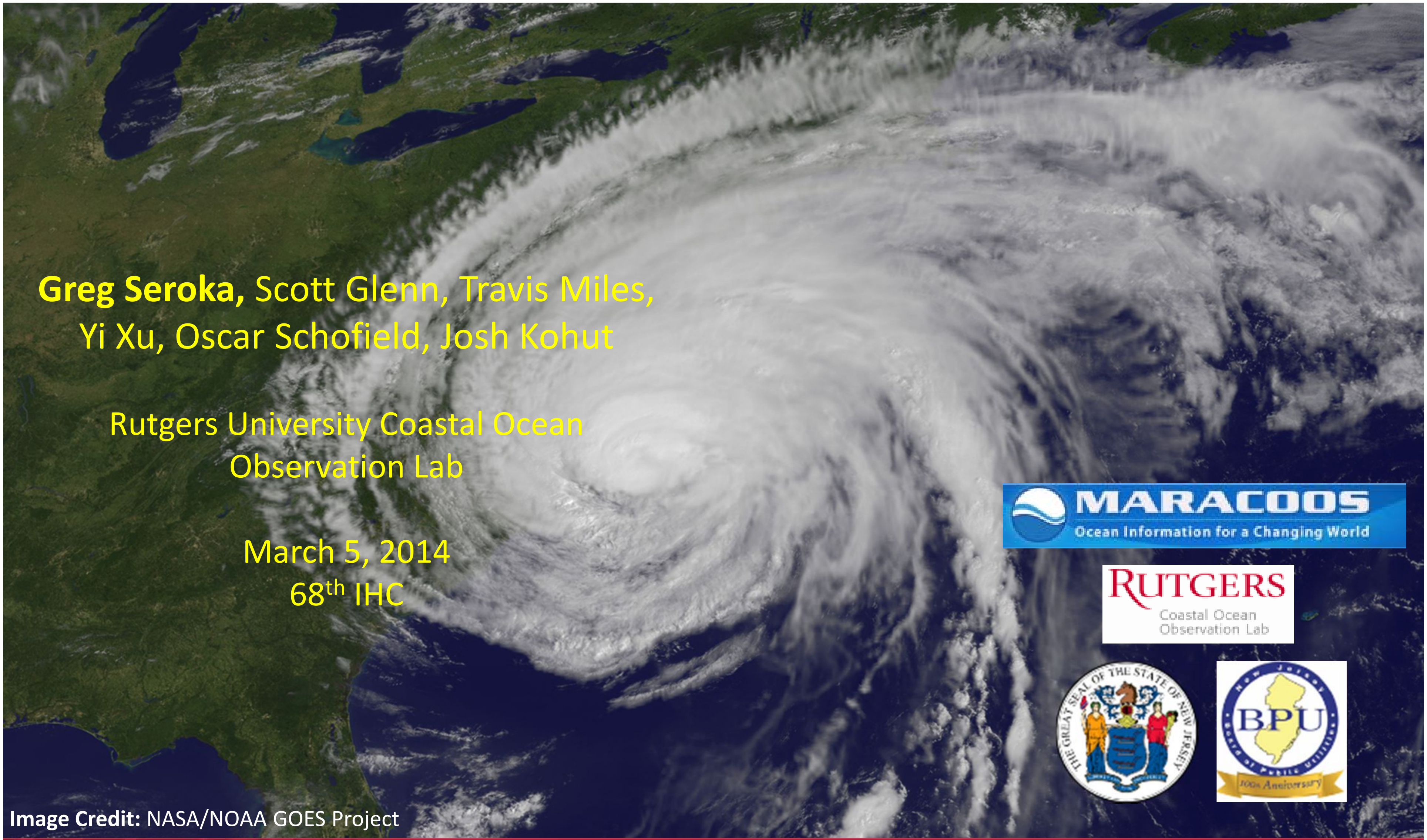
Impact of simple parameterizations of upper ocean heat content on modeled Hurricane Irene (2011) intensity



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Rutgers University Coastal Ocean
Observation Lab

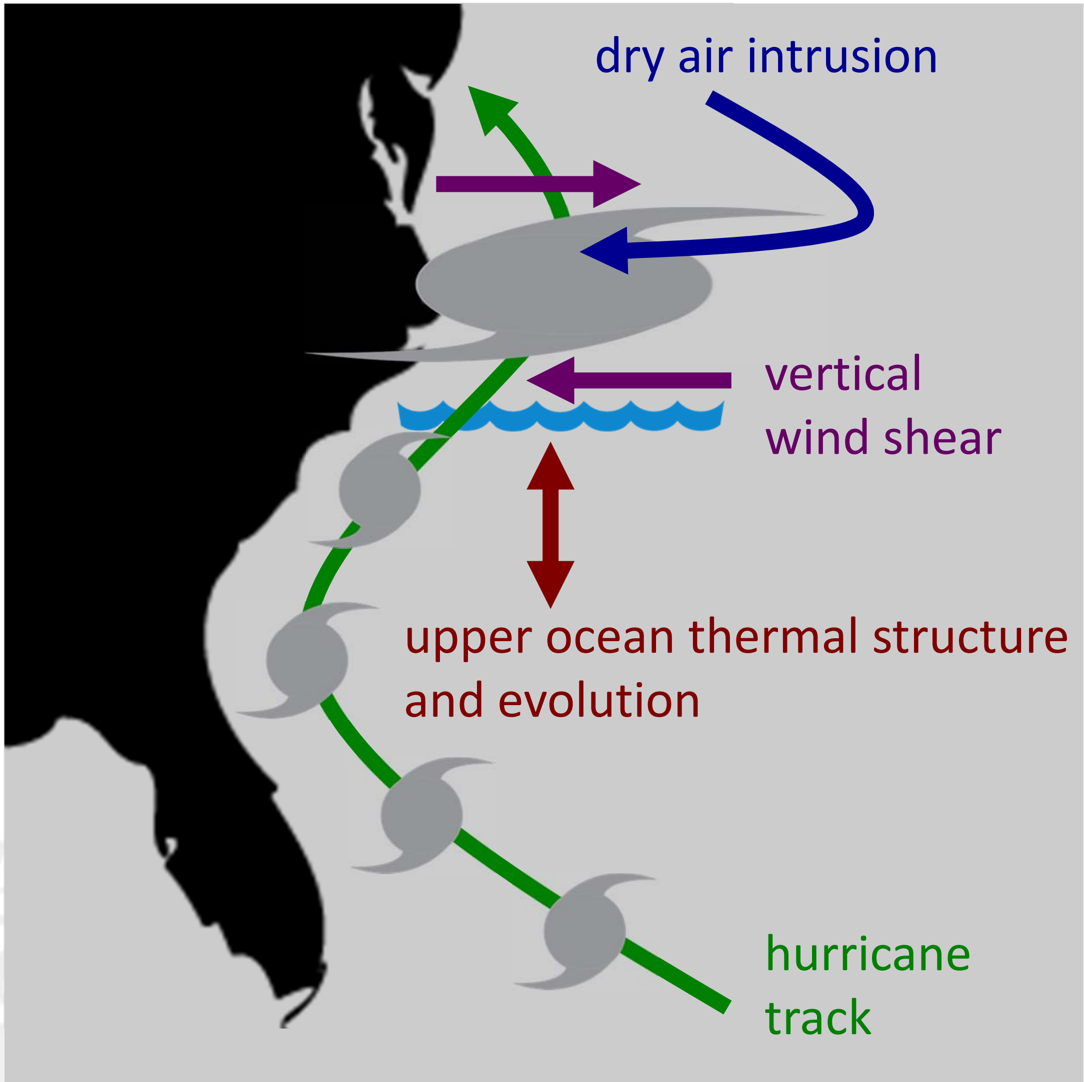
March 5, 2014
68th IHC

Image Credit: NASA/NOAA GOES Project

Motivation

- In August 2011, Hurricane Irene's intensity was over-predicted by several hurricane models and over-forecast by the National Hurricane Center (NHC)
  - NHC final report on Irene:
    1. Consistent high bias in official intensity **forecasts**
       - Incomplete eyewall replacement cycle in light wind shear and over warm South Atlantic Bight waters
    2. High bias in operational **analysis** of intensity
       - Deep central pressure, strong flight-level winds but low surface winds

Governing factors of hurricane intensity



After Emanuel et al. (2004)

Question:

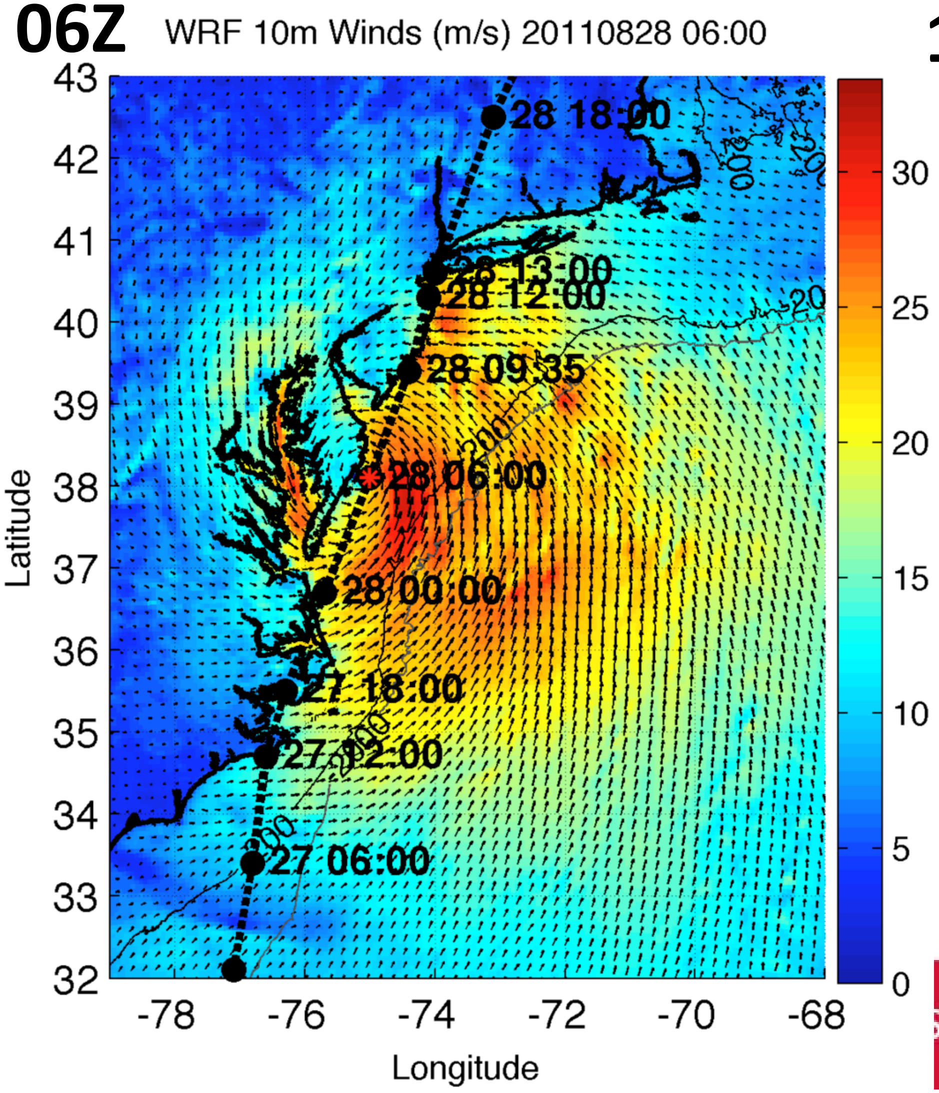
Did the upper ocean thermal structure and evolution (i.e. evolution of sea surface temperature, SST) contribute to Irene's intensity over-prediction?

Hypothesis

We *hypothesize* that the models handled well:

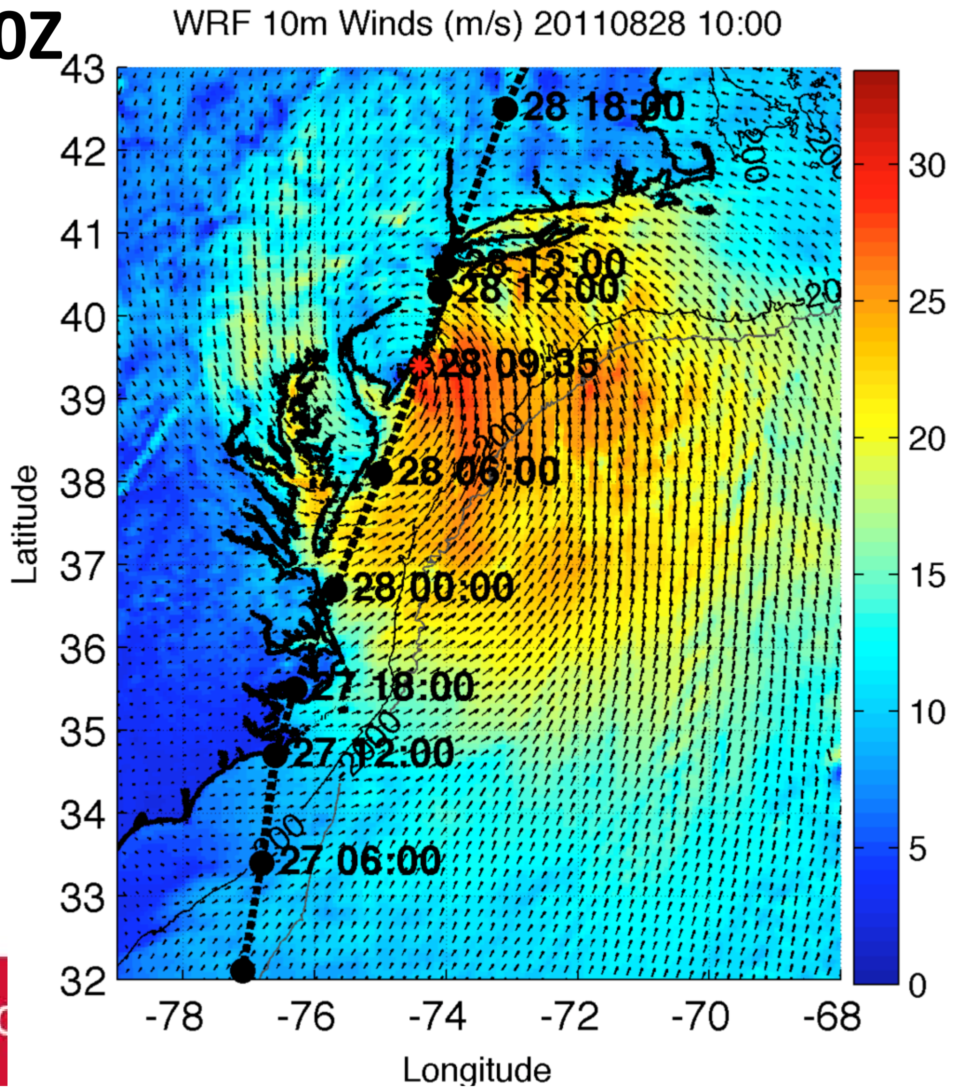
- hurricane track (use best boundary conditions);

06Z



WRF 10m Winds (m/s) 20110828 06:00

10Z



WRF 10m Winds (m/s) 20110828 10:00

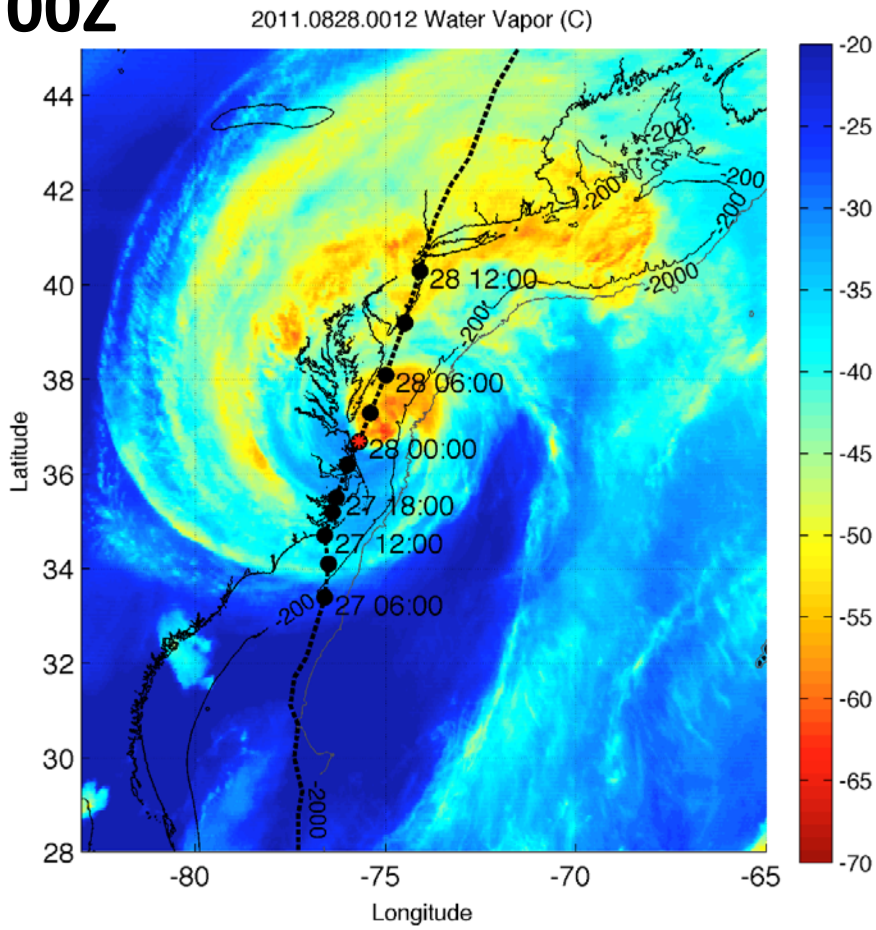
Hypothesis

We *hypothesize* that the models handled well:

- hurricane track (use best boundary conditions);
- vertical wind shear (TBD);
- dry air intrusion (TBD);

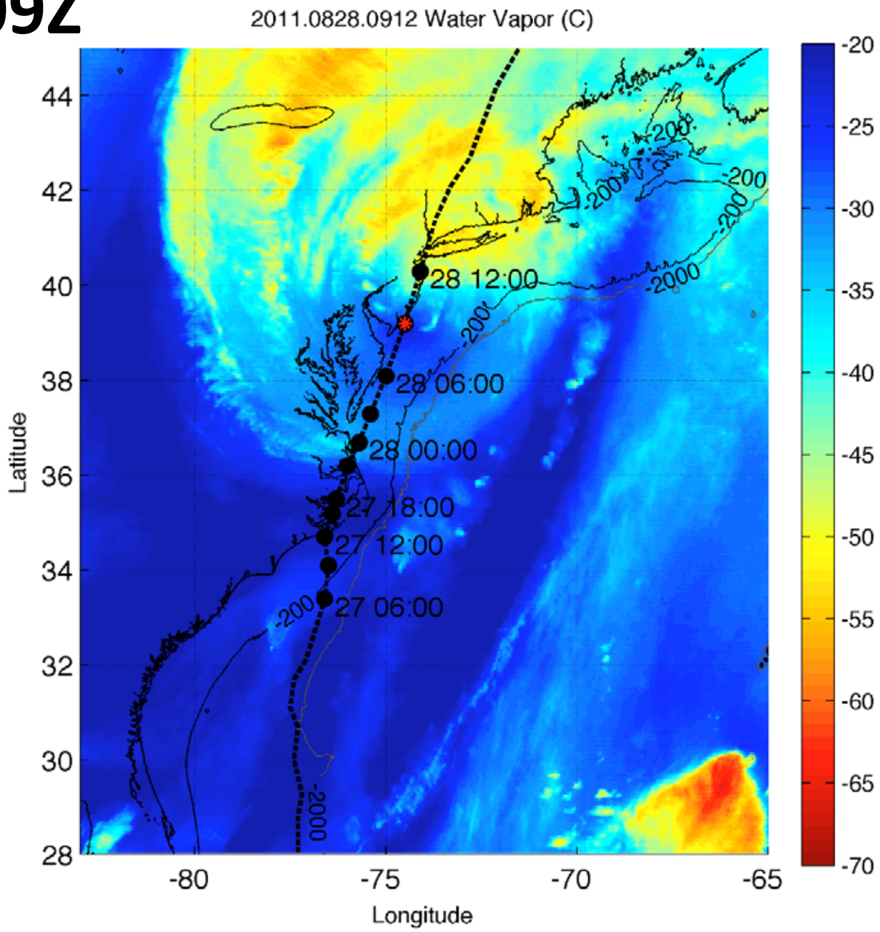
GOES 13 Channel 3

00Z



DTS, GLO

09Z



Hypothesis

We *hypothesize* that the models handled well:

- hurricane track (use best boundary conditions);
- vertical wind shear (TBD);
- dry air intrusion (TBD);

Some possible reasons:

- Models have improved considerably on predicting tracks
- Atmosphere tends to receive more attention in modeling
- Models resolve large-scale processes fairly well

But models handled poorly:

- upper ocean thermal structure and evolution

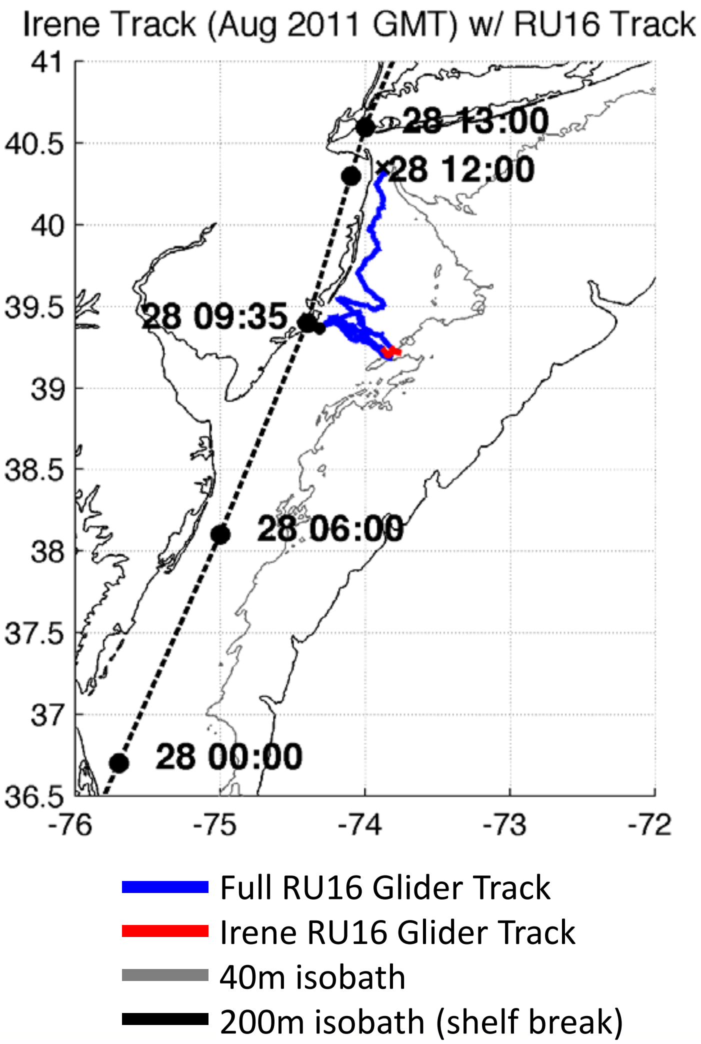
This talk aims to show the relative importance of ocean prediction for intensity forecasting of Hurricane Irene

Methods – Observations and Model

RU16 Glider: at 40m isobath, right of eye track

Satellite (“Rutgers SST”): 1km AVHRR 3-day *coldest dark pixel* SST composite (preserve cold wake); NASA SPoRT 2km SST for cloudy gaps

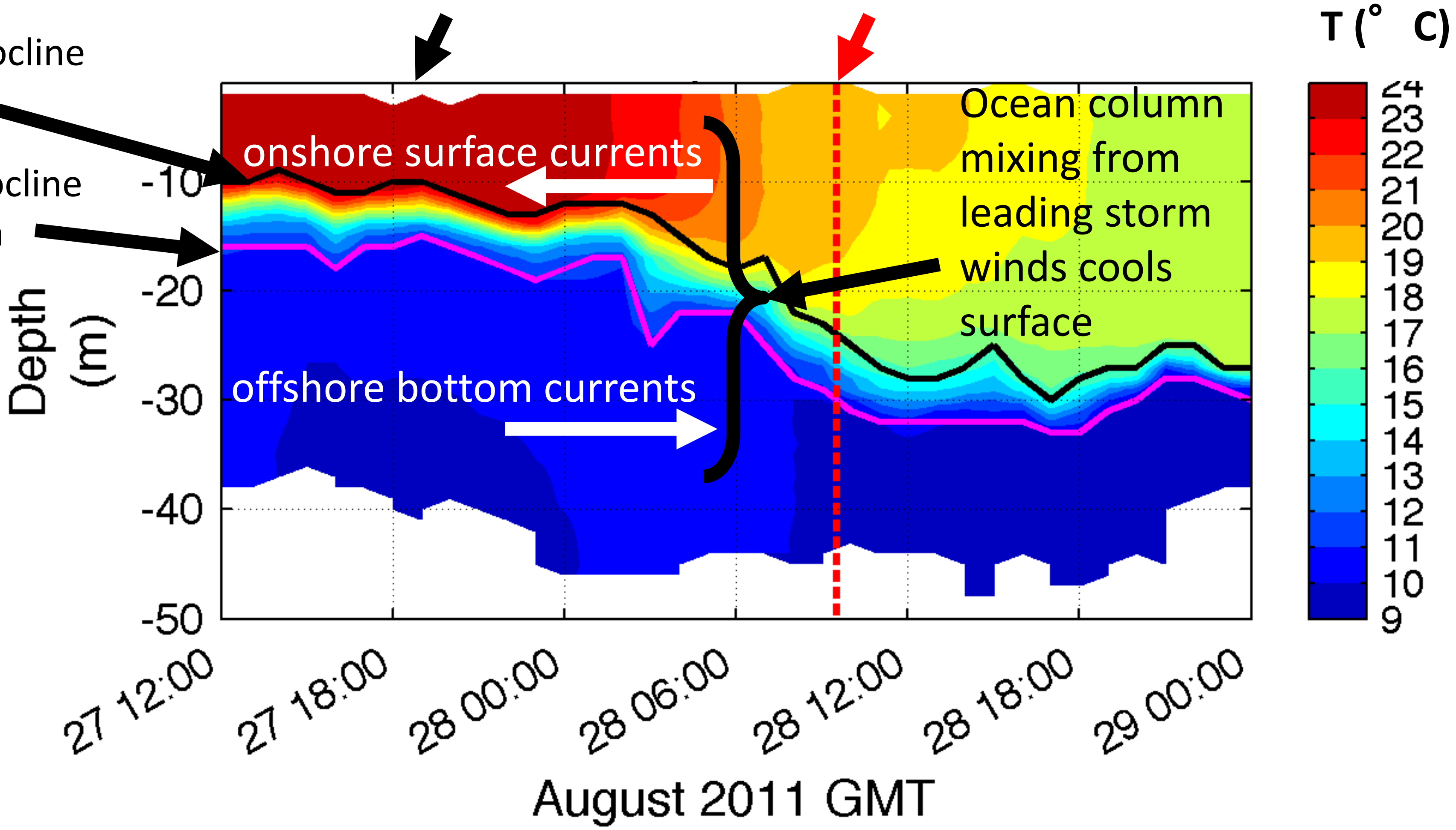
Model: 6km WRF-ARW, boundary conditions to get track correct (important because close to coast); no data assimilation



Results

1. Glider data revealed that ocean mixing and resulting surface cooling preceded the passage of the eye
2. Improved satellite SST product revealed that this surface ocean cooling was <u>not</u> captured by:
   - Basic satellite products
   - Ocean models used for forecasting hurricane intensity
3. Over 100 sensitivity tests showed that Hurricane Irene intensity is very sensitive to this “ahead-of-eye” SST cooling

1. Glider revealed “ahead-of-eye” cooling



warm SSTs before storm

passage of eye

thermocline top

thermocline bottom

onshore surface currents

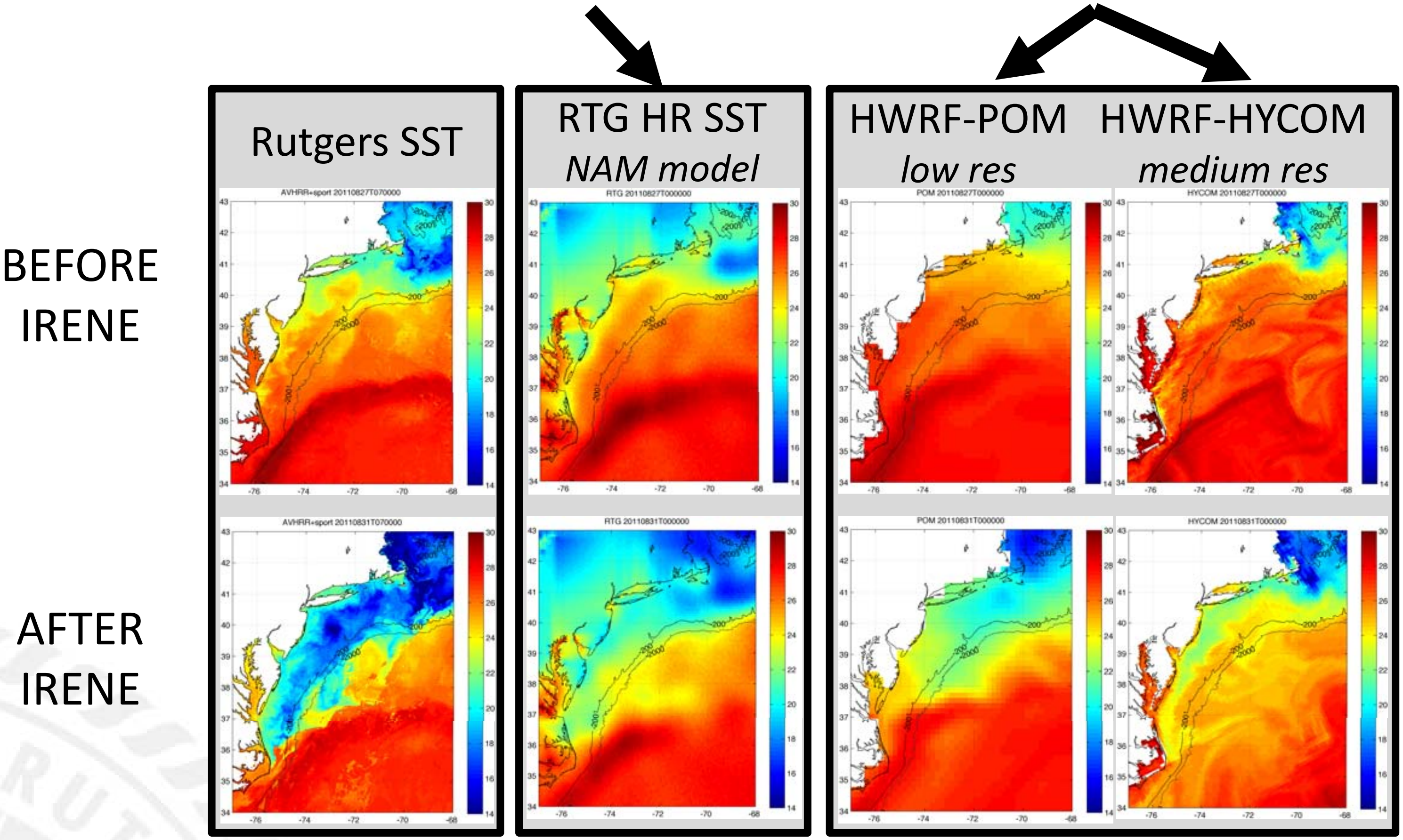
offshore bottom currents

Ocean column mixing from leading storm winds cools surface

2. Improved satellite SST product revealed that this cooling was not captured by:

basic satellite product

ocean models used for forecasting hurricane intensity



Rutgers SST

RTG HR SST
NAM model

HWRF-POM
low res

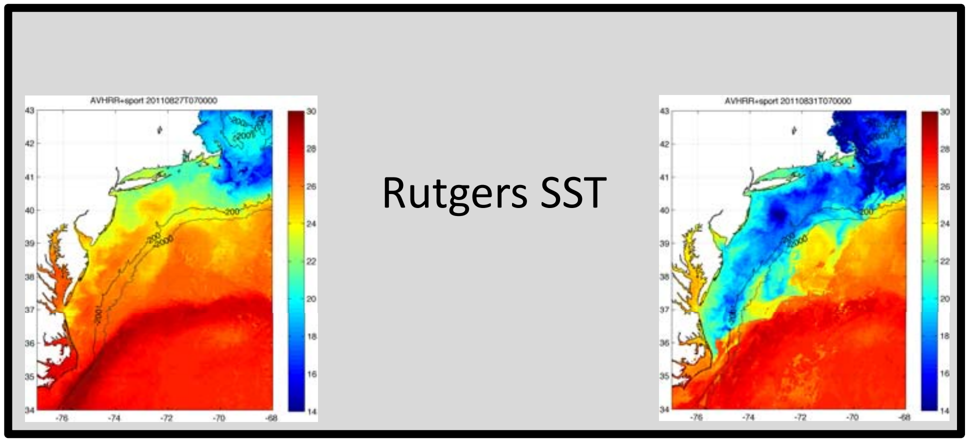
HWRF-HYCOM
medium res

BEFORE IRENE

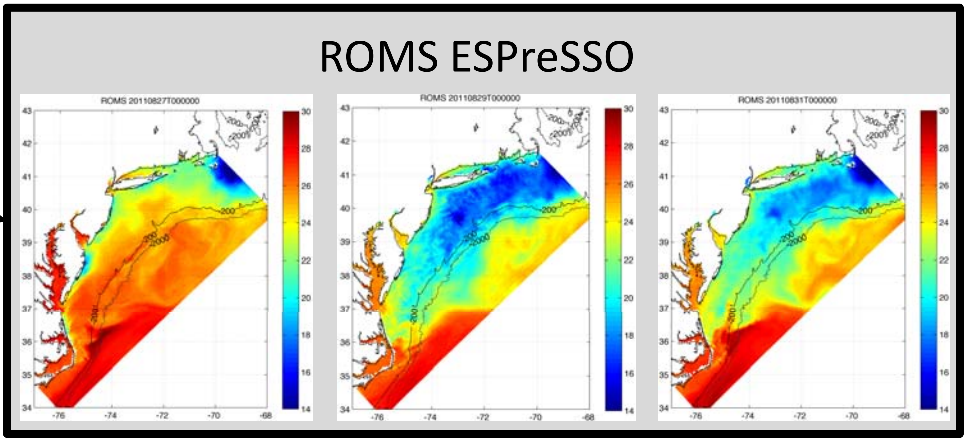
AFTER IRENE

2. However, cooling was captured by high res ocean models

Rutgers composite showed that cooler SSTs are captured relatively well by <u>high res coastal ocean models not specifically used for forecasting hurricanes</u>



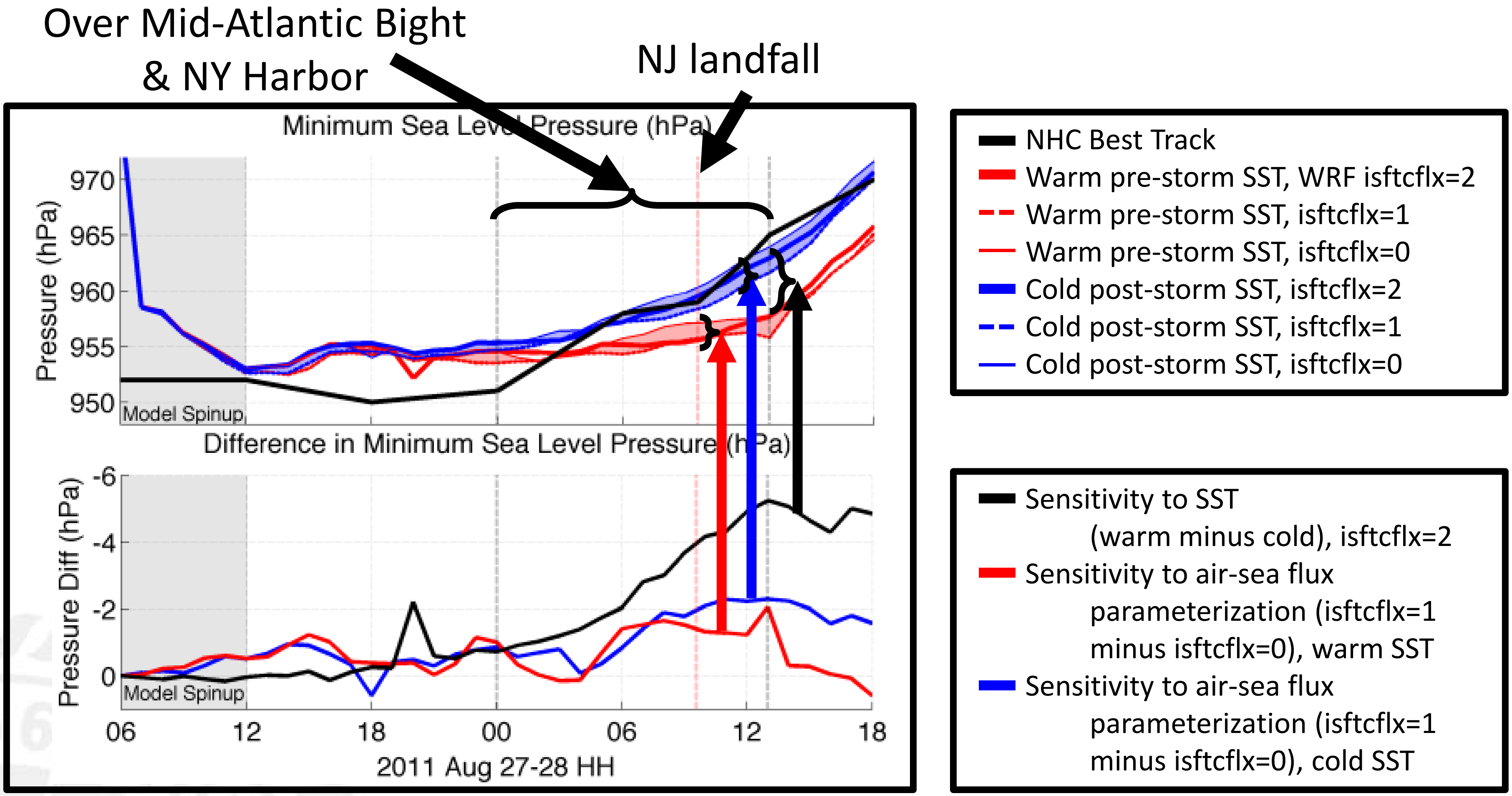
Rutgers SST



ROMS ESPreSSO

BEFORE RIGHT AFTER AFTER

3. >100 sensitivity tests showed Irene intensity very sensitive to this “ahead-of-eye” SST cooling



Conclusions

- Large majority of SST cooling occurred ahead of Irene’s eye
  - Glider observed coastal downwelling, which resulted in shear across thermocline, turbulence/entrainment, and finally surface cooling
- We determined max impact of this cooling on storm intensity (fixed cold vs. fixed warm SST)
  - One of the largest among tested model parameters
- Some surface cooling occurred during/after eye passage
  - Actual impact of SST cooling on storm intensity may be slightly lower
- A 1D ocean model cannot capture 3D coastal ocean processes resulting in important “ahead-of-eye” SST cooling
- A 3D high res ocean model (e.g. ROMS) nested in a synoptic ocean model could add significant value to tropical cyclone (TC) prediction in the coastal ocean—the last hours before landfall

Future work

- Improve model spin-up issues
- Validate wind shear and dry air intrusion
- Evaluate storm size and structure
- Compare modeled to observed heat fluxes (need air T, SST)
- Move towards accurate fully coupled WRF-ROMS system
    - WRF w/ hourly ROMS SST
    - WRF coupled w/ 3D Price-Weller-Pinkel ocean model
    - WRF-ROMS
- More case studies to quantify value of 3D ocean prediction to TC intensity forecasting, eventually across season(s)

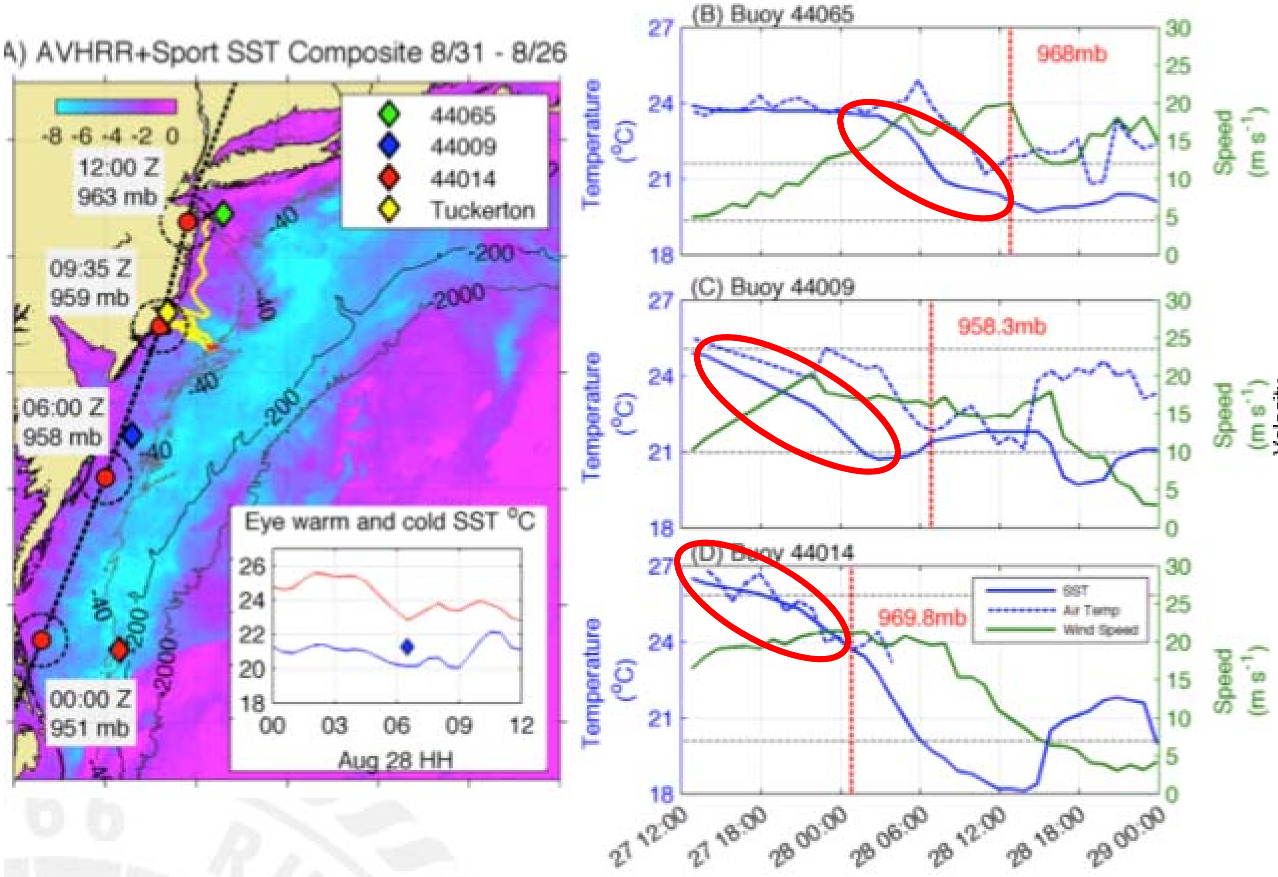
Thank You

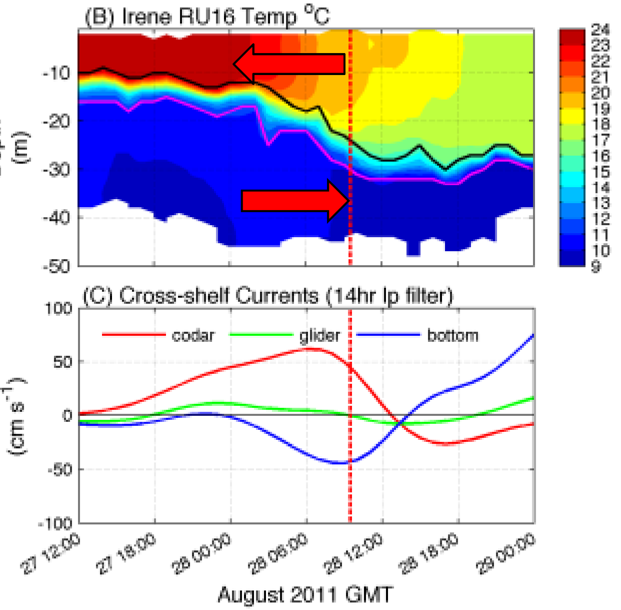
Extra Slides

Glider, buoy, and HF radar obs.

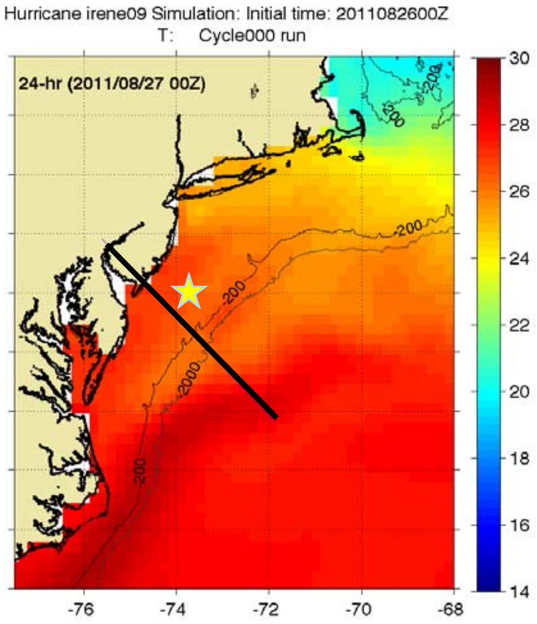
At surface

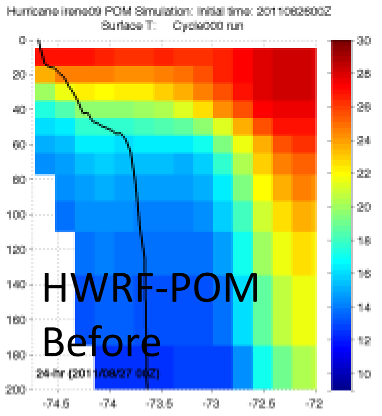
Below surface

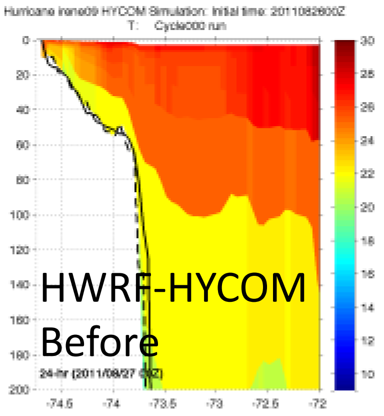


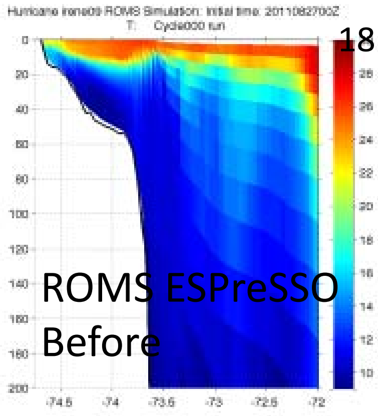


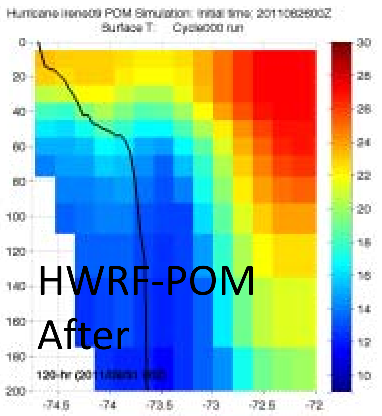
Cross-shelf Transects

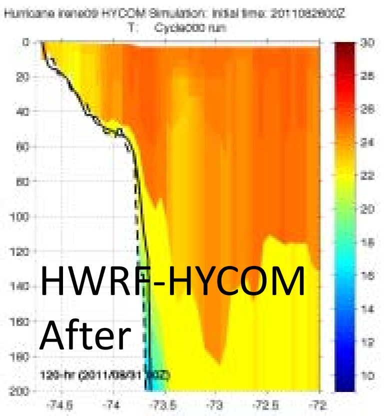


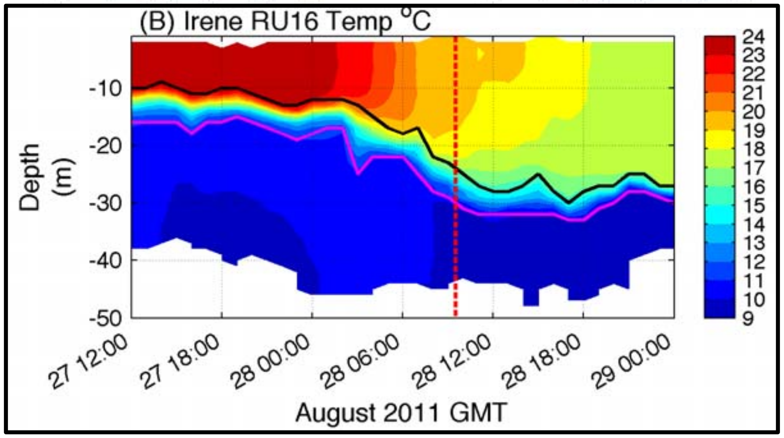












Observed bathymetry from NOAA National Geophysical Data Center, U.S. Coastal Relief Model, Retrieved date goes here, http://www.ngdc.noaa.gov/mgg/coastal/crm.html

Explanation of Air-Sea Flux Changes in WRF

- $\boldsymbol{\tau} = -\rho u_*^2 \quad = \boldsymbol{-\rho C_D U^2}$ momentum flux (τ)
- $\mathbf{H} = -\rho c_p u_* \theta_* = \boldsymbol{-(\rho c_p) C_H U \Delta\theta}$ sensible heat flux (H)
- $\mathbf{E} = -\rho L_v u_* q_* \quad = \boldsymbol{-(\rho L_v) C_Q U \Delta q}$ latent heat flux (E)

ρ: density of air
(u_*,θ_*,q_*): friction velocity, surface layer temperature and moisture scales
U: 10m wind speed
c_p: specific heat capacity of air, L_v: enthalpy of vaporization
$\Delta(\theta,q)$: temperature, water vapor difference between z_{ref}=10m and z=sfc

Our Changes in SST:

$\Delta\theta = \theta_{(2\text{ or }10m)} - \theta_{sfc}$ ($\theta \propto T$)
$\Delta q = q_{(2\text{ or }10m)} - q_{sfc}$
$\therefore \Delta(SST) \rightarrow \Delta\theta_{sfc} \rightarrow \Delta\theta \rightarrow \Delta H$
(sensible heat flux)
$\Delta(SST) \rightarrow$(indirectly)$\Delta q_{sfc} \rightarrow \Delta q \rightarrow \Delta E$
(latent heat flux)

In *neutrally stable* surface layer within TC eyewall (e.g. Powell et al. 2003):

- $\mathbf{C_D = k^2/[\ln(z_{ref}/z_0)]^2}$ drag coefficient
- $\mathbf{C_H = (C_D^{1/2}) \times [k/\ln(z_{ref}/z_T)]}$ sensible heat coefficient
- $\mathbf{C_Q = (C_D^{1/2}) \times [k/\ln(z_{ref}/z_Q)]}$ latent heat coefficient
- $\mathbf{C_k = C_H + C_Q}$ moist enthalpy coefficient

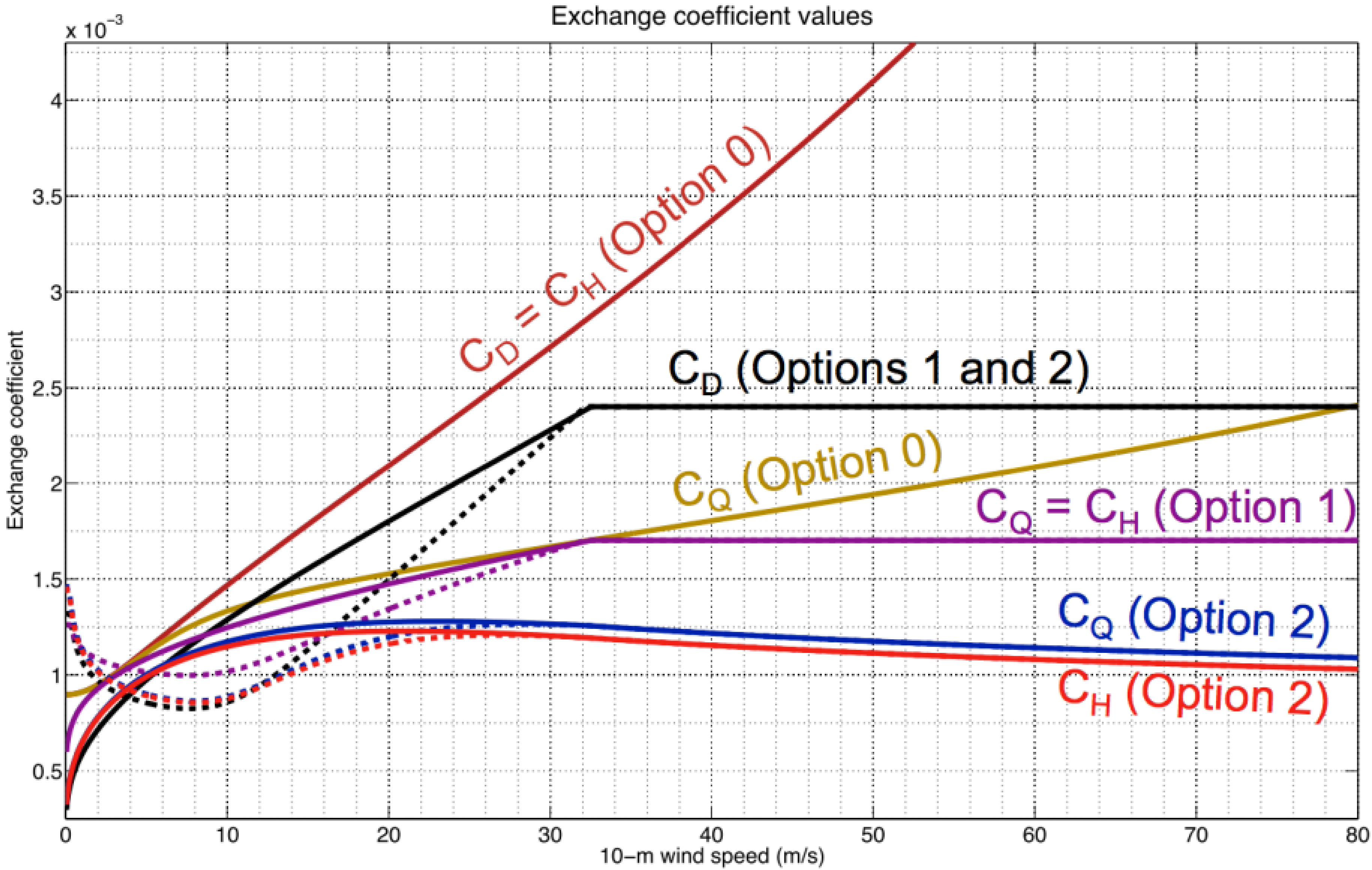
k: von Kármán constant
z_{ref}: (usually 10m) reference height

WRF isftcflx	**z_0: momentum roughness length**	**z_T: sensible heat roughness length**	**z_Q: latent heat roughness length**	**Dissipative heating?**
0	$z_0 = 0.0185u_*^2/g + 1.59E\text{-}5$ Charnock (1955)	z_0	$z_Q = (z_0^{-1} + ku_*K_a^{-1})^{-1}$ Carlson & Boland (1978)	No
1	See Green & Zhang (2013) for eq. Powell (2003), Donelan (2004)	10^{-4} m	10^{-4} m Large & Pond (1982)	Yes
2	Same as z_0 for Option 1 Powell (2003), Donelan (2004)	$z_T = z_0\exp[k(7.3Re_*^{1/4}Pr^{1/2}-5)]$ Brutsaert (1975)	$z_Q = z_0\exp[-k(7.3Re_*^{1/4}Sc^{1/2}-5)]$ Brutsaert (1975)	Yes

K_a= 2.4E-5 m^2s^{-1} (background molecular viscosity)
$Re_* = u_*Z_0/\nu$ (Roughness Reynolds number), Pr = 0.71 (Prandtl number), Sc = 0.6 (Schmidt number)

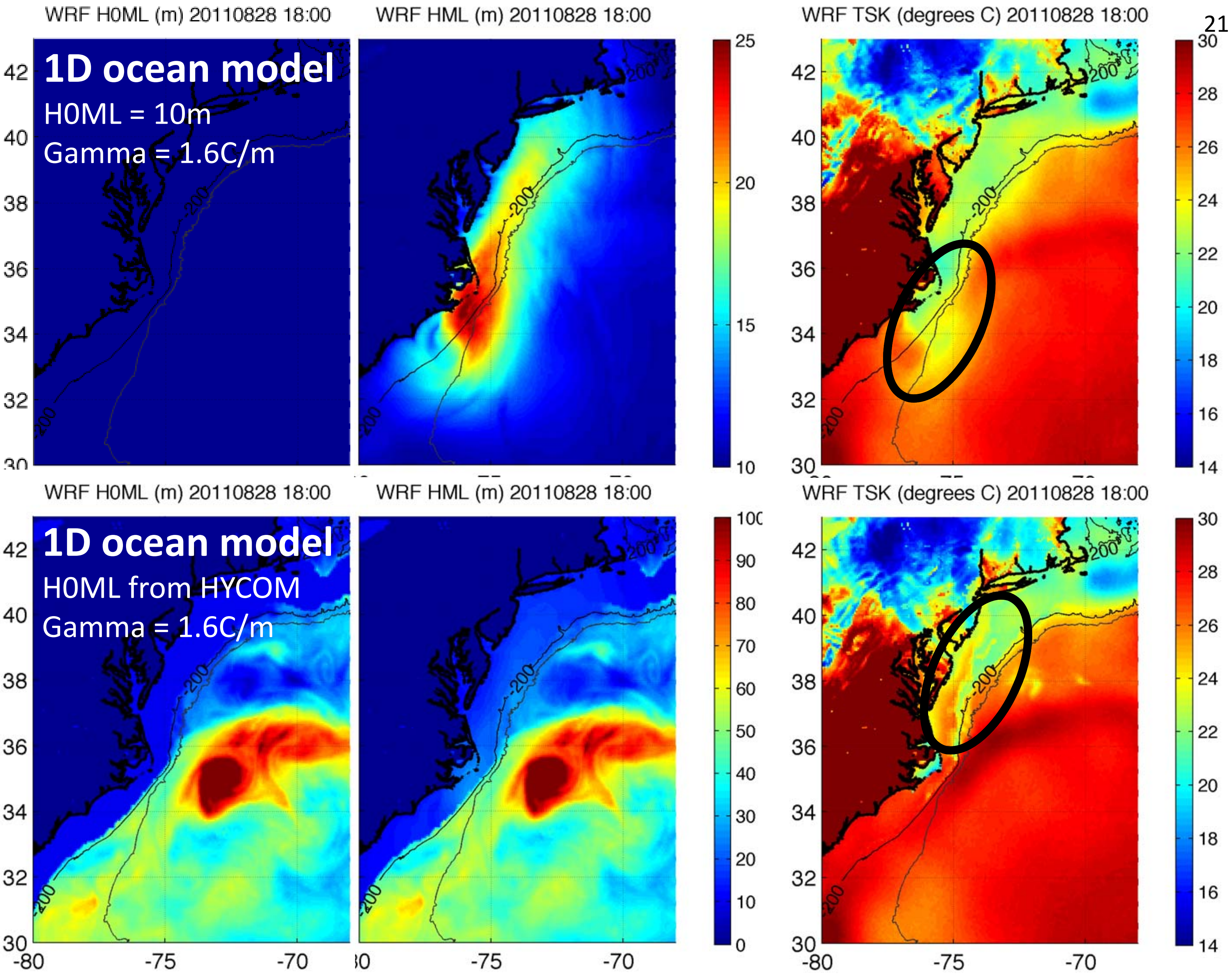
After Green & Zhang (2013)

Plot of Resulting Exchange Coefficients



Solid (dashed) lines: Formulas in V3.4 (V3.3.1) of WRF

After Zhang et al. (2012)
Presentation for HFIP



1D ocean model

H0ML = 10m

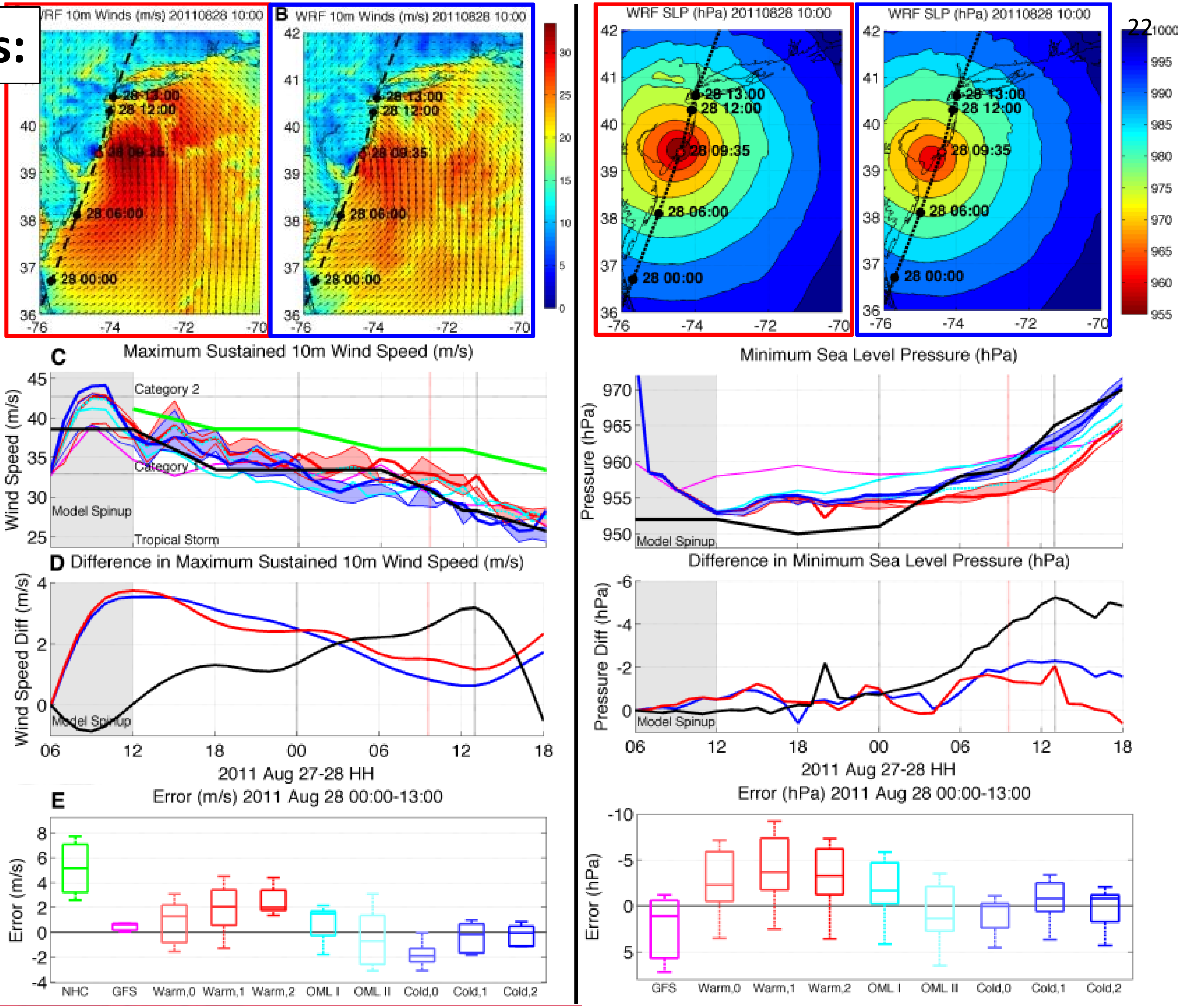
Gamma = 1.6C/m

1D ocean model

H0ML from HYCOM

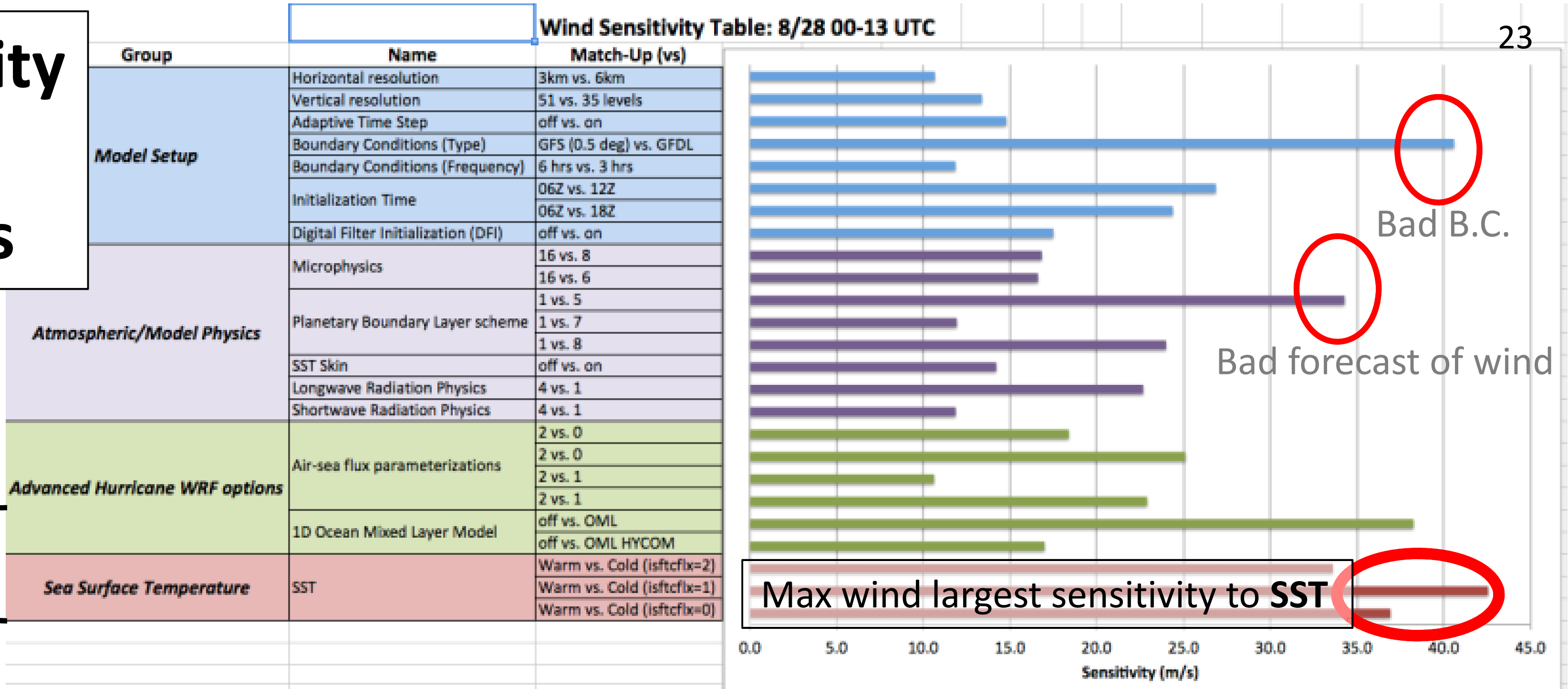
Gamma = 1.6C/m

Results:



A
WRF 10m Winds (m/s) 20110828 10:00
B
WRF 10m Winds (m/s) 20110828 10:00
28 13:00
28 12:00
28 09:35
28 06:00
28 00:00
42
41
40
39
38
37
36
-76
-74
-72
-70
30
25
20
15
10
5
0
WRF SLP (hPa) 20110828 10:00
WRF SLP (hPa) 20110828 10:00
1000
995
990
985
980
975
970
965
960
955
C
Maximum Sustained 10m Wind Speed (m/s)
Wind Speed (m/s)
45
40
35
30
25
Category 2
Category 1
Tropical Storm
Model Spinup
Minimum Sea Level Pressure (hPa)
Pressure (hPa)
970
965
960
955
950
Model Spinup
D
Difference in Maximum Sustained 10m Wind Speed (m/s)
Wind Speed Diff (m/s)
4
2
0
Model Spinup
06
12
18
00
06
12
18
2011 Aug 27-28 HH
Difference in Minimum Sea Level Pressure (hPa)
Pressure Diff (hPa)
-6
-4
-2
0
Model Spinup
2011 Aug 27-28 HH
E
Error (m/s) 2011 Aug 28 00:00-13:00
Error (m/s)
8
6
4
2
0
-2
-4
NHC
GFS
Warm,0
Warm,1
Warm,2
OML I
OML II
Cold,0
Cold,1
Cold,2
Error (hPa) 2011 Aug 28 00:00-13:00
Error (hPa)
-10
-5
0
5
GFS
Warm,0
Warm,1
Warm,2
OML I
OML II
Cold,0
Cold,1
Cold,2

Sensitivity tables: 110 runs



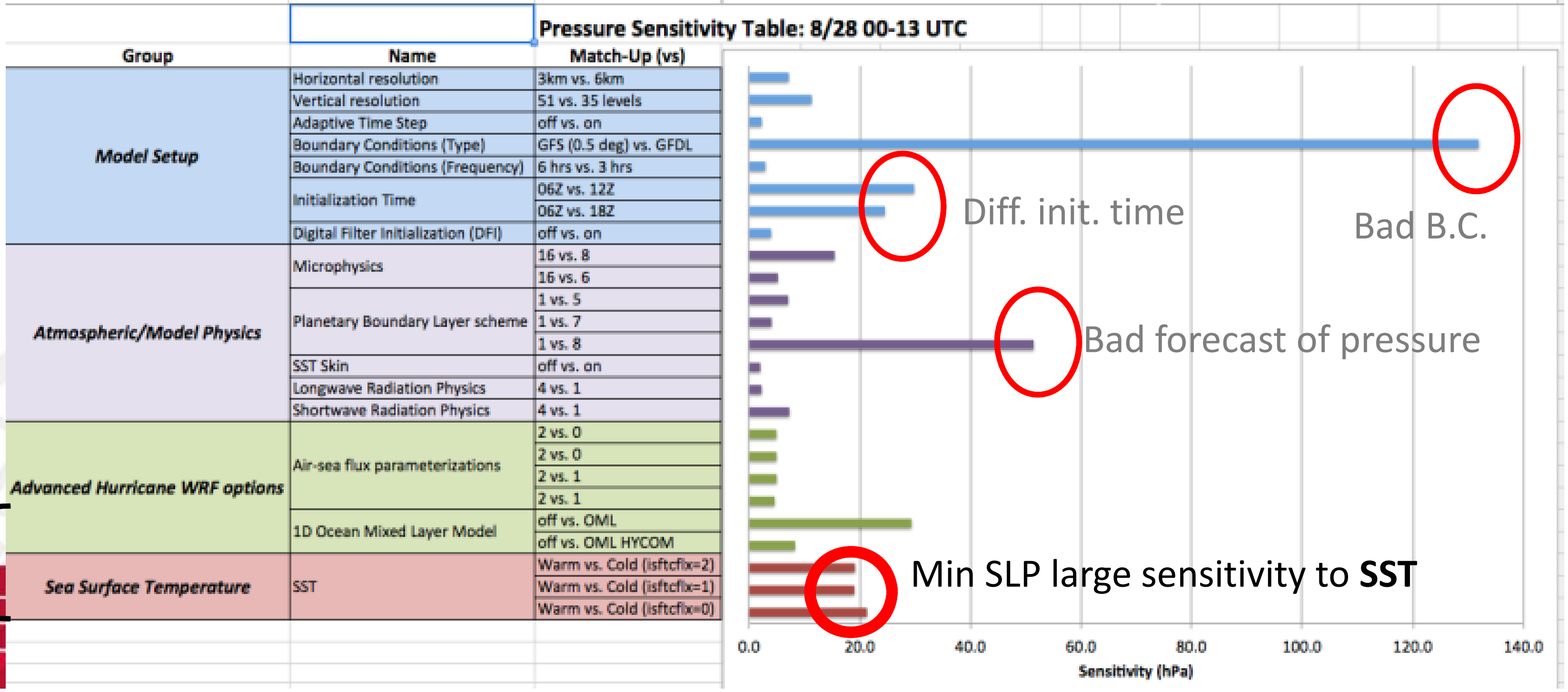
Wind Sensitivity Table: 8/28 00-13 UTC

Group	Name	Match-Up (vs)
Model Setup	Horizontal resolution	3km vs. 6km
	Vertical resolution	51 vs. 35 levels
	Adaptive Time Step	off vs. on
	Boundary Conditions (Type)	GFS (0.5 deg) vs. GFDL
	Boundary Conditions (Frequency)	6 hrs vs. 3 hrs
	Initialization Time	06Z vs. 12Z
		06Z vs. 18Z
	Digital Filter Initialization (DFI)	off vs. on
Atmospheric/Model Physics	Microphysics	16 vs. 8
		16 vs. 6
	Planetary Boundary Layer scheme	1 vs. 5
		1 vs. 7
		1 vs. 8
	SST Skin	off vs. on
	Longwave Radiation Physics	4 vs. 1
	Shortwave Radiation Physics	4 vs. 1
Advanced Hurricane WRF options	Air-sea flux parameterizations	2 vs. 0
		2 vs. 0
		2 vs. 1
		2 vs. 1
	1D Ocean Mixed Layer Model	off vs. OML
		off vs. OML HYCOM
Sea Surface Temperature	SST	Warm vs. Cold (isftcflx=2)
		Warm vs. Cold (isftcflx=1)
		Warm vs. Cold (isftcflx=0)

Bad B.C.

Bad forecast of wind

Max wind largest sensitivity to **SST**



Pressure Sensitivity Table: 8/28 00-13 UTC

Group	Name	Match-Up (vs)
Model Setup	Horizontal resolution	3km vs. 6km
	Vertical resolution	51 vs. 35 levels
	Adaptive Time Step	off vs. on
	Boundary Conditions (Type)	GFS (0.5 deg) vs. GFDL
	Boundary Conditions (Frequency)	6 hrs vs. 3 hrs
	Initialization Time	06Z vs. 12Z
		06Z vs. 18Z
	Digital Filter Initialization (DFI)	off vs. on
Atmospheric/Model Physics	Microphysics	16 vs. 8
		16 vs. 6
	Planetary Boundary Layer scheme	1 vs. 5
		1 vs. 7
		1 vs. 8
	SST Skin	off vs. on
	Longwave Radiation Physics	4 vs. 1
	Shortwave Radiation Physics	4 vs. 1
Advanced Hurricane WRF options	Air-sea flux parameterizations	2 vs. 0
		2 vs. 0
		2 vs. 1
		2 vs. 1
	1D Ocean Mixed Layer Model	off vs. OML
		off vs. OML HYCOM
Sea Surface Temperature	SST	Warm vs. Cold (isftcflx=2)
		Warm vs. Cold (isftcflx=1)
		Warm vs. Cold (isftcflx=0)

Diff. init. time

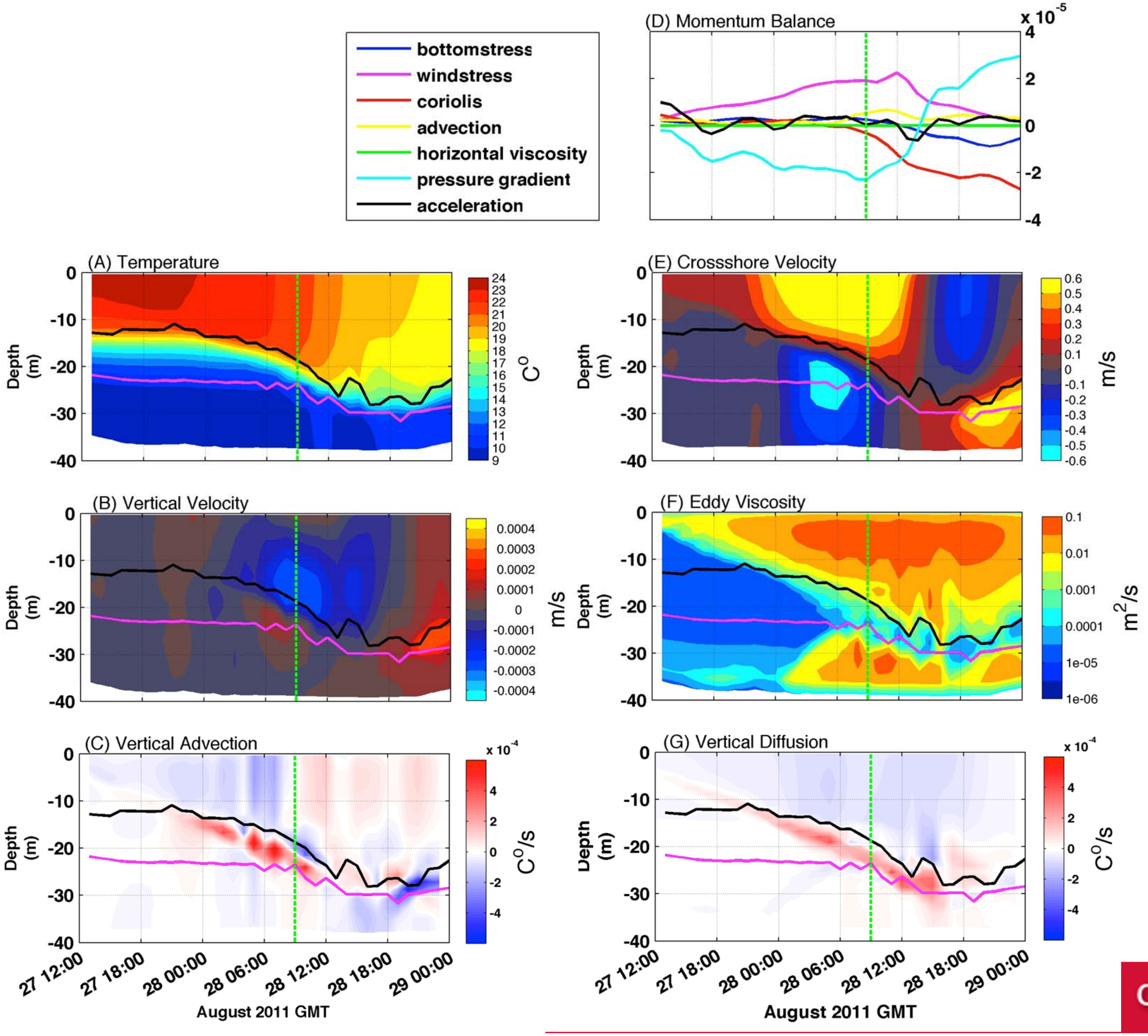
Bad B.C.

Bad forecast of pressure

Min SLP large sensitivity to **SST**

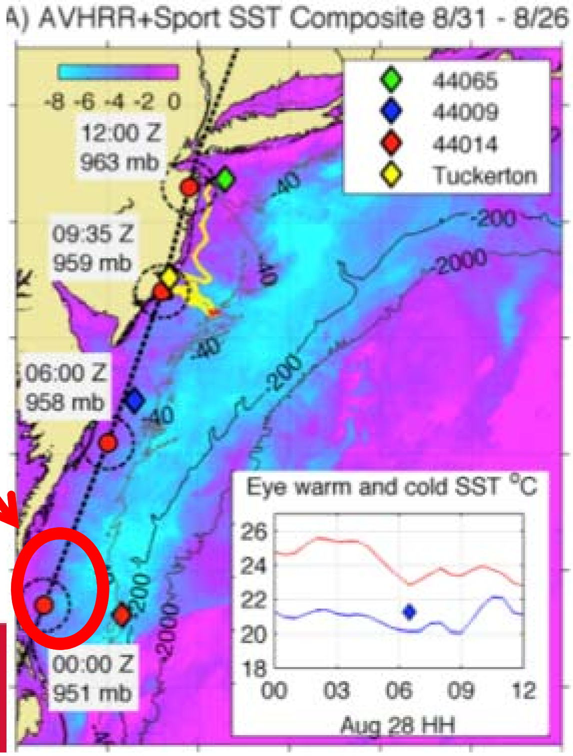
Parameterized
Upper Ocean
Heat Content

ROMS simulation results



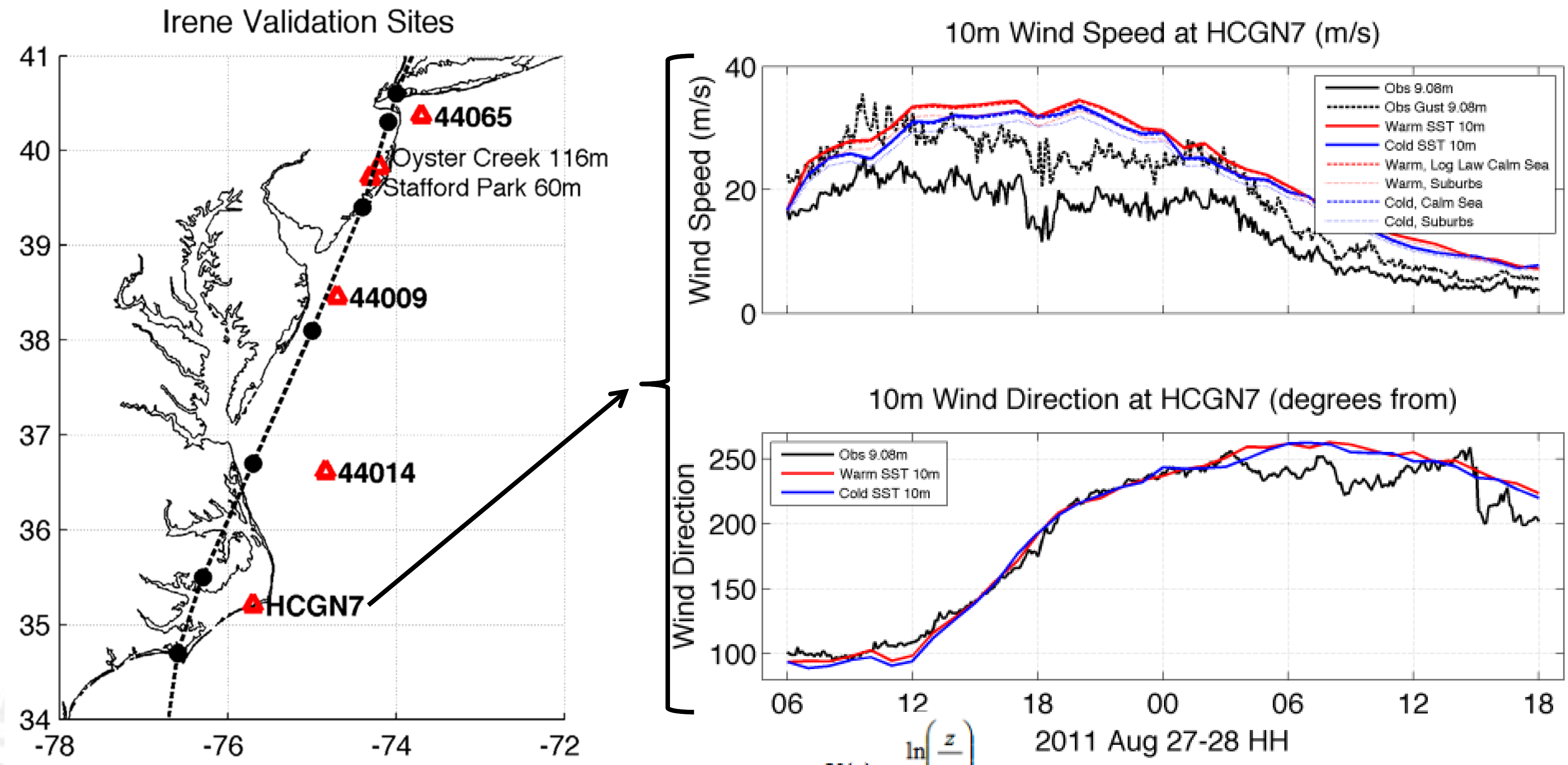
Simple Uncoupled WRF Hindcast Sensitivities:
SST Setup

- Modify SST input to “simulate” SST cooling:
  - – From fixed warm pre-storm SST (e.g. NAM, GFS) to what?
- 2 methods to determine optimal timing of SST cooling:
  1. **When did models show mixing in southern MAB?**
  2. **When did “critical mixing” wind speed occur in southern MAB?** *(Critical mixing w.s. = w.s. observed at buoys and modeled at glider when sea surface cooled).* ***Assumes similar stratification across MAB.***



- **Cooling Time = 8/27 ~10:00 UTC**
- Model Init. Time = 8/27 06:00 UTC
- **∴ Used fixed cold post-storm SST**

Model Validation



$$\frac{U(z)}{U(z_r)} = \frac{\ln\left(\frac{z}{z_o}\right)}{\ln\left(\frac{z_r}{z_o}\right)}$$

Ray et al. (2006)

- Height 9.08m (obs) vs. 10m (WRF) [log law]
- Averaging time 2-min (land stations)*, 8-min (buoys) vs. instantaneous (WRF) [obs gusts]
- Validate at 44014, 44009, 44065, and tall met towers (for boundary layer shear profile- NHC indicated it as large during Irene)

*OYC: 15-min, Stafford Park: 10- and 60-min

Model Validation