Effects of surface waves on air-sea momentum and energy fluxes and ocean response to hurricanes

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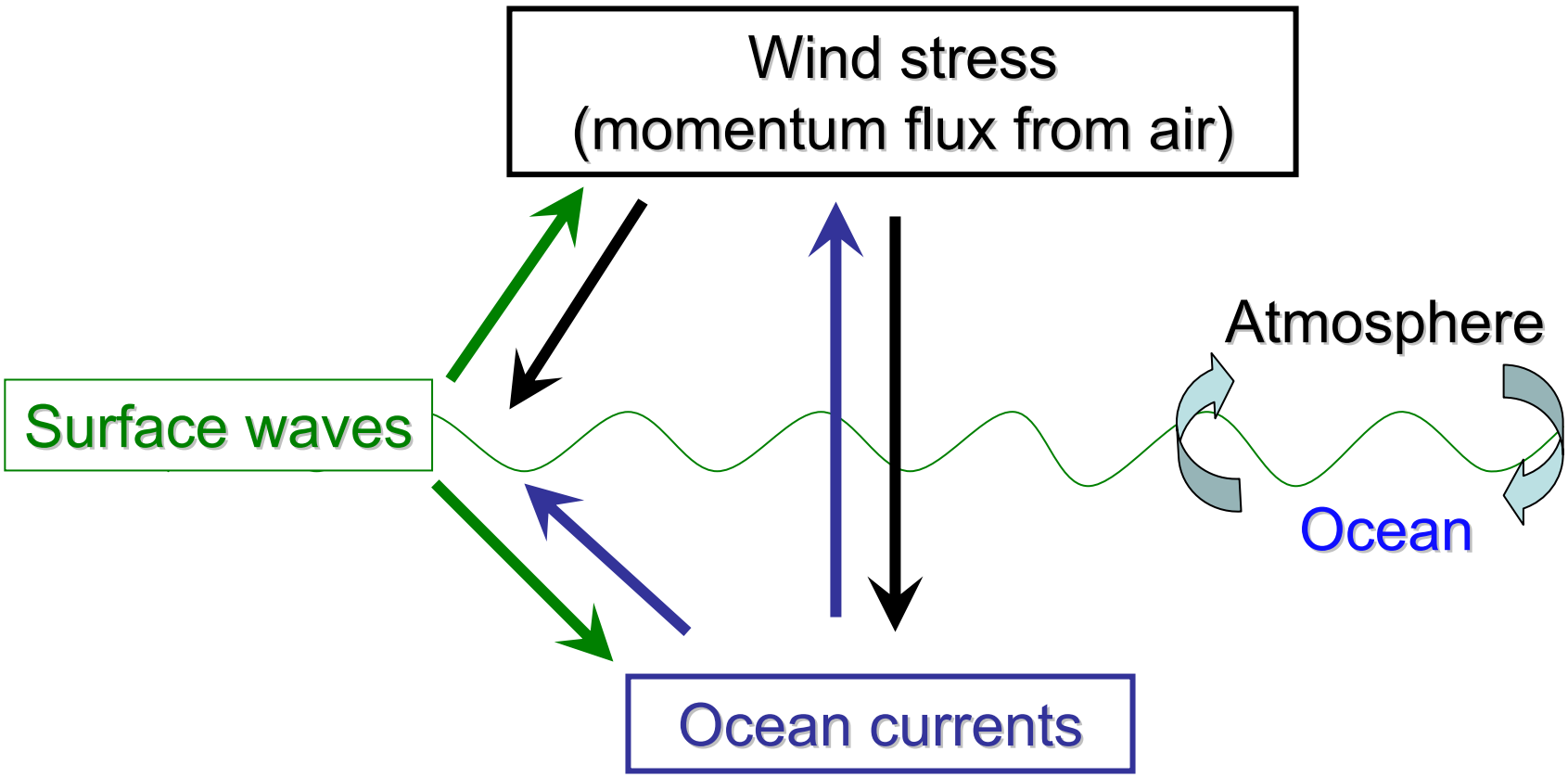
Outline

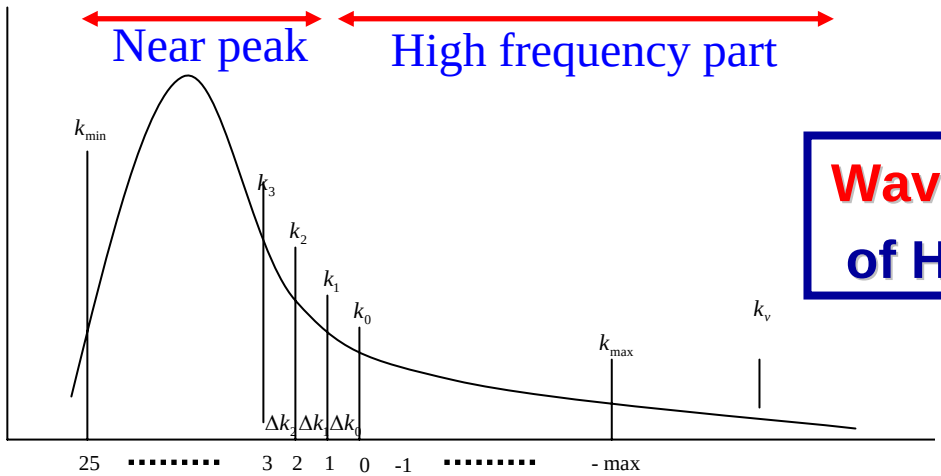
1. Energy and momentum flux budget across air-sea interface
   - Uniform wind
   - Hurricanes
2. Wind-wave-current interaction in hurricanes
3. Case study: Hurricane Ivan (2004)

Wind-Wave-Current Interaction



URI Coupled Wave-Wind (CWW) 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 (WBL) model of Hara and Belcher (JPO, 2004)

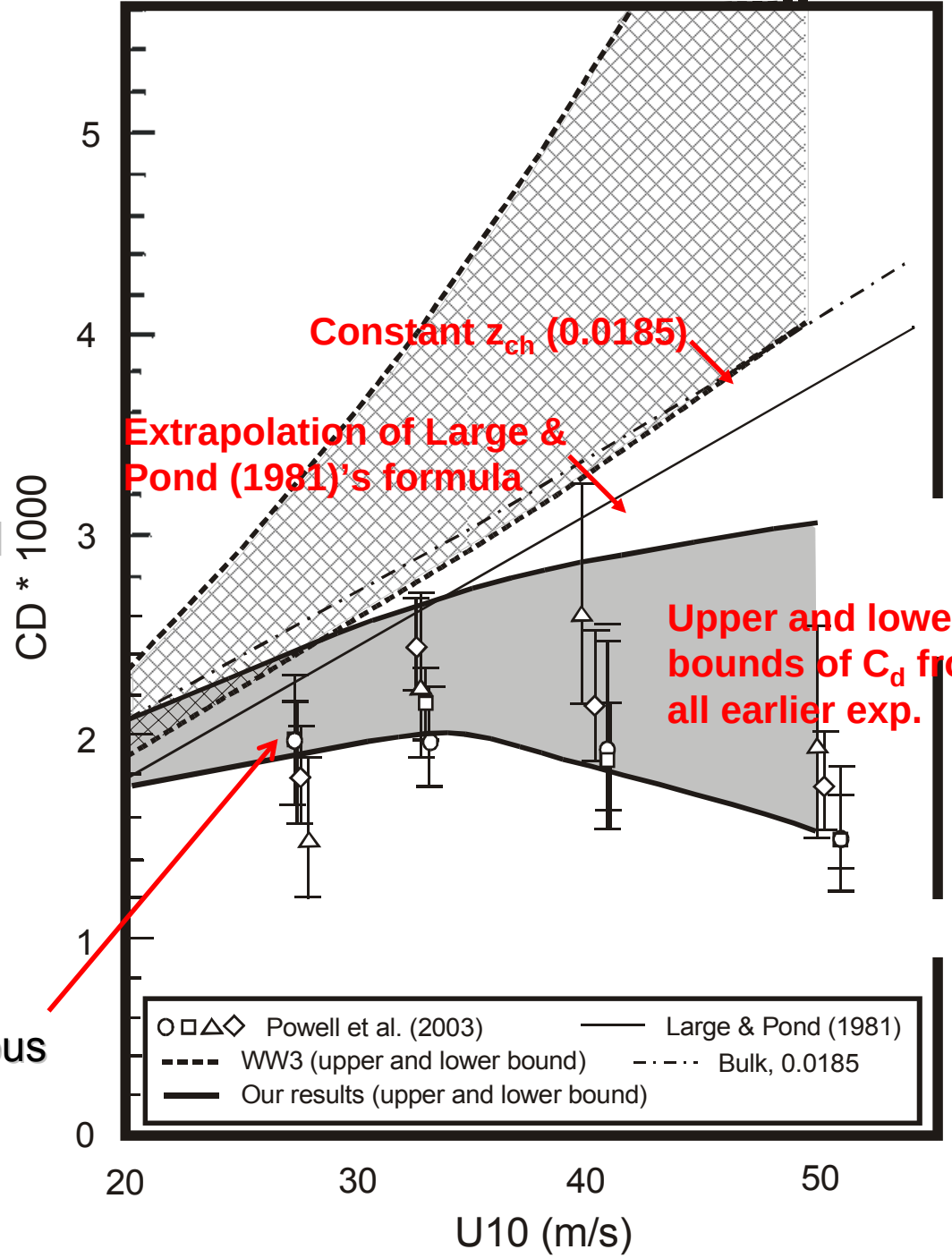
Explicitly calculates wave-induced stress

Wind profile and drag coefficient over any given seas

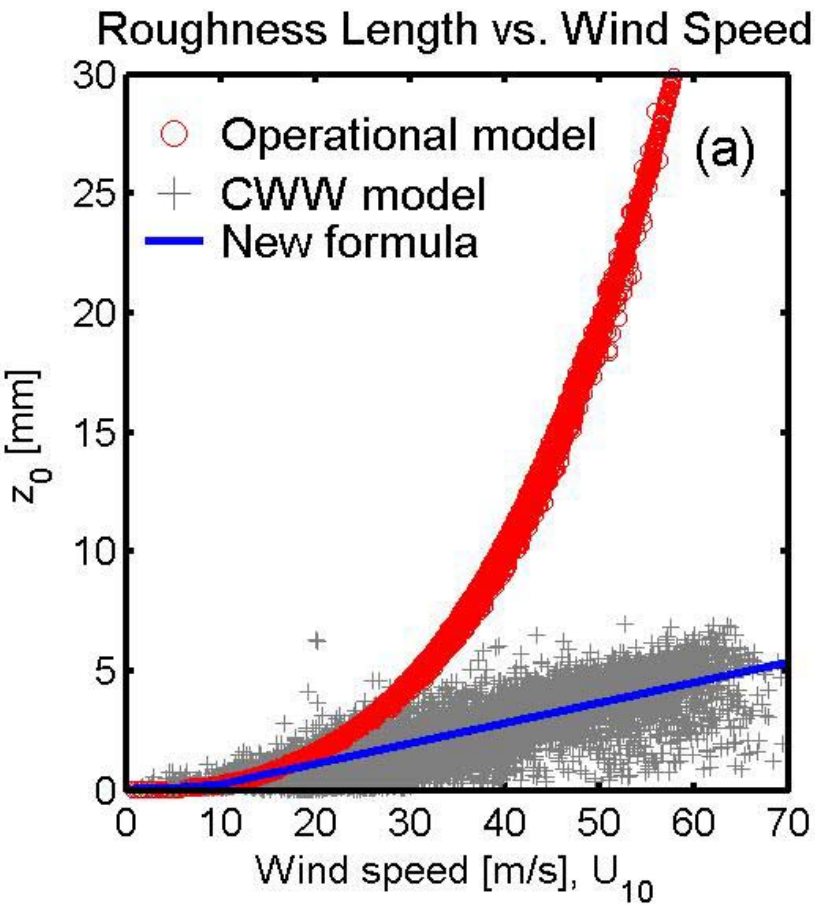
Drag Coefficient in the CWW model

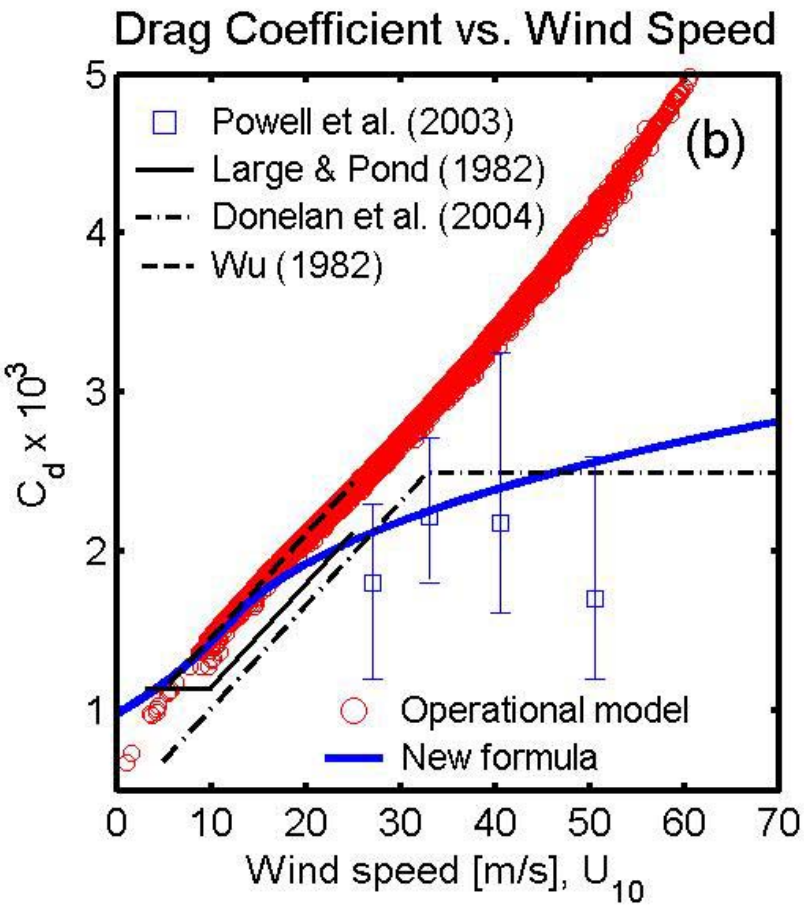
- At high wind speeds, C_d levels off and even decrease with wind speed

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



Roughness Length and Drag Coefficients Parameterizations based on CWW



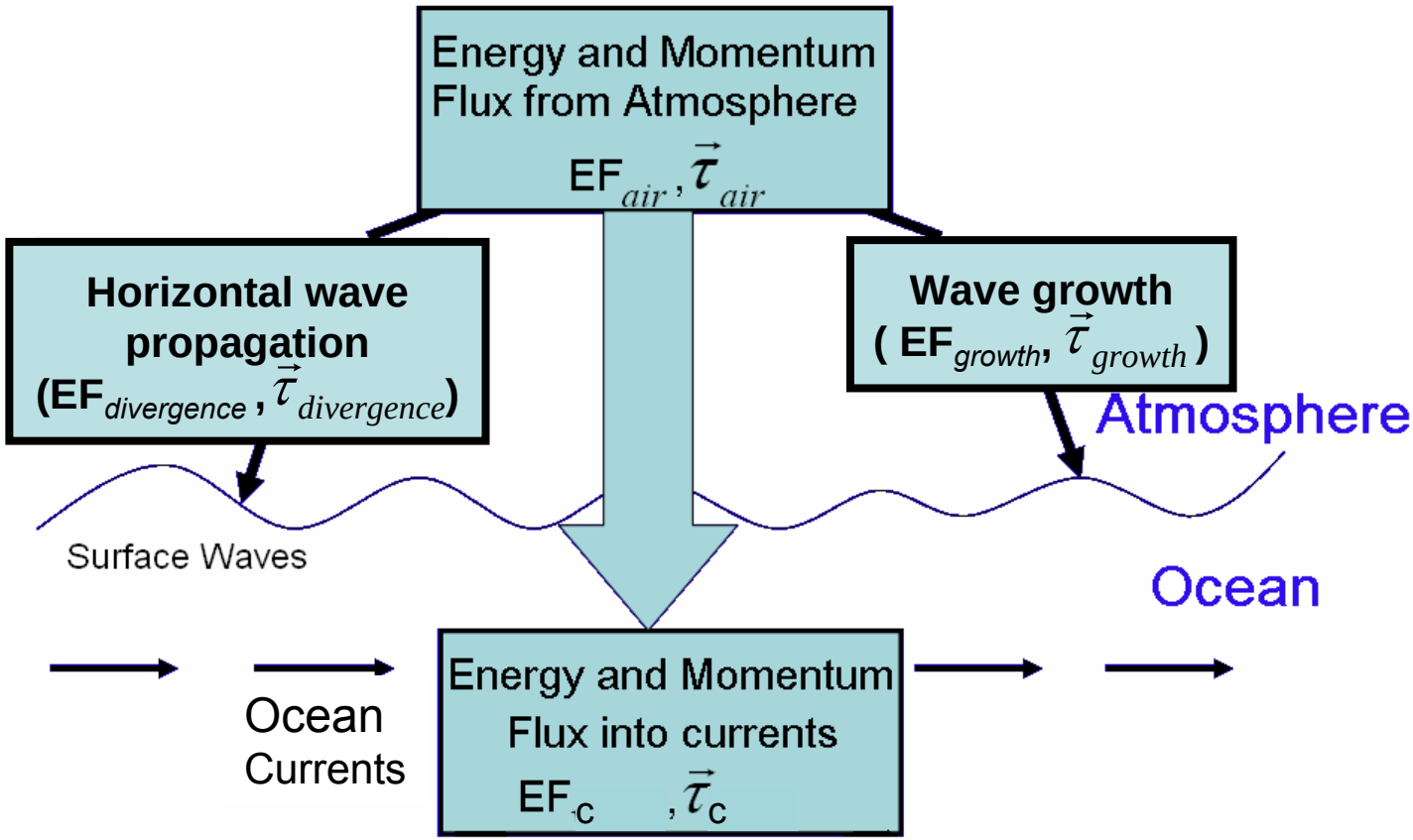


1. Modeling of air-sea fluxes in hurricanes

❖ Effect of surface gravity waves on air-sea fluxes

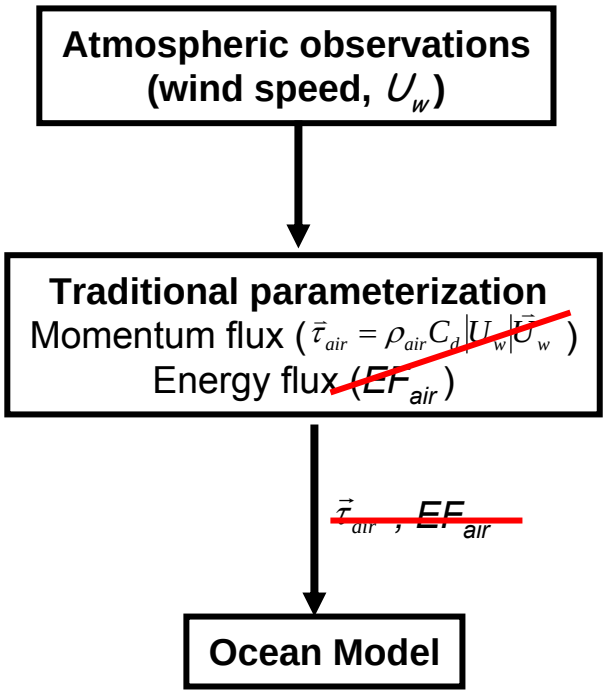
$$EF_{air} = EF_c + (EF_{growth} + EF_{divergence})$$

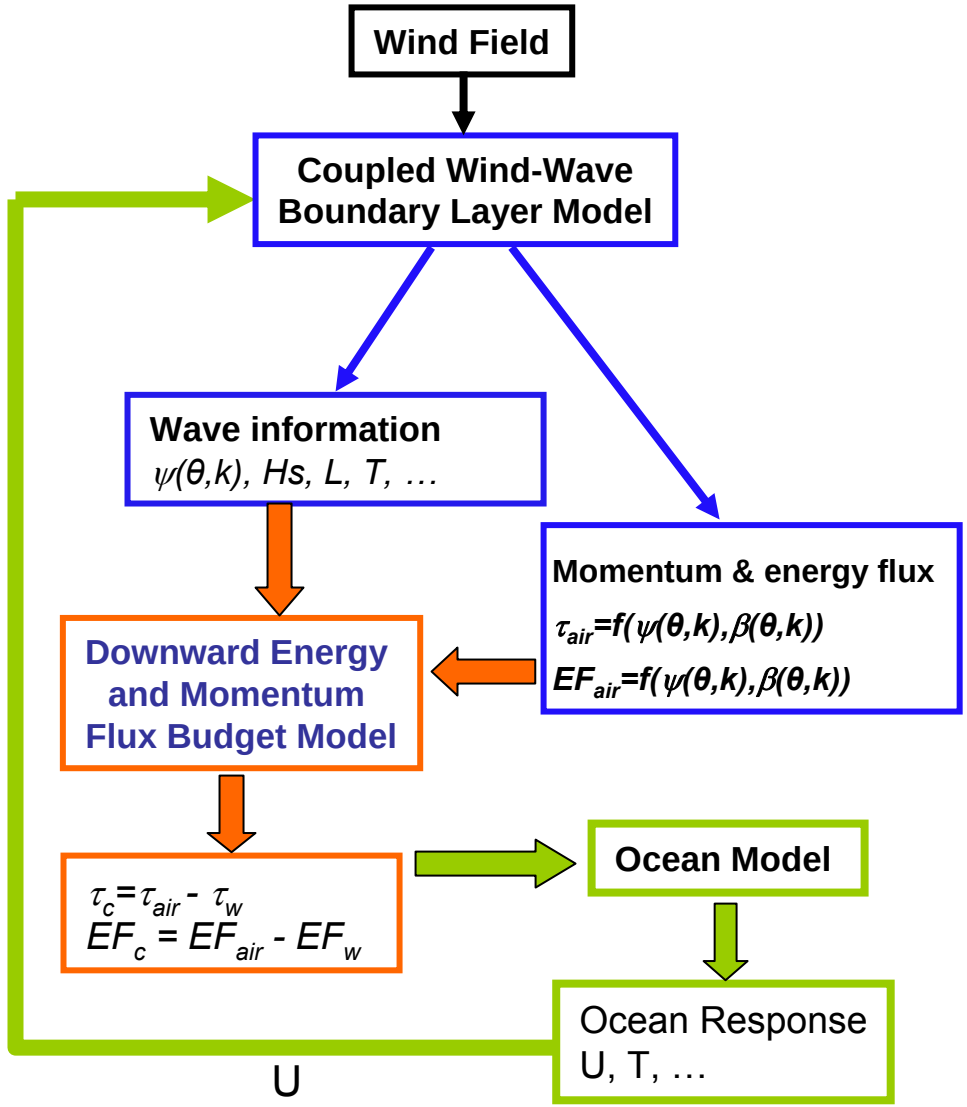
$$\vec{\tau}_{air} = \vec{\tau}_c + \left(\vec{\tau}_{growth} + \vec{\tau}_{divergence}\right)$$



1. Modeling of air-sea fluxes in hurricanes

❖ Air-sea flux calculations

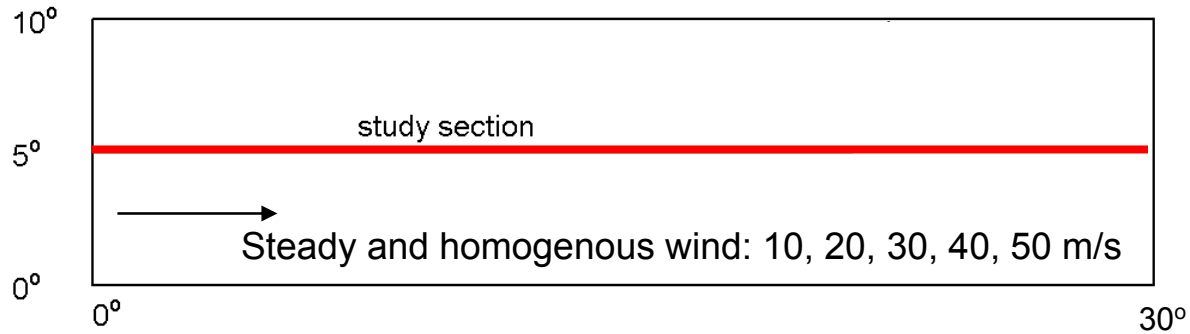




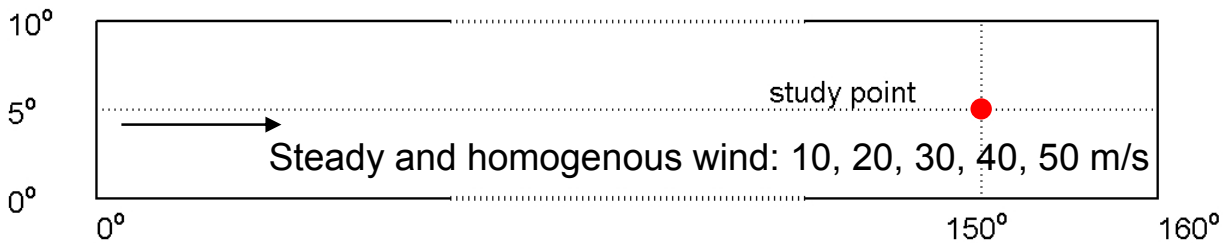
2. Energy and momentum flux budget across air-sea interface

❖ Uniform wind experiments

Fetch limited (space variation) experiment



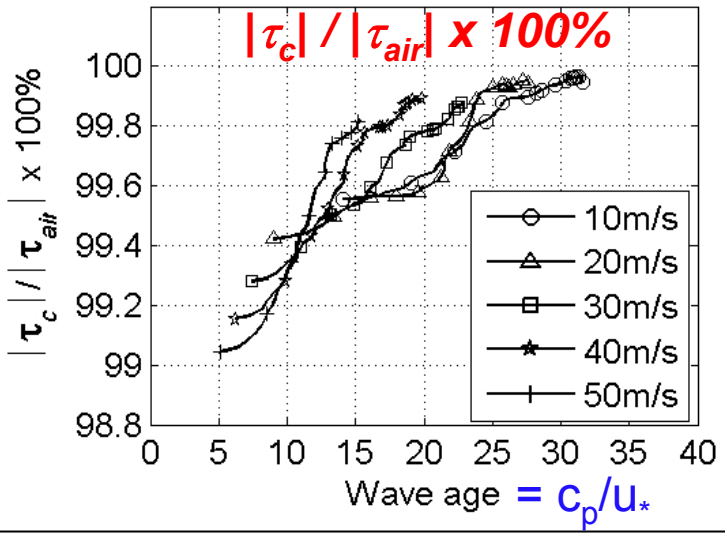
Duration limited (time variation) experiment

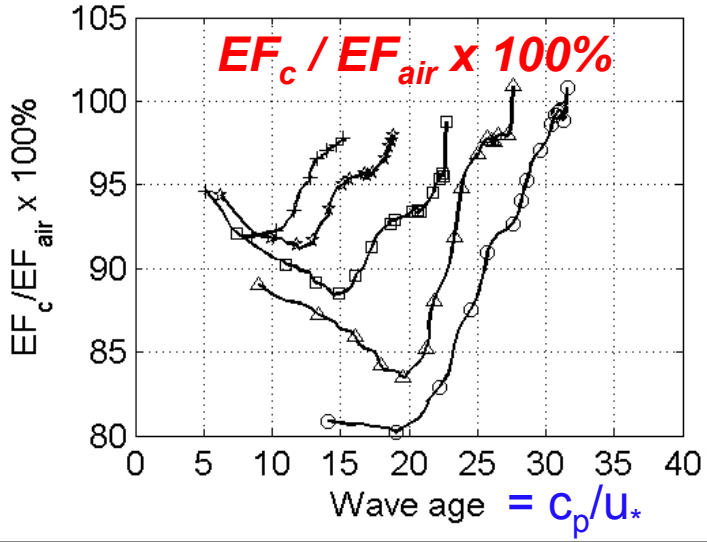


2. Energy and momentum flux budget across air-sea interface

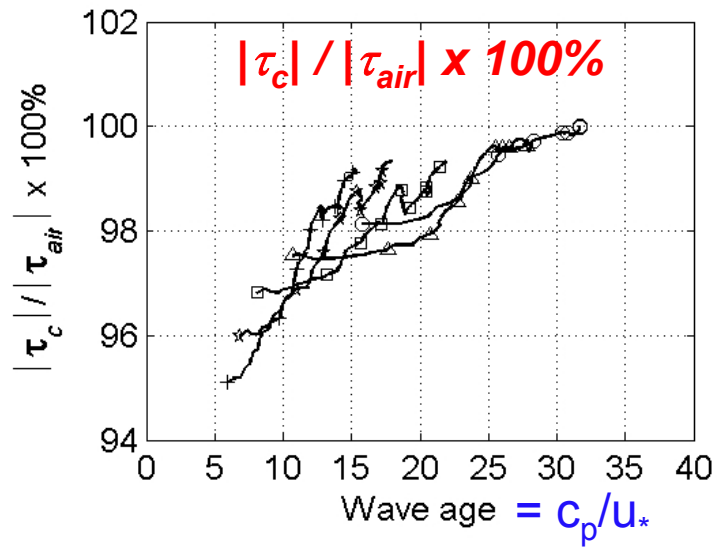
❖ Uniform Wind experiments: Momentum and energy fluxes

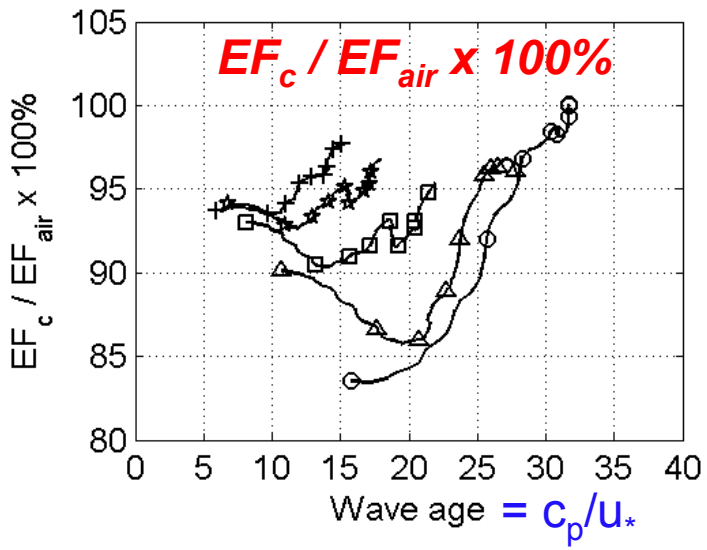
Time Dependent





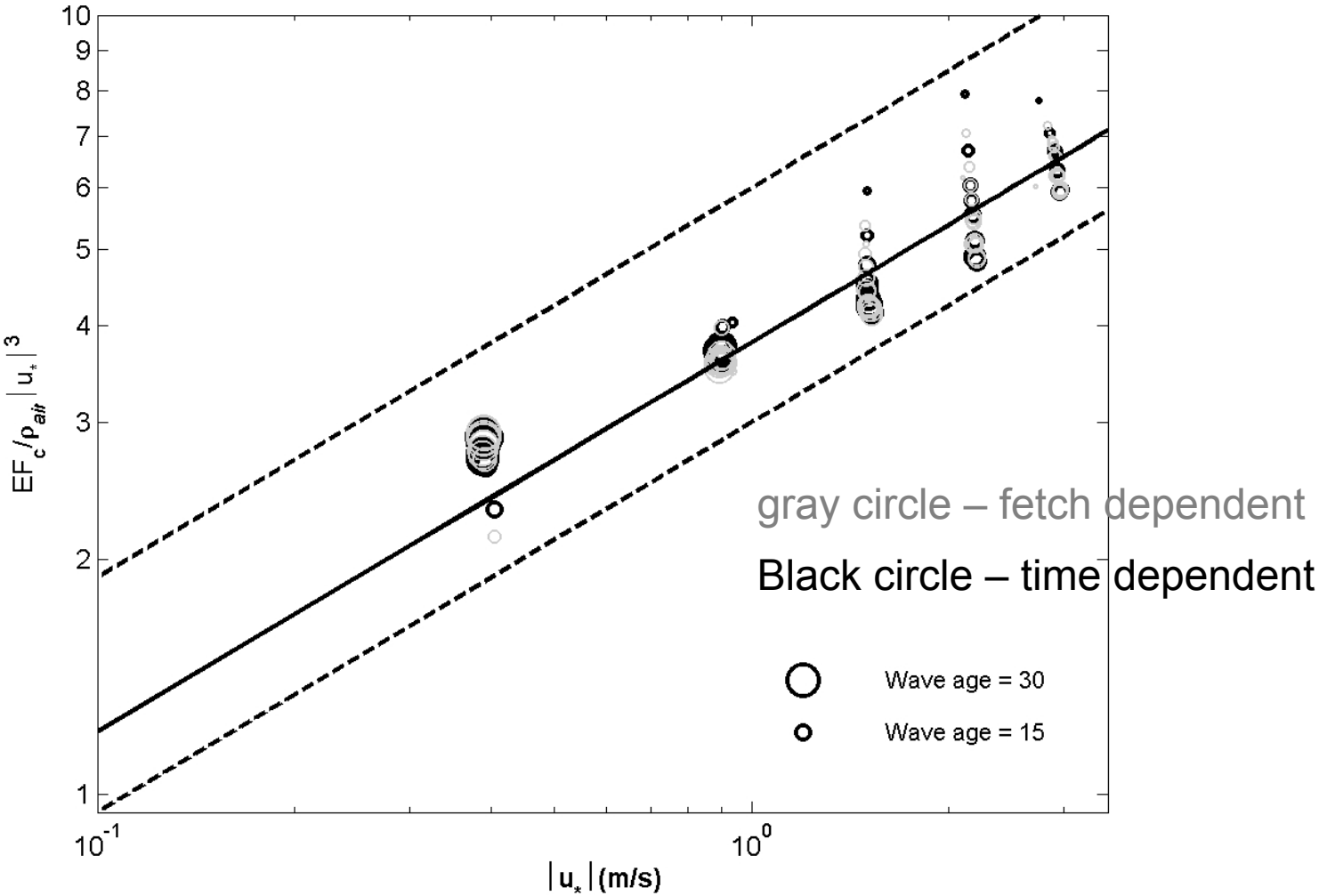
Fetch Dependent





2. Energy and momentum flux budget across air-sea interface

- **Uniform wind: Energy flux into currents (EF_c) as a function of u_***

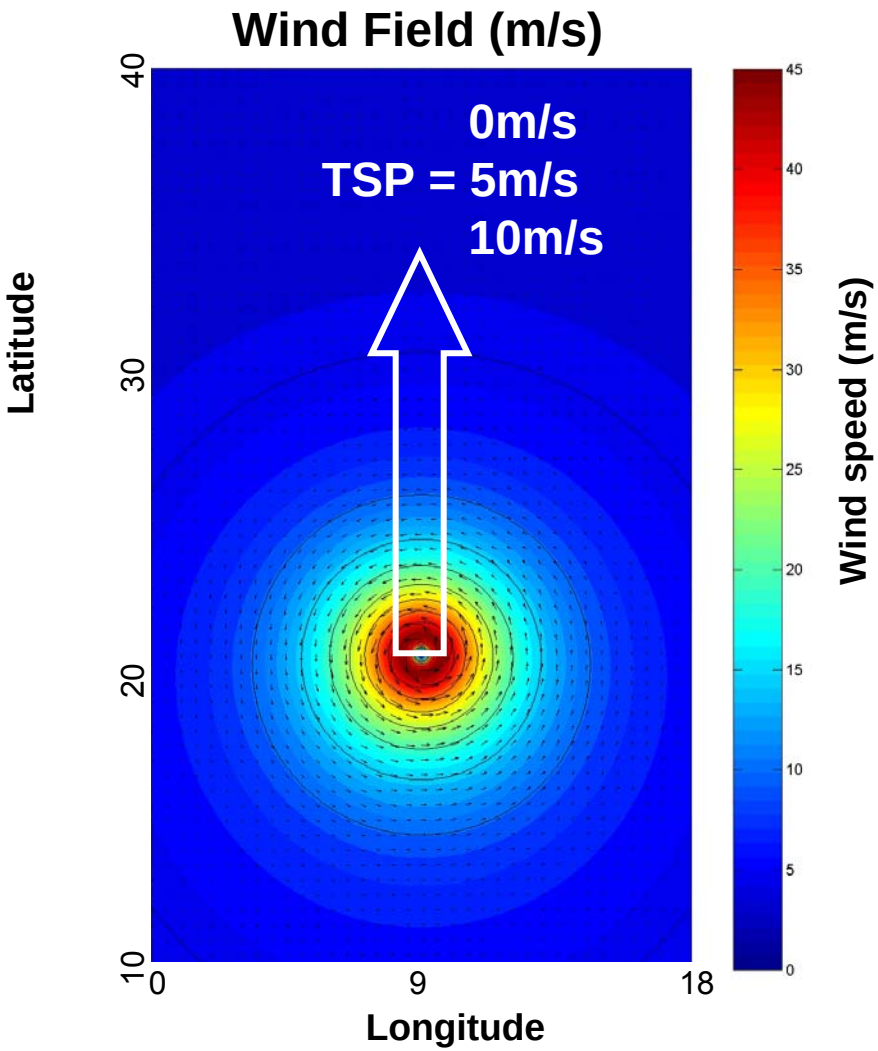


Previous studies: $EF_c \sim \rho_{air} |u_*|^3$

This study: $\boldsymbol{EF_c \sim \rho_{air} |u_*|^{3.5}}$

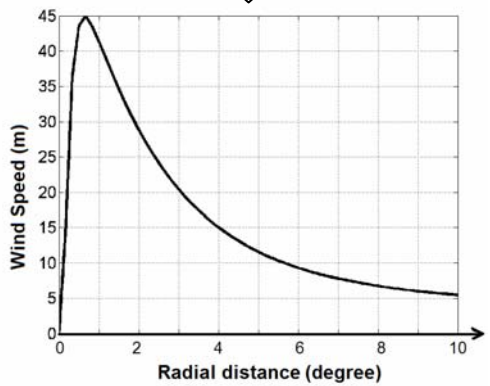
2. Energy and momentum flux budget across air-sea interface

❖ Hurricane experiments



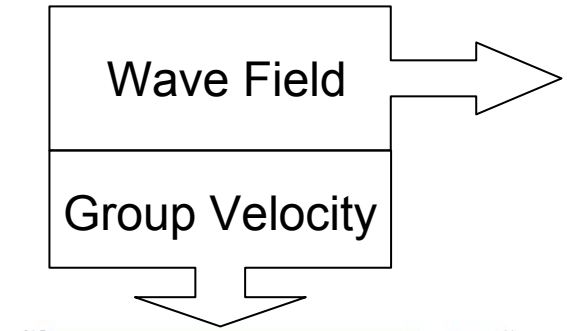
Holland Hurricane Wind Model

<u>Input parameters:</u>
Maximum wind speed (MWS)
Radius of MWS (RMW)
Central & environmental sea-level pressure

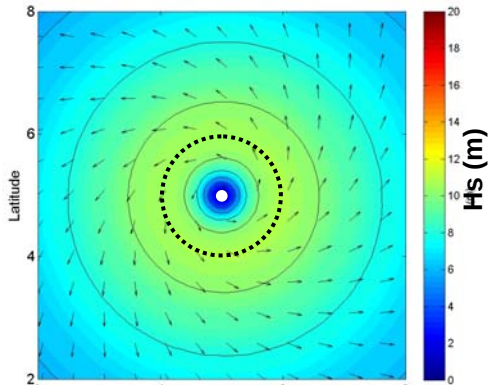


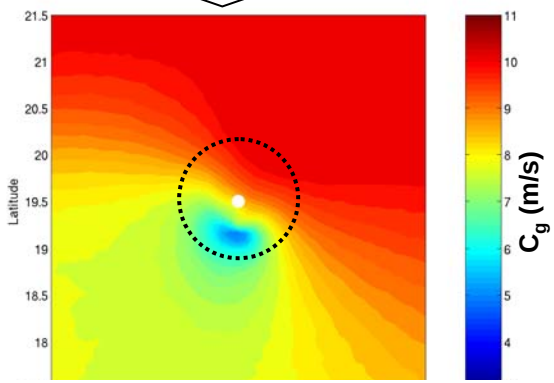
2. Energy and momentum flux budget across air-sea interface

- **Hurricane experiments**

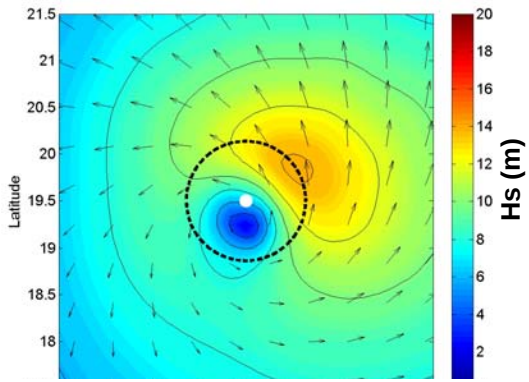


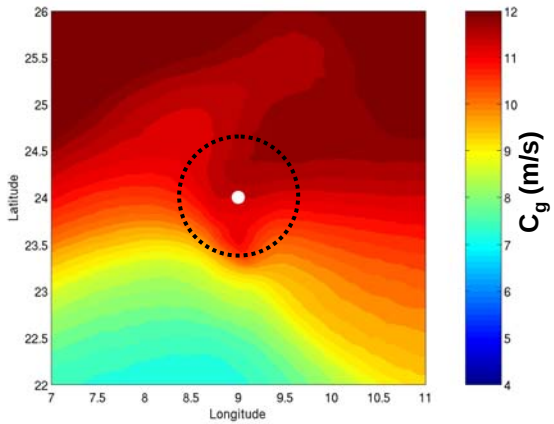
TSP
0m/s



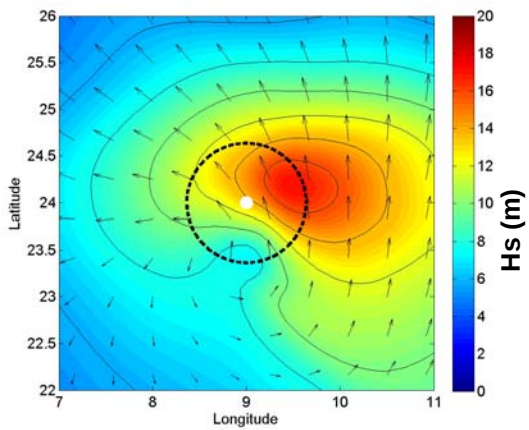


TSP
5m/s



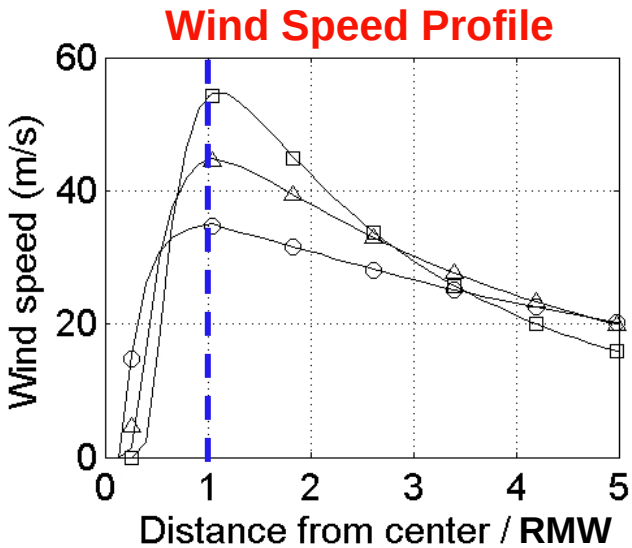


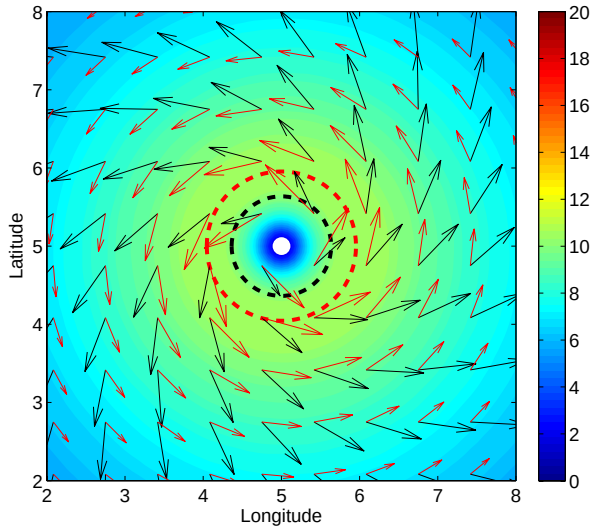
TSP
10m/s

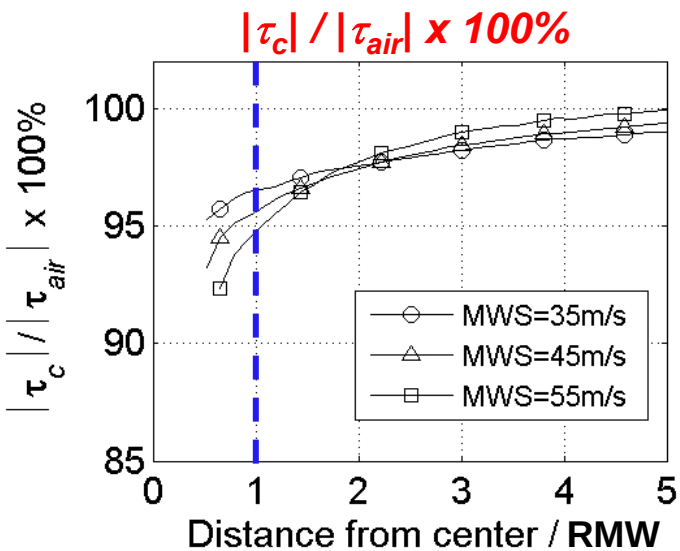


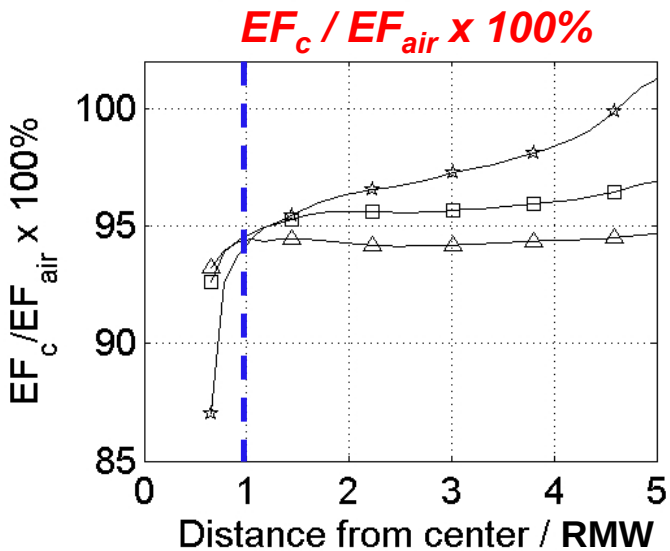
2. Energy and momentum flux budget across air-sea interface

❖ Hurricane experiments: Stationary Case (TSP = 0 m/s)



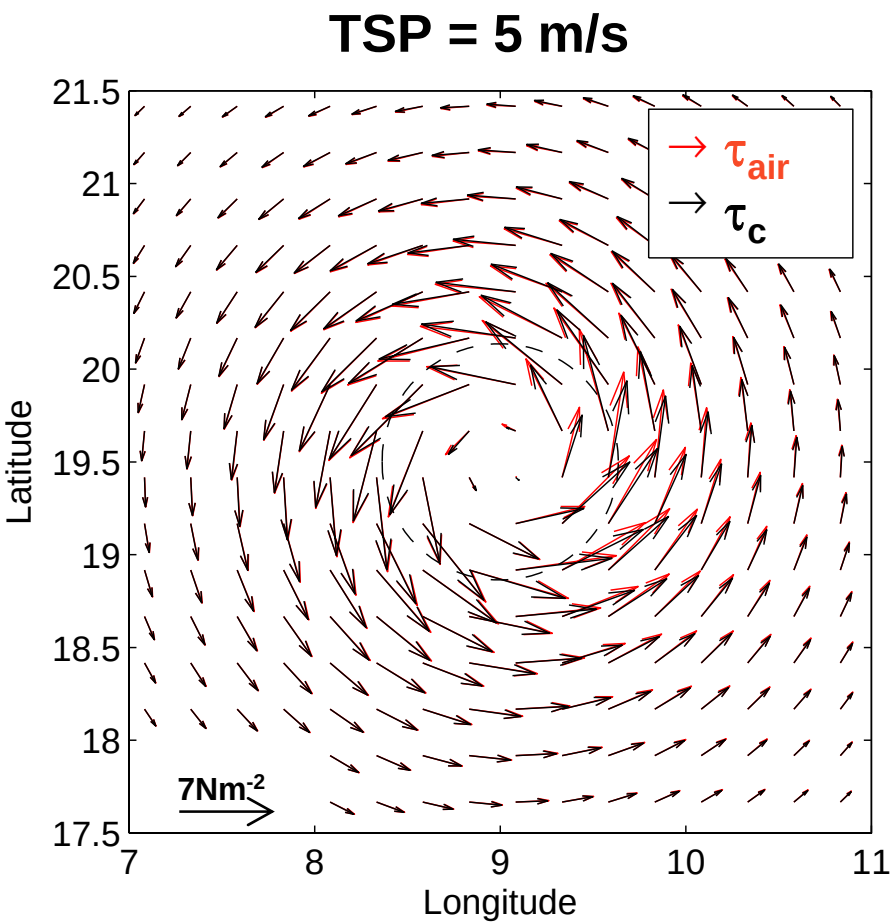


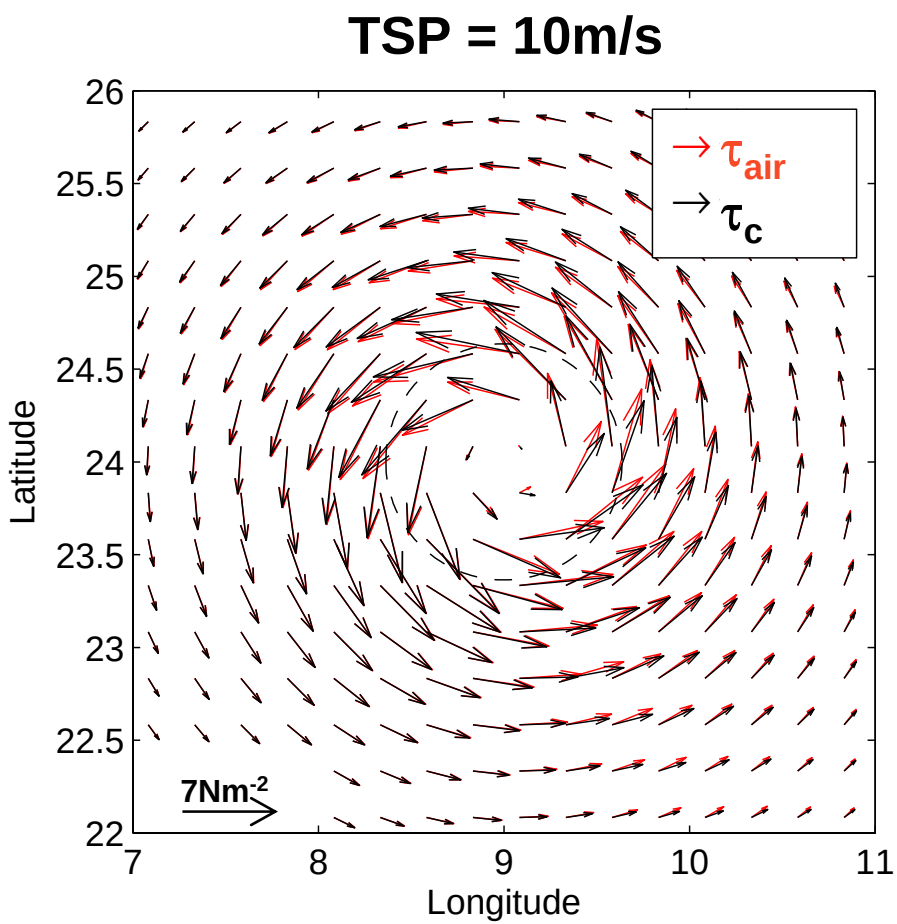




2. Energy and momentum flux budget across air-sea interface

- **Hurricane experiments: Moving cases (TCP = 5 m/s and 10 m/s)**





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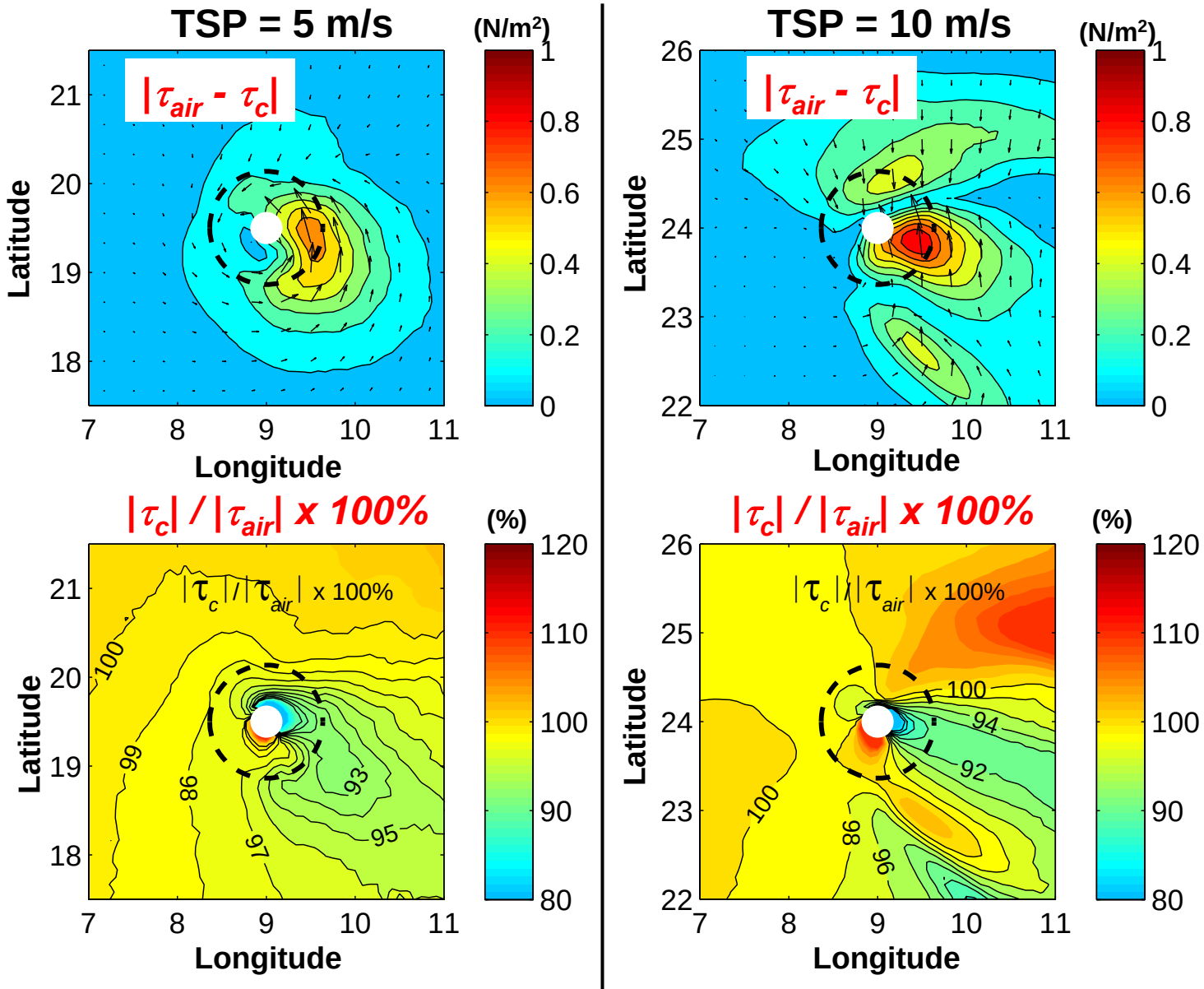

2. Energy and momentum flux budget across air-sea interface

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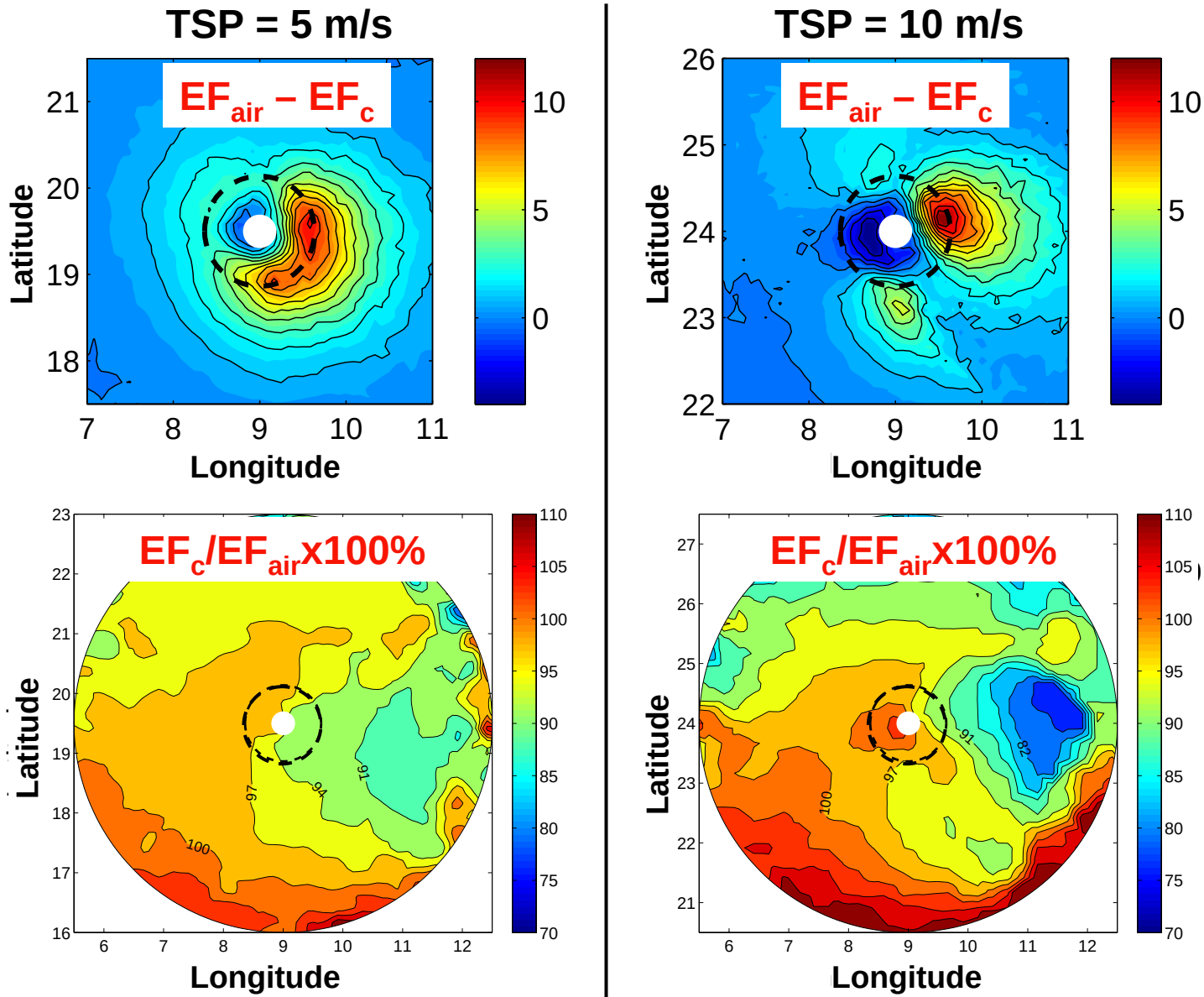
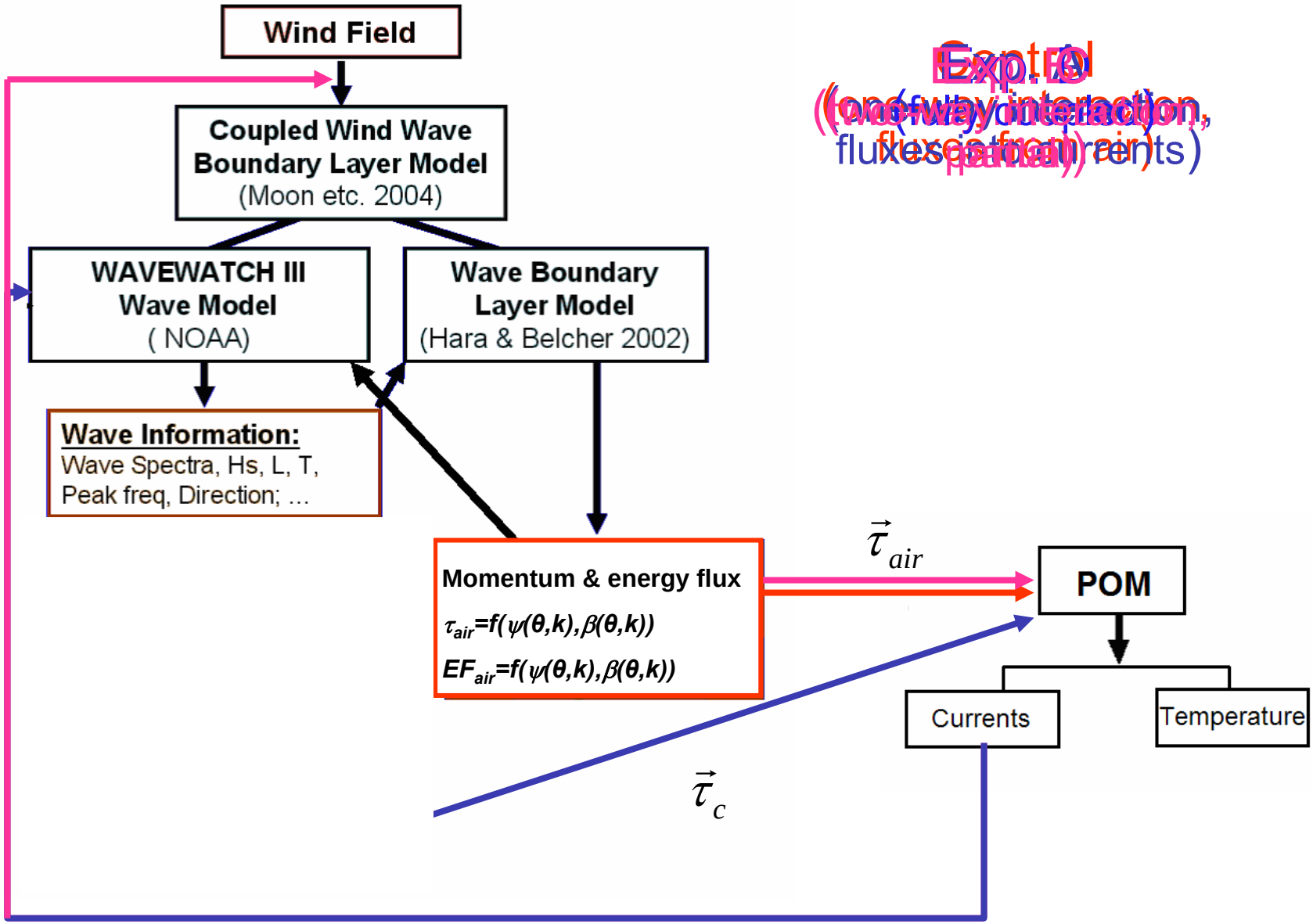
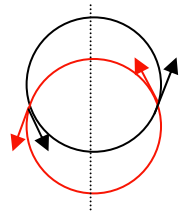


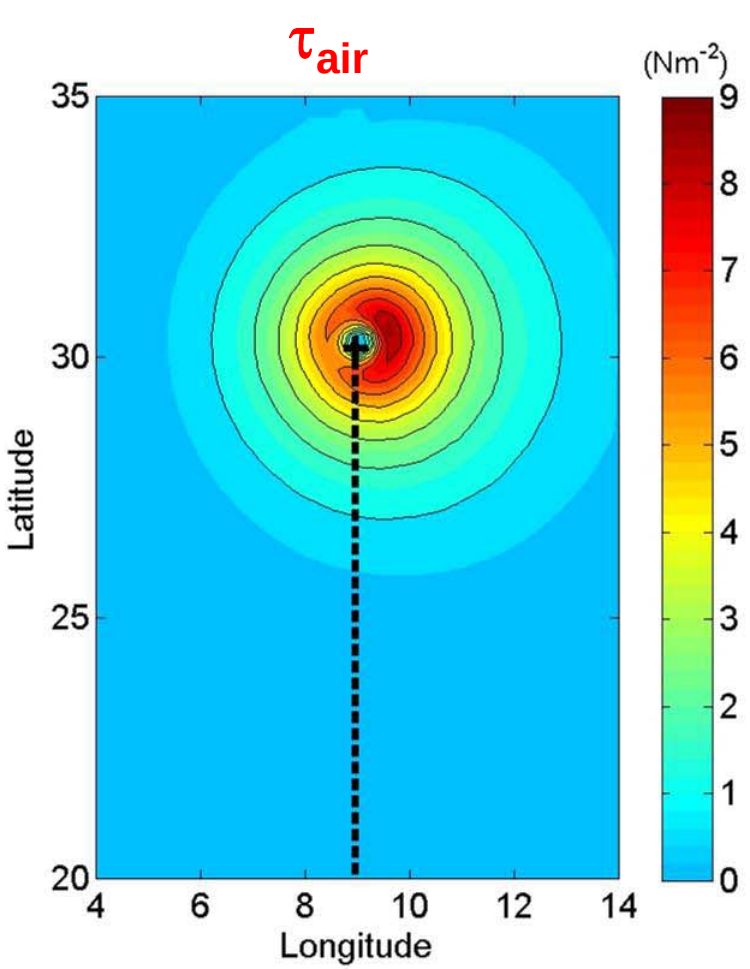
3. Wind-wave-current interaction in hurricanes

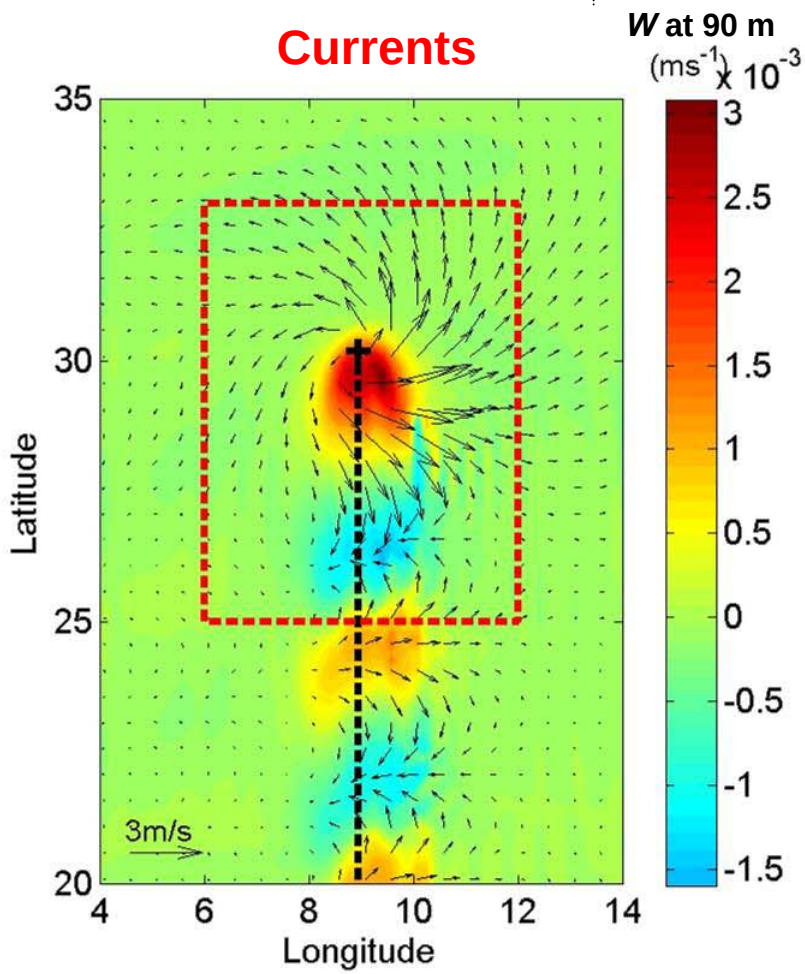


3. Wind-wave-current interaction in hurricanes

❖ **Ocean response in Control Experiment**



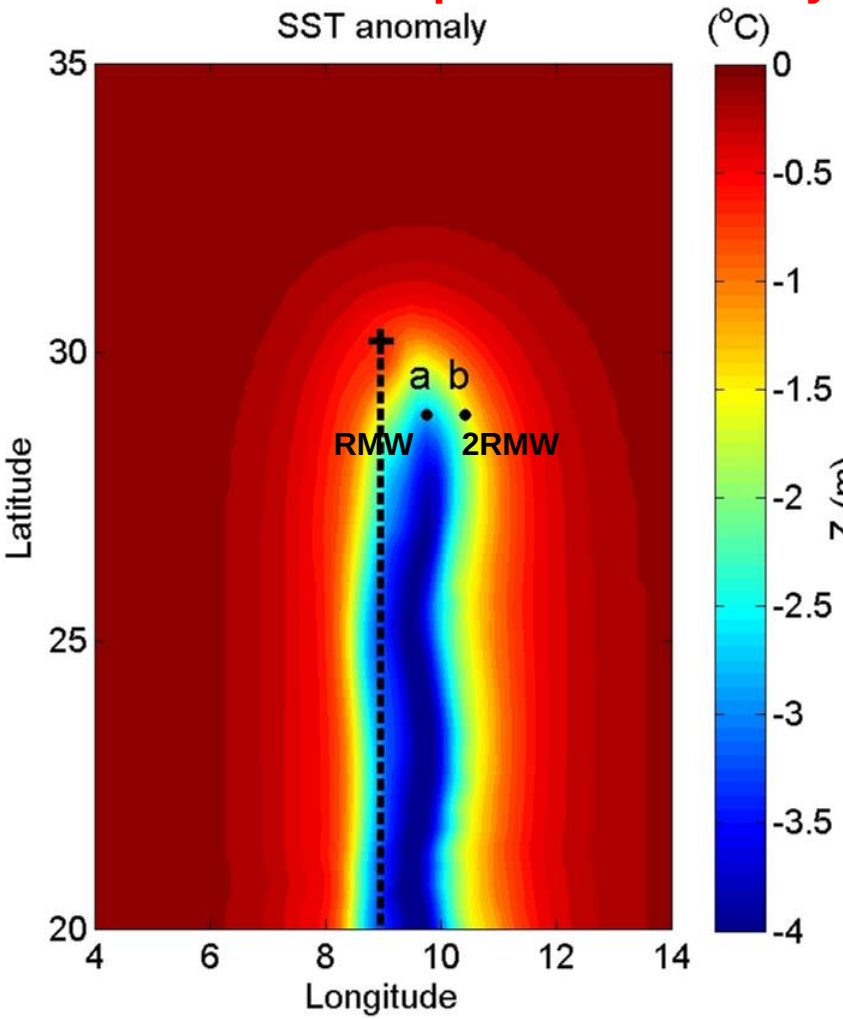




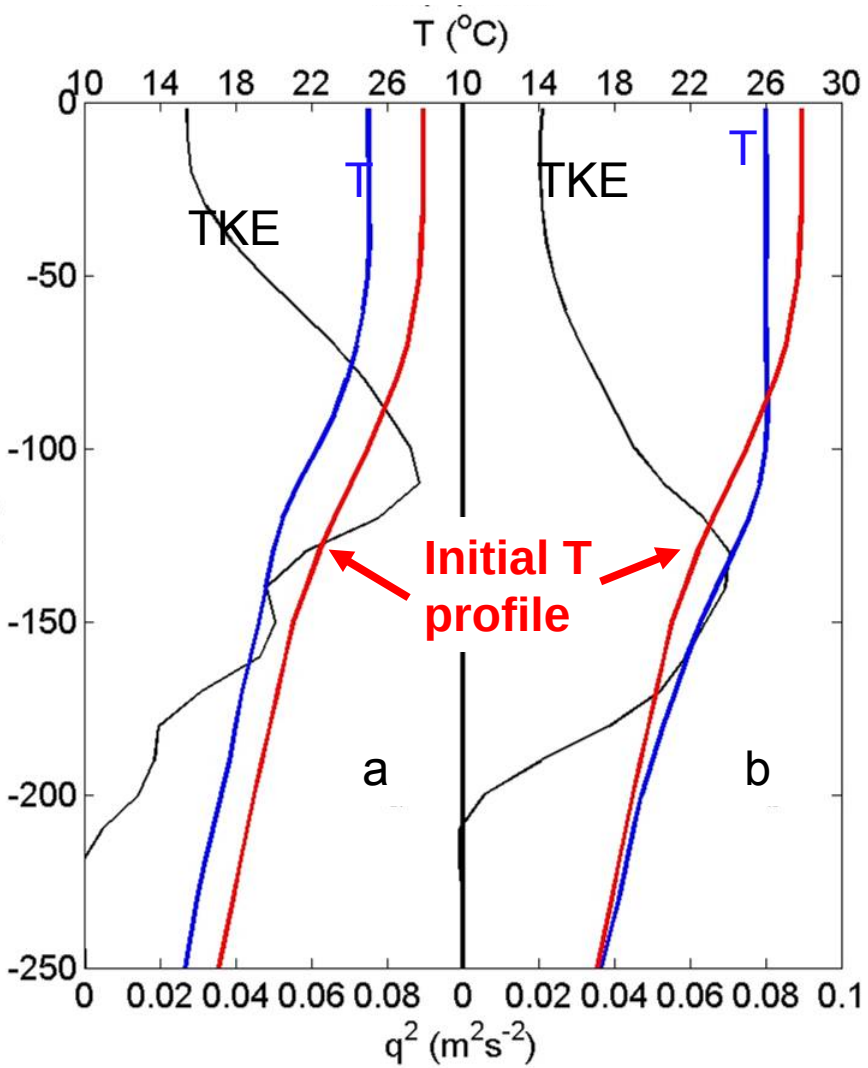
3. Wind-wave-current interaction in hurricanes

- **Ocean response in Control Experiment**

Sea Surface Temperature anomaly



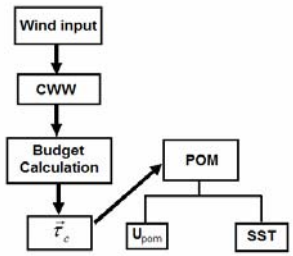
Temperature, TKE profile



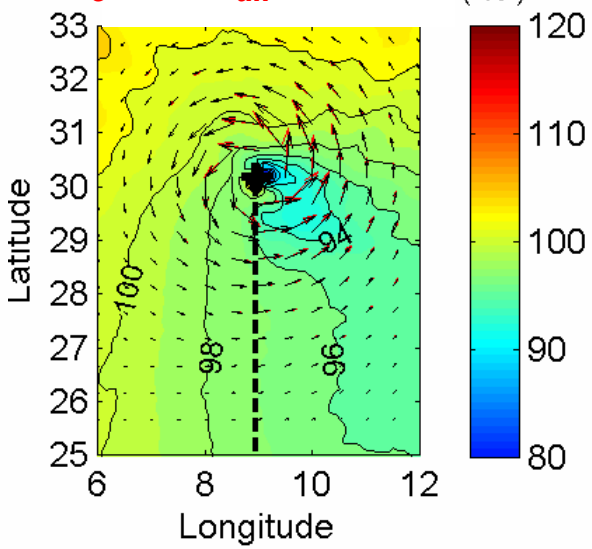
3. Wind-wave-current interaction in hurricanes

❖ Momentum Flux ratio

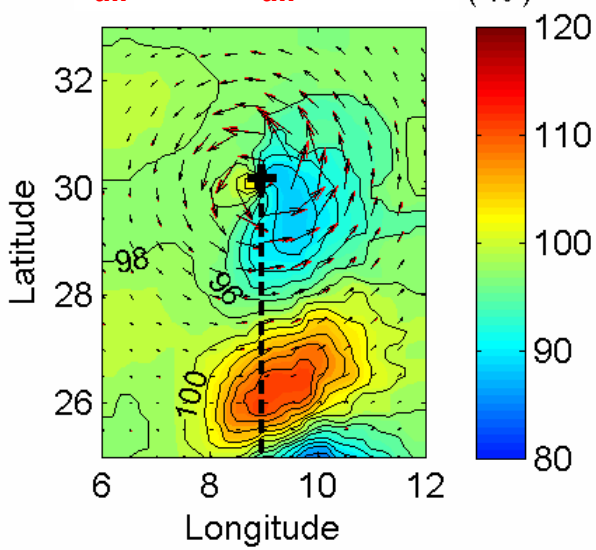
Exp A (one way)



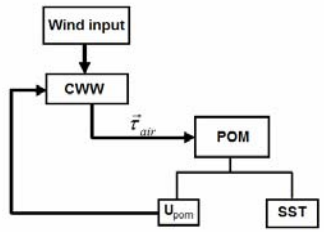
τ_c in A / τ_{air} in Control (%)



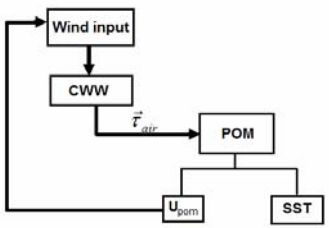
τ_{air} in B / τ_{air} in Control (%)



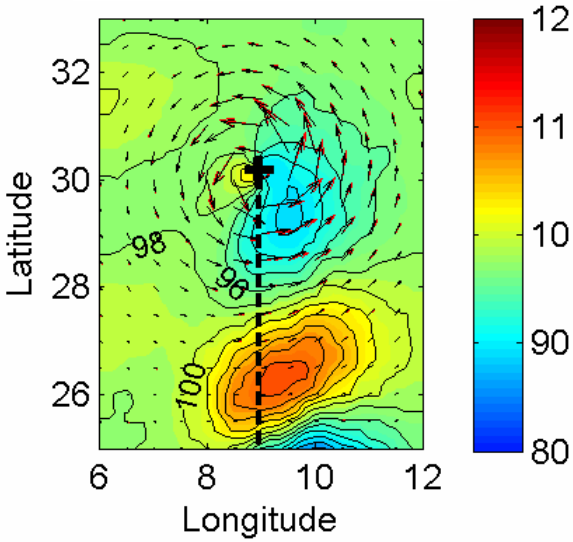
Exp B (two way)



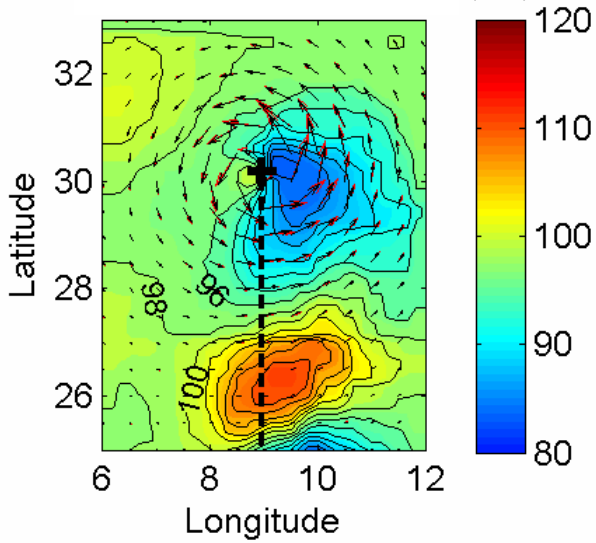
Exp C (two way Partial)



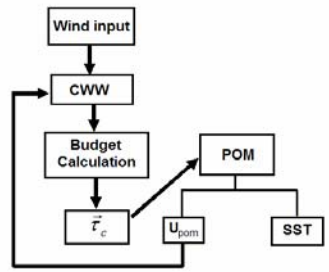
τ_{air} in C / τ_{air} in Control (%)



τ_c in D / τ_{air} in Control (%)



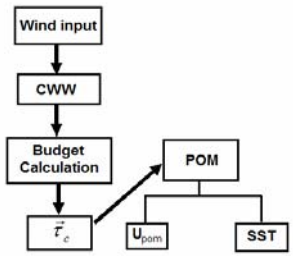
Exp D (fully coupled)

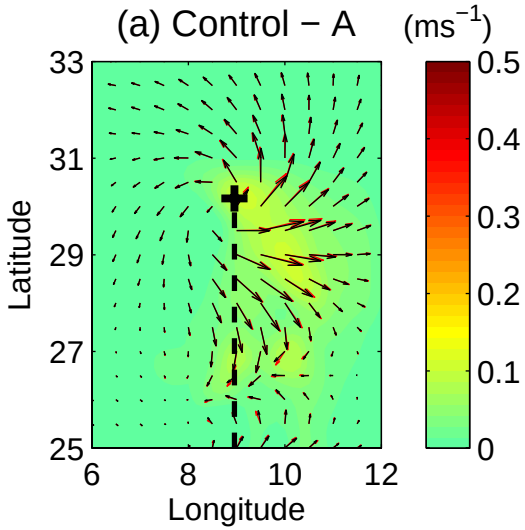


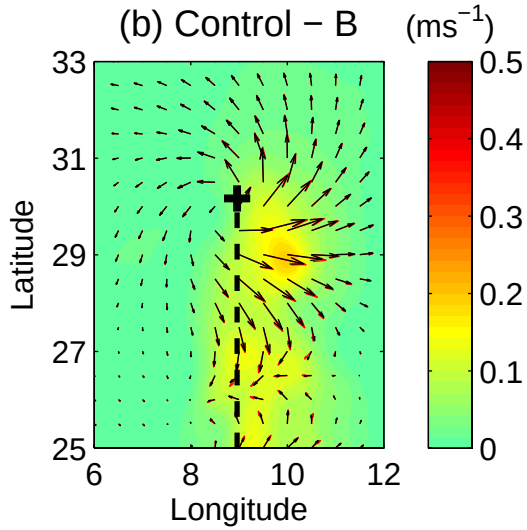
3. Wind-wave-current interaction in hurricanes

❖ Differences in surface current

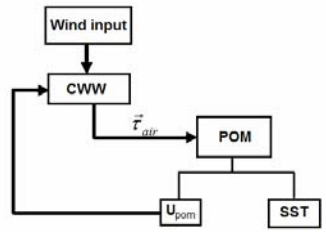
Exp A
(one way)



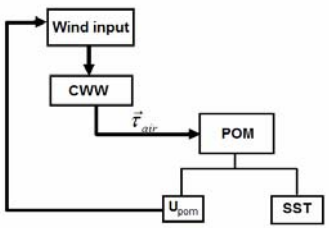


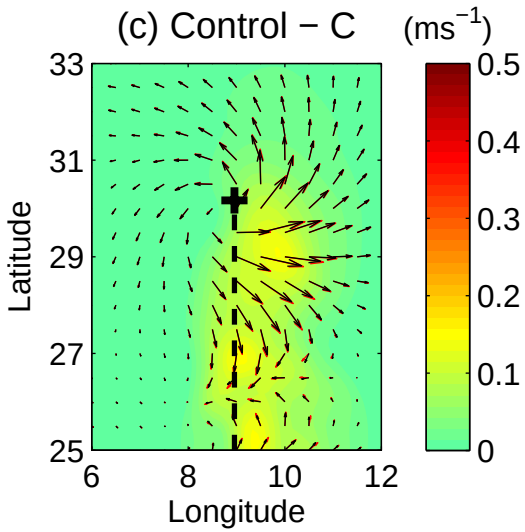


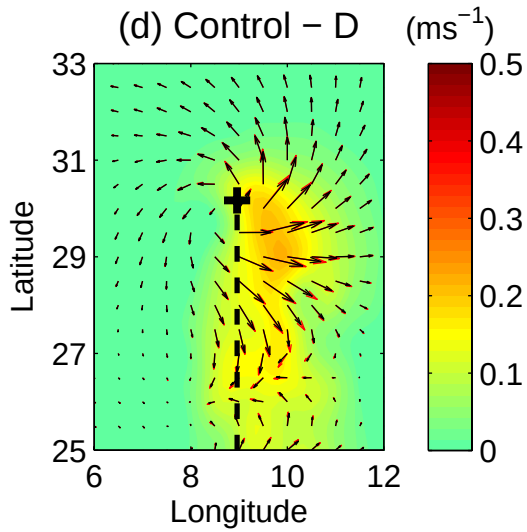
Exp B
(two way)



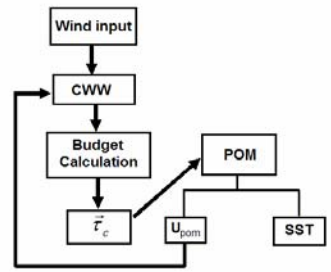
Exp C
(two way
Partial)







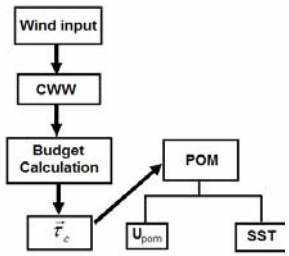
Exp D
(fully coupled)

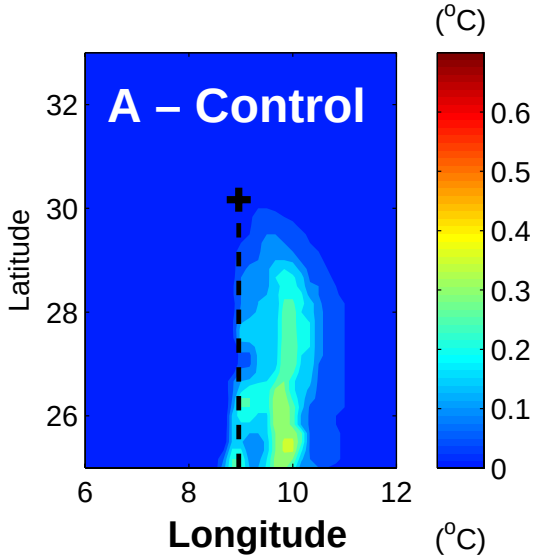


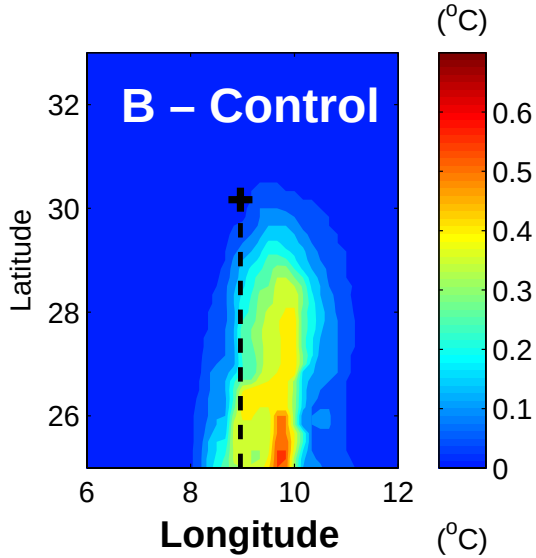
3. Wind-wave-current interaction in hurricanes

❖ Differences in the Sea Surface Temperature cooling

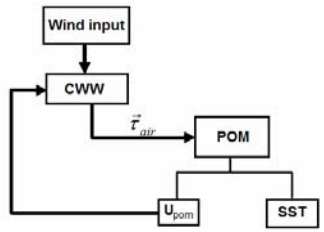
Exp A
(one way)



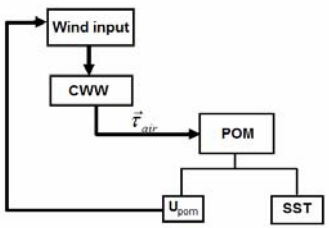


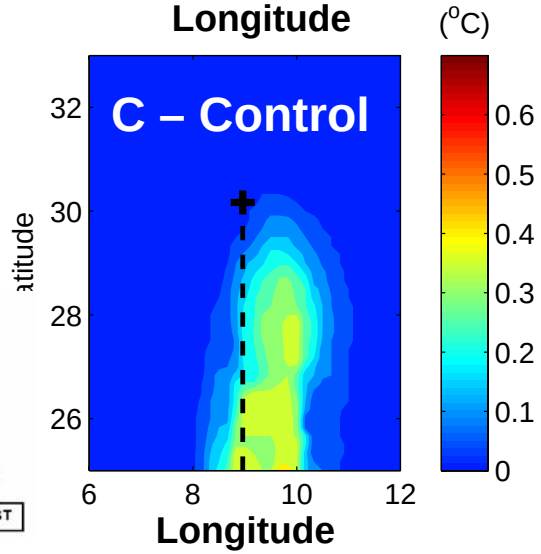


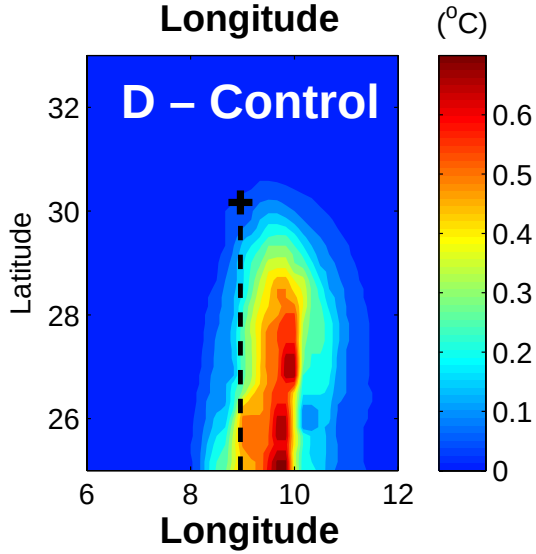
Exp B
(two way)



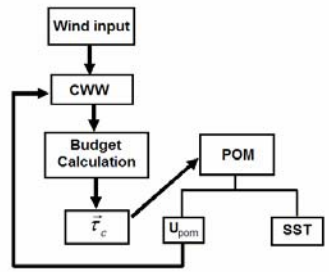
Exp C
(two way
Partial)





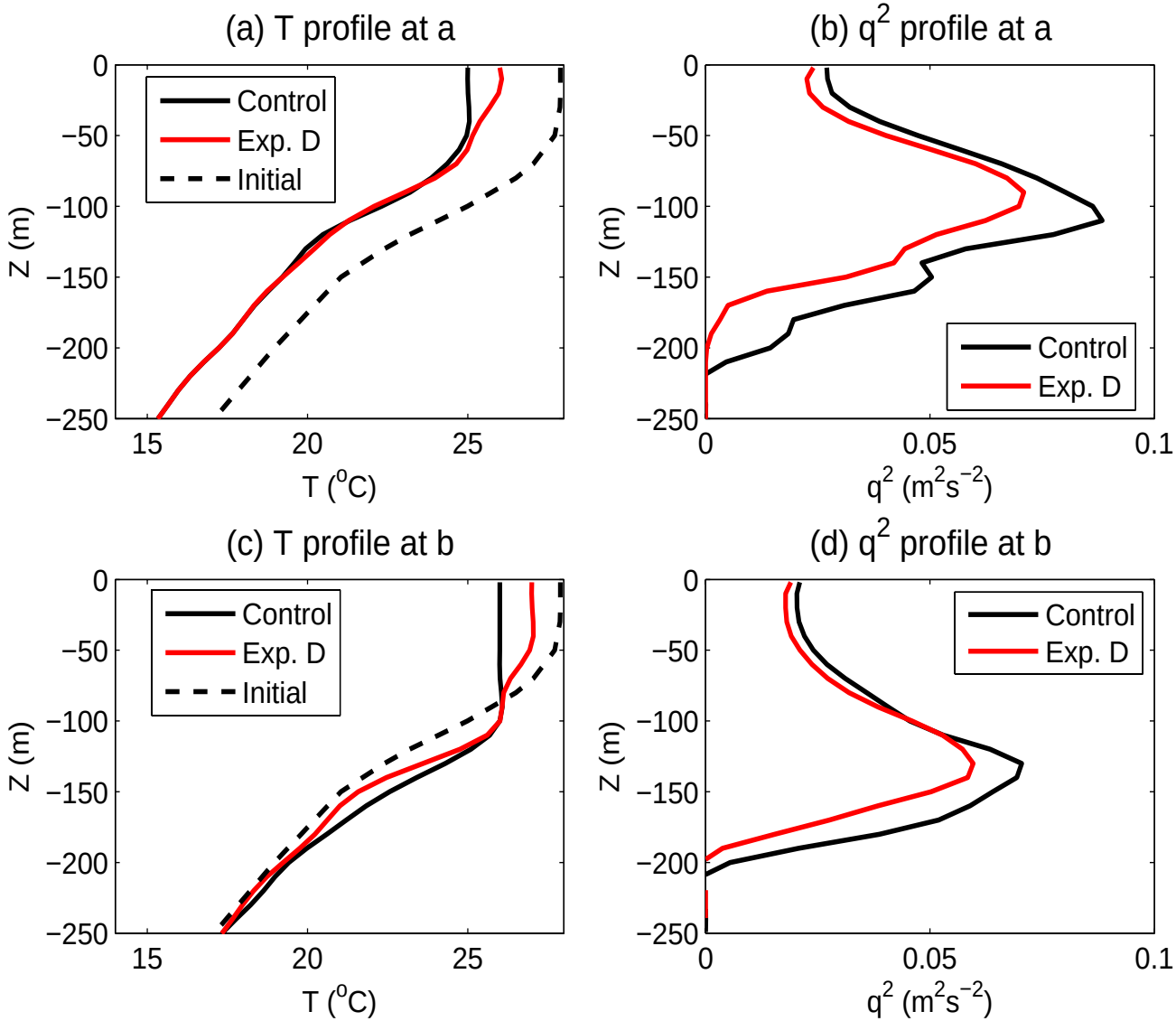


Exp D
(fully coupled)



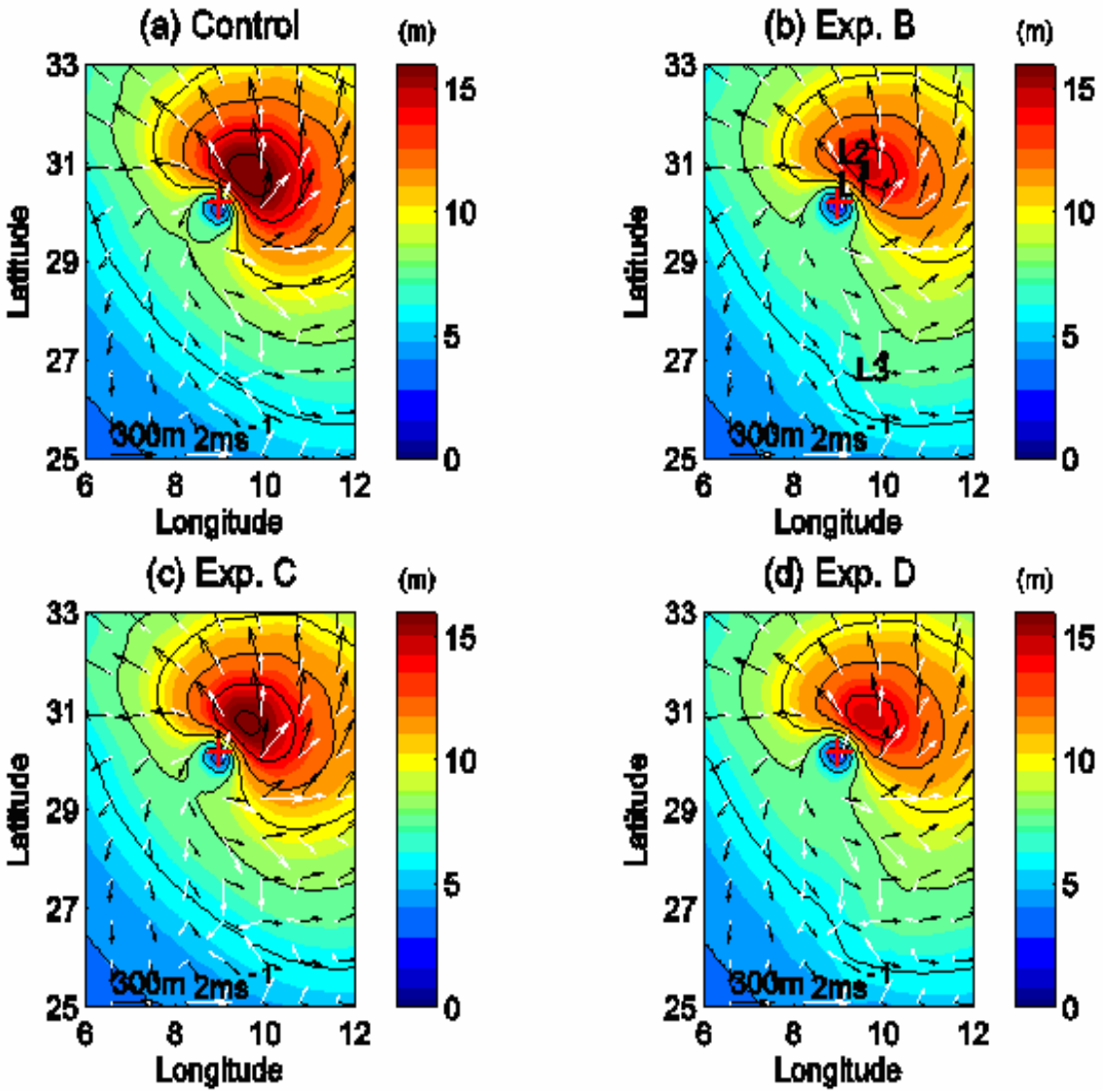
3. Wind-wave-current interaction in hurricanes

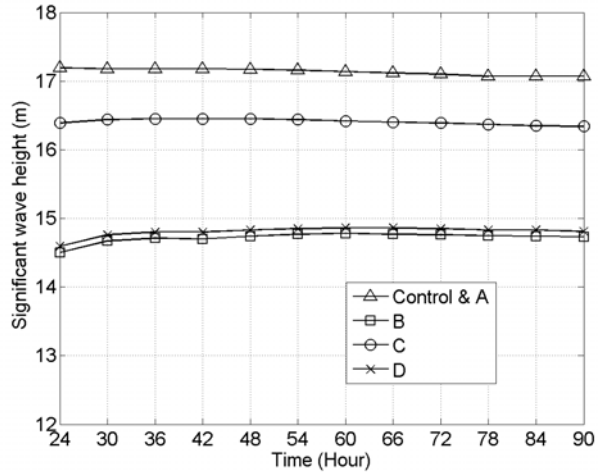
❖ Temperature and TKE profiles

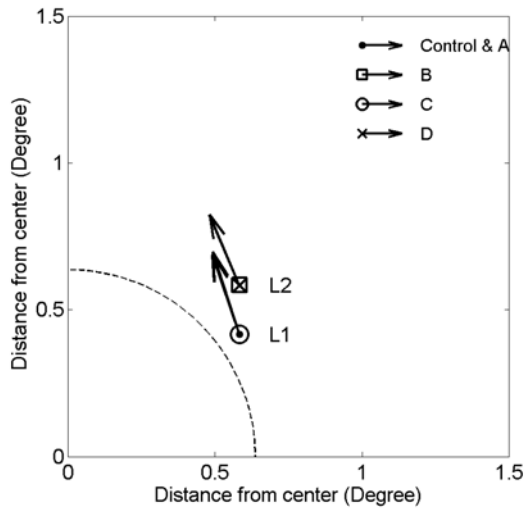


3. Wind-wave-current interaction in hurricanes

❖ Impact of wind-wave-current interaction on the wave field

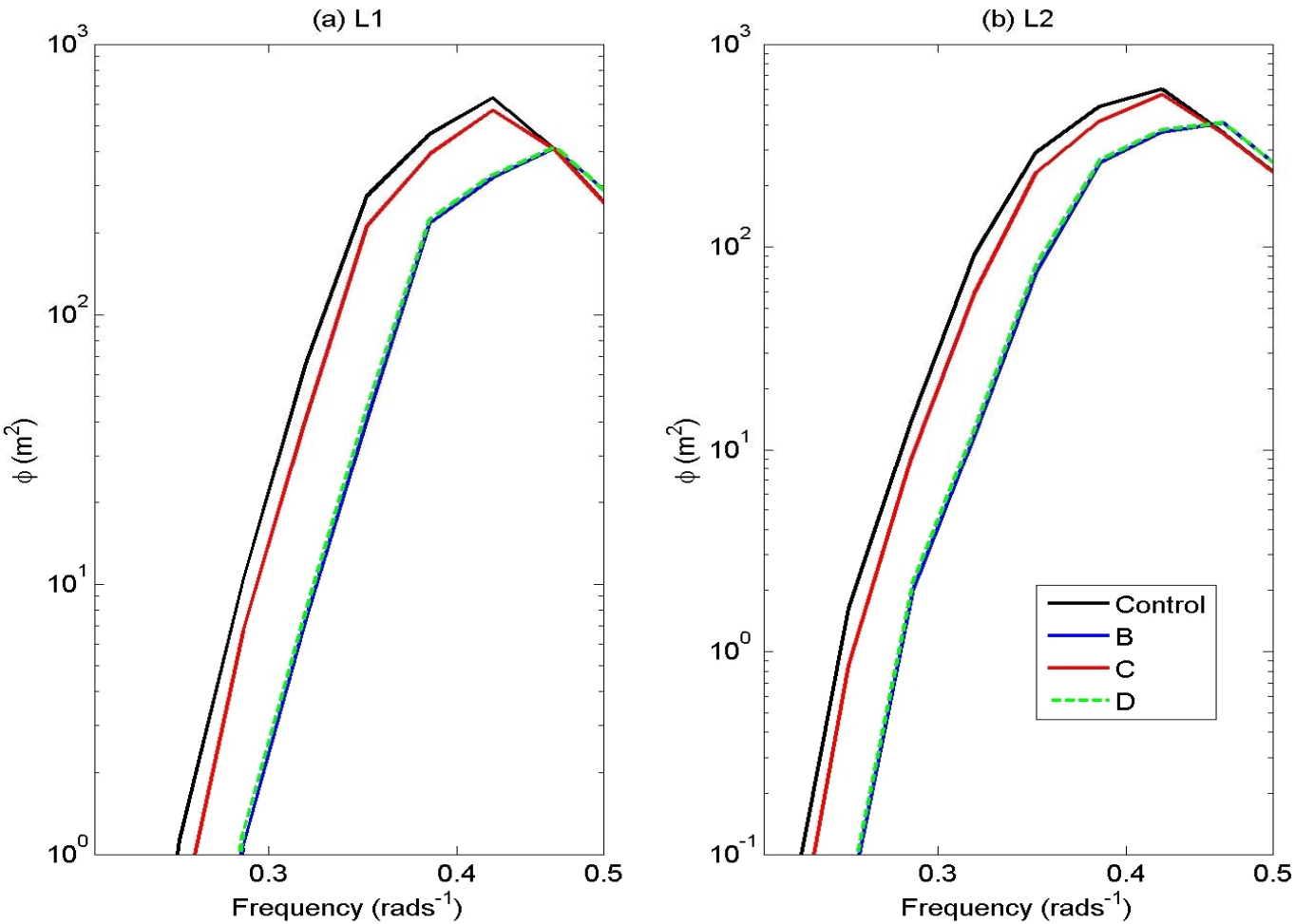






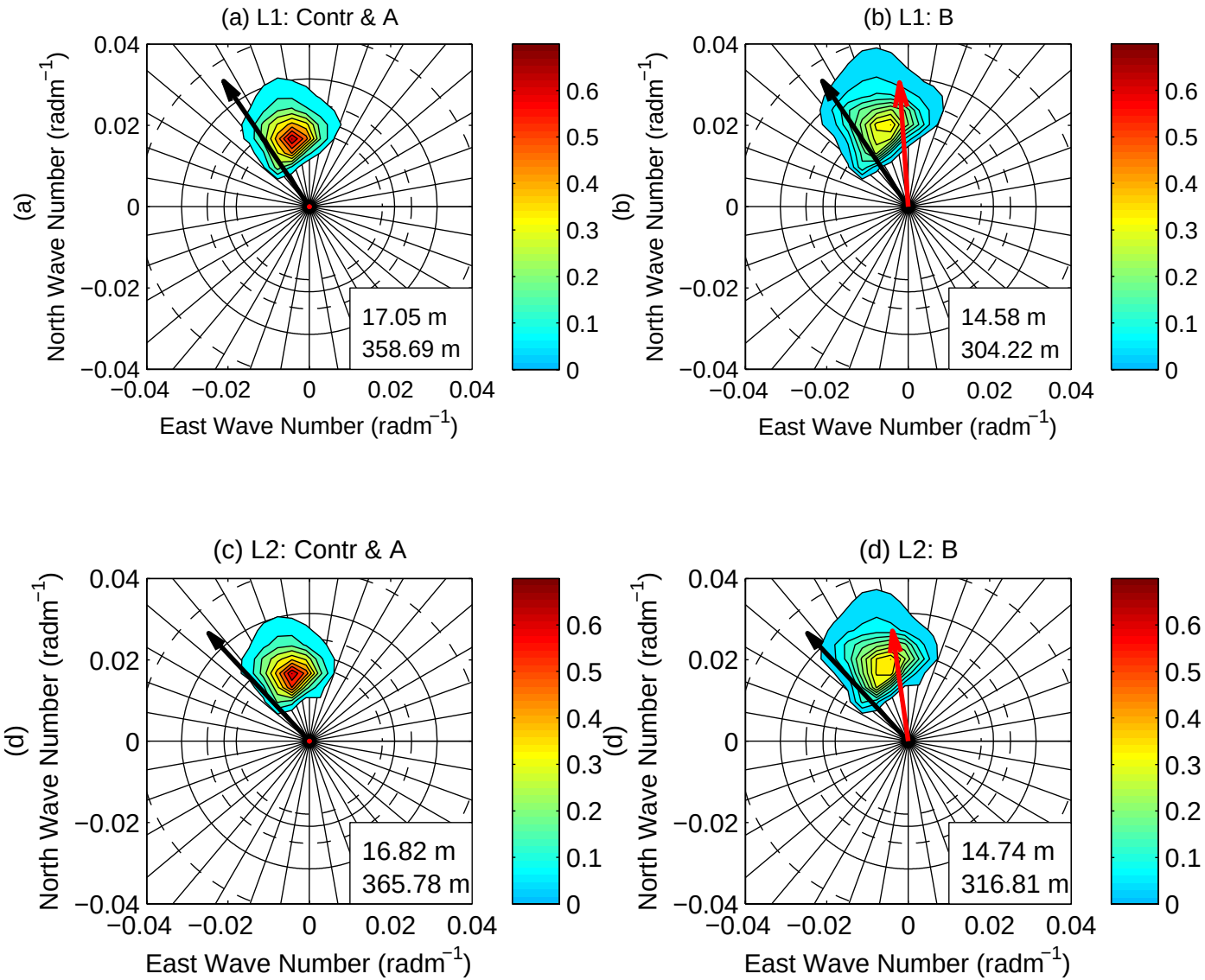
3. Wind-wave-current interaction in hurricanes

❖ Frequency spectrum for different experiments



3. Wind-wave-current interaction in hurricanes

❖ WW3 2-D spectrum in two locations



3. Wind-wave-current interaction in hurricanes

❖ Explanation of the ocean current effect on wave spectrum

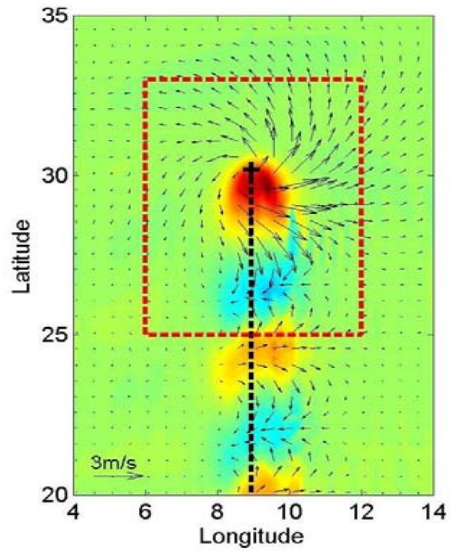
Steady state equation of wave action conservation:

$$\frac{\partial N}{\partial x}\left(U + C_g - U_t\right) - k\frac{\partial N}{\partial k}\frac{\partial U}{\partial x} = 0$$

$\frac{\partial U}{\partial x} > 0$ for $x < 0$

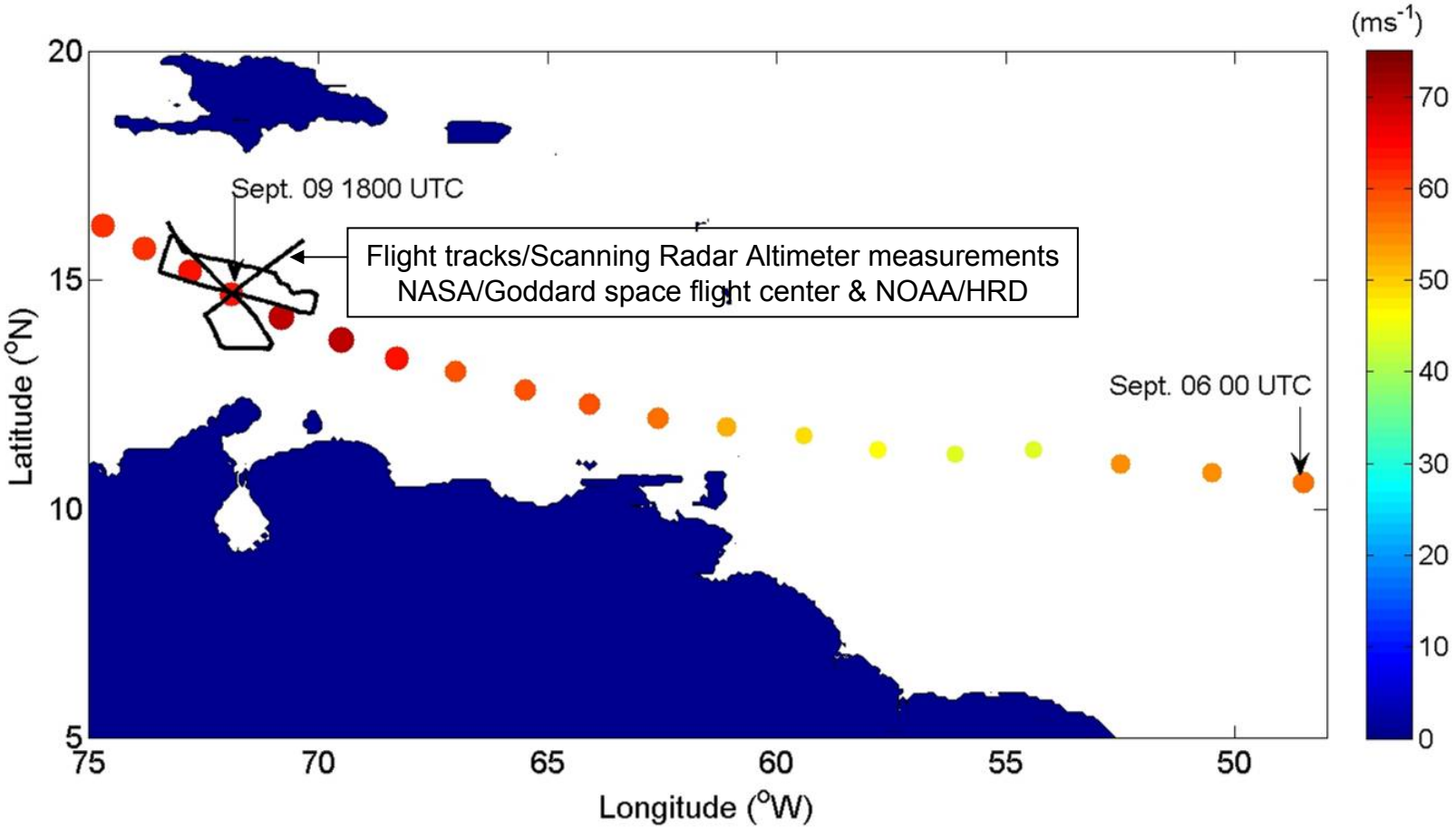
$\frac{\partial U}{\partial x} < 0$ for $x > 0$.

$k\frac{\partial N}{\partial k}$ is always negative



4. Case study: Hurricane Ivan (2004)

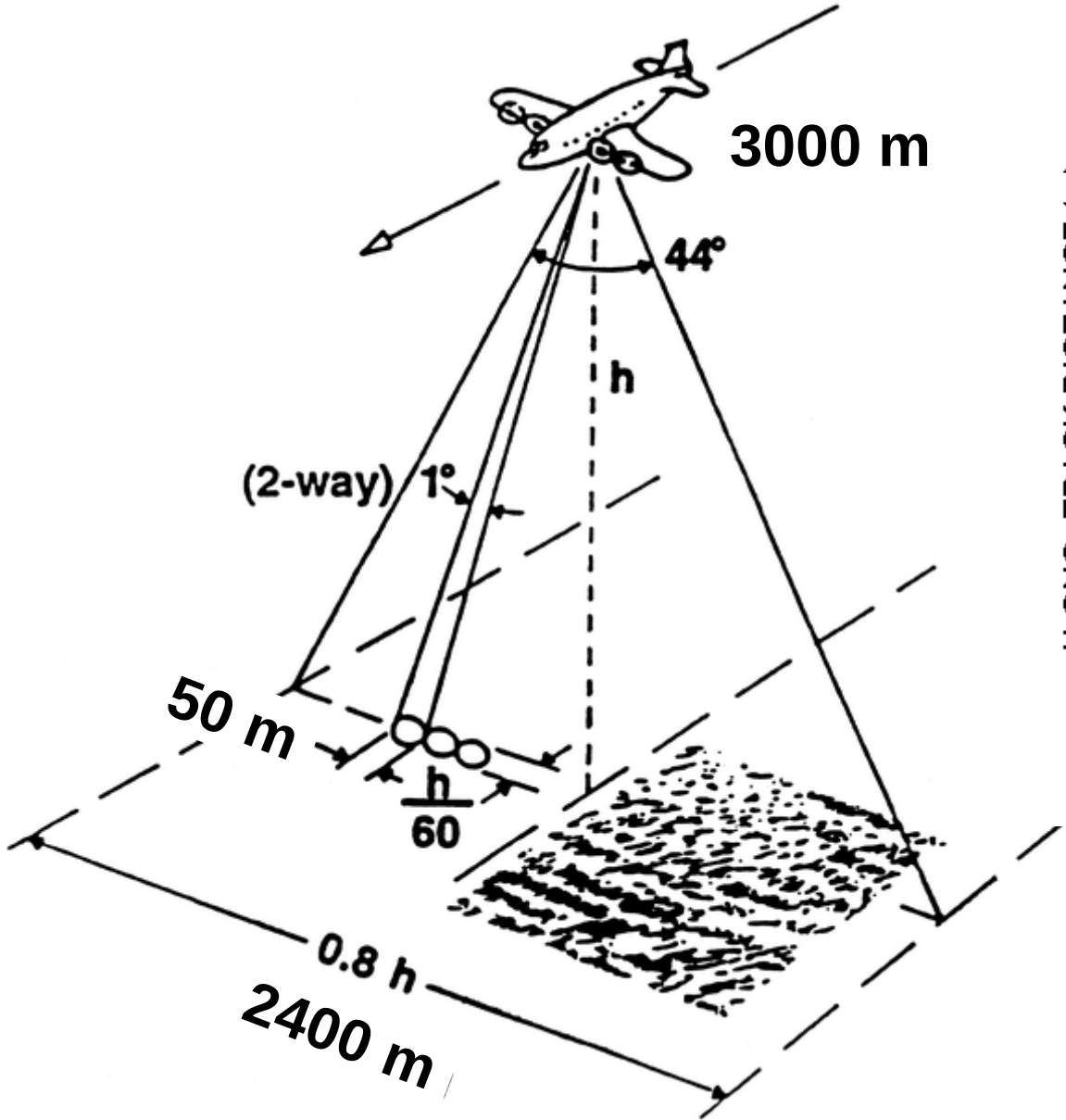
❖ **Ivan track and reconnaissance flight tracks**

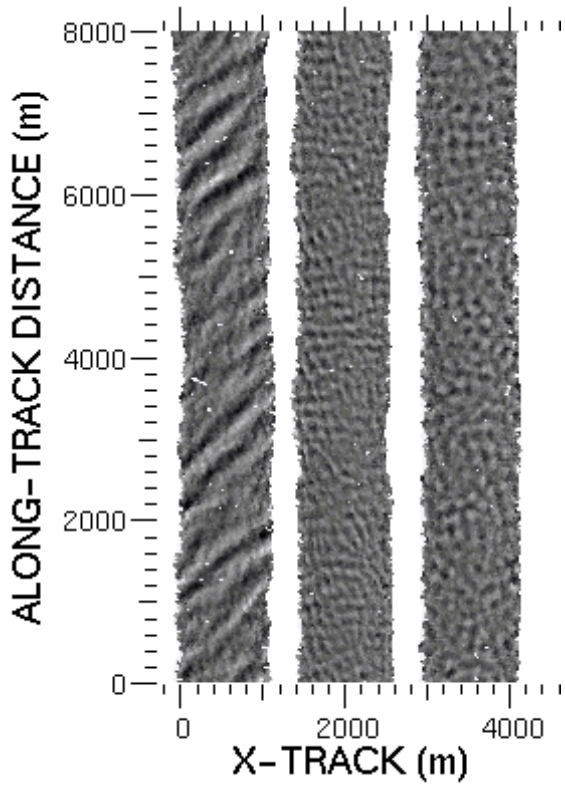


Exp. A: WAVEWATCH III wave model (operational model)
Exp. B: Coupled wind-wave model
Exp. C: Coupled wind-wave-current model

4. Case study: Hurricane Ivan (2004)

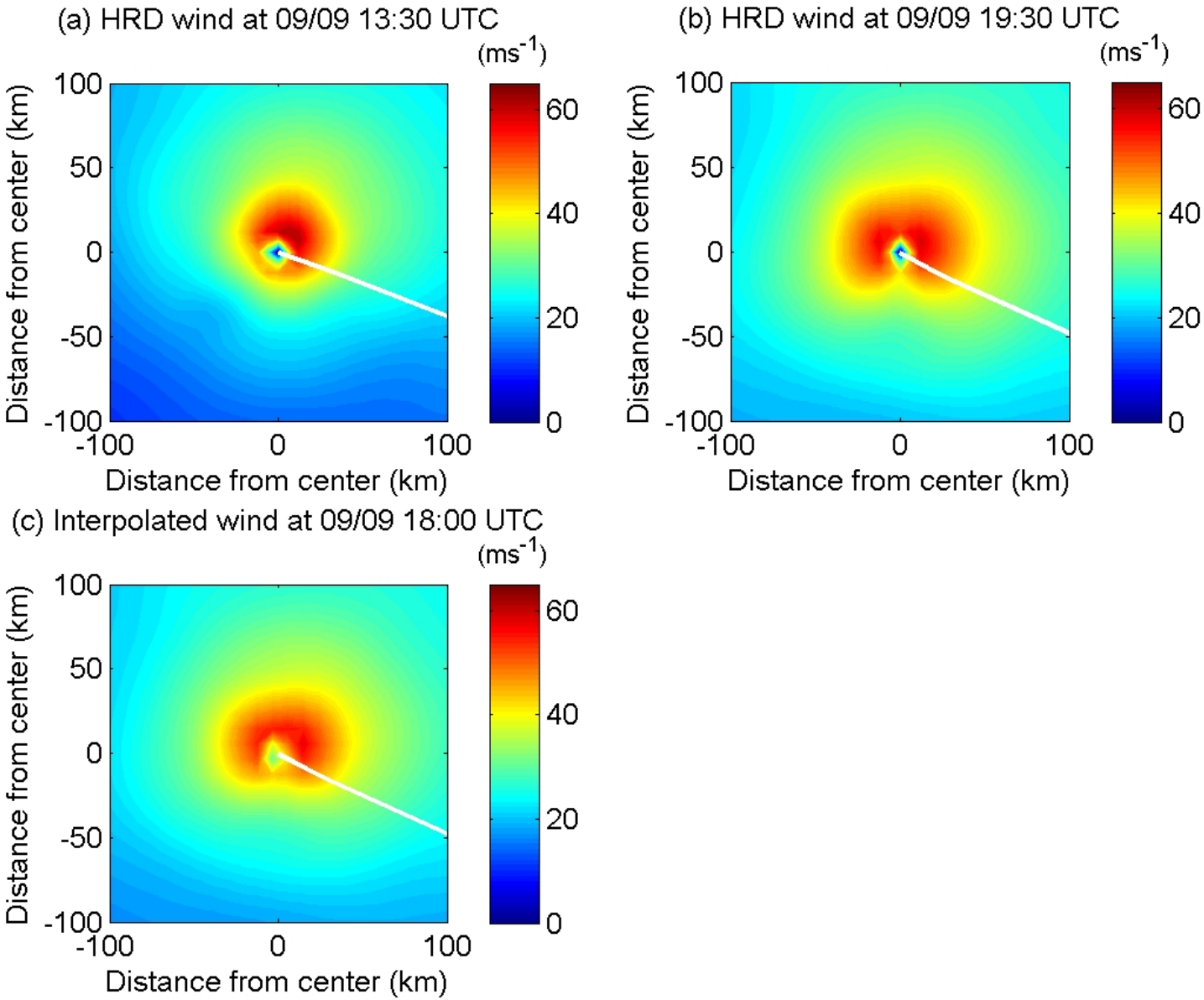
❖Scanning Radar Altimeter (SRA) measurements





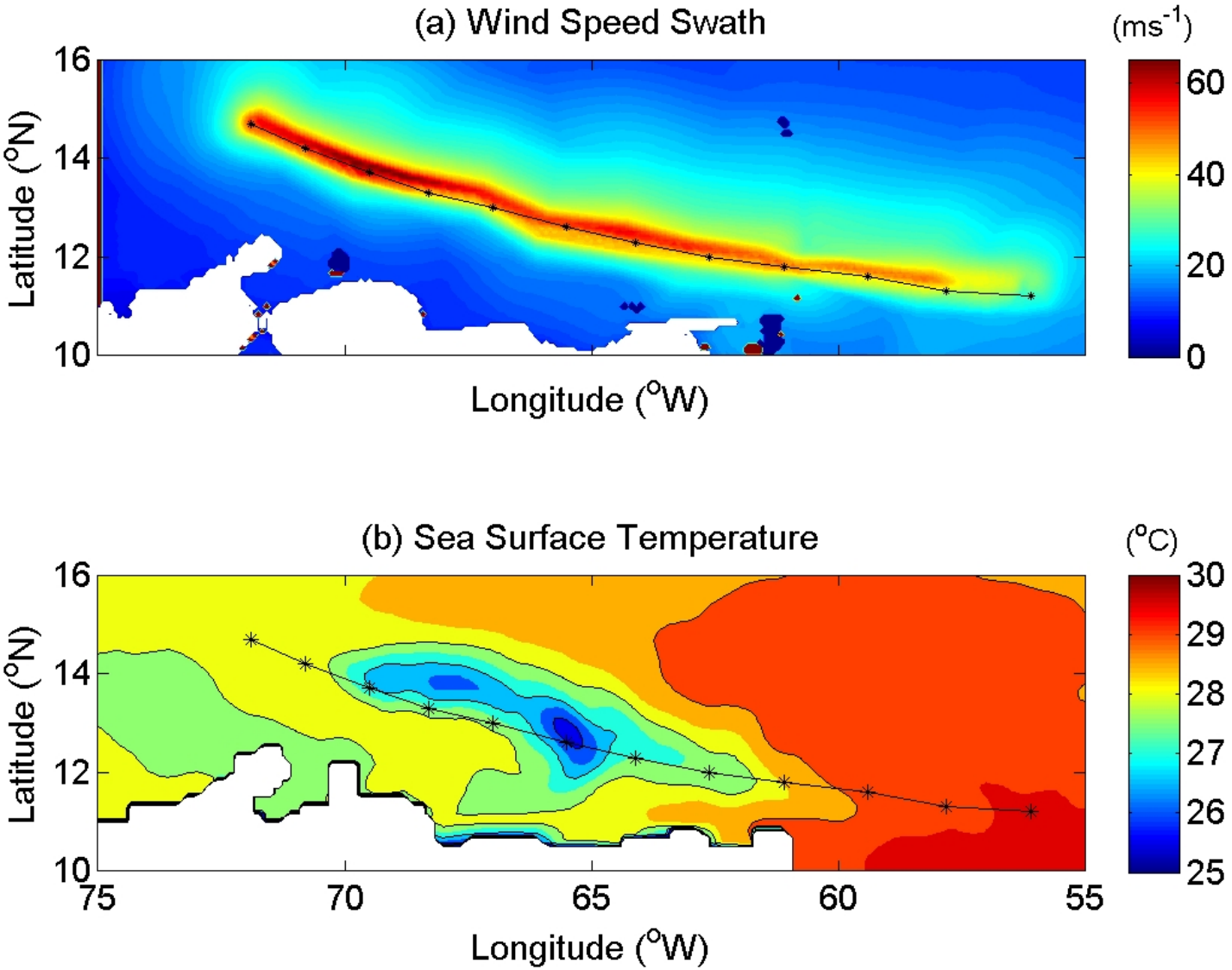
4. Case study: Hurricane Ivan (2004)

❖ HRD H*wind



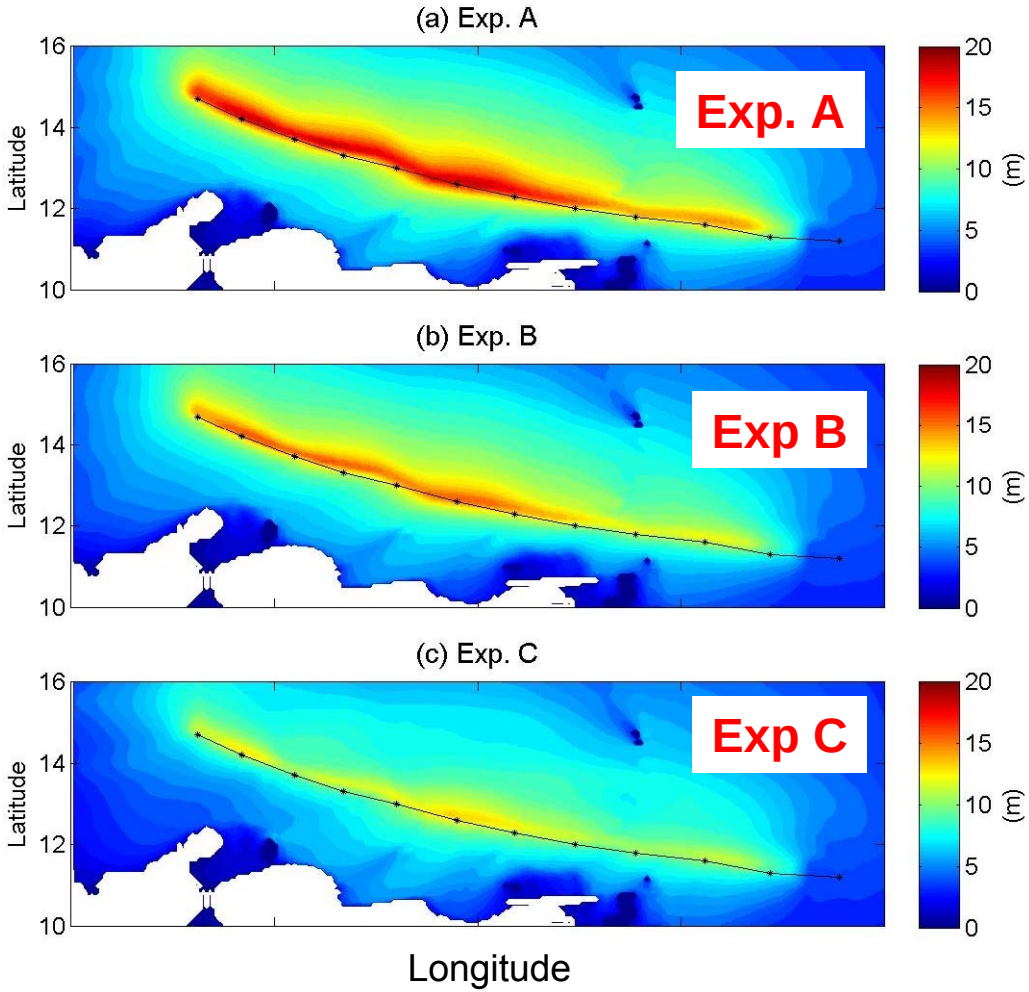
4. Case study: Hurricane Ivan (2004)

- **Wind swath and sea surface temperature**



4. Case study: Hurricane Ivan (2004)

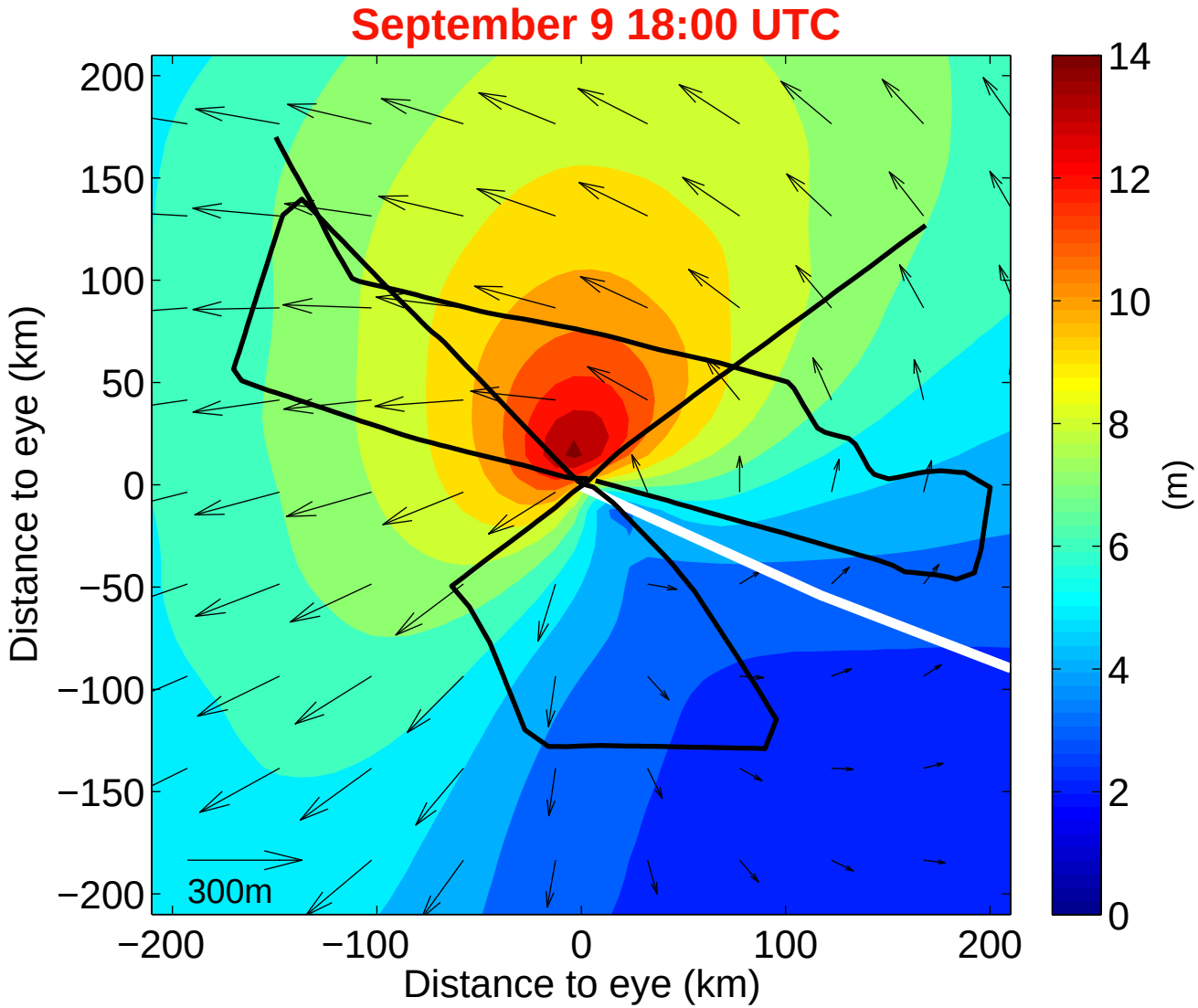
❖ Significant Wave Height Swaths



Exp. A: WAVEWATCH III wave model (operational model)
Exp. B: Coupled wind-wave model
Exp. C: Coupled wind-wave-current model

4. Case study: Hurricane Ivan (2004)

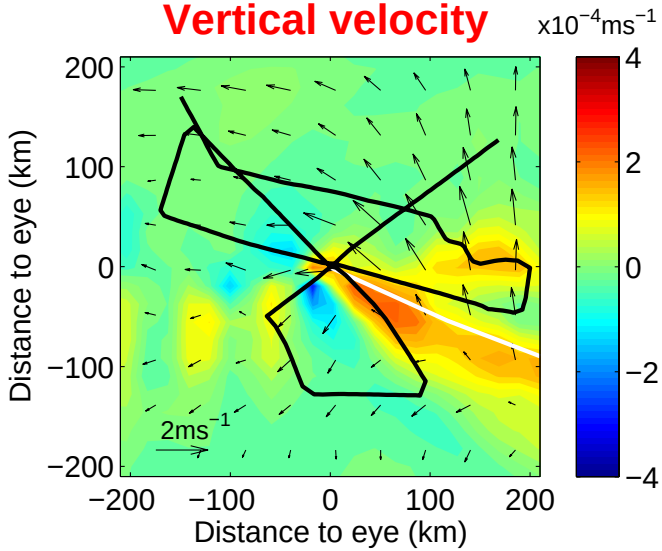
- **Surface wave field & flight track**



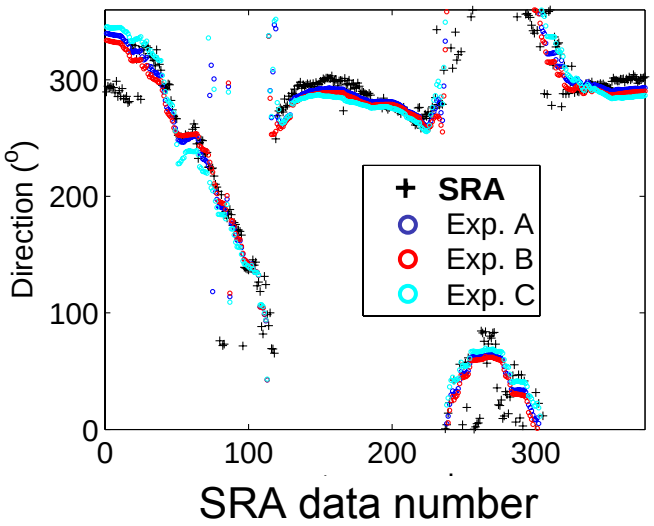
4. Case study: Hurricane Ivan (2004)

❖ Wave parameter comparisons between model and SRA data

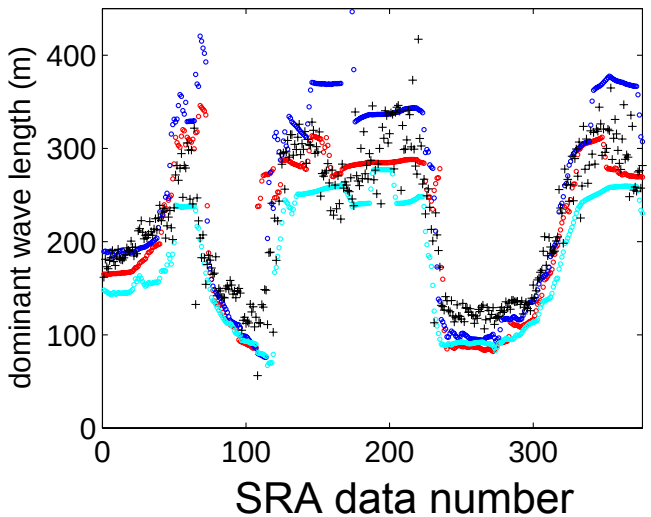
Vertical velocity



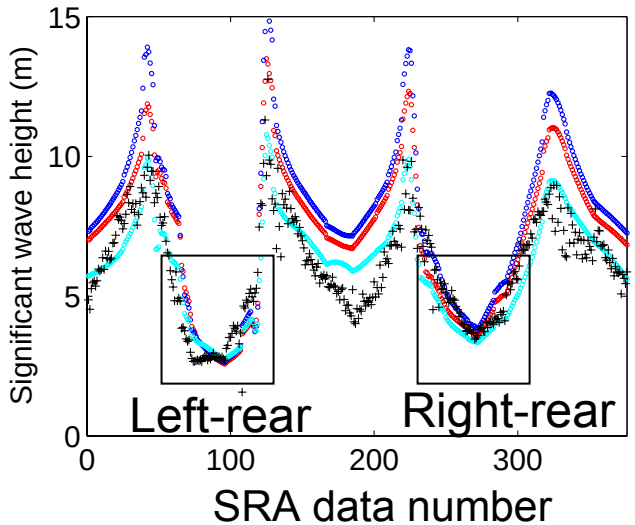
Wave Direction



Dominant Wave Length

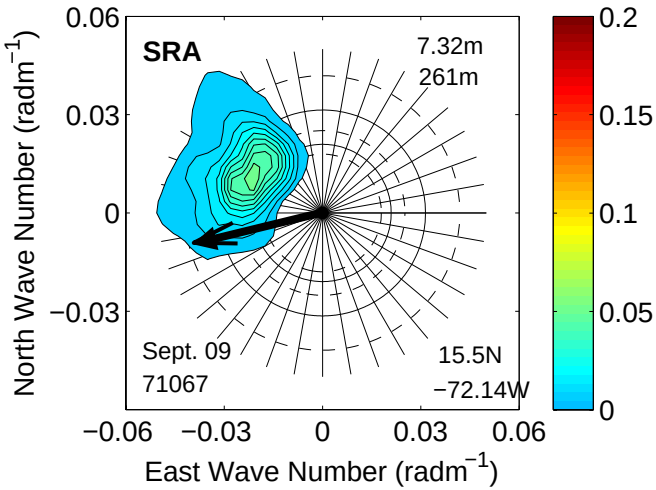


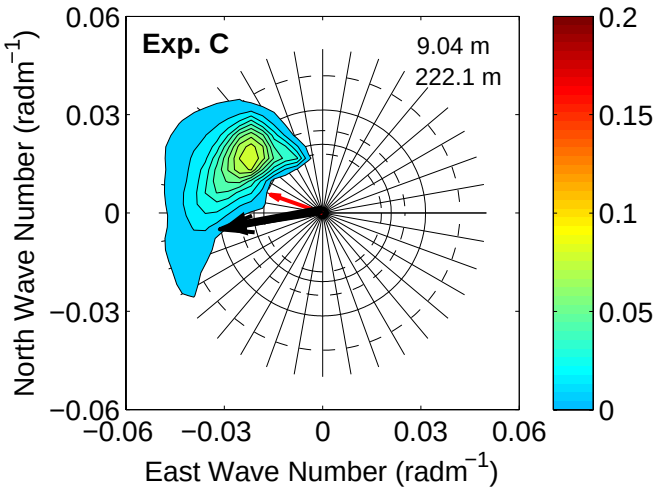
Significant Wave Height



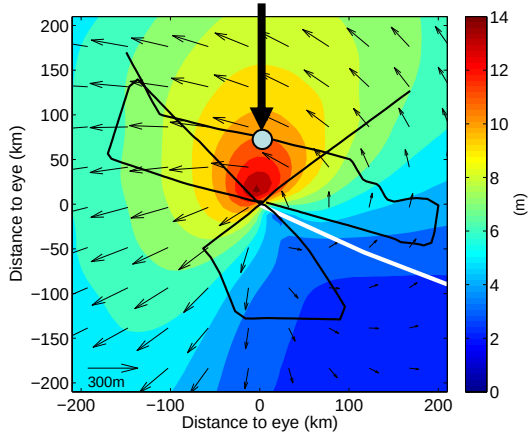
4. Case study: Hurricane Ivan (2004)

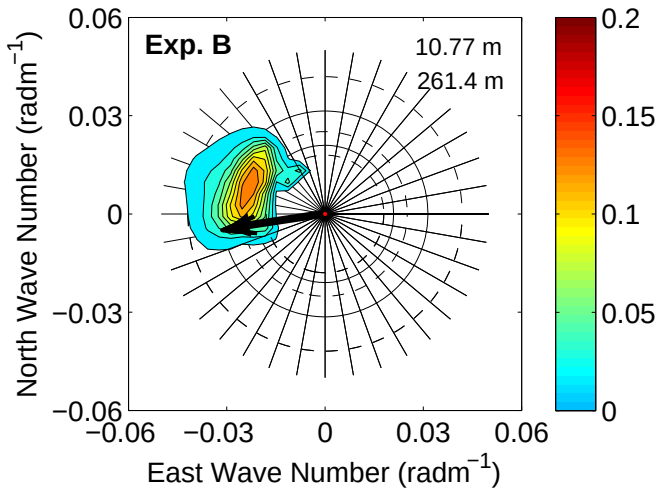
❖ Wave spectrum comparisons

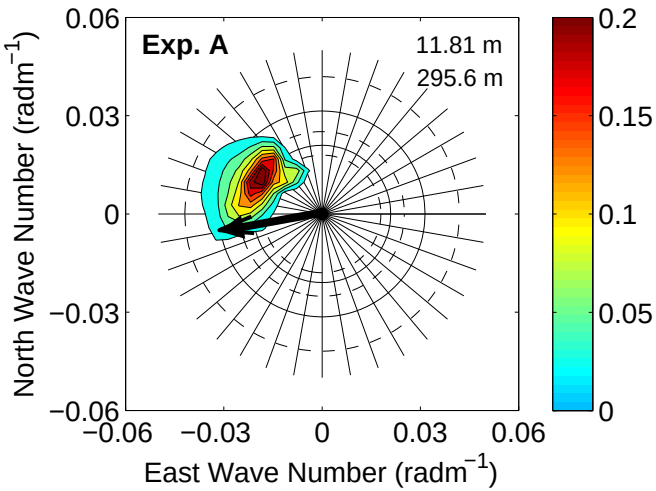




Location of Spectrum Comparison







Conclusions

- For momentum flux calculations at the air-sea interface, the effect of time variation of the wave field is small but the effect of spatial variation is important. Both effects, however, are important for energy flux calculations.

- The surface wave effects on the air-sea fluxes are most significant in the rear-right quadrant of the hurricane and consequently reduce the magnitude of subsurface currents and sea surface temperature cooling to the right of the storm track.

- Wave-current interaction reduces the momentum flux into currents mainly due to the reduction of wind speed input into the wave model relative to the ocean currents.

- The improved momentum flux parameterization, together with wave-current interaction is shown to improve forecast of significant wave height and wave energy in Hurricane Ivan.

Energy and Momentum Flux Budget Model

Energy Flux Budget

$$E = \iint \rho_w g \psi(\omega,\theta) d\theta d\omega$$

$$EF_x = \iint \rho_w g C_g \psi(\omega,\theta) \cos\theta \cdot d\theta \cdot d\omega$$

$$EF_y = \iint \rho_w g C_g \psi(\omega,\theta) \sin\theta \cdot d\theta \cdot d\omega$$

$$EF_c = EF_{air} - \left[\left(\frac{\partial EFx}{\partial x} + \frac{\partial EFy}{\partial y} \right) + \frac{\partial E}{\partial t} \right]$$

Wave component

$\psi(\omega,\theta)$ wave spectrum

C_g group velocity

ρ_w water density

Momentum Flux budget

$$M_x = \iint \rho_w \omega \psi(\omega,\theta) \cos\theta \cdot d\theta \cdot d\omega$$

$$M_y = \iint \rho_w \omega \psi(\omega,\theta) \sin\theta \cdot d\theta \cdot d\omega$$

$$MF_{xx} = \iint \rho_w \omega C_g \psi(\omega,\theta) \cos^2\theta \cdot d\theta \cdot d\omega$$

$$MF_{xy} = \iint \rho_w \omega C_g \psi(\omega,\theta) \cos\theta \sin\theta \cdot d\theta \cdot d\omega$$

$$MF_{yy} = \iint \rho_w \omega C_g \psi(\omega,\theta) \sin^2\theta \cdot d\theta \cdot d\omega$$

$$MF_{yx} = \iint \rho_w \omega C_g \psi(\omega,\theta) \sin\theta \cos\theta \cdot d\theta \cdot d\omega$$

$$\tau_{c_x} = \tau_{air_x} - \left[\left(\frac{\partial MF_{xx}}{\partial x} + \frac{\partial MF_{xy}}{\partial y} \right) + \frac{\partial M_x}{\partial t} \right]$$

$$\tau_{c_y} = \tau_{air_y} - \left[\left(\frac{\partial MF_{yx}}{\partial x} + \frac{\partial MF_{yy}}{\partial y} \right) + \frac{\partial M_y}{\partial t} \right]$$