CBLAST-Hurricane and High-Resolution Fully Coupled Atmosphere-Wave-Ocean Models

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In the eye of Katrina

Motivation:

> to better understand and predict hurricane structure and intensity

Hurricane Maximum Potential Intensity (MPI)

Emanuel (1988), Holland (1997), etc.

$$\mathrm{MPI} = f\,\{\, (C_k/C_D),\ \varepsilon,\ \mathrm{SST},\ \mathrm{RH} \,\}$$

RH = relative humidity

SST = sea surface temperature

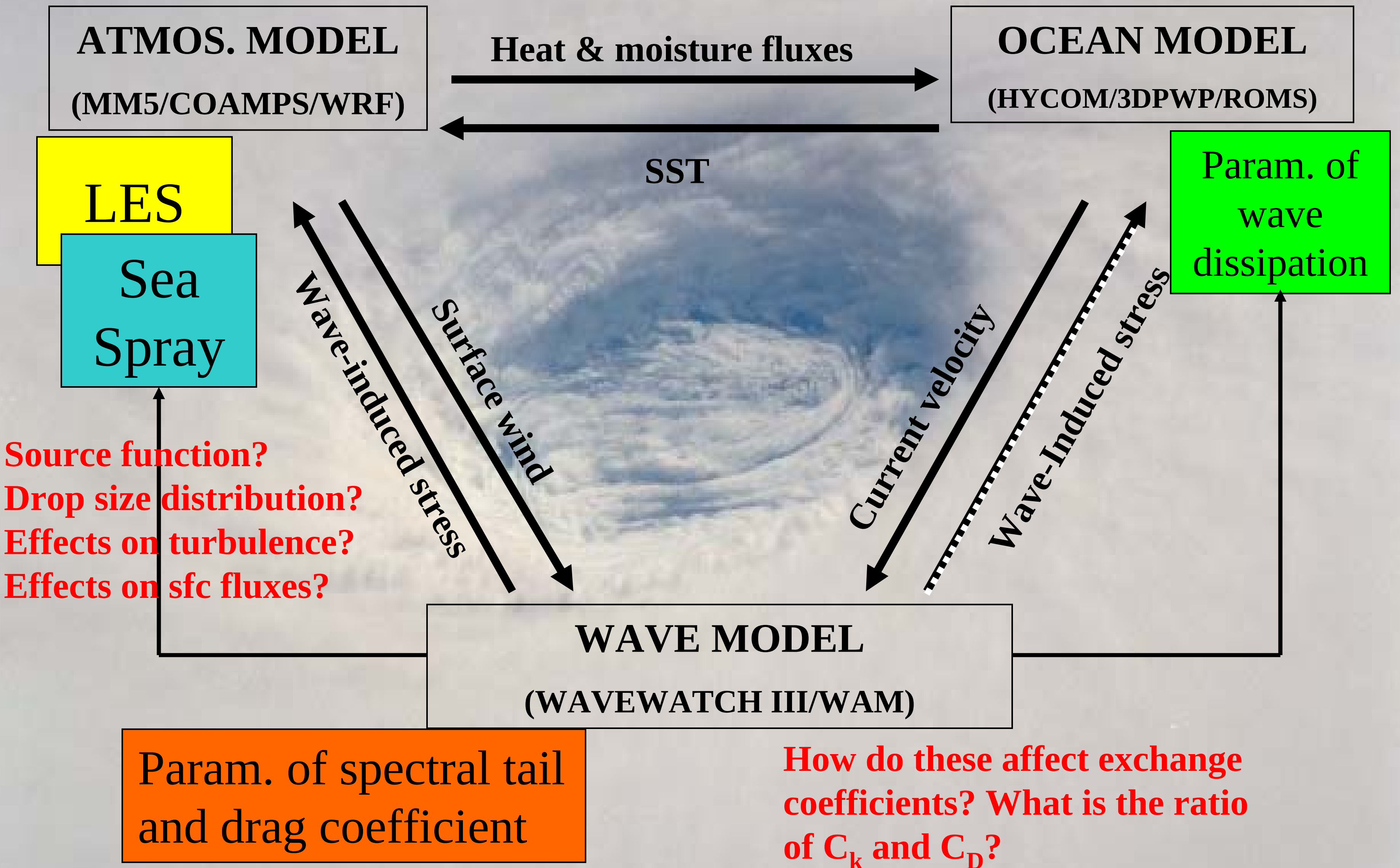
$\varepsilon = (T_B - T_O)/T_B$ (thermodynamic efficiency)

C_k and C_D are exchange coefficients of enthalpy and momentum fluxes

*W*hy most hurricanes do not reach their MPI?

- Inner core (eye and eyewall) dynamics
- Environmental conditions (atmosphere and ocean)

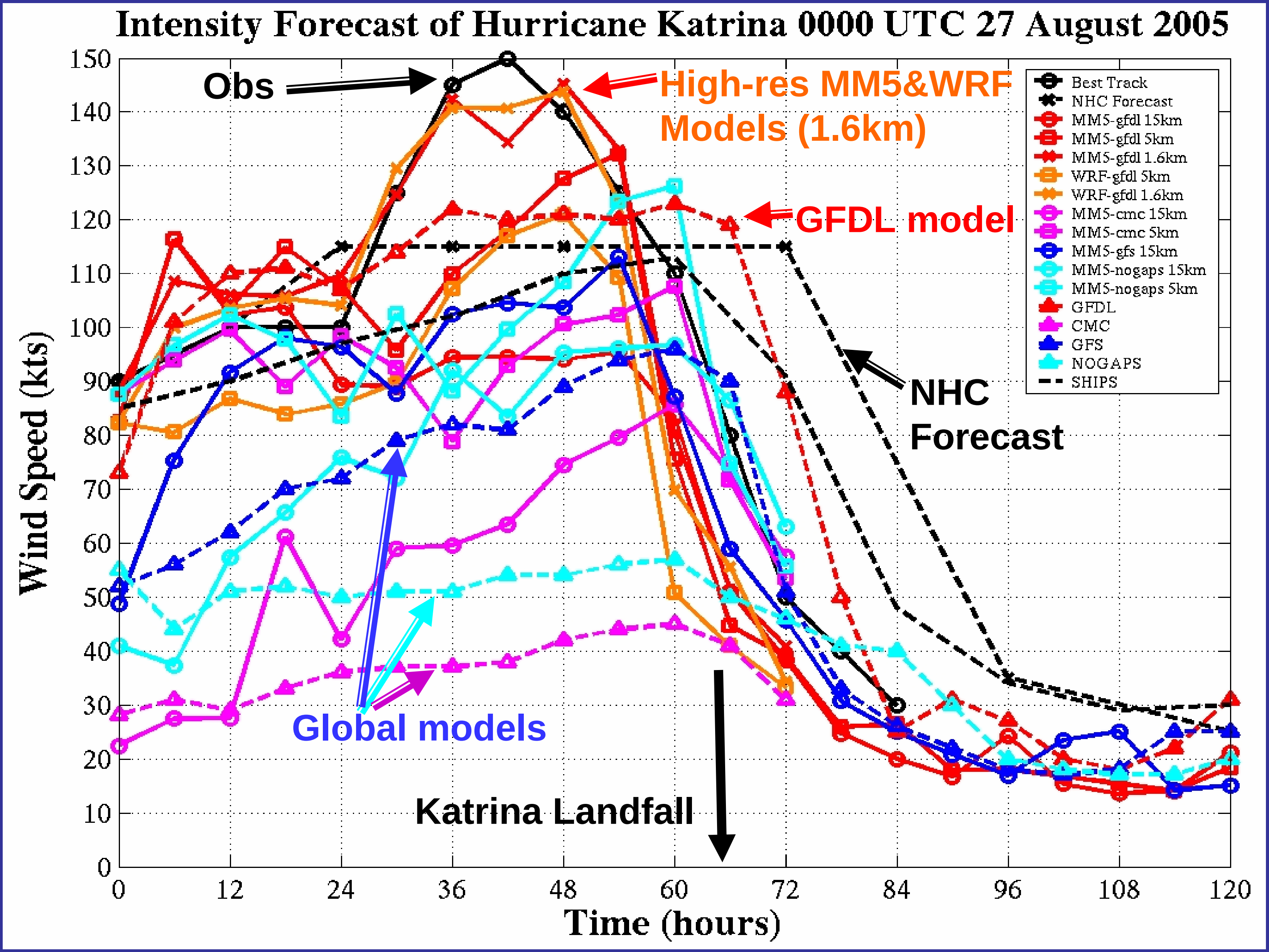
Coupled Atmosphere-Wave-Ocean Modeling System for Hurricane Predictions



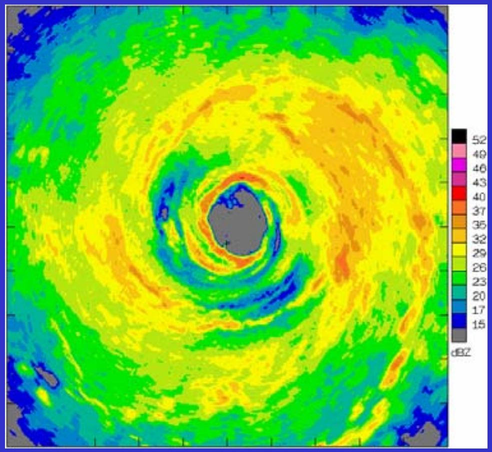
Summary of Conclusions

- Fully coupled, high-res models improve intensity prediction and provide a tool to better understand physical processes that lead to extreme winds and heavy rain in hurricanes
- Wind-wave coupling with 2D wave stress is critical in forecasting hurricane surface winds
- C_k/C_D varies spatially in hurricanes from 0.4-0.8 (inner-outer)

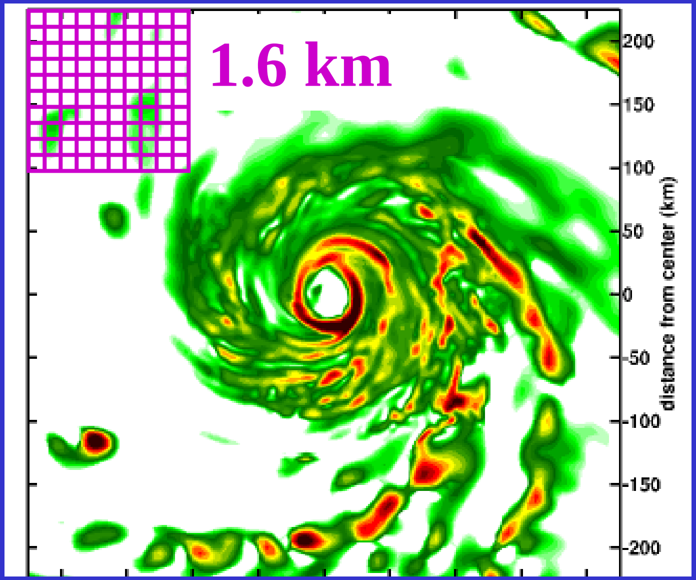
“Ensemble” Model Forecasts of Storm Intensity During Hurricane Katrina



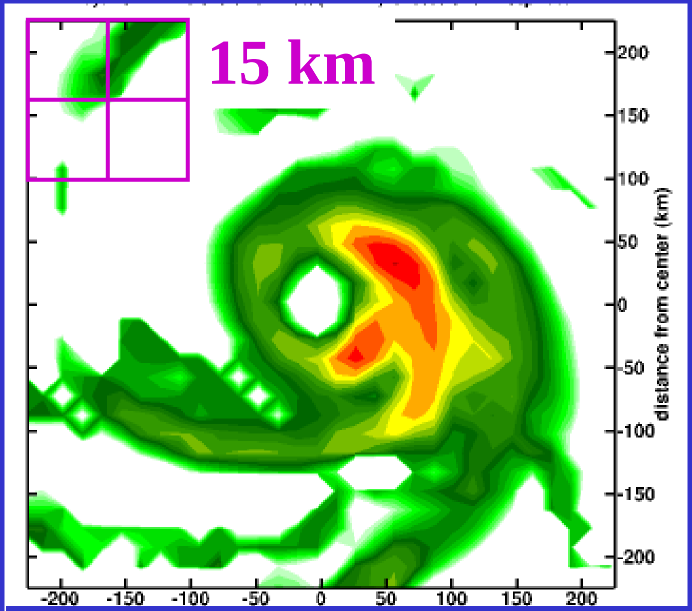
Impact of Model Grid Resolution on Hurricane Forecast



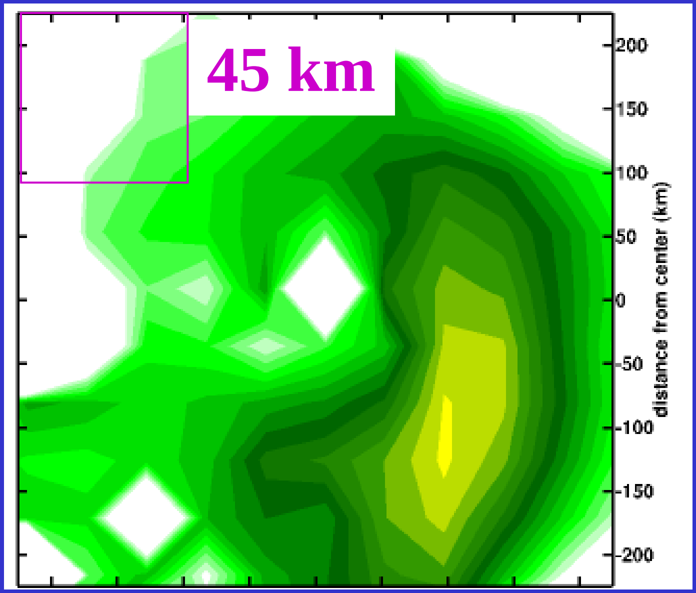
Airborne radar observed rain in Hurricane Floyd (1999)



High-resolution research model



The best operational model



Most global operational models

CBLAST-Hurricane

Coupled Atmosphere-Wave-Ocean Modeling

- A goal of CBLAST is to better understand how hurricanes interact with the ocean, and to use this to improve hurricane forecast models.

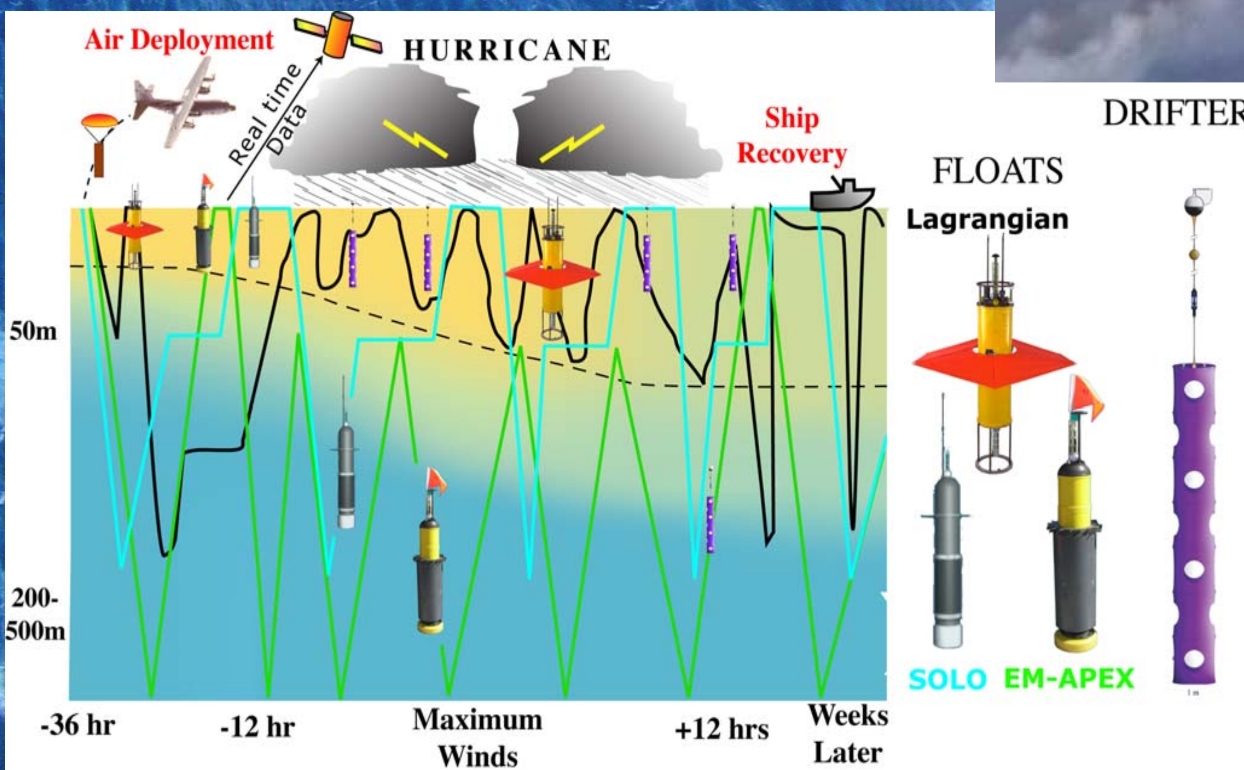
- Through CBLAST we have improved our knowledge about the processes which fuel hurricanes (heat from the ocean), as well as the frictional forces (drag on the sea surface) which mix the ocean and result in extreme ocean waves.

Specific Objectives:

- Wind-Wave Coupling
- Effects of Sea Spray
- Atmosphere-Ocean Coupling

CBLAST (Coupled Boundary Layer Air-Sea Transfer)

A goal of CBLAST is to better understand how hurricanes interact with the ocean, and to use this to improve hurricane forecast models



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Coupled Modeling System

- MM5 (PSU/NCAR)

  (vortex-following nests with 45, 15, 5, and 1.67 km grid spacing, NCEP analysis and AVHRR or TMI/AMSR-E SST)

- WAVEWATCH III (NOAA/EMC)

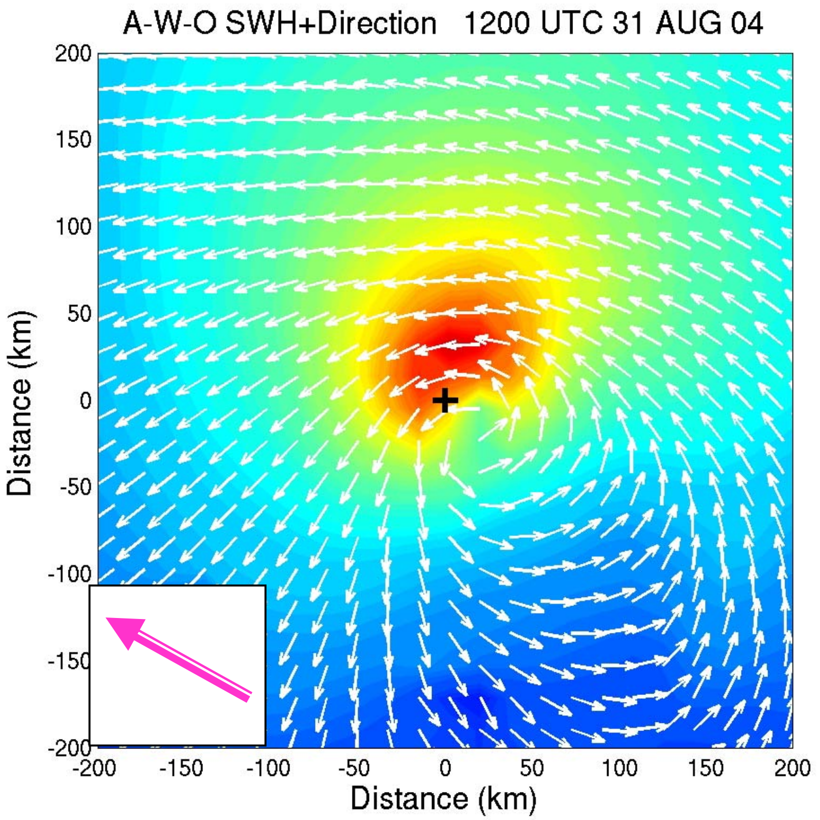
  (1/12^{o}, 25 frequency bands, 48 directional frequency bands)

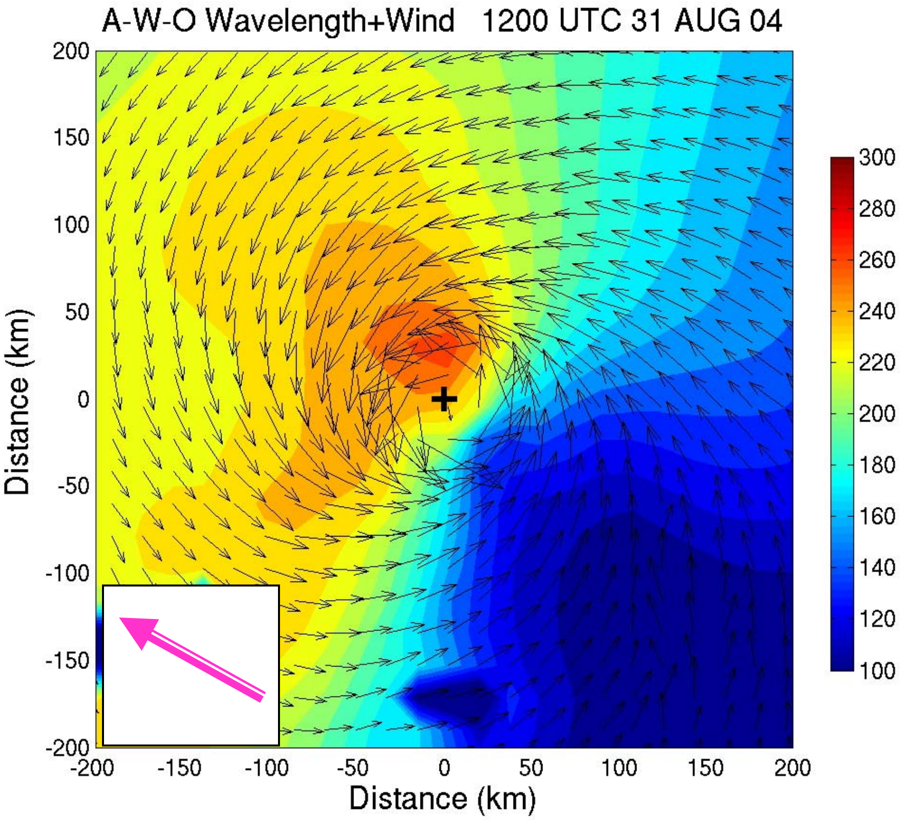
- HYCOM (UMiami/NRL)

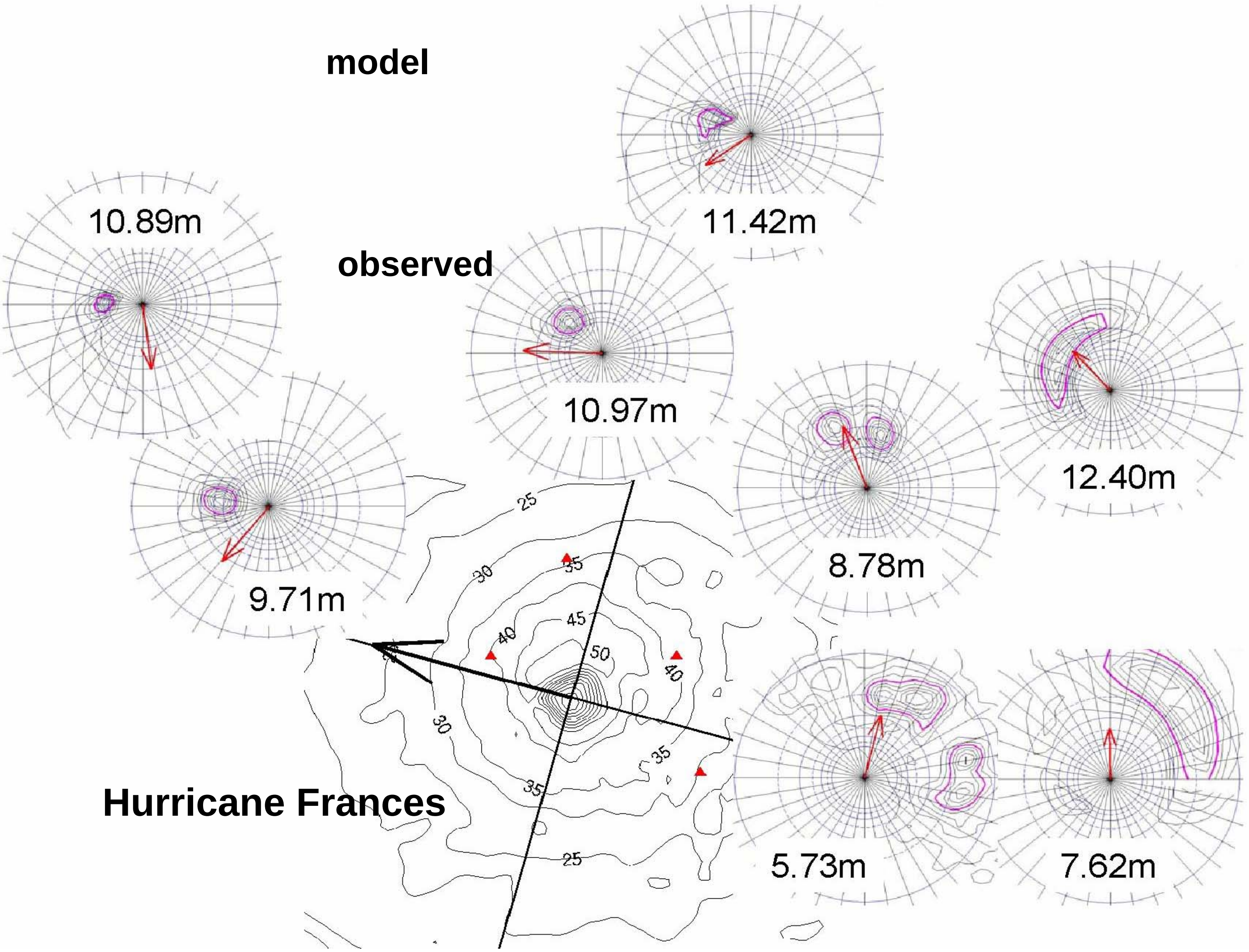
  (1/12^{o}, 22 vertical levels with 4-6 in the ocean mixed layer)

- 3DPWP (Price's 3-D Upper Ocean Circulation Models) **(5 km, 25 vertical levels)**

Ocean surface waves in Hurricane Frances (2004)






model
observed
10.89m
11.42m
10.97m
12.40m
8.78m
9.71m
5.73m
7.62m
Hurricane Frances
25
30
35
40
45
50

Uncoupled Atmosphere Model

Charnock Relationship: $z_o = \alpha\, u_*/g$

Coupled Atmosphere-Wave Model

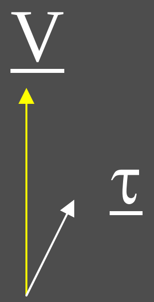
- **Roughness Length (non-directional)**

$$\tau = \tau_t + \tau_w \longrightarrow z_o$$

(e.g., Janssen at ECMWF)

z_o - wave-age dependent

- **Stress Vector (directional)**



$$M_x = -\,\tau_x$$

$$M_y = -\,\tau_y$$

τ_x , τ_y - components of stress from integral of

momentum input to the wave spectrum.

(π / k)

Wind-Wave Coupling Parameterization

Spectra Tail Parameterization:

$$\tau_x = g\rho_w \int_0^{\infty} \int_{-\pi}^{\pi} \frac{\gamma}{\omega} F(k,\vartheta) k_x k dk d\vartheta$$

X-component of stress from integral of momentum input to the spectrum:

$$\frac{\gamma}{\omega} = S \frac{\rho_a}{\rho_w} \left[\frac{U_{(\pi/k)} \cos\theta}{C(k)} - 1 \right] . \left| \frac{U_{(\pi/k)} \cos\theta}{C(k)} - 1 \right|$$

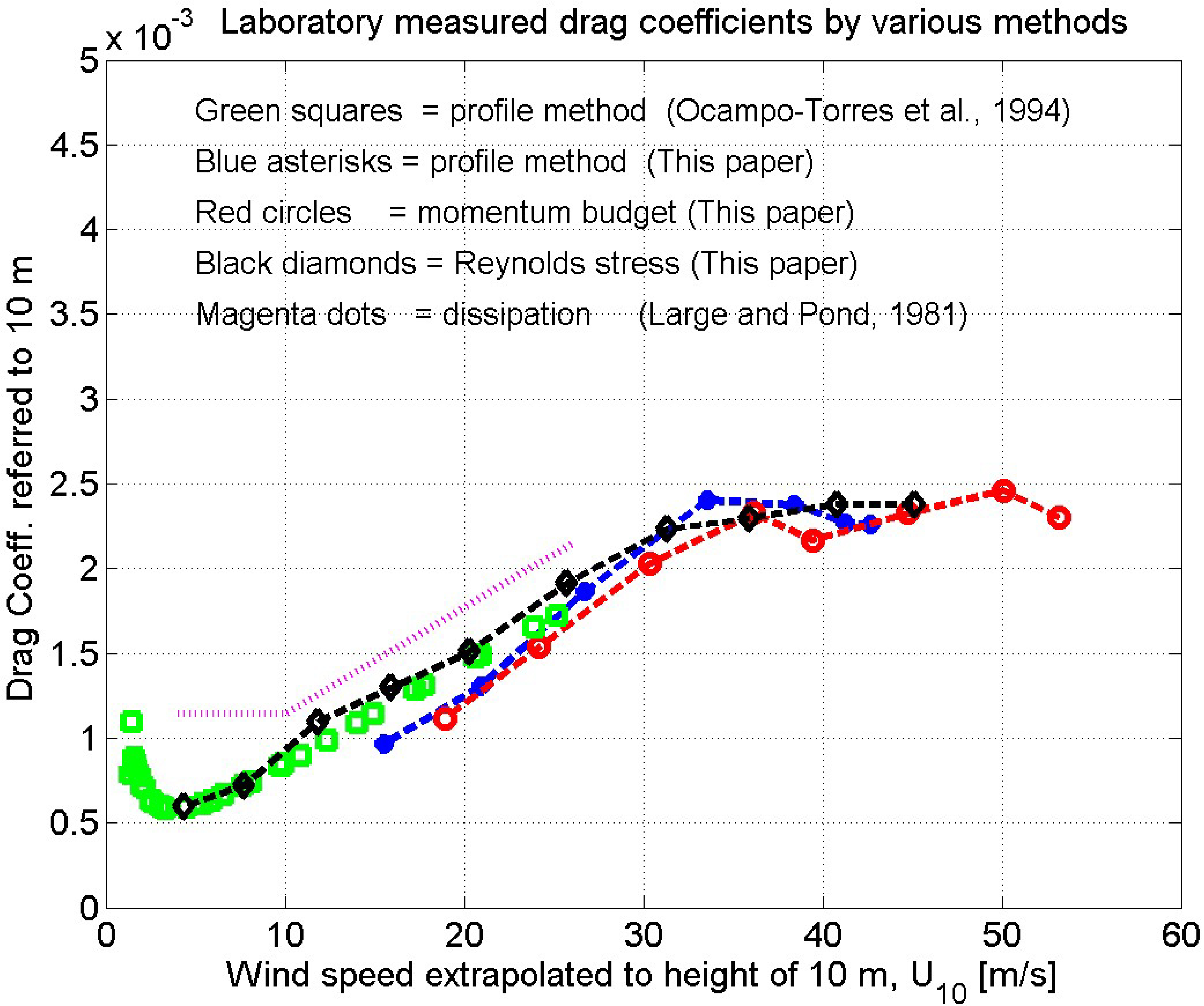
Growth rate of each component from measurement of pressure-slope correlation (S-shelter coefficient, C-phase speed, U(π/k)-half wavelengh height wind speed)

$$F(k,\vartheta) = \alpha k^{-5} \sec h^2 (\beta(\vartheta_k))$$

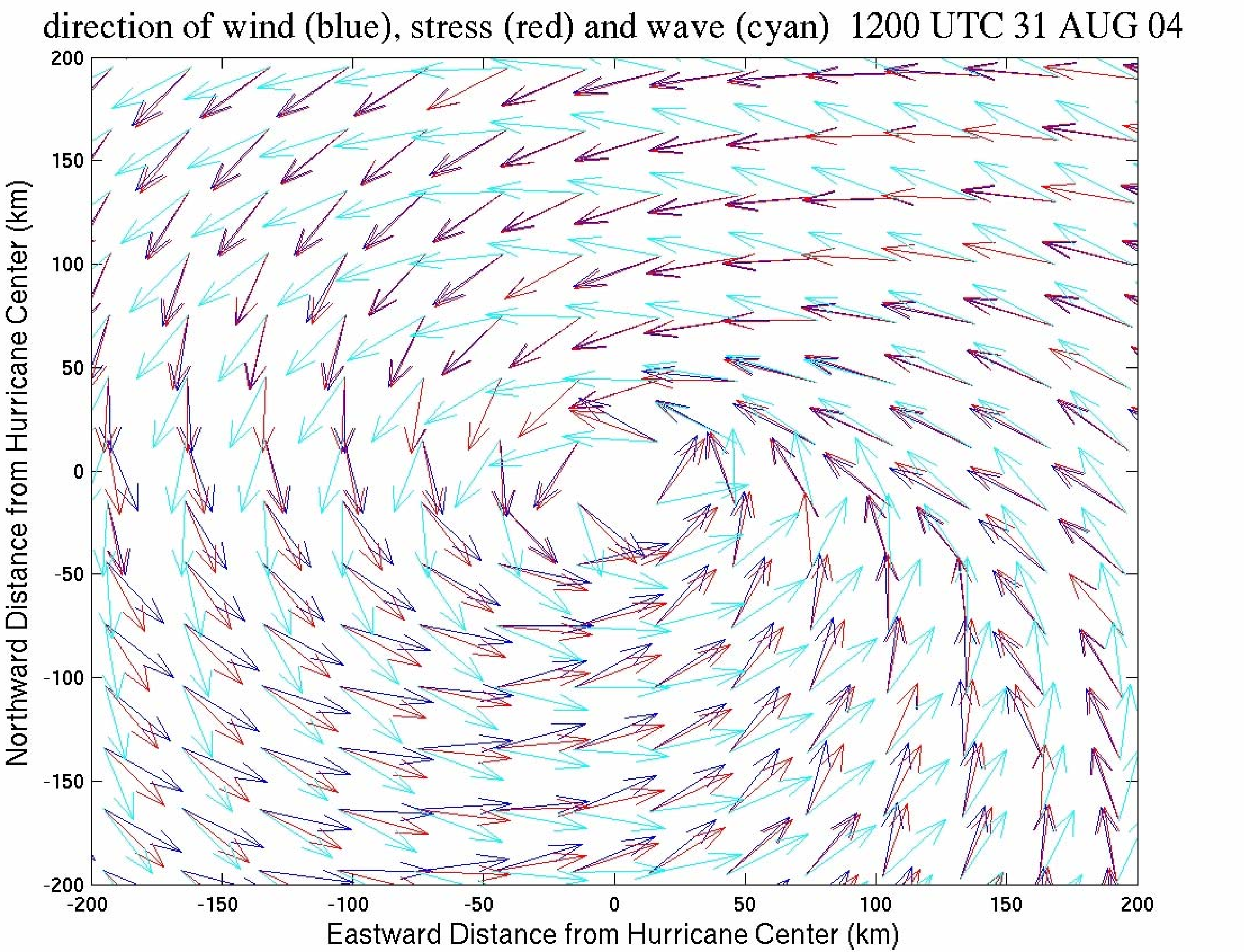
Spectrum of long waves from WAVEWATCH III; spectrum of short waves from fit to tail given below. α is adjusted to fit the highest modeled wavenumbers.

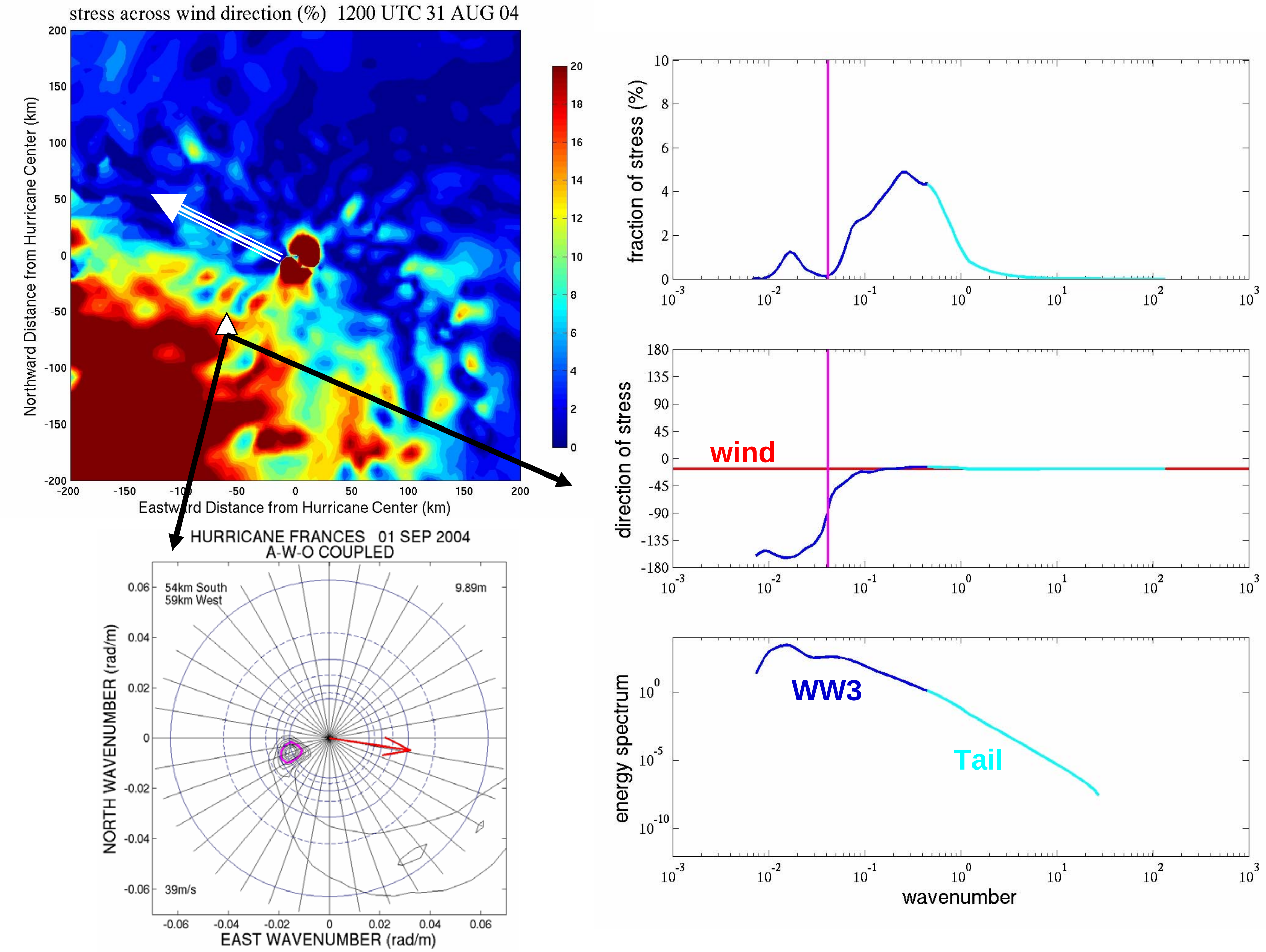
$$\beta = \frac{1.2}{\cos^{-1}(C/U)}; C/U < 0.9$$

β is the spreading function for the short waves.



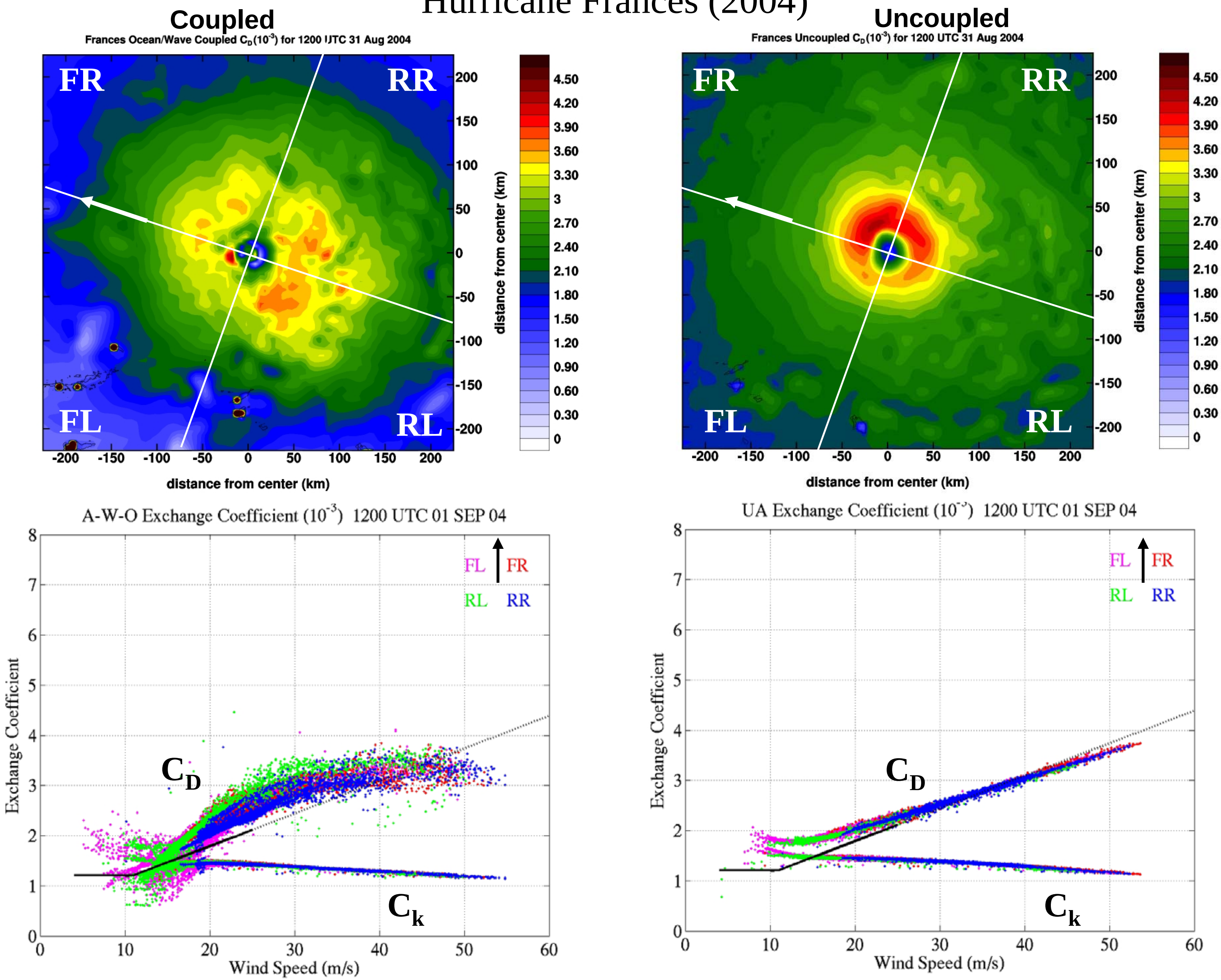
Laboratory measured drag coefficients by various methods
x 10^-3
Green squares = profile method (Ocampo-Torres et al., 1994)
Blue asterisks = profile method (This paper)
Red circles = momentum budget (This paper)
Black diamonds = Reynolds stress (This paper)
Magenta dots = dissipation (Large and Pond, 1981)
Drag Coeff. referred to 10 m
Wind speed extrapolated to height of 10 m, U10 [m/s]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60


direction of wind (blue), stress (red) and wave (cyan) 1200 UTC 31 AUG 04
Northward Distance from Hurricane Center (km)
Eastward Distance from Hurricane Center (km)
200
150
100
50
0
-50
-100
-150
-200
-200
-150
-100
-50
0
50
100
150
200

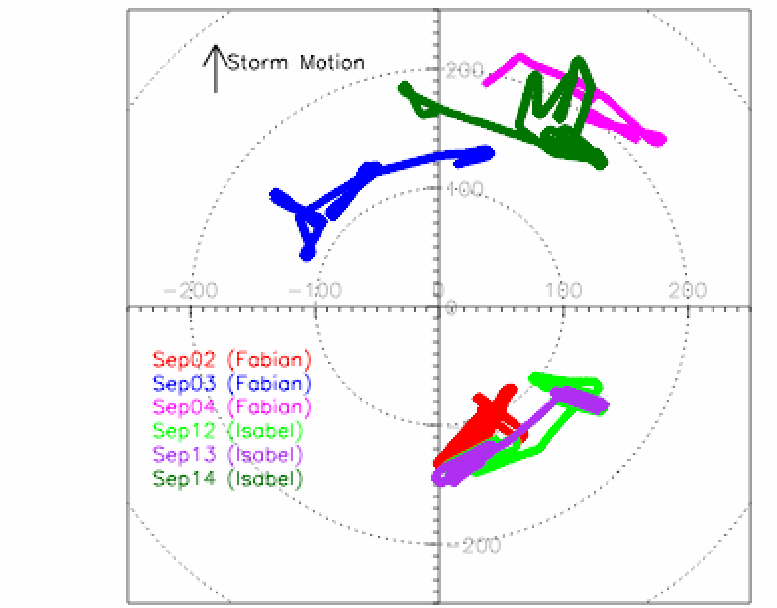


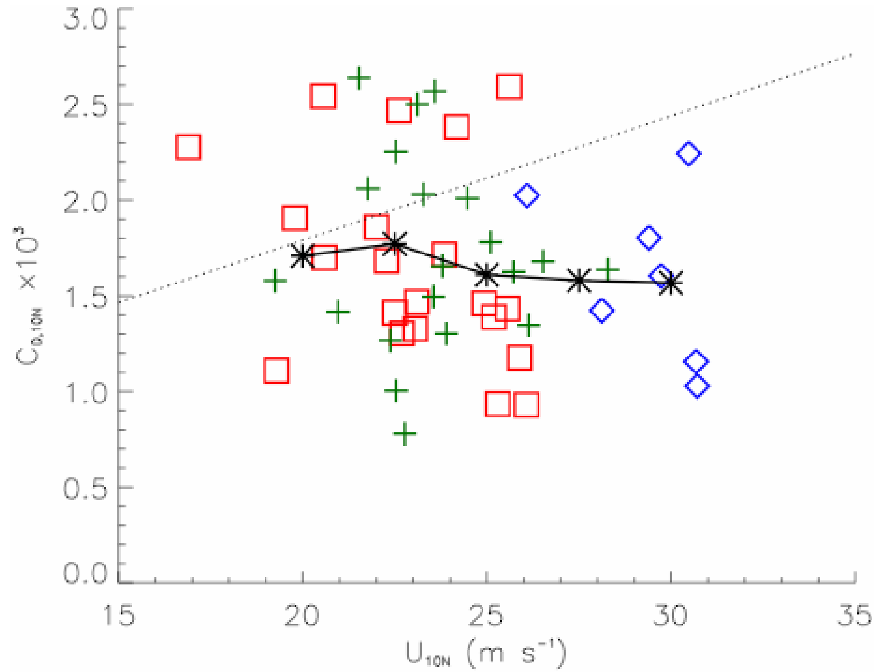
stress across wind direction (%) 1200 UTC 31 AUG 04
Northward Distance from Hurricane Center (km)
Eastward Distance from Hurricane Center (km)
HURRICANE FRANCES 01 SEP 2004
A-W-O COUPLED
54km South
59km West
9.89m
39m/s
NORTH WAVENUMBER (rad/m)
EAST WAVENUMBER (rad/m)
fraction of stress (%)
direction of stress
wind
energy spectrum
WW3
Tail
wavenumber

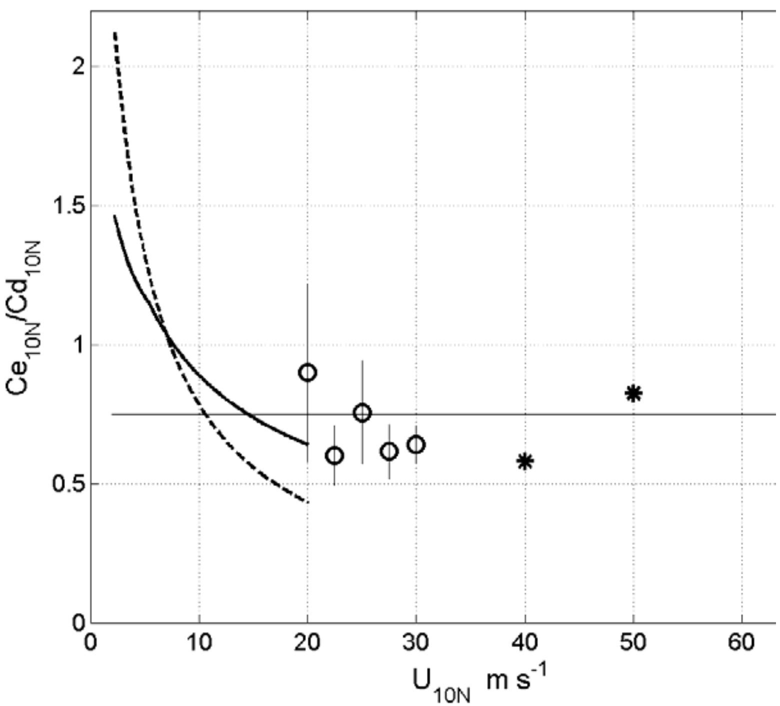
Hurricane Frances (2004)

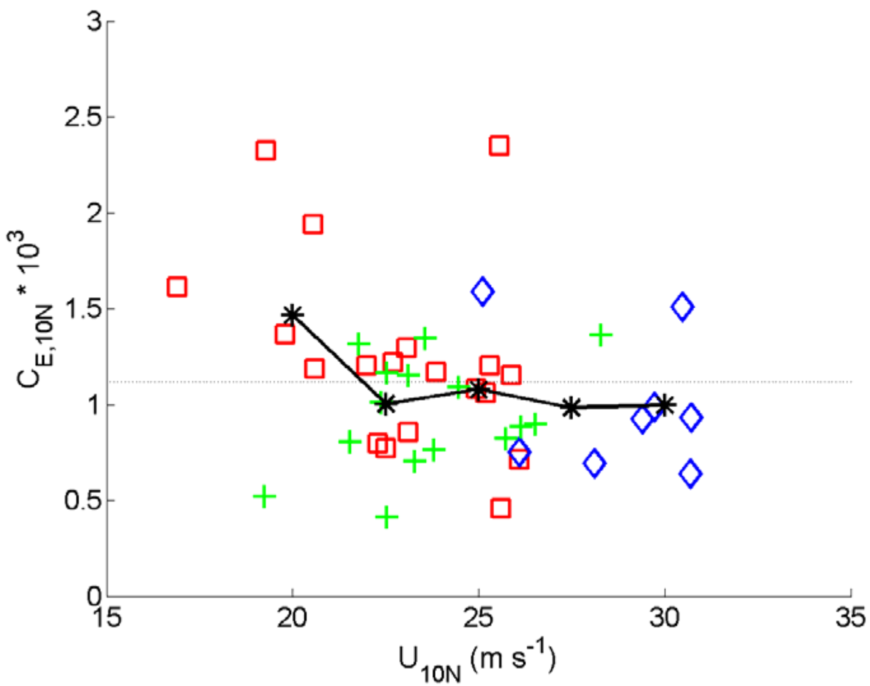


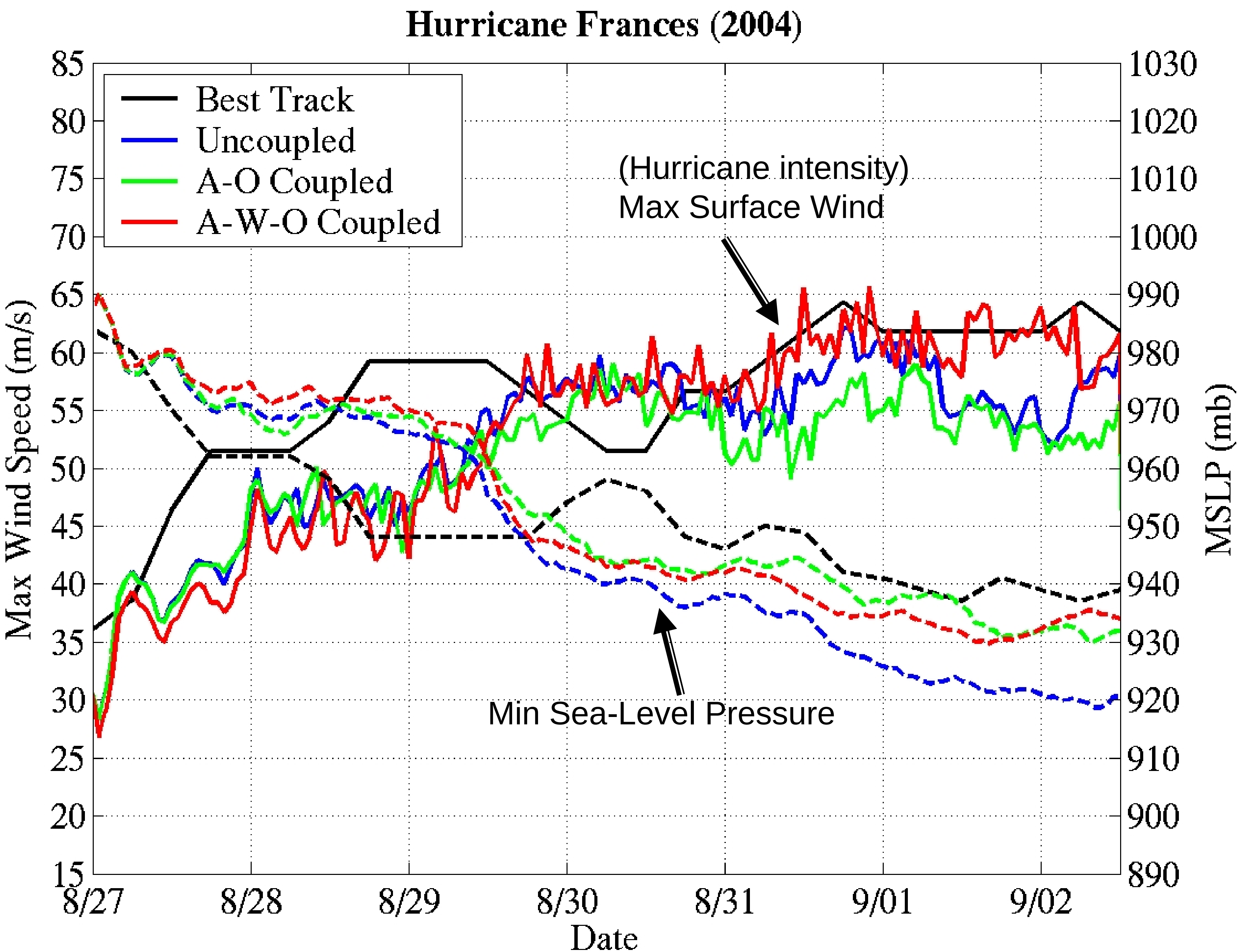
Black et al (2007), Drennan et al (2007), French et al (2007)

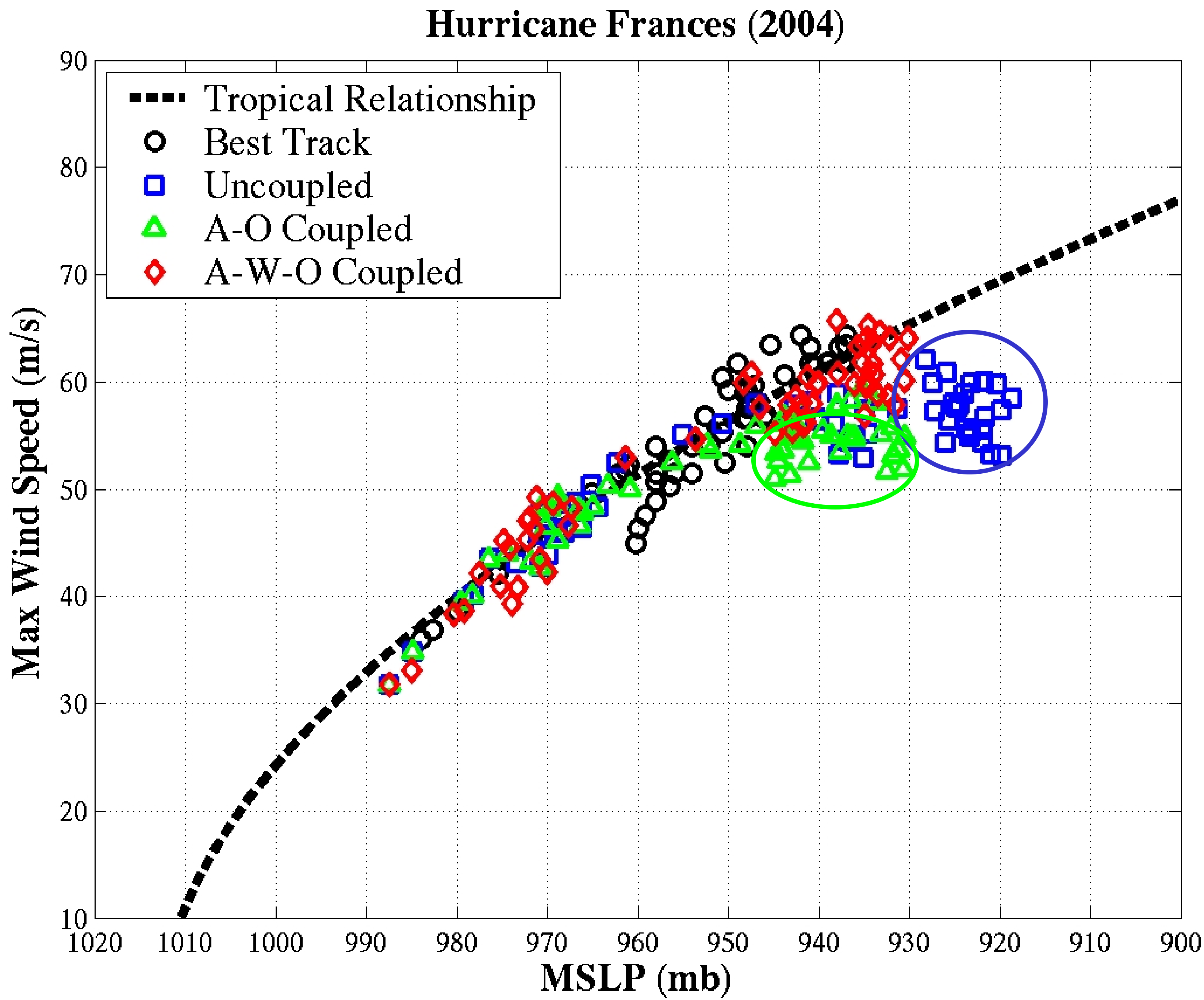




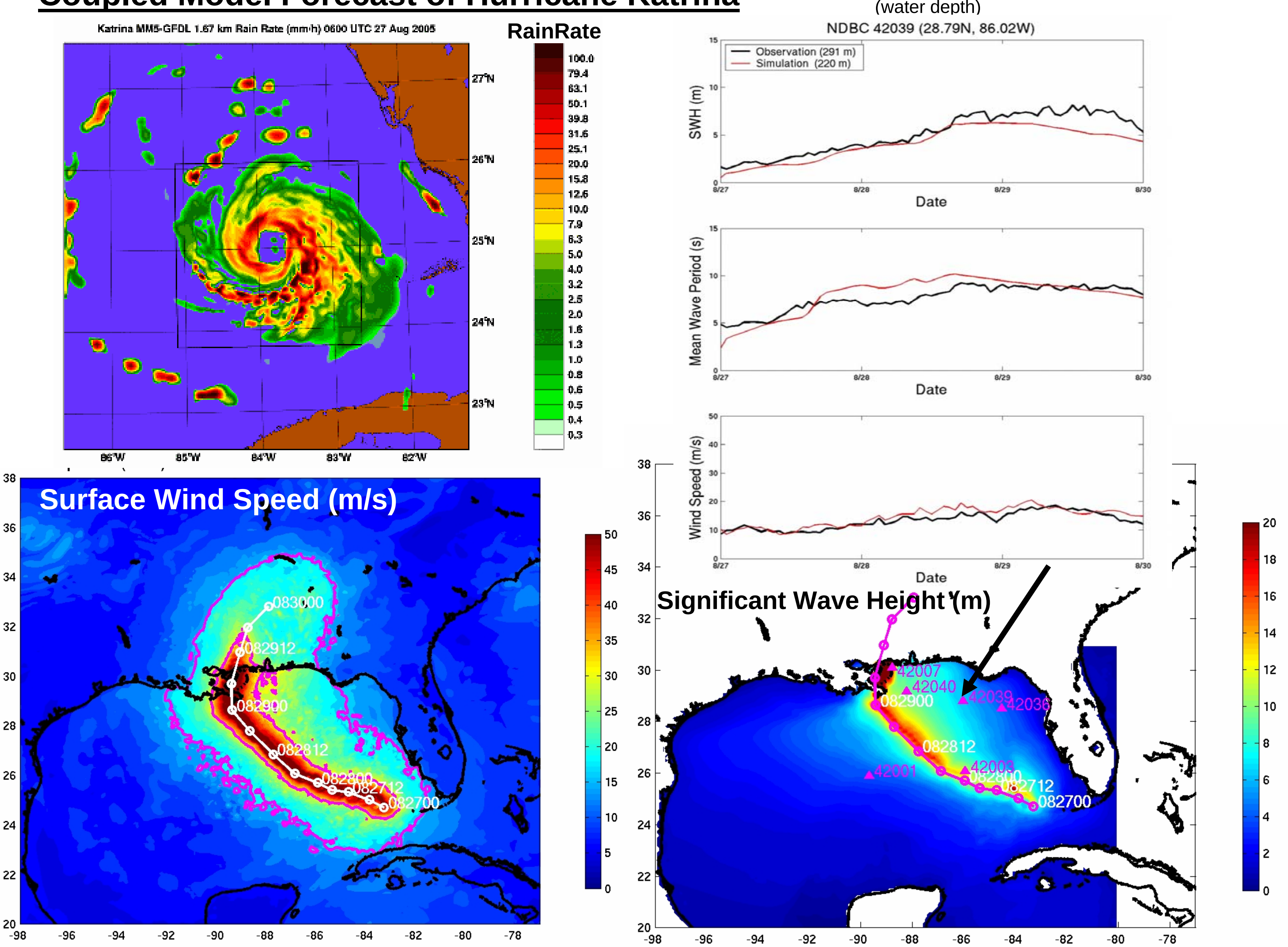


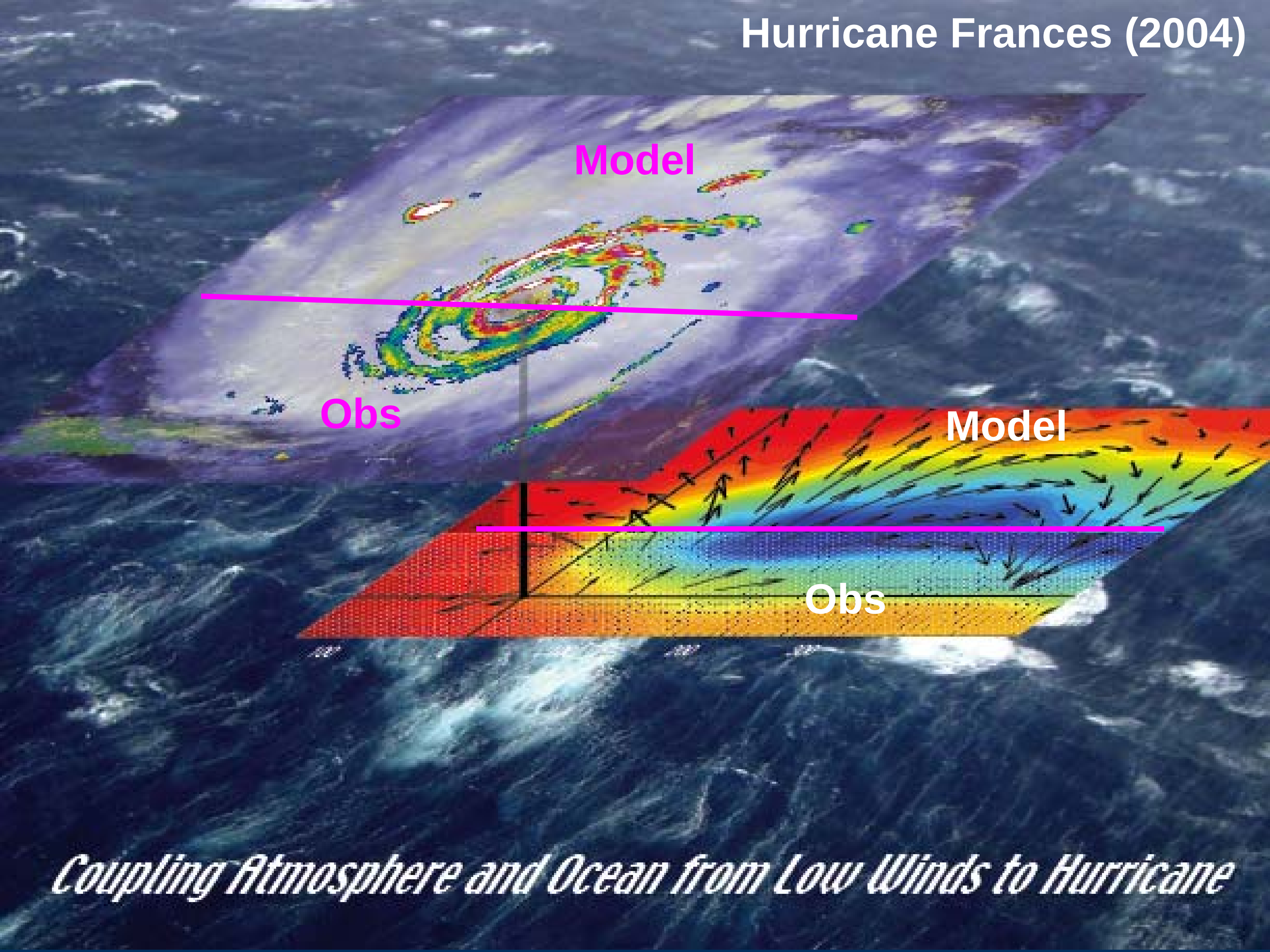


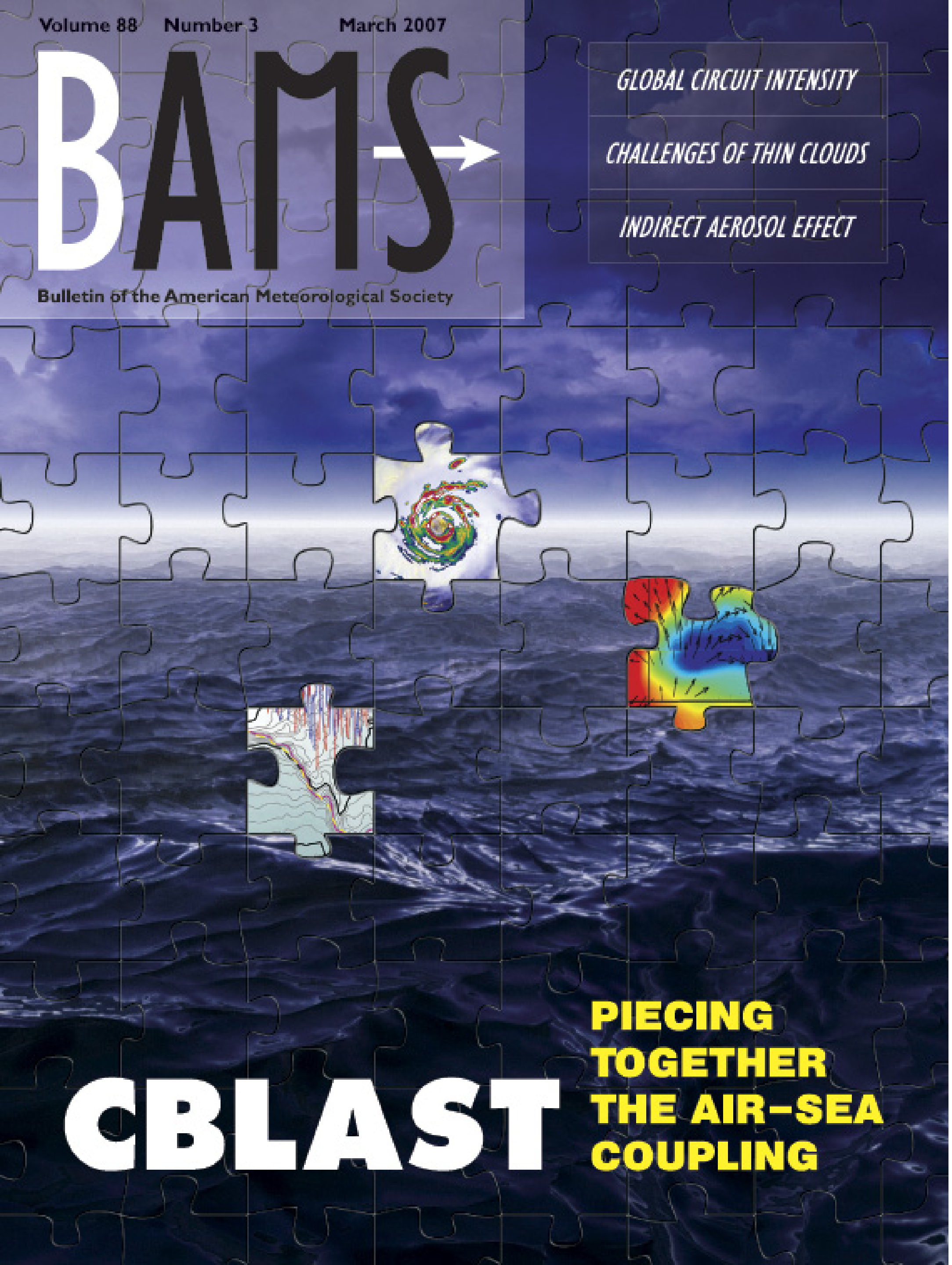

Hurricane Frances (2004)
Best Track
Uncoupled
A-O Coupled
A-W-O Coupled
(Hurricane intensity)
Max Surface Wind
Min Sea-Level Pressure
Max Wind Speed (m/s)
MSLP (mb)
Date
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
1030
1020
1010
1000
990
980
970
960
950
940
930
920
910
900
890
8/27
8/28
8/29
8/30
8/31
9/01
9/02


Hurricane Frances (2004)
Tropical Relationship
Best Track
Uncoupled
A-O Coupled
A-W-O Coupled
Max Wind Speed (m/s)
MSLP (mb)
90
80
70
60
50
40
30
20
10
1020
1010
1000
990
980
970
960
950
940
930
920
910
900

Coupled Model Forecast of Hurricane Katrina




Hurricane Frances (2004)
Model
Obs
Model
Obs
Coupling Atmosphere and Ocean from Low Winds to Hurricane



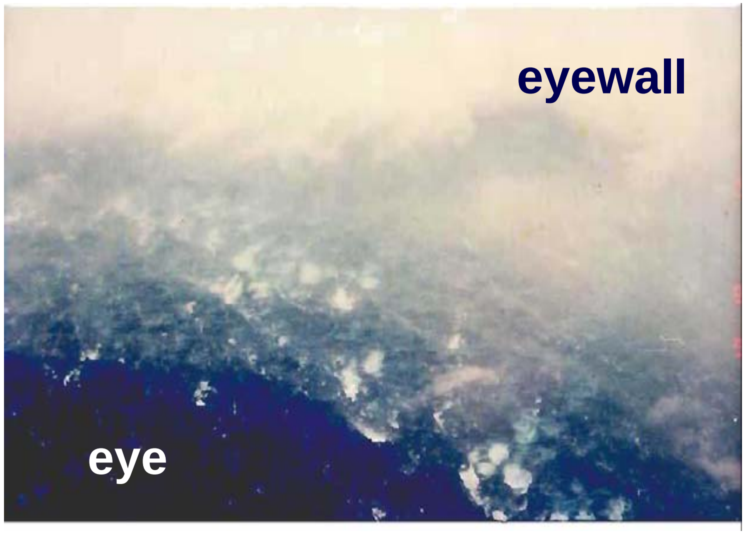
<u>BAMS issue on CBLAST:</u>

Chen et al., 2007**:** The CBLAST-Hurricane Program and the next-generation fully coupled atmosphere-wave-ocean models for hurricane research and prediction. *BAMS, 311-317*.

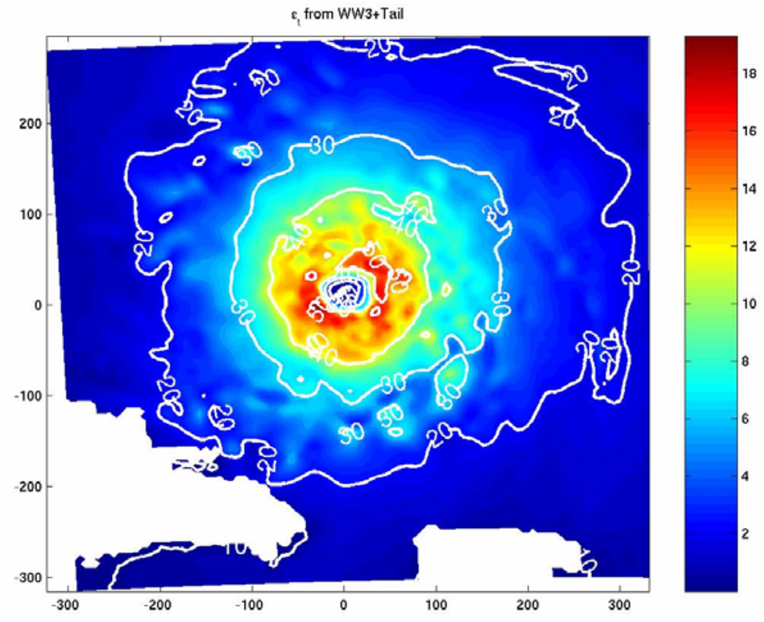
Black et al., 2007**:** Air-Sea Exchange in Hurricanes: Synthesis of Observations from the Coupled Boundary Layer Air-Sea Transfer Experiment, *BAMS*, 357-374.

Edson et al.,, 2007**:** The Coupled Boundary Layers and Air-Sea Transfer Experiment in Low Winds (CBLAST-LOW). *BAMS, 346*-356.

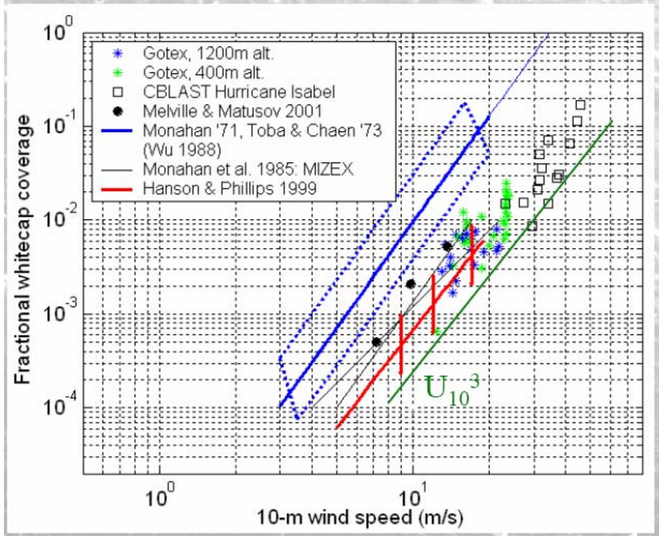
White cap in hurricane environment



Wave energy dissipation



Whitecap coverage vs. U_{10}



The fractional whitecap coverage found from our video images falls consistently below the curve fit by Wu of some data from Monahan, and Toba and Chaen.

It is consistent with video image processing performed on higher and lower wind speeds, and the MIZEX and Gulf of Alaska experiments.

Note that Wu's fit would give 100% coverage at approx. 35 m/s!

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Conclusions and Challenges

- **Fully coupled, high-res models improve intensity prediction and provide a tool to better understand physical processes that lead to extreme winds and heavy rain in hurricanes**
- **Wind-wave coupling with 2D wave stress is critical in forecasting hurricane surface winds**
- **C_k/C_D varies spatially in hurricanes from 0.4-0.8 (inner-outer)**
- **Observations at the air-sea interface for $U_{10} > 30$ m/s**
- **Wave-breaking and sea-spray remains to be an unresolved issue and need to be further examined in the coupled model (e.g., link to wave dissipation and breaking parameters, etc.).**
- **Accurate surface flux (especially enthalpy flux) and PBL measurements to evaluate coupled model results and improve model parameterizations**
- **Lack of good model initial conditions – we need robust and efficient data assimilation system for coupled models**