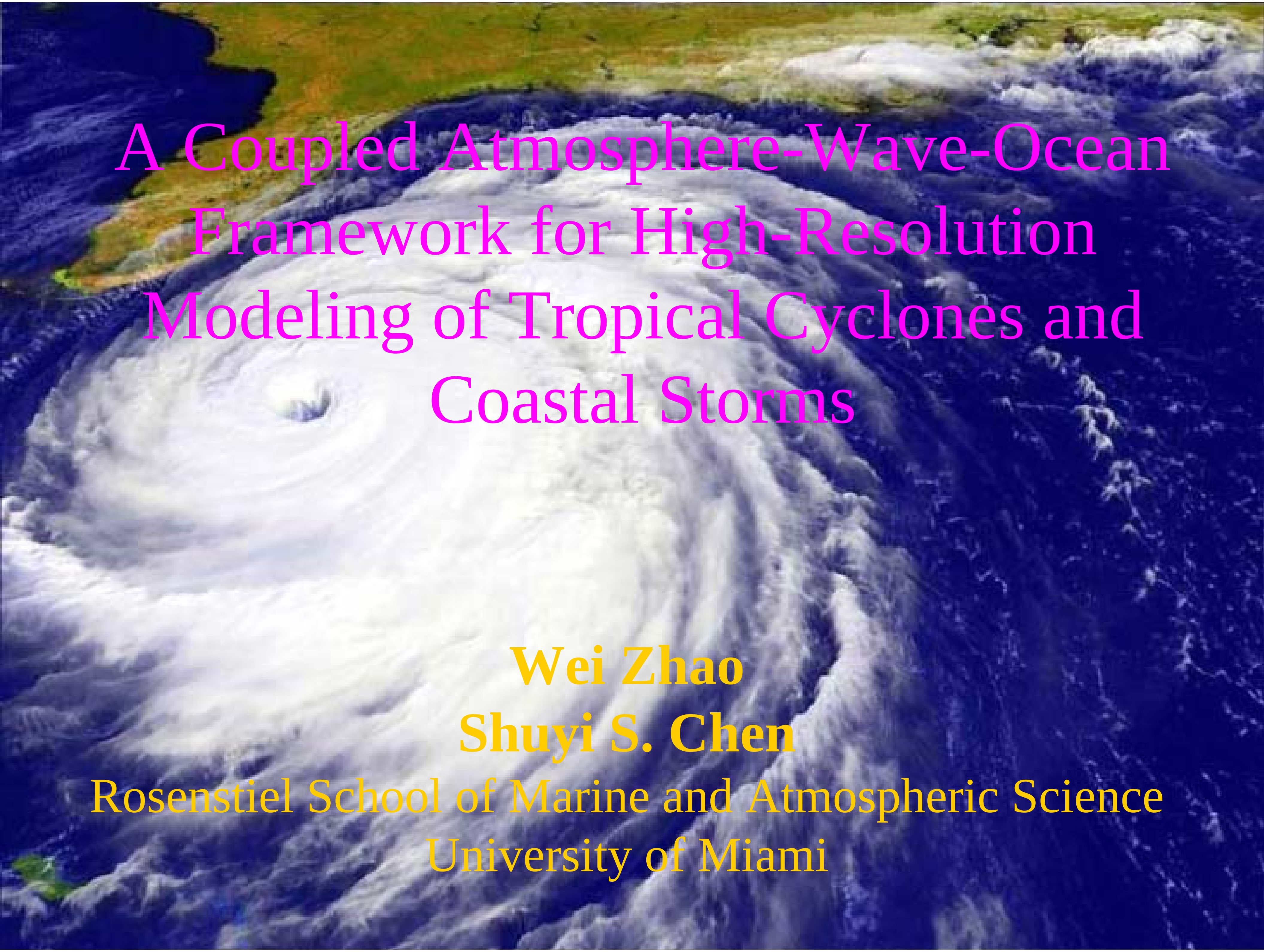

A Coupled Atmosphere-Wave-Ocean Framework for High-Resolution Modeling of Tropical Cyclones and Coastal Storms

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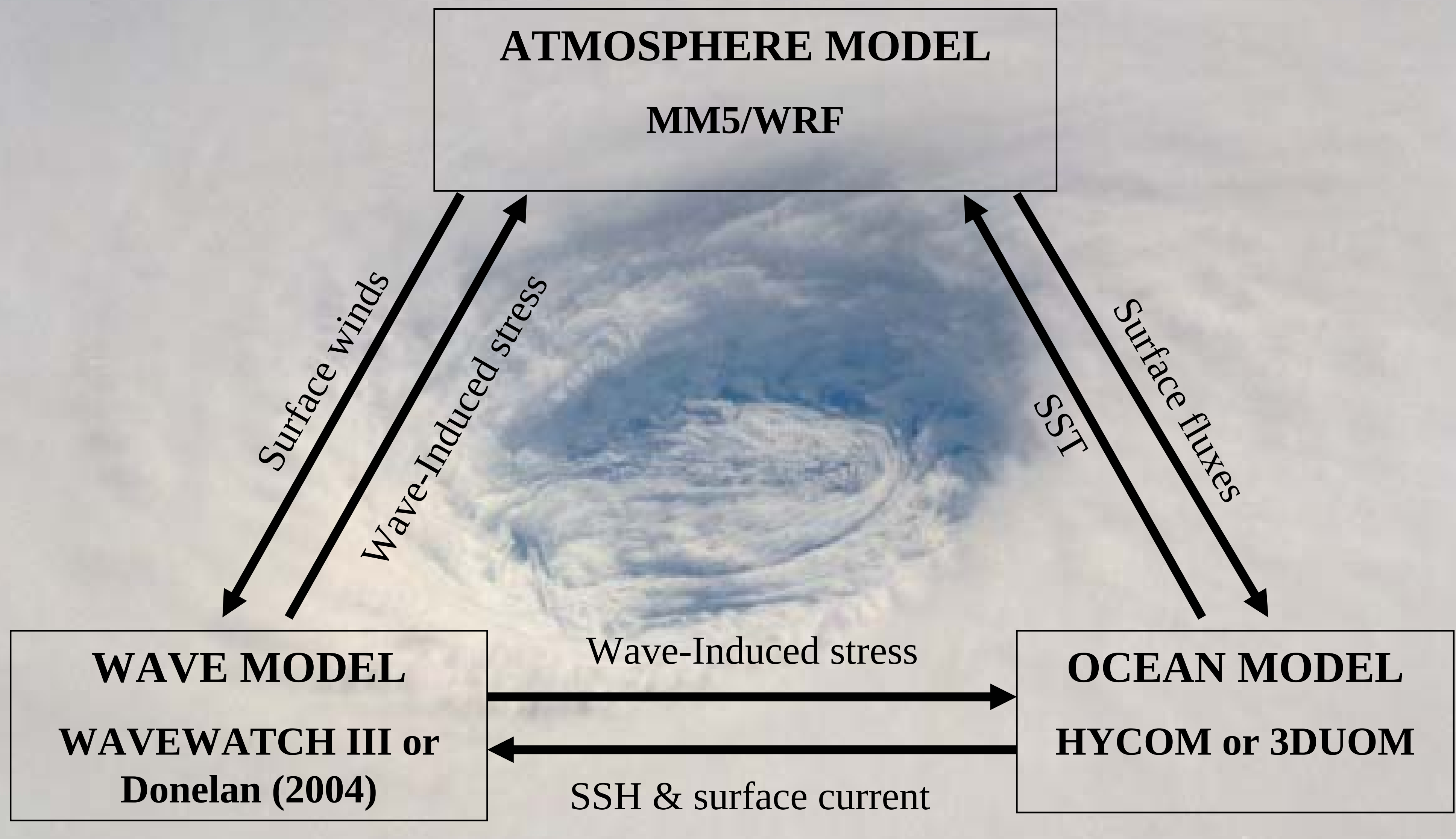
Shuyi S. Chen
Rosenstiel School of Marine and Atmospheric Science
University of Miami

Coupled Atmosphere-Wave-Ocean Modeling System for Hurricane Predictions



Coupled Modeling System

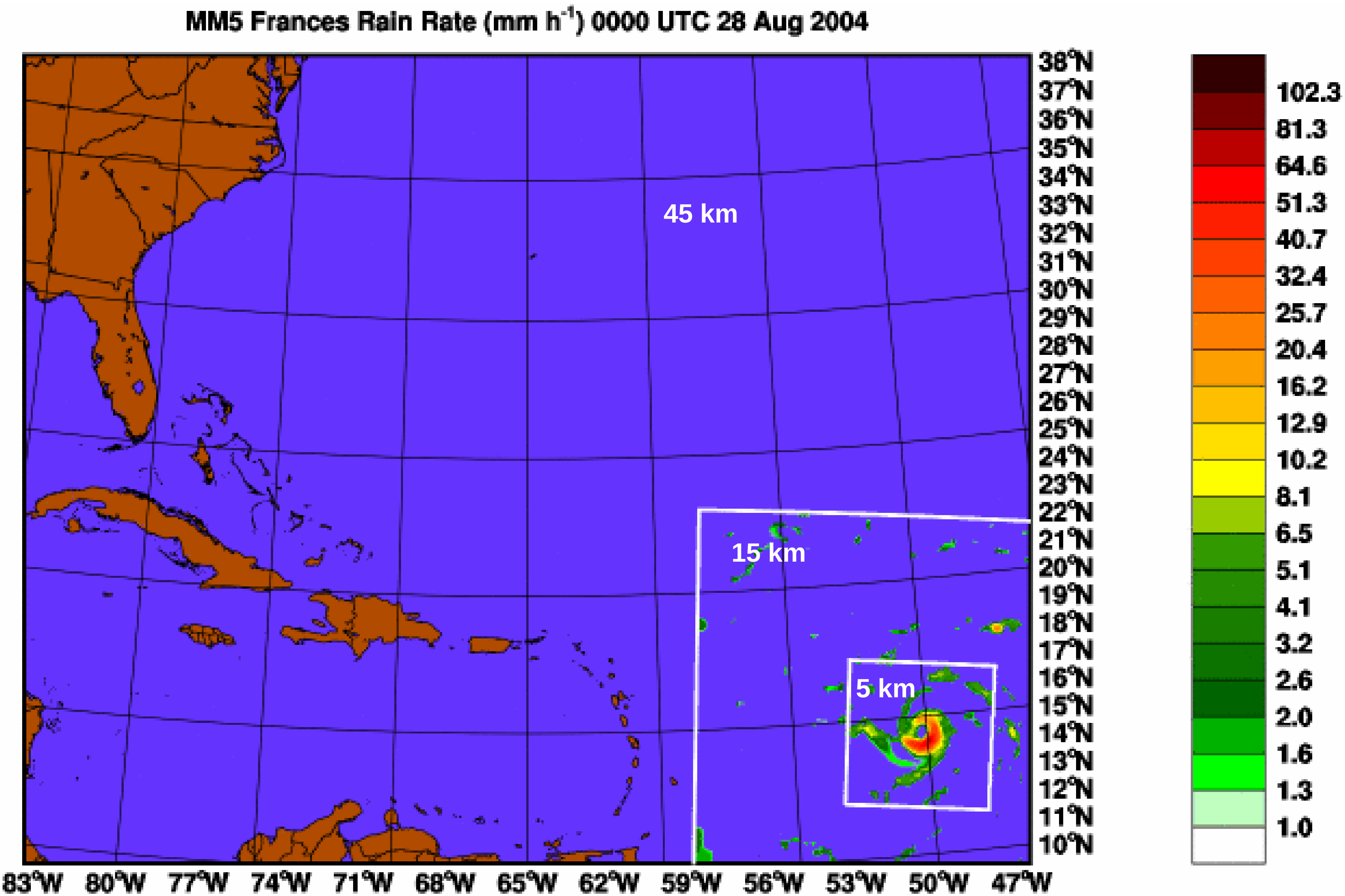
- MM5 (or WRF)

  (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)

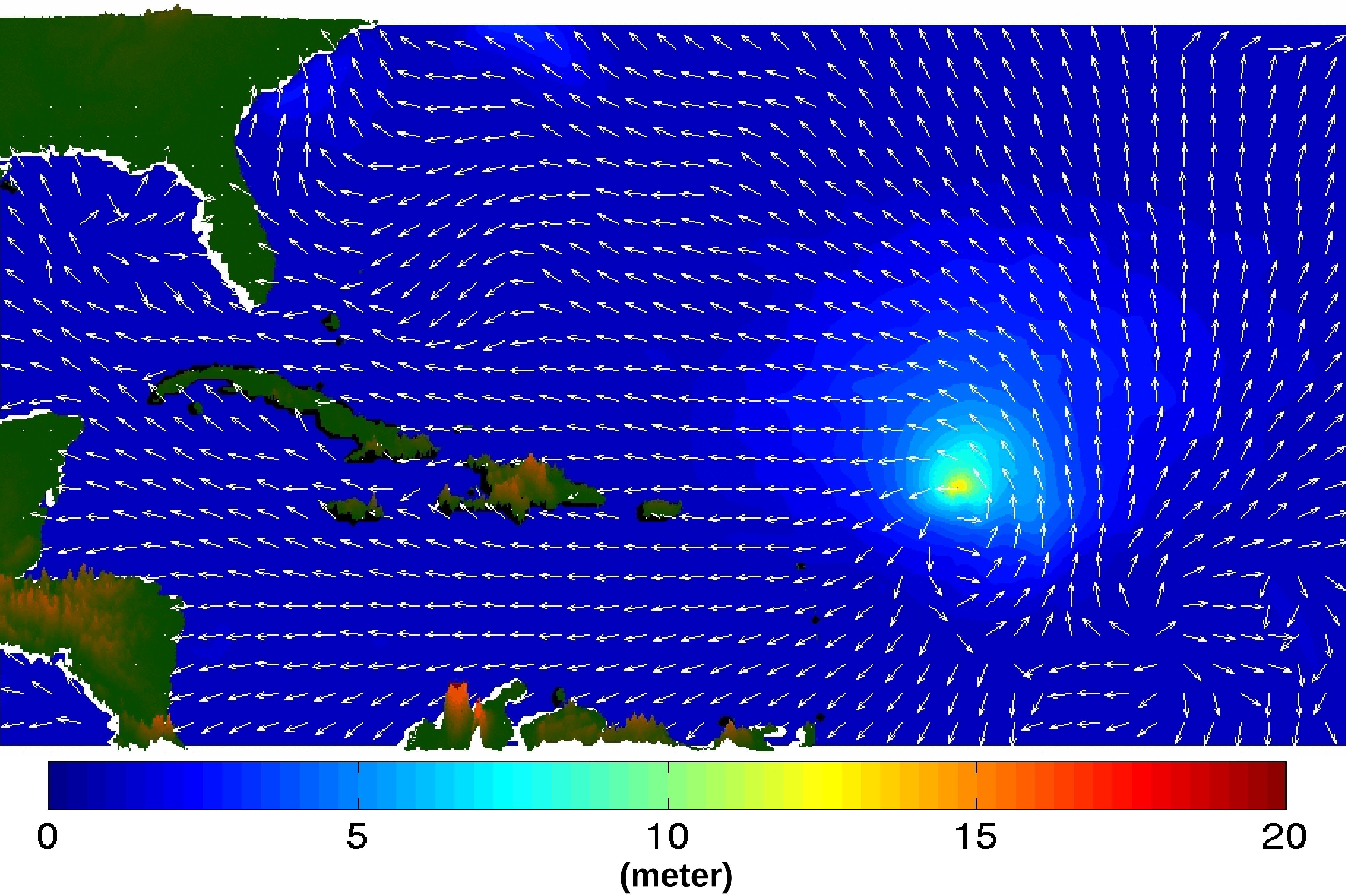
  (1/6^o, 25 frequency bands, 48 directional bands)
- HYCOM (UMiami/NRL)

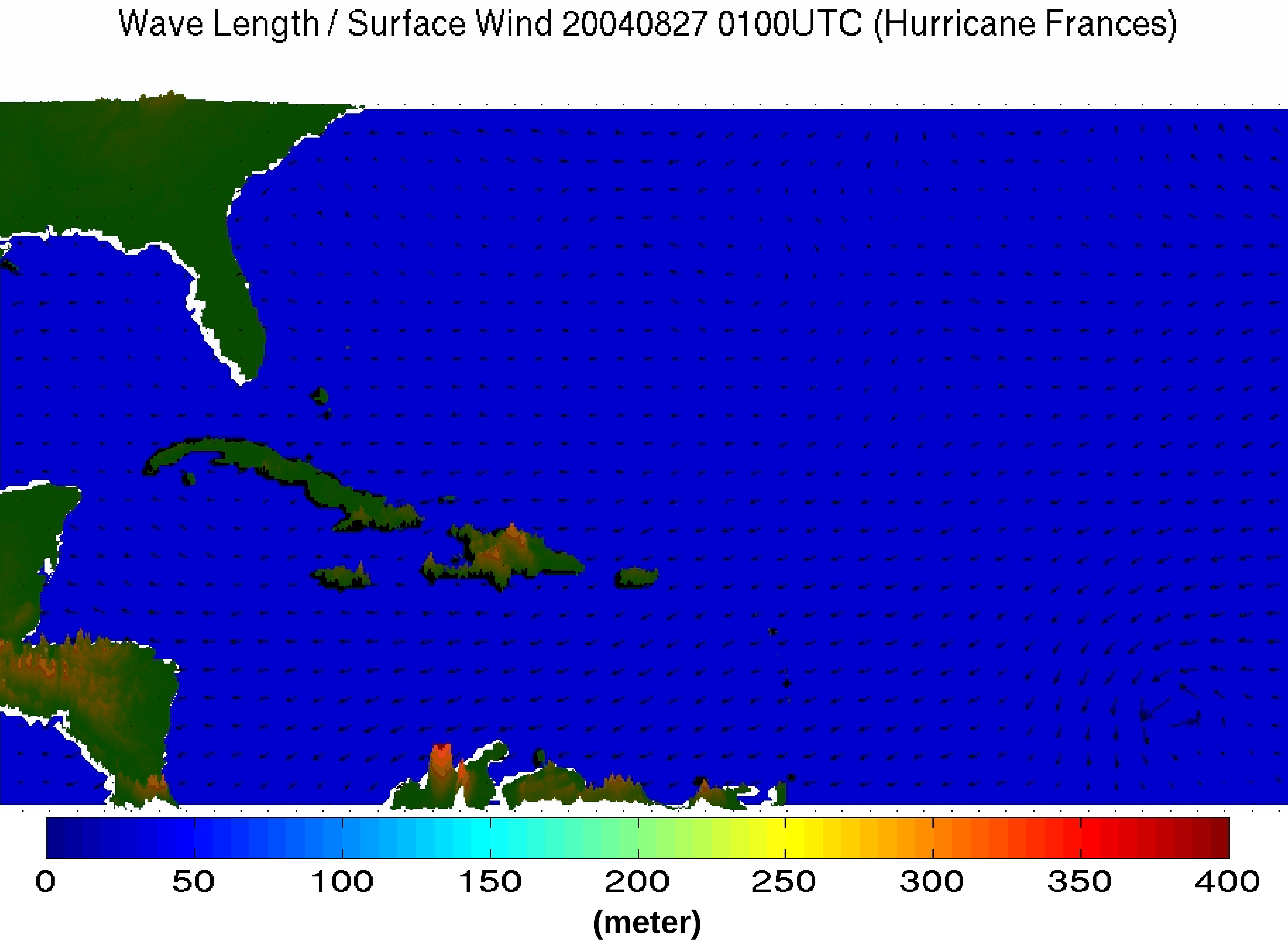
  (1/12^o, 26 vertical levels with 4-6 in the ocean mixed layer)
- 3DUOM (Price's 3-D Upper Ocean Circulation Models)

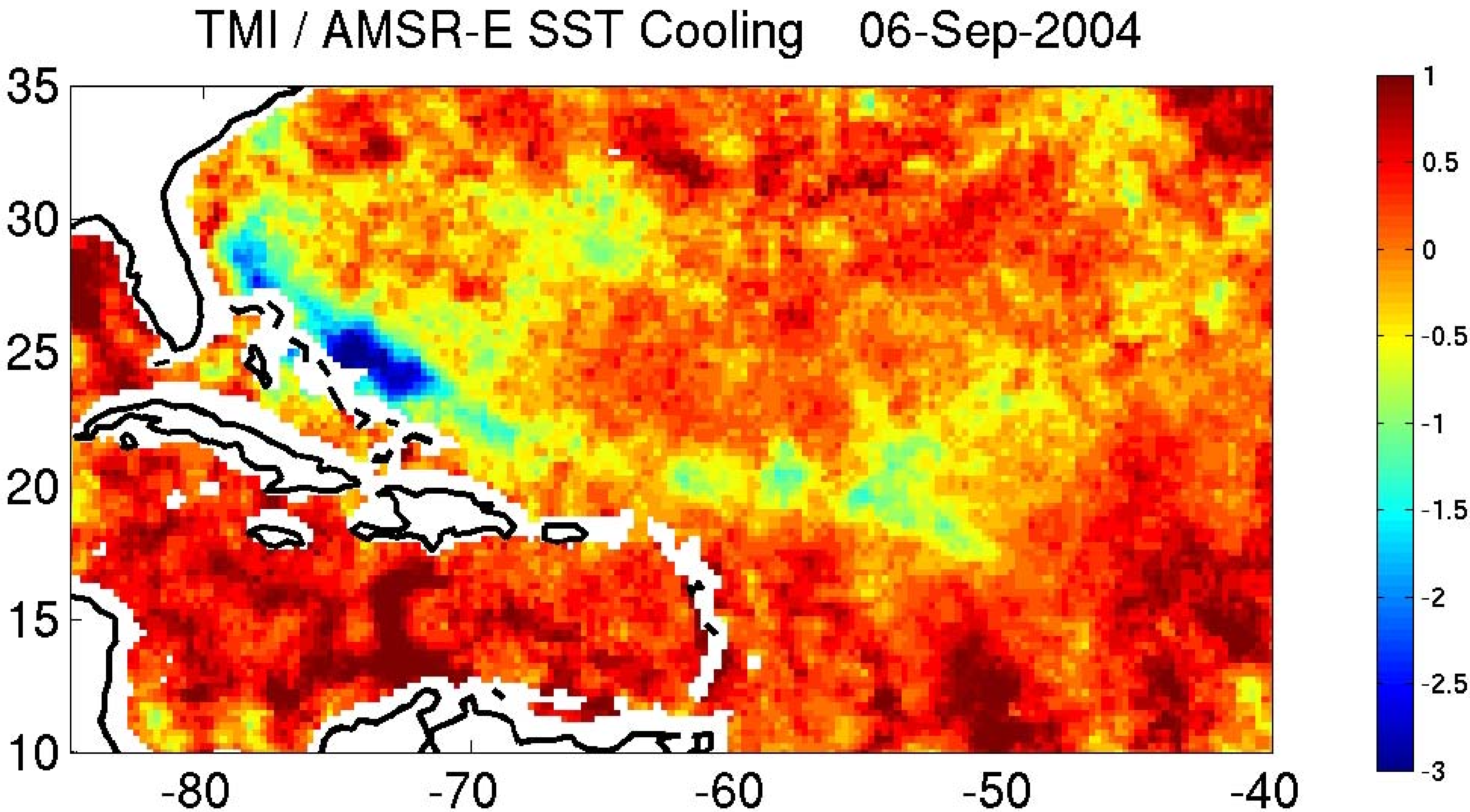
  (15 km, 30 vertical levels with 4-6 in the ocean mixed layer)


MM5 Frances Rain Rate (mm h^{-1}) 0000 UTC 28 Aug 2004
45 km
15 km
5 km
38°N
37°N
36°N
35°N
34°N
33°N
32°N
31°N
30°N
29°N
28°N
27°N
26°N
25°N
24°N
23°N
22°N
21°N
20°N
19°N
18°N
17°N
16°N
15°N
14°N
13°N
12°N
11°N
10°N
83°W
80°W
77°W
74°W
71°W
68°W
65°W
62°W
59°W
56°W
53°W
50°W
47°W
102.3
81.3
64.6
51.3
40.7
32.4
25.7
20.4
16.2
12.9
10.2
8.1
6.5
5.1
4.1
3.2
2.6
2.0
1.6
1.3
1.0

Significant Wave Height / Wave Direction 20040830 0000UTC (Hurricane Frances)

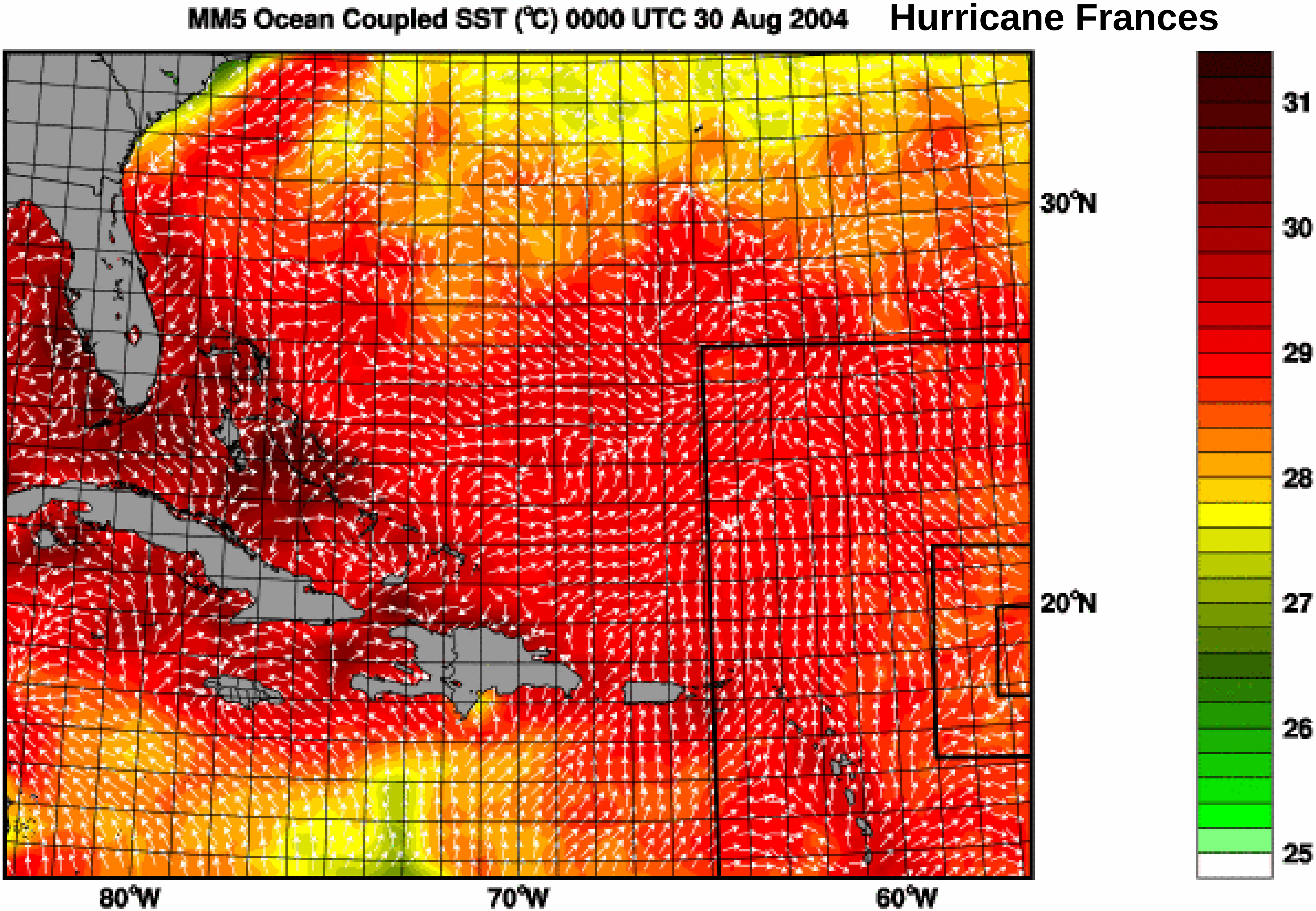


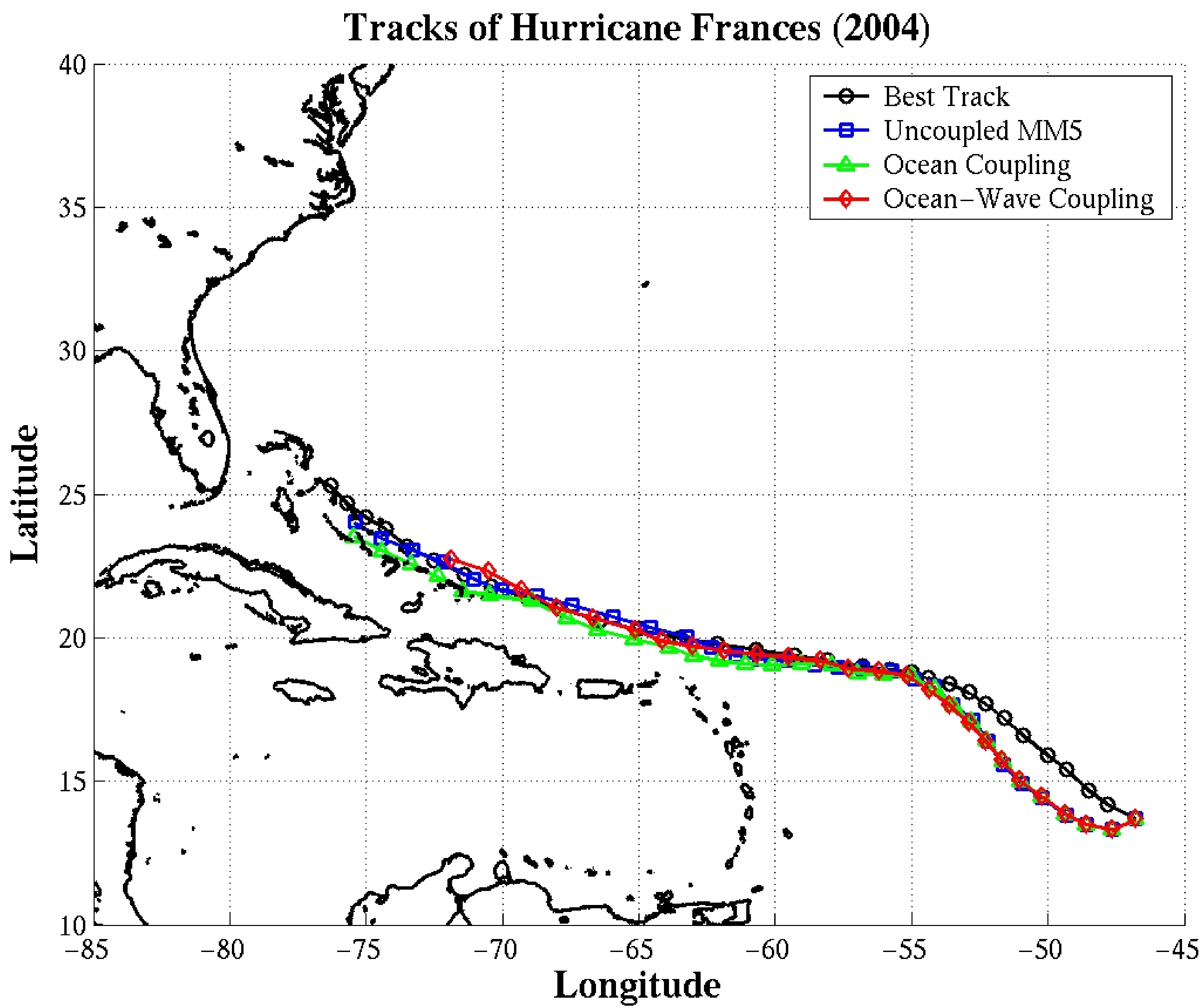

Wave Length / Surface Wind 20040827 0100UTC (Hurricane Frances)
0
50
100
150
200
250
300
350
400
(meter)

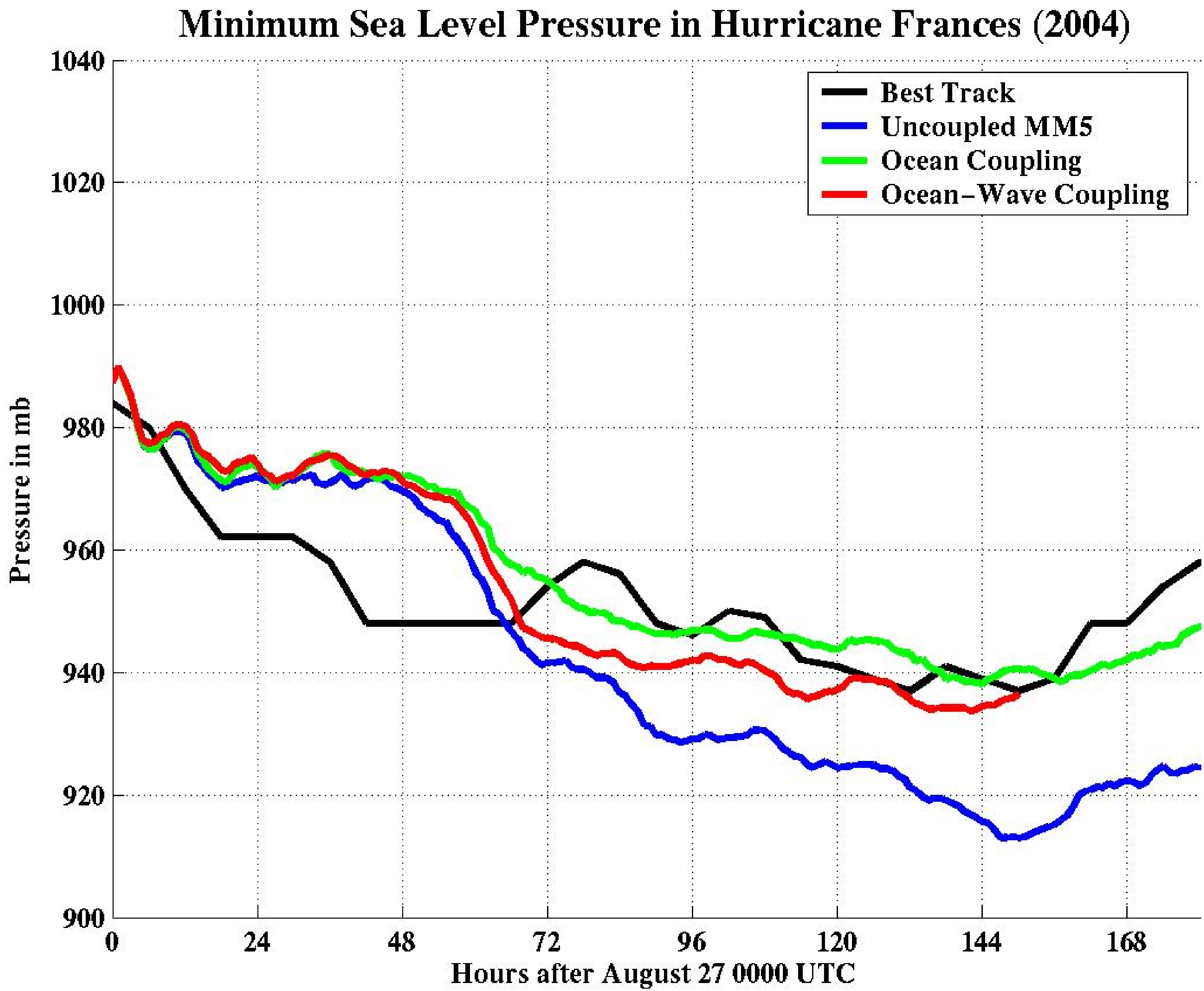


TMI / AMSR-E SST Cooling 06-Sep-2004
35
30
25
20
15
10
-80
-70
-60
-50
-40
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3

Hurricane Frances




Tracks of Hurricane Frances (2004)
Best Track
Uncoupled MM5
Ocean Coupling
Ocean−Wave Coupling
Latitude
Longitude
40
35
30
25
20
15
10
−85
−80
−75
−70
−65
−60
−55
−50
−45



Minimum Sea Level Pressure in Hurricane Frances (2004)
Best Track
Uncoupled MM5
Ocean Coupling
Ocean−Wave Coupling
1040
1020
1000
980
960
940
920
900
Pressure in mb
0
24
48
72
96
120
144
168
Hours after August 27 0000 UTC

Effects of Ocean Surface Waves on Hurricane Structure and Intensity

Coupled MM5-WAVEWATCH III

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

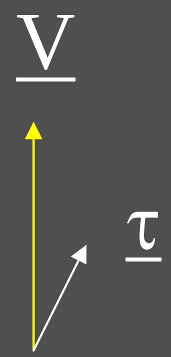
$$\tau = \tau_t + \tau_w \longrightarrow z_o$$

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.

Wind-Wave Coupling Parameterization

Spectra Tail Parameterization:

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

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

$$\frac{\gamma}{\omega} = 0.28\frac{\rho_a}{\rho_w}\left[\frac{U_{(\pi/k)}\cos\theta}{C(k)}-1\right].\left|\frac{U_{(\pi/k)}\cos\theta}{C(k)}-1\right|$$

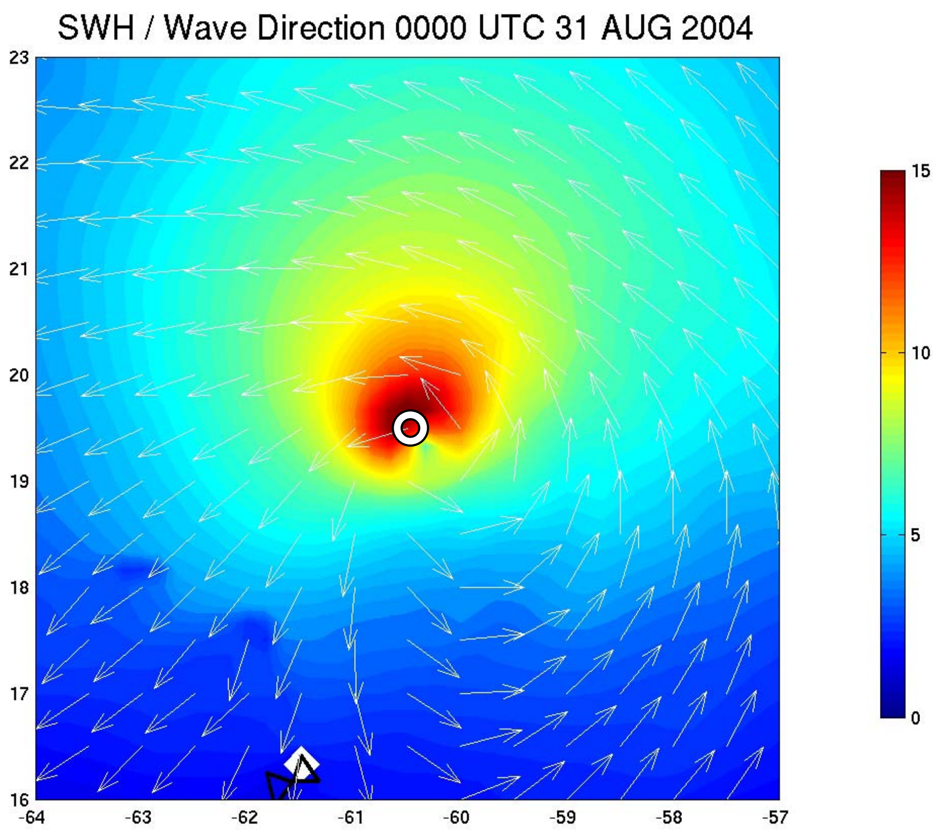
Growth rate of each component from measurement of pressure-slope correlation

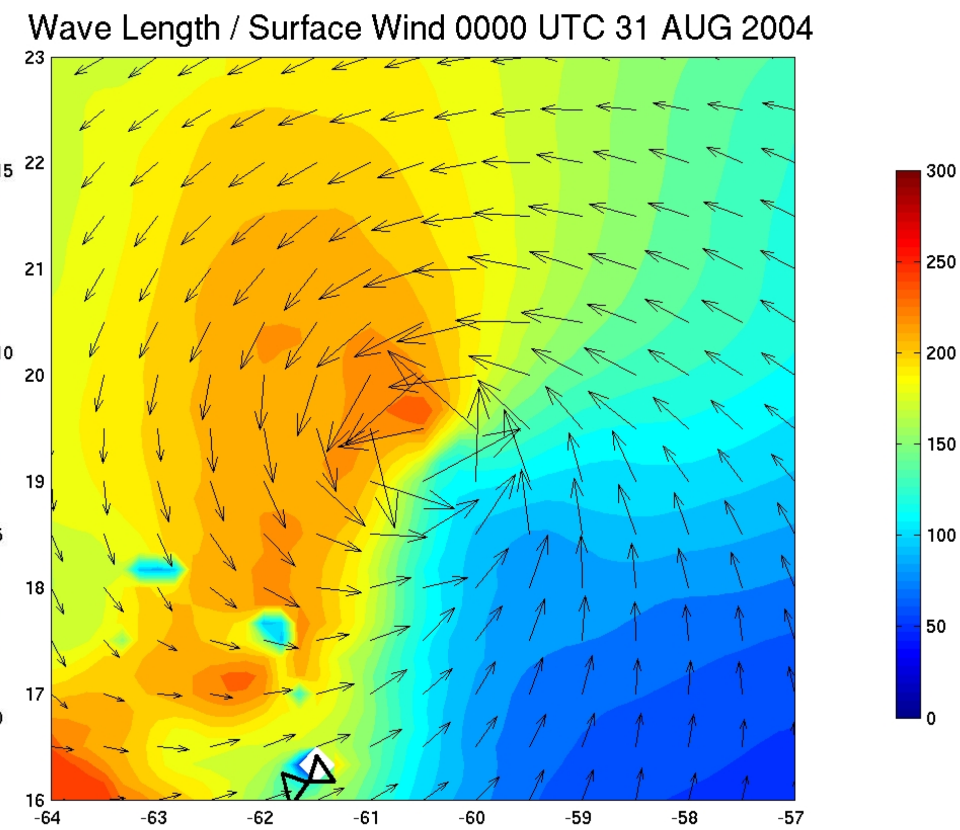
$$F(k,\vartheta) = \alpha k^{-5}\sec h^2(\beta(\vartheta_k))$$

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.

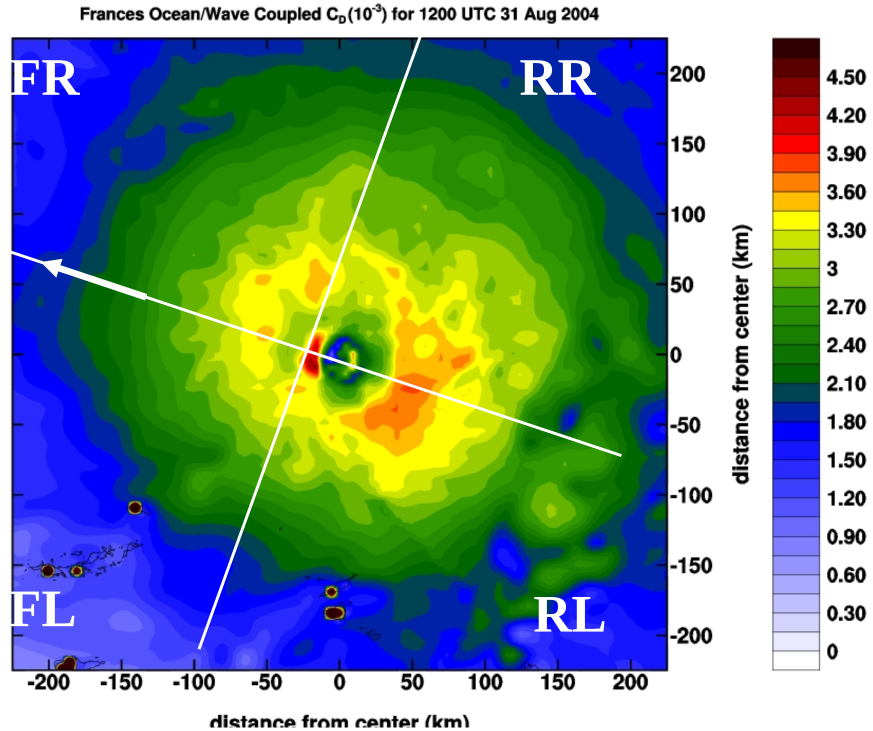
$$\beta = \frac{1.2}{\cos^{-1}(C/U)};C/U < 0.9$$

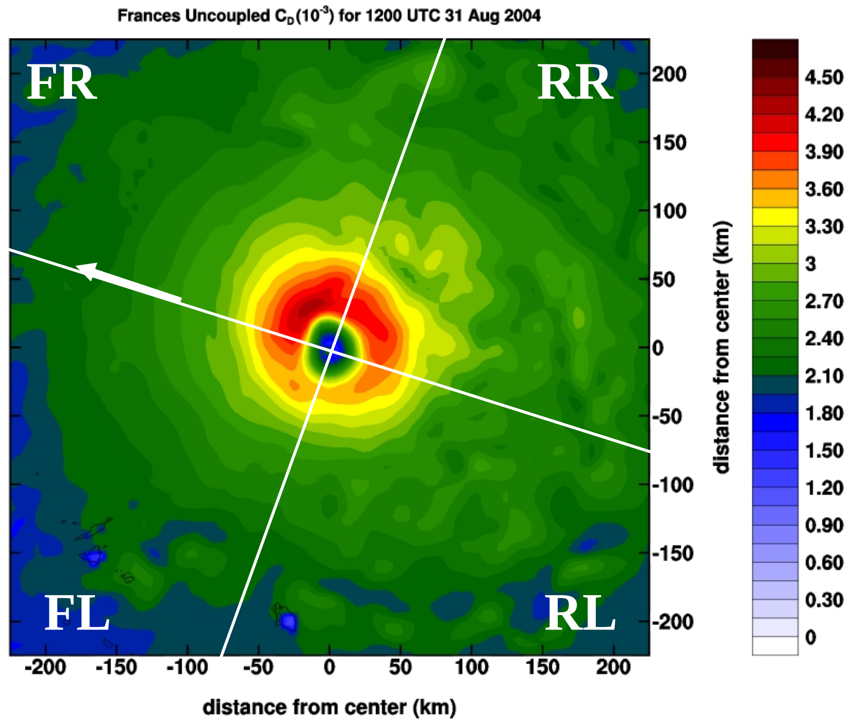
β is the spreading function for the short waves.

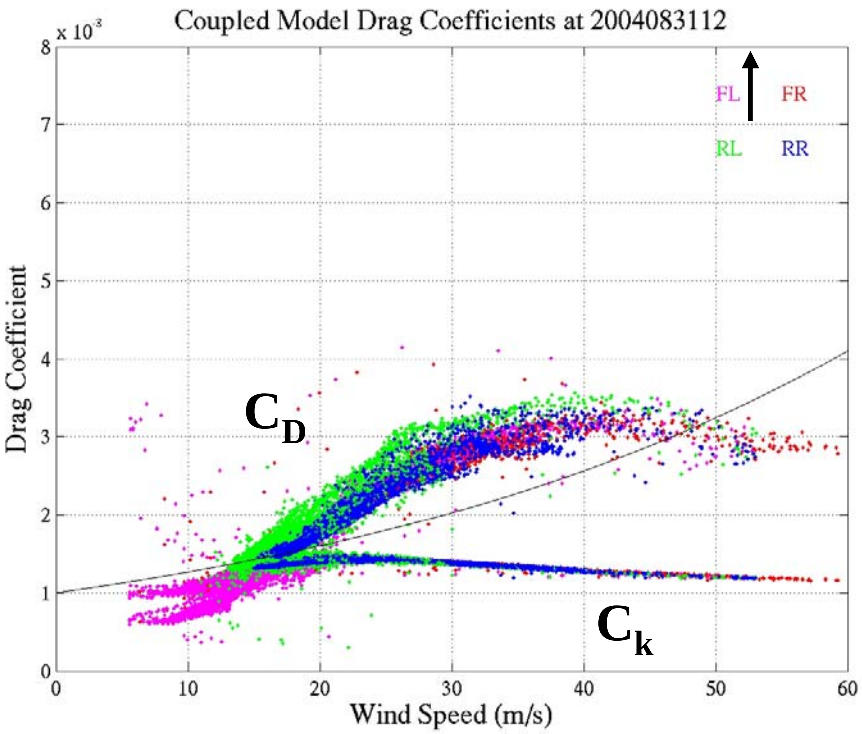

SWH / Wave Direction 0000 UTC 31 AUG 2004
23
22
21
20
19
18
17
16
-64
-63
-62
-61
-60
-59
-58
-57
15
10
5
0

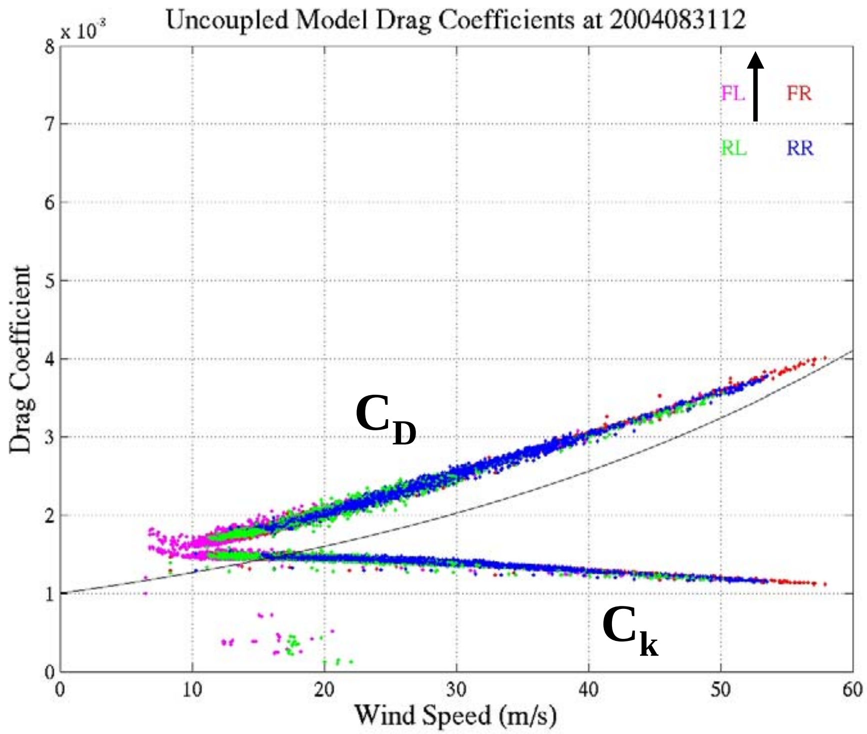

Wave Length / Surface Wind 0000 UTC 31 AUG 2004
23
22
21
20
19
18
17
16
-64
-63
-62
-61
-60
-59
-58
-57
300
250
200
150
100
50
0

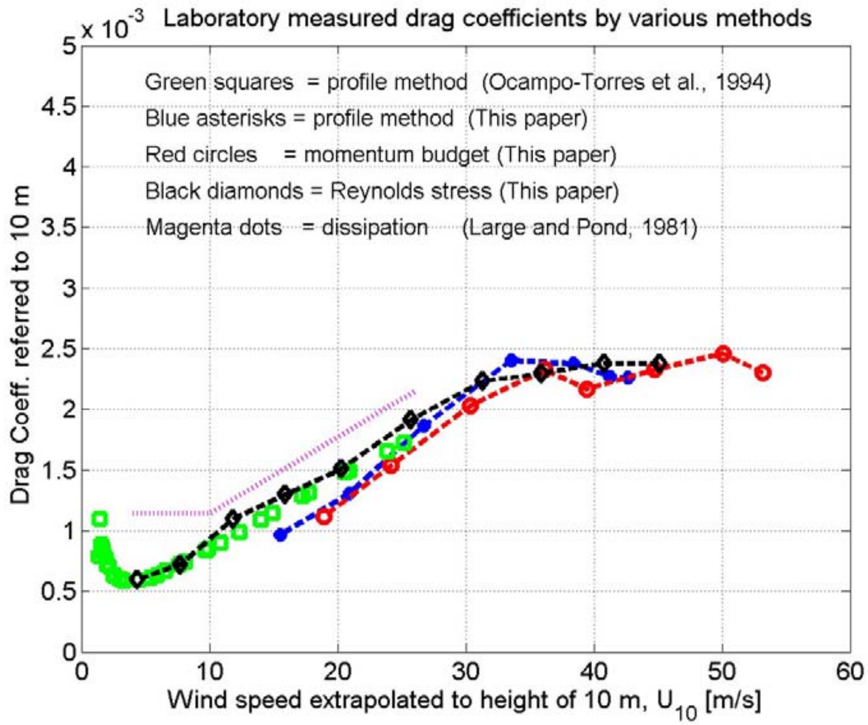
Hurricane Frances (2004)



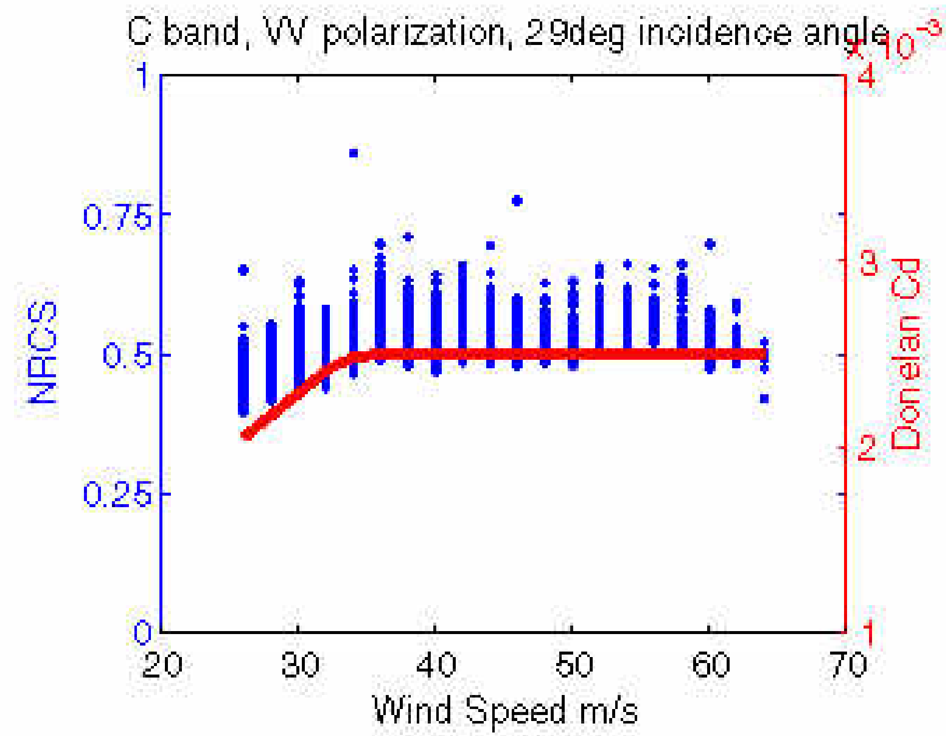




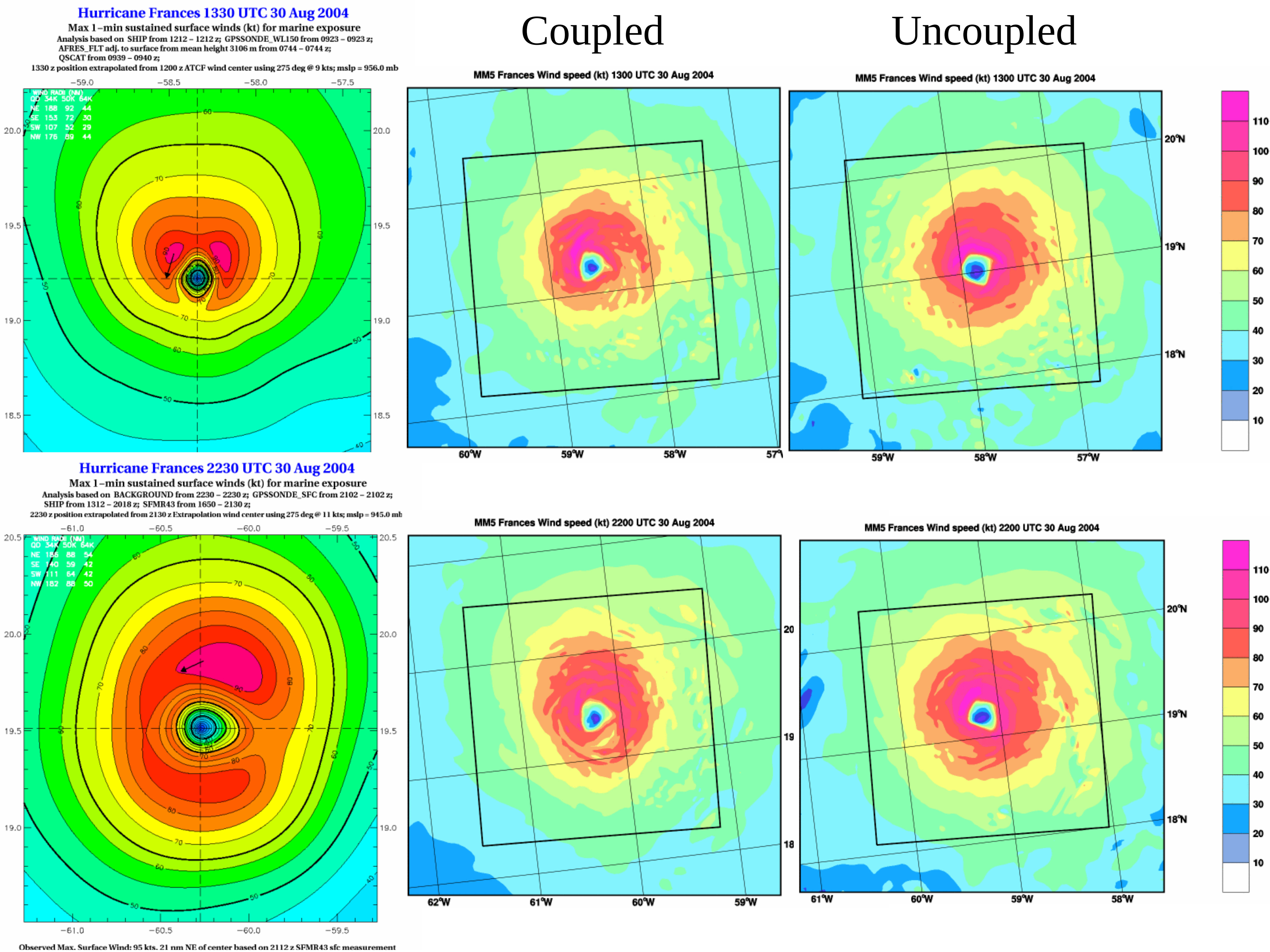




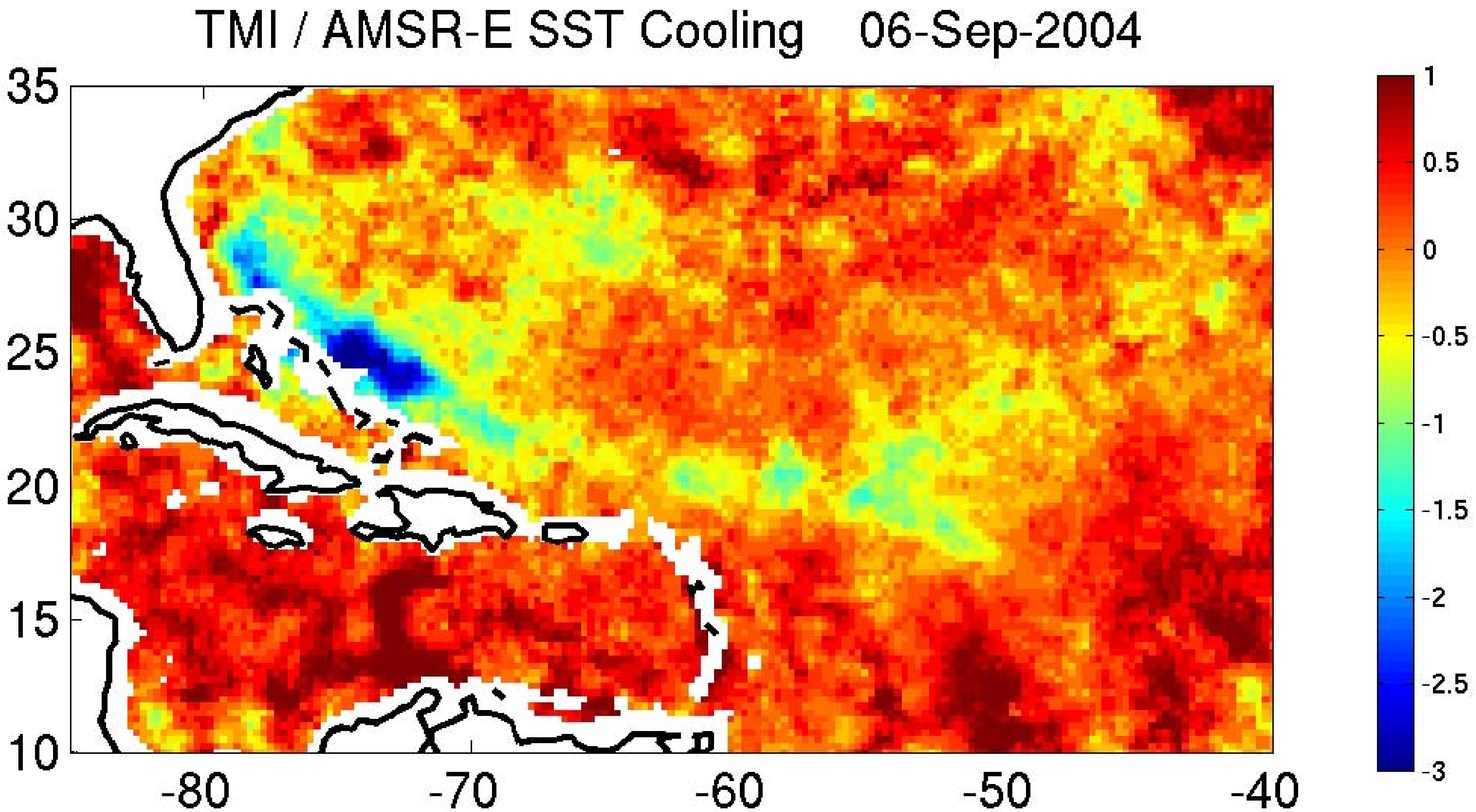
Laboratory measured drag coefficients by various methods
Green squares = profile method (Ocampo-Torres et al., 1994)
Blue asterisks = profile method (This paper)
Red circles = momentum budget (This paper)
Black diamonds = Reynolds stress (This paper)
Magenta dots = dissipation (Large and Pond, 1981)
Drag Coeff. referred to 10 m
Wind speed extrapolated to height of 10 m, U_{10} [m/s]

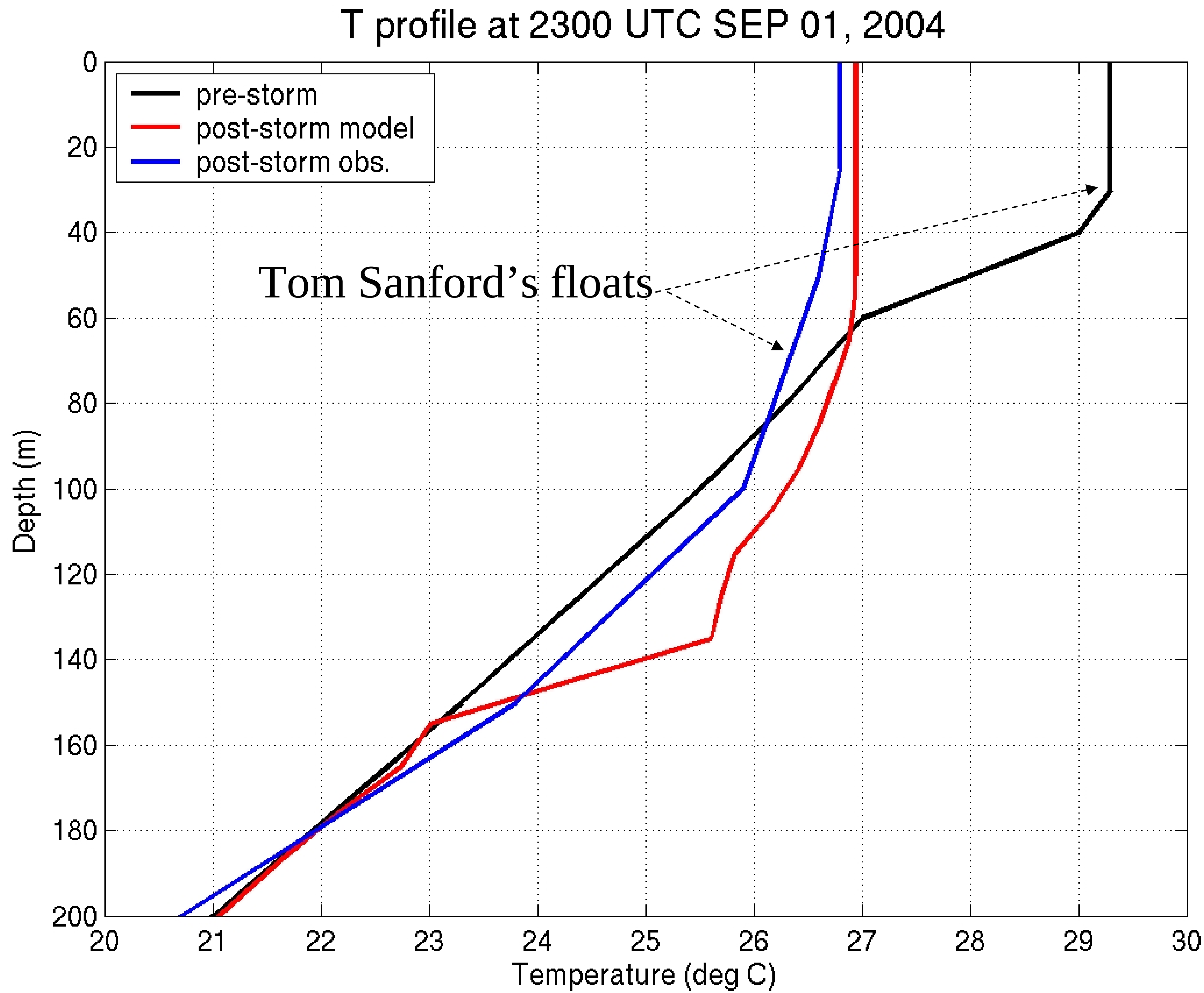


C band, VV polarization, 29deg incidence angle
NRCS
Donelan Cd
Wind Speed m/s


Coupled
Uncoupled
Hurricane Frances 1330 UTC 30 Aug 2004
Max 1-min sustained surface winds (kt) for marine exposure
Analysis based on SHIP from 1212 – 1212 z; GPSSONDE_WL150 from 0923 – 0923 z;
AFRES_FLT adj. to surface from mean height 3106 m from 0744 – 0744 z;
QSCAT from 0939 – 0940 z;
1330 z position extrapolated from 1200 z ATCF wind center using 275 deg @ 9 kts; mslp = 956.0 mb
MM5 Frances Wind speed (kt) 1300 UTC 30 Aug 2004
MM5 Frances Wind speed (kt) 1300 UTC 30 Aug 2004
Hurricane Frances 2230 UTC 30 Aug 2004
Max 1-min sustained surface winds (kt) for marine exposure
Analysis based on BACKGROUND from 2230 – 2230 z; GPSSONDE_SFC from 2102 – 2102 z;
SHIP from 1312 – 2018 z; SFMR43 from 1650 – 2130 z;
2230 z position extrapolated from 2130 z Extrapolation wind center using 275 deg @ 11 kts; mslp = 945.0 mb
MM5 Frances Wind speed (kt) 2200 UTC 30 Aug 2004
MM5 Frances Wind speed (kt) 2200 UTC 30 Aug 2004
Observed Max. Surface Wind: 95 kts, 21 nm NE of center based on 2112 z SFMR43 sfc measurement

Effects of Upper Ocean on Hurricane Structure and Intensity


TMI / AMSR-E SST Cooling 06-Sep-2004
35
30
25
20
15
10
-80
-70
-60
-50
-40
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3

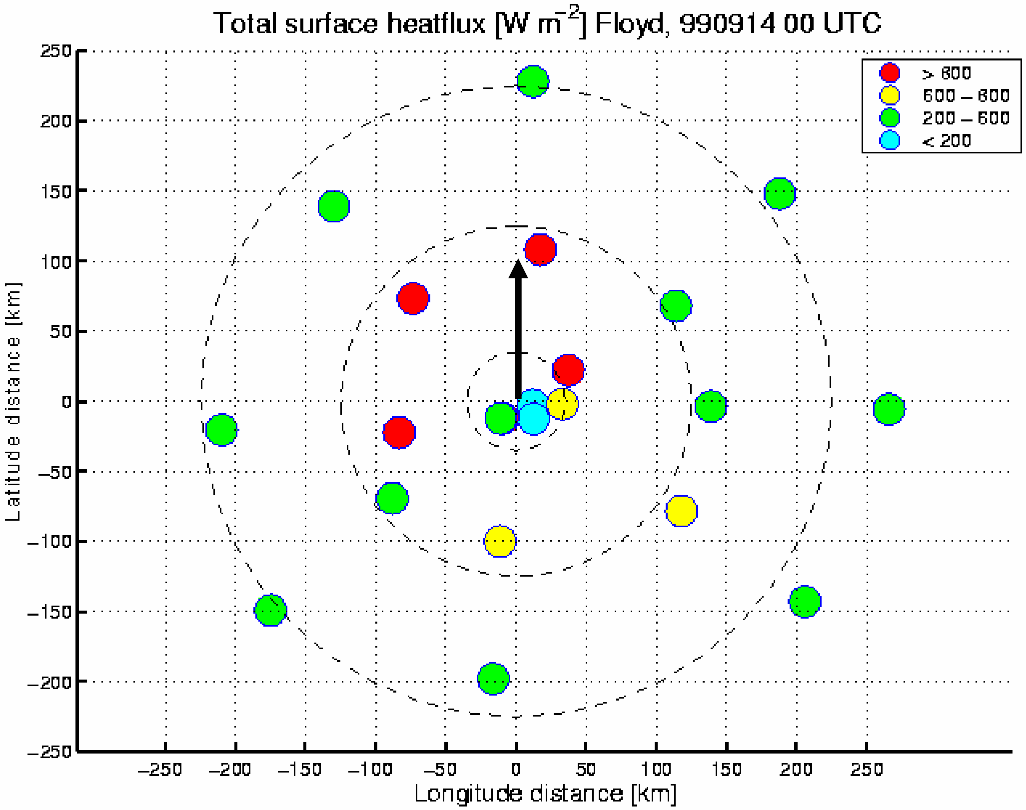


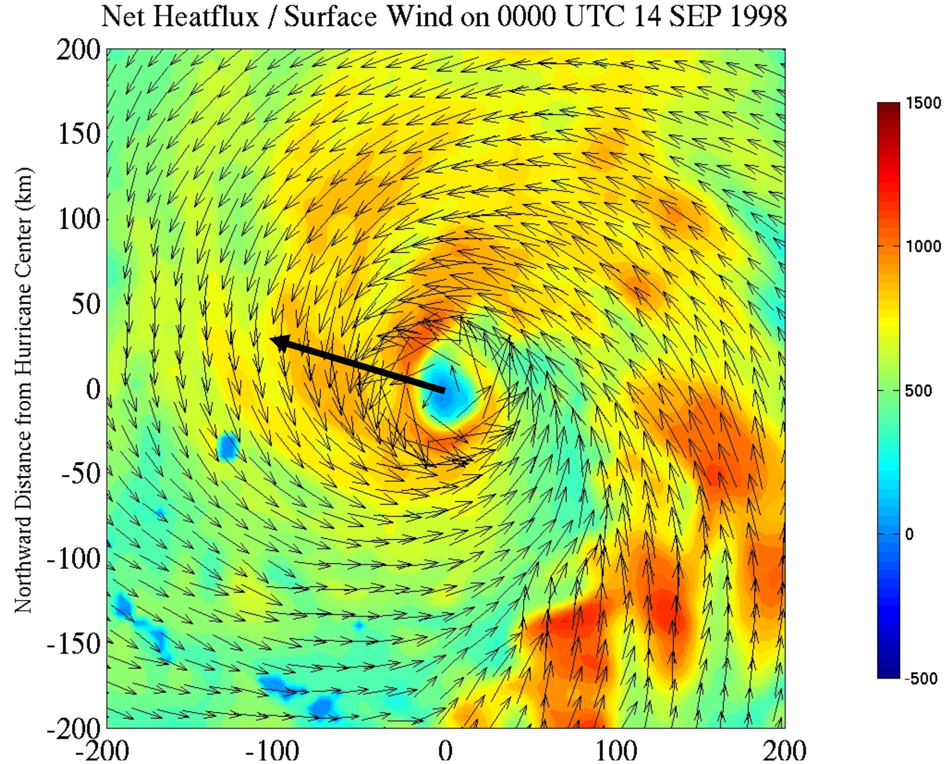
T profile at 2300 UTC SEP 01, 2004
pre-storm
post-storm model
post-storm obs.
Tom Sanford's floats
Depth (m)
Temperature (deg C)
0
20
40
60
80
100
120
140
160
180
200
20
21
22
23
24
25
26
27
28
29
30

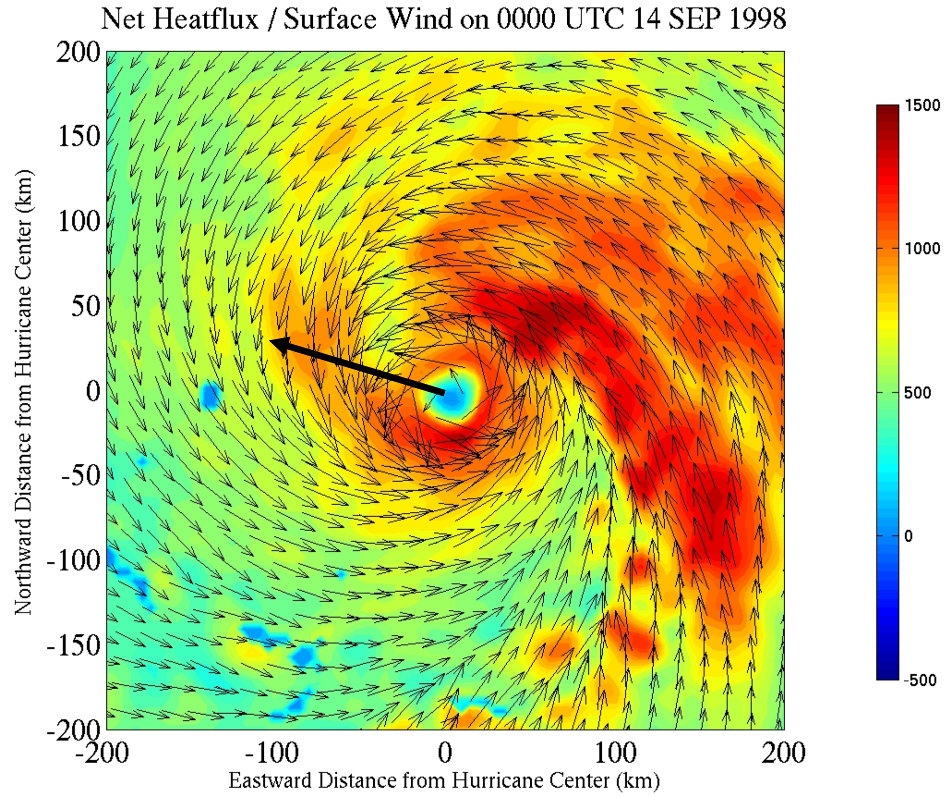
Hurricane Floyd (1999)

Coupled

GPS Dropsondes



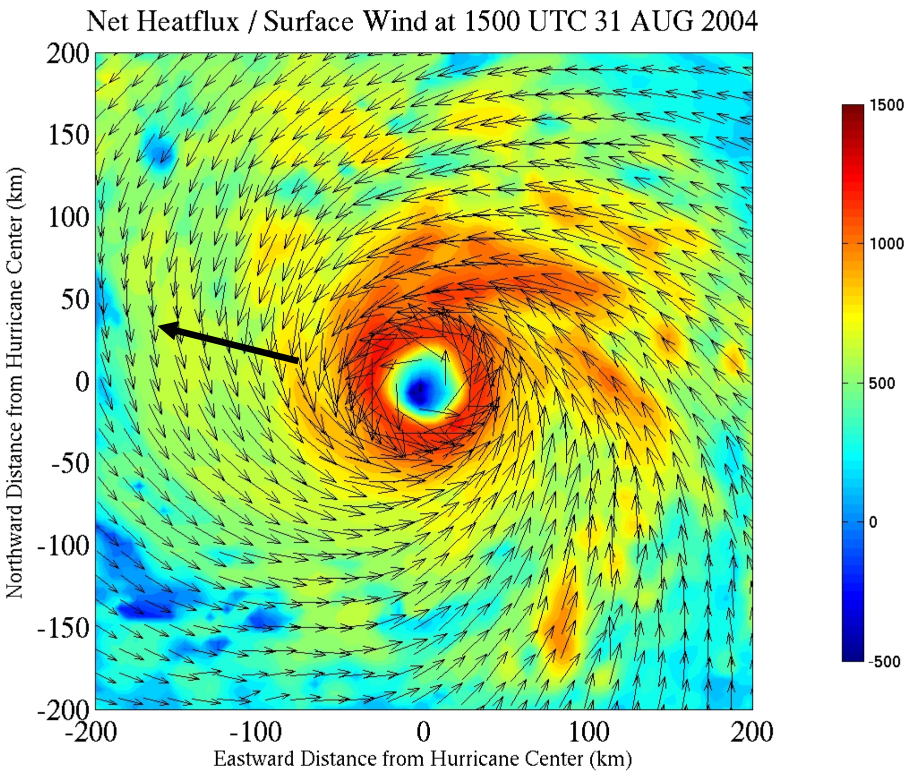




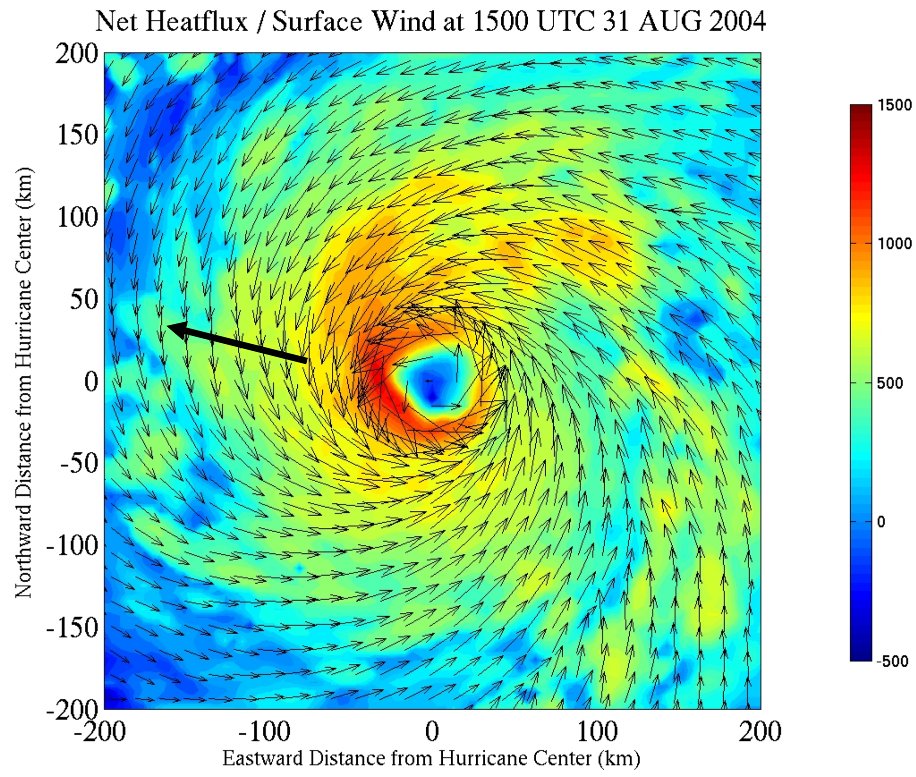
Uncoupled

Total Surface Heat Flux

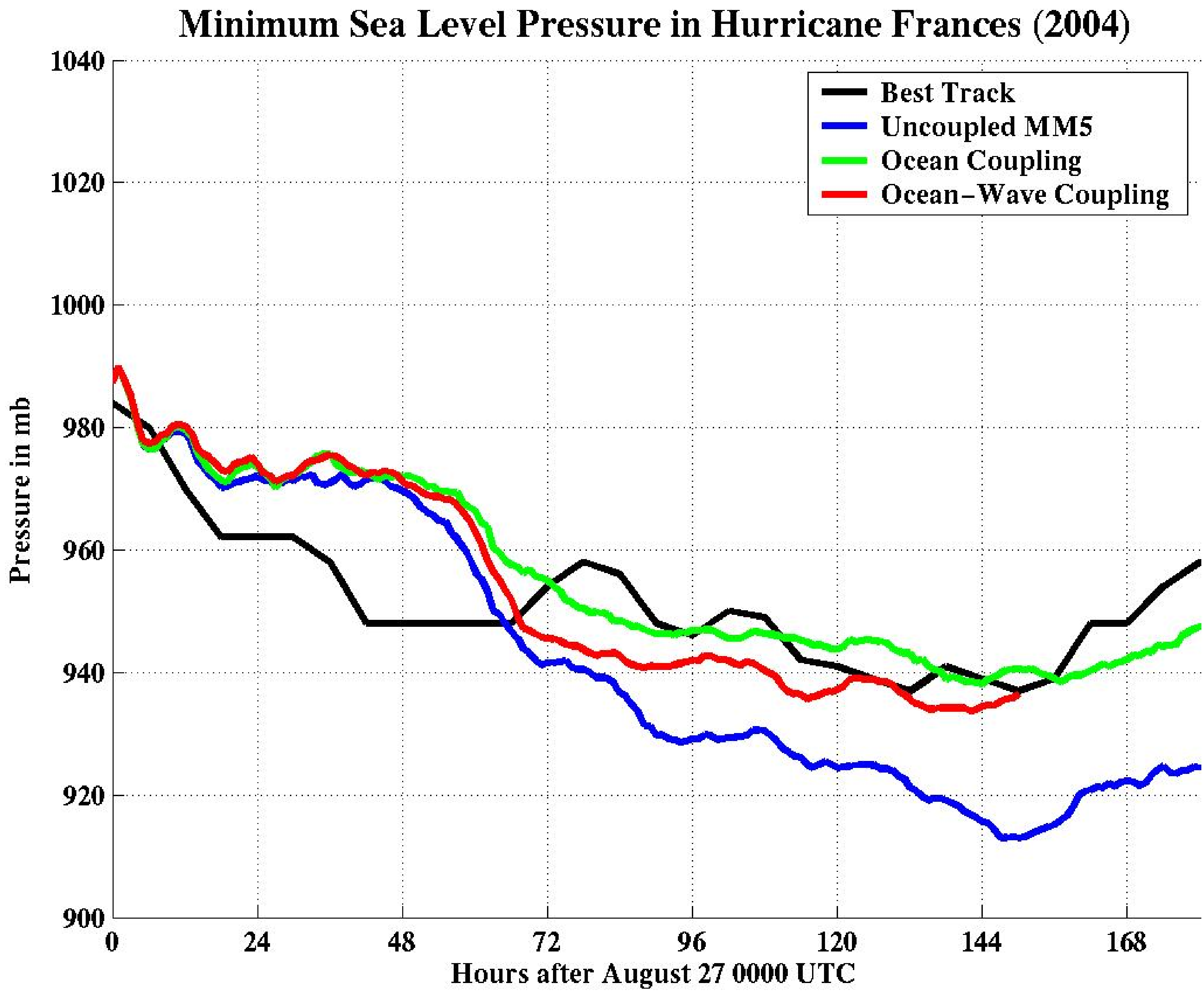
Uncoupled



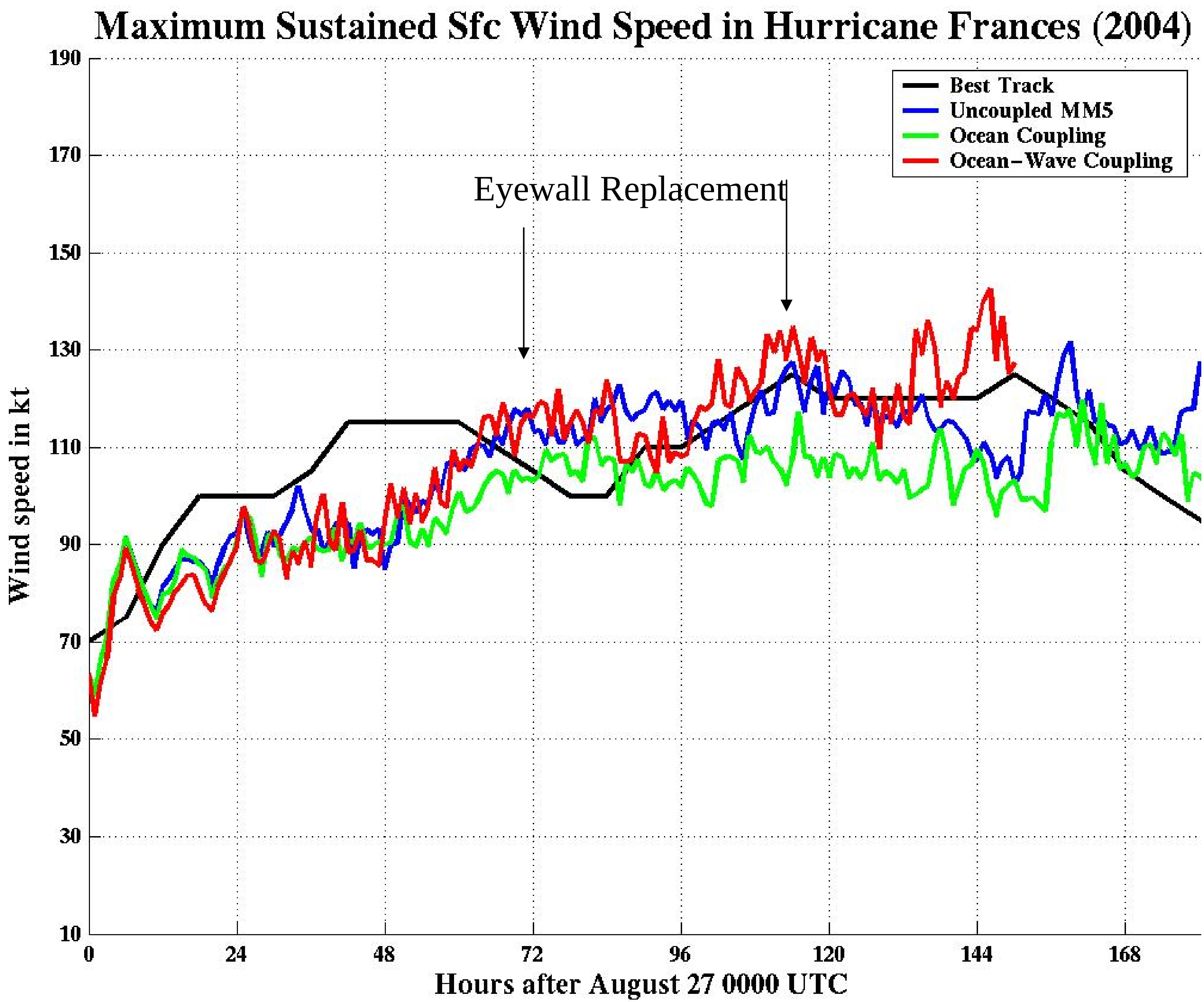
Coupled Atmos-Wave-Ocean



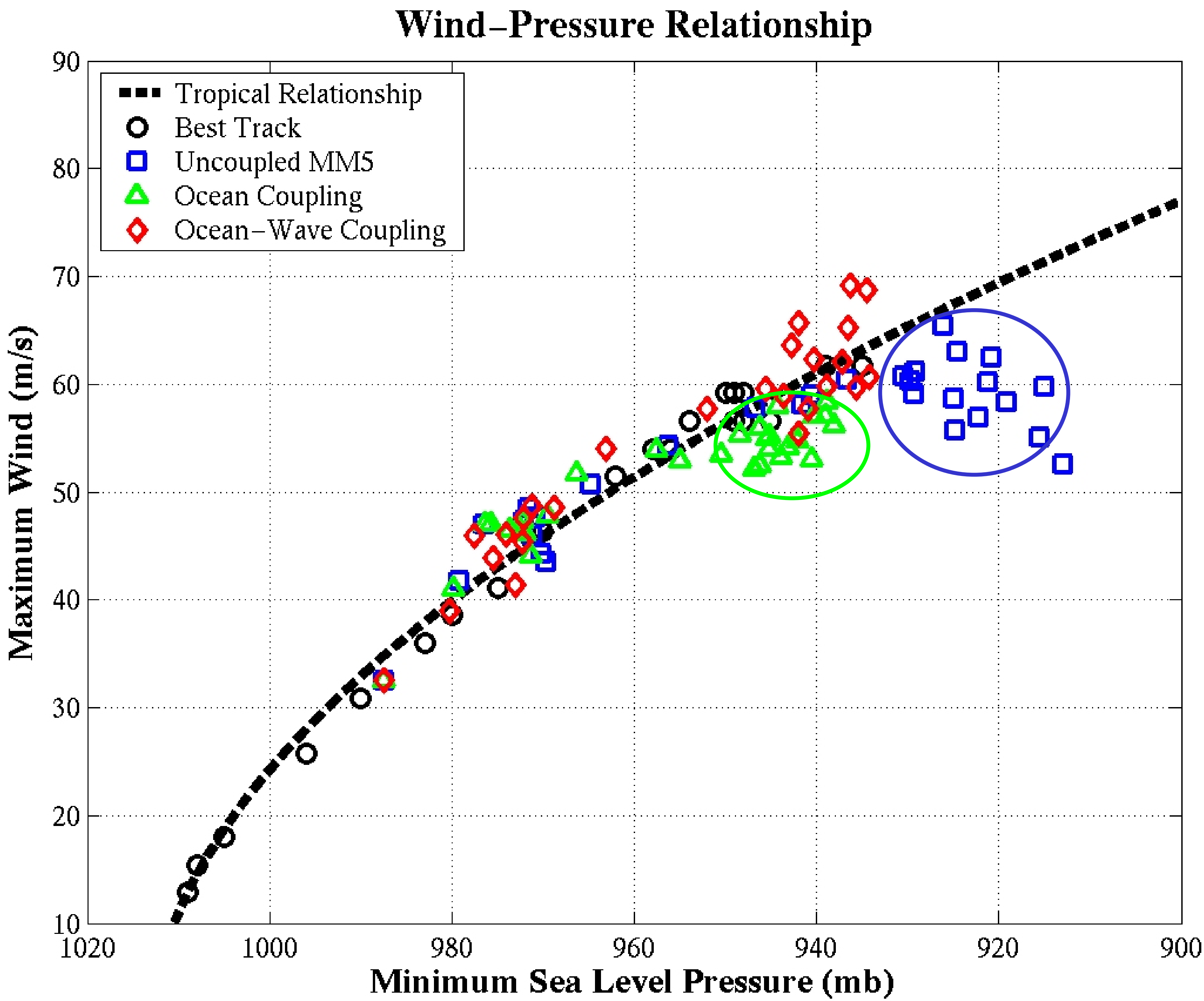
Hurricane Wind-Pressure Relationship



Minimum Sea Level Pressure in Hurricane Frances (2004)
Best Track
Uncoupled MM5
Ocean Coupling
Ocean–Wave Coupling
Pressure in mb
1040
1020
1000
980
960
940
920
900
0
24
48
72
96
120
144
168
Hours after August 27 0000 UTC



Maximum Sustained Sfc Wind Speed in Hurricane Frances (2004)
Best Track
Uncoupled MM5
Ocean Coupling
Ocean−Wave Coupling
Eyewall Replacement
Wind speed in kt
Hours after August 27 0000 UTC
190
170
150
130
110
90
70
50
30
10
0
24
48
72
96
120
144
168



Wind–Pressure Relationship
Tropical Relationship
Best Track
Uncoupled MM5
Ocean Coupling
Ocean–Wave Coupling
Maximum Wind (m/s)
Minimum Sea Level Pressure (mb)
90
80
70
60
50
40
30
20
10
1020
1000
980
960
940
920
900

Conclusions

✓Atmosphere-Ocean coupling improves tropical cyclone intensity forecasts, especially at very high resolution when eyewalls are explicitly resolved.

✓Both wind-wave and ocean coupling contribute to storm asymmetry.

✓Fully coupled Atmosphere-Wave-Ocean model produces the best wind-pressure relationship compared to observations.

✓We have developed and tested a number of air-sea coupling parameterizations for fully coupled atmosphere-wave-ocean modeling systems for hurricane prediction, which are designed to be general and easy to be implemented in both research and operational coupled models.

Future Work

✓Apply the coupled parameterizations to the WRF-WW3-HYCOM coupled system using ESMF (Earth System Modeling Framework).