NC STATE UNIVERSITY

USGS
science for a changing world

An Integrated Ocean Environmental Prediction System: Implementation and Examples

Ruoying He[1], John Warner[2]

Joe Zambon[1], Maitane Olabarrieta[2], George Xue[1]
Jill Nelson[1], Brandy Armstrong[2]

[1] Dept. of Marine, Earth & Atmospheric Sciences
North Carolina State University

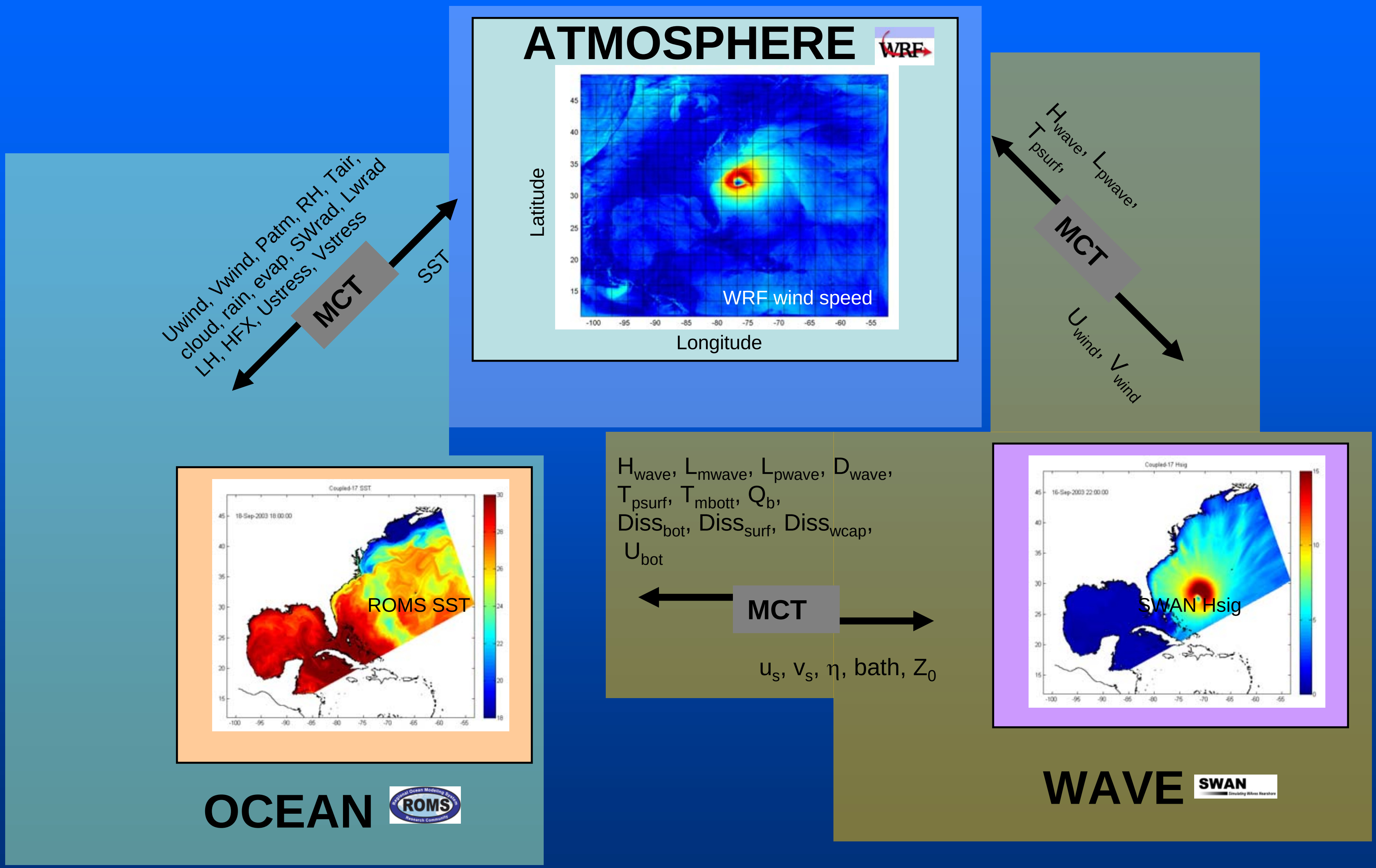
[2] US Geological Survey
Woods Hole, MA

COAWST

Coupled Ocean– Atmosphere – Wave – Sediment Transport Modeling System to investigate variability of coastal environments.

C = Coupled	MCT v 2.6.0	http://www-unix.mcs.anl.gov/mct/
O = Ocean	ROMS svn 455	http://www.myroms.org/
A = Atmosphere	WRF v 3.2.1	http://www.wrf-model.org/
W = Wave	SWAN v 40.81	http://vlm089.citg.tudelft.nl/swan
ST = Sediment Transport	CSTMS	http://woodshole.er.usgs.gov/project-pages/sediment-transport/

Modeling System

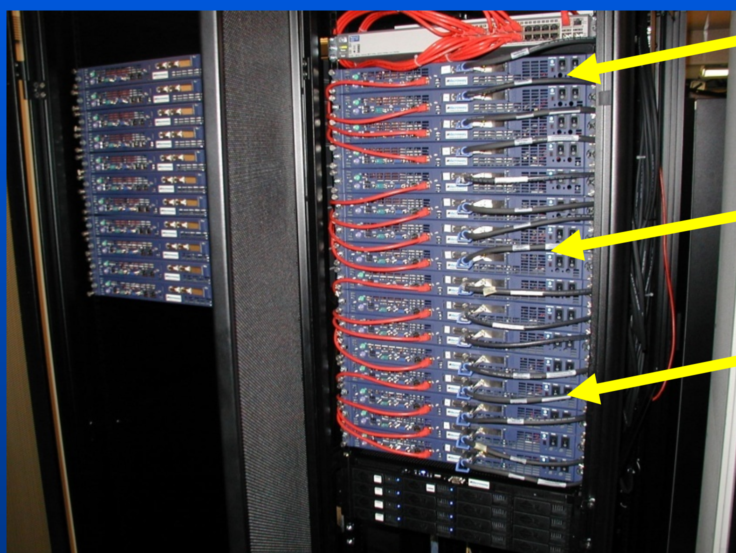

ATMOSPHERE
WRF
Latitude
Longitude
WRF wind speed
Uwind, Vwind, Patm, RH, Tair,
cloud, rain, evap, SWrad, Lwrad
LH, HFX, Ustress, Vstress
MCT
SST
H_{wave}, L_{pwave},
T_{psurf},
MCT
U_{wind}, V_{wind}
H_{wave}, L_{mwave}, L_{pwave}, D_{wave},
T_{psurf}, T_{mbott}, Q_b,
$Diss_{bot}$, $Diss_{surf}$, $Diss_{wcap}$,
U_{bot}
MCT
u_s, v_s, η, bath, Z_0
ROMS SST
OCEAN
ROMS
SWAN Hsig
WAVE
SWAN

Coupled Modeling System

Model Coupling Toolkit

Mathematics and Computer Science Division Argonne National Laboratory
http://www-unix.mcs.anl.gov/mct/

MCT is an open-source package that provides MPI based communications between all nodes of a distributed memory modeling component system. Download and compile as libraries that are linked to.



Model A running on M nodes.

Model B running on N nodes.

Model C ....

....

MCT provides communications between all models.

(it also works here)

Warner, J.C., Perlin, N., and Skyllingstad, E. (2008). Using the Model Coupling Toolkit to couple earth system models. Environmental Modeling and Software

ATM Impact on OCN

#define ATM2OCN_FLUXES

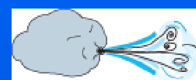
Use momentum + heat fluxes computed in WRF for both ROMS+WRF

Ustress, Vstress,
Swrad, Lwrad
LH, HFX

or

#define BULK_FLUXES

Use wrf vars in COARE algorithm



Uwind, Vwind
Swrad, Lwrad,
RH, Tair, cloud

LH + HFX computed in bulk_fluxes

Salt flux

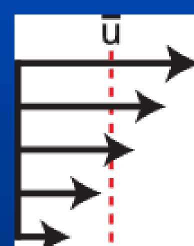
#define EMINUSP

rain,
evap

stflx_salt = evap - rain

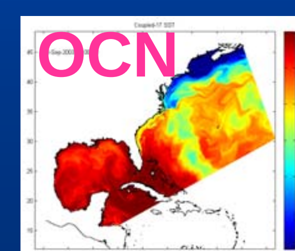
#define ATM_PRESS - Patm

stflx_temp = Swrad+Lwrad +LH+HFX

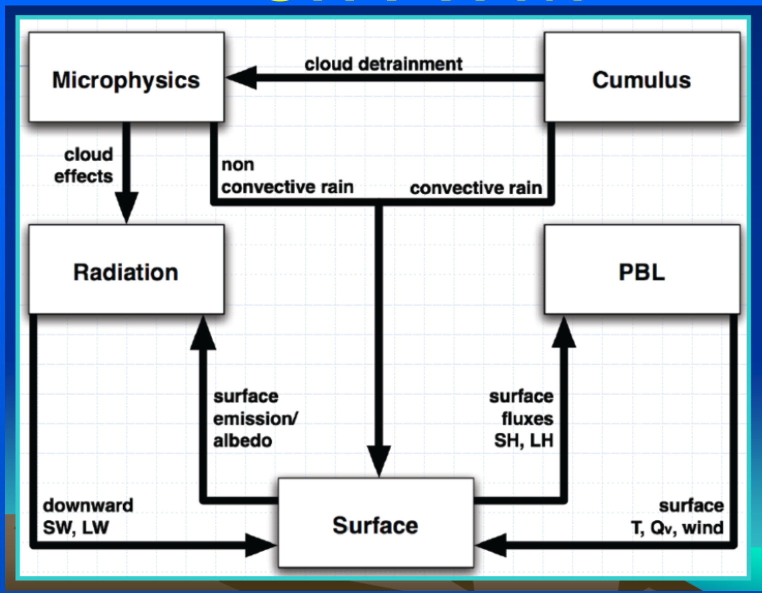


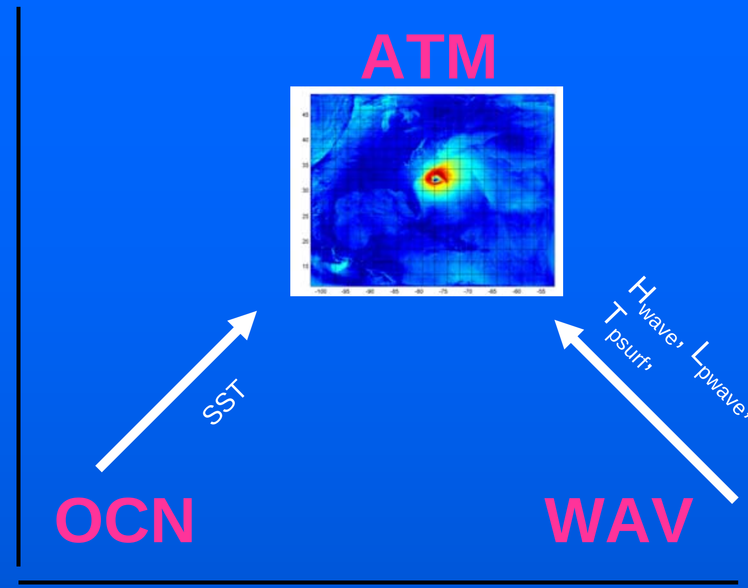
ATM

Uwind, Vwind, Patm, RH, Tair,
cloud, rain, evap, SWrad, Lwrad
LH, HFX, Ustress, Vstress



OCN & WAV Impact on ATM





SST **OCN**

Surface fluxes

Momentum
Heat
Moisture

$$F_m = C_m |\vec{V_{SL}}|^2 ,$$
$$F_h = \rho_1 c_p C_{hq} (\theta_{sk} - \theta_1) ,$$
$$F_q = \rho_1 L C_{hq} M (q_{vsk} - q_{v1}) .$$

$$|\vec{V_{SL}}|^2 = u^2 + v^2$$

C_m is the exchange coefficient for momentum and is expressed as

$$C_m = \frac{u_*^2}{|\vec{V_{SL}}|^2} .$$

C_{hq} is the exchange coefficient valid for both heat and water vapor as

$$C_{hq} = u_* \kappa \left[\psi_h\left(\frac{z}{L_{MO}}\right) - \psi_h\left(\frac{z_{0T}}{L_{MO}}\right) + \ln\left(\frac{z}{z_{0T}}\right)\right]^{-1} ,$$

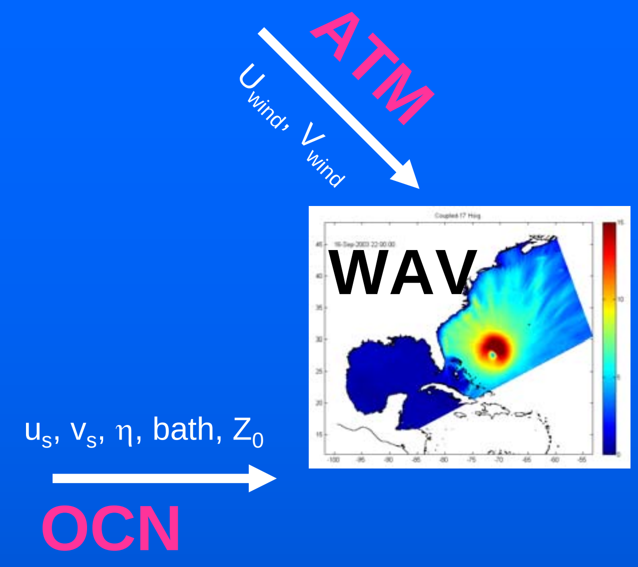
u_* is the friction velocity and is expressed as

$$u_* = \kappa |\vec{V_{SL}}| \left[\psi_m\left(\frac{z}{L_{MO}}\right) - \psi_m\left(\frac{z_{0m}}{L_{MO}}\right) + \ln\left(\frac{z}{z_{0m}}\right)\right]^{-1}$$

$$z_{0m} = f (H_{wave}, L_{pwave}, T_{psurf})$$

WAV

ATM & OCN impact on WAV



$$\frac{\partial N}{\partial t}+\frac{\partial c_x N}{\partial x}+\frac{\partial c_y N}{\partial y}+\frac{\partial c_\sigma N}{\partial \sigma}+\frac{\partial c_\theta N}{\partial \theta}=\frac{S_w}{\sigma}$$

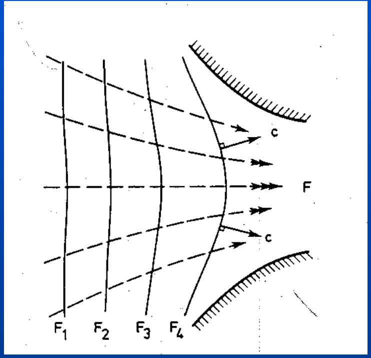
1) **Generation** – wind speed forcing is modified by ocean currents:

$S(w) = f(\, U_{wind} - u_s \;;\; V_{wind} - v_s \,)$

2) **Propagation**

– wave celerity in geographic space is modified by ocean currents

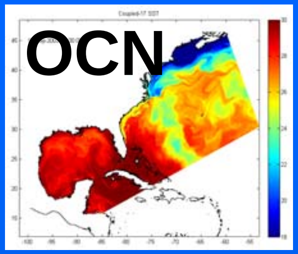
$$c_x = c_{gx} + u_s \;,\; c_y = c_{gy} + v_s$$



– wave celerity in frequency and direction spaces are dependent on η, bathy, and currents

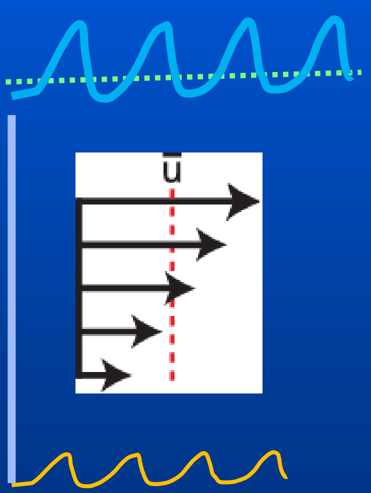
$$C_{g,\theta}=\frac{\sigma}{\sinh(2kh)}\left(\frac{\partial h}{\partial x}\sin\theta-\frac{\partial h}{\partial y}\cos\theta\right)+\cos\theta\left(\frac{\partial U}{\partial x}\sin\theta-\frac{\partial U}{\partial y}\cos\theta\right)+\sin\theta\left(\frac{\partial V}{\partial x}\sin\theta-\frac{\partial V}{\partial y}\cos\theta\right)$$

WAV impact on OCN



H_{wave}, L_{mwave}, L_{pwave}, D_{wave}, T_{psurf}, T_{mbott}, Q_b, $Diss_{bot}$, $Diss_{surf}$, $Diss_{wcap}$, U_{bot}

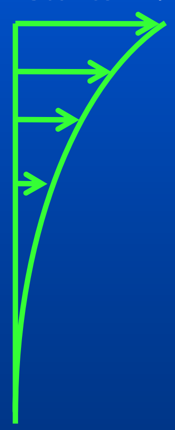
WAVE



#define WEC_VF

Water column

Stokes + VF



H_{wave}, L_{mwave}, D_{wave}, T_{psurf}, Q_b, $Diss_{bot}$, $Diss_{surf}$, $Diss_{wcap}$,

#define CRAIG_BANNER
#define CHARNOK
or
#define ZOS_HSIG
#define TKE_WAVEDISS

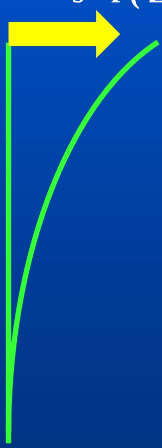
Surface tke flux

H_{wave}, L_{pwave}, D_{wave}, T_{psurf},

#define COARE_OOST
#define COARE_TAYLOR_YELLAND
#define DRENNAN
CRAIG_BANNER (default)

Surface stress

$\tau_s = f(Z_{os})$

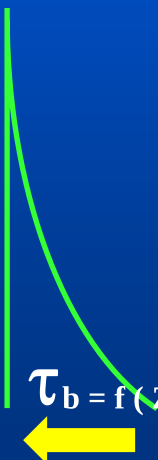


H_{wave}, L_{pwave}, D_{wave}, T_{psurf},

#define SSW_BBL

Bottom stress

Zoa



$\tau_b = f(Z_{ob})$

H_{wave}, L_{mwave}, D_{wave}, T_{mbott}, U_{bot}

WAV impact on ATM

SURFACE ROUGHNESS CLOSURE MODELS

$H_s =$ significant wave height

$z_0 =$ ocean surface roughness

$u_* =$ wind friction velocity

$C_p =$ peak wave celerity

$L_p =$ peak wave length

$\frac{u_*}{C_p} =$ wave age

CHARNOCK 1955 (default)

$$z_{0m} = \frac{0.011(u_*)^2}{g}$$

TAYLOR & YELLAND 2001: TY2001 (#define COARE_TAYLOR_YELLAND)

$$\frac{z_{0m}}{H_s} = 1200\left(H_s/L_p\right)^{4.5}$$

- *Wave steepness based parameterization.*
- *Based on three datasets representing sea-state conditions ranging from strongly forced to shoaling.*

DRENNAN 2003: DGQH (#define DRENNAN)

$$\frac{z_{0m}}{H_s} = 3.35\left(u_*/C_p\right)^{3.4}$$

- *Wave age based formula to characterize the ocean roughness.*
- *They combined data from many field experiments representing a variety of condition and grouped the data as a function of the wind friction velocity.*

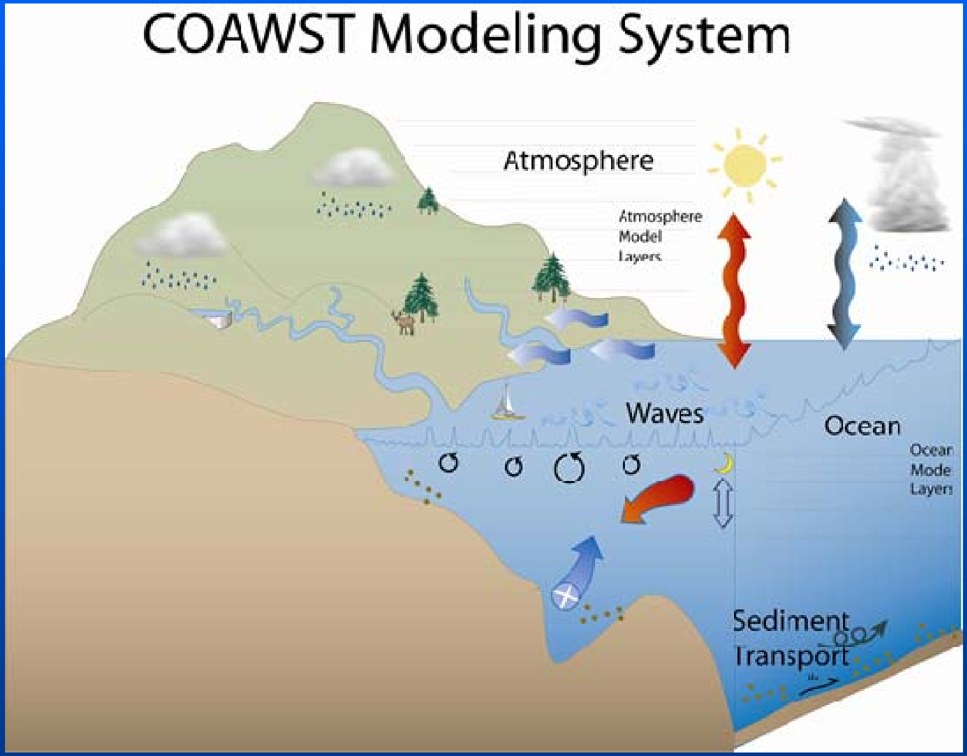
OOST 2002: OOST (#define COARE_OOST)

$$\frac{z_{0m}}{L_p} = \frac{25.0}{\pi}\left(u_*/C_p\right)^{4.5}$$

- *Wave age dependent formula but it also considers the effect of the wave steepness.*

Sediment Transport Components

John Warner, Chris Sherwood and Alfredo Aretxabaleta

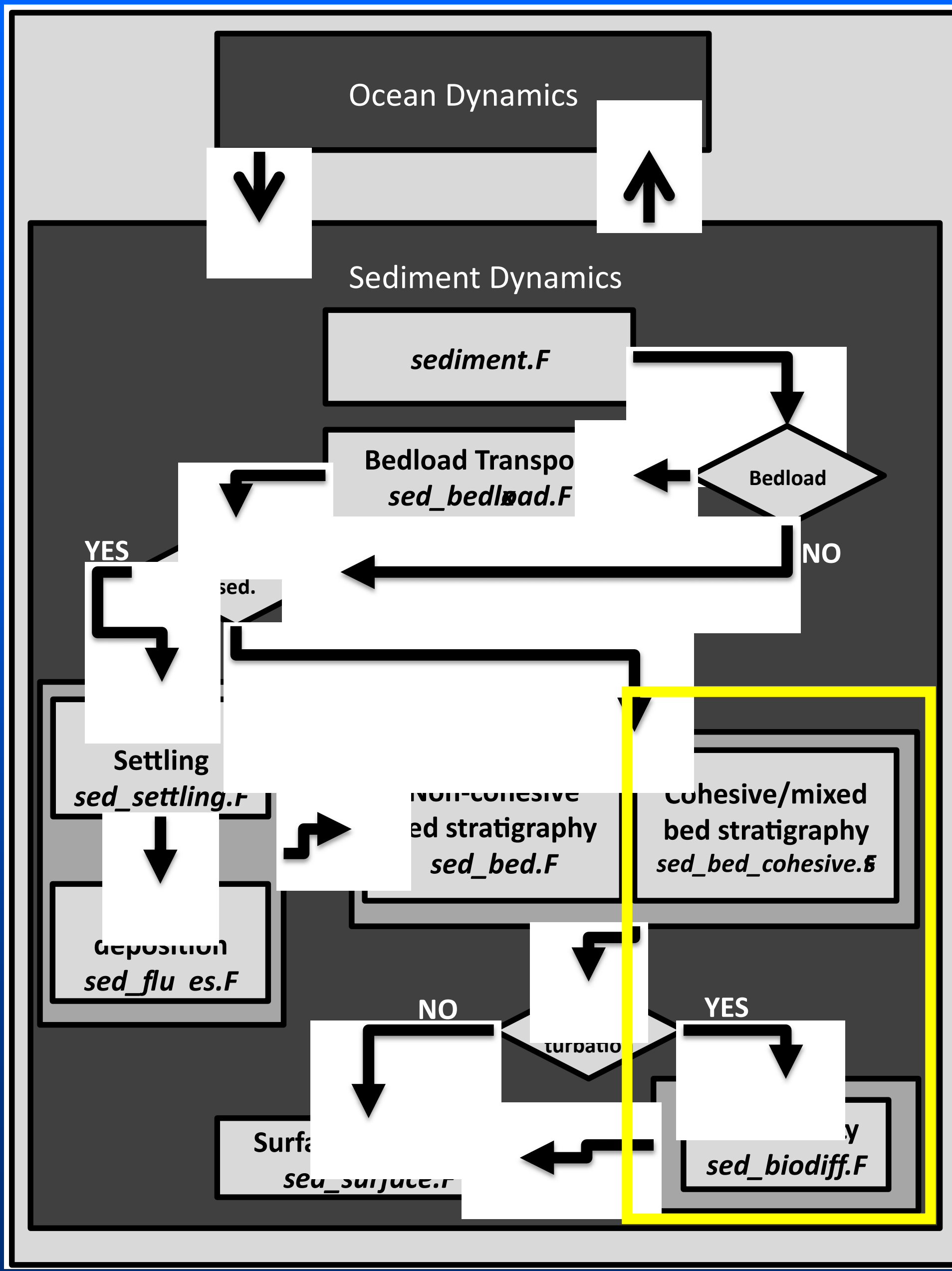


Contributions to cohesive code from Courtney Harris and J. Paul Rinehimer

Sediment Transport Components

- MPDATA – Positive-definite advection scheme
- Sediment influence on density
- Wave input (specified, or SWAN, 1- or 2-way coupled)
- Wave-current combined bottom stresses
- Erosion / deposition / bed model (sand, mud, or mixed)
- Settling
- Bedload transport and flux divergence
- Morphological evolution
- Wetting and drying

CSTMS Evolution



Current released version of ROMS:

- No cohesive behavior
- No bioturbation

New developments:

- Cohesive/mixed bed
- Biodiffusion
- Altered stratigraphy

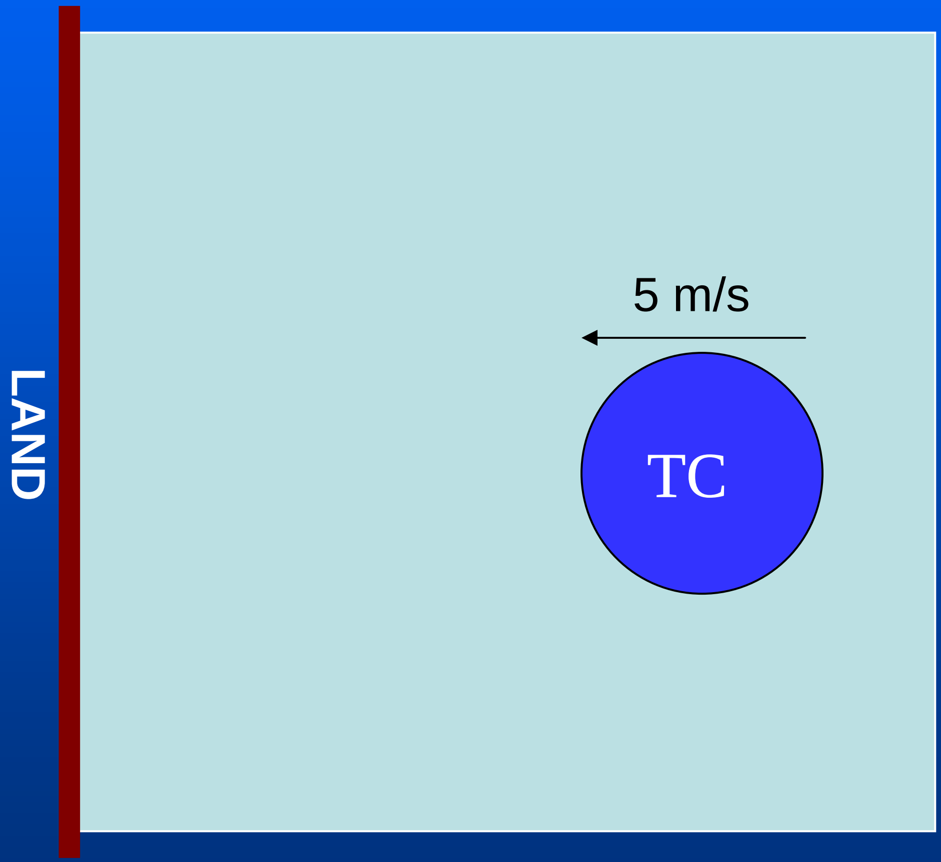
Examples

- Idealized Tropical Cyclone
- Hurricane Ivan
- Hurricane Irene
- Winter extratropical storm
- Sediment transport
- Quasi-operational system

Example 1: Idealized TC

- Closed ocean basin
- 200 points in X, 150 in Y
- 12 km grid spacing among all 3 models
- Run from 1-6 September (00Z)

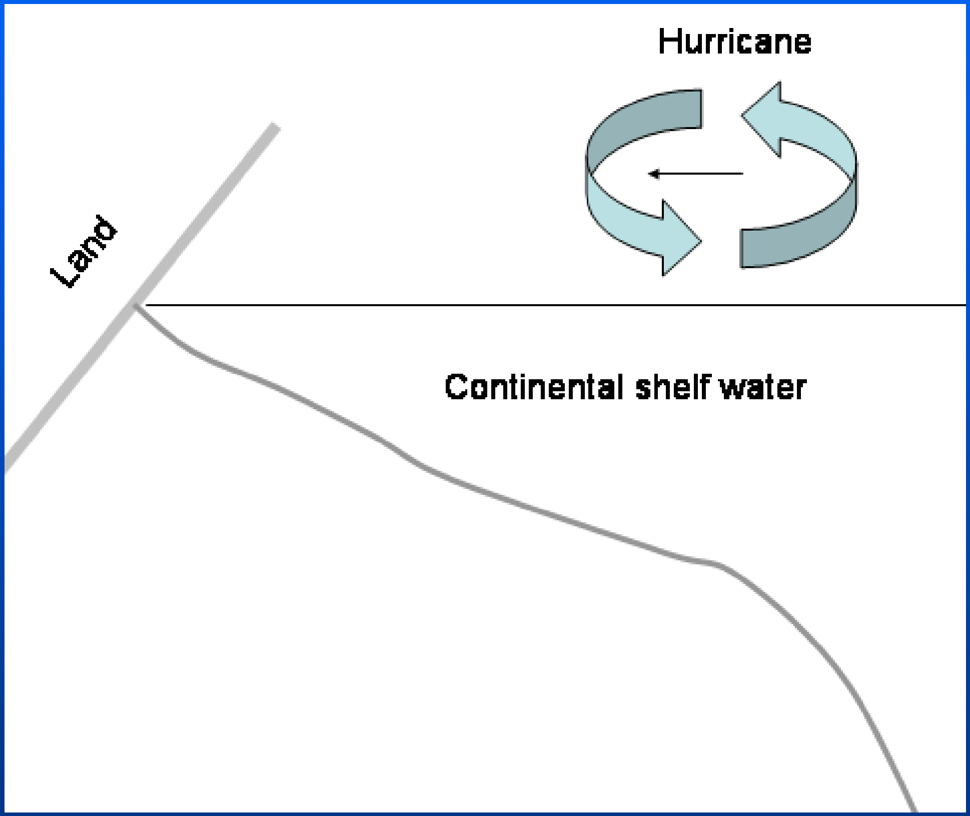
- TC located at X=150, Y=75
- Moving westward at 5 m s^{-1} (background wind field)
- Bathymetry along X:
  - 50-69, dz/dx = -10m/12km
  - 70-89, dz/dx = -40m/12km
  - 90-197, z = 1000m



Zambon (2009)

TC initialization

- Idealized TC
  - Initialized using an Idealized TC algorithm Developed by Kwok and Chan (2005)
    - Maximum wind of initial vortex is set to 20 ms^{-1}, 50 km from center
    - Horizontal wind profile set by Chan and Williams (1987)
    - SST defined to be 29 ° C
  - Simulation run on an *f*-plane, *f* defined to 20 ° N



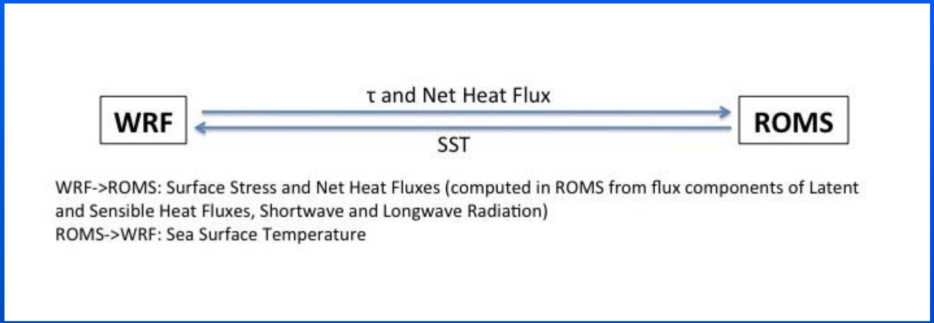
- ROMS Configuration
  - 3-D advection
  - Coriolis
  - Viscosity
  - Mellor-Yamada level-2.5 closure scheme
  - 21 vertical levels
  - 25 s timestep
  - Closed ocean basin – no boundary conditions

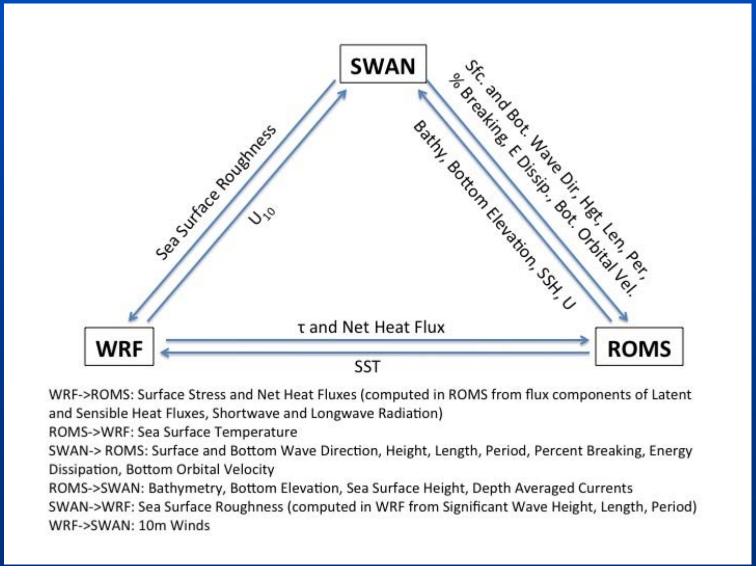
- WRF Configuration
  - 200x150, 12km spacing, 31 vertical levels
  - 75 s timestep
  - Kain-Fritsch cumulus parameterization scheme
  - Radiation: RRTM (longwave) and Dudhia (shortwave) schemes (every 10 minutes)
  - Monin-Obukhov (Eta) surface layer physics
  - Thermal Diffusion land surface physics
  - Mellor-Yamada-Janjic TKE PBL scheme (every timestep)

- SWAN Configuration
  - Configured on a Cartesian grid
  - Direction computed in a circular grid with 36 10° bins
  - Waves represented with a PSD between 1s and 25s, broken into 24 1s bins
  - Waves computed in 5-dimensions: west-east, south-north, period, wavelength, and direction of propagation
  - Depth induced breaking constant set to 0.73
    - The ratio of wave height to water depth required to break waves
  - Wind waves created using Komen formulation
  - Backward-in-space, backward-in-time advection scheme

Sensitivity Experiments

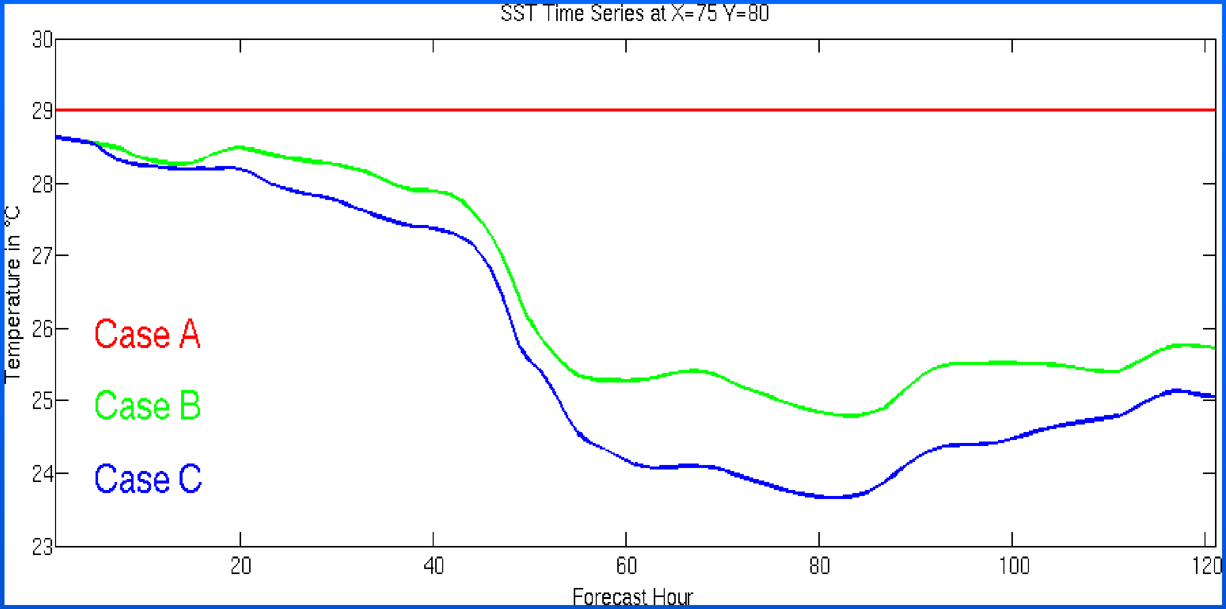
- Case A: WRF only
- Case B: WRF-ROMS
  2-way coupling
- Case C:
  WRF-ROMS-SWAN
  3-way coupling



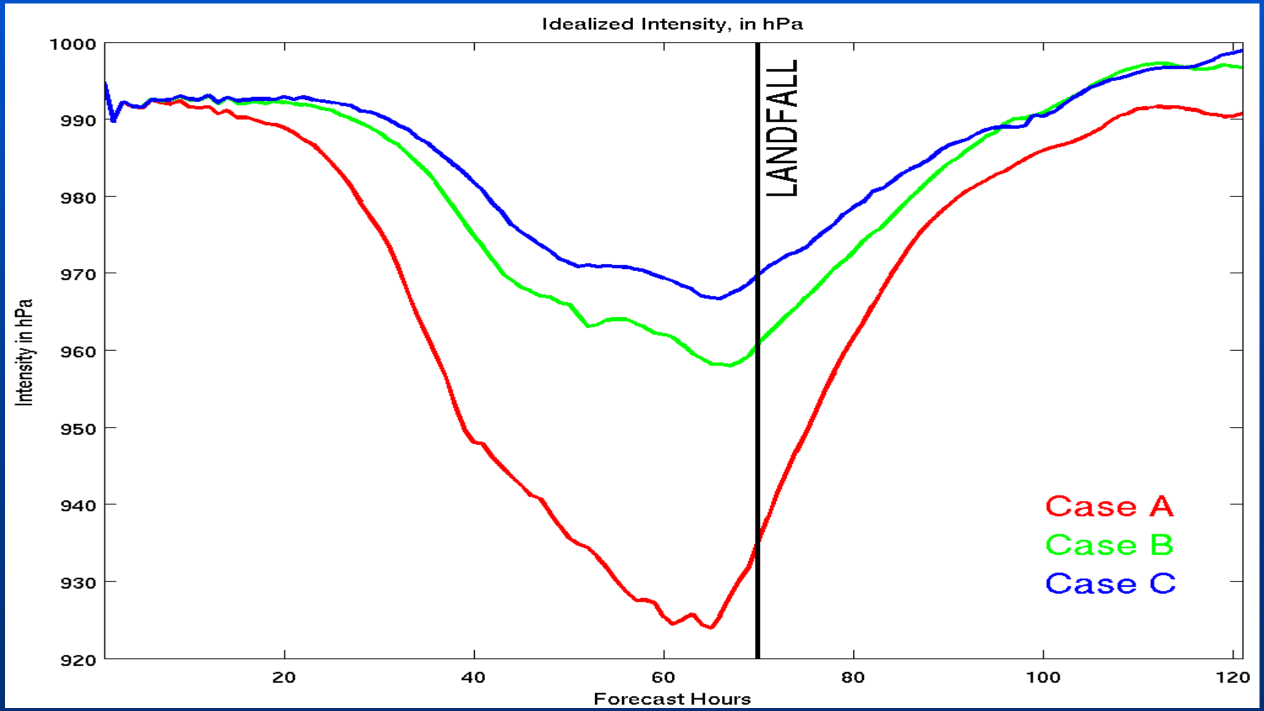


Results

- SST change
  - A: 0 ºC
  - B: 4 ºC
  - C: 5 ºC

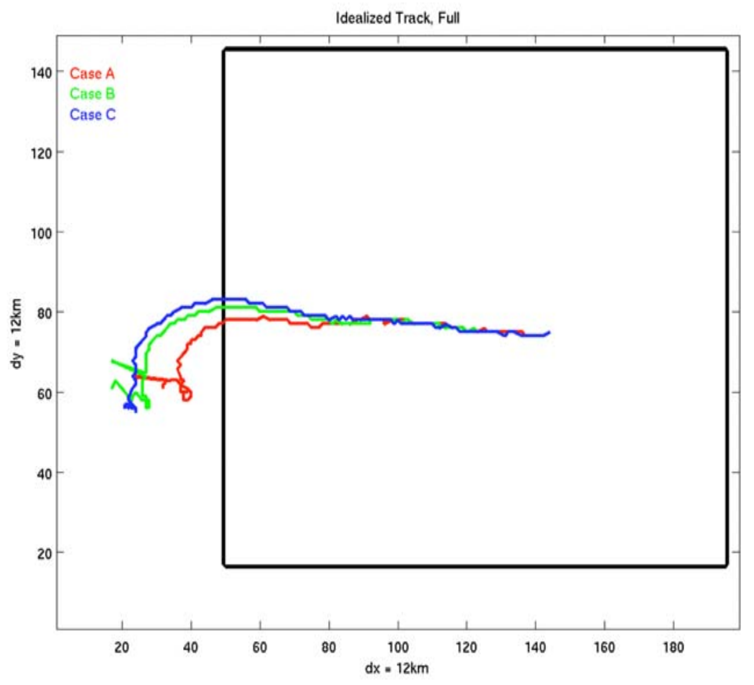


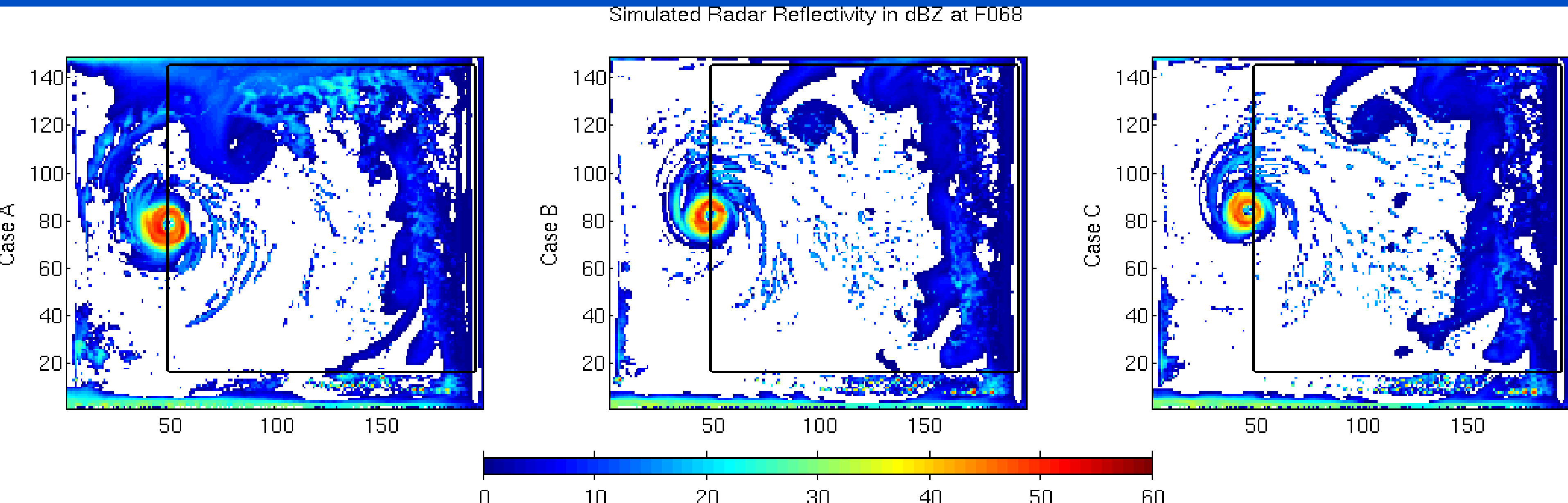
- Intensity
  - A: 924 hPa
  - B: 960 hPa
  - C: 967 hPa



Results

- Track
  - Northward Drift strongest in C, weakest in A, B is in the middle
- Size
  - Largest in A, weakest in C, B is in the middle

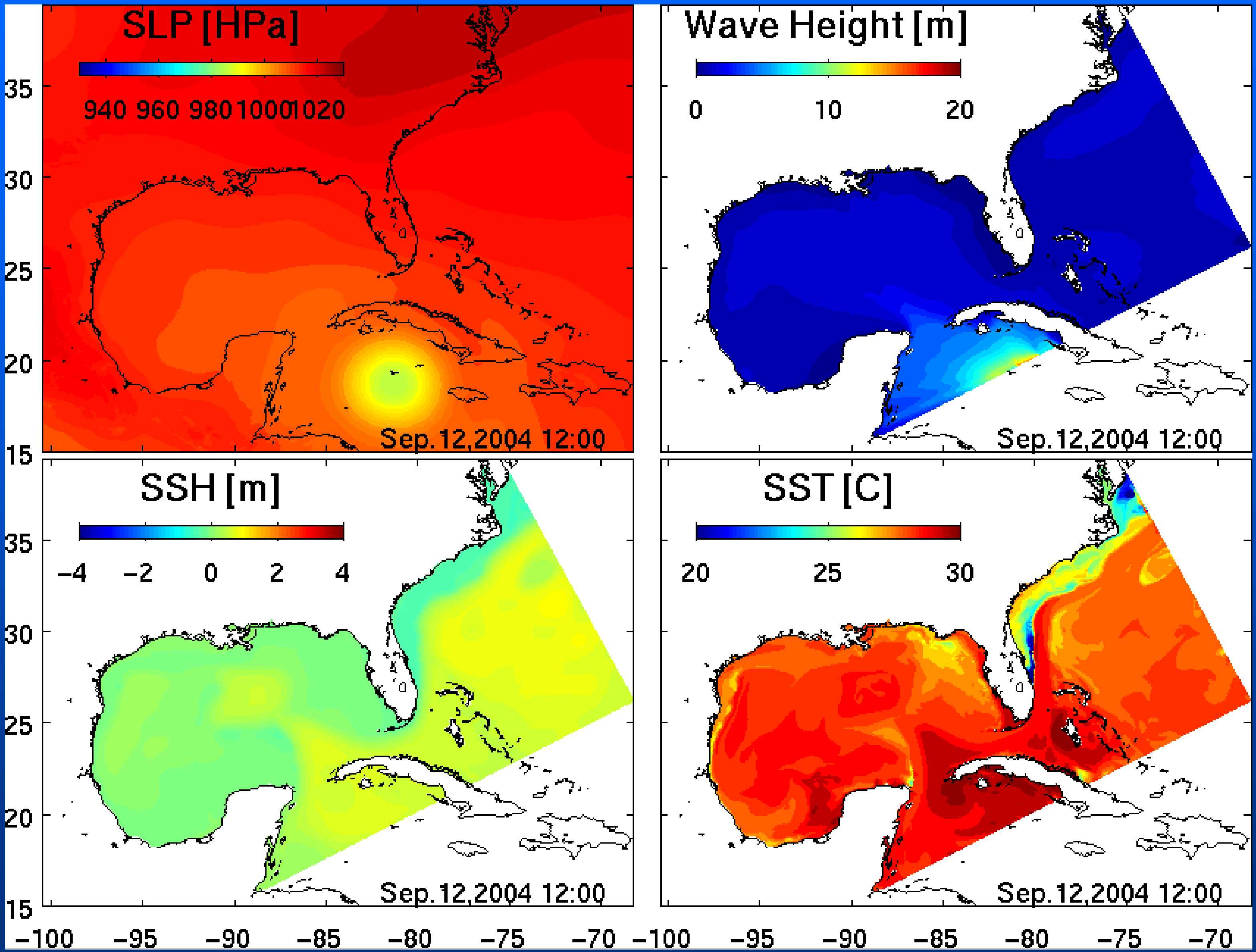




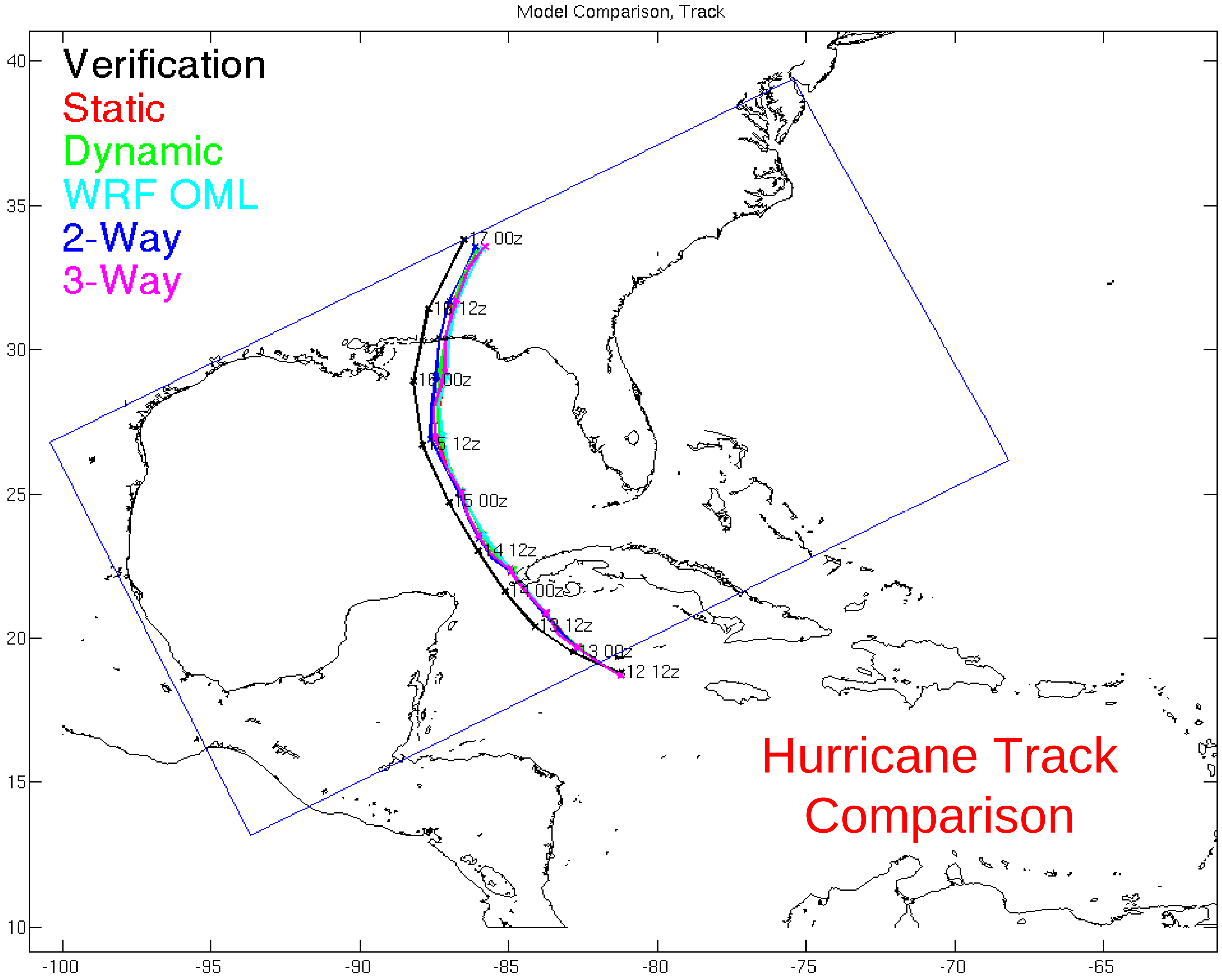
Example 2: Hurricane Ivan

- ROMS Configuration
  - Domain encompasses South Atlantic Bight and Gulf of Mexico (SABGOM) with a horizontal resolution of 5 km
  - nested inside of the HYCOM/NCODA (Hybrid Coordinate Model/NRL Coupled Ocean Data Assimilation) global model
  - 36 vertical levels, 25s timestep
  - Mellor and Yamada (1982) scheme to compute vertical turbulent mixing
- WRF Configuration
  - GFS 1° data used for initialization/LBCs (updated every 6 hours), GFDL merged in initialization
  - 8 km grid spacing, 24 s timestep, 31 vertical layers
  - Inner 3-to-1 nest (301x301x31)
  - WSM-6 MP scheme
  - Kain-Fritsch CP scheme (outer domain only)
  - RRTM (LW) and Dudhia (SW) schemes – 8 min
  - Monin-Obukov Sfc Physics, Noah LSM
  - Mellor-Yamada-Janjic TKE PBL scheme – every timestep
- SWAN Configuration
  - Lateral Boundary data provided by WaveWatch 3 (WW3) global wave model
  - Configured on a Cartesian grid
  - Direction computed in a circular grid with 36 10° bins
  - Waves represented with a PSD between 1s and 25s, broken into 24 1s bins
  - Waves computed in 5-dimensions: west-east, south-north, period, wavelength, and direction of propagation

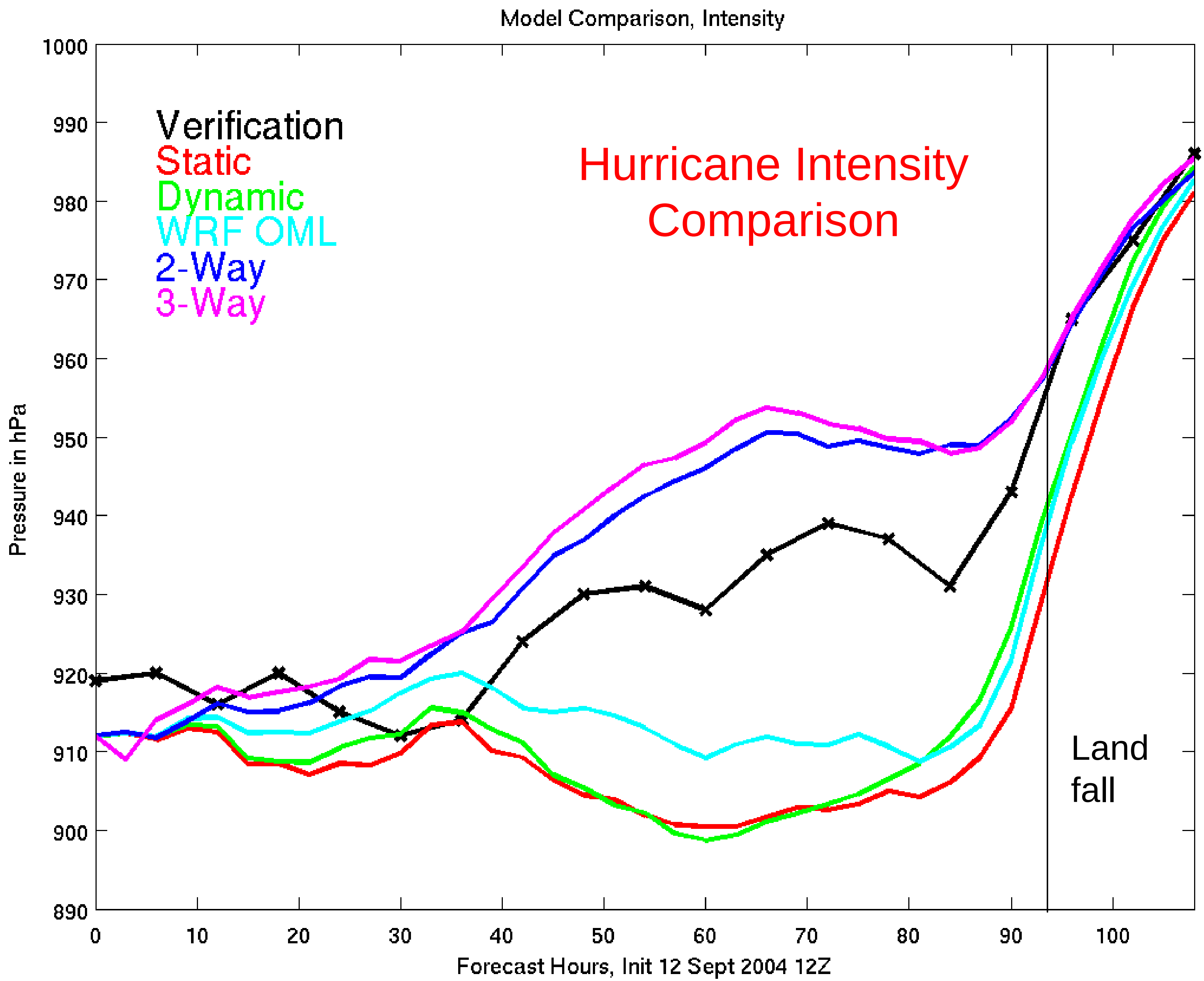
WRF-ROMS-SWAN Coupled Simulation: Hurricane Ivan



Zambon (2009); Zambon, He and Werner (2012)

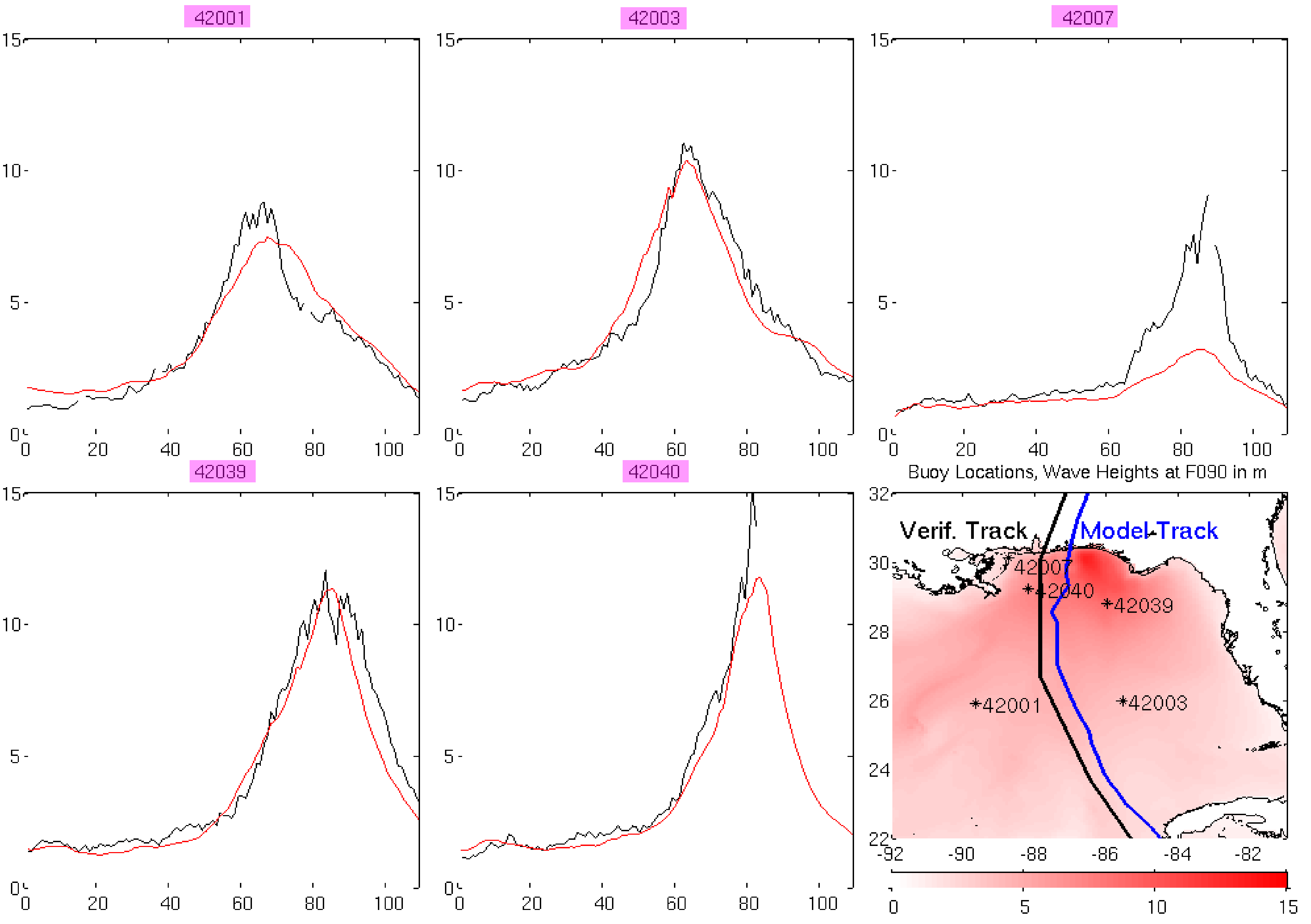


Model Comparison, Track
Verification
Static
Dynamic
WRF OML
2-Way
3-Way
17 00z
16 12z
16 00z
15 12z
15 00z
14 12z
14 00z
13 12z
13 00z
12 12z
Hurricane Track Comparison

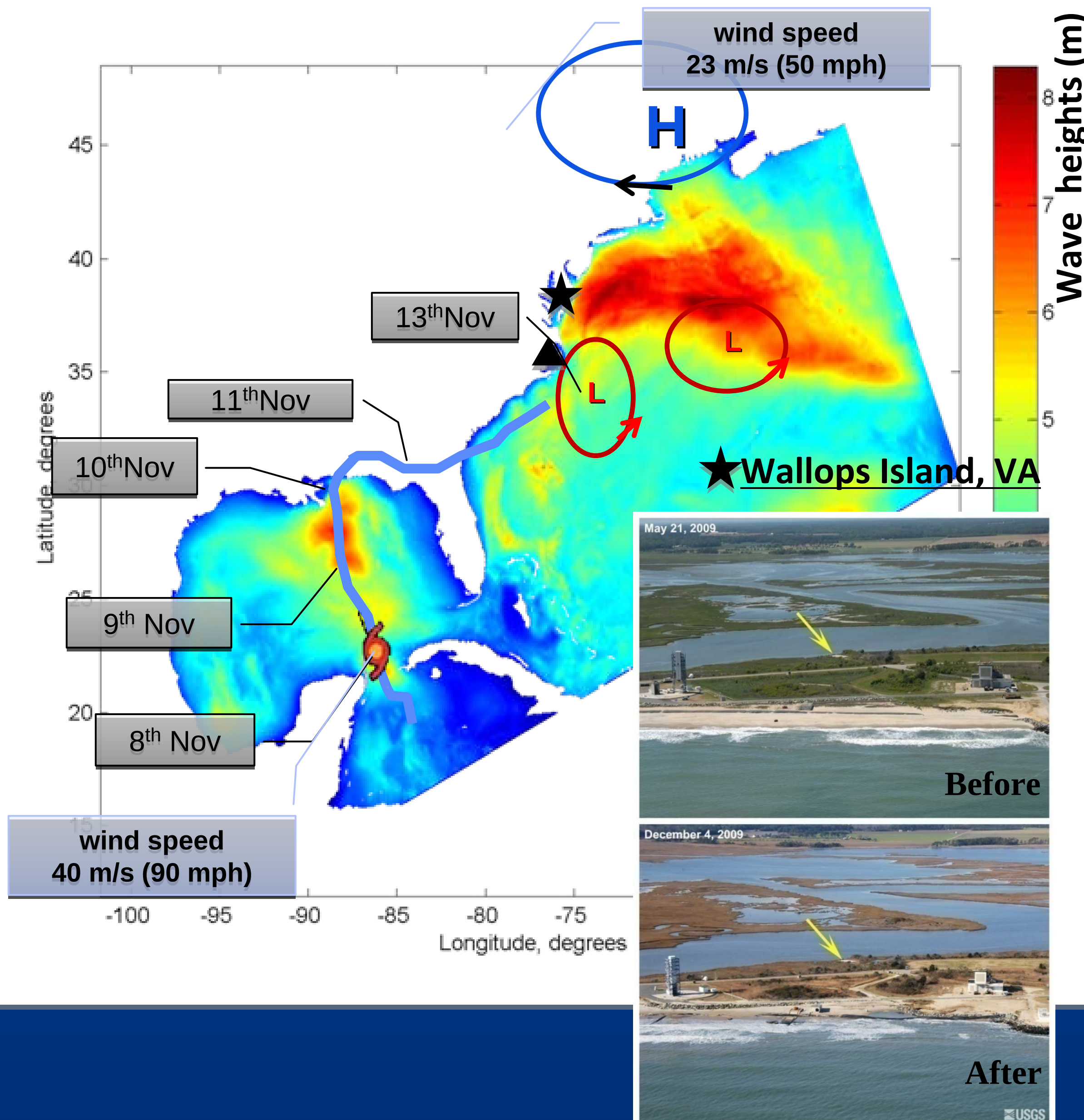


Model Comparison, Intensity
Verification
Static
Dynamic
WRF OML
2-Way
3-Way
Hurricane Intensity Comparison
Land fall
Pressure in hPa
1000
990
980
970
960
950
940
930
920
910
900
890
0
10
20
30
40
50
60
70
80
90
100
Forecast Hours, Init 12 Sept 2004 12Z

Wave Height (in m) Time Series (Valid 12-Sept-04 12Z through 17-Sept-04 00Z)

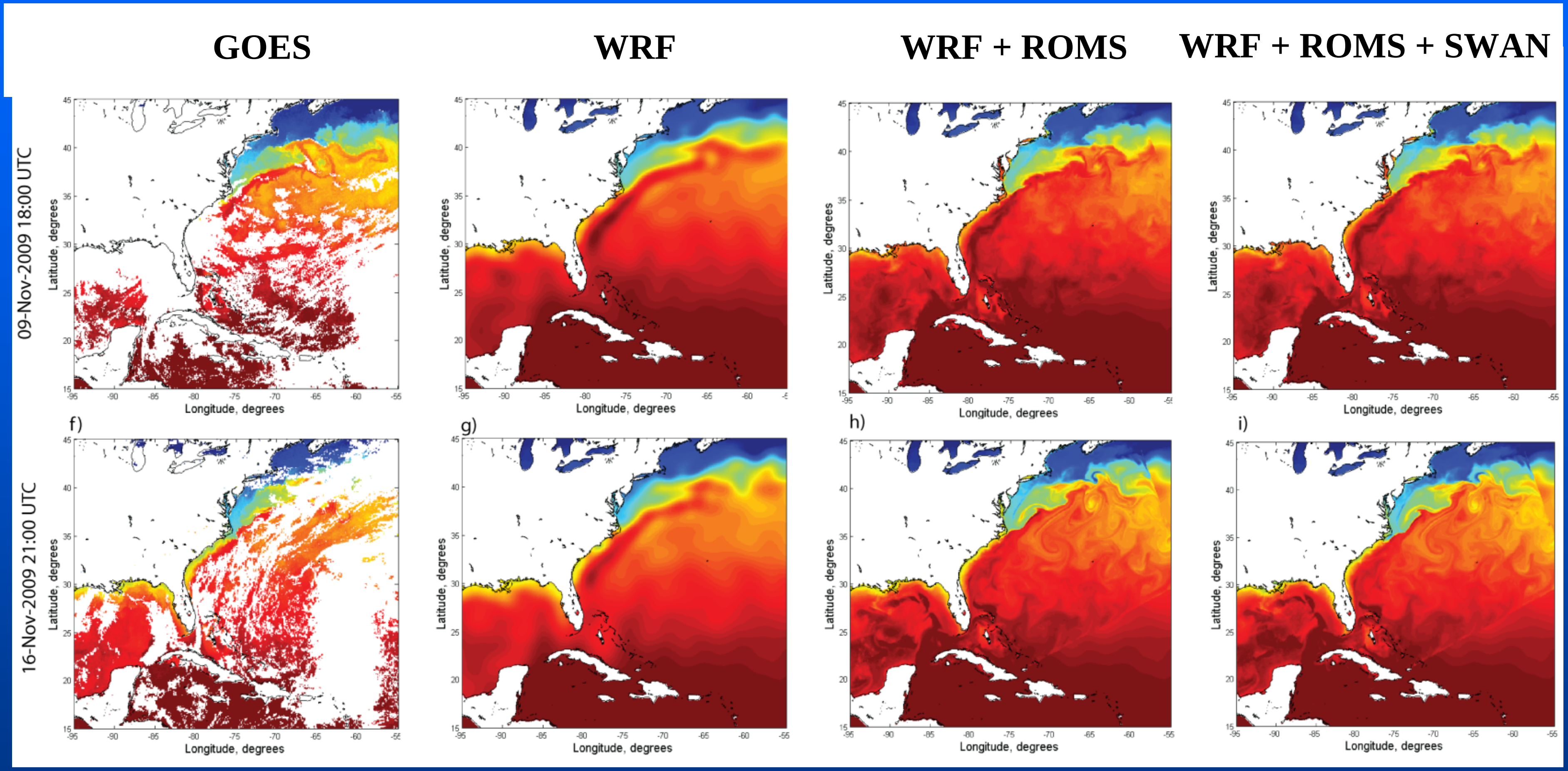


Example 3: Nor'Ida Nov 2009



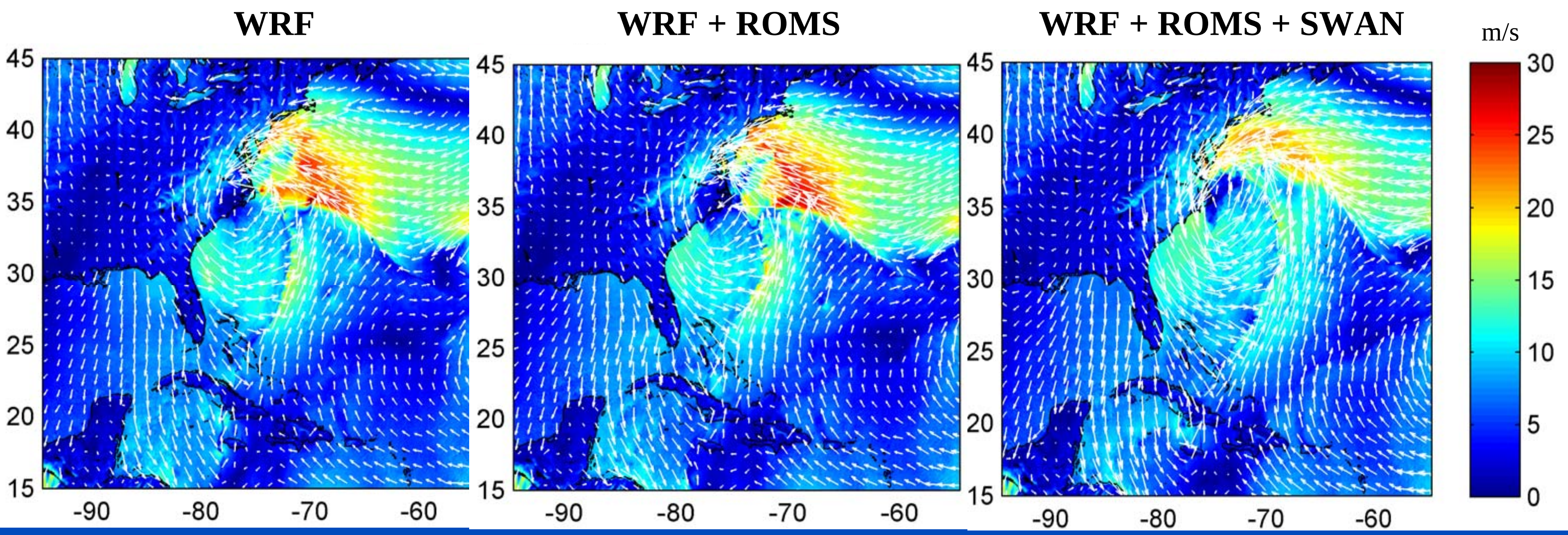
http://coastal.er.usgs.gov/hurricanes/norida/

SST Comparison

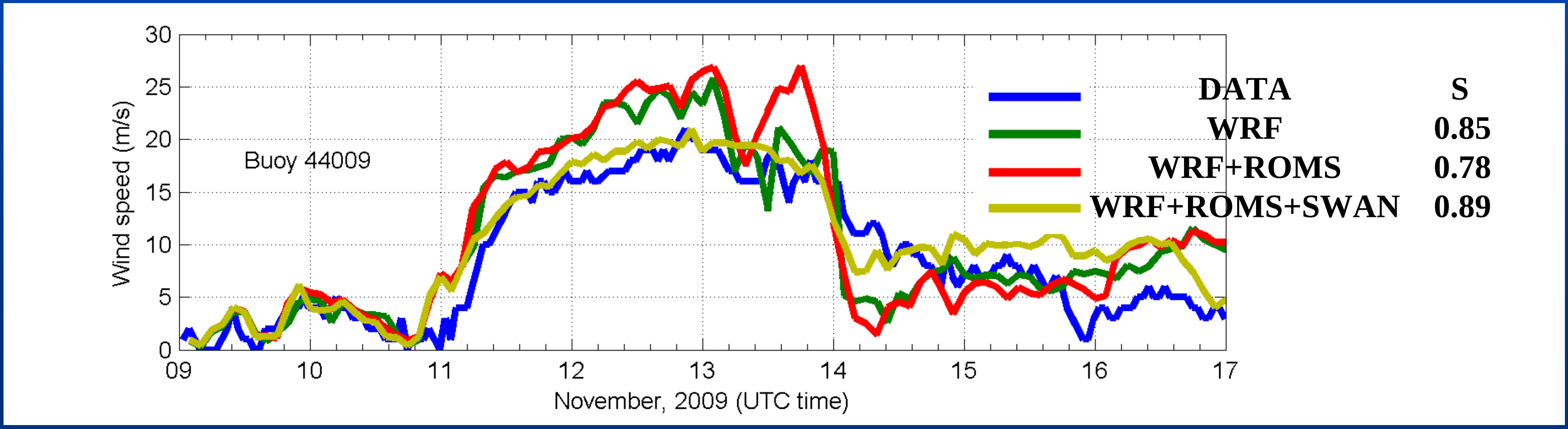


Olabarieta, M., Warner, J., Armstrong, B., Zambon, J., and He, R. (2012)

Surface Wind Comparison (Nov 13)



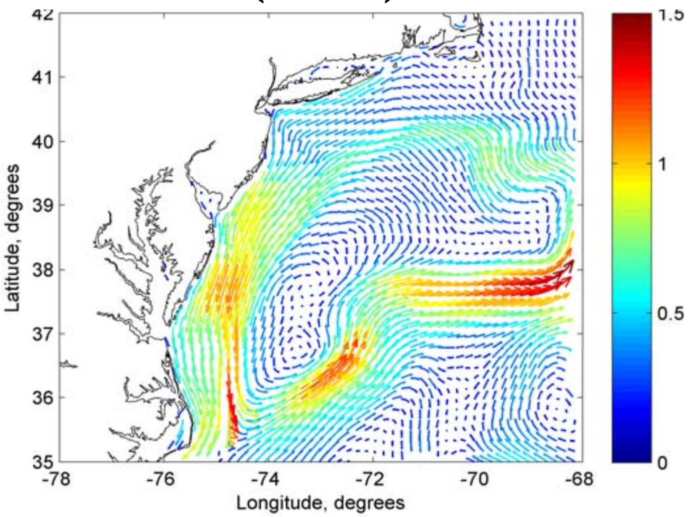
Reduced wind speed with waves coupling



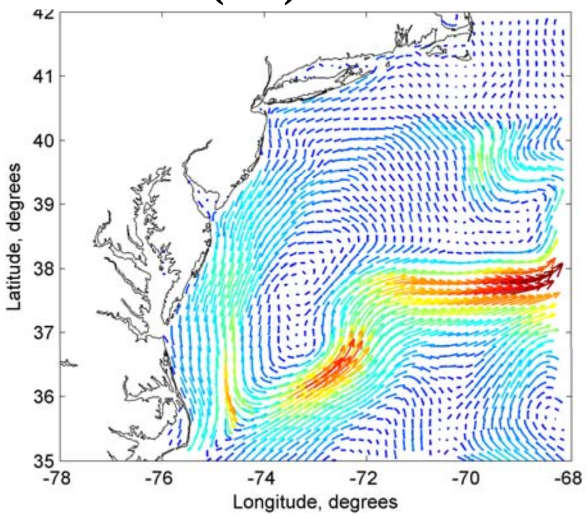
Surface Current Comparison (Nov 13)

WRF + ROMS + SWAN

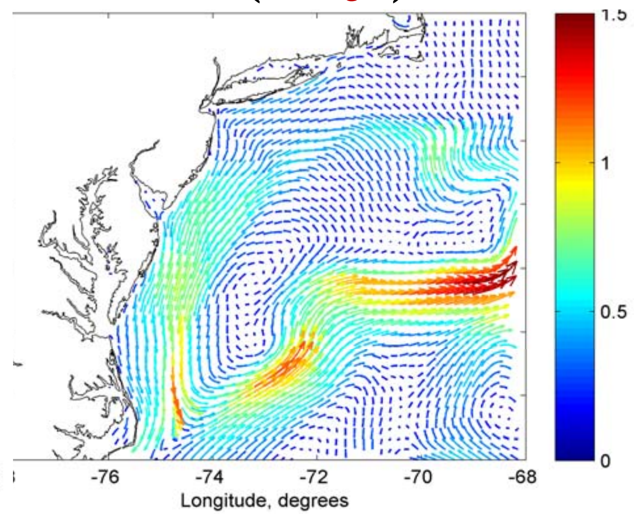
(OOST)



(TY)

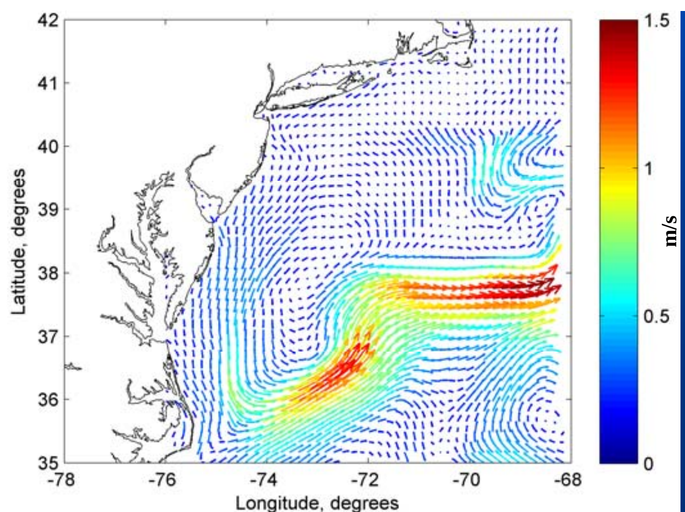


(DGQH)

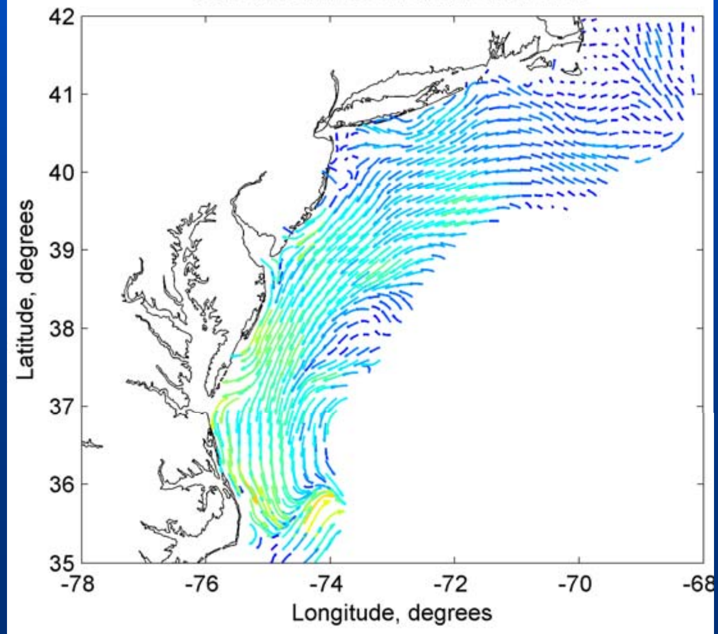


Increased current speed with waves coupling.

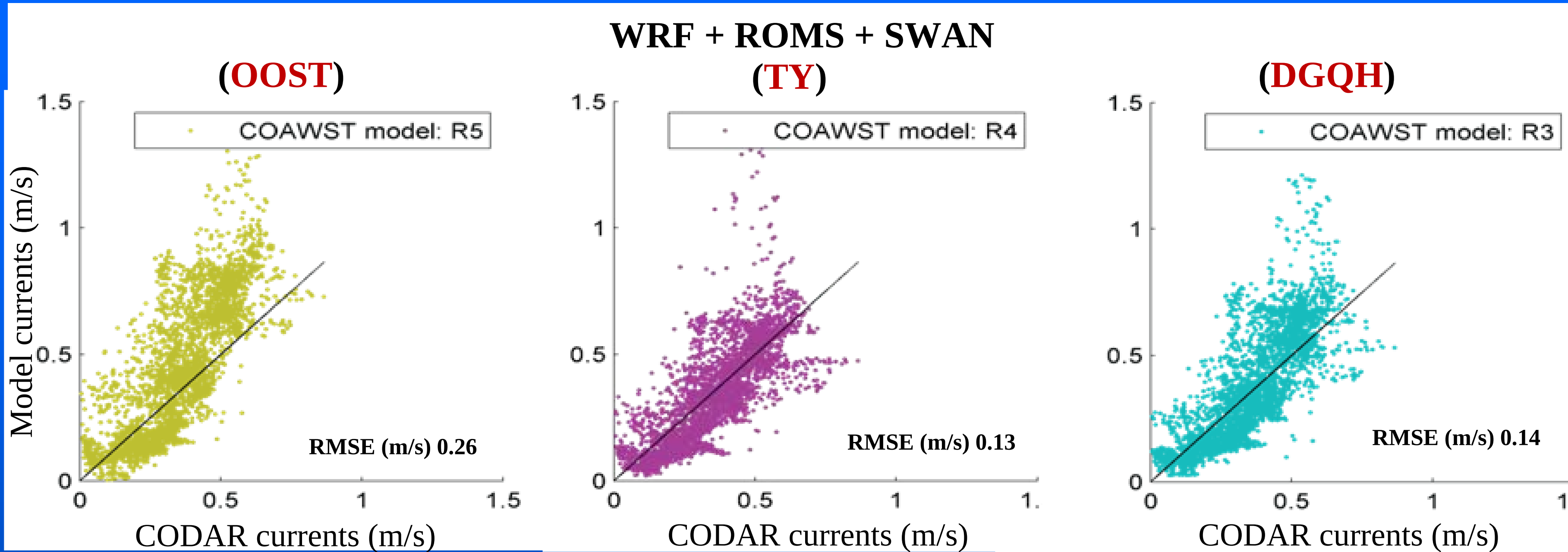
WRF + ROMS (charnock)



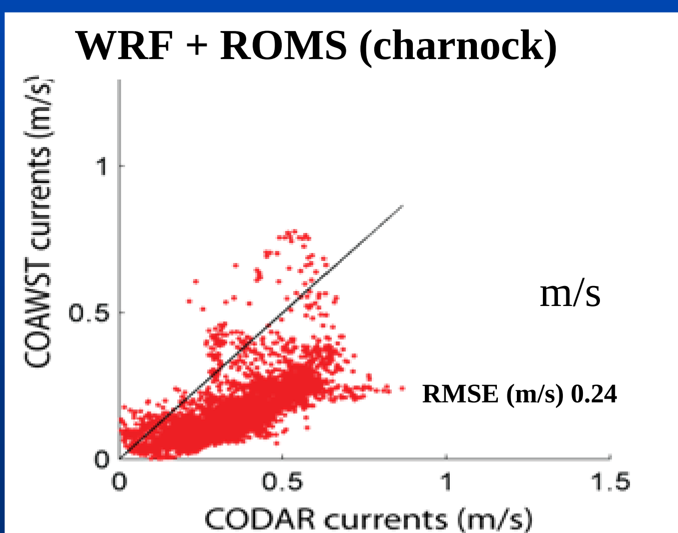
CODAR CODAR Surface currents:13-Nov-2009

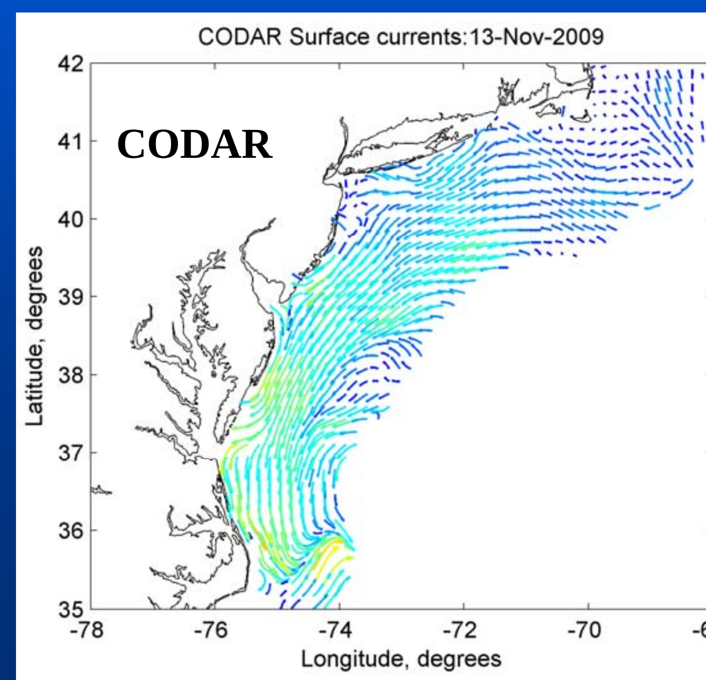


Surface Current Comparison

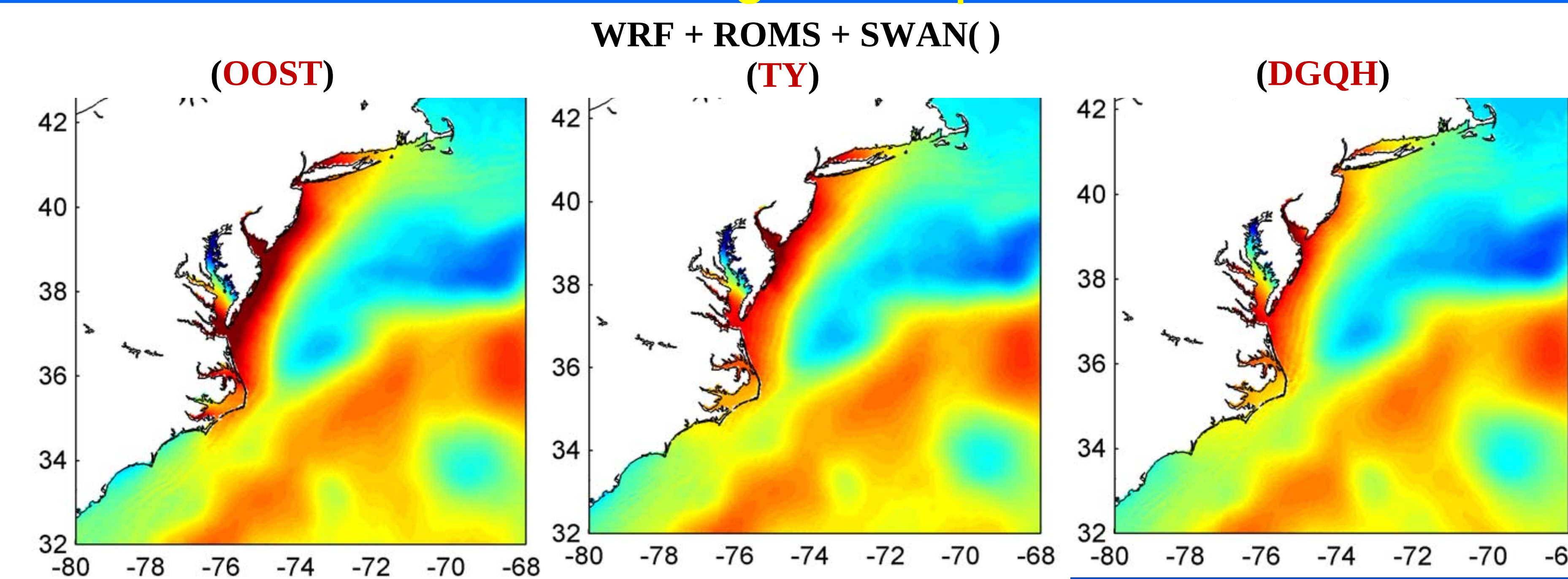


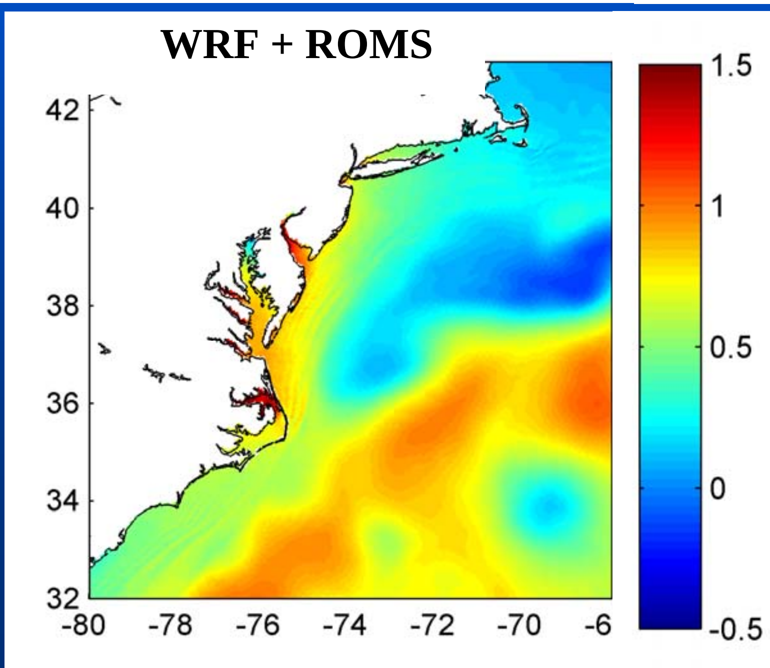
Increased current speed with waves coupling.
TY / DGQH best.



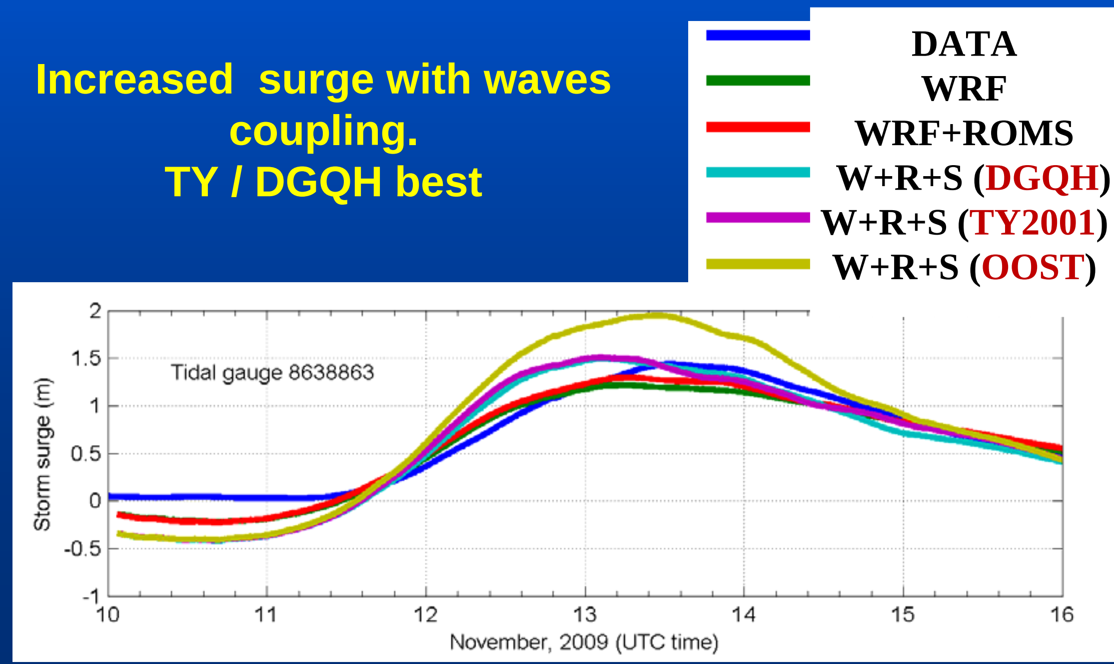


Storm Surge Comparison





Increased surge with waves coupling.
TY / DGQH best



Example 4: Winter Extratropical Storm in January 2005

[*Dave's Weather America*]

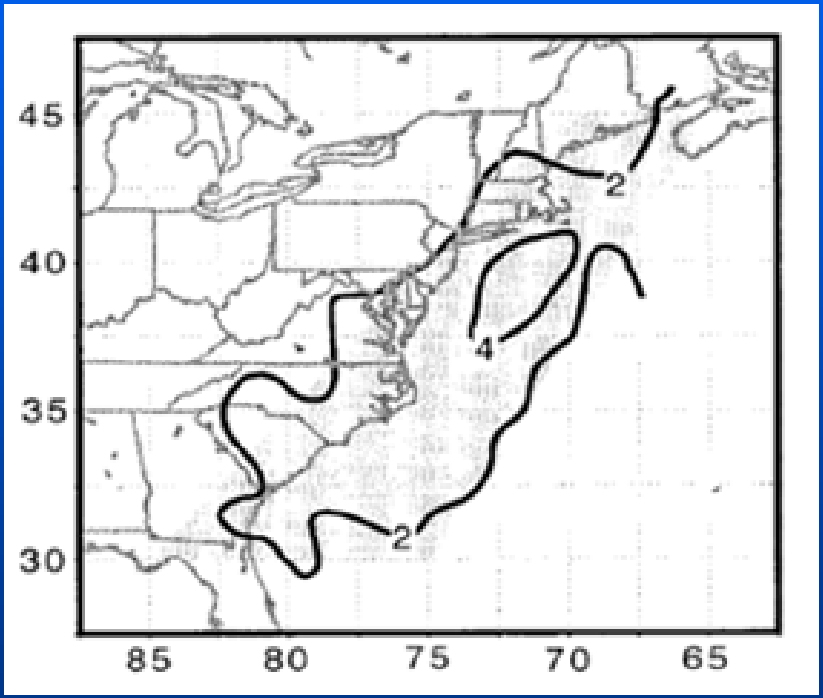
- Widespread rain, snow, and ice
- Strong winds and extreme cold
- Affects densely populated areas

[*FINCH Project*]

- Coastal storm surge and flooding
- Severe beach erosion
- Commercial fishing industry affected

Example 4: Winter Extratropical Cyclone (ETC)

Cyclogenesis Areas
[# storms form each January]

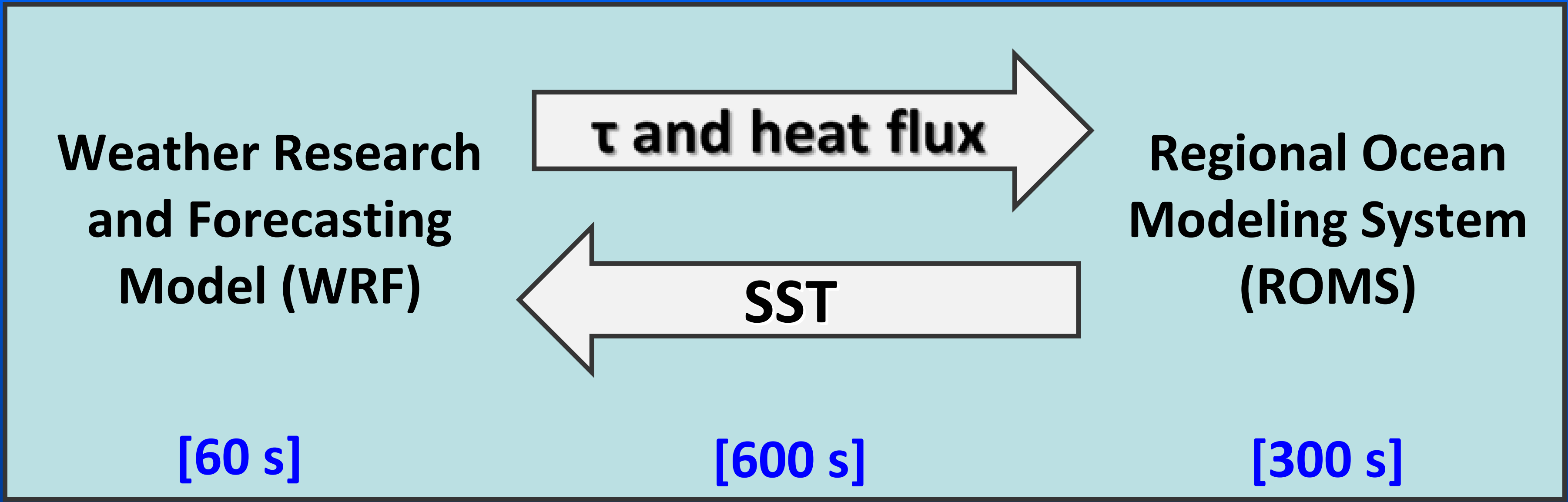


[*Zishka and Smith,* 1980]

- 12 east coast ETCs per winter
- Intense ETCs most common in January
- "Bomb" cyclones (SLP deepens at least 1 mb/hr for 24 hrs) typically develop:
  - near the strongest SST gradients
  - along the leading edge of an Arctic air mass

Coupled Modeling Study of ETCs in January 2005

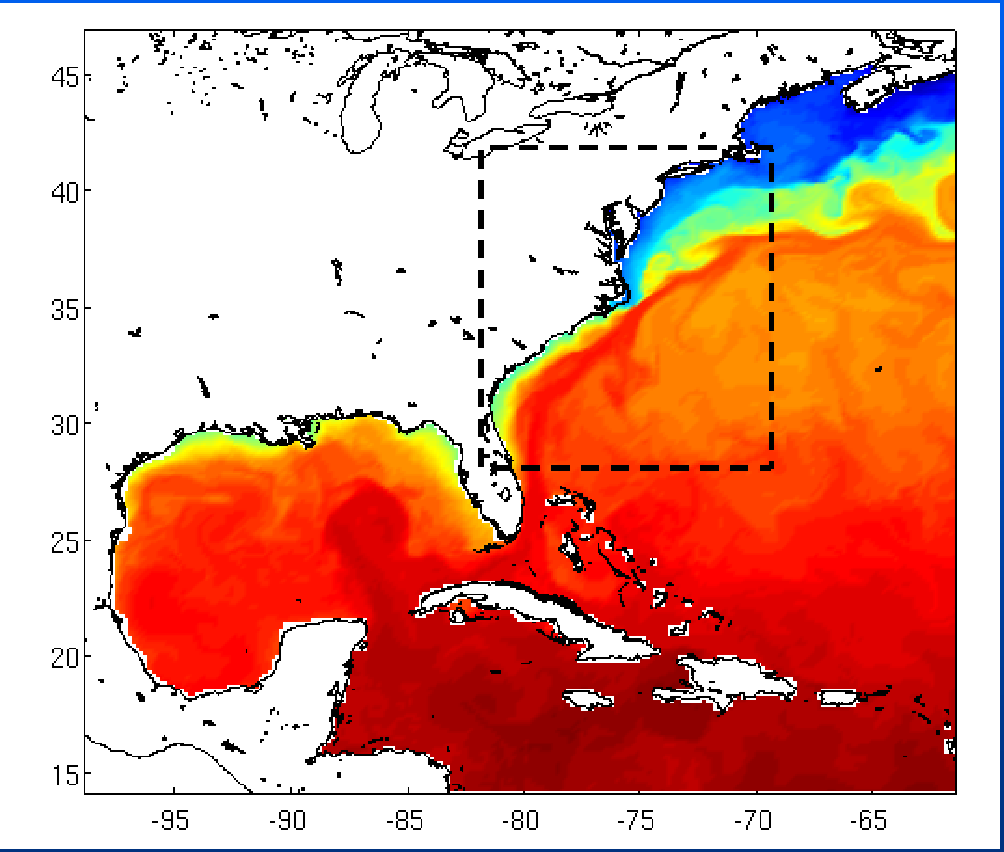
2-way coupled WRF/ROMS system



Neslon, J (2011), Nelson and He (2012)

Model Setup

Study Domain

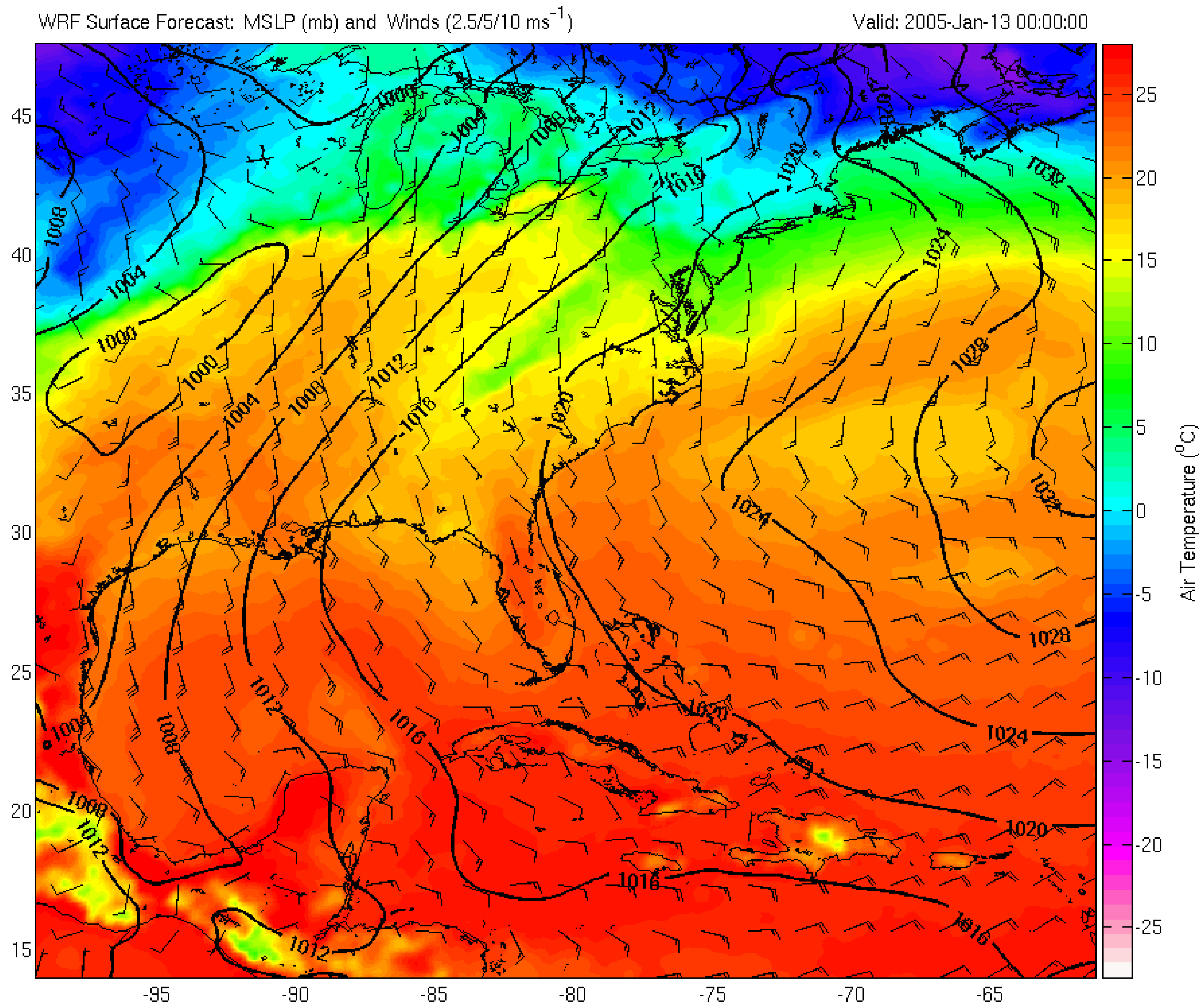


<u>WRF Setup</u>

- 15 km horizontal resolution
- 48 vertical levels
- Initial and boundary conditions from 3-hrly, 32-km NCEP North American Regional Reanalysis (NARR)

<u>ROMS Setup</u>

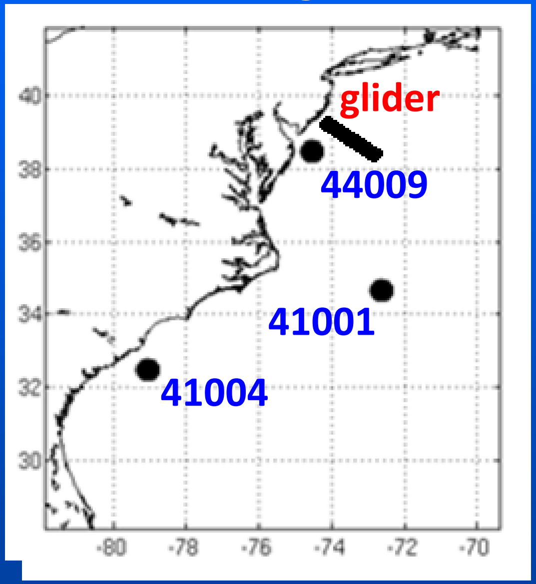
- 5 km horizontal resolution
- 18 vertical levels
- Initial and boundary conditions from daily, 10-km global HYCOM simulation
- Open BCs at southern and eastern boundaries

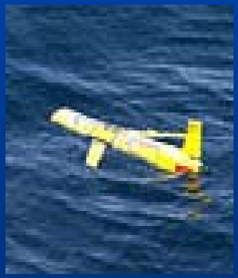


January 22- 24, "Bomb" cyclones deepen at least 1 mb/hr for 24 hrs

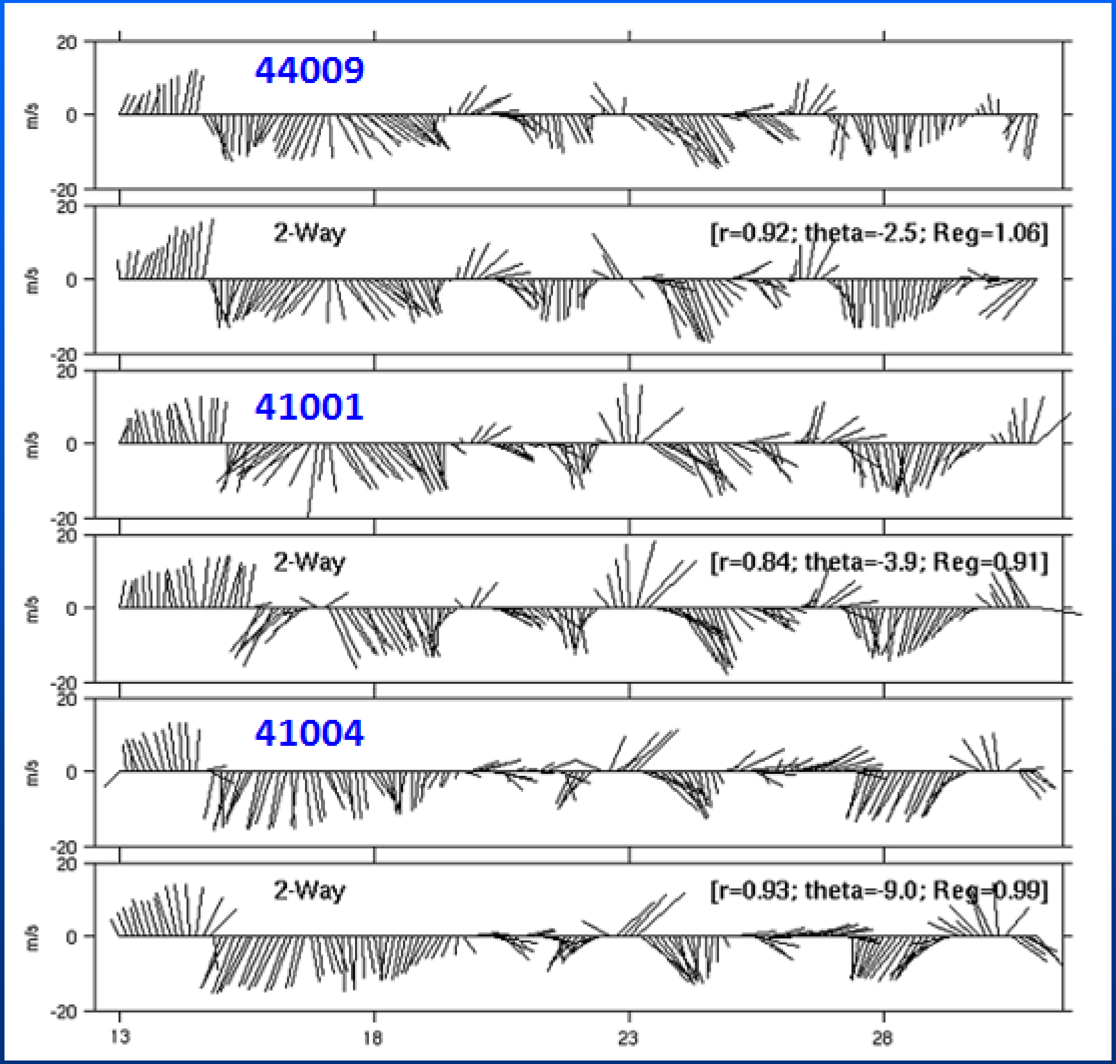
Model/Data Comparisons

Observing Sites



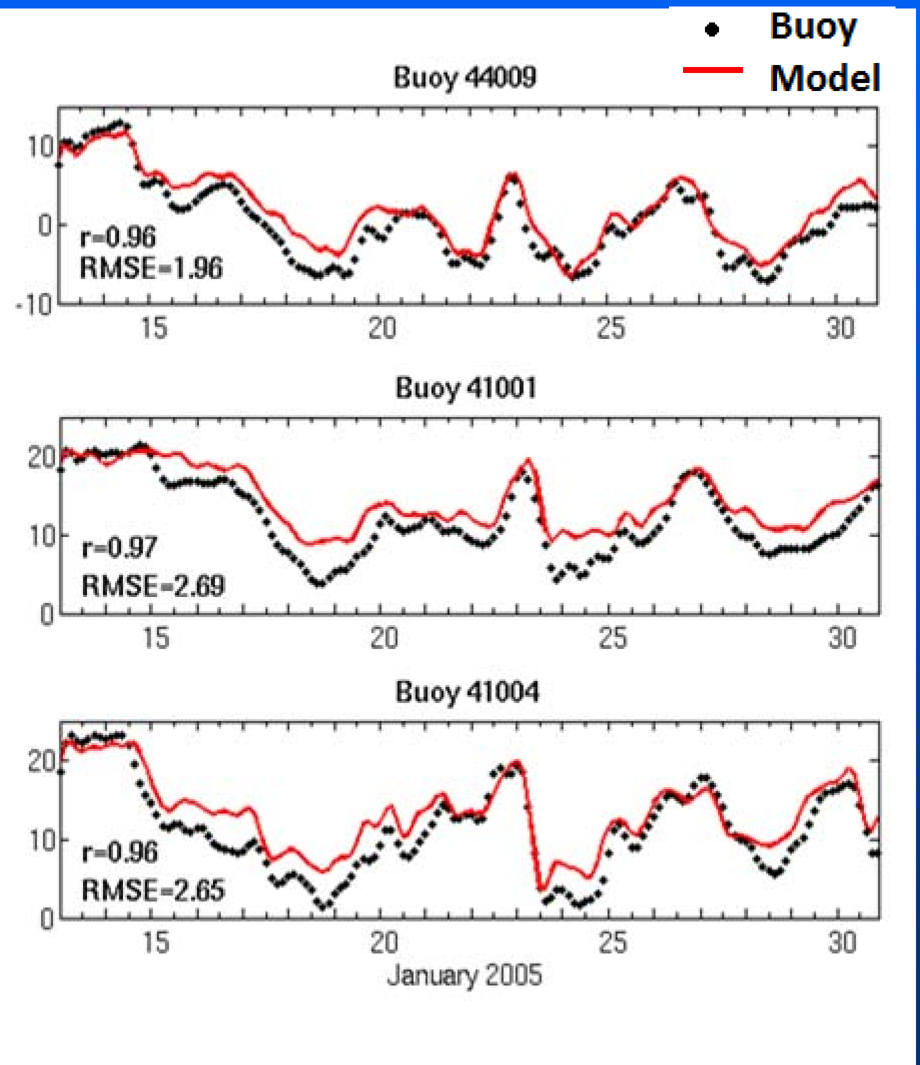


Surface Wind Comparison



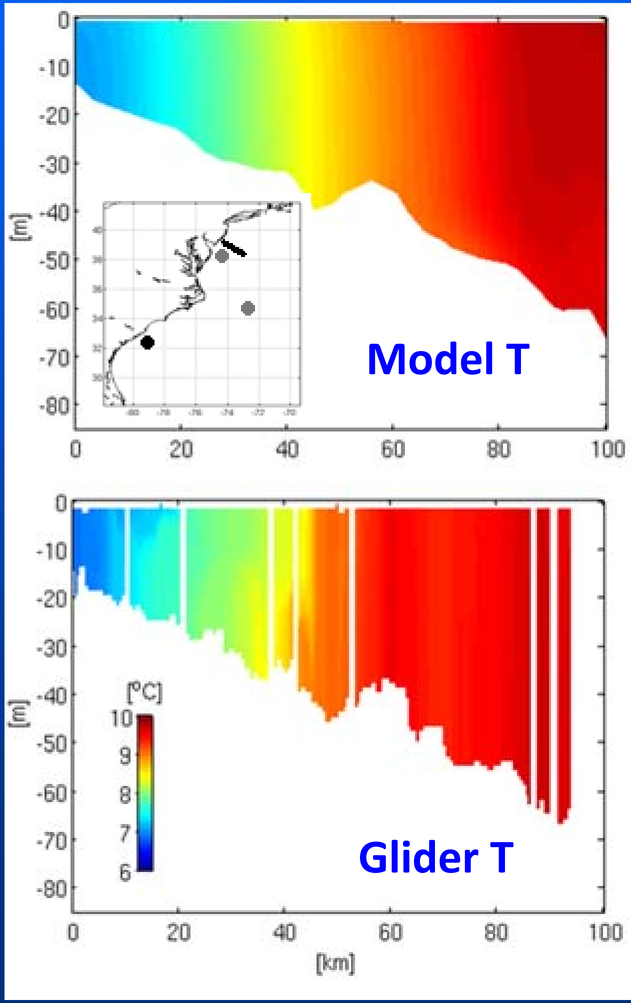
Model/Data Comparisons

Surface Air Temperature



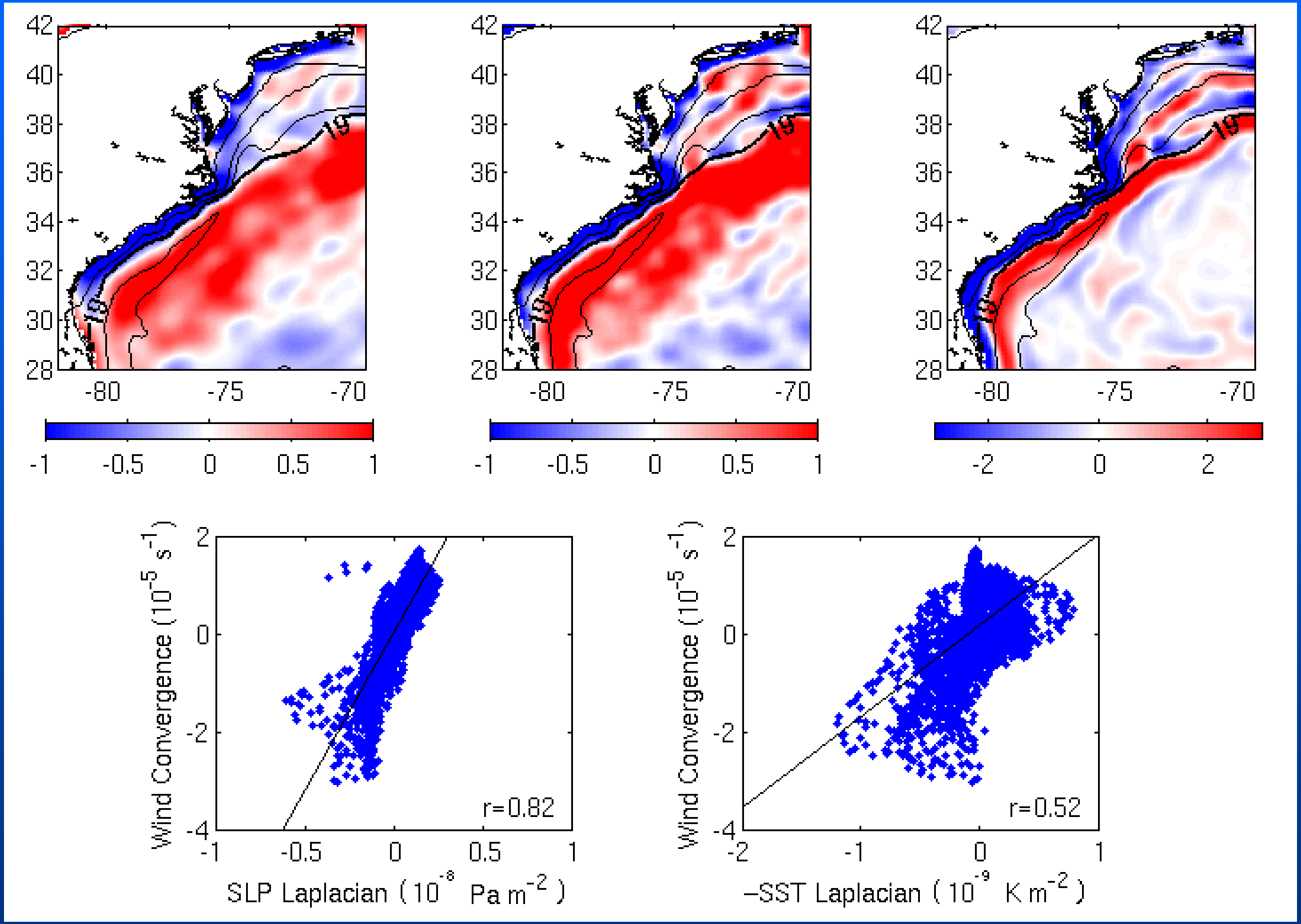
Shelf water Temperature

14 January 2005



Wind Convergence vs Laplacian of SLP and SST

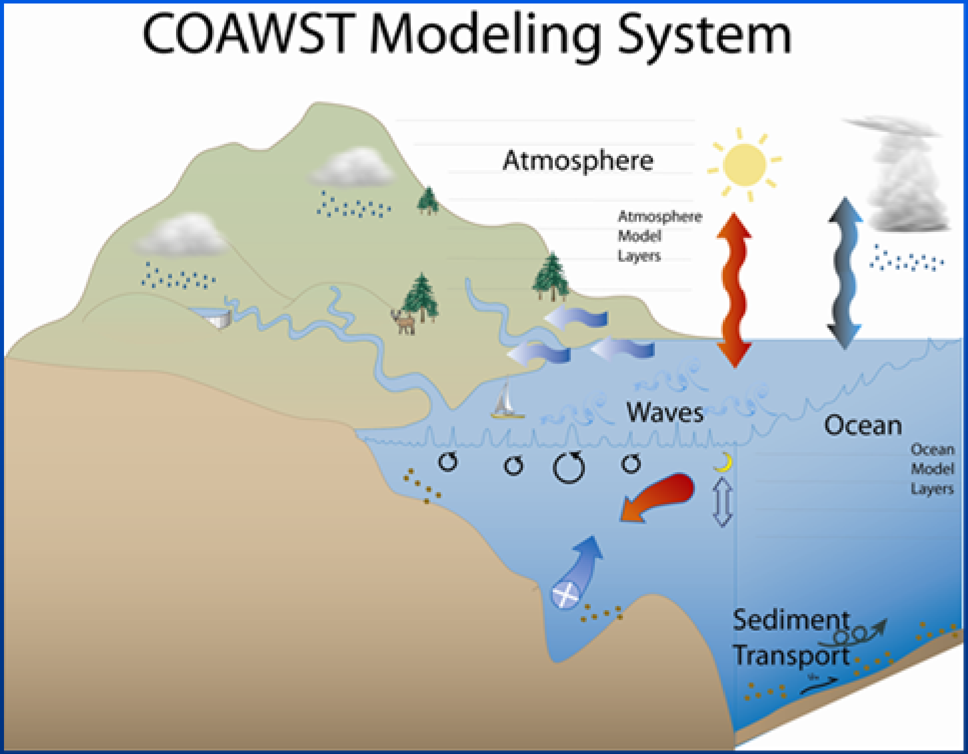
Synoptic Mean Wind Convergence [10^{-5} s^{-1}] | **Synoptic Mean SLP Laplacian [10^{-9} Pa m^{-2}]** | **Synoptic Mean –SST Laplacian [10^{-10} K m^{-2}]**



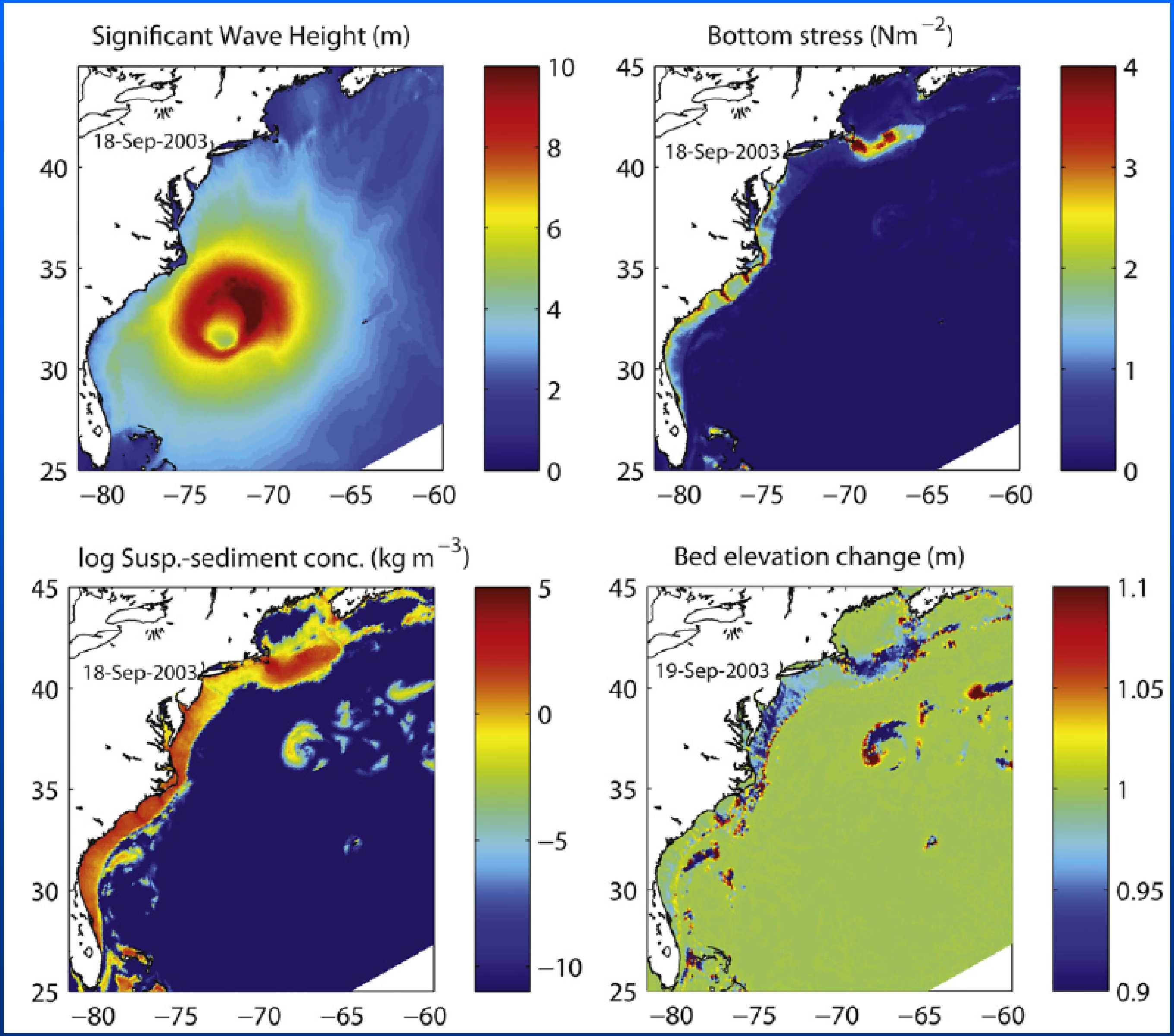
$-(u_x + v_y)\,\rho_0 \sim -(T_{xx} + T_{yy})$

Minobe et al. (2008); Nelson (2011), Nelson and He (2012)

Example 5: Modeling the Coastal Sediment transport

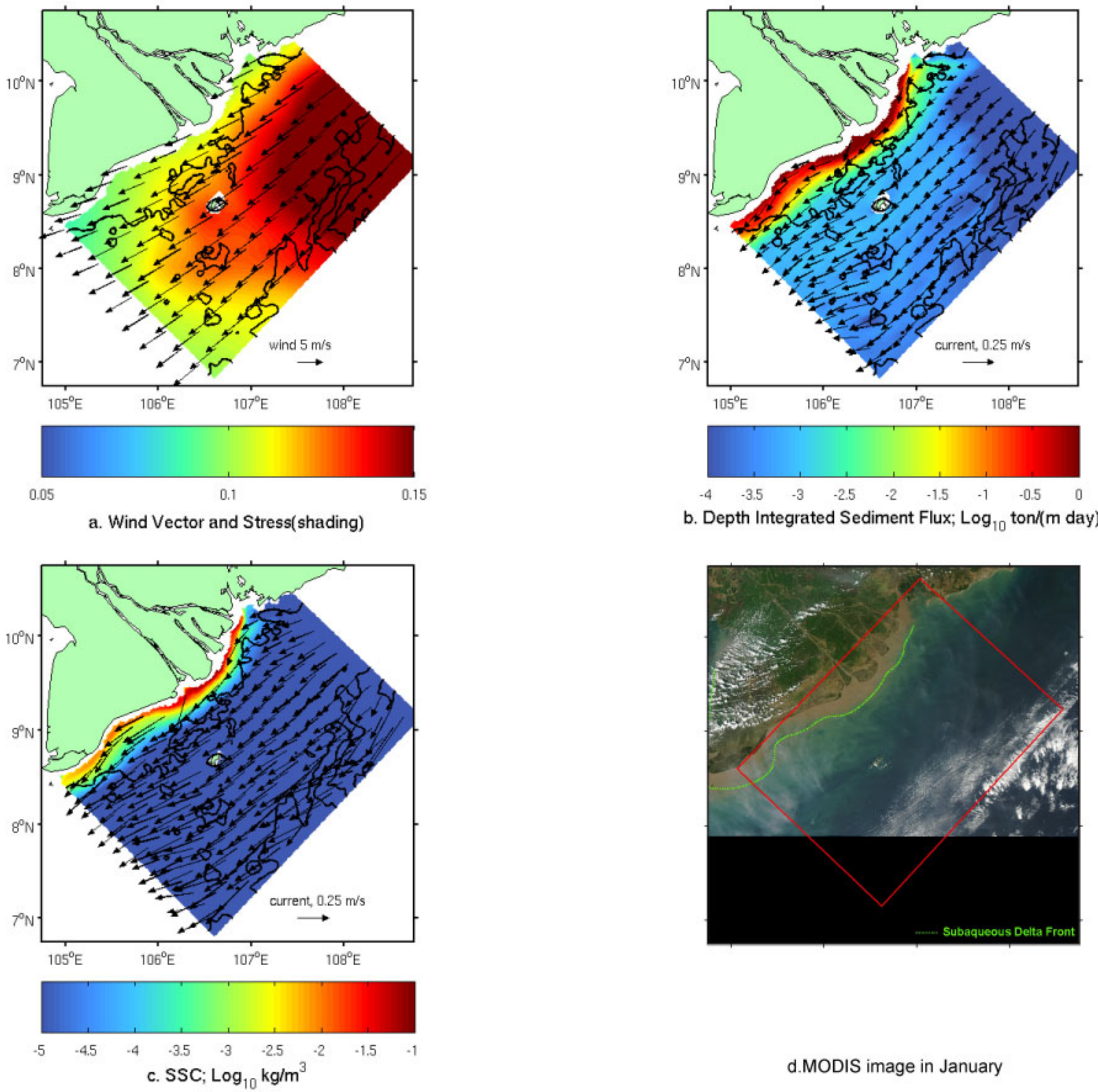


Sediment transport, suspension and Erosion During Hurricane Isabel in September 2003



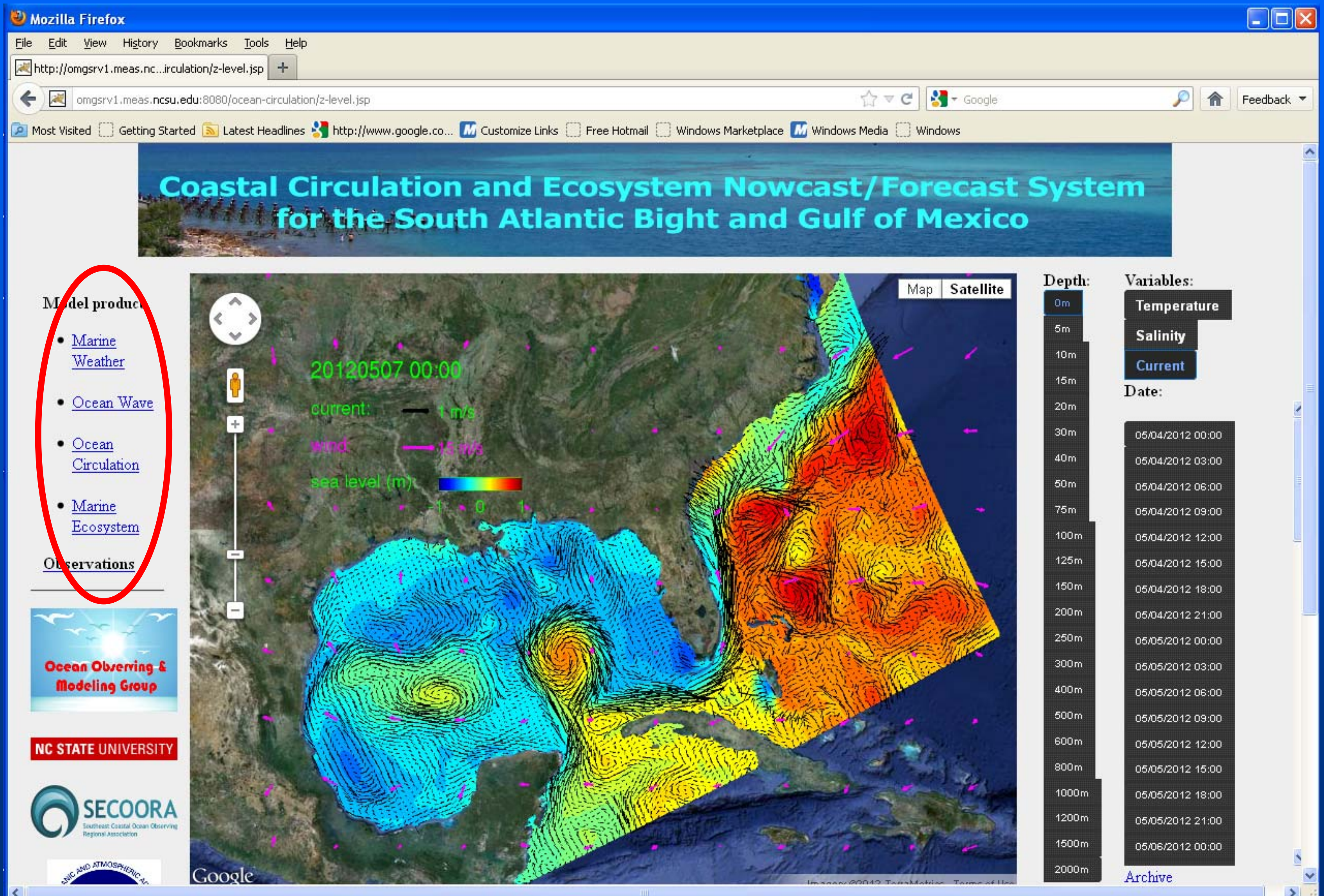
Warner, Armstrong, He and Zambon (2010)

Mekong River Sediment Re-suspension and Transport: December 2005



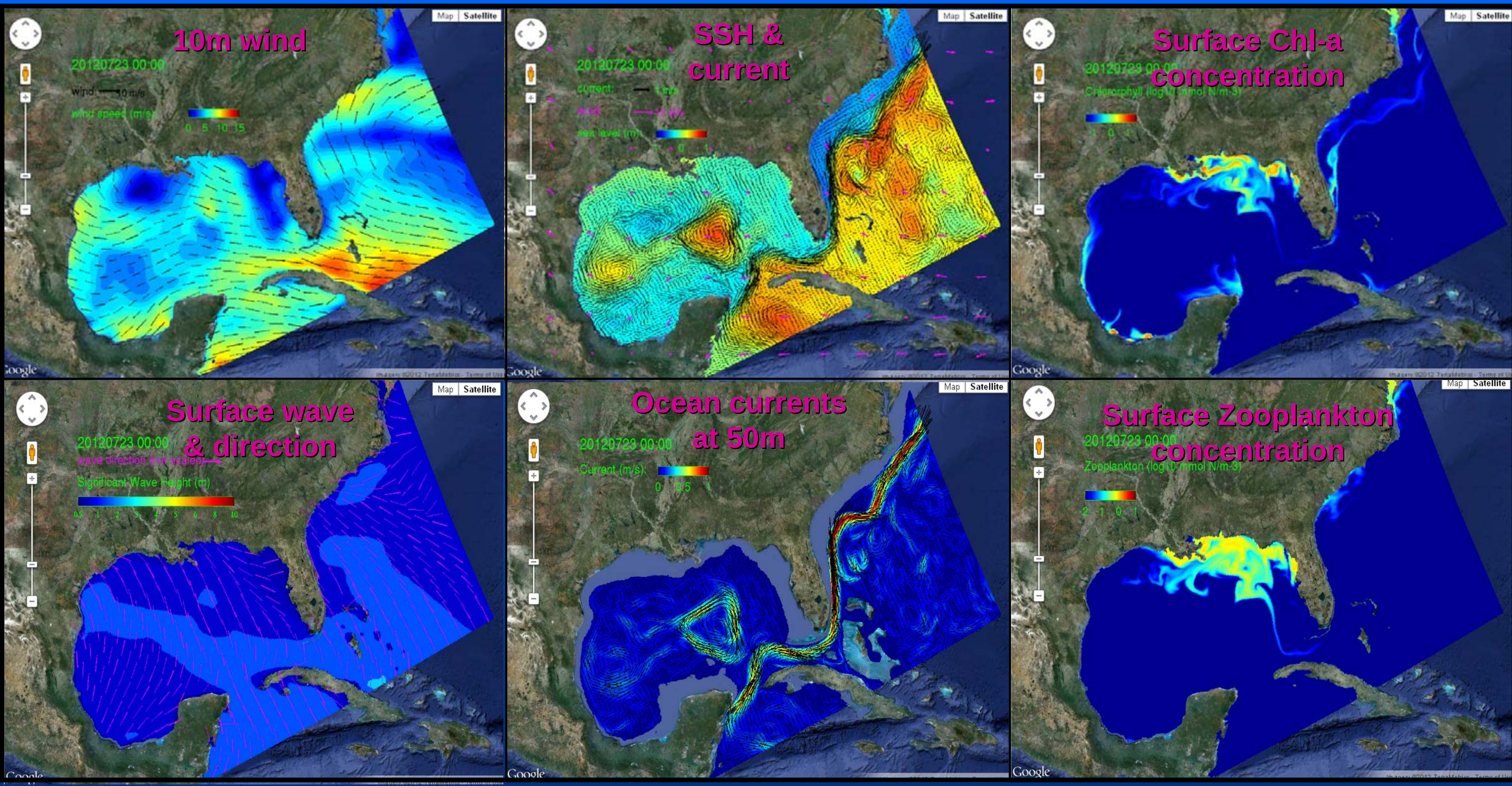
Xue, He, Liu and Warner (2012)

Example 6: An integrated Ocean Circulation, Wave, Atmosphere and Marine Ecosystem Prediction System for the South Atlantic Bight and Gulf of Mexico



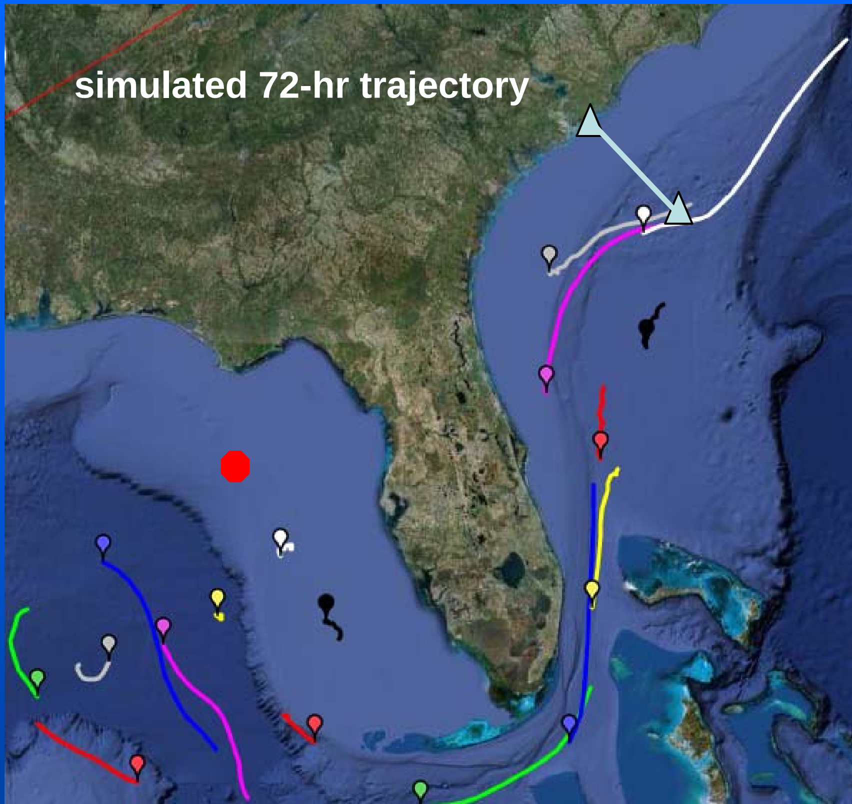
SABGOM Model Prediction 7/23/2012

Marine Weather & Ocean Wave | Ocean Circulation | Marine Ecosystem

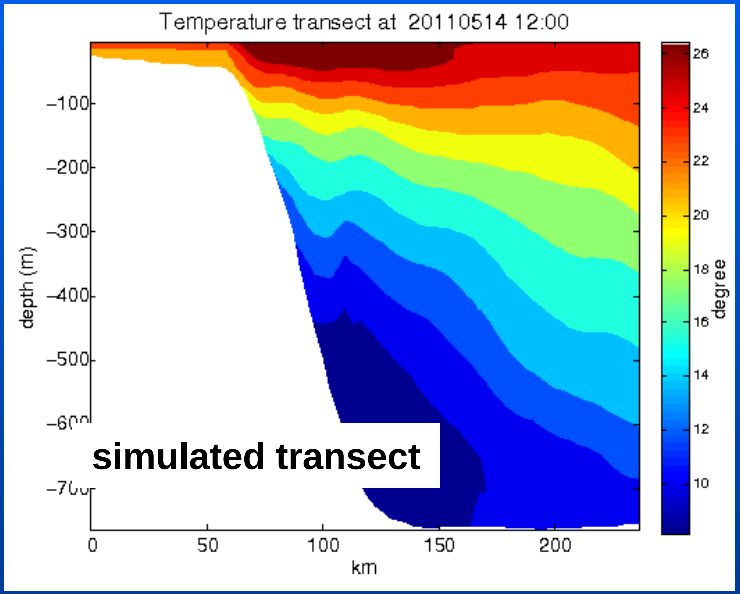


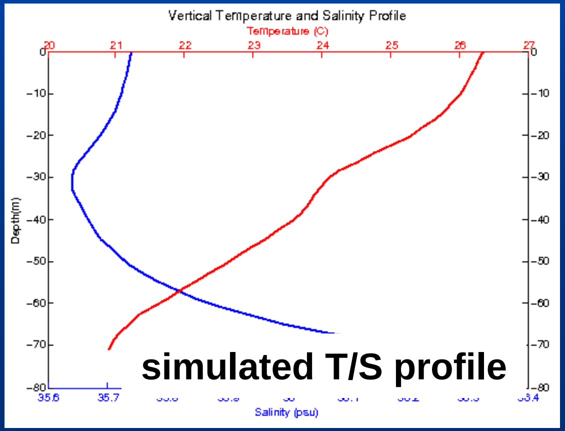
http://omgsrv1.meas.ncsu.edu:8080/ocean-circulation
112-Processor Linux cluster is dedicated to the operation

Web Interface & User Defined Online Functions

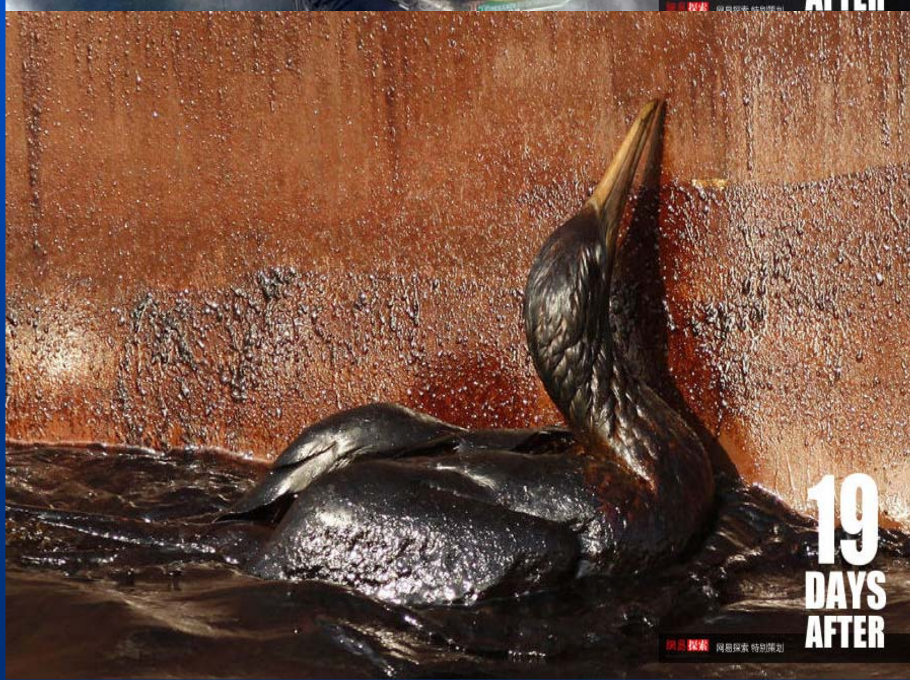


http://omgsrv1.meas.ncsu.edu:8080/ocean-circulation





2010 The Gulf of Mexico BP Oil Spill



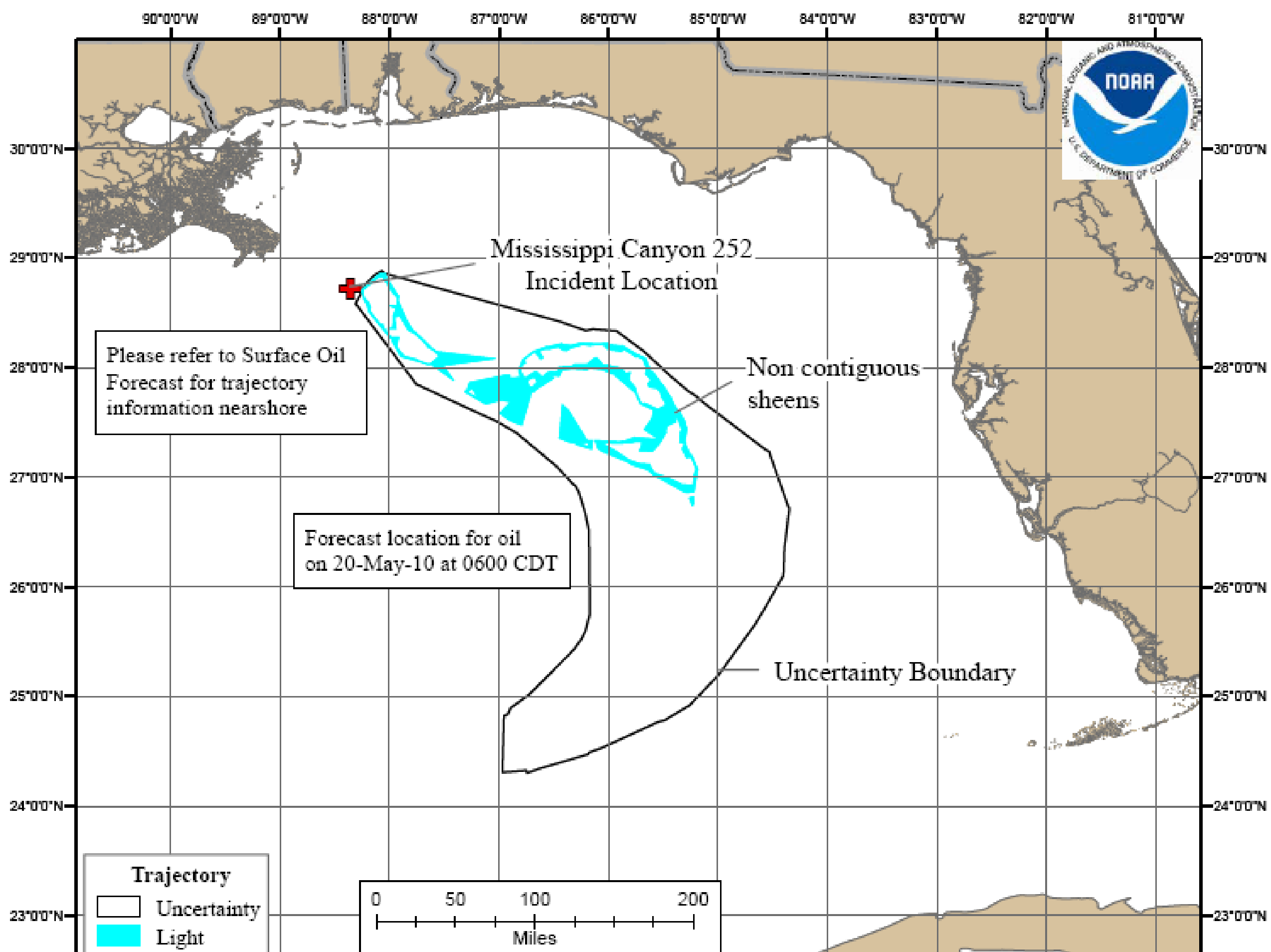
SABGOM OPeNDAP Server

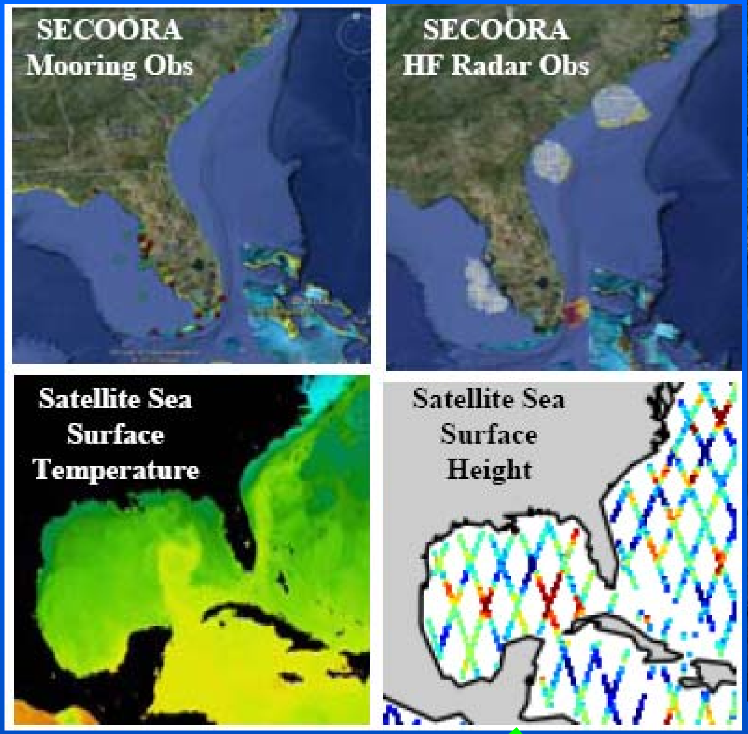
http://omglnx1.meas.ncsu.edu:8080/thredds/catalog/fmrc/sabgom/catalog.html

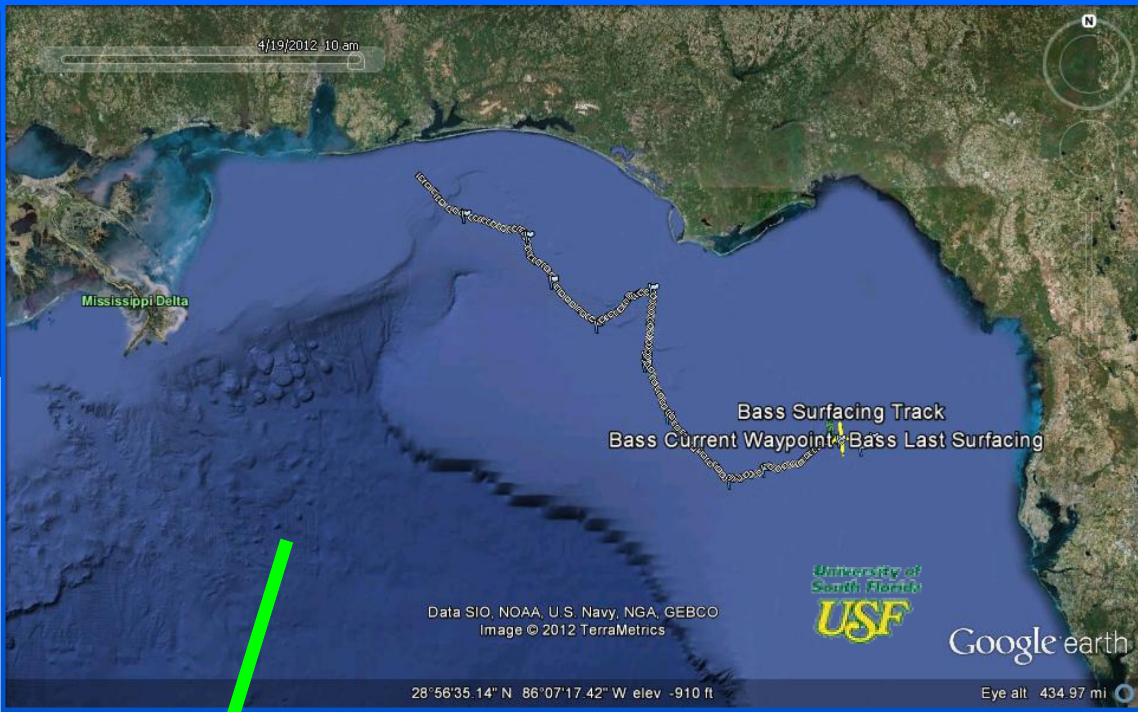
Offshore Surface Oil Forecast Mississippi Canyon 252

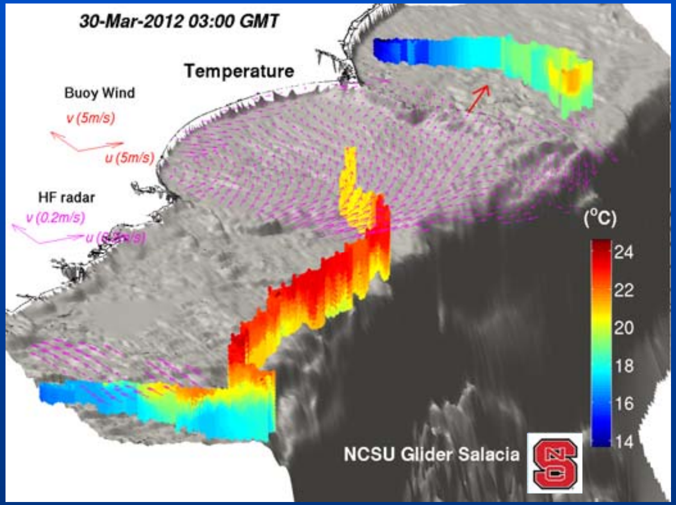
NOAA/NOS/OR&R
Estimate for: 0600 CDT, Thursday, 5/20/10
Date Prepared: 2100 CDT, Tuesday, 5/18/10

This map shows the predicted location of oil that has entered the loop current. Currents were obtained from four models: NOAA Gulf of Mexico, West Florida Shelf/USF, NRL IASNFS and NC State SABGOM. Each include Loop Current dynamics. Gulf wide winds were obtained from the gridded NCEP product. The model was initialized from Tuesday AM satellite imagery analysis (NOAA/NESDIS).



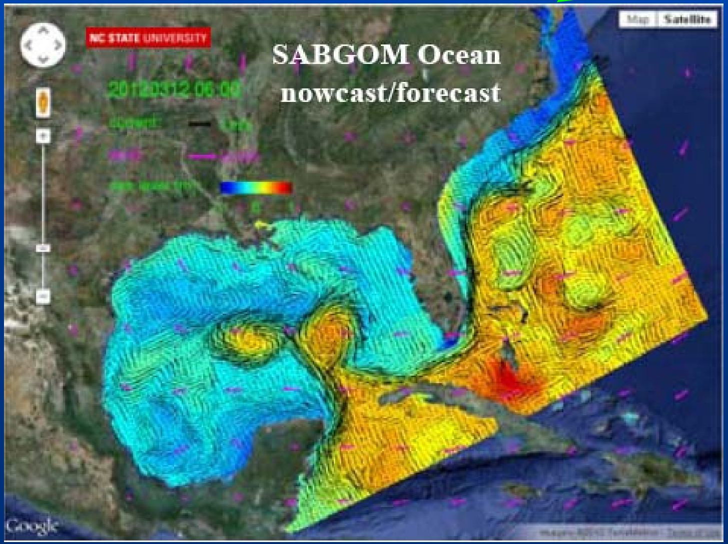






linking Model & Data though

Data Assimilation

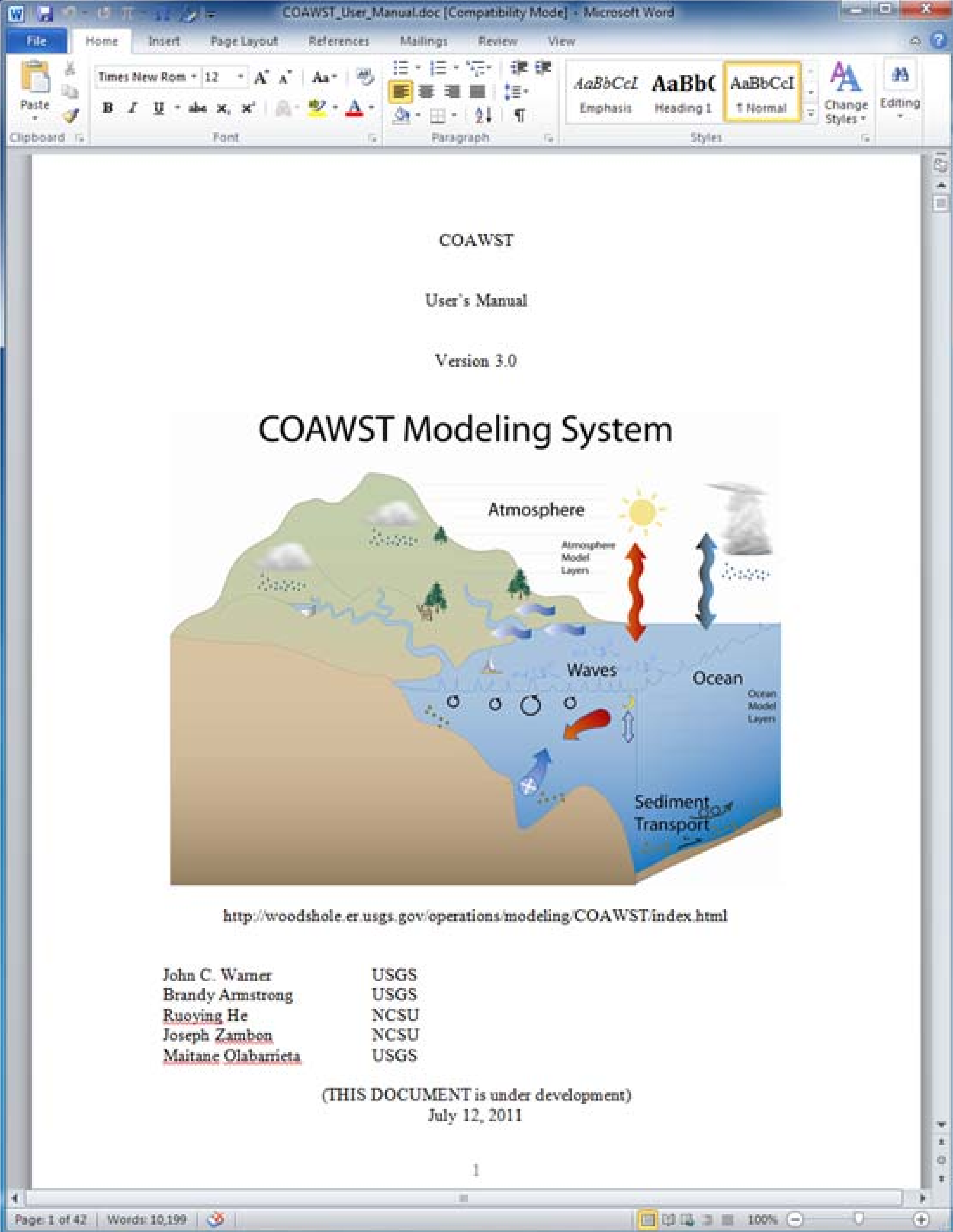


Summary

- It is important to take coupled ocean, wave, and atmospheric dynamical processes into consideration

- Coupled modeling systems provides a powerful tool to address both scientifically important and societal relevant problems (e.g., storm prediction, and hazard assessment and mitigation) in the coastal ocean.

- Deterministic predictions of the coastal ocean environment will require refined models, advanced observational infrastructure together with sophisticated techniques for data assimilation.



- Coupling of WRF-ROMS-SWAN

- ROMS 2-way flux conserving grid refinement

-SWAN 1 way grid refinement

- WRF has its own grid refinement

- roms+swan coupled on multiple levels of refinement

- Any one WRF level can drive the roms+swan. All grids can be different and we use SCRIP for flux conserving remapping

COAWST related publications

- Warner, J.C., Armstrong, B., He, R., and Zambon, J.B. (2010), Development of a Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system: *Ocean Modeling*, v. 35, no. 3, p. 230-244.

- Kumar, N., Voulgaris, G., and Warner, J.C. (2011). Implementation and modification of a three-dimensional radiation stress formulation for surf zone and rip-current applications, *Coastal Engineering*, 58, 1097-1117, doi:10.1016/j.coastaleng.2011.06.009.

- Olabarrieta, M., J. C. Warner, and N. Kumar (2011), Wave-current interaction in Willapa Bay, *J. Geophys. Res*., 116, C12014, doi:10.1029/2011JC007387.

- Kumar, N., Voulgaris, G., Warner, J.C., and M., Olabarrieta (2012). Implementation of a vortex force formalism in a coupled modeling system for inner-shelf and surf-zone applications. *Ocean Modeling*.

- Olabarieta, M., Warner, J., Armstrong, B., Zambon, J., and He, R. (2012), Ocean-Atmosphere Dynamics During Hurricane Ida and Nor'Ida: An Application of the Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System, *Ocean Modelling*, 43-44, 112-137.

- Xue, Z., He, R., Liu, J. P, J. C. Warner (2012), Modeling Transport and Deposition of the Mekong River Sediment, *Continental Shelf Research,* doi:10.1016/j.csr.2012.02.010.

- Nelson, J. and He. R. (2012), Effect of the Gulf Stream on Winter Extratropical Cyclone Outbreaks, *Atmospheric Research Letter,* doi: 10.1002/asl.400.