Atmosphere-Ocean Interaction in Tropical Cyclones

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Air-Sea Interaction in Tropical Cyclones

Two U.S. operational hurricane prediction models are coupled with ocean models: GFDL (since 2001) and HWRF (since 2007)

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Critical Aspects of TC-Ocean Interaction

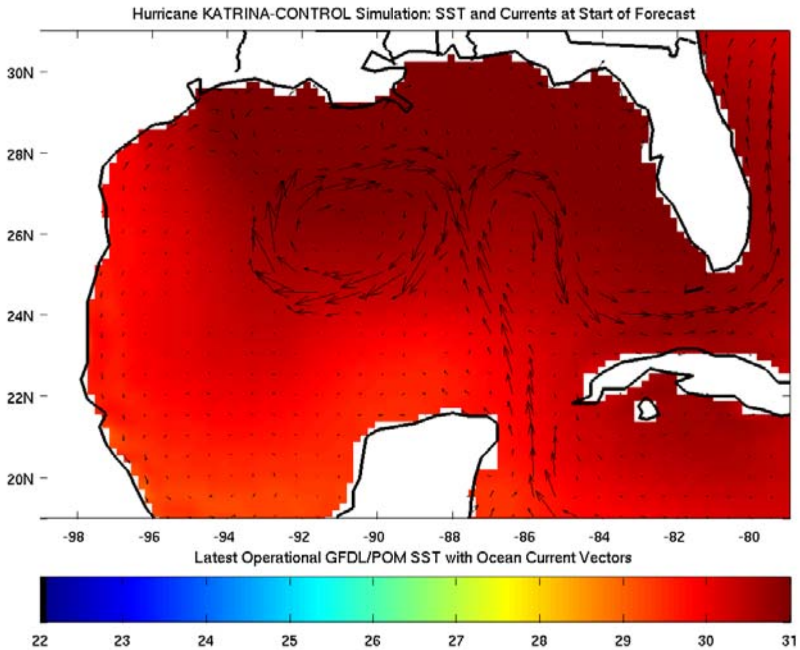
- Accurate initialization of ocean mesoscale features.

- Dynamical and microphysical processes near and at the sea surface that influence air-sea momentum and heat fluxes.

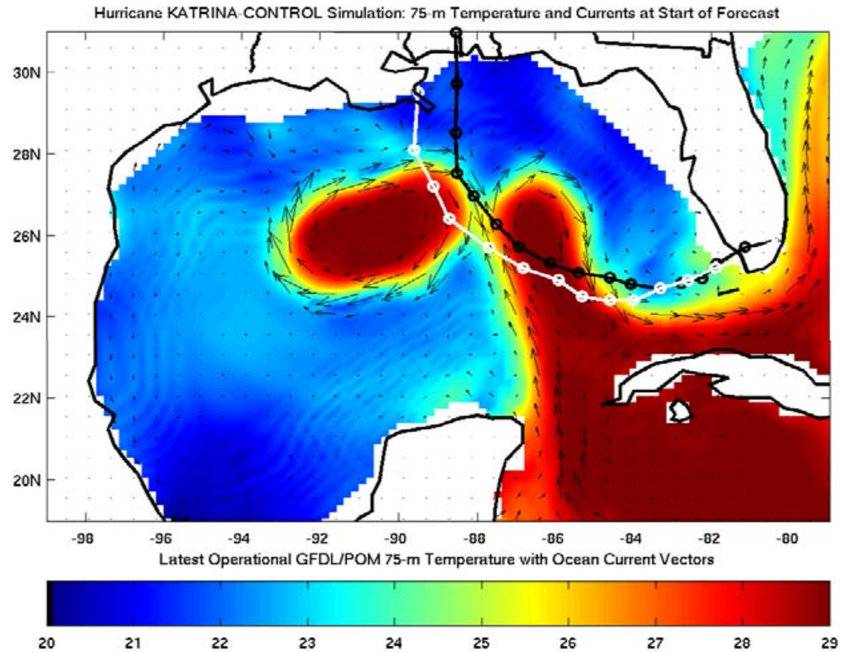
Accurate Ocean Initialization of Mesoscale Features

Hurricane Katrina GFDL Model Forecast: Initial time August 26, 00 UTC, 2005

SST and Surface Current



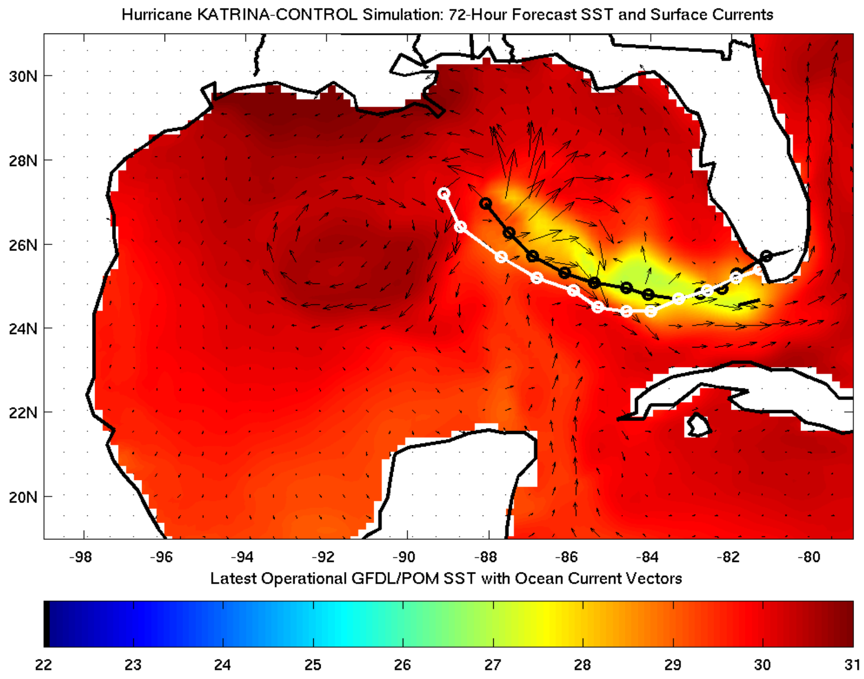
Temperature and Current at 75 m



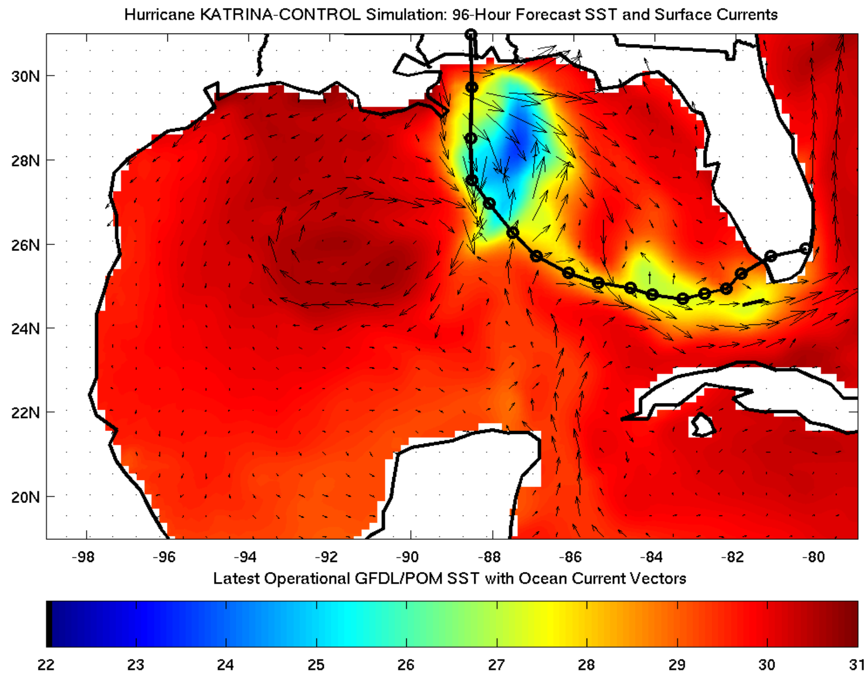
Feature-based ocean initialization assimilates satellite altimeter, sea surface temperature and in situ data in the Gulf of Mexico (Yablonsky and Ginis 2008) implemented operationally

GFDL Hurricane Katrina Forecast: SST and Surface Current

72 h Forecast

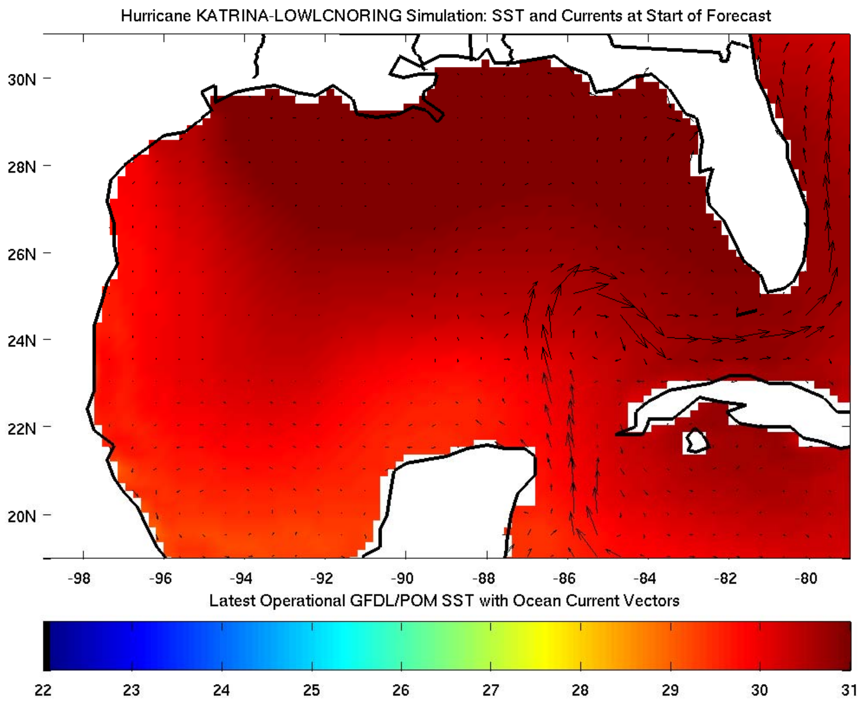


96 h Forecast

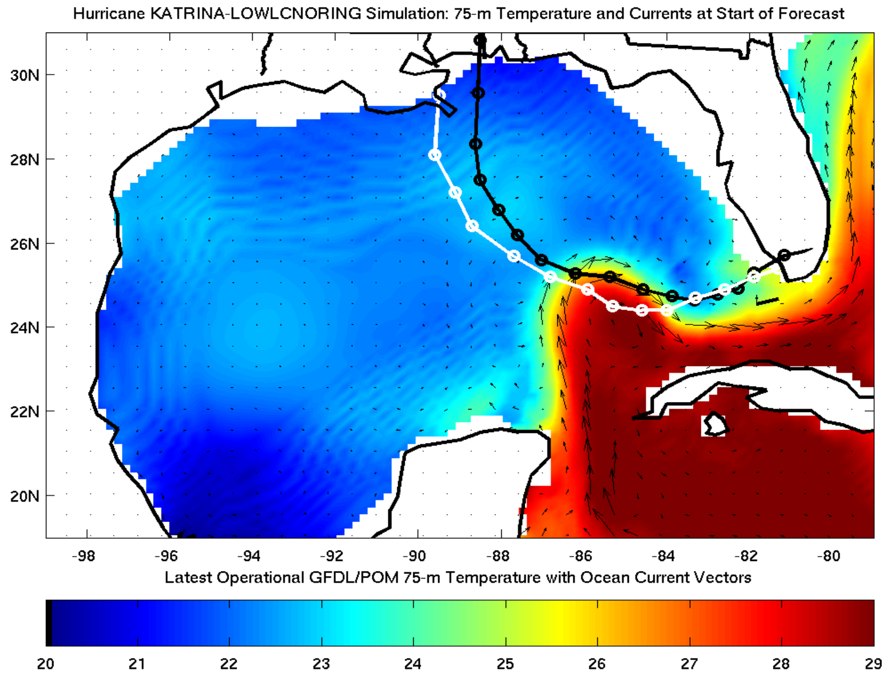


Hurricane Katrina Forecast: Modified LC and No Warm-core Ring

SST and Surface Current

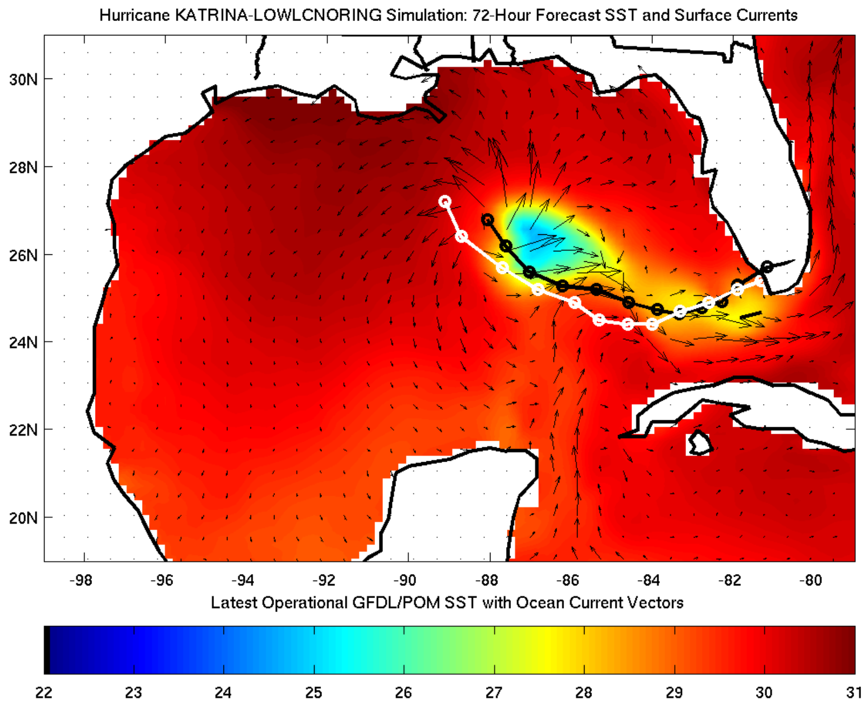


Temperature and Current at 75 m

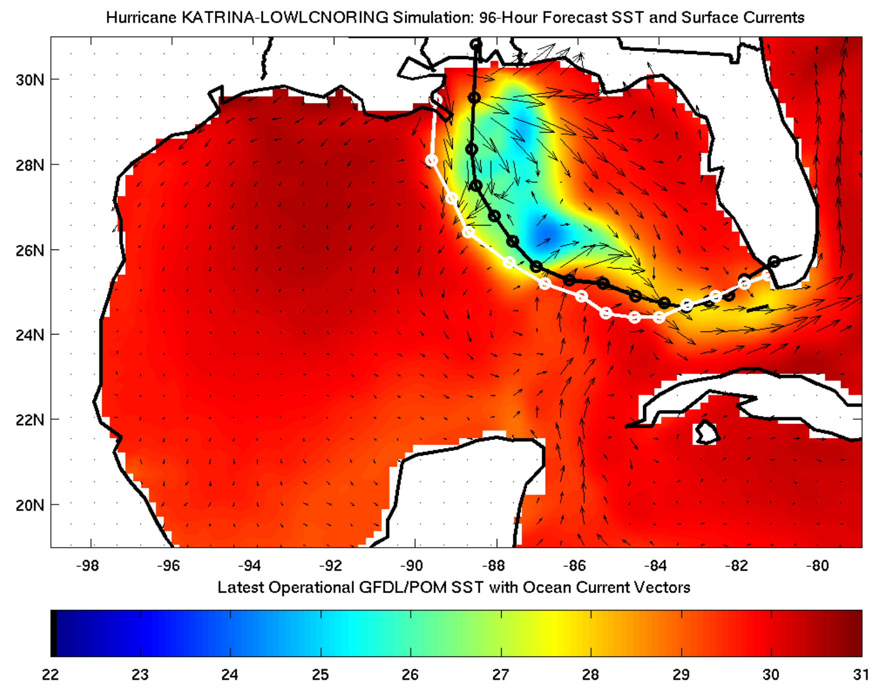


Hurricane Katrina: Modified LC and no Warm-core Ring

72 h Forecast

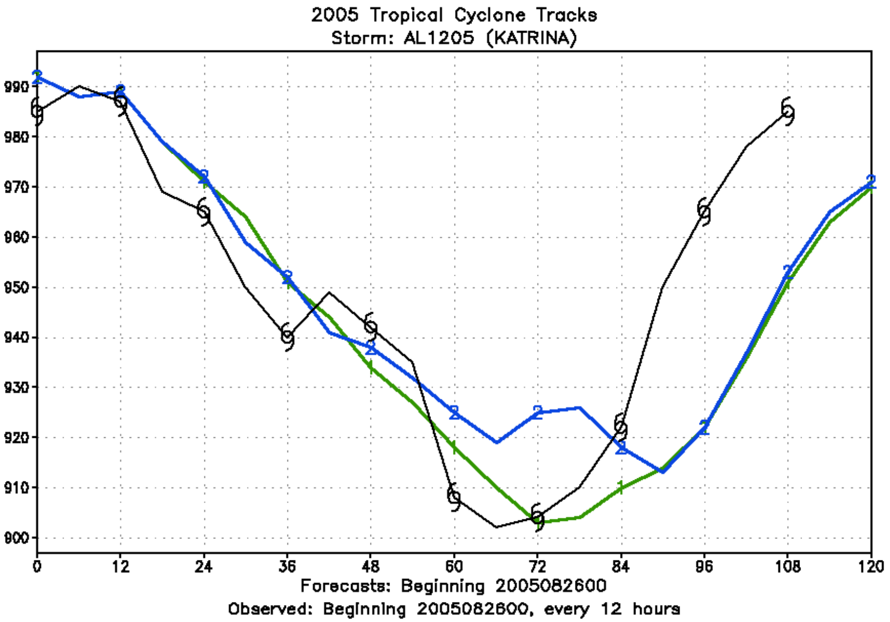


96 h Forecast

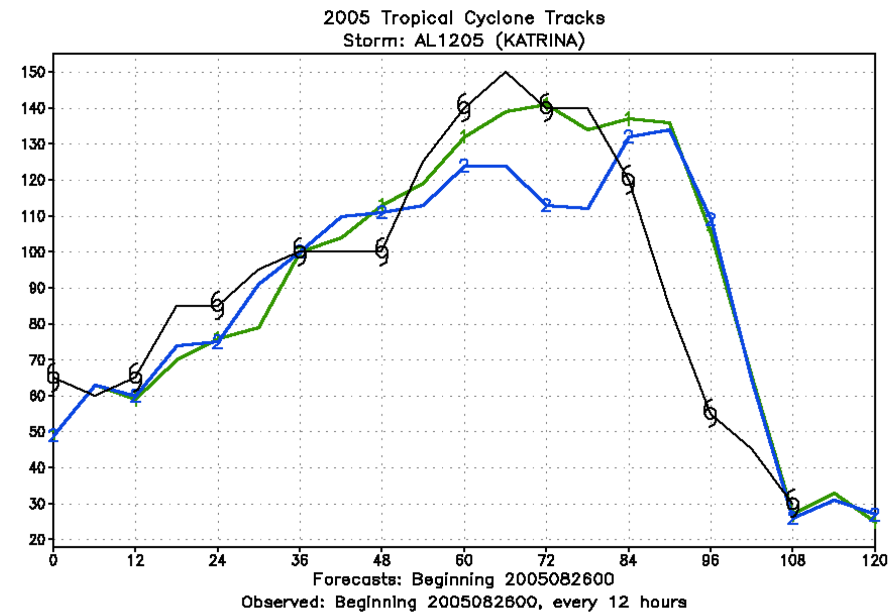


Hurricane Katrina Intensity Forecasts

Central Pressure



Maximum Winds

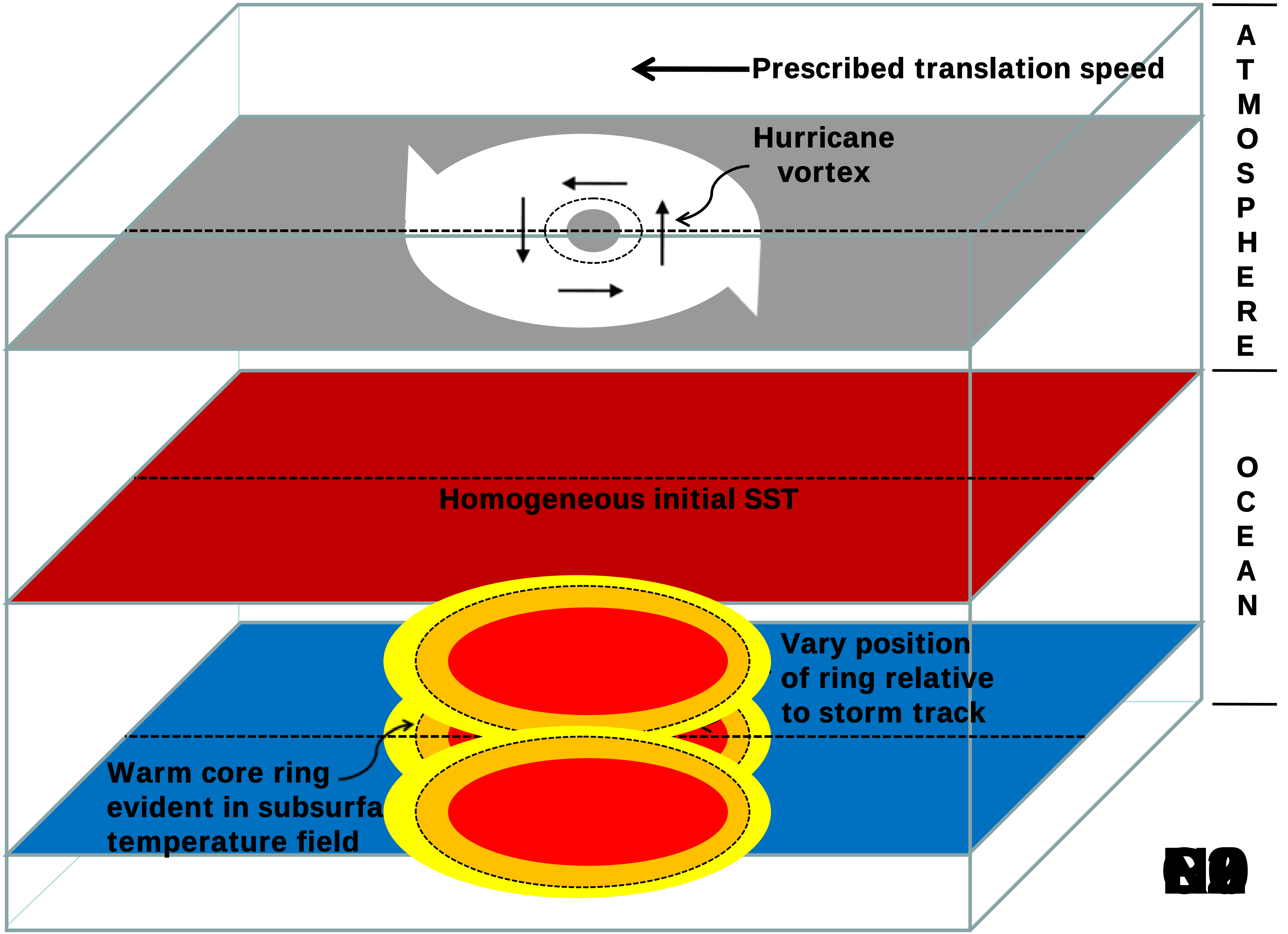


Green– Real-time forecast
Blue – Modified LC and no warm-core ring
Black - Observations

3D vs. 1D Ocean Coupling

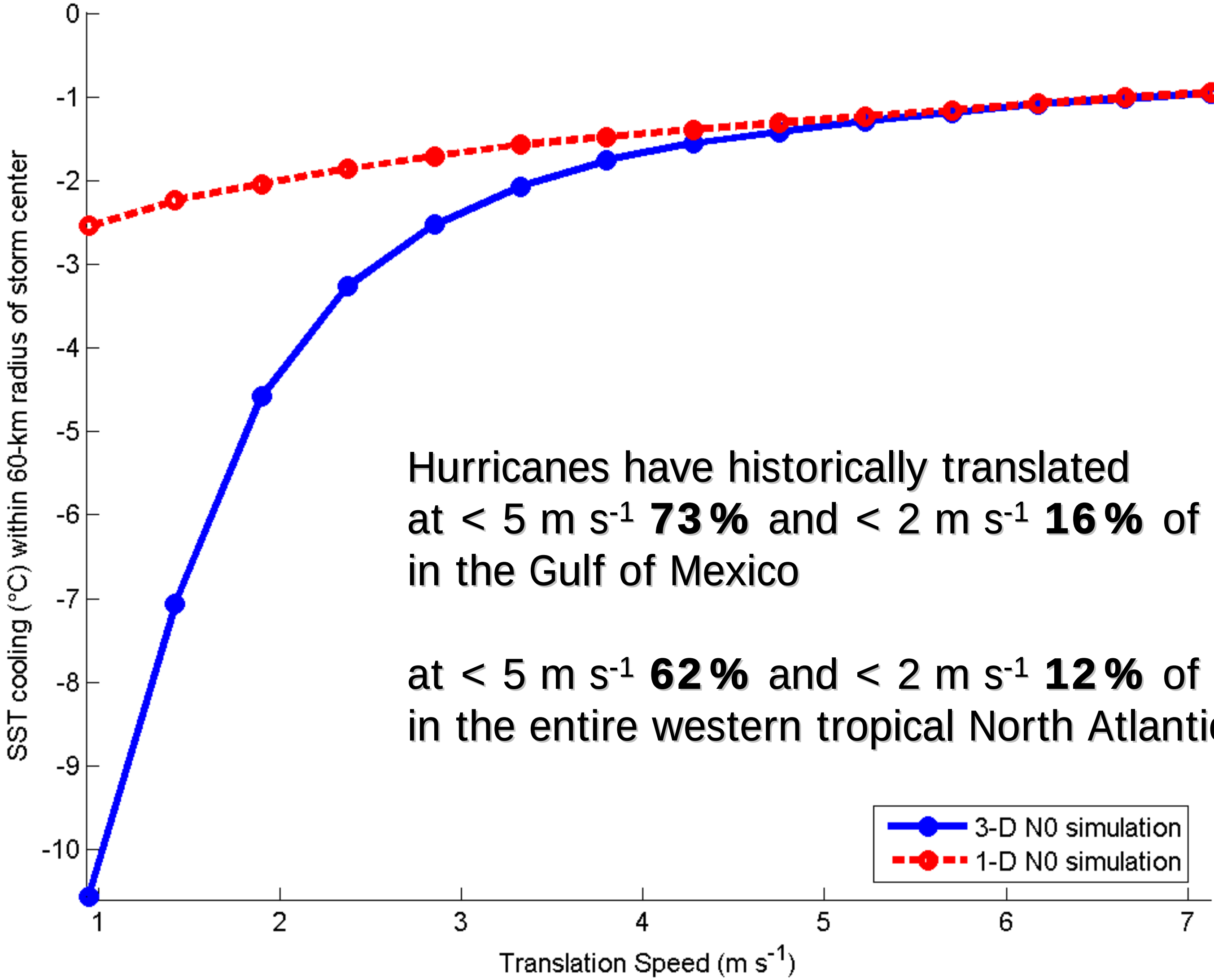
- Some recent studies (Emanuel et al. 2004; Lin et al. 2005, 2008; Bender et al. 2007; Davis et al. 2008) suggest that coupling a 1D ocean model to a TC model may be sufficient for capturing the storm-induced SST cooling in the region providing heat energy to the TC.

- If a 1D model is sufficient, valuable computational resources can be saved as compared to coupled models that employ a fully three-dimensional (3D) ocean component.



Prescribed translation speed
Hurricane vortex
ATMOSPHERE
Homogeneous initial SST
OCEAN
Vary position of ring relative to storm track
Warm core ring evident in subsurfa
temperature field

Difference in SST Response Underneath the TC Core Using a 1D and a 3D Version of the Same Ocean Model

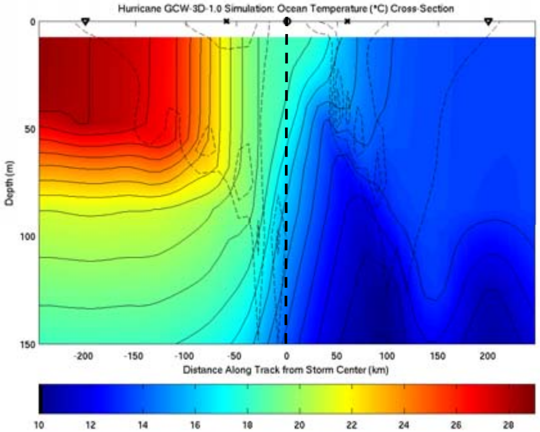


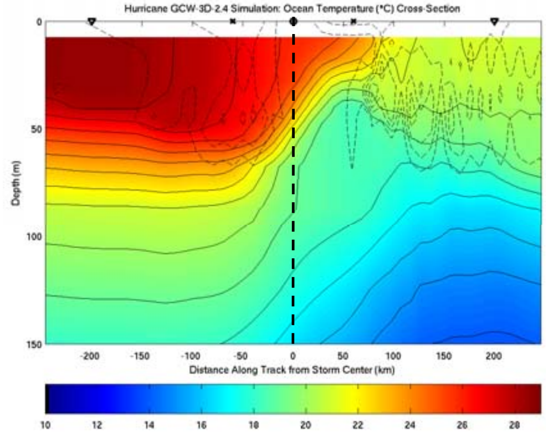
Hurricanes have historically translated at < 5 m s^{-1} **73%** and < 2 m s^{-1} **16%** of the time in the Gulf of Mexico

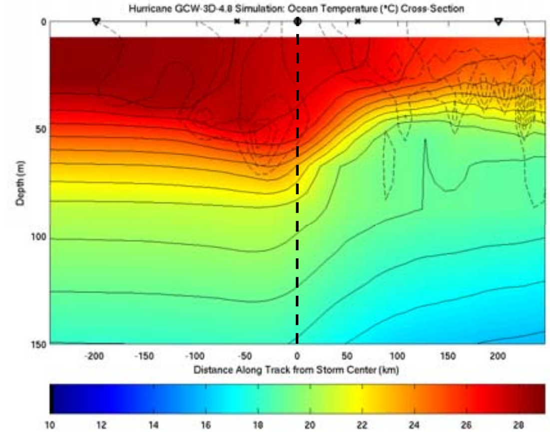
at < 5 m s^{-1} **62%** and < 2 m s^{-1} **12%** of the time in the entire western tropical North Atlantic

Along-track temperature cross-sections

3-D

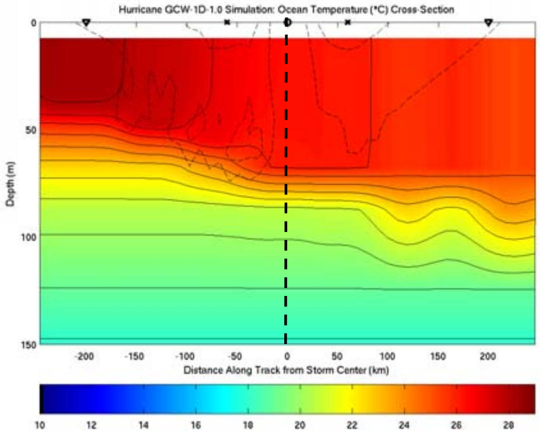


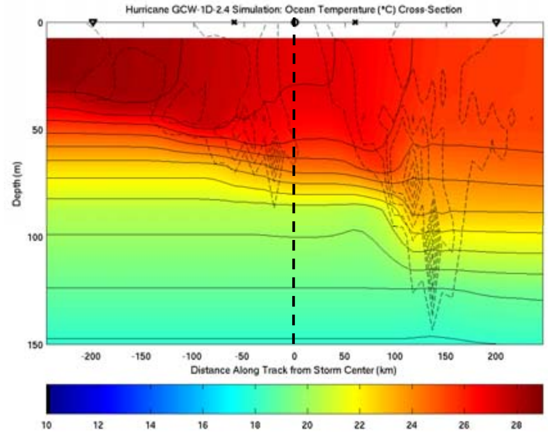


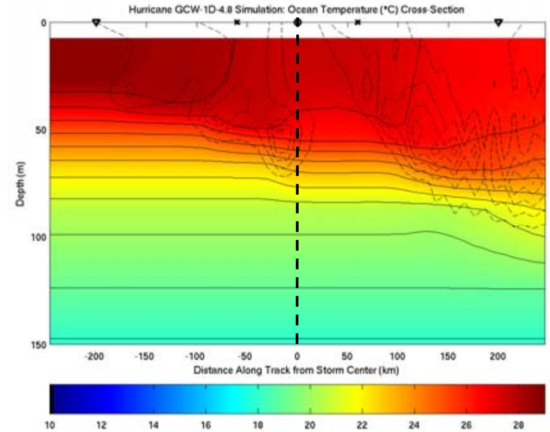


← **1.0 m s^{-1}** ← **2.4 m s^{-1}** ← **4.8 m s^{-1}**

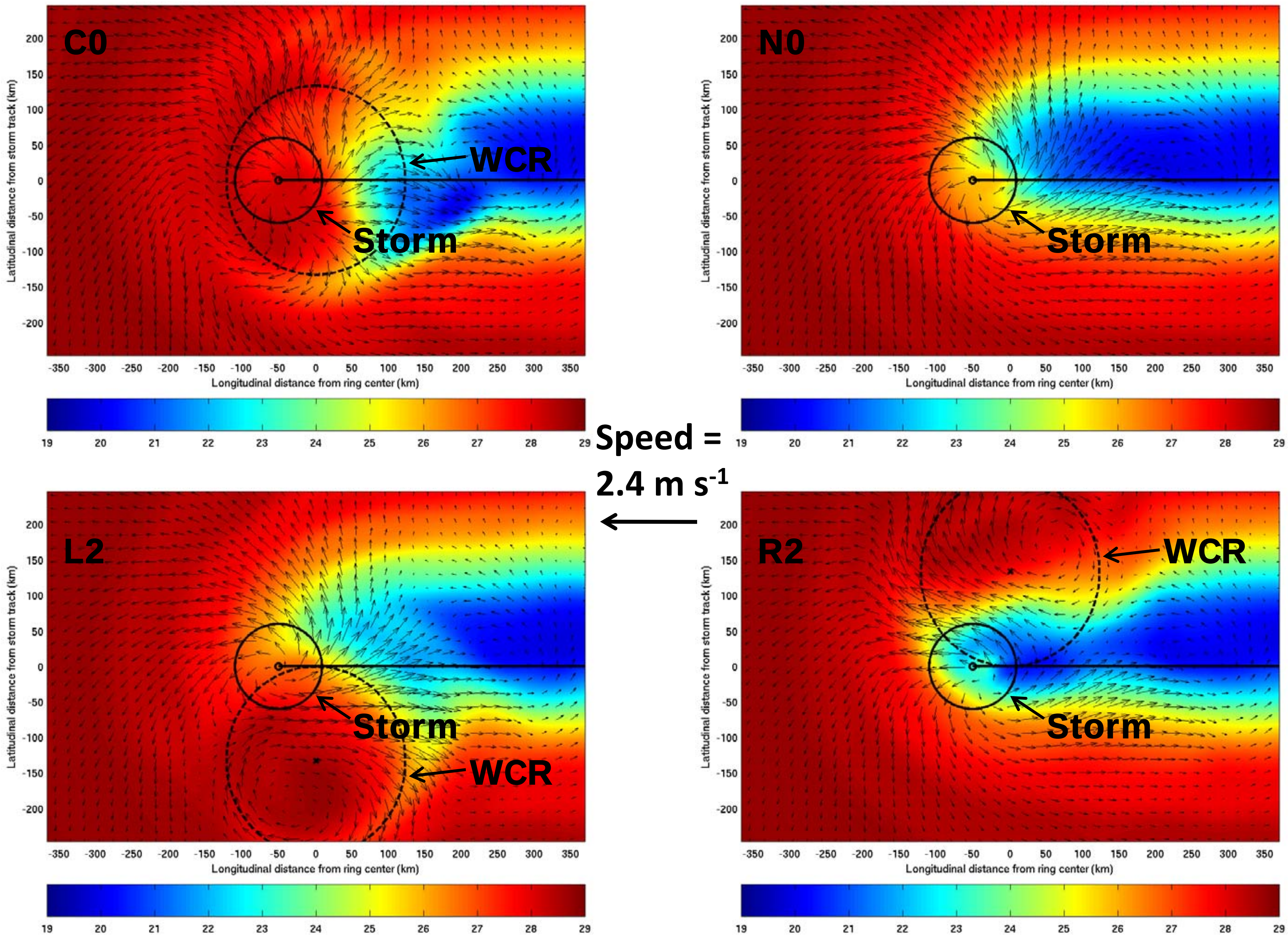
1-D



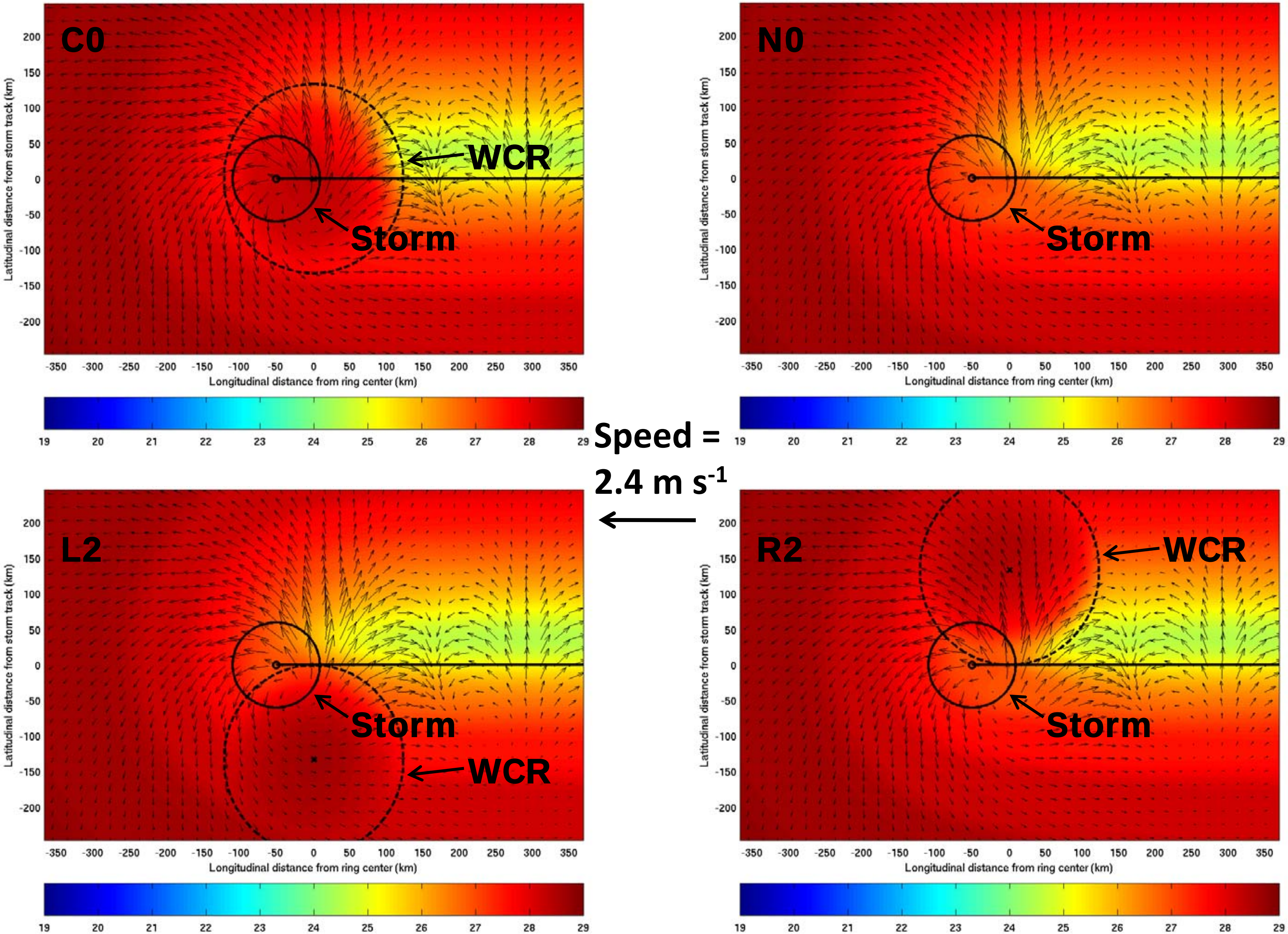




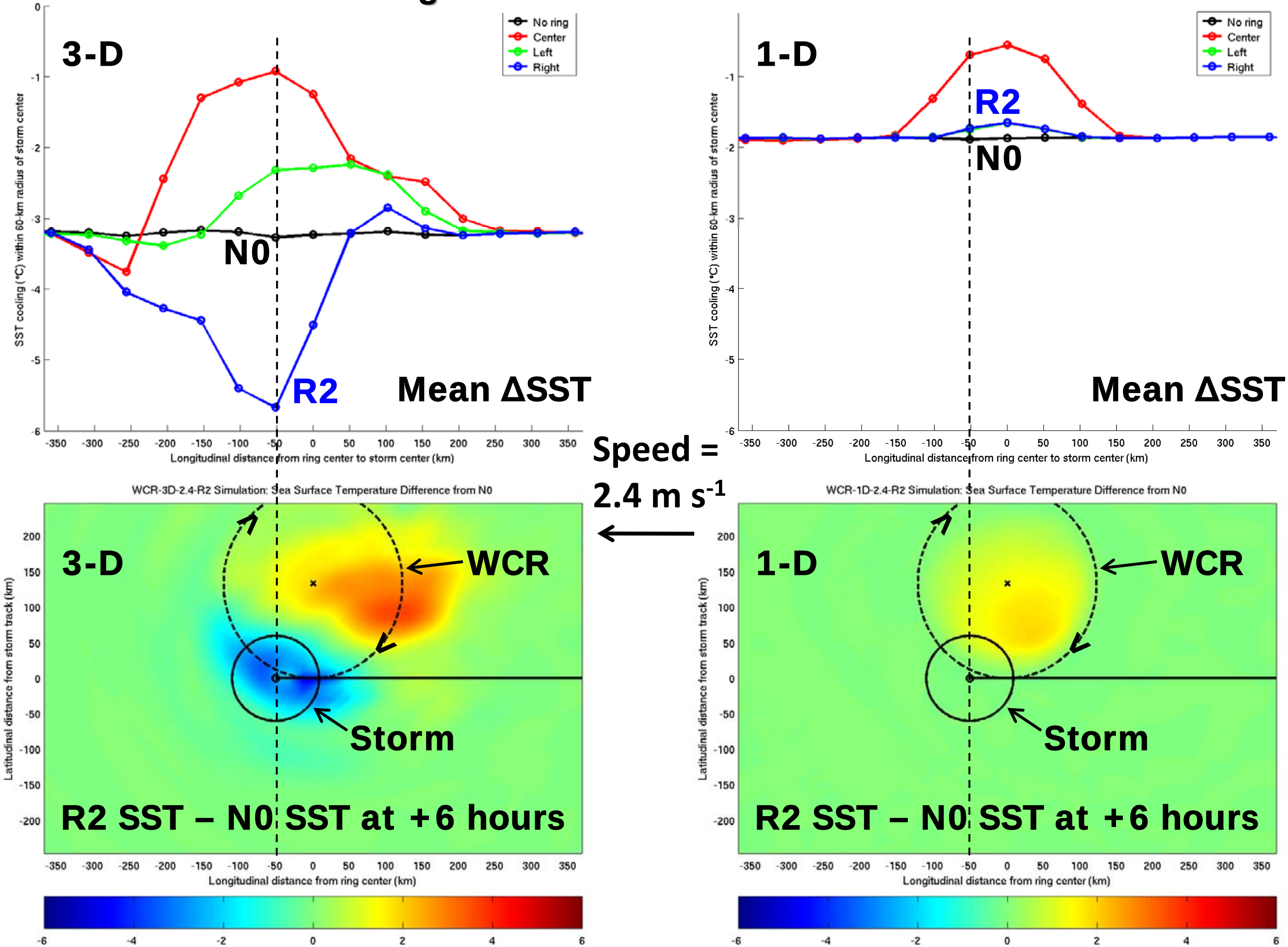
SST and currents 6 hrs after storm passes WCR center longitude: **3-D experiments**



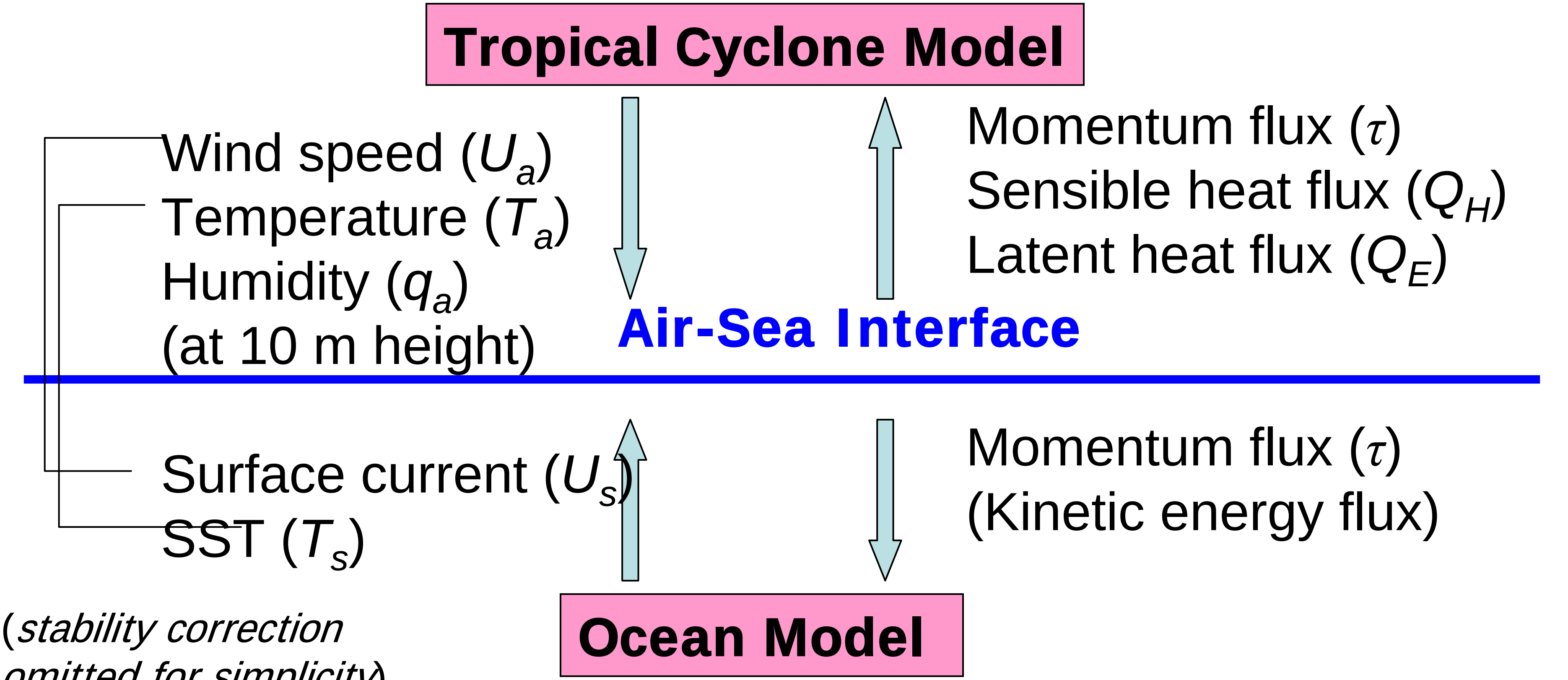
SST and currents 6 hrs after storm passes WCR center longitude: **1-D experiments**



SST cooling within 60-km radius of storm center



Conventional coupling between TC models and ocean models



(*stability correction omitted for simplicity*)

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

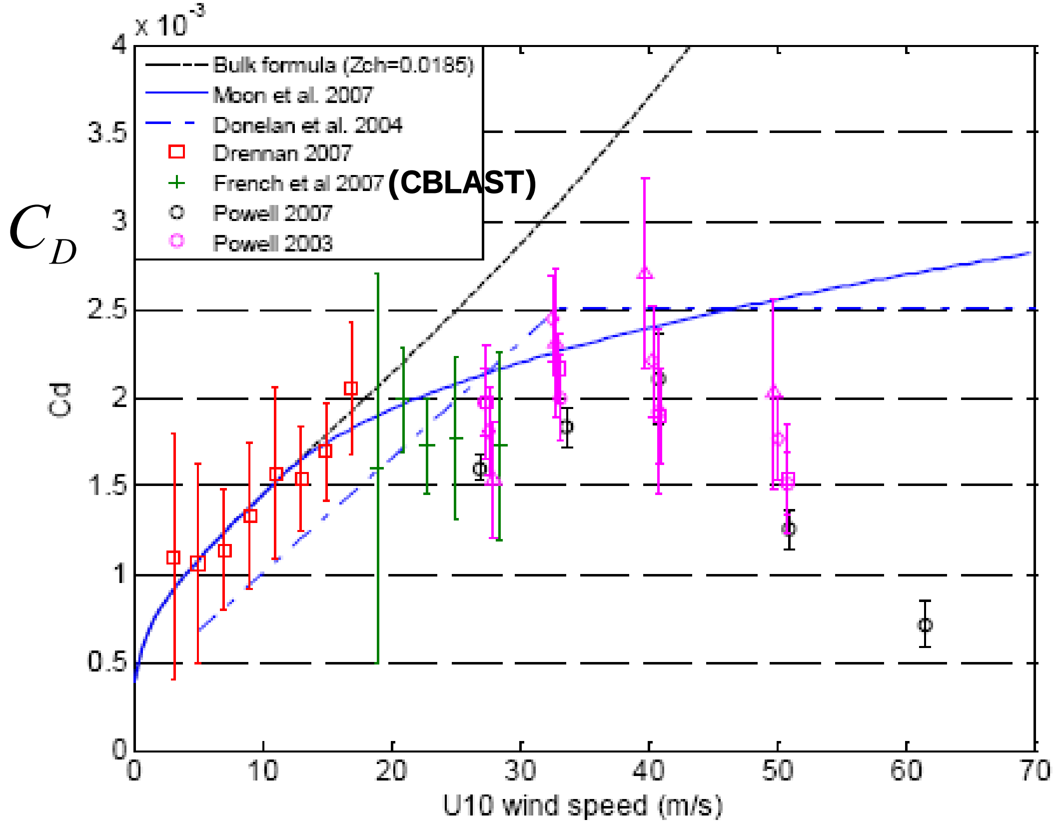
$$Q_H = C_H (U_a - U_s)(T_a - T_s)$$

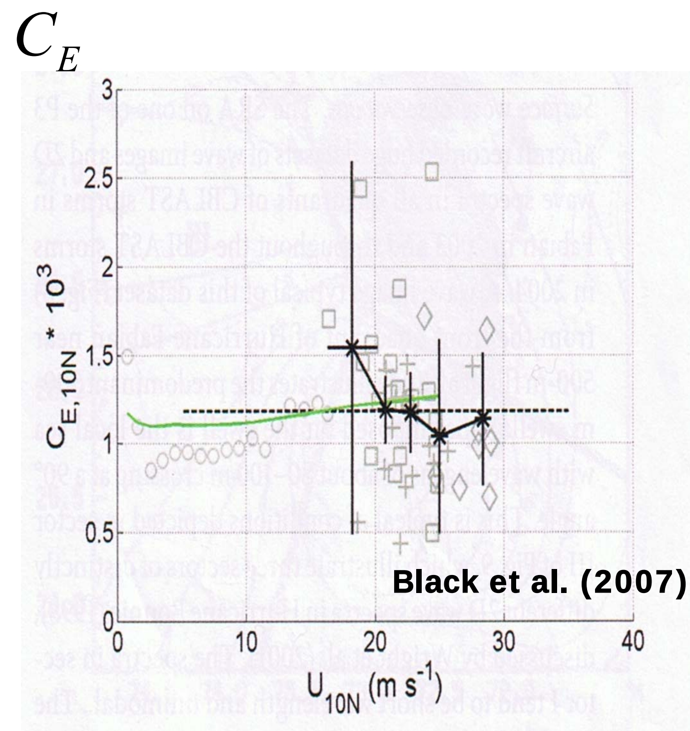
$$Q_E = \frac{L_V}{C_P} C_E (U_a - U_s)(q_a - q_s)$$

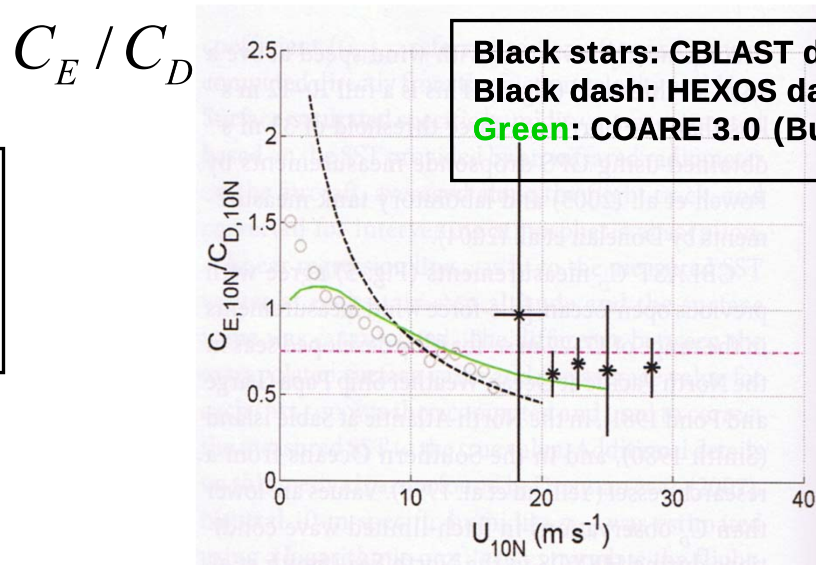
C_D Drag Coefficient

C_H Heat Transfer Coefficient

C_E Humidity Transfer Coeff. (Dalton Number)







Black stars: CBLAST data
Black dash: HEXOS data
Green: COARE 3.0 (Bulk)

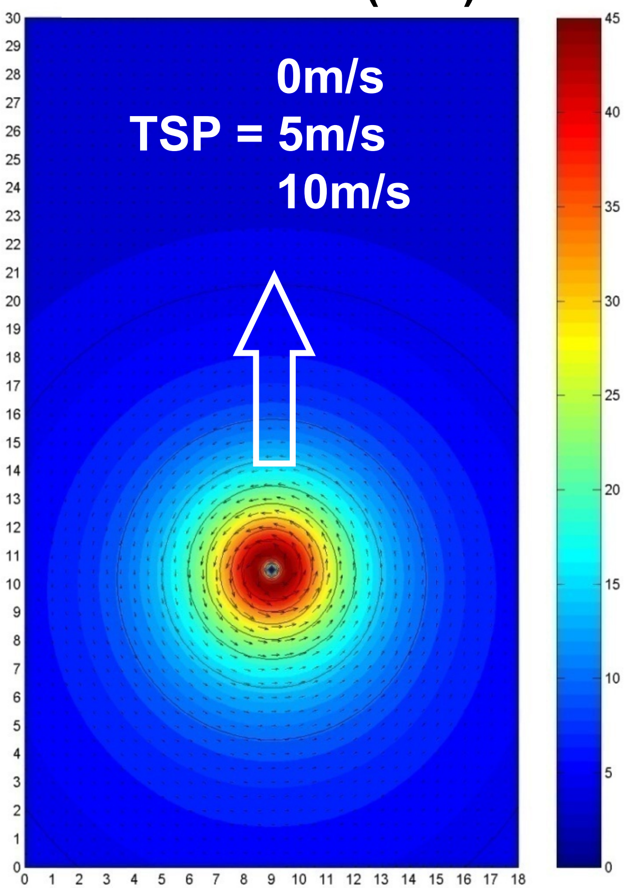
Observations of exchange coefficients

Waves Generated by Tropical Cyclones

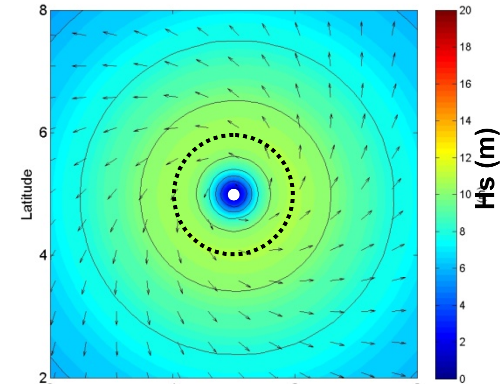
WAVEWATCH III wave model calculations

Wave Field

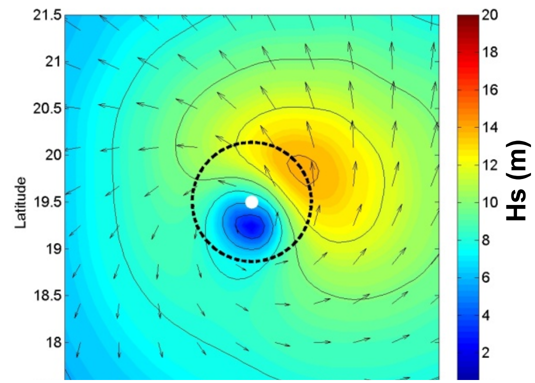
Wind Field (m/s)



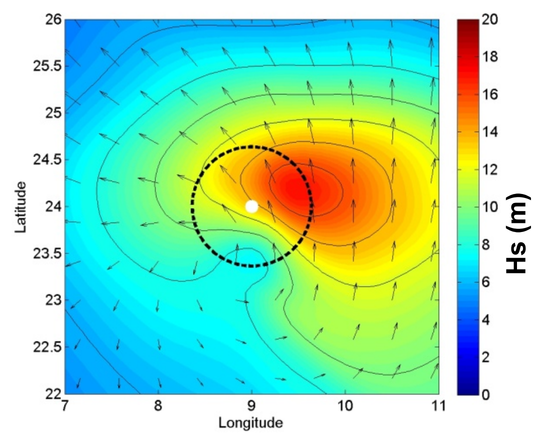
TSP 0m/s



TSP 5m/s

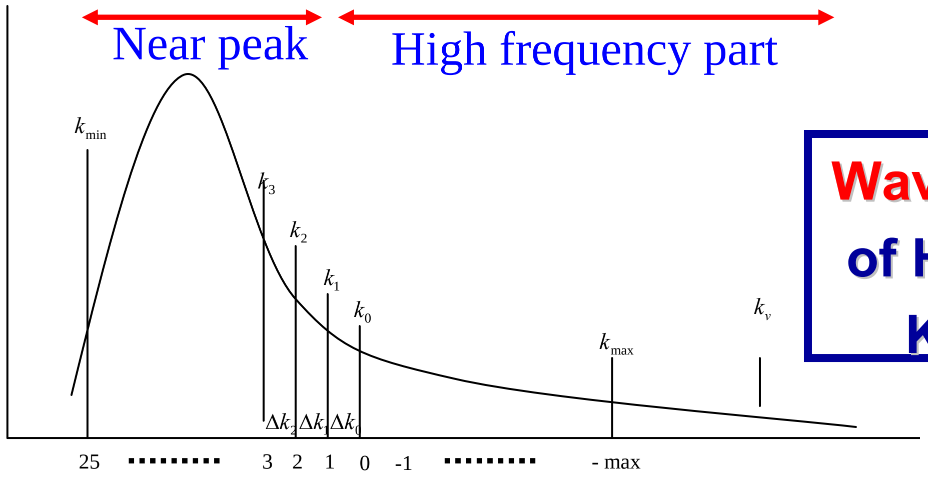


TSP 10m/s



Coupled Wind-Wave Model

- **Near the peak : WAVEWATCH III (WW3) model.**
- **High frequency part : Equilibrium Spectrum model of Hara and Belcher (JFM, 2002)**



Full wave spectrum

Wave Boundary Layer model
of Hara and Belcher (JPO, 2004)
Kukulka and Hara (JPO, 2008)

Explicitly calculates
wave-induced stress

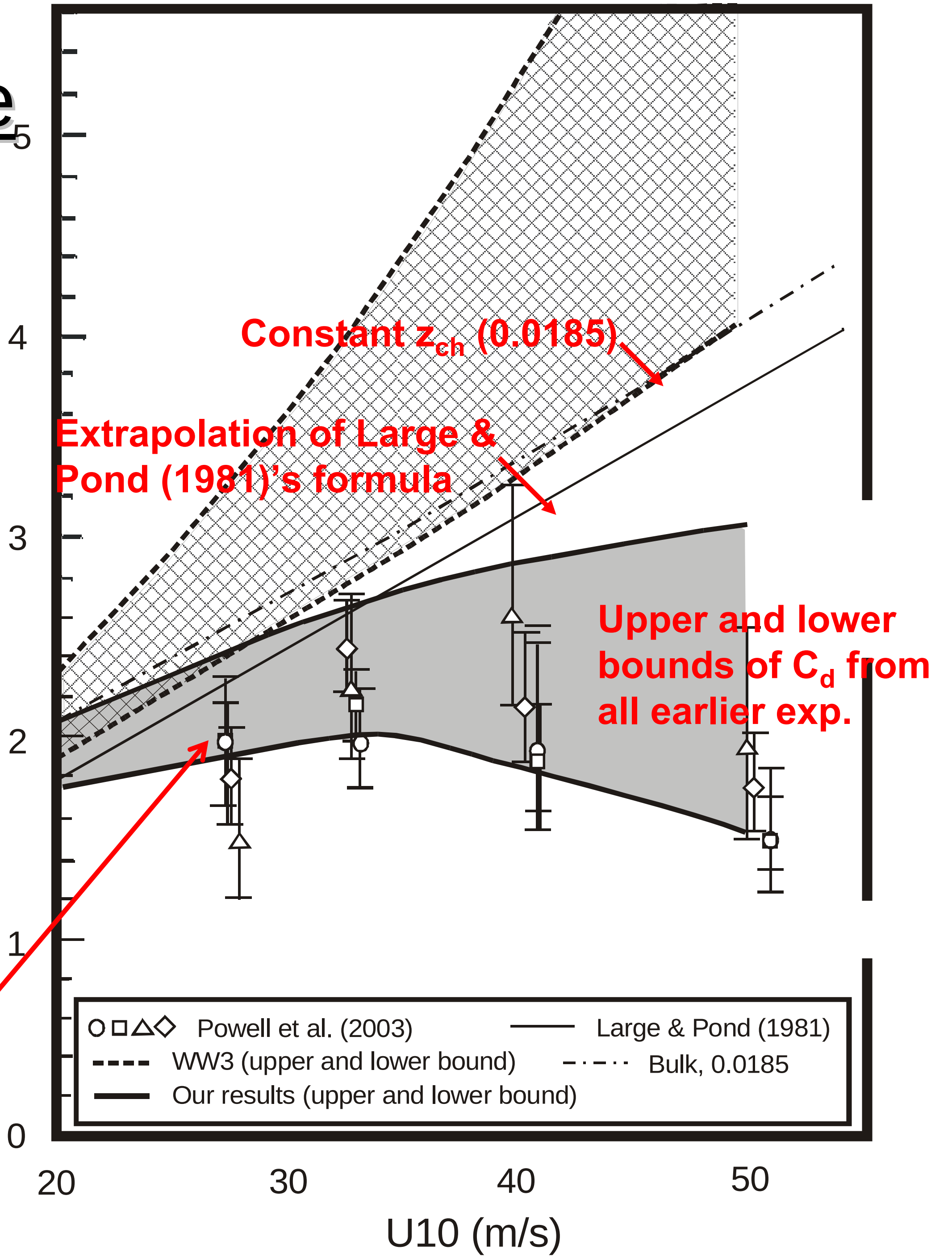
Wind profile and drag coefficient over any given seas

Sea state dependence

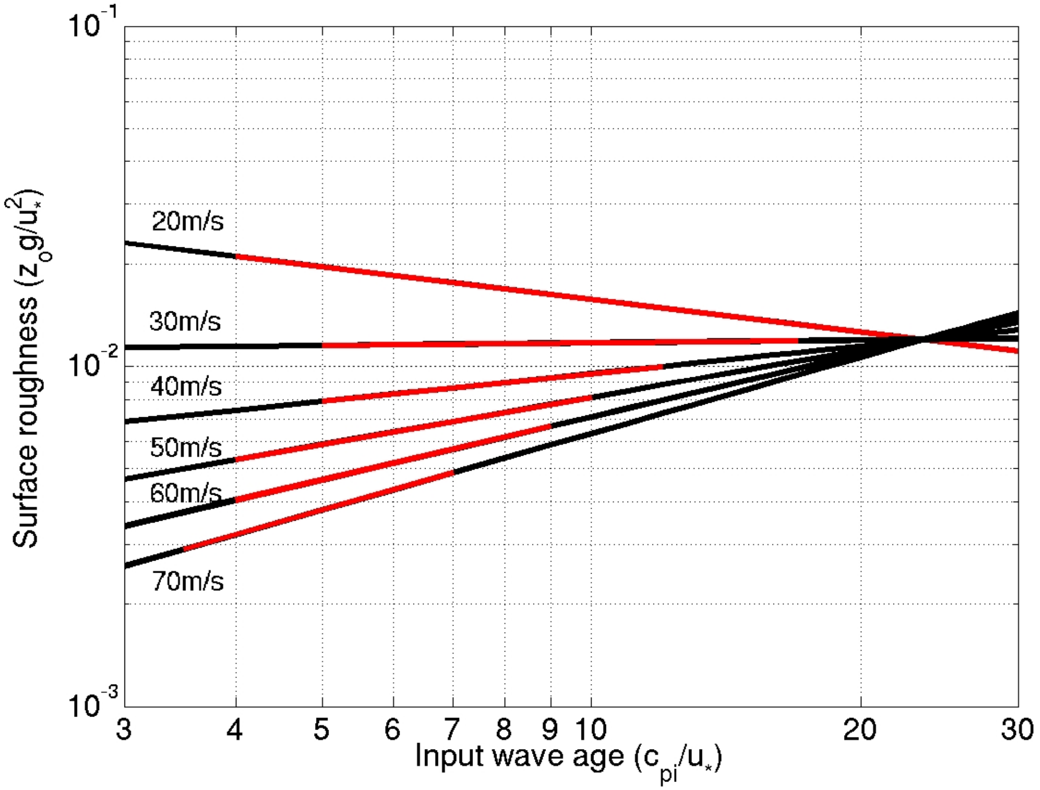
Calculations are based on observed hurricane winds in the Atlantic basin.

At high wind speeds, C_d levels off and even decrease with wind speed

GPS sonde observation under various hurricanes (Powell et al., 2003).



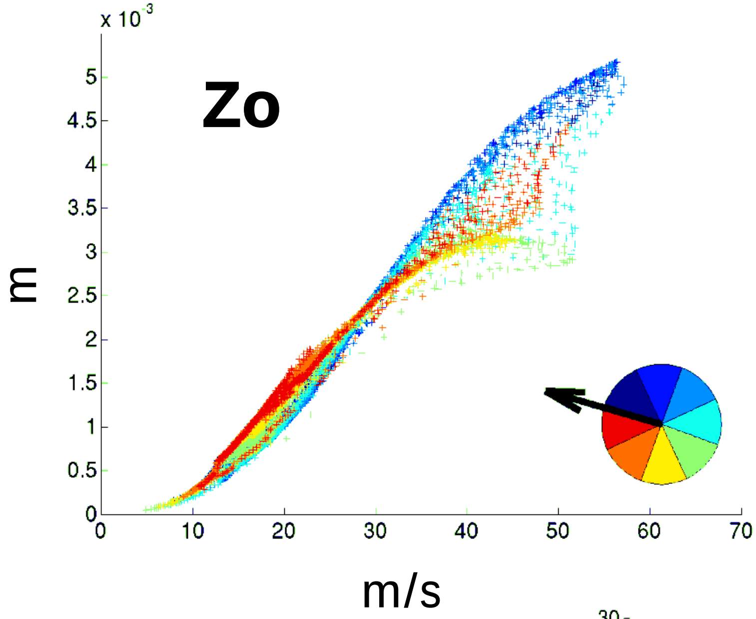
Charnock Coefficient vs. Wind Speed and Input Wave Age

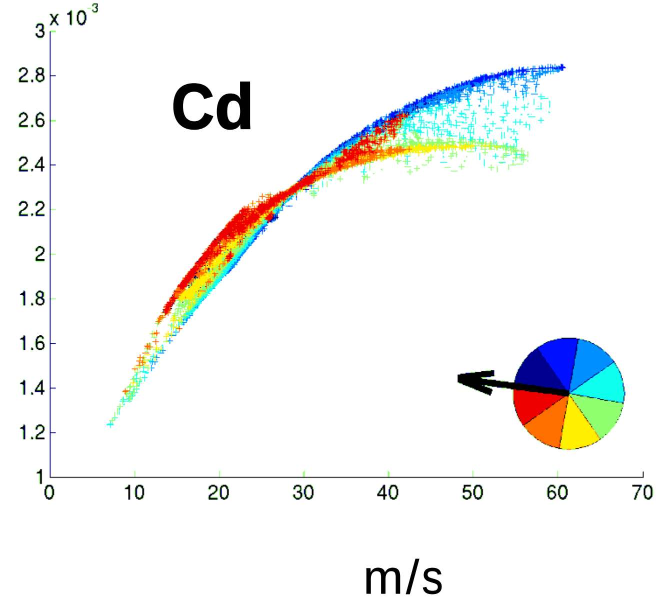


Red indicates the range of realizable input wave age for given wind speed

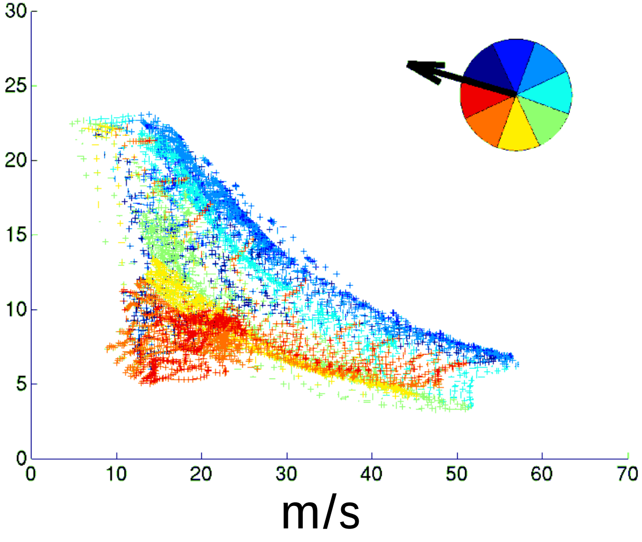
Input wave age is one of the output parameters of WW3 and is a measure of the development stage of locally wind forced waves, excluding the effects of long swell and waves that are misaligned with the local wind

Sea State Dependence in Coupled TC-Wave Model

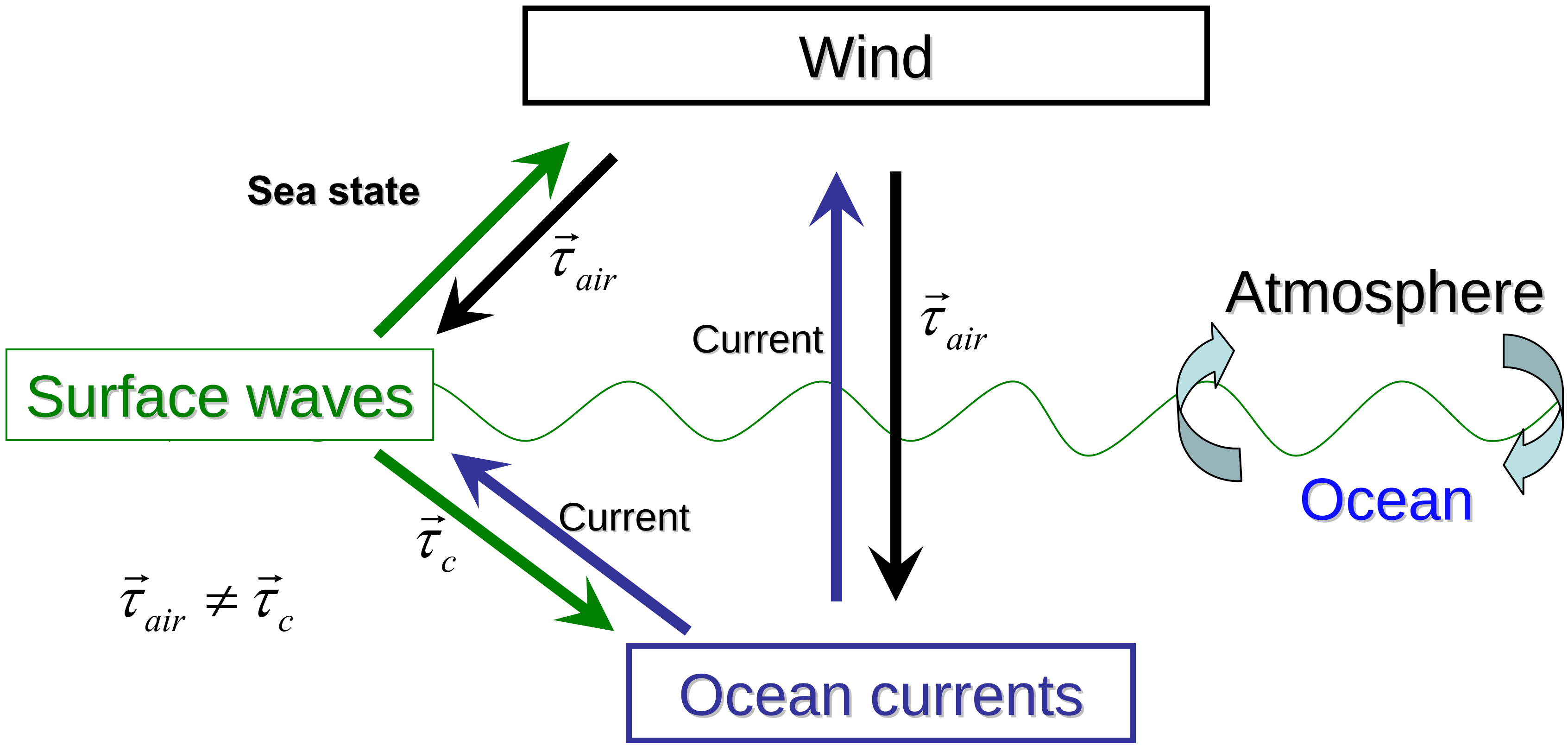




Input Wave age



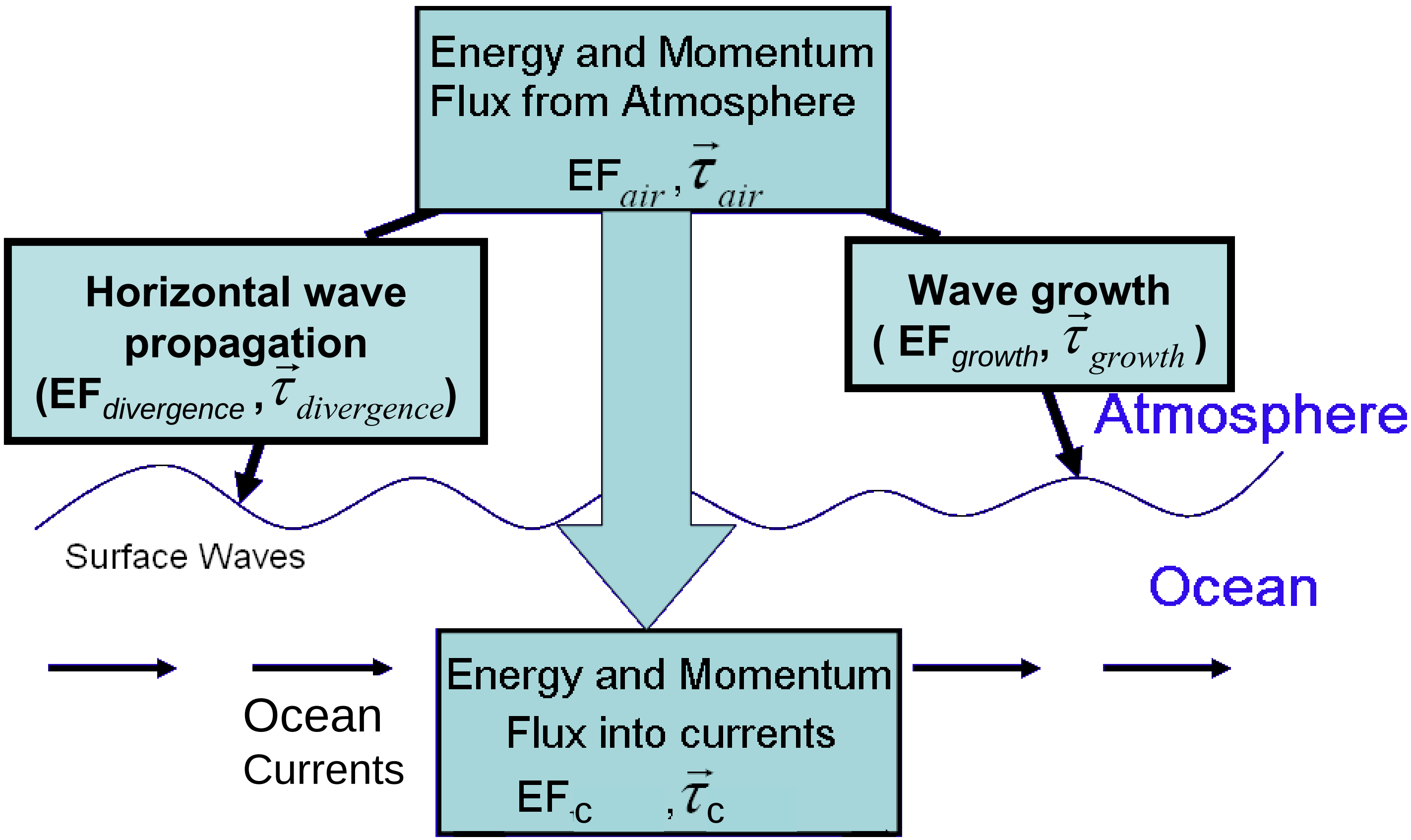
Wind-Wave-Current Interaction



Energy and Momentum Flux Budget Across Air-sea Interface

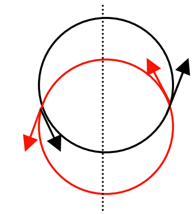
$$\mathbf{EF_{air} = EF_c + (EF_{\mathit{growth}} + EF_{\mathit{divergence}})}$$

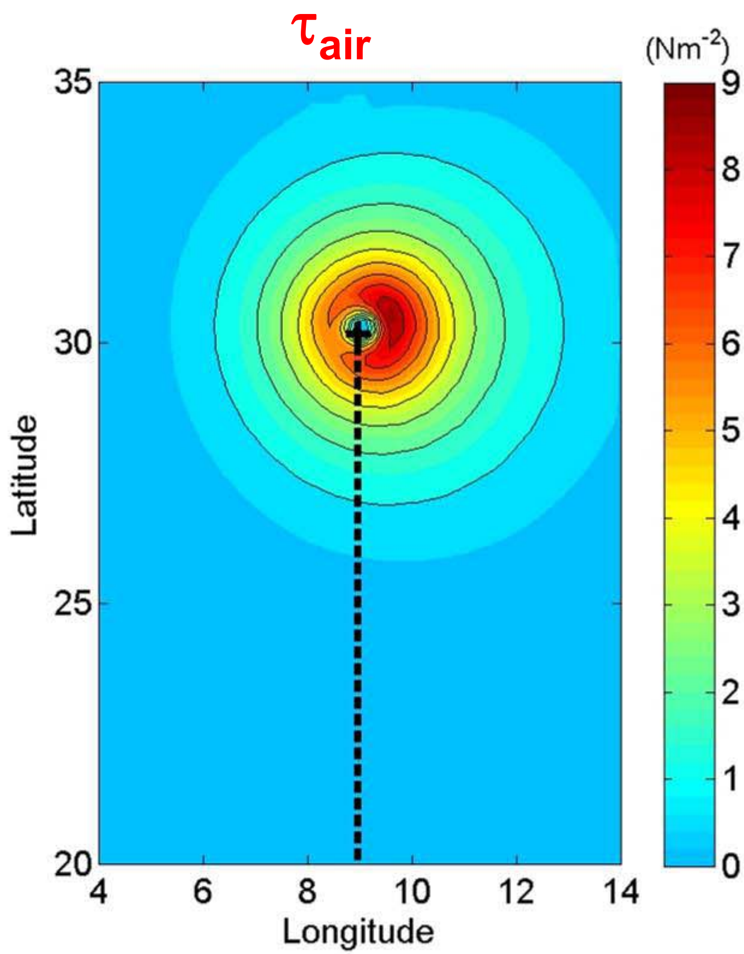
$$\vec{\tau}_{air} = \vec{\tau}_c + \left(\vec{\tau}_{growth} + \vec{\tau}_{divergence}\right)$$

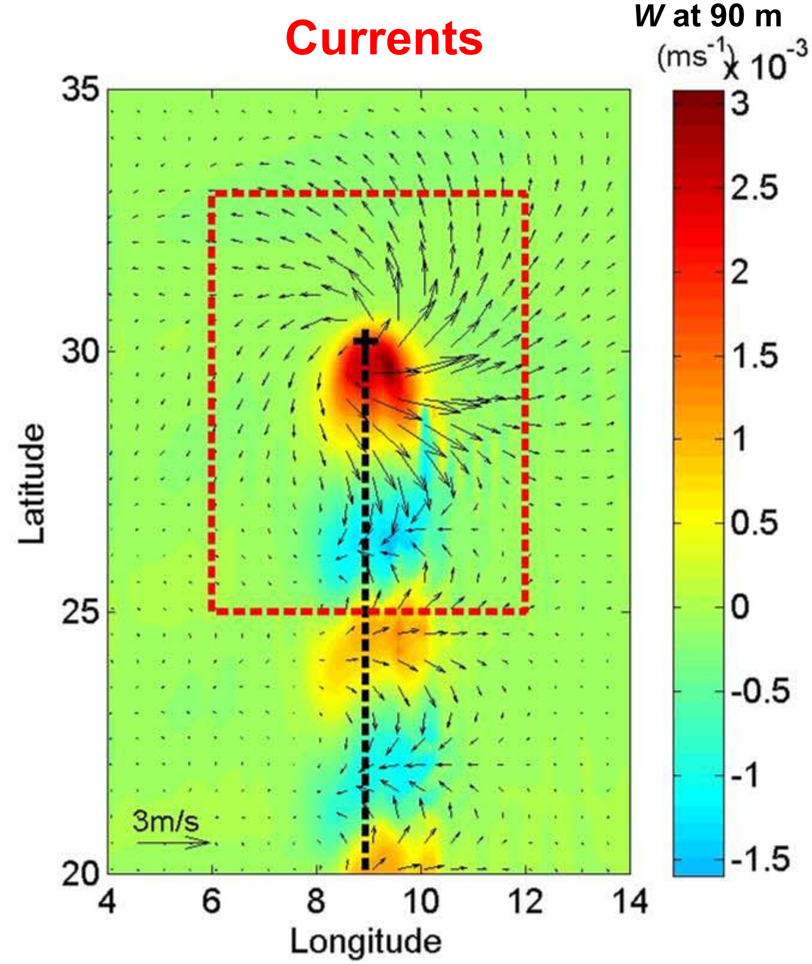


Wind-wave-current interaction

- **Ocean response**

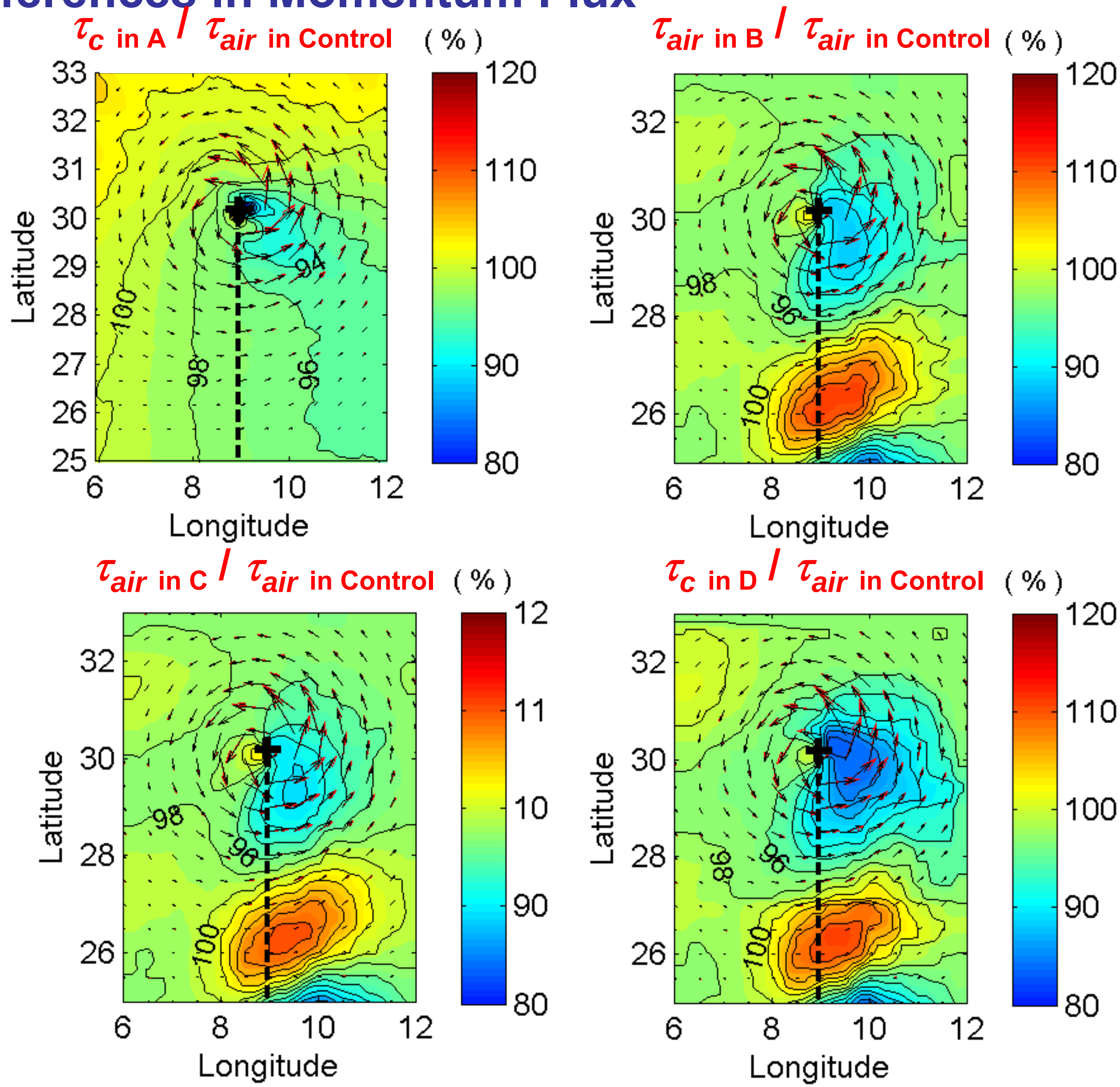






Wind-wave-current interaction

❖ **Differences in Momentum Flux**



<u>Exp A</u>

Budget
No current →wind
No current →wave

<u>Exp B</u>

No budget
Current →wind
Current →wave

<u>Exp C</u>

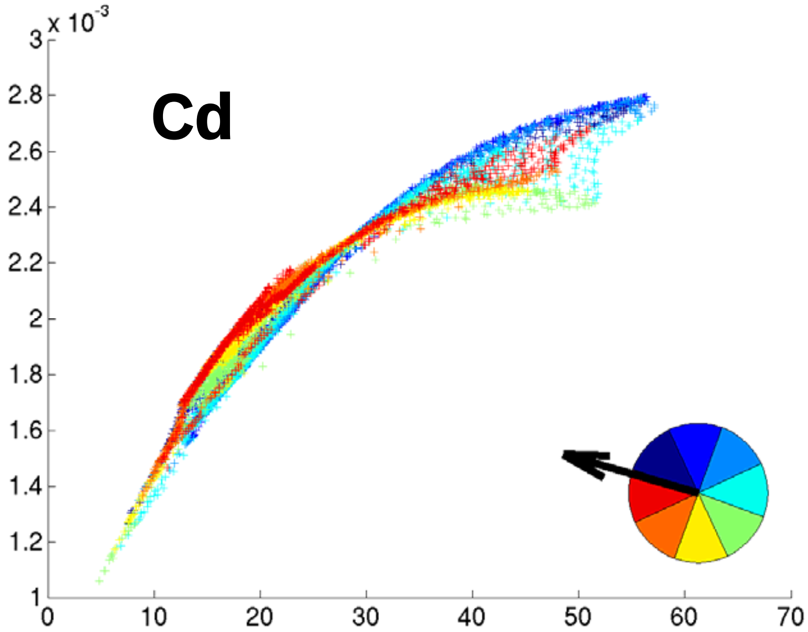
No budget
Current →wind
No current →wave

<u>Exp D</u>

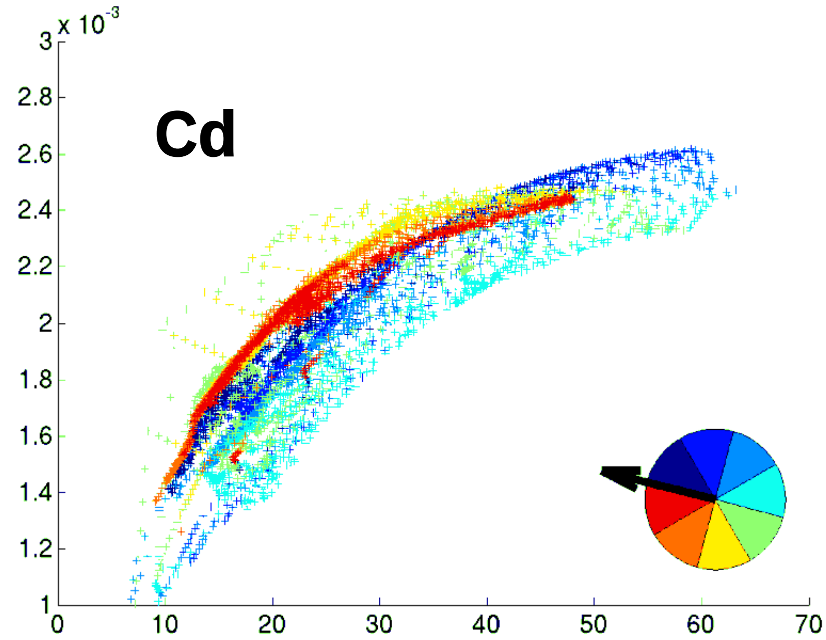
Budget
Current →wind
Current →wave

Effect of Wind-Wave-Current Interaction on Drag Coefficient

Wind-wave coupling only

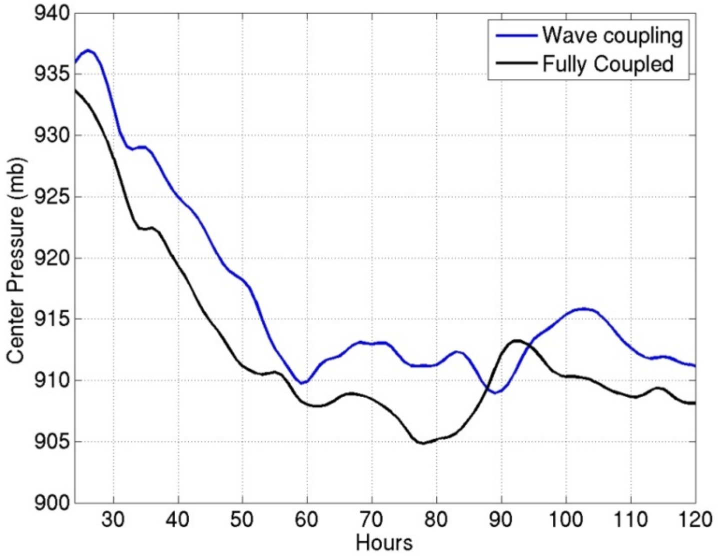


Wind-wave-current coupling

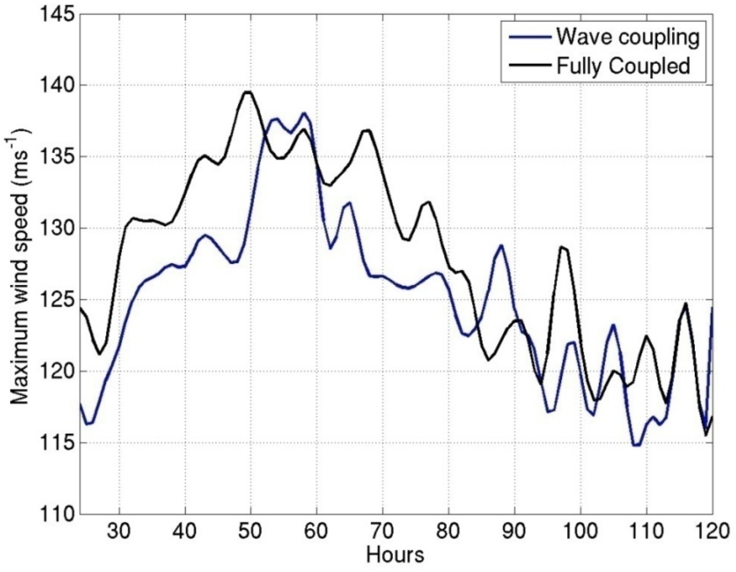


Effect of Atmosphere-Wave-Ocean Interaction on TC forecasts
(Idealized experiments)

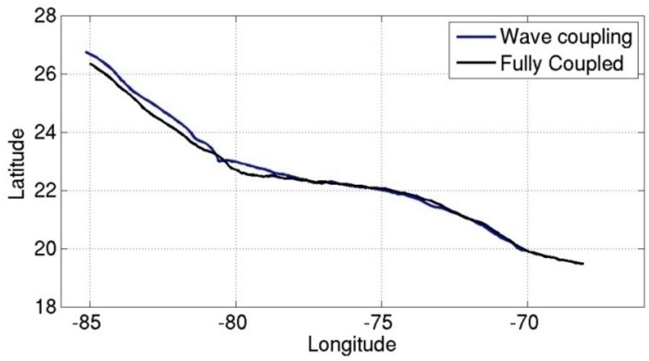
Central Pressure



Maximum Winds



Track



Air-Sea Coupling Strategies for Tropical Models

- In the TC model, parameterizations of the air-sea heat and momentum fluxes and sea spray source functions explicitly include *SST, sea state dependence*, and *ocean current effects*.

- The wave model is forced by a) *sea-state dependent momentum flux* and includes *ocean current effects*.

- The ocean model is forced by *sea-state dependent momentum* and *kinetic energy fluxes* calculated from the air-sea flux budget.

Summary

- Accurate initialization of ocean mesoscale features is critical for skillful coupled TC-Ocean forecasts.

- By neglecting upwelling 1D mixed layer models are inadequate for TCs translating at 5 m/s or less and misrepresent TC-induced SST cooling in the vicinity of oceanic fronts and eddies.

- Improved predictions of TC intensity, structure, and motion will require fully coupled ocean-wave-atmospheric models that explicitly resolve the effects of sea state on air-sea fluxes and spray generation.