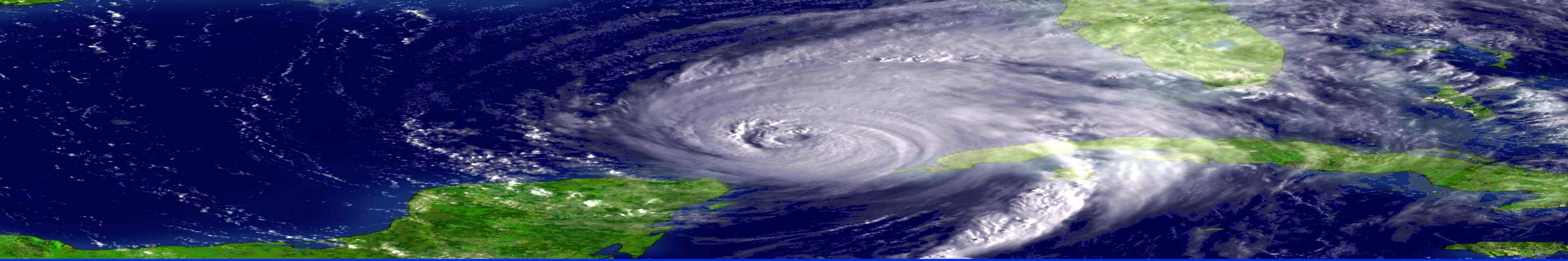

# Coupled Atmosphere-Wave-Ocean Modeling for Improving Tropical Cyclone Prediction Models

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HFIP Teleconference, June 6 2012

University of Rhode Island
GSO
Graduate School
of Oceanography

# Air-sea (heat and momentum) fluxes and turbulent mixing above/below air-sea interface are significantly modified by surface waves

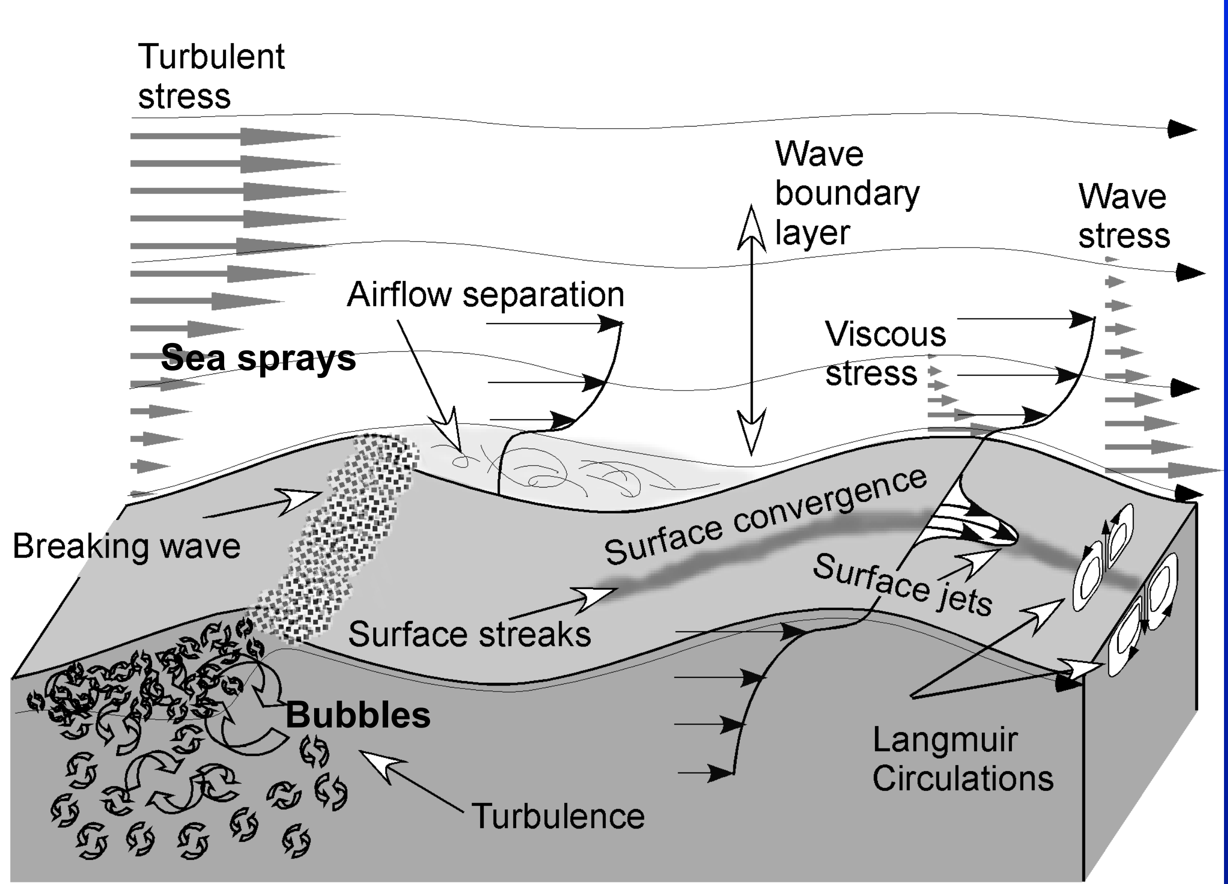
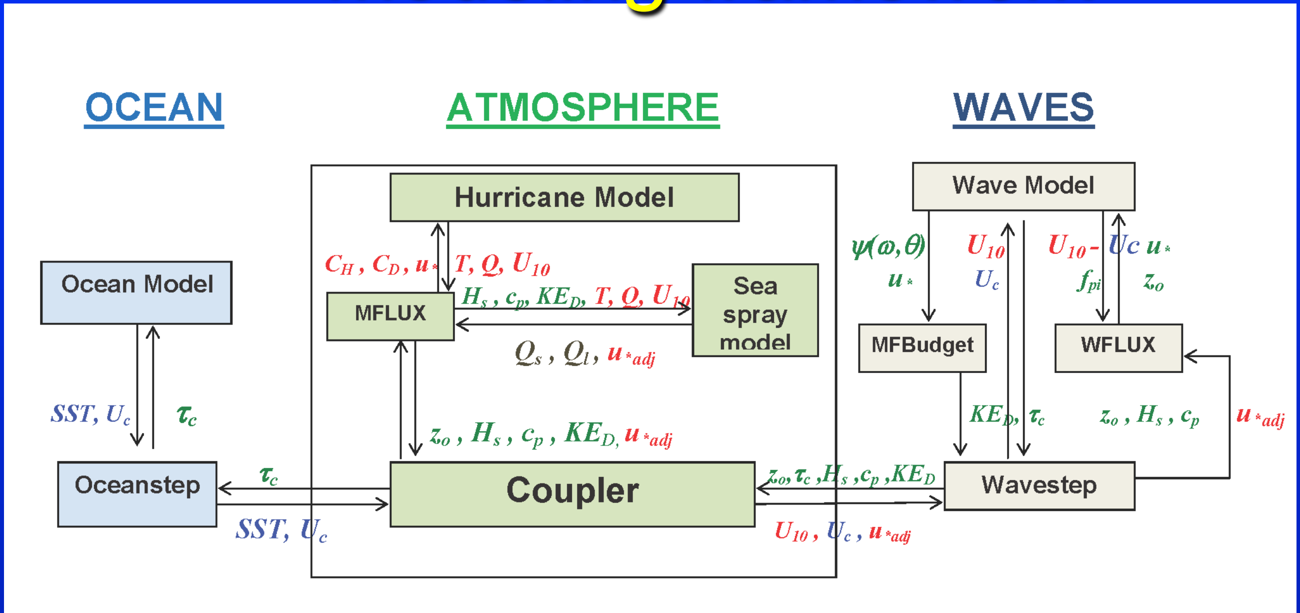


Image courtesy of Fabrice Veron

# Coupled atmosphere-wave-ocean modeling framework



**Red - atmospheric parameters, Green – wave parameters, Blue - ocean parameters**

- ***Hurricane model (HWF or GFDL):*** air-sea fluxes depend on *sea state, sea spray* and include *surface current.*

- ***Wave model (WAVEWATCH):*** forced by *sea state* dependent wind forcing and includes *surface current*

- ***Ocean model (POM or HYCOM):*** forced by *sea state* dependent wind stress modified by *growing or decaying wave fields* and *Coriolis-Stokes*. Turbulent mixing is modified by the Stokes drift (*Langmiur turbulence*).

# Discussion outline

- Sea state (wave) dependent drag coefficient
- Effect of surface waves on ocean currents and turbulence

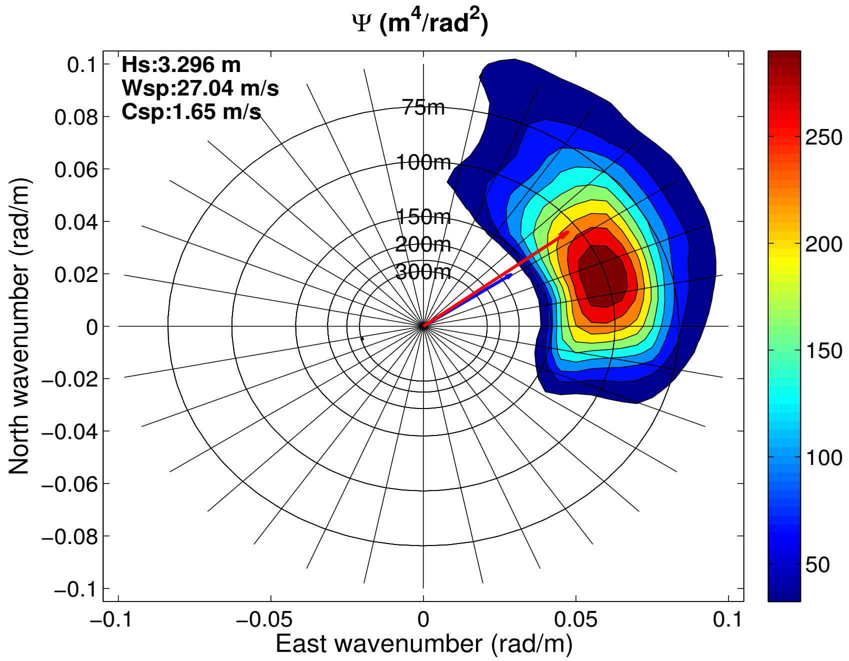
# Sea state dependent drag coefficient

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

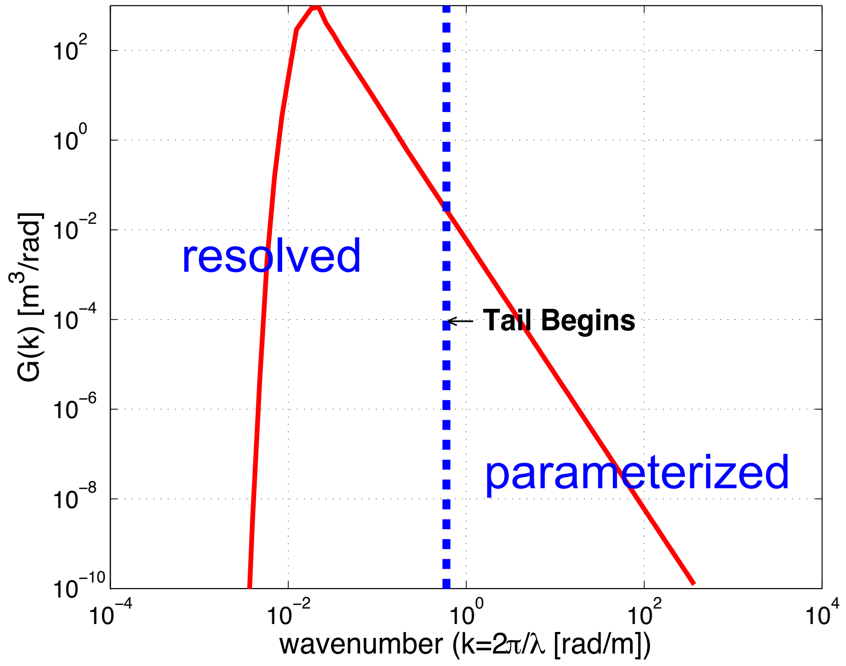
- We examined three recently developed sea state dependent momentum flux models as potential candidates for ASIM.

# Wind drag and wave spectrum

2D wave spectrum



Omnidirectional wave spectrum

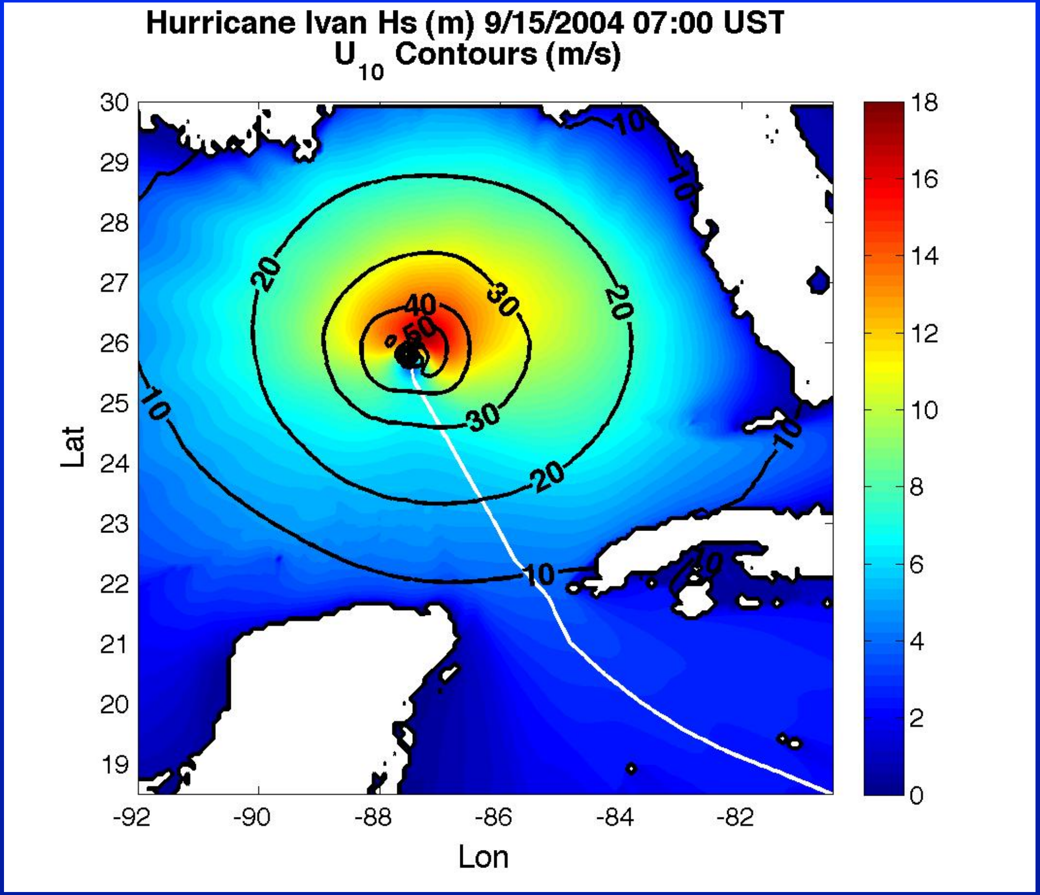


The wave field is expressed as a spectrum $\Psi$ in terms of wavenumber *k* and direction $\theta$.

The wind drag has two components: form (wave) drag and skin (viscous) drag.

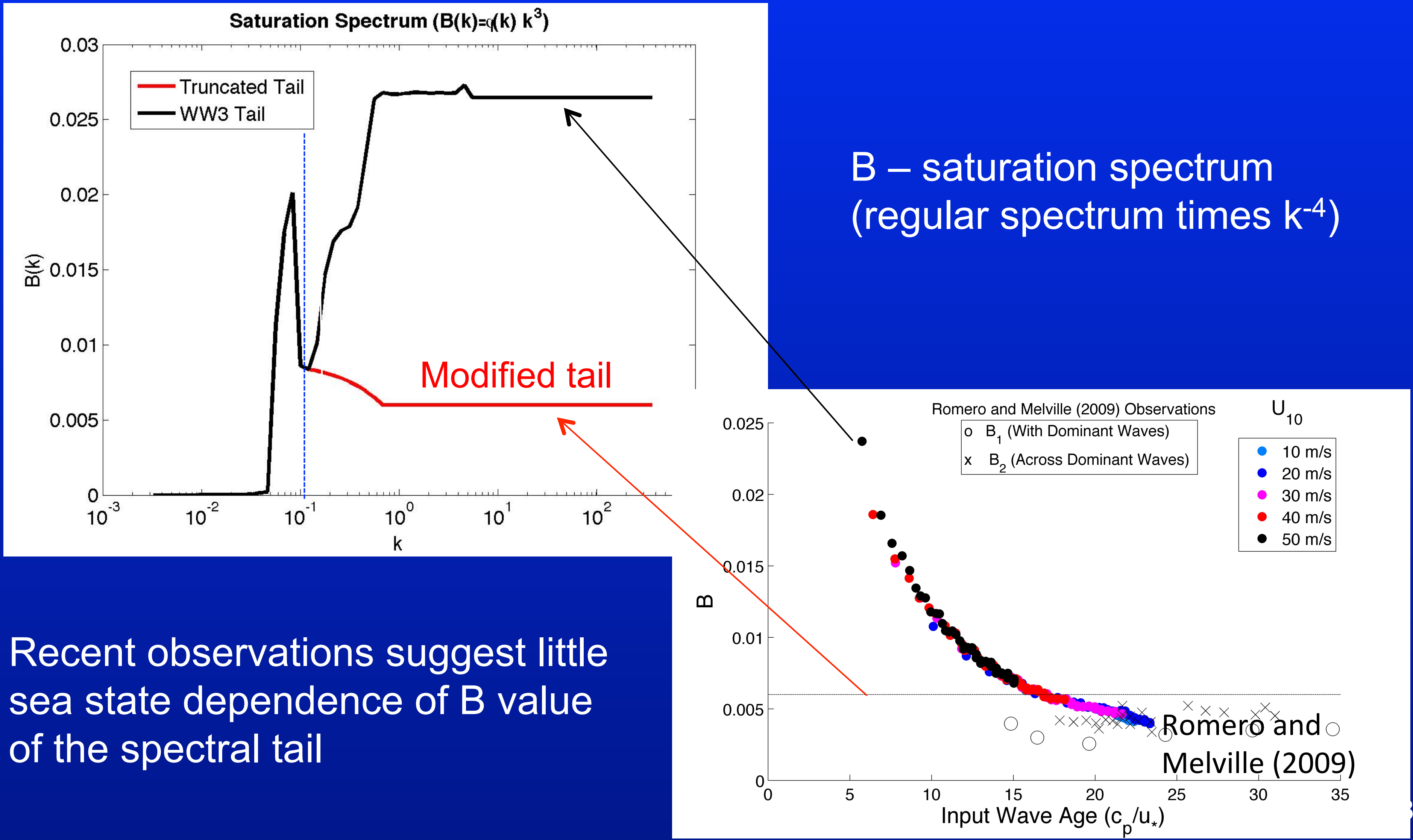
The form drag is obtained by integrating the spectrum times the growth rate over all wavenumbers/directions.

# Hurricane Ivan (2004) wave simulation with H*WIND forcing



Significant wave height ($H_s$) and wind speed ($U_{10}$)

# Evaluation of wave spectrum and its high frequency tail in a hurricane



Modified tail

Romero and Melville (2009)

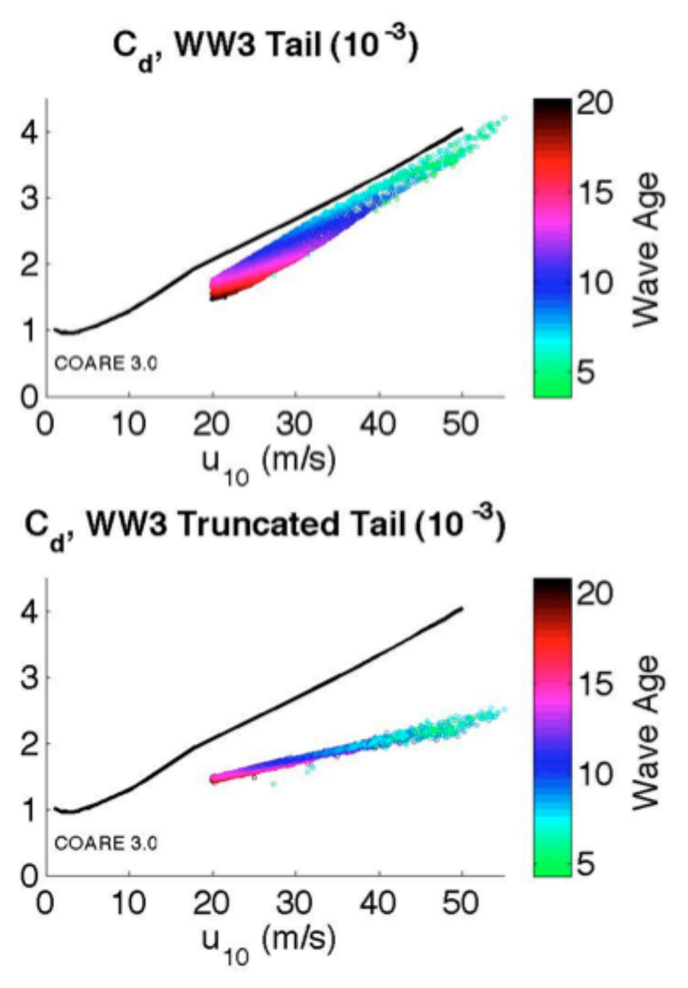
B – saturation spectrum (regular spectrum times k$^{-4}$)

Recent observations suggest little sea state dependence of B value of the spectral tail

# Sea state dependent drag coefficient for different wave spectral tails

WW3 Tail

Modified Tail

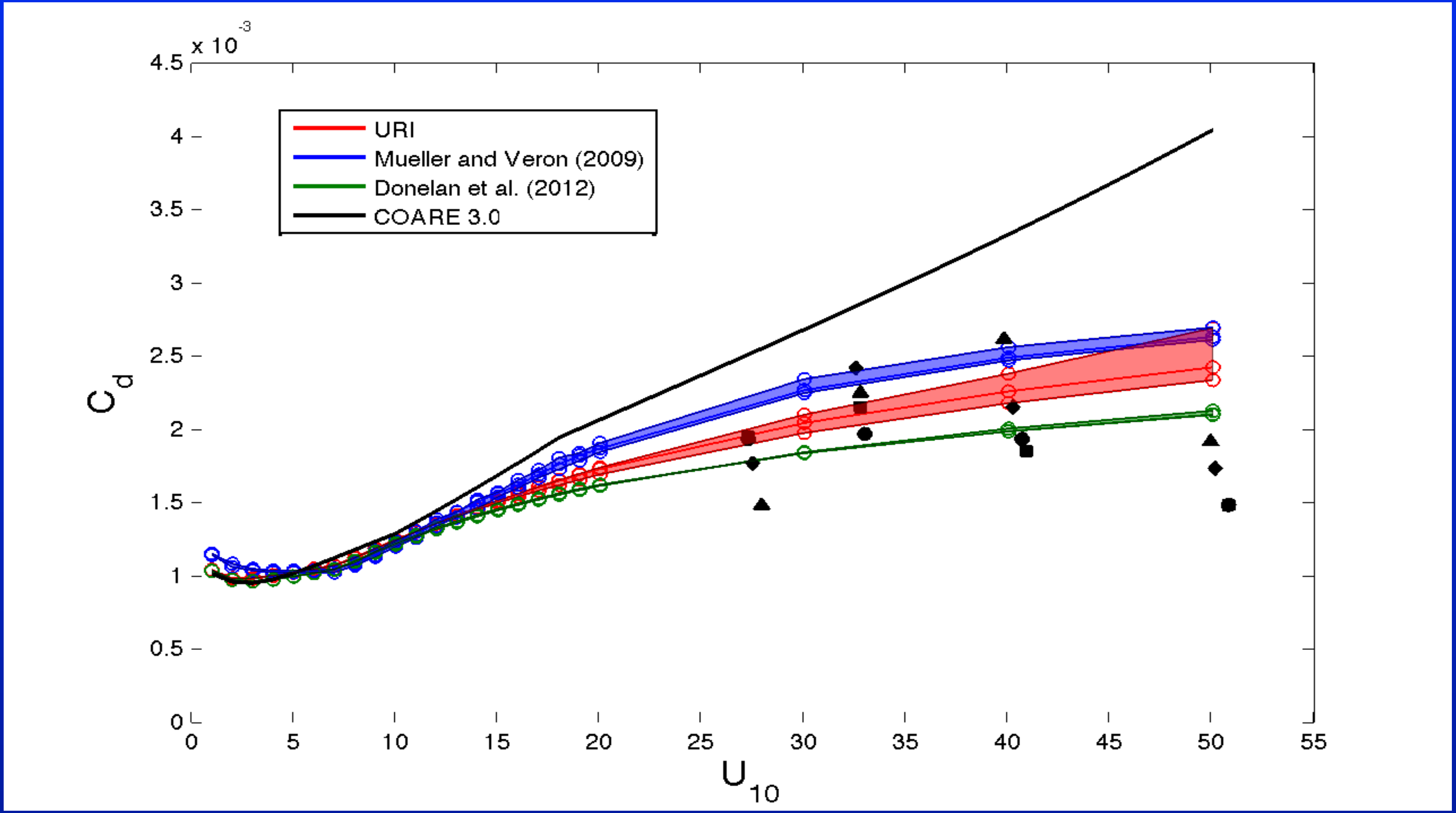


Only data for $U_{10}$ > 20 m/s are shown

Drag coefficient is greatly dependent on the spectral tail

With the modified tail sea state dependence is weak

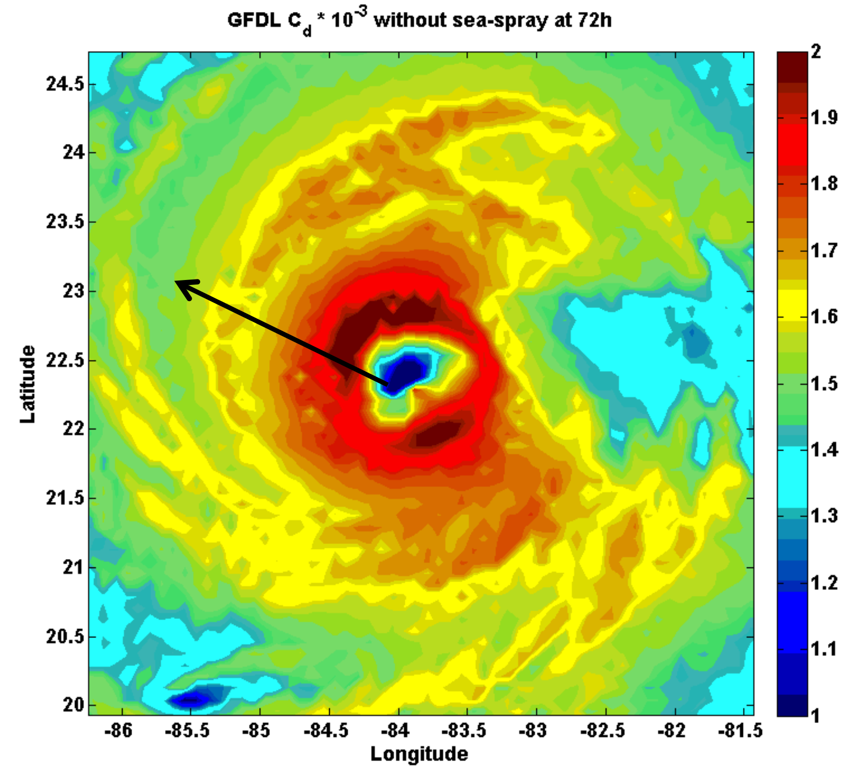
# Comparing different sea-state dependent momentum flux models



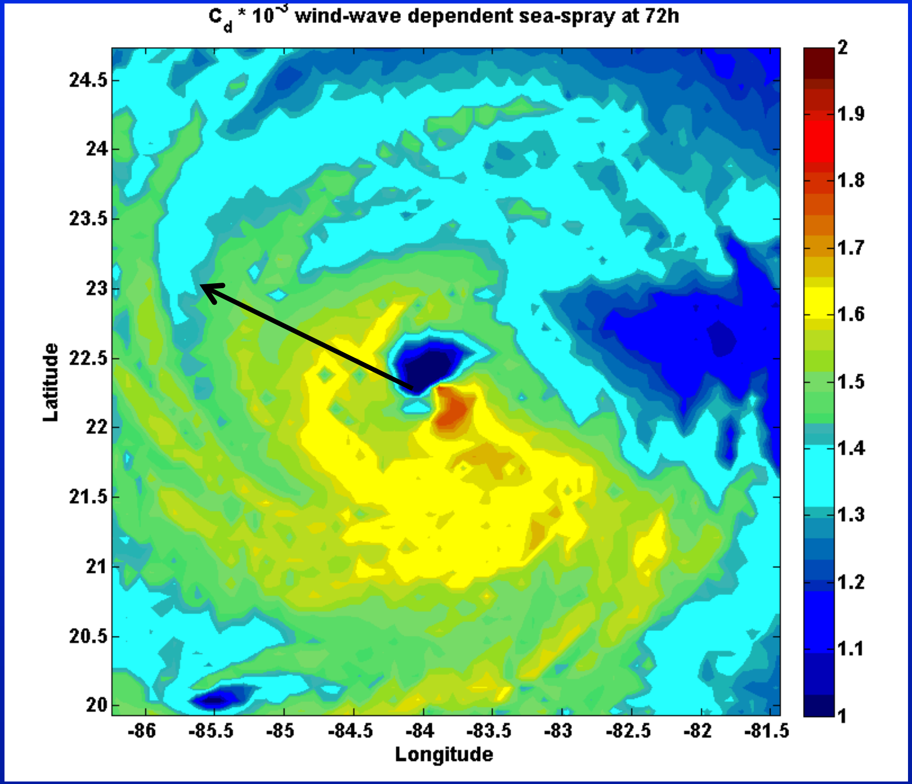
All tested models used the same empirically derived wave spectrum based on the Joint North Sea Wave Project (JONSWAP) Elfounhaily et al. (1997)

# Sea spray effect on drag coefficient using ESRL model

## Without sea spray



## With sea spray



# Effect of surface waves on ocean currents/turbulence

Several theories of wave-current interaction have been developed (e.g., Mellor, 2003, 2005, 2008; Ardhuin et al., 2008; McWilliams and Restrepo, 1999).

Mellor's (2008) momentum equation with wave effects:

$$\frac{\partial}{\partial t}U_{c\alpha}+\frac{\partial}{\partial x_\beta}\left(U_{c\alpha}U_{c\beta}\right)+\frac{\partial}{\partial z}\left(WU_{c\alpha}\right)-\varepsilon_{\alpha\beta z}fU_{c\beta}=-\frac{1}{\rho}\frac{\partial P}{\partial x_\alpha}+\frac{\partial\bar{\tau}_{t\alpha}}{\partial z}$$

Traditional ocean current equation

$$+\frac{\partial\bar{\tau}_{p\alpha}}{\partial z}-\frac{\partial}{\partial t}u_{s\alpha}-\frac{\partial}{\partial x_\beta}S_{\alpha\beta}+\varepsilon_{\alpha\beta z}fu_{s\beta}$$

Surface wave effects (linear terms)

$$-\frac{\partial}{\partial x_\beta}\left(u_{s\alpha}u_{s\beta}\right)-\frac{\partial}{\partial x_\beta}\left(U_{c\alpha}u_{s\beta}\right)-\frac{\partial}{\partial x_\beta}\left(u_{s\alpha}U_{c\beta}\right)-\frac{\partial}{\partial z}\left(Wu_{s\alpha}\right)$$

Surface wave effects (nonlinear terms) including Langmuir forcing

$U_{c\alpha}$ :(Eulerian) ocean current

$u_{s\alpha}$ : Stokes drift

$S_{\alpha\beta}$ : Radiation stress

# Effect of surface waves on ocean currents/turbulence

**URI model:**

$$\frac{\partial}{\partial t}U_{c\alpha} + \frac{\partial}{\partial x_\beta}\left(U_{c\alpha}U_{c\beta}\right) + \frac{\partial}{\partial z}\left(WU_{c\alpha}\right) - \varepsilon_{\alpha\beta z} f U_{c\beta} = -\frac{1}{\rho}\frac{\partial P}{\partial x_\alpha} + \frac{\partial \bar{\tau}_{t\alpha}}{\partial z}$$

Turbulence closure (modified)

Traditional ocean current equation

$$\bar{\tau}_{t\alpha} = \tau_{air\alpha} - \frac{\partial}{\partial t}M_\alpha - \frac{\partial}{\partial x_\beta}MF_{\alpha\beta} - \tau_{s\alpha} \quad at \quad z = \hat{\eta}$$

Surface boundary condition (modified)

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

○ : wave-dependent momentum flux budget terms (Fan et al. 2010)

○ : Coriolis-Stokes forcing term (Polton et al. 2005)

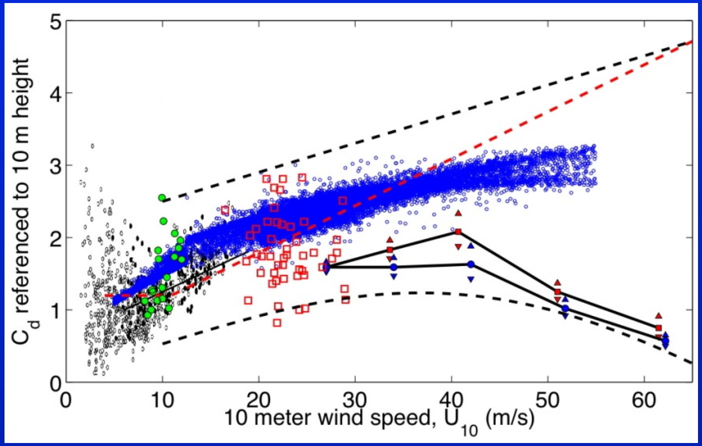
○ : Langmuir turbulence effect – will be included in the turbulence closure model (in collaboration with Tobias Kukulka, U. Delaware)

Reichl, Hara, Ginis (2012)

# Air-sea flux budget under (idealized) hurricanes

**Relative reduction of the momentum flux to ocean** $\frac{\tau_{ocean}}{\tau_{air}}$

depends on wind stress $\tau_{air}$, which is not well constrained at high winds.



*Upper bound: extrapolation of bulk parameterization*

*URI wind-wave model (blue)*

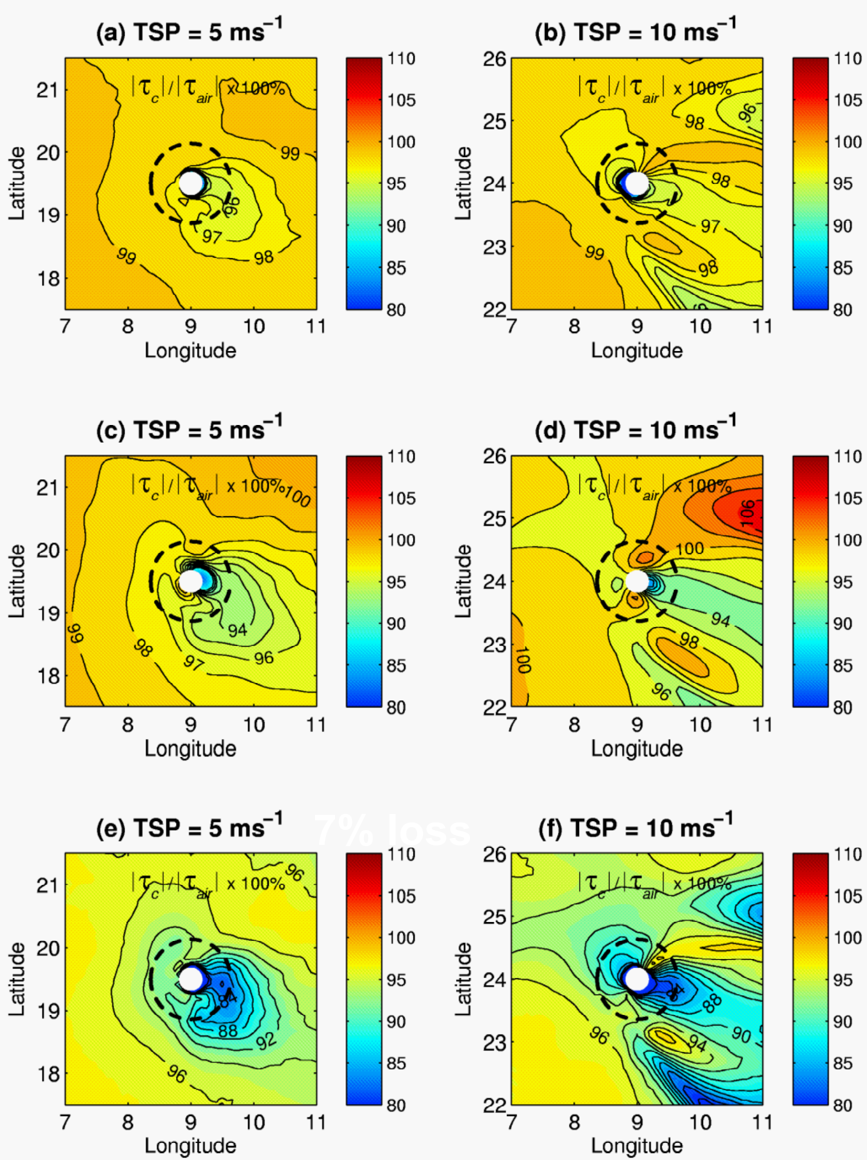
*Lower bound: observations by Powell et al. (2007)*

Hurricane translation

Upper bound of wind stress

URI model of wind stress

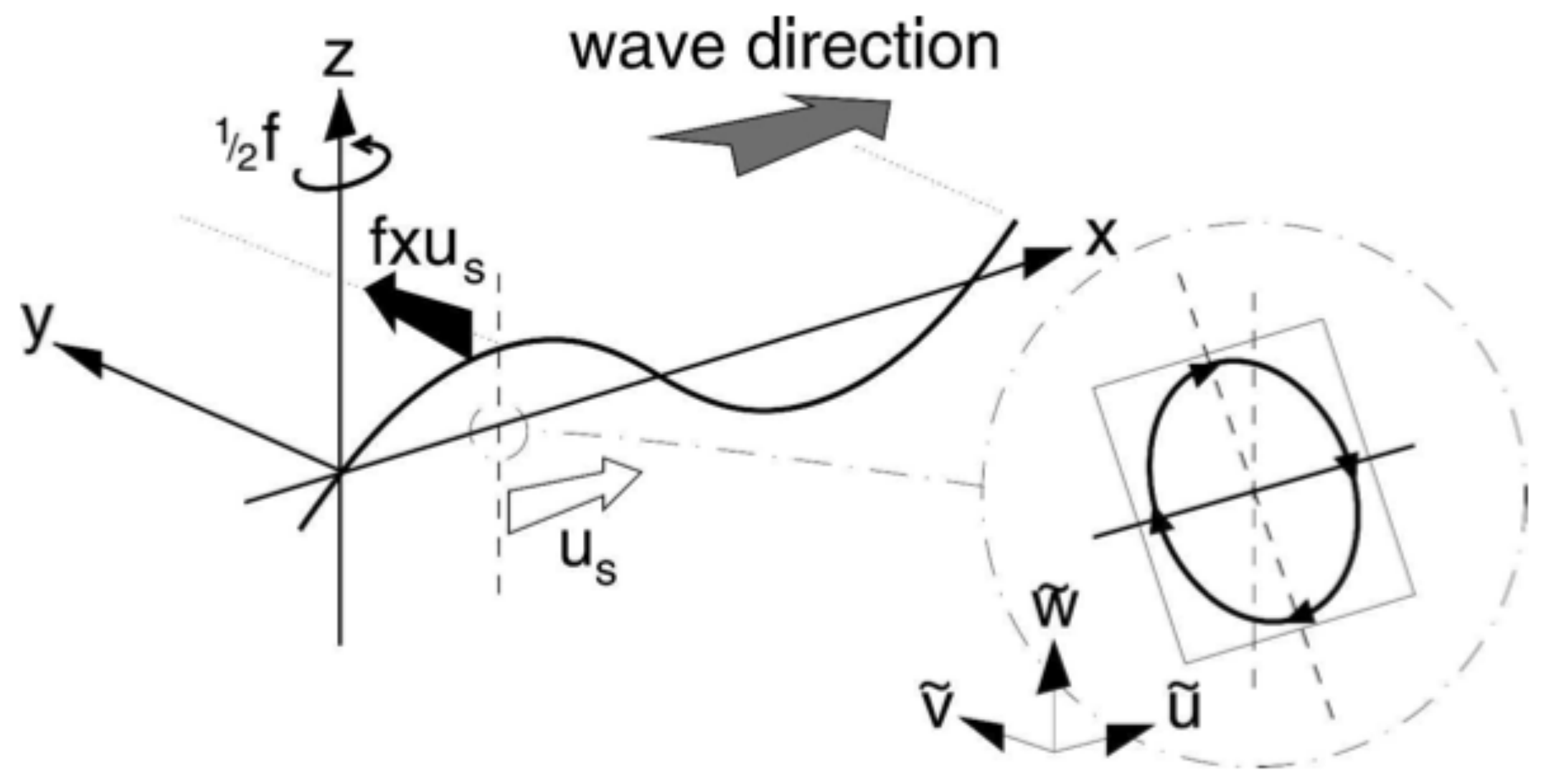
Lower bound of wind stress



**15-20% reduction of stress**

Fan, Ginis, Hara (2010)

# Coriolis-Stokes forcing



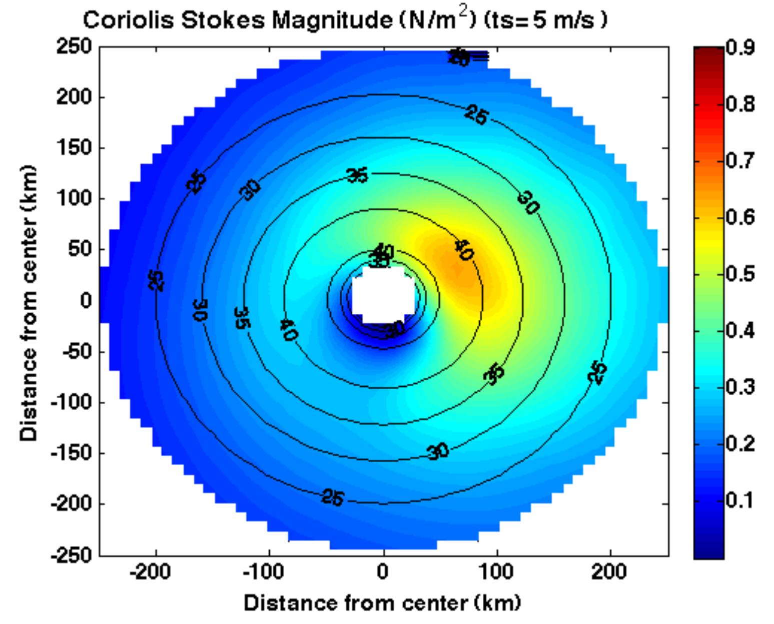
The orbital path for a particle under a wave is tilted by planetary rotation in the along–wave crest direction, resulting in additional forcing (Hasselmann 1970).

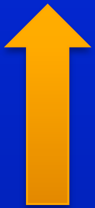
Figure from Polton et al. (2005)

# Coriolis-Stokes forcing under idealized axisymmetric moving hurricane

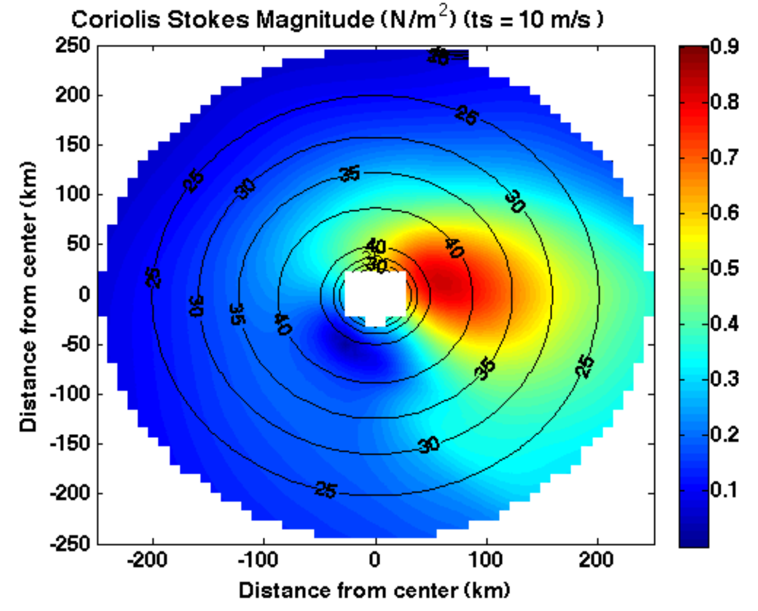
$R_m$=70 km and $V_m$=45 $ms^{-1}$

$U_T$=5 m/s



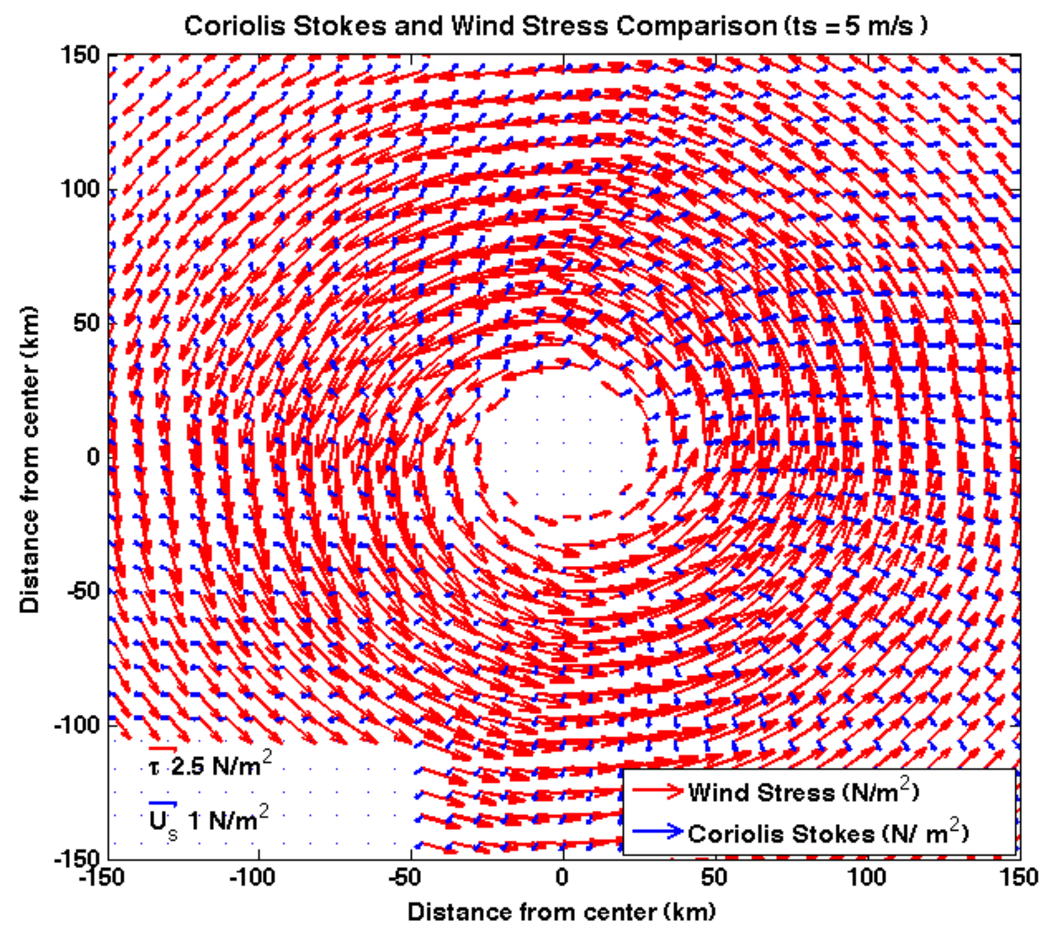


$U_T$=10 m/s



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

# Wind stress and Coriolis-Stokes vectors



5 m/s

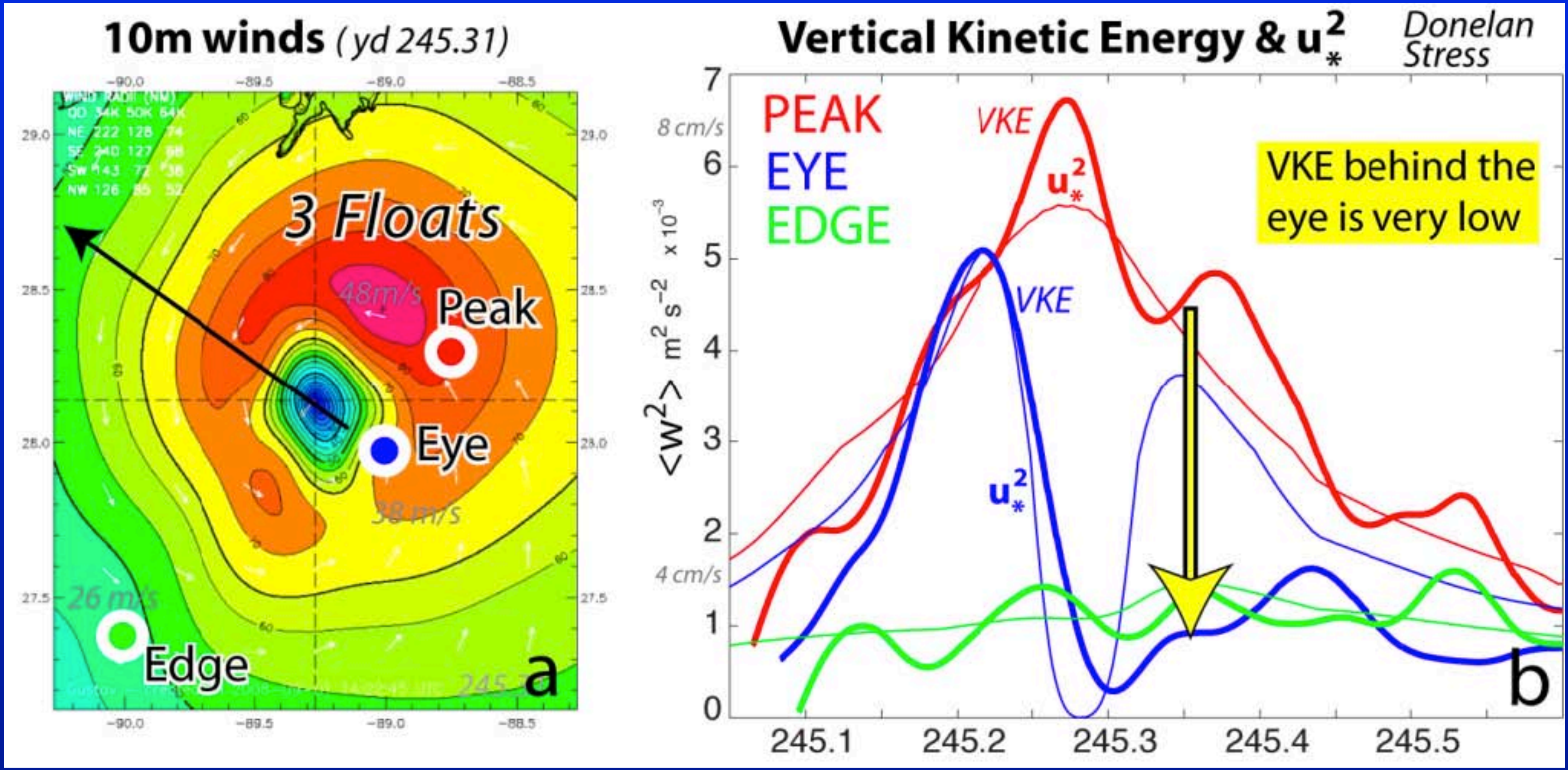
# Stokes drift due to surface waves and Langmuir turbulence

- Surface wave motions induce 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 90$^{o}$. In such cases the Stokes drift may suppress Langmuir turbulence and consequent sea surface cooling.

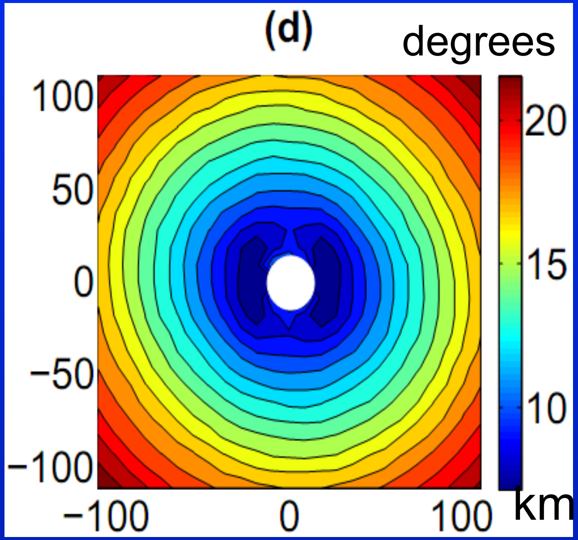
# Langmuir turbulence under hurricanes

D' Asaro et al. suggest that near surface turbulence and upper ocean mixing may be significantly reduced when surface waves are opposing the wind and suppress the Langmuir turbulence.

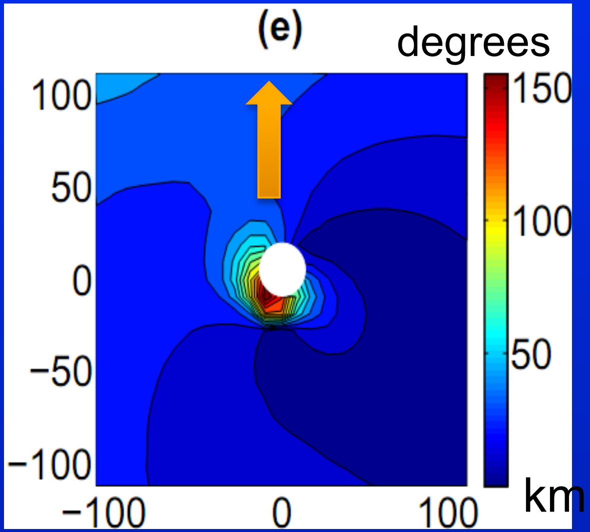


Courtesy of Eric D'Asaro

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

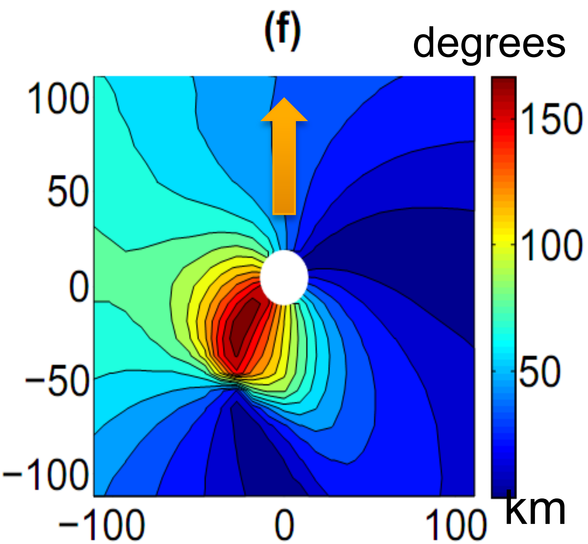


$U_T=0$



$U_T=5$ m/s

Angle exceeds 90° behind a translating hurricane.



$U_T=10$ m/s

# Summary

- The sea state dependence of the drag coefficient in hurricanes is very sensitive to the parameterization of the high frequency part (tail) of the wave spectrum.

- All three tested momentum flux models indicate leveling off Cd at high wind speeds.

- Sea state dependent momentum flux budget and Coriolis-Stokes forcing may significantly modify the magnitude and direction of momentum flux into ocean currents (relative to wind stress) under hurricanes.

- Simulations of the Stokes drift under hurricanes suggest that the Langmuir turbulence may be enhanced or suppressed, depending on the alignment of wind and surface waves.