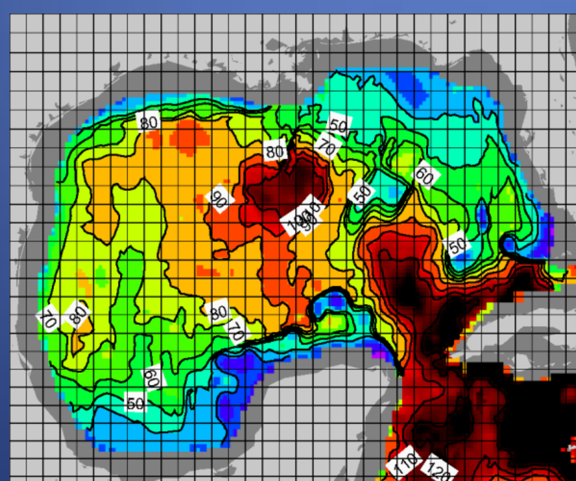


1



2

3



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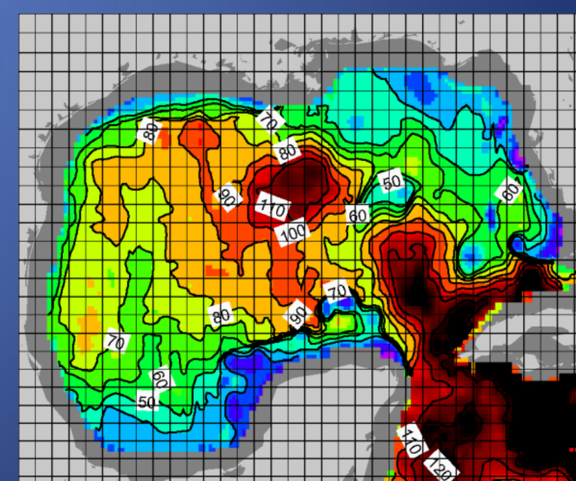
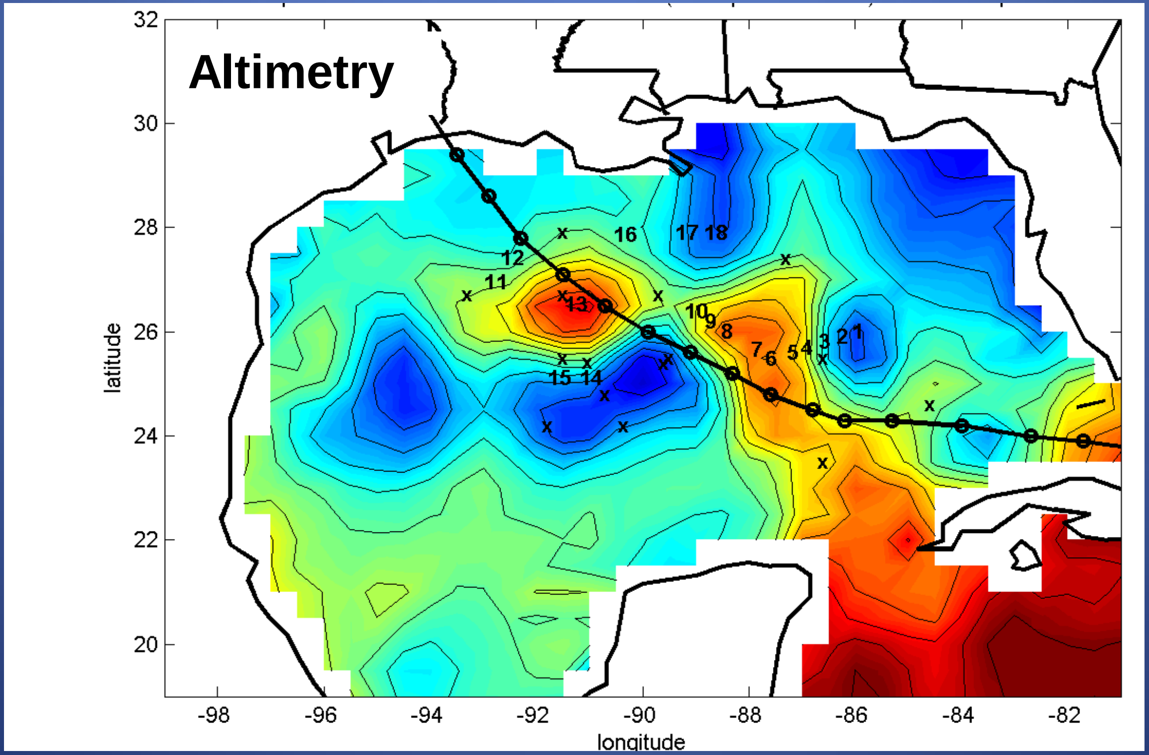


Courtesy of
G. Goni

Validating Mesoscale Features in Ocean Model in GoM

- Targeted in situ data deployment (e.g. AXBTs) may be used to supplement altimetry and to validate the model-initialized subsurface (upper thermocline) horizontal temperature gradient across the Loop Current and rings

Numbers 1-18 indicate AXBT locations

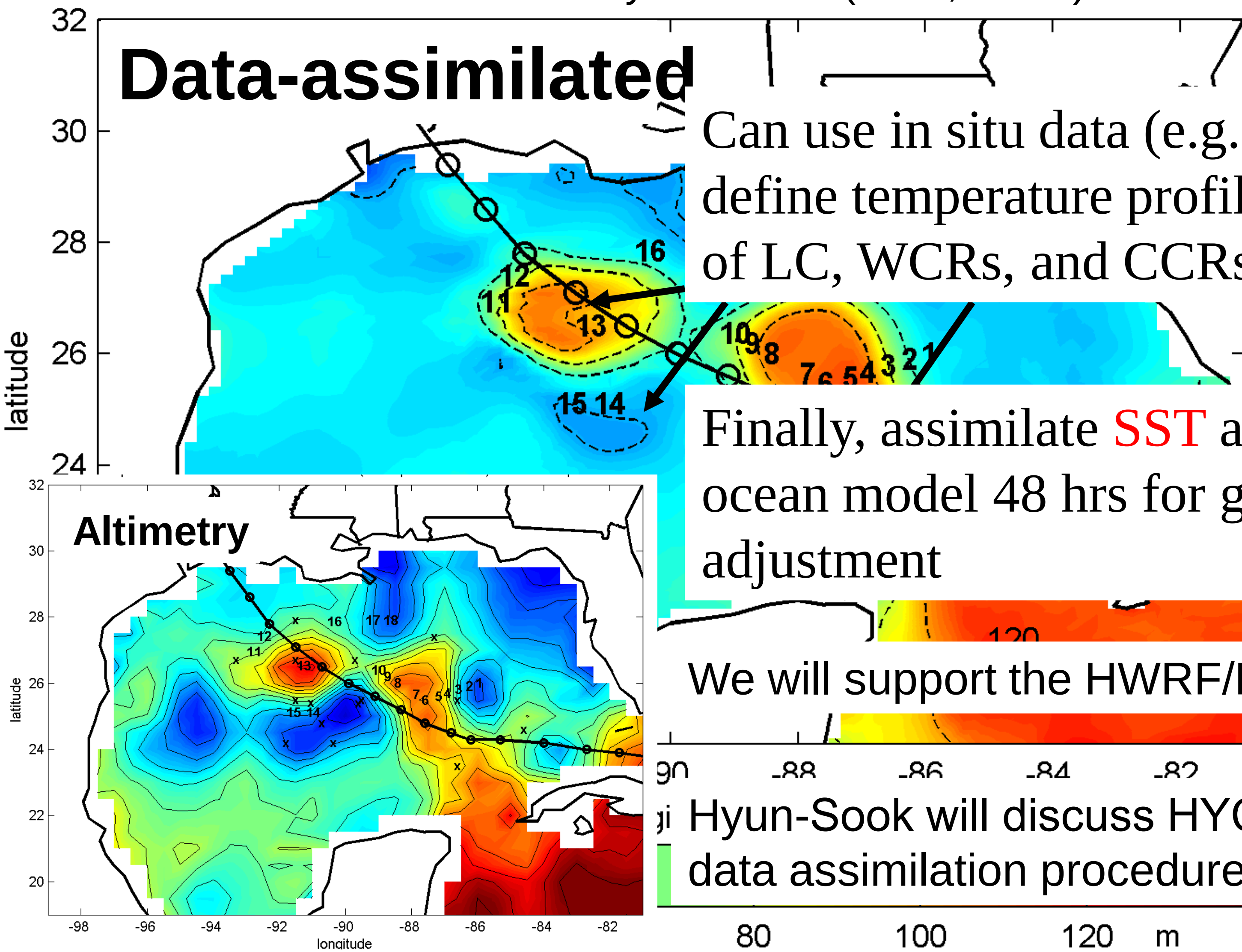


15 Sept. 2005

Rita's future track

Feature-based assimilation in GFDL/POM & HWRF/POM initialization

Yablonsky and Ginis (2008, MWR)



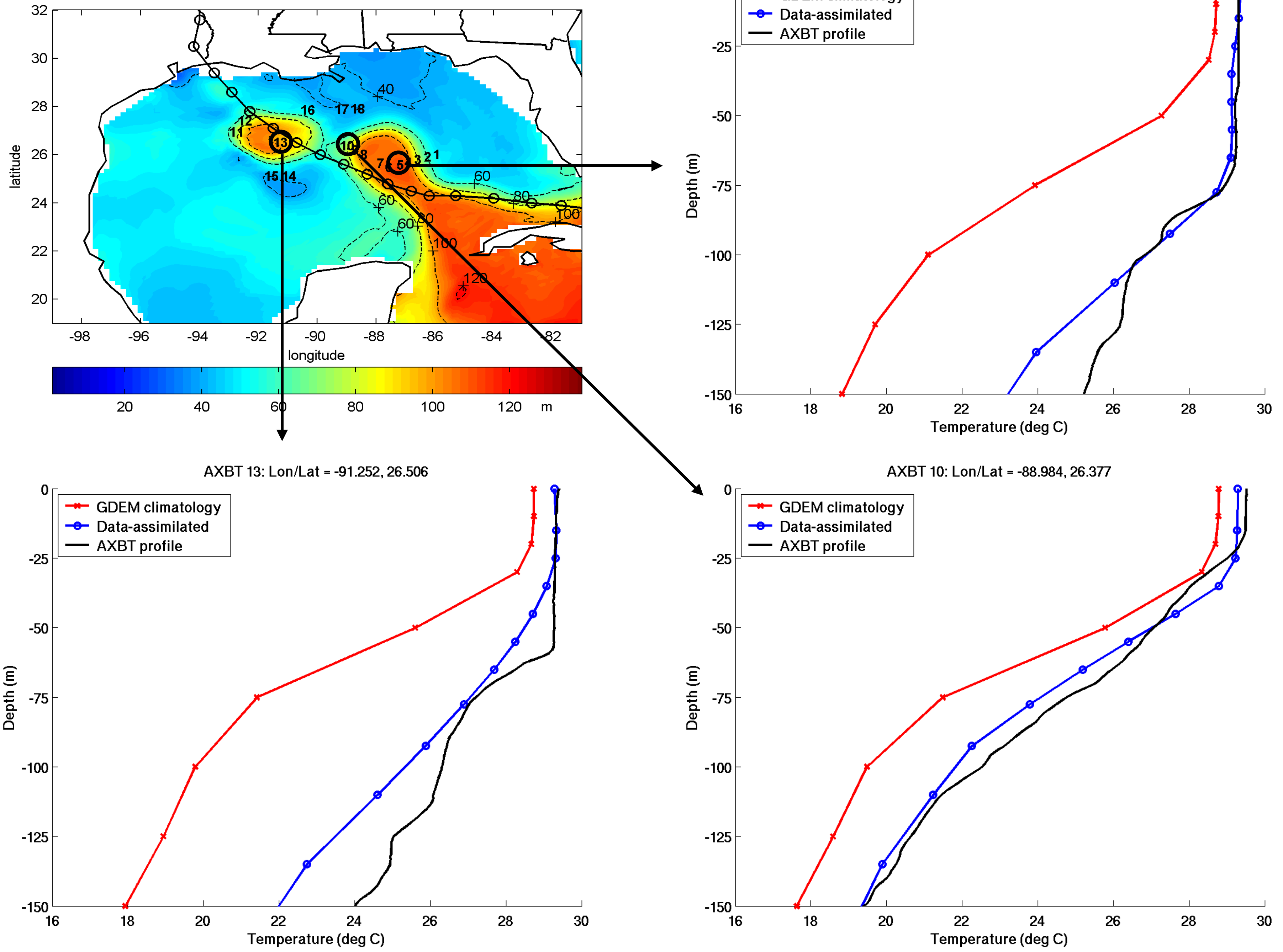
Can use in situ data (e.g. AXBTs) to define temperature profiles in center of LC, WCRs, and CCRs

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

We will support the HWRF/POM at the DTC

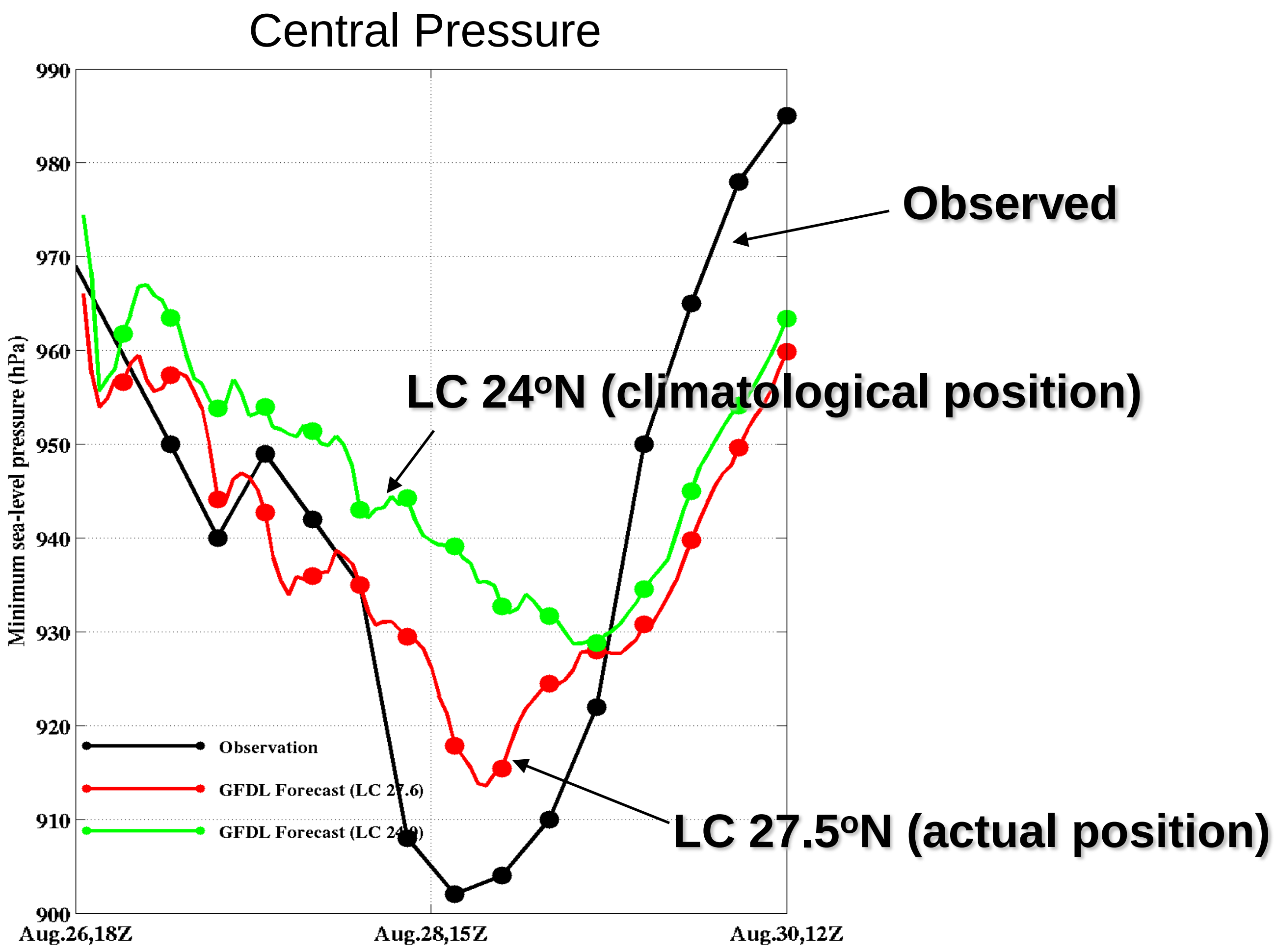
Hyun-Sook will discuss HYCOM's continuous data assimilation procedure, which is different

Yablonsky and Ginis (2008, MWR)

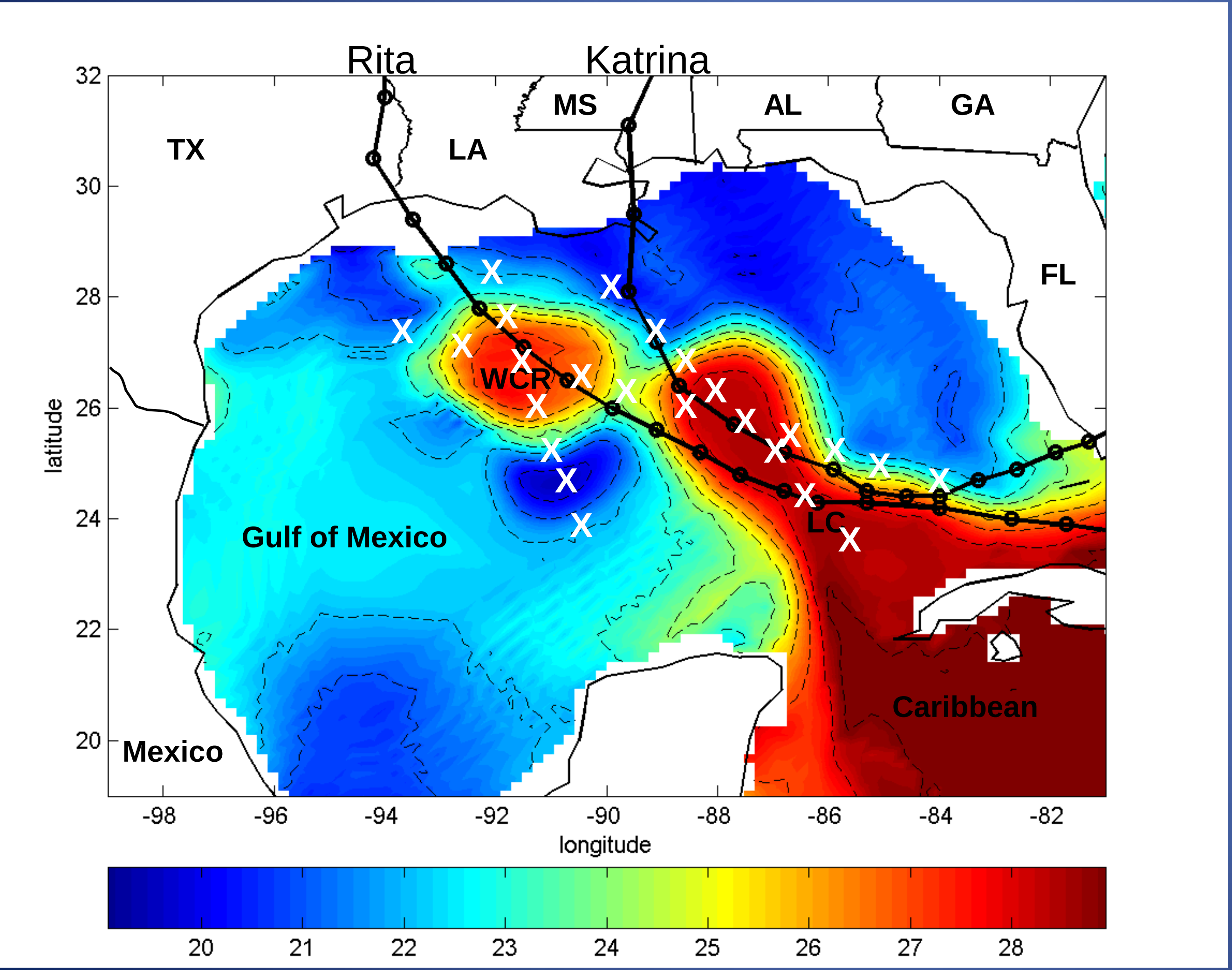


Impact of improved initialization of the Loop Current (LC) on a GFDL model intensity forecast

Hurricane Katrina
Forecast:
Initial time:
Aug. 26, 18Z



Where do we want measurements?



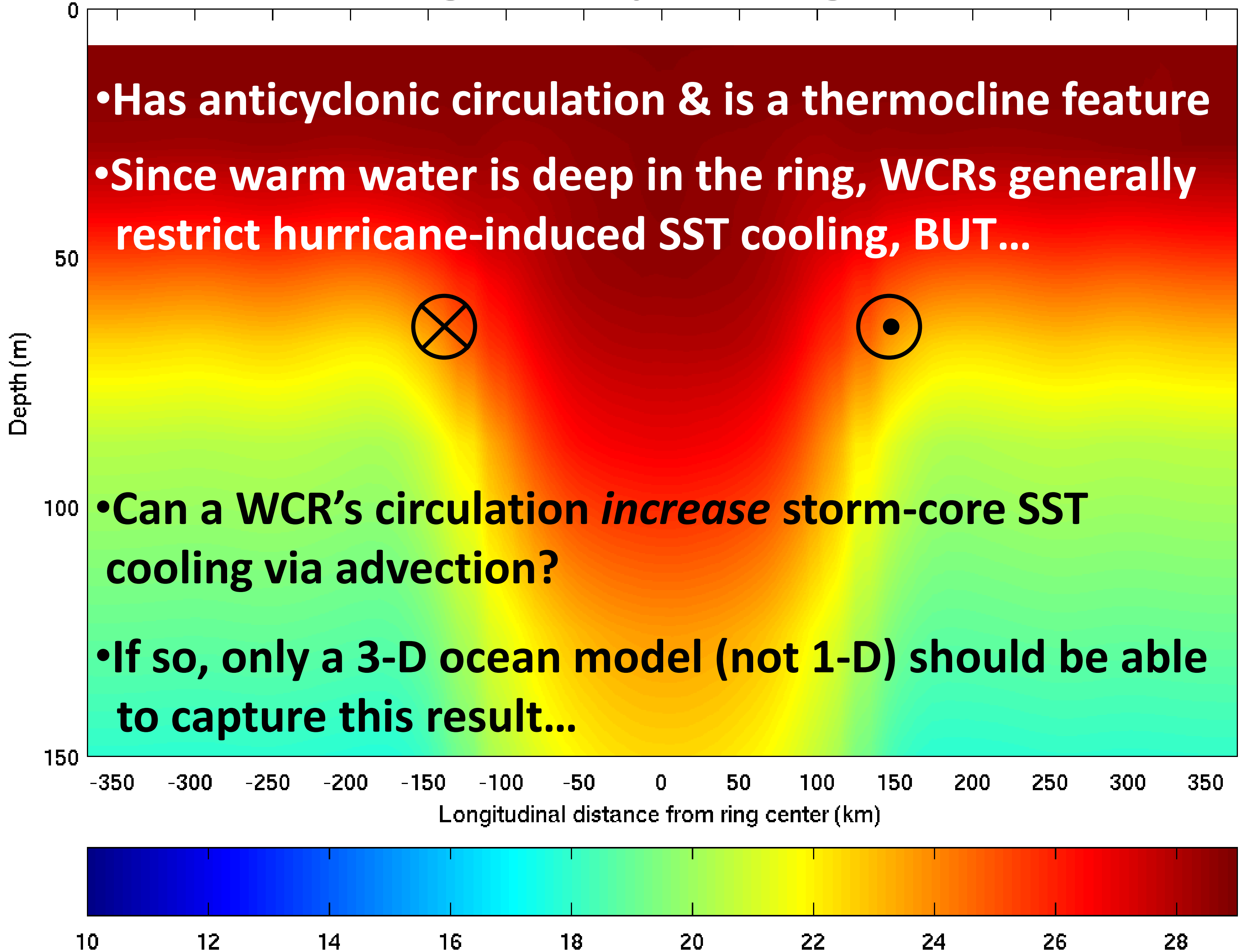
Subsurface (75-m) ocean temperature

AXBTs dropped along these 3 flight legs would help validate LC, WCR, and CCR structure, frontal location, and magnitude *prior to* storm passage

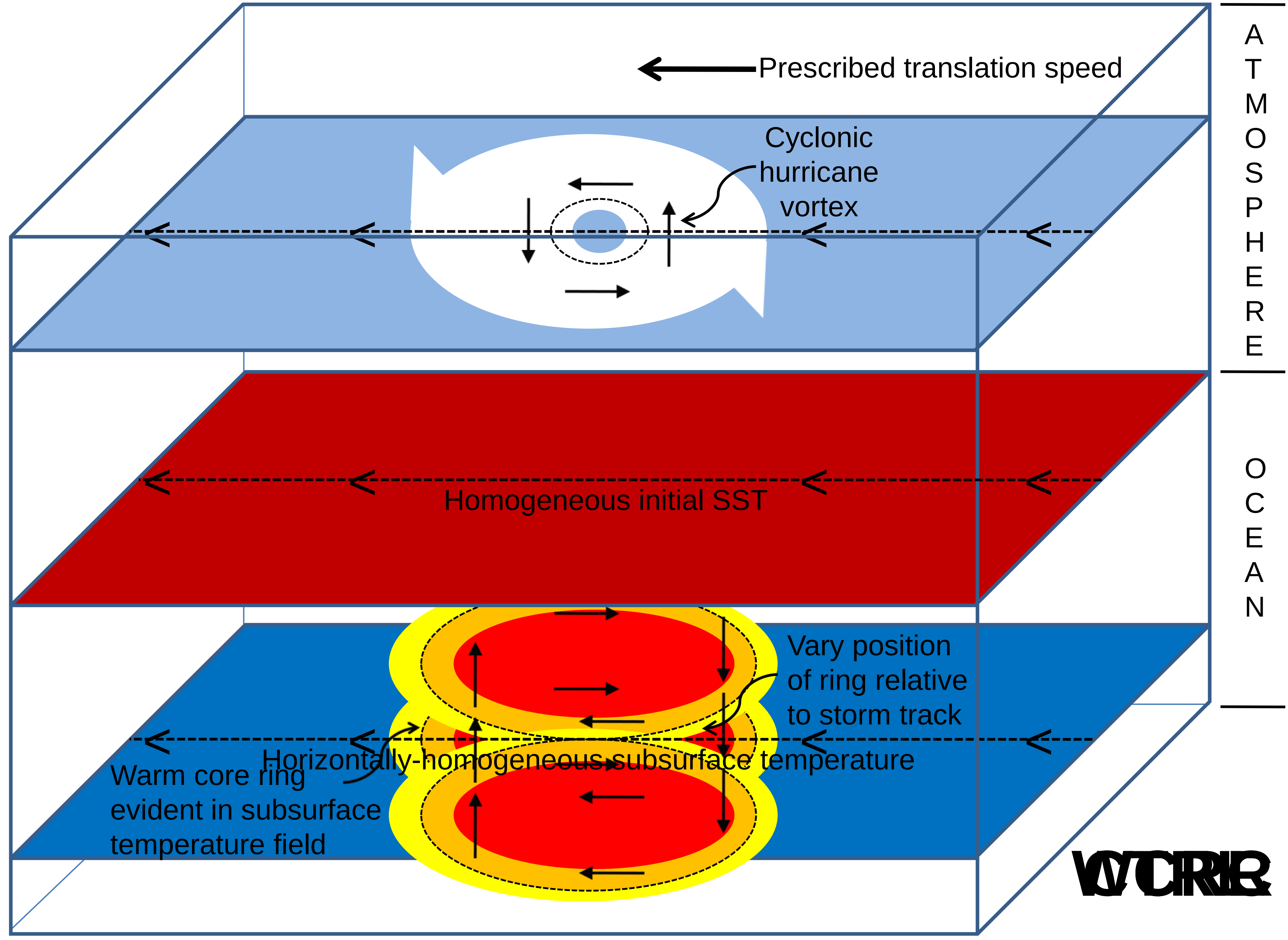
Storm-core SST reduction (revisited)

- SST can decrease in the hurricane's core by:
  1) ~~**Vertical mixing/entrainment**~~ **Earlier…**
  2) ~~**Upwelling**~~ **Earlier…**
  3) **Horizontal advection of a surface cold pool**
  4) ~~**Heat flux to the atmosphere**~~ **Small by comparison**

Warm Core Ring: Not just high heat content

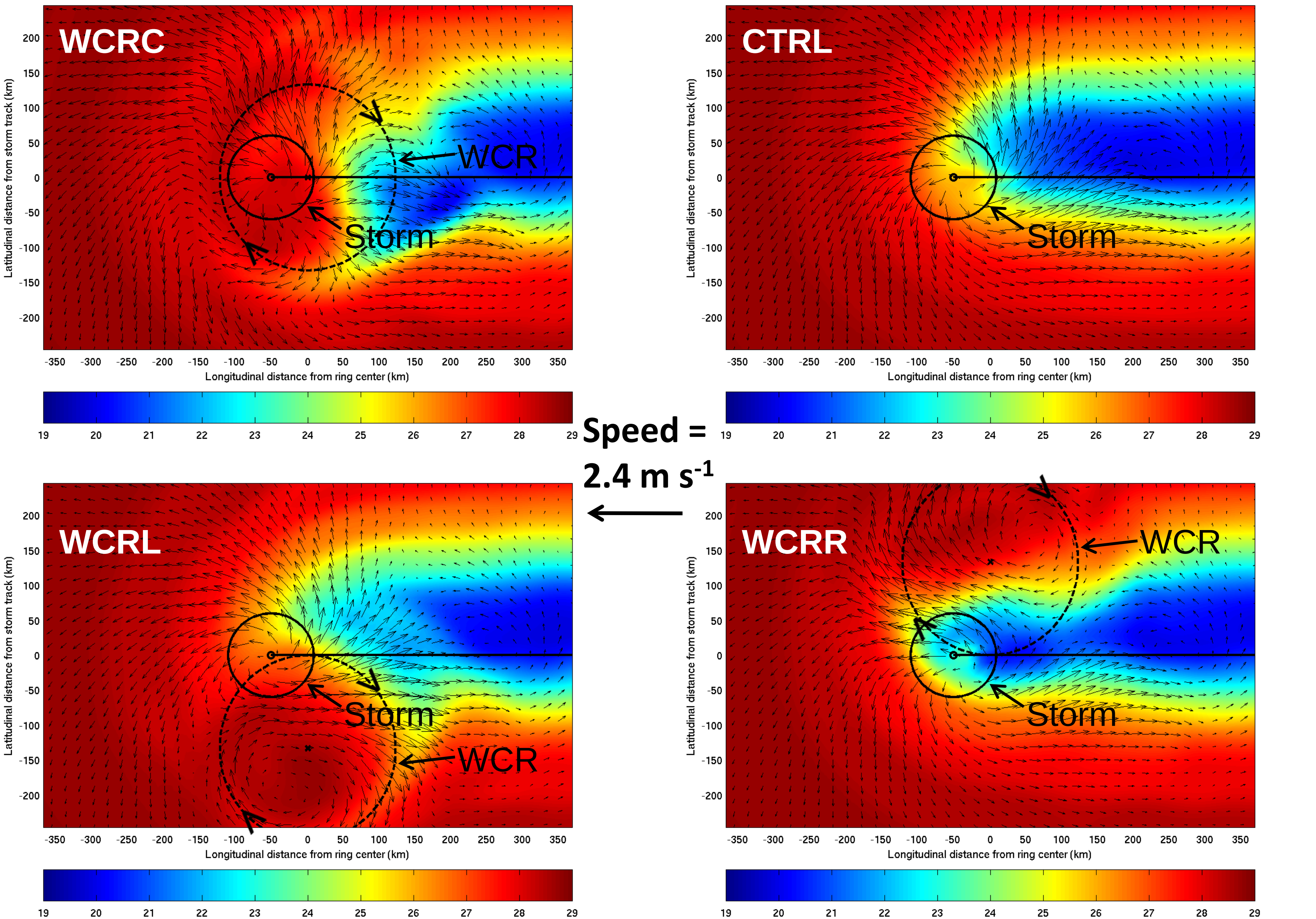


Yablonsky and Ginis (2009, MWR, in review)



Prescribed translation speed
Cyclonic hurricane vortex
Homogeneous initial SST
Vary position of ring relative to storm track
Horizontally-homogeneous subsurface temperature
Warm core ring evident in subsurface temperature field
ATMOSPHERE
OCEAN

SST & current vectors… storm is ~50 km past center of WCR… 3-D experiments



Conventional Coupling Between Hurricane and Ocean Models

Hurricane 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

<u>Assumption</u>

- **Atmosphere is in equilibrium with sea state**
- **Waves are fully developed**

Momentum flux (τ)

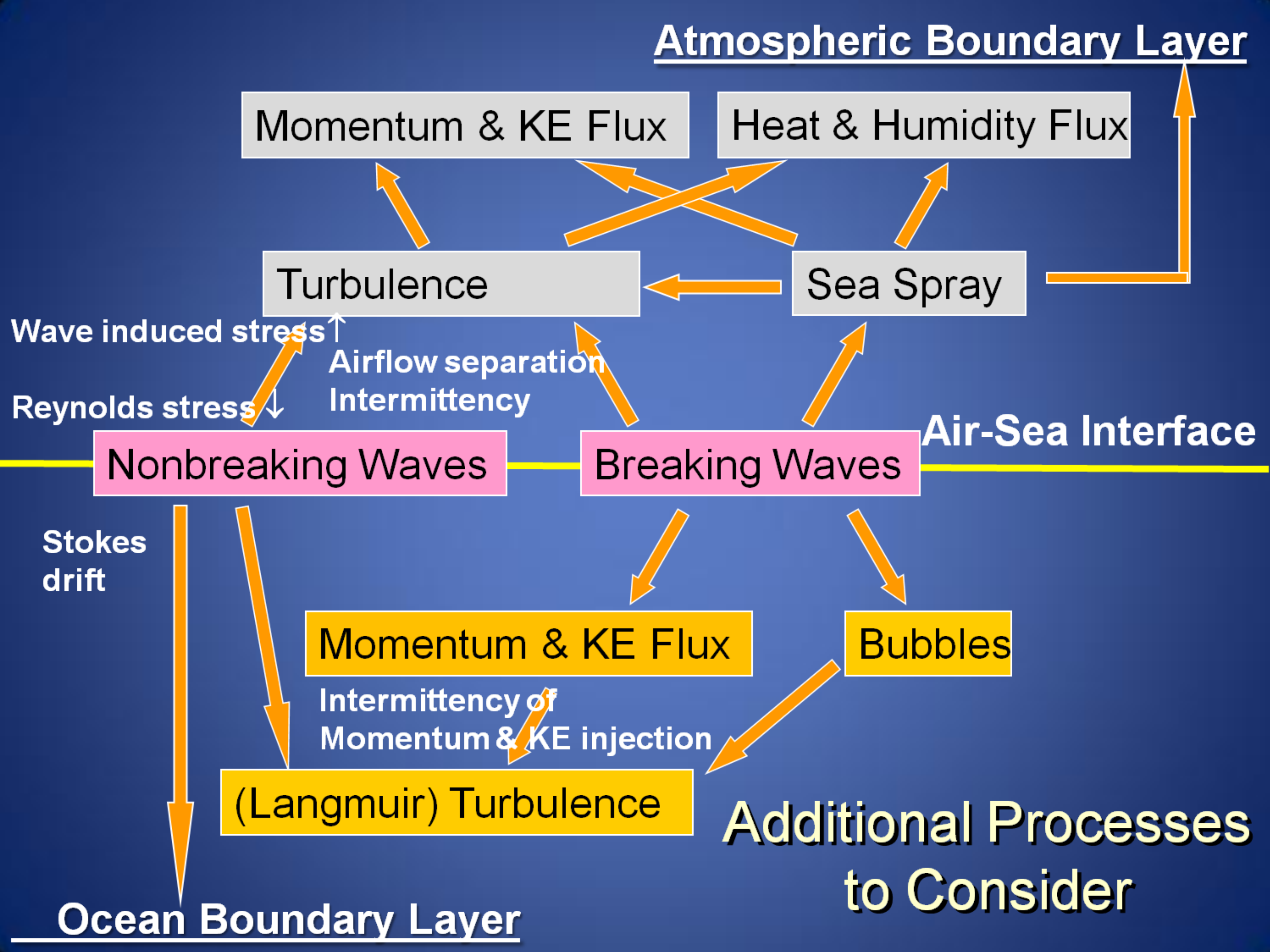
Surface current (U_s)
SST (T_s)

Ocean Model

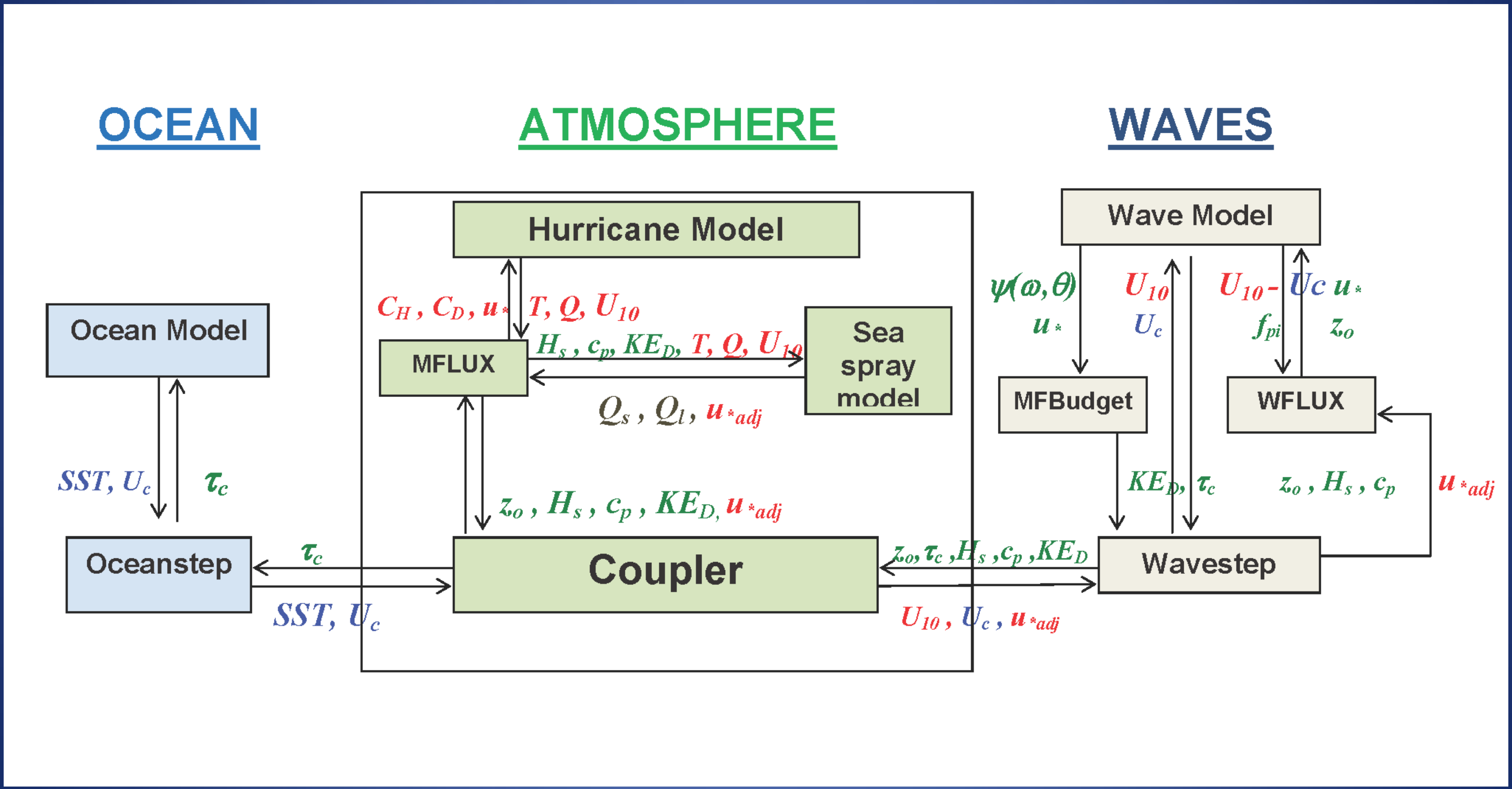
$$\tau = \rho_a C_D (U_a - U_s)(U_a - U_s)$$

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

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


Atmospheric Boundary Layer
Momentum & KE Flux
Heat & Humidity Flux
Turbulence
Sea Spray
Wave induced stress↑
Reynolds stress↓
Airflow separation
Intermittency
Air-Sea Interface
Nonbreaking Waves
Breaking Waves
Stokes
drift
Momentum & KE Flux
Bubbles
Intermittency of
Momentum & KE injection
(Langmuir) Turbulence
Additional Processes
to Consider
Ocean Boundary Layer

Coupled Hurricane-Wave-Ocean Framework for Future HWRF and GFDN Models



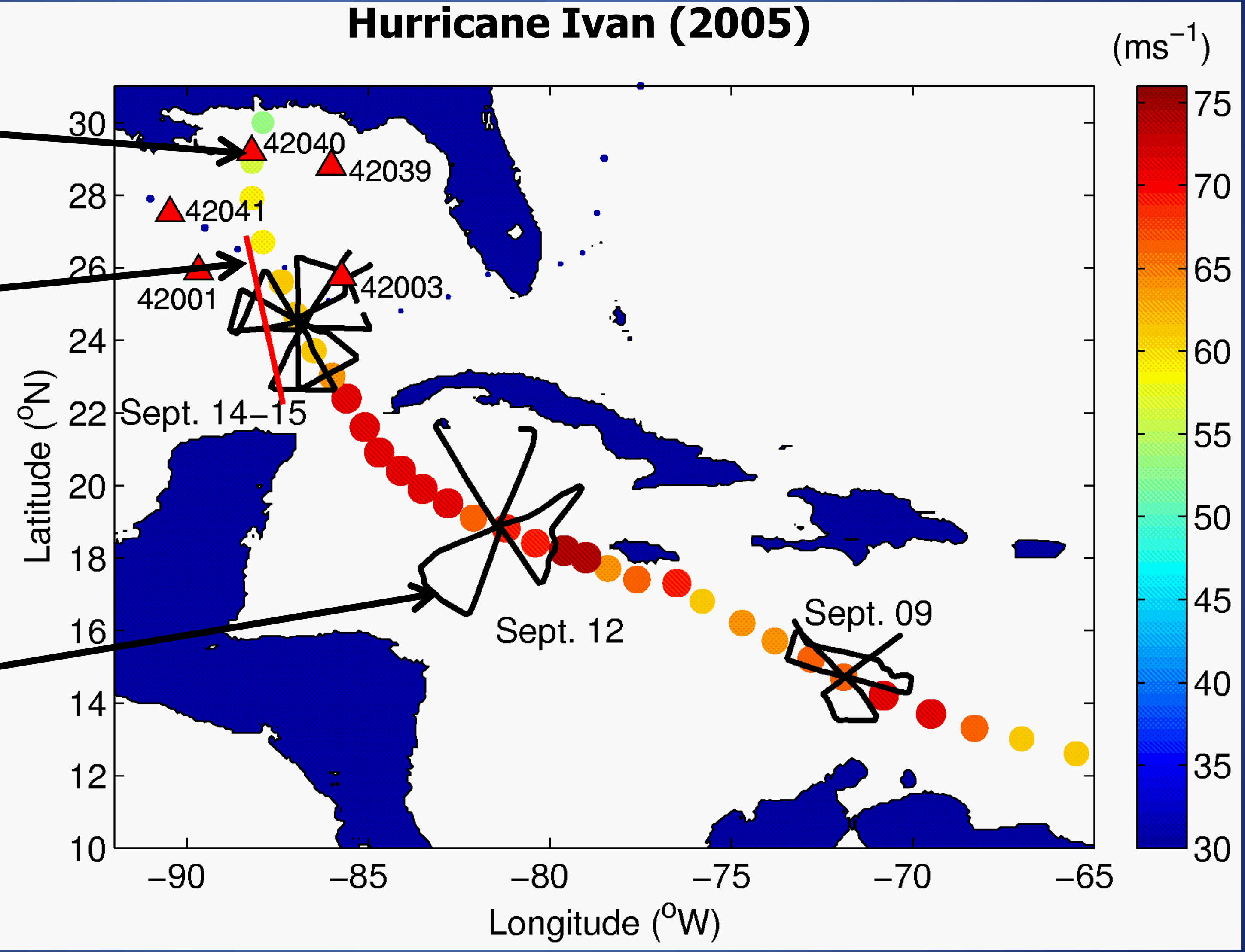
With wave and spray coupling, measurements near the air-sea interface are critical for validating heat and momentum fluxes

Wave Model Validation

Buoy measurements

Satellite measurements

SRA measurements



Fan, Ginis, Hara & Walsh (2009)

Wave Model Validation: Hurricane Ivan

<u>**Experiment A:**</u>

WAVEWATCH III wave model (operational model)

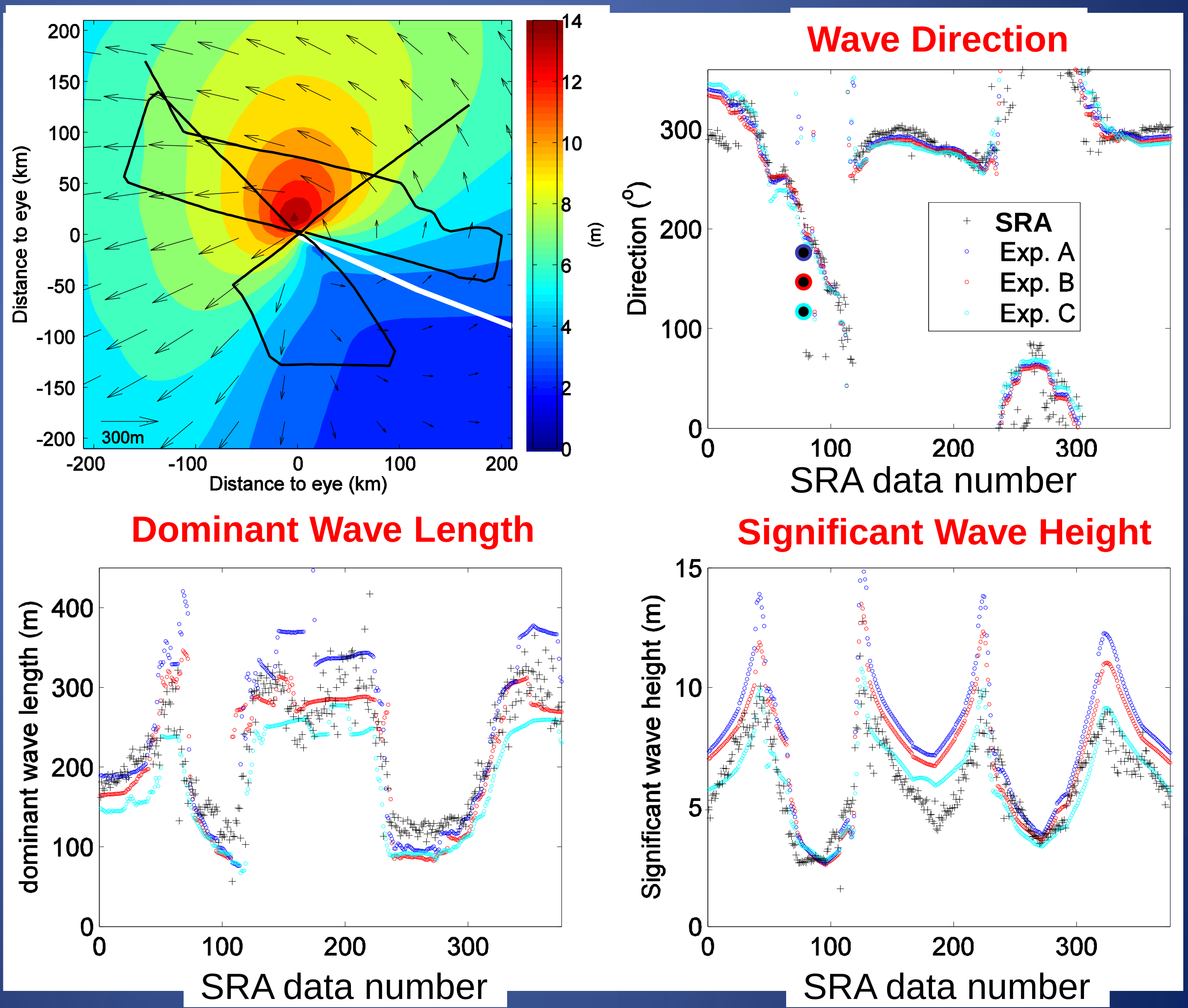
<u>**Experiment B:**</u>

Coupled wind-wave model (accounts for sea state)

<u>**Experiment C:**</u>

Coupled wind-wave-current model

Sept. 09: Using SRA Measurements For Validation



Questions?

Supplemental Slides

Other instrumentation?

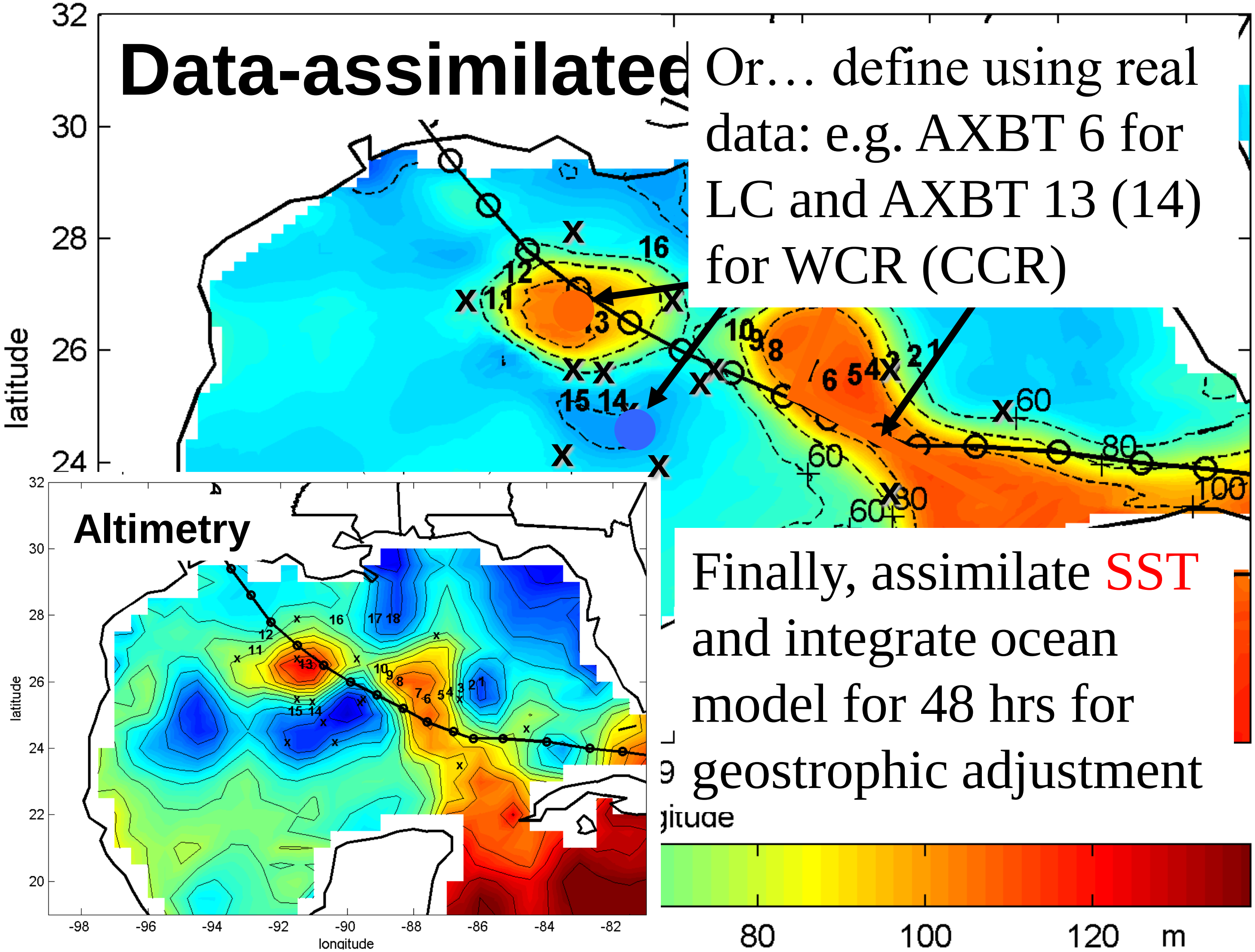
- D’Asaro et al. (2007, GRL): Surface drifters, profiling SOLO floats, profiling EM-APEX floats, & Lagrangian floats deployed during Hurricane Frances (2003)

- Jarosz et al. (2007, Science): Current and wave/tide gauge moorings used to estimate air-sea momentum flux on the GoM continental shelf during the passage of Hurricane Ivan (2004) just prior to landfall

- *Communication between modelers and those who make relevant observations is essential*

How we modify GDEM T/S Climatology:

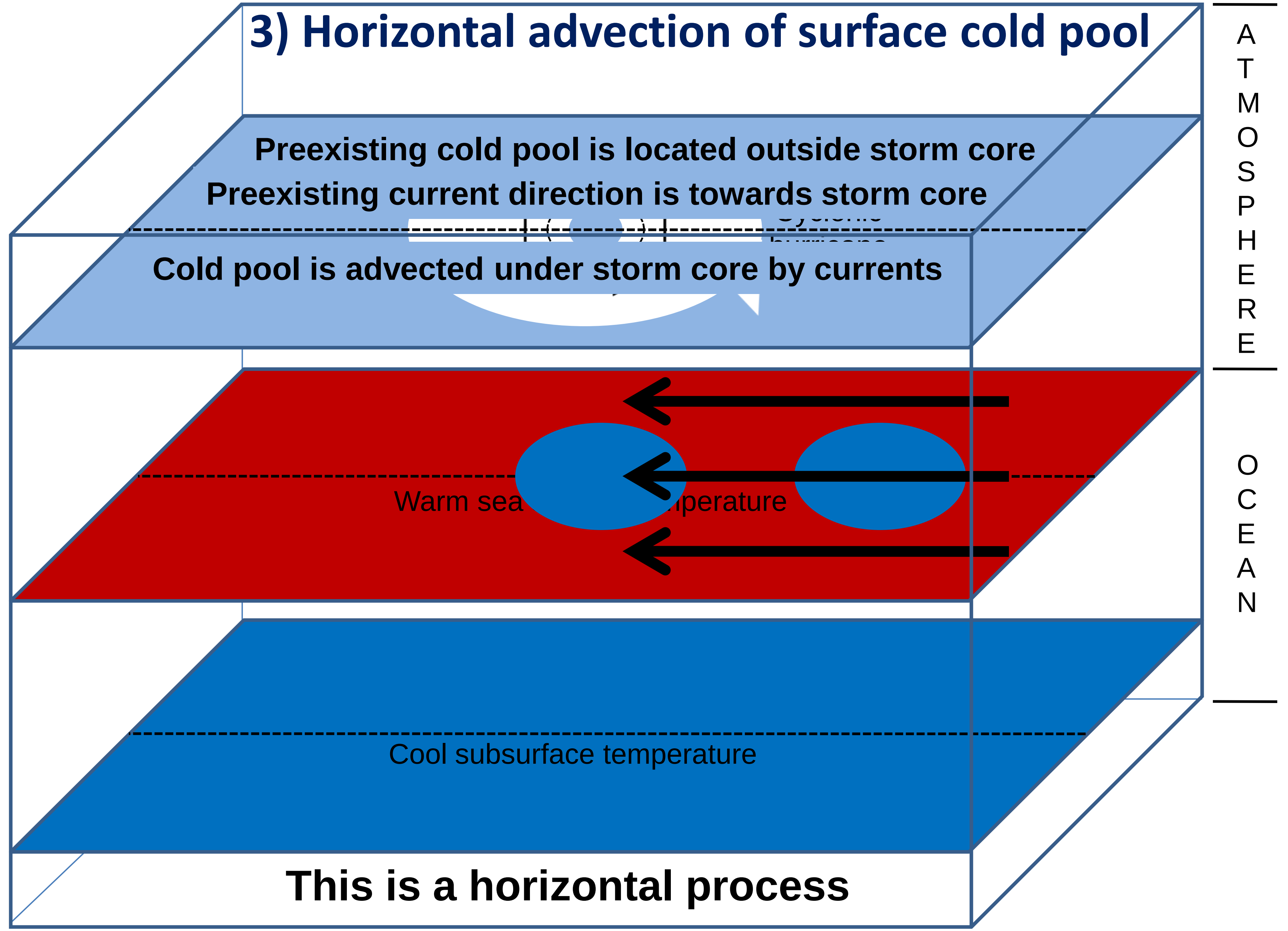
Feature-based modeling!

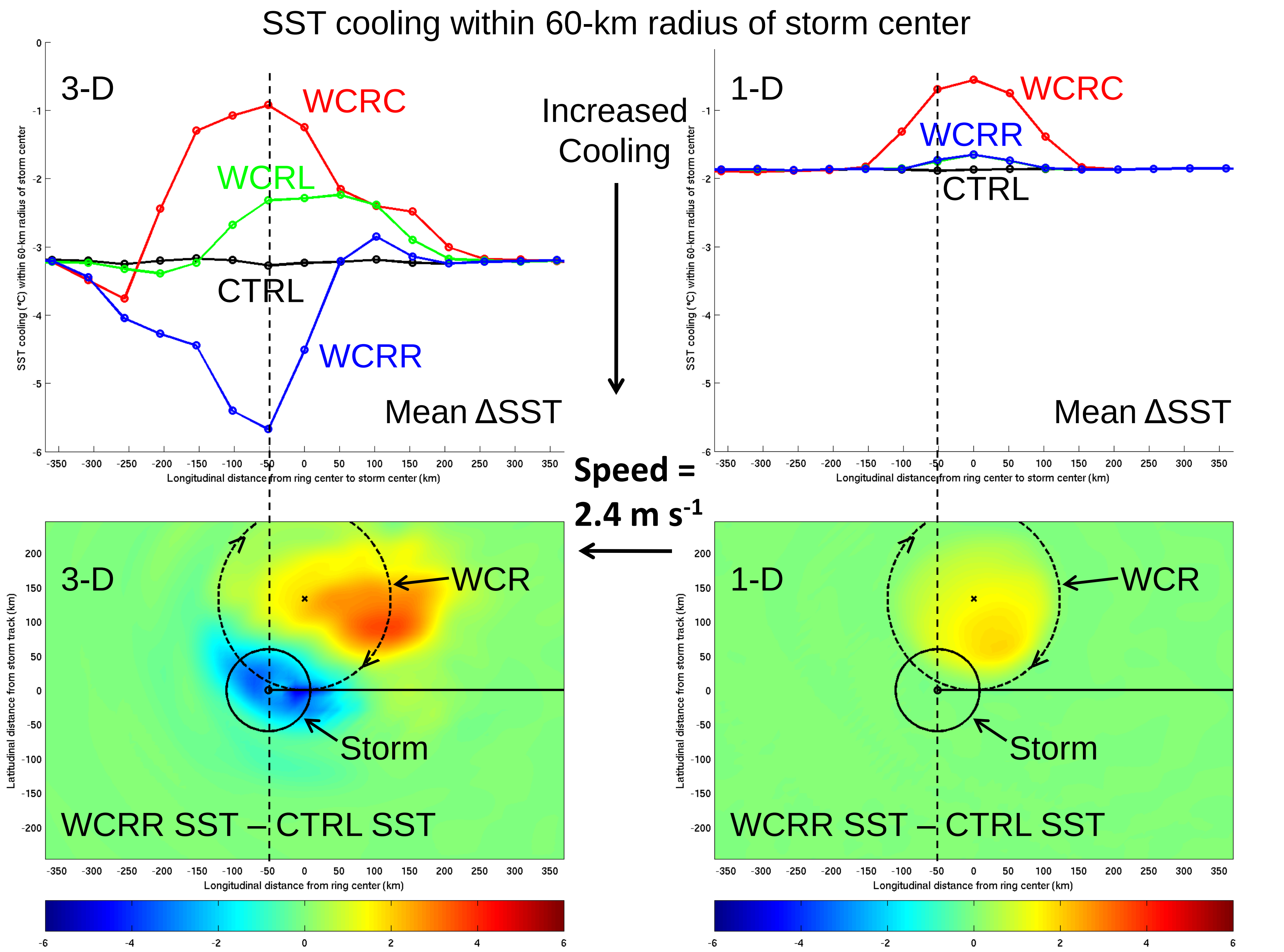


Or… define using real data: e.g. AXBT 6 for LC and AXBT 13 (14) for WCR (CCR)

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

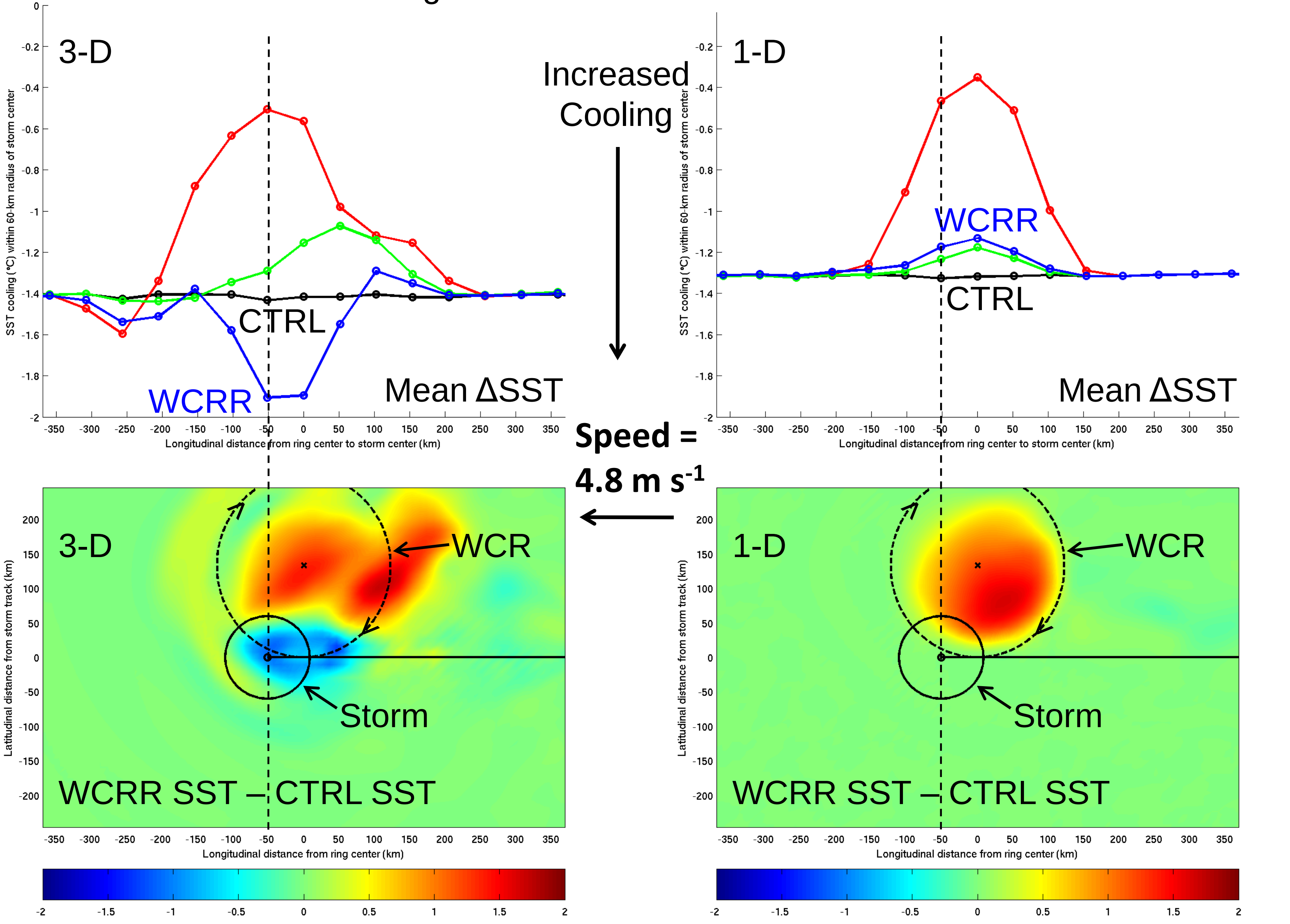
- Start with Sept. GDEM
- Look at altimetry/axbts
- Define LC & ring positions
- Use Caribbean water along LC axis & in warm core ring center
- Make cold core ring center colder than env.
- Blend features w/ env. & sharpen fronts


3) Horizontal advection of surface cold pool
Preexisting cold pool is located outside storm core
Preexisting current direction is towards storm core
Cold pool is advected under storm core by currents
Warm sea
perature
Cool subsurface temperature
This is a horizontal process
ATMOSPHERE
OCEAN



SST cooling within 60-km radius of storm center
3-D
WCRC
WCRL
CTRL
WCRR
Mean ΔSST
SST cooling (°C) within 60-km radius of storm center
Longitudinal distance from ring center to storm center (km)
Increased Cooling
1-D
WCRC
WCRR
CTRL
Mean ΔSST
Speed = 2.4 m s-1
3-D
WCR
Storm
WCRR SST – CTRL SST
Latitudinal distance from storm track (km)
Longitudinal distance from ring center (km)
1-D
WCR
Storm
WCRR SST – CTRL SST

SST cooling within 60-km radius of storm center



Summary

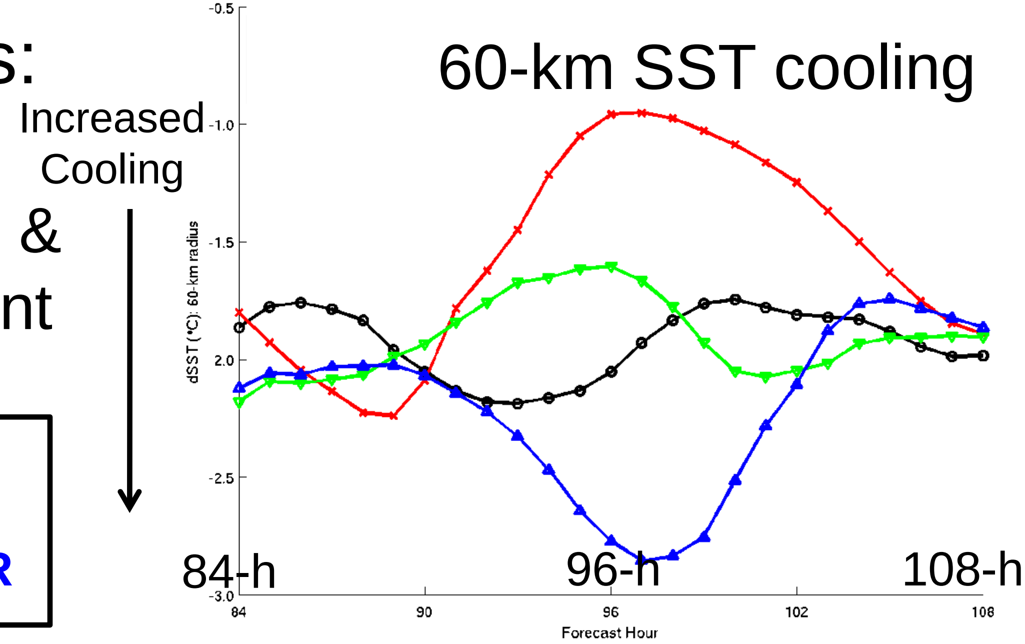
- It is well-established that **WCRs** may impart a non-negligible influence on hurricane intensity by altering storm-core SST cooling
- BUT it is misleading to treat **WCRs** as simply regions of increased heat content without regard for:
    1) translation speed of the storm
    2) location of the ring relative to the storm track
- 3-D models are necessary to capture **upwelling** and **horizontal advection of a surface cold pool**

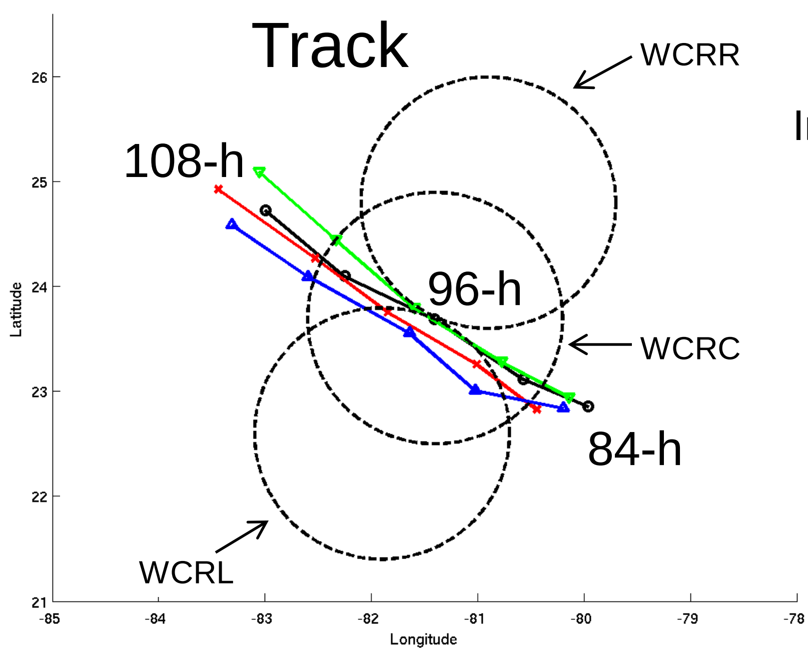
Coupled Model Results:

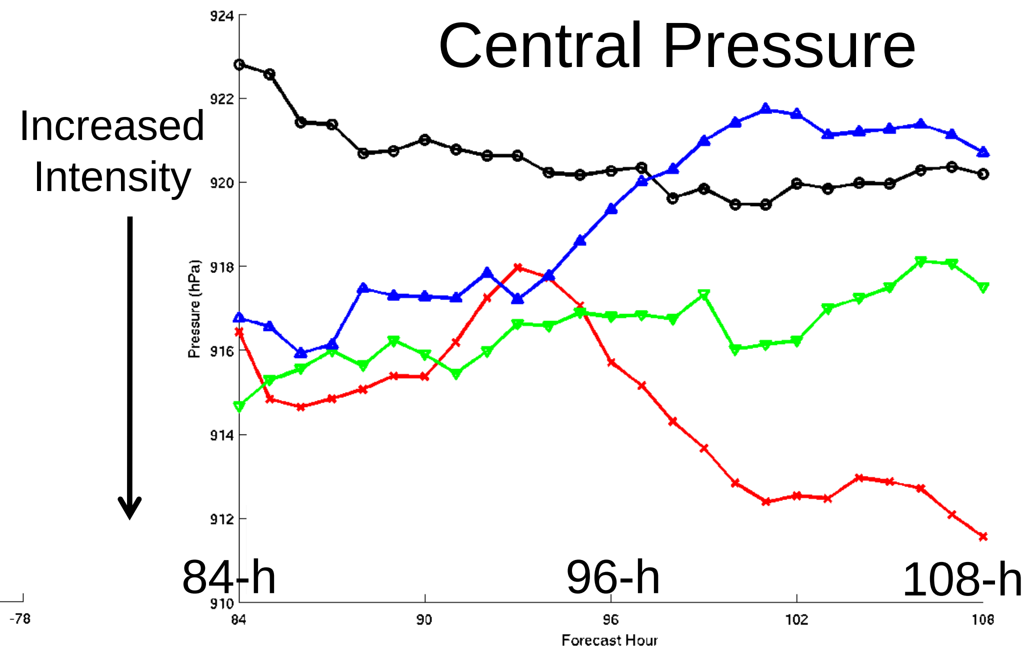
2.5 m/s environmental wind &
3-D ocean model component

<u>Legend</u>

CTRL **WCRC** **WCRL** **WCRR**







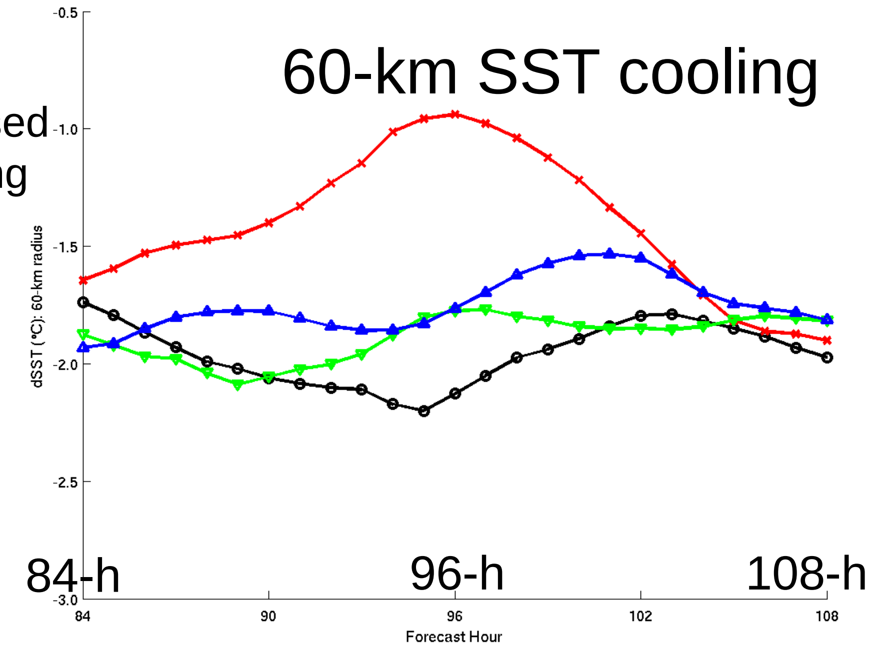
Coupled Model Results:

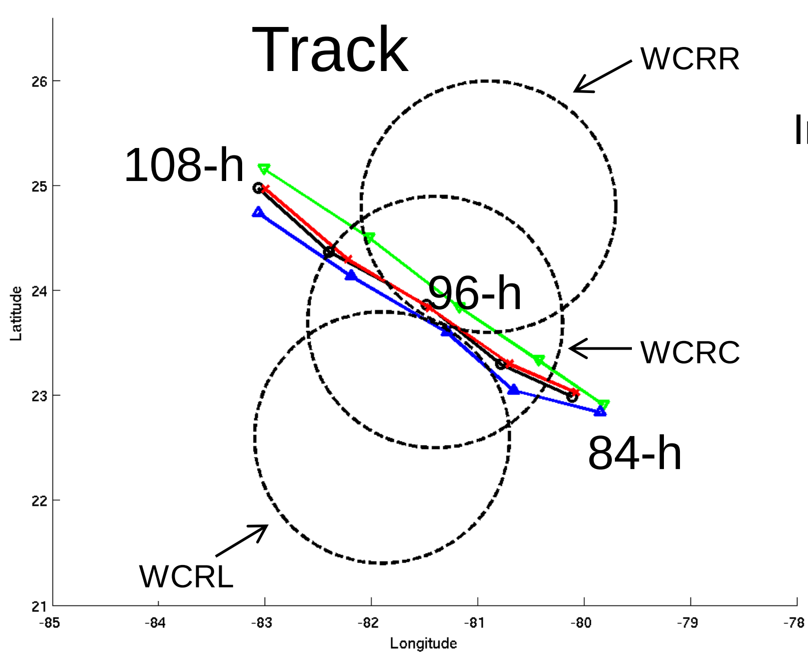
2.5 m/s environmental wind &
1-D ocean model component

Legend

CTRL **WCRC** **WCRL** **WCRR**

Increased Cooling





Increased Intensity