# Advancing NOAA's HWRF prediction system through enhanced physics of the air-sea coupling and ocean model initialization


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# HWRF Coupled Model Structure

- HWRF fully coupled Atmosphere-Ocean-Wave system will include:
  - a triple-nested (27/9/3km) HWRF atmospheric model,
  - POM or HYCOM ocean model, and
  - a multi-grid WAVEWATCH III wave model.

# Air-Sea Interface Module

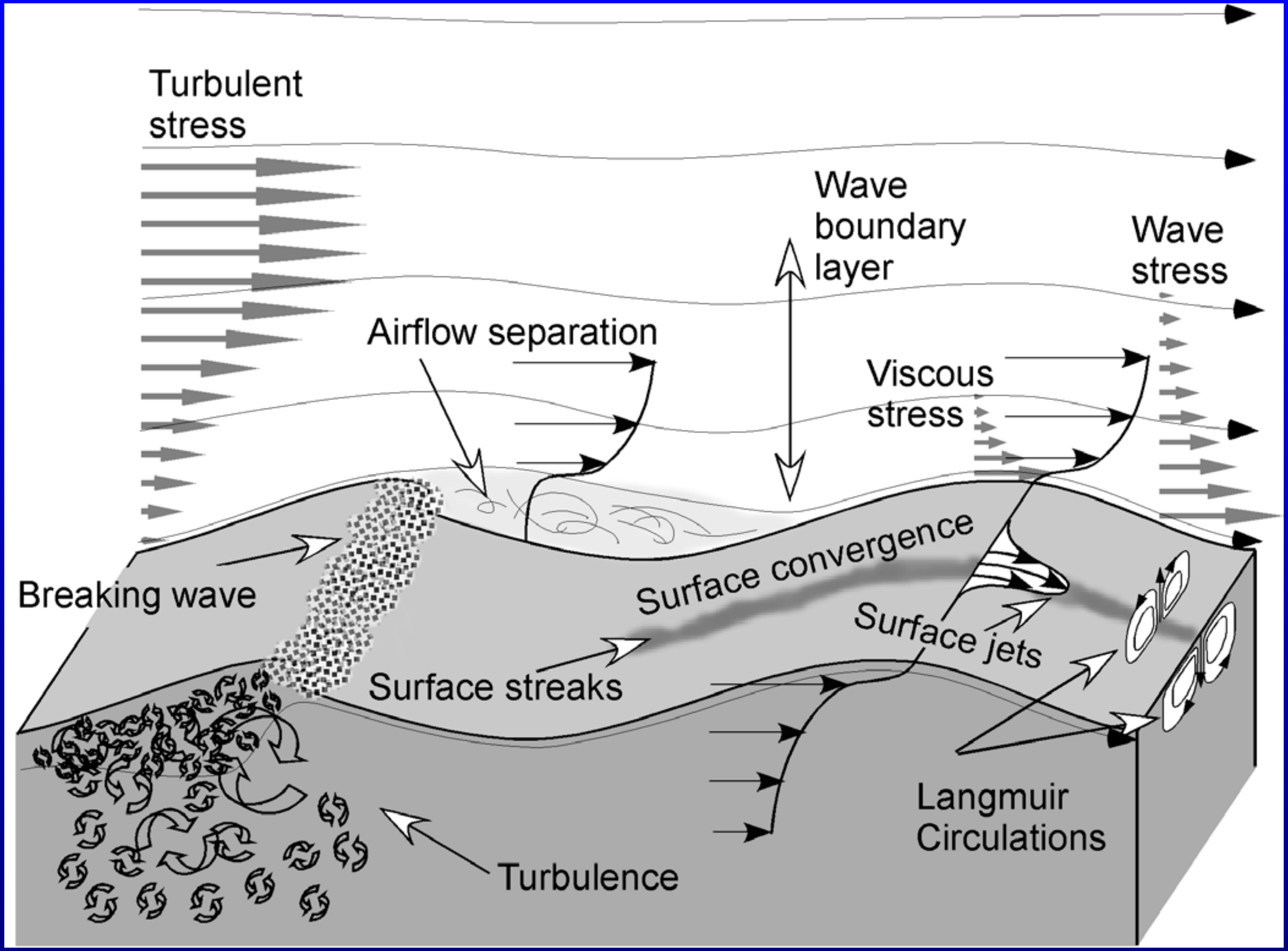



Image courtesy of Fabrice Veron

# Discussion Outline

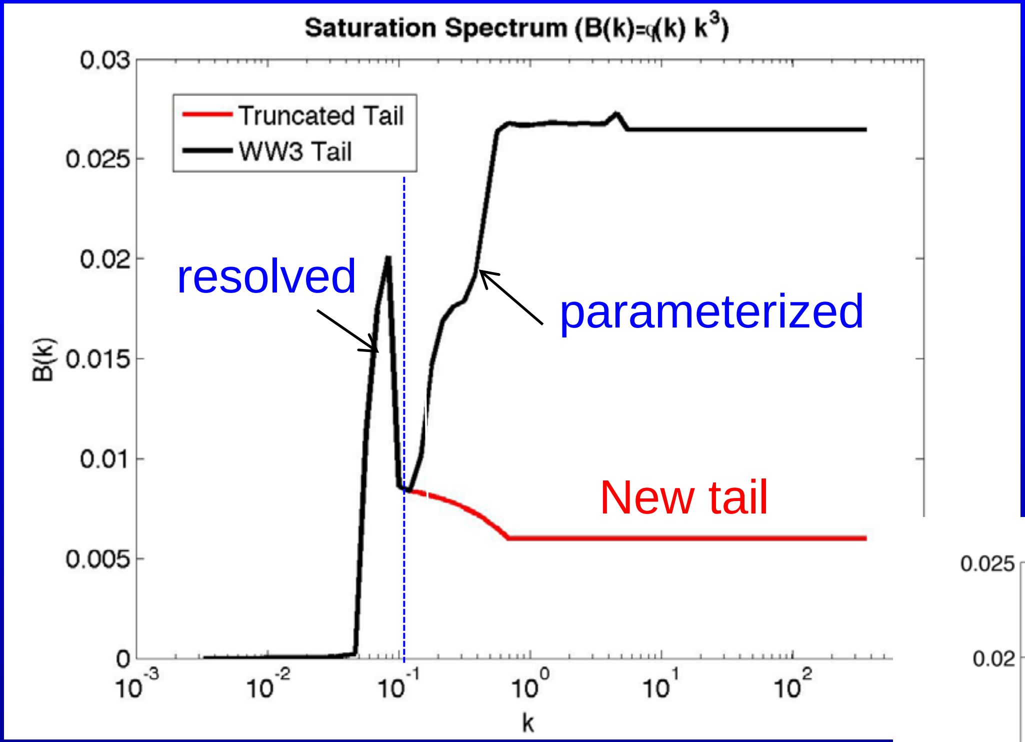
- Sea state (wave) dependent drag coefficient
- Wave-induced Stokes drift and upper ocean mixing
- Wave-induced Coriolis-Stokes effect
- Princeton Ocean Model initialization upgrade

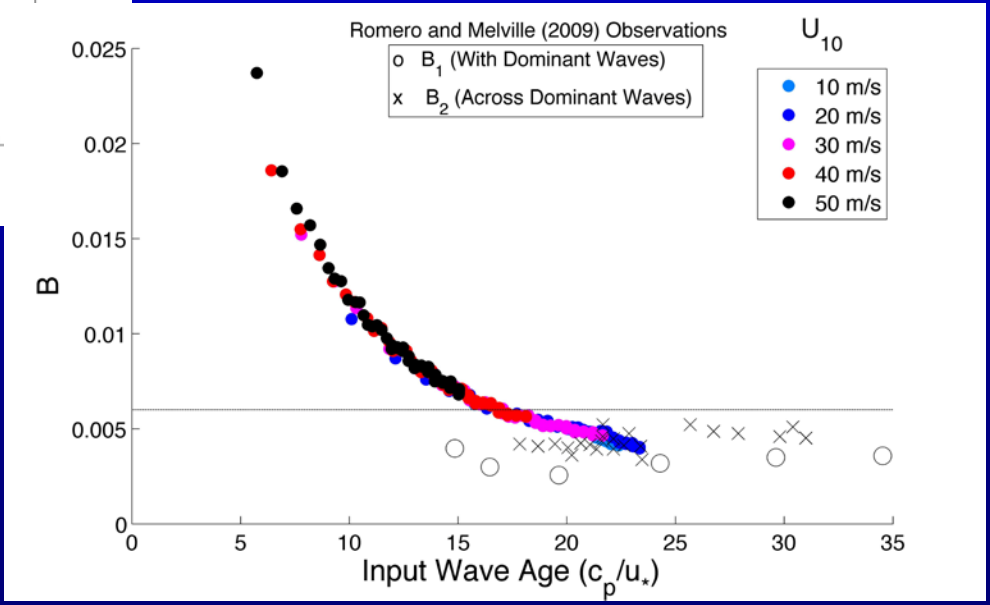
# Sea State Dependent Drag Coefficient

- In the air-sea interface module, the momentum flux (drag coefficient) is calculated using the wave model output and a wave-boundary layer model.

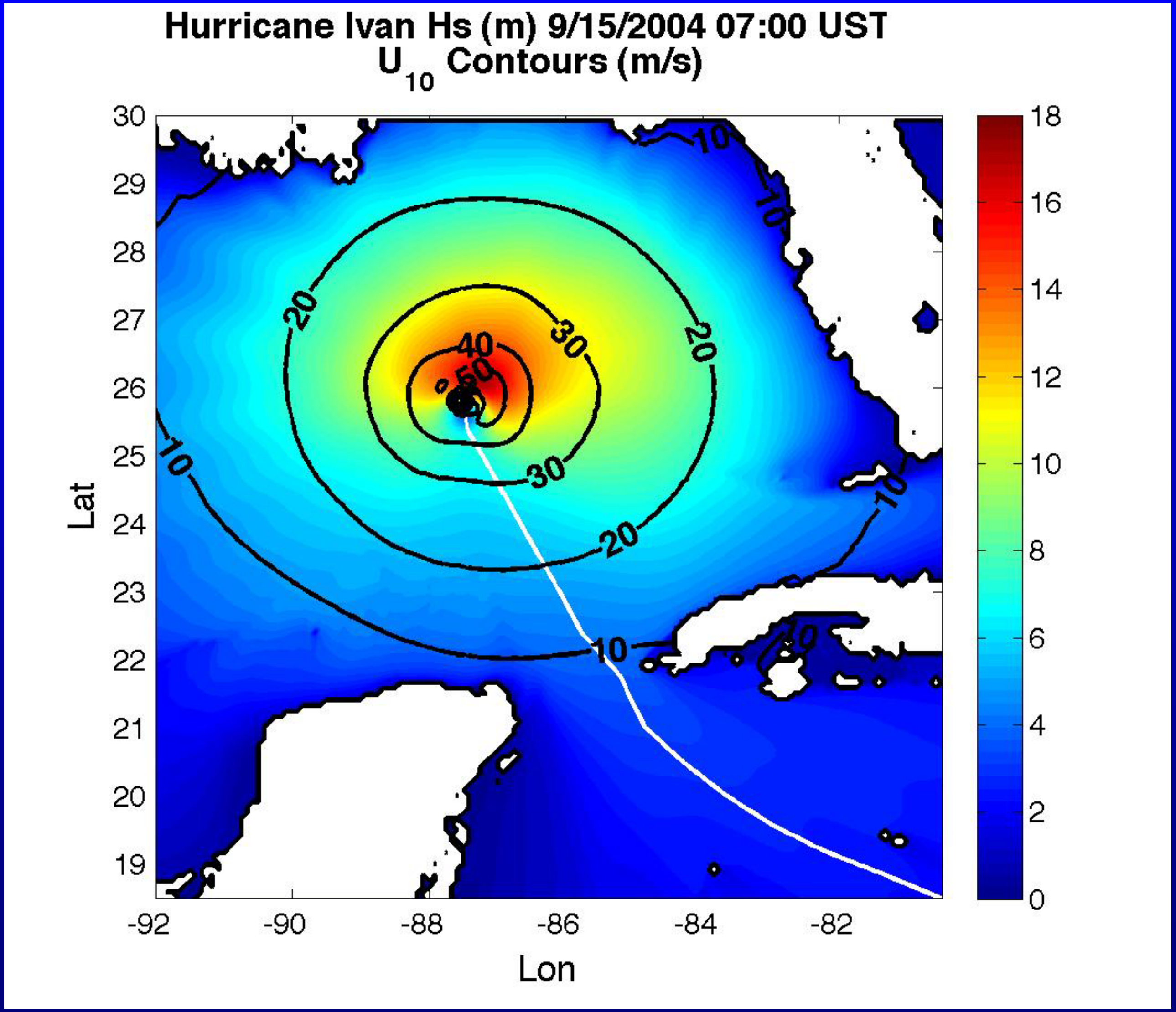
- We have examined two momentum flux models, developed at University of Rhode Island (URI) and University of Miami (UM) as potential candidates for the air-sea interface module.

# Evaluation of Wave Spectrum in WW3 and its Impact on Drag Coefficient in the URI flux model



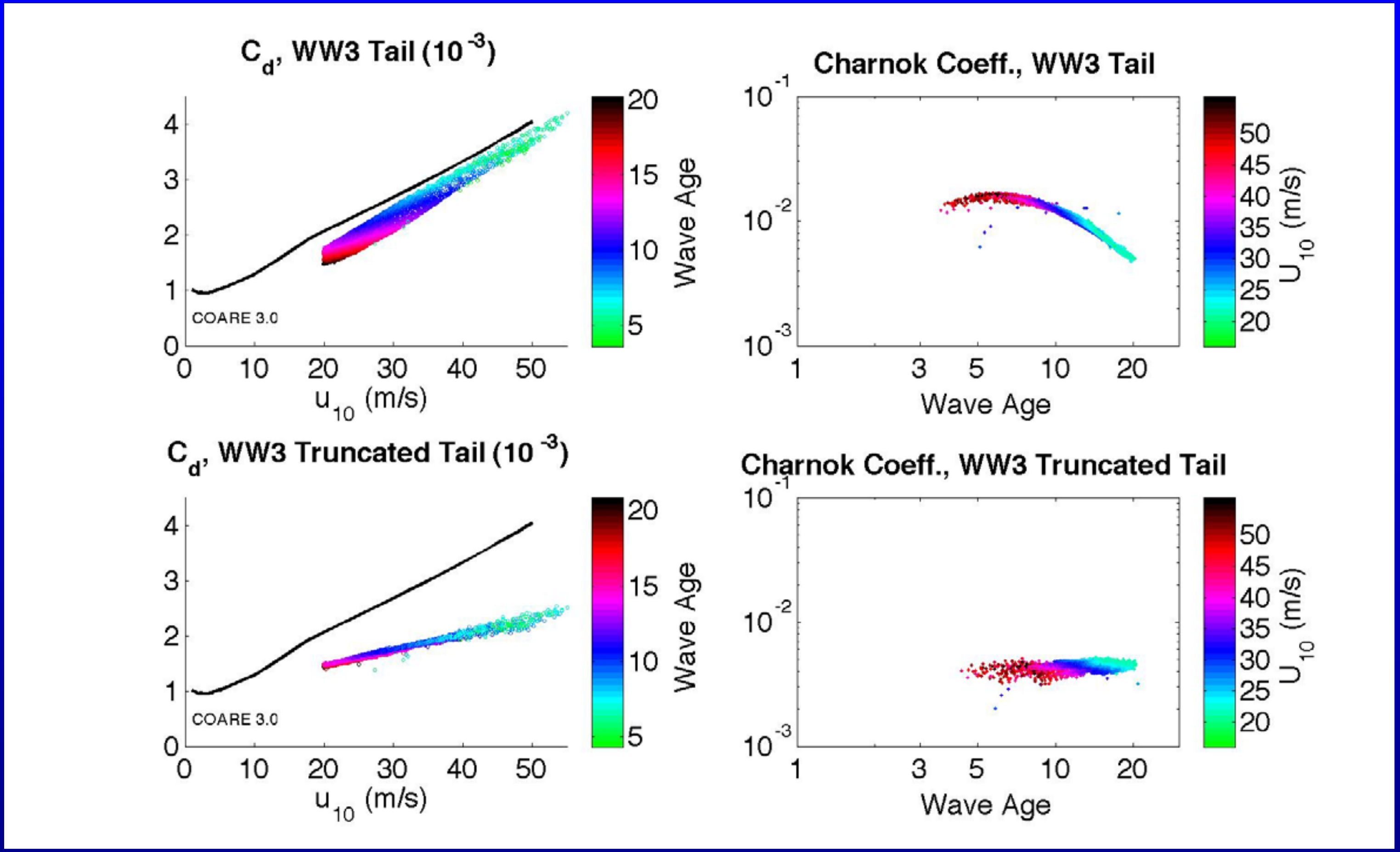
# Hurricane Ivan (2004) Simulation with WAVEWATCH and H*Wind Forcing



# Sea-State Dependent Drag Coefficient

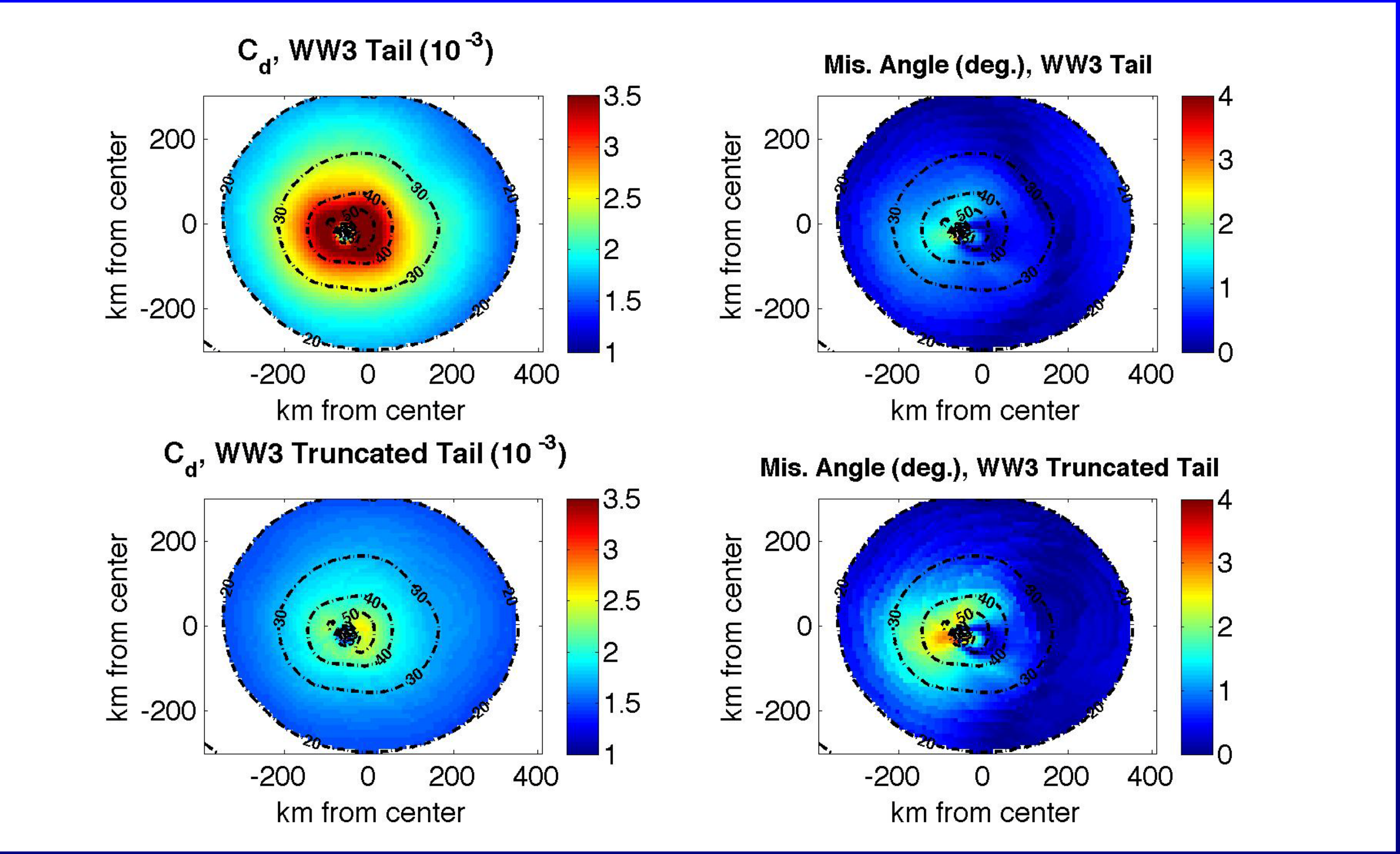
WW3 Tail

New Tail




Only data for $U_{10}$ > 20 m/s are shown

# Drag Coefficient and Wind Stress - Wind Misalignment



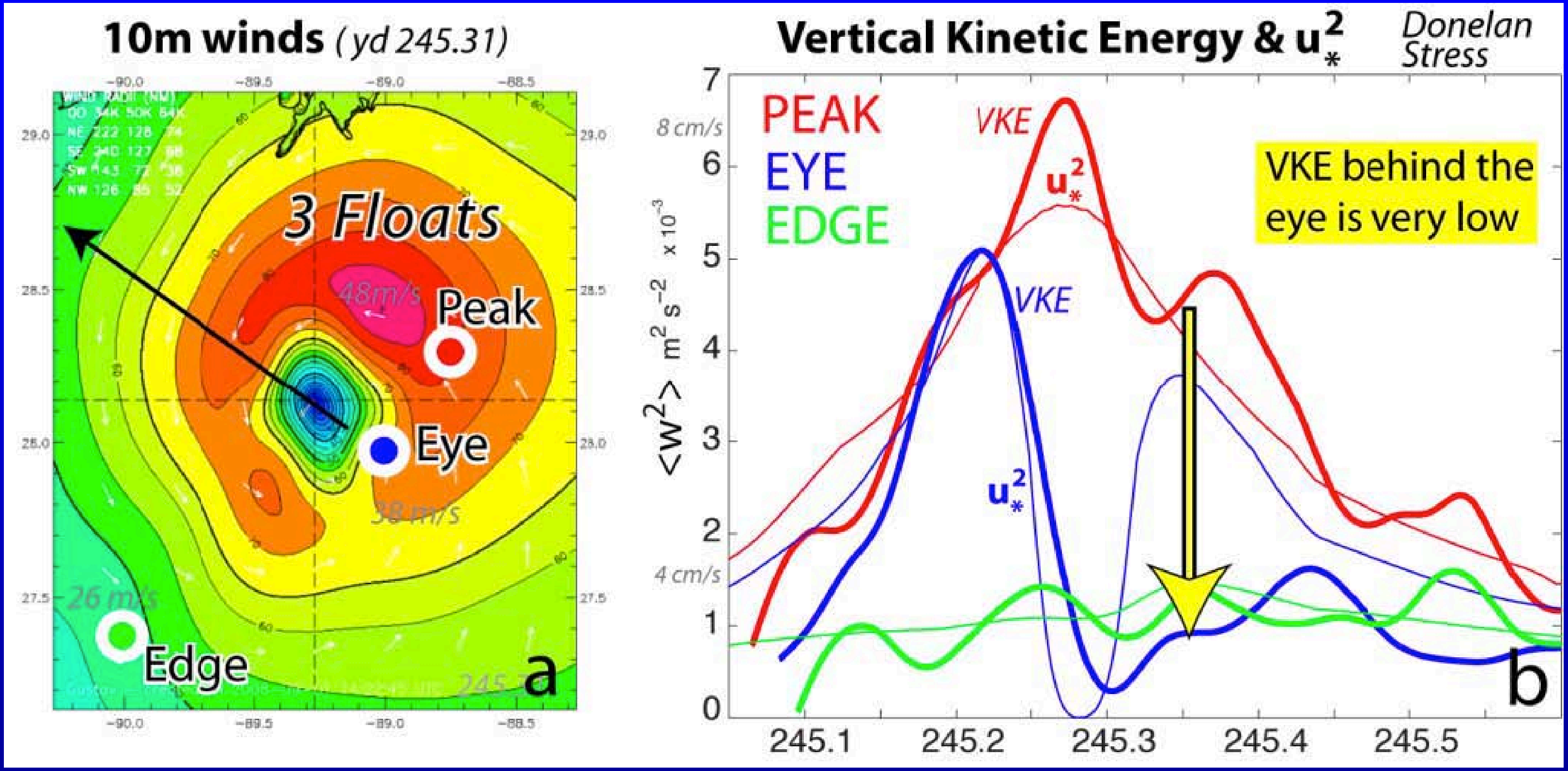

Only data for $U_{10}$ > 20 m/s are shown

# Stokes Drift Due to Surface Waves Under Hurricane Conditions

- Surface wave motions introduce net mass transport, “Stokes drift”, which has the effect of tilting and organizing the upper ocean turbulent eddies. The resulting turbulence is called “Langmuir turbulence”.

- In hurricanes, of particular interest is the conditions in which wind is misaligned with waves at angles greater than 90º. In such cases the Stokes drift may suppress  Langmuir turbulence and consequent sea surface cooling.

# Mixed Layer Kinetic Energy Measurements in Hurricanes




Lagrangian floats deployed ahead of Hurricane Gustav (2008) found reduced vertical kinetic energy in the mixed layer behind the storm.

Courtesy of Eric D'Asaro

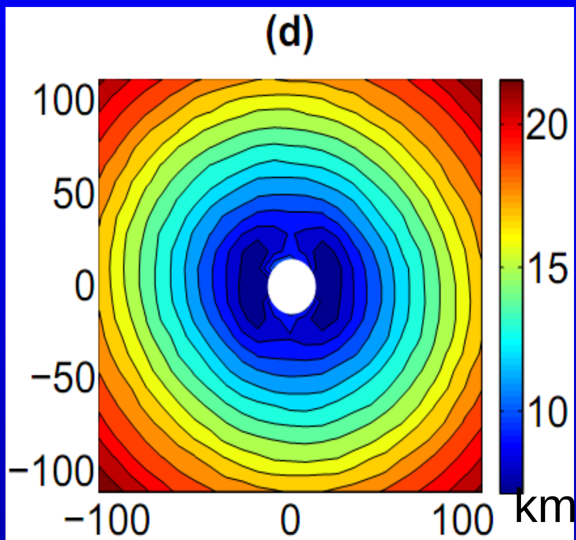
# Stokes Drift Calculations in Idealized Hurricane

- We examine the vertical profile of Stokes drift under idealized hurricanes.

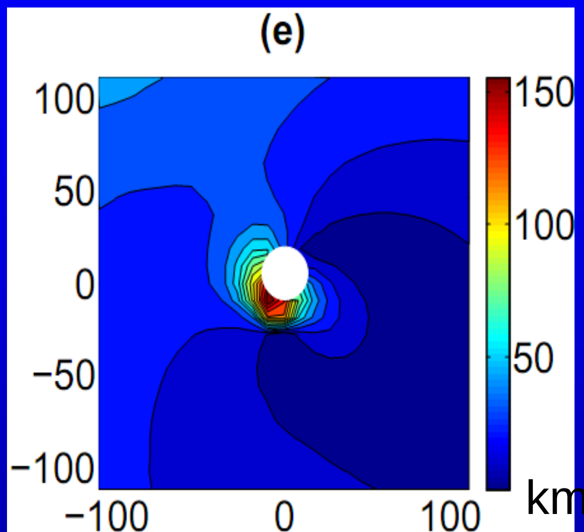
- WAVEWATCH is used to calculate directional wavenumber spectra under stationary and translating hurricanes (at 5 $ms^{-1}$ and 10 $ms^{-1}$), with a $R_m$=70 km and $V_m$=45 $ms^{-1}$.

- Stokes drift is calculated from the surface down to 240 m depth.

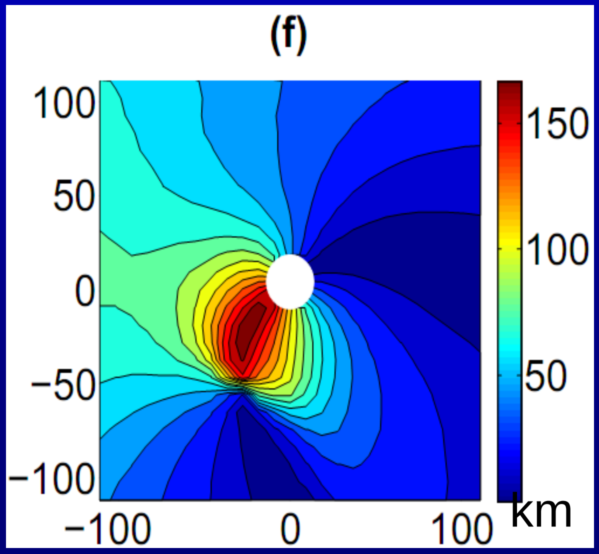
# Angle difference between wind direction and Stokes drift direction at $z = k_{peak}^{-1}$




$U_T = 0$




$U_T = 5$ m/s




$U_T = 10$ m/s

Angle exceeds 90$^o$ behind a translating hurricane.

# Coriolis–Stokes Effect

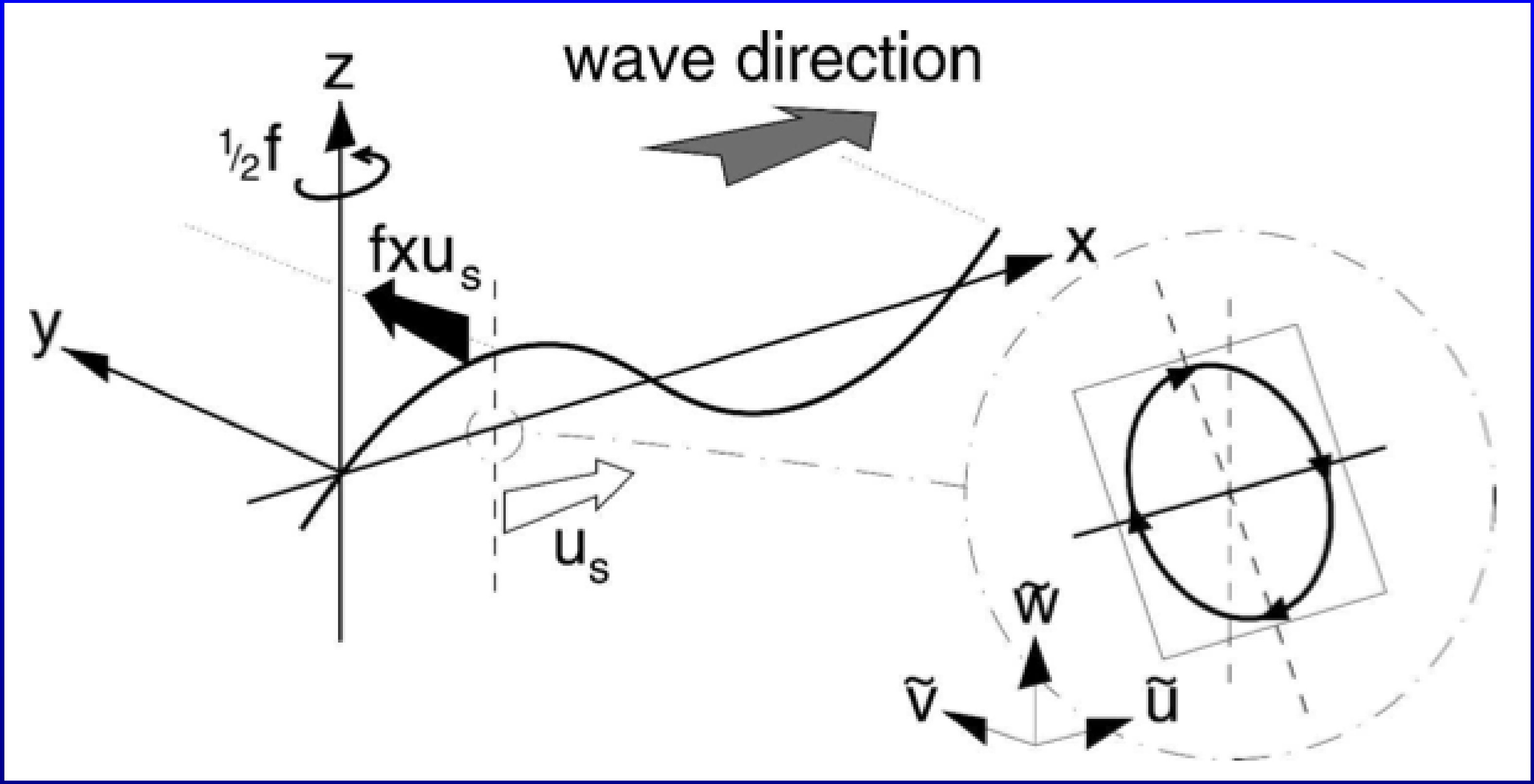



Figure from Polton et al. (2005)

# Ocean Momentum Equations and Coriolis–Stokes Forcing

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} + w \frac{\partial u_i}{\partial z} - \epsilon_{ijz} f_z u_j = -\frac{g}{\rho_o} \int_z^\eta \frac{\partial \rho}{\partial x_i} dz - g \frac{\partial \eta}{\partial x_i} + \frac{\partial \tau_{iz}}{\partial z}$$

surface boundary condition is modified:

$$\tau_{iz} = \tau_{air,i} - \frac{\partial M_i}{\partial t} - \frac{\partial F_{ij}}{\partial x_j} - \tau_{cs,i} \quad at \quad z = \eta$$

Coriolis-Stokes Forcing

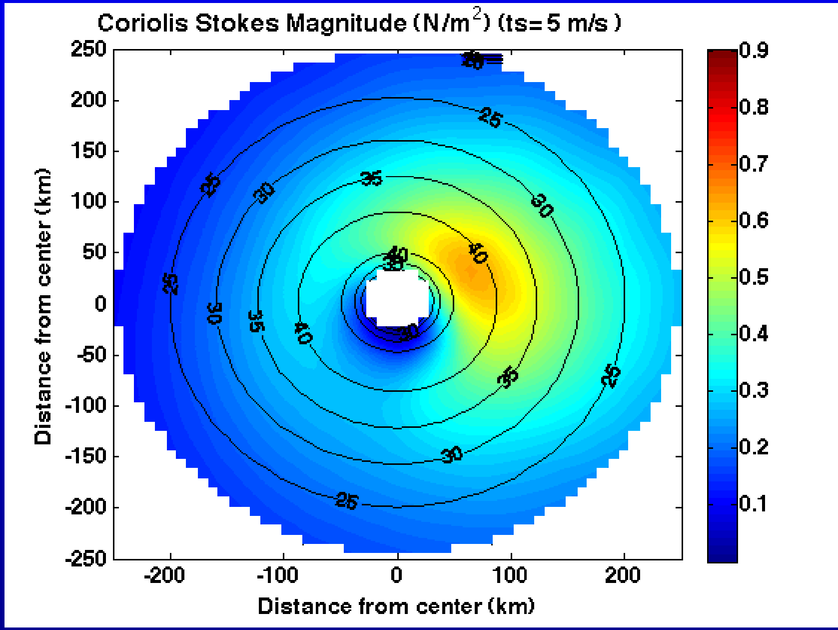
Momentum flux into the ocean ≠ wind stress!

Wave effect on momentum flux (Fan et al., 2010) already included in ASIM

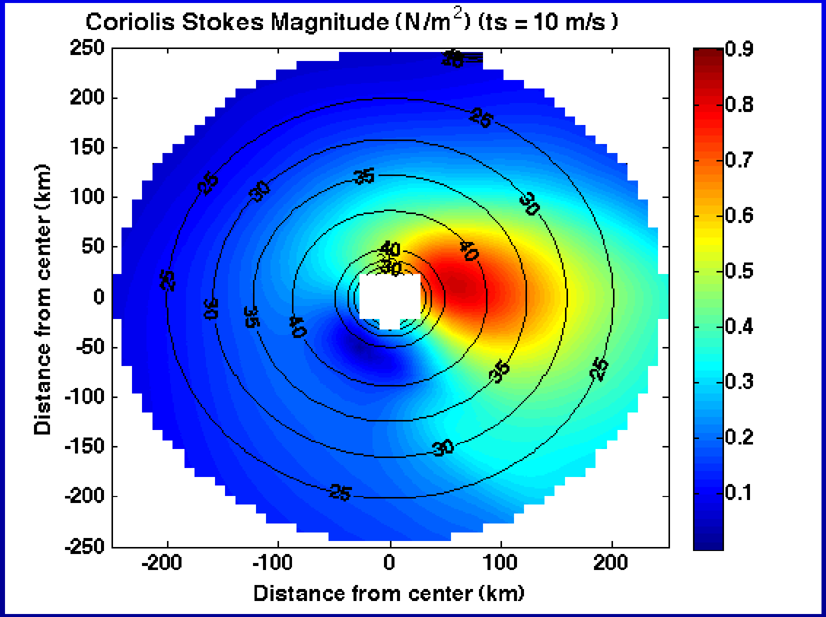
$$\tau_{cs,i} = - \int_{-\infty}^{\eta} \epsilon_{ijz} f_z u_{s,j} dz$$

# Coriolis–Stokes Forcing Under Idealized Moving Hurricane

$U_T$=5 m/s



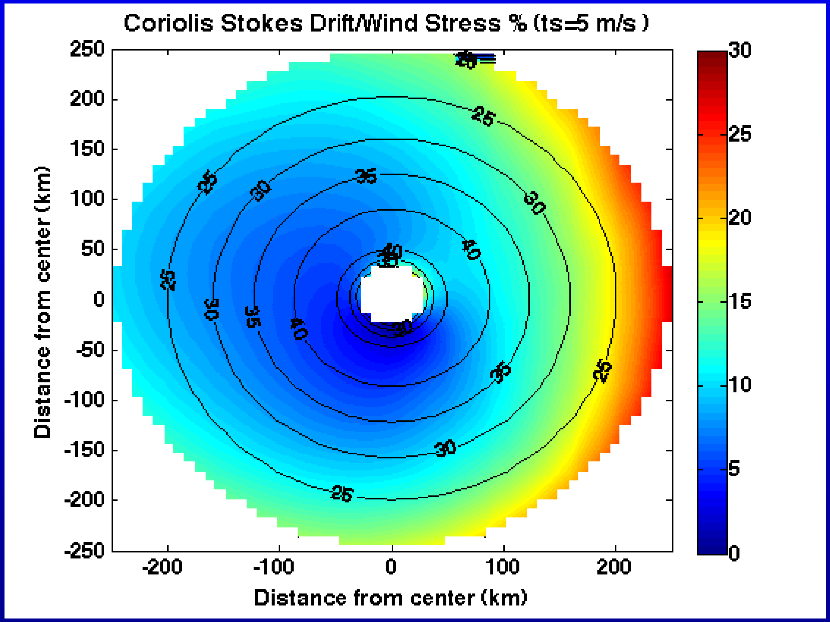

$U_T$=10 m/s



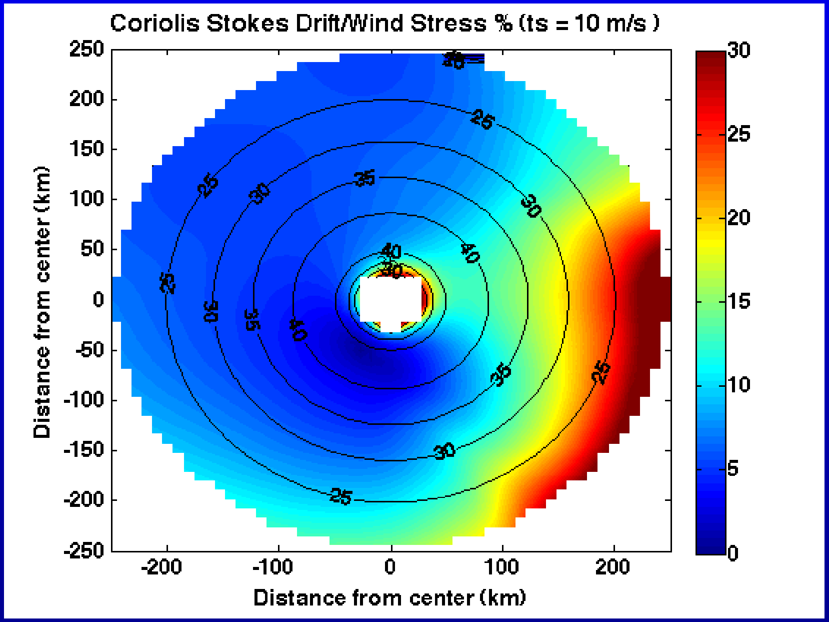

Only data for $U_{10}$ > 20 m/s are shown

# Coriolis–Stokes/Wind Stress Ratio Under Idealized Moving Hurricane

$U_T$=5 m/s




$U_T$=10 m/s



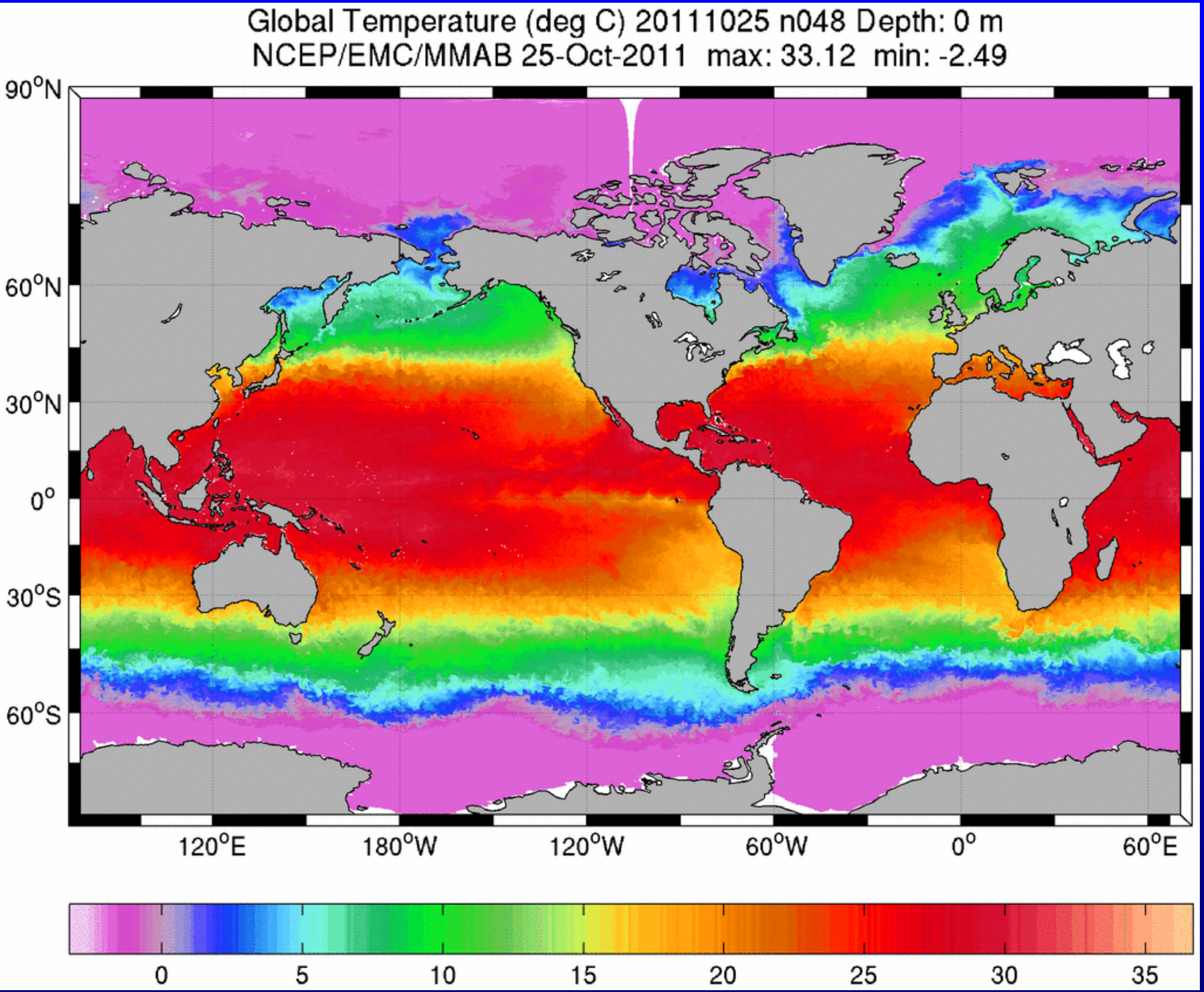

Only data for $U_{10}$ > 20 m/s are shown

# Princeton Ocean Model Initialization Upgrade

- POM is the ocean component of the GFDL, GFDN, HWRF operational models

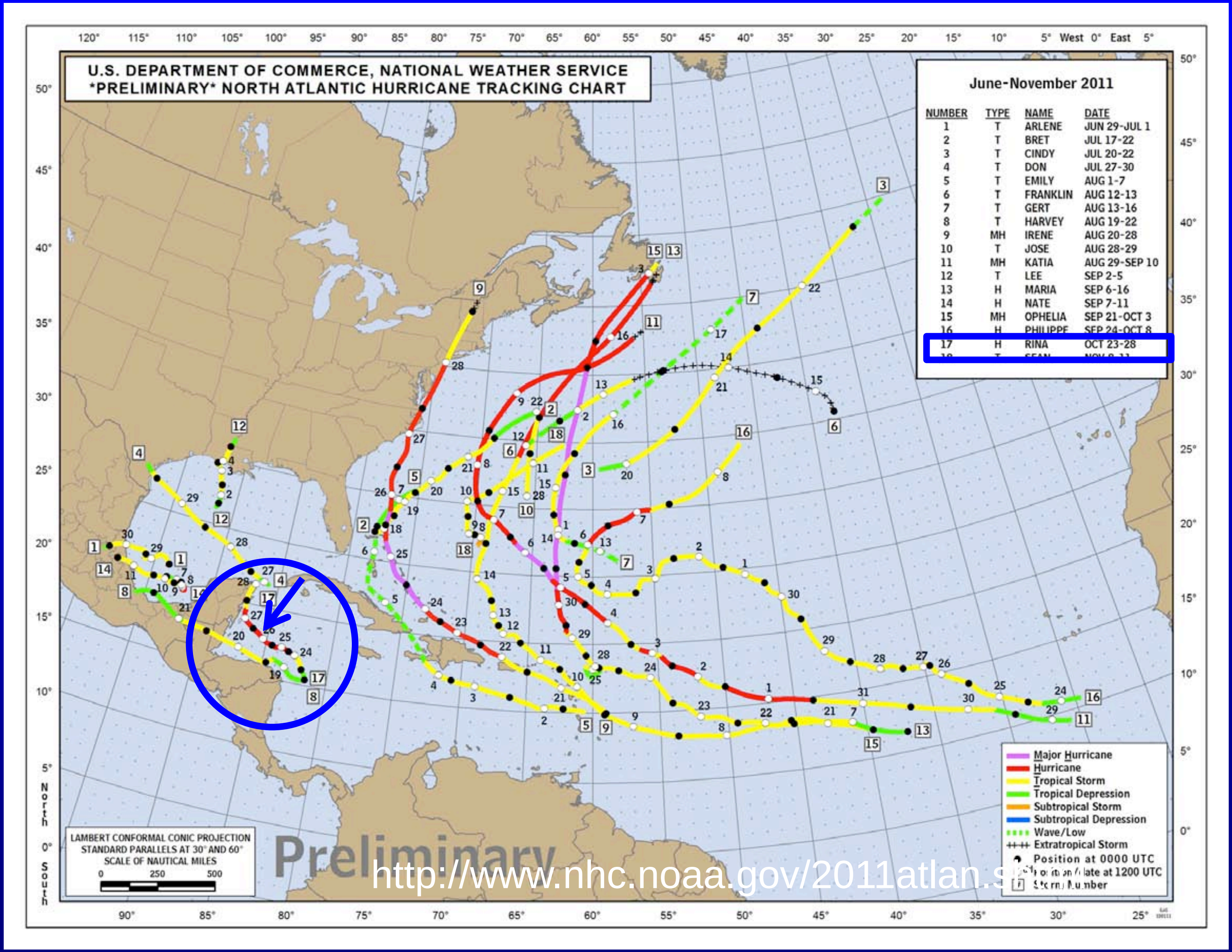
- It is initialized differently in different ocean basins:
  - Atlantic: GDEM climatology, feature-based initialization
  - Eastern Pacific: GDEM monthly climatology in GFDL and HWRF, but NCODA in GFDN
  - Western Pacific and other ocean basins: NCODA in GFDN

# NCEP's RTOFS (operational since 10.25.2011) based on 1/12º Global HYCOM




http://polar.ncep.noaa.gov/global/

# 2011 Atlantic Hurricane Season

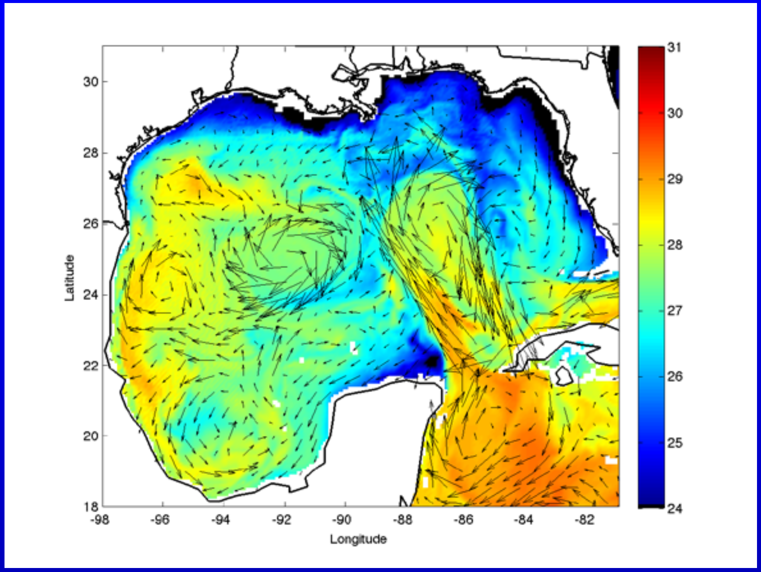


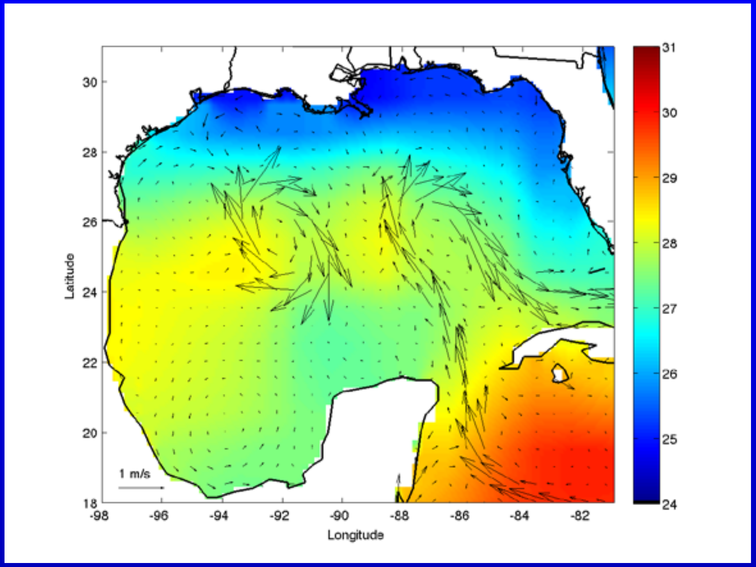

http://www.nhc.noaa.gov/2011atlan.shtml

# 10/25/11: RTOFS-Global vs. Feature-based

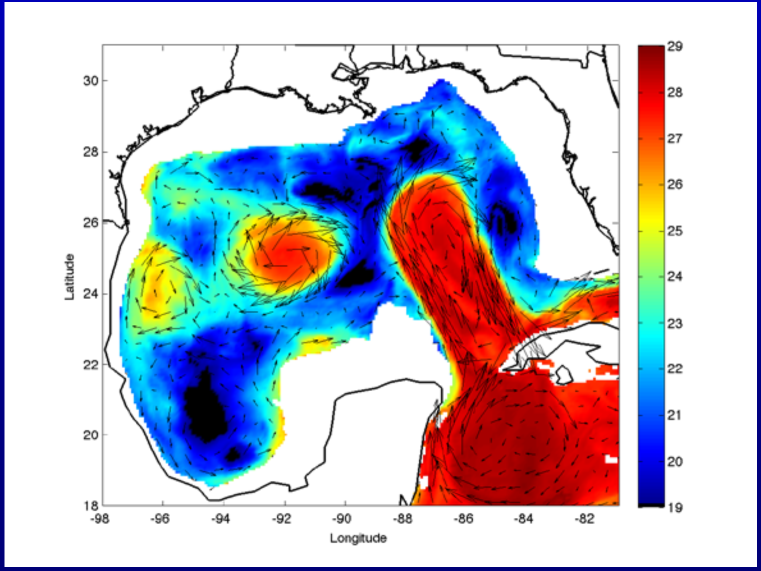
RTOFS-Global

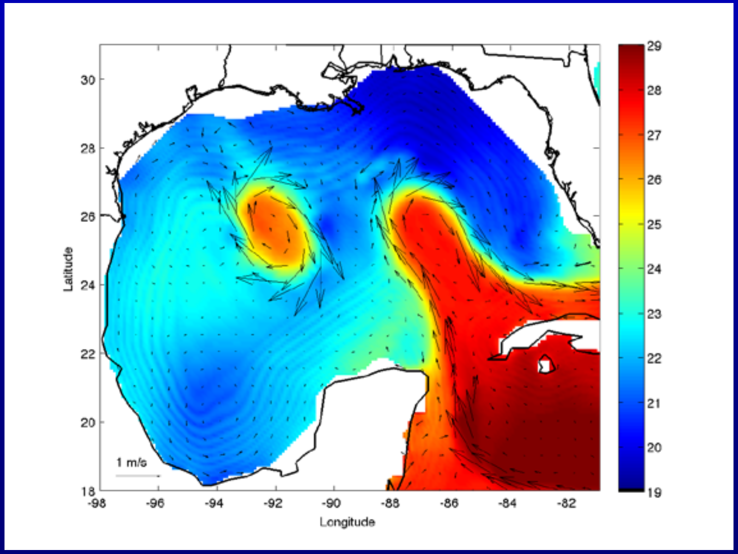
Feature-based w/GFS SST




SST




75-m T

# 10/25/11: RTOFS-Global vs. Feature-based

| RTOFS-Global | Feature-based w/ GFS SST | |
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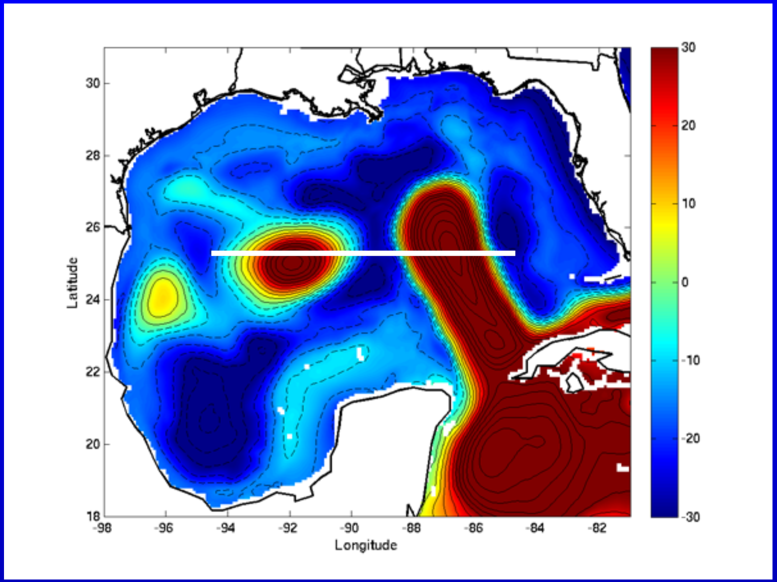
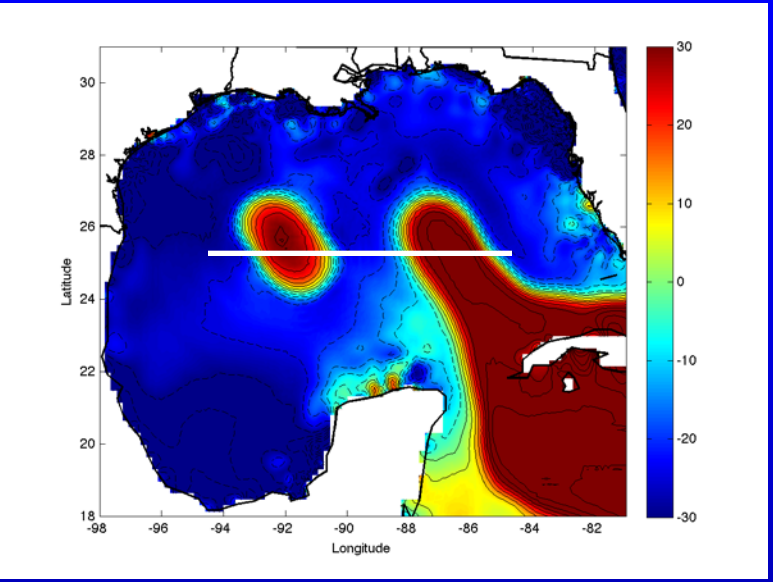
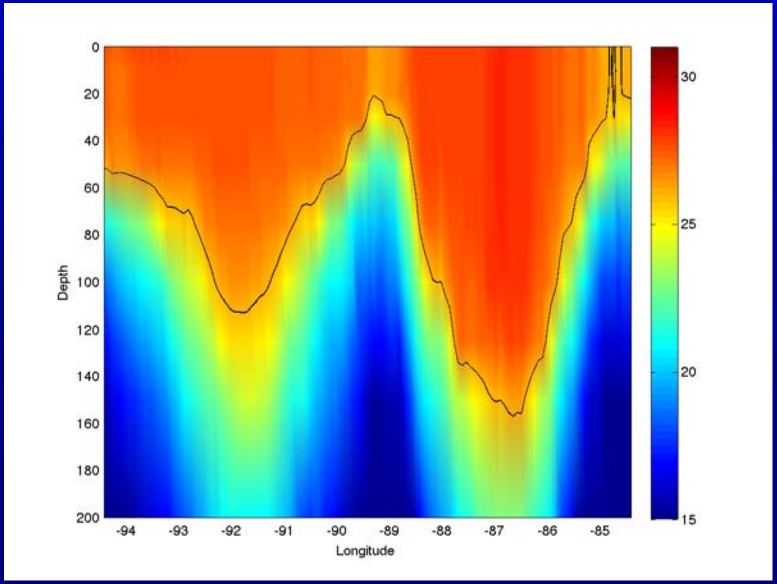
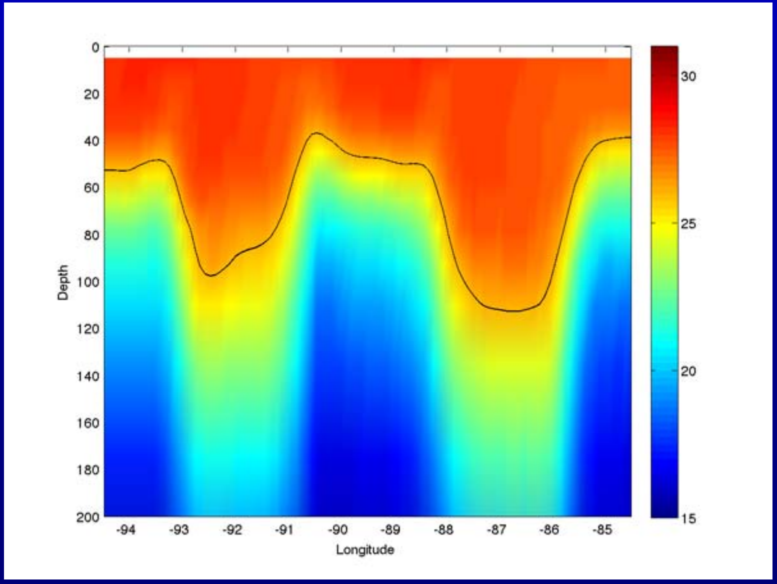
|  |  | SSH |
|  |  | Cross-section |

# Summary

- In the process of developing of the Air-Sea Interface Module for HWRF we examined
  - 1) sea state dependent momentum flux,
  - 2) Stokes drift effect on upper-ocean mixing, and
  - 3) Coriolis-Stokes forcing
- Modeling results suggest that behind the hurricane the Stokes drift may suppress Langmuir turbulence and consequent sea surface cooling.

# Summary

- Coriolis-Stokes forcing may reduce momentum flux into the ocean by 15% of the wind stress near the radius of maximum wind and to the right of the hurricane center.

- Plans for 2012:
  - Implement the air-sea interface module (ASIM) into the coupled HWRF-WAVEWATCH-POM/HYCOM system. Insure that all components of ASIM are modular and can be transitioned to other TC coupled models, including COAMPS-TC.
  - Test the ocean model initialization in GFDL/POM and HWRF/POM based Global RTOFS.

# Ocean Observations Needed for Coupled Atmosphere-Wave-Ocean Model Evaluations

- Directional wave spectra (to be available from WSRA measurements)

- Temperature and current measurements within the hurricane core regions. Only a few available in the Atlantic.