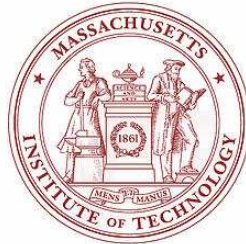**Pierre Lermusiaux, Pat Haley, Wayne Leslie, Oleg Logoutov**

(and AWACS team)

Mechanical Engineering, MIT

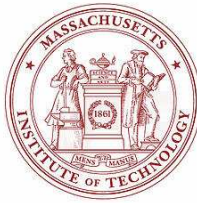http://modelseas.mit.edu/

❖ **MIT-HU AWACS Research Goals and Objectives**

❖ **Selected Research Progress so far**

1. **Assimilation of all data sets from AWACS-SW06-NMFS, with real-time web-based dissemination**

2. **Tides/internal tides and their interactions with mesoscales: processes, modeling and predictions**

3. **Nested Ocean Modeling**

4. **Adaptive sampling with ESSE and MILP or genetic algorithms**

5. **Future Plans**

MIT AWACS **Five-year** Research Objectives

Goal: Improve modeling of ocean dynamics, and develop and evaluate new adaptive sampling and search methodologies, for the environments in which the main AWACS-06, -07 and -09 experiments will occur, using the re-configurable REMUS cluster and coupled data assimilation

Specific objectives are to:

i. Provide near real-time fields and uncertainties in AWACS-06, -07 and -09 experiments and, in the final 2 years, develop algorithms for fully-coupled physical-acoustical DA among relocatable nested 3D physical and 2D acoustical domains (with NPS)

ii. Develop new adaptive ocean model parameterizations for specific AWACS-06, -07 and -09 processes, and compare these regional dynamics (with WHOI)

iii. Evaluate current methods and develop new algorithms for adaptive environmental-acoustic sampling, search and coupled DA techniques (Stage 1), based on a re-configurable REMUS cluster and on idealized and realistic simulations (with NPS/OASIS/Duke)

iv. Research optimal REMUS configurations for the sampling of interactions of the oceanic mesoscale with inertial oscillations, internal tides and boundary layers (with WHOI/NPS/OASIS)

v. Provide adaptive sampling guidance for array performance and surveillance (Stage 2), and link HU research with vehicle models and command and control

Autonomous Wide Aperture Cluster for Surveillance (AWACS):
Adaptive Sampling and Search Using Predictive Models with Coupled Data Assimilation and Feedback - Harvard Page
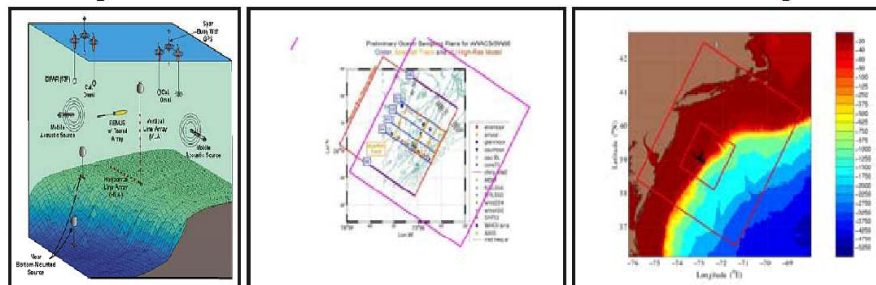
P.F.J. Lermusiaux, P.J. Haley, Jr.,
W.G. Leslie, O. Logoutov, A.R. Robinson

HARVARD UNIVERSITY
Division of Engineering and Applied Sciences
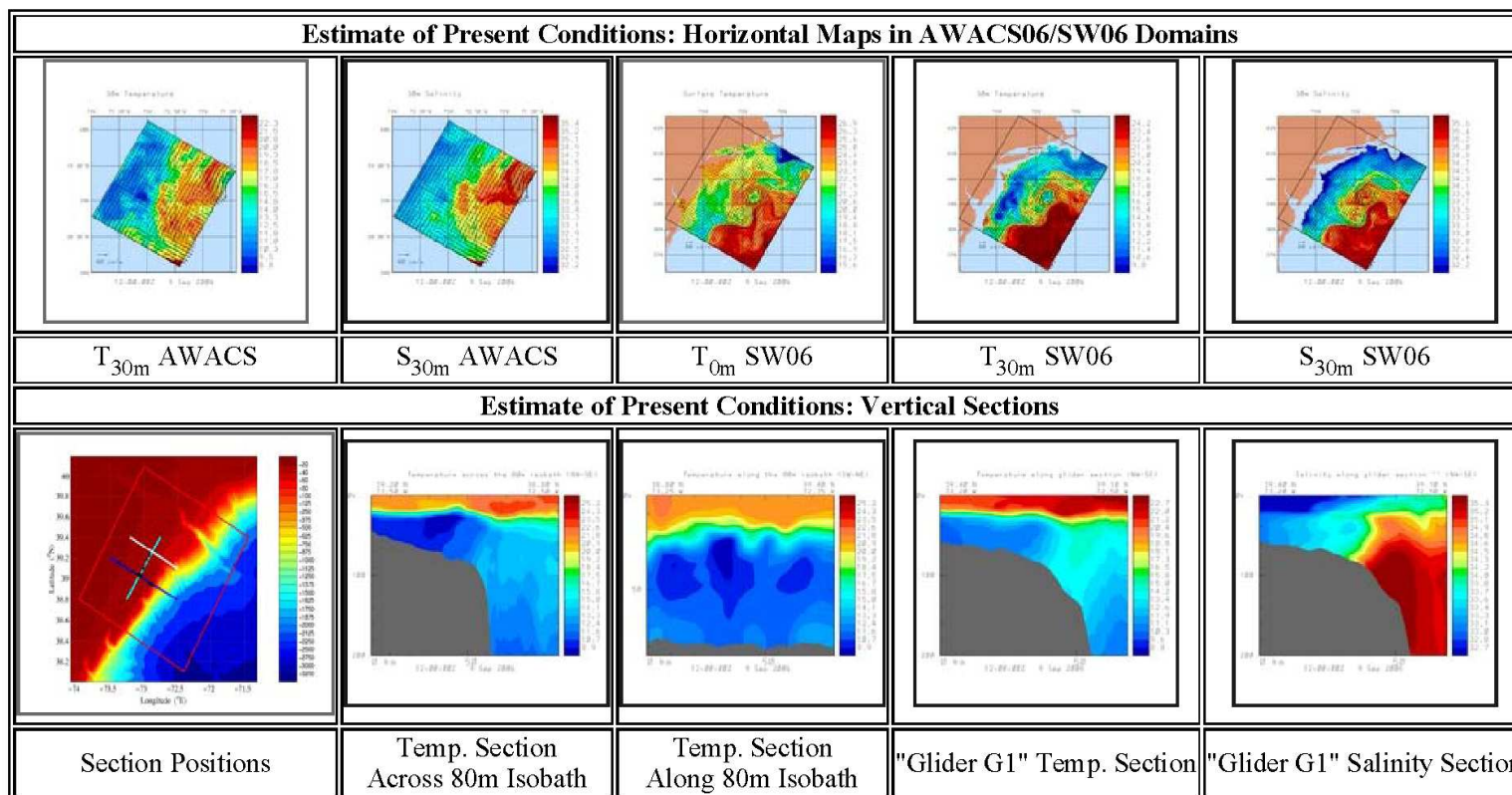**Department of Earth and Planetary Sciences**
Cambridge, Massachusetts

- Real-time Exercises Pages (Data, Analyses, Forecasts)
- AWACS Harvard Descriptive Pages
- Some References and Presentations
- Additional AWACS Links
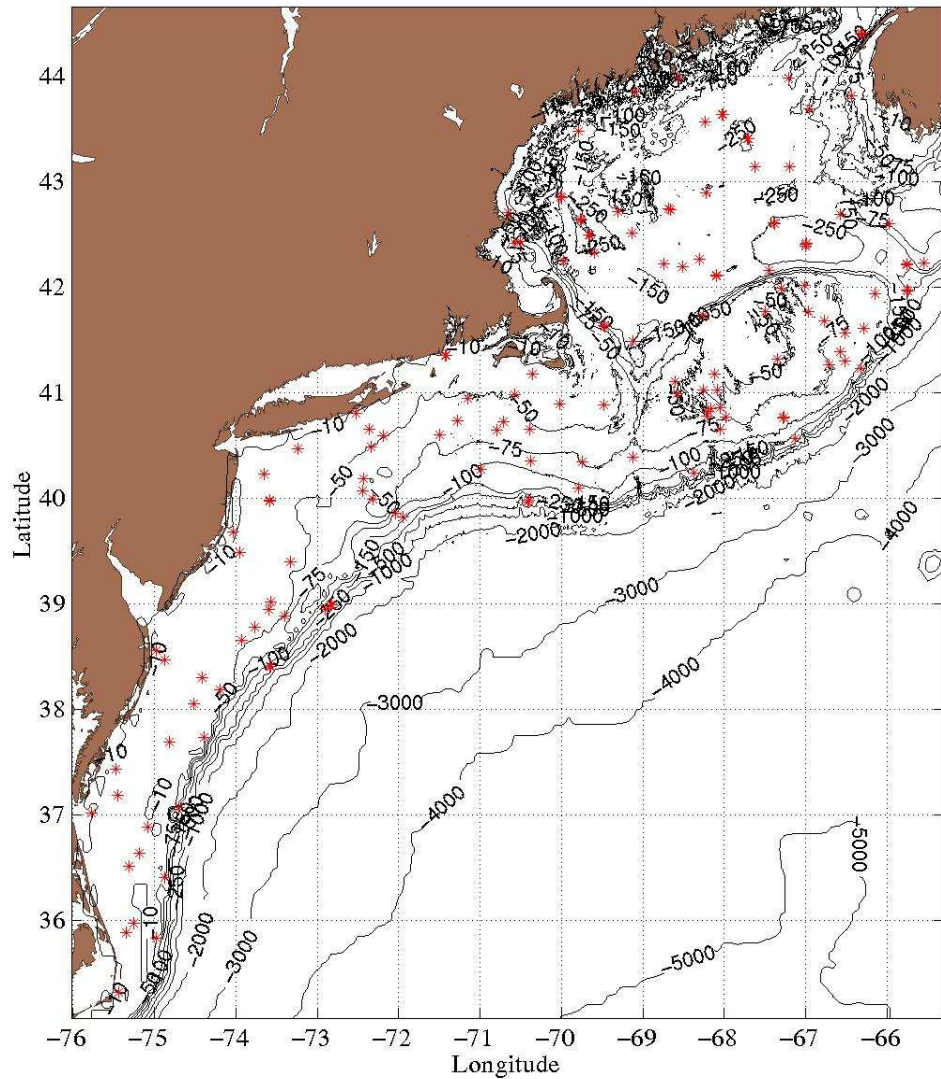- Data Sites
- Links to other Projects
- Asset Deployment

AWACS PIs:
P. Abbot, B. Carey, C.-S. Chiu, G. Gawarkiewicz, J. Krolik, P.F.J. Lermusiaux, J. Lynch, S. Smith.
Collaborators: T. Duda, K.D. Heaney

http://oceans.deas.harvard.edu/AWACS

AWACS Real-time New Jersey Shelf/Hudson-Canyon 06 Exercise

Estimate of Present Conditions: Horizontal Maps in AWACS06/SW06 Domains

T_{30m} AWACS	S_{30m} AWACS	T_{0m} SW06	T_{30m} SW06	S_{30m} SW06

Estimate of Present Conditions: Vertical Sections

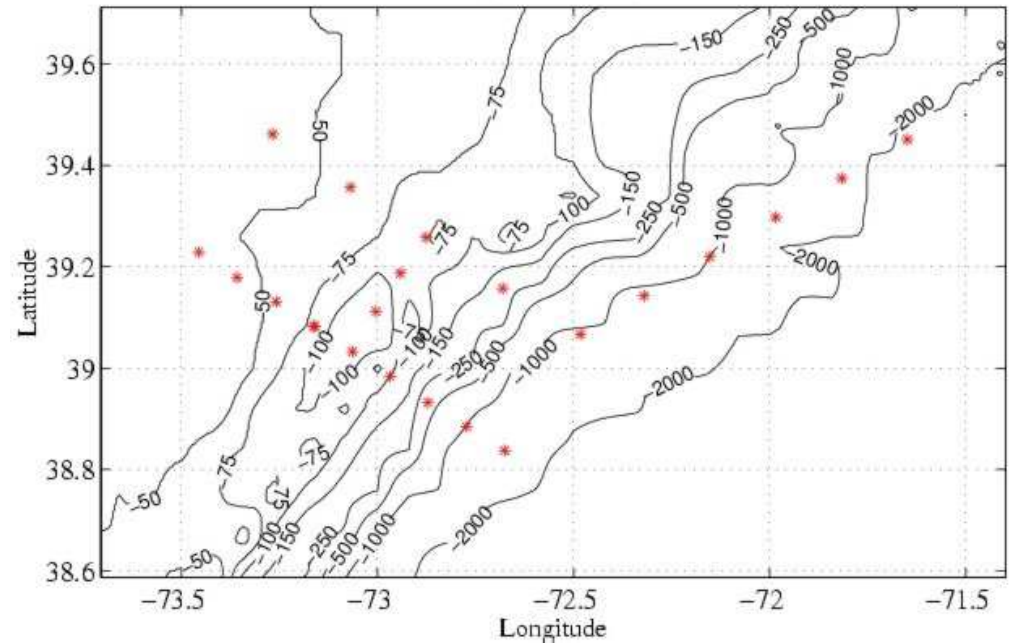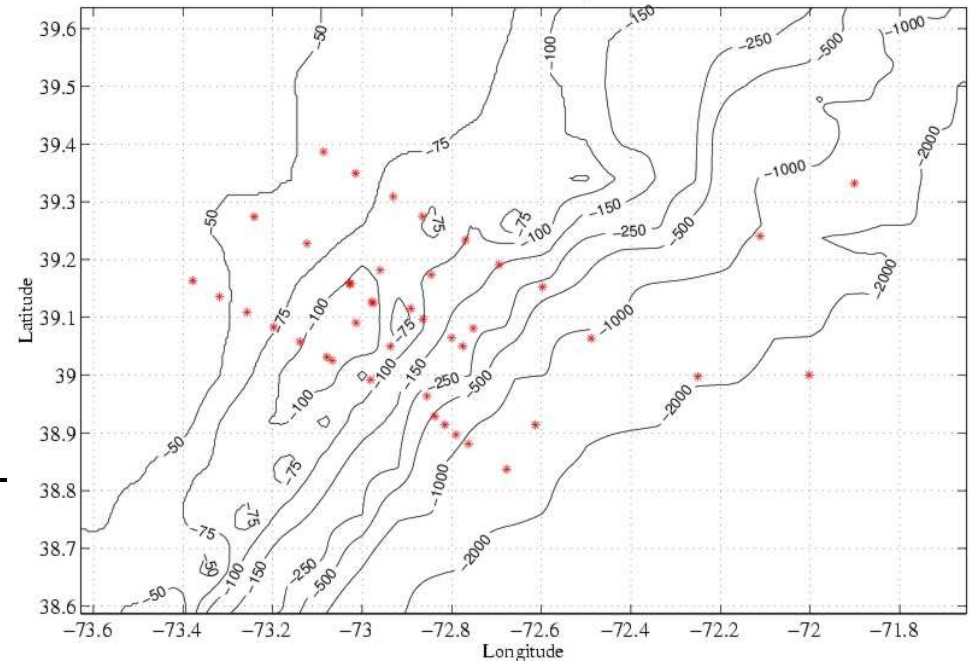| Section Positions	Temp. Section Across 80m Isobath	Temp. Section Along 80m Isobath	"Glider G1" Temp. Section	"Glider G1" Salinity Section

R/V Albatross: 1–14 June 2006

R/V Tioga: 17–19 July 2006

R/V Knorr: 1–30 July 2006

Station positions for the: (a) R/V Albatross 1-
14 June 2006 survey; (b) WHOI R/V Tioga 17-
19 July 2006; and, (c) WHOI Knorr 1-31 July.
All of these data sets were used only to
estimate background initial fields.

Two-way Nested Modeling and Data Assimilation, with Free-Surface and Tidally Driven PE model
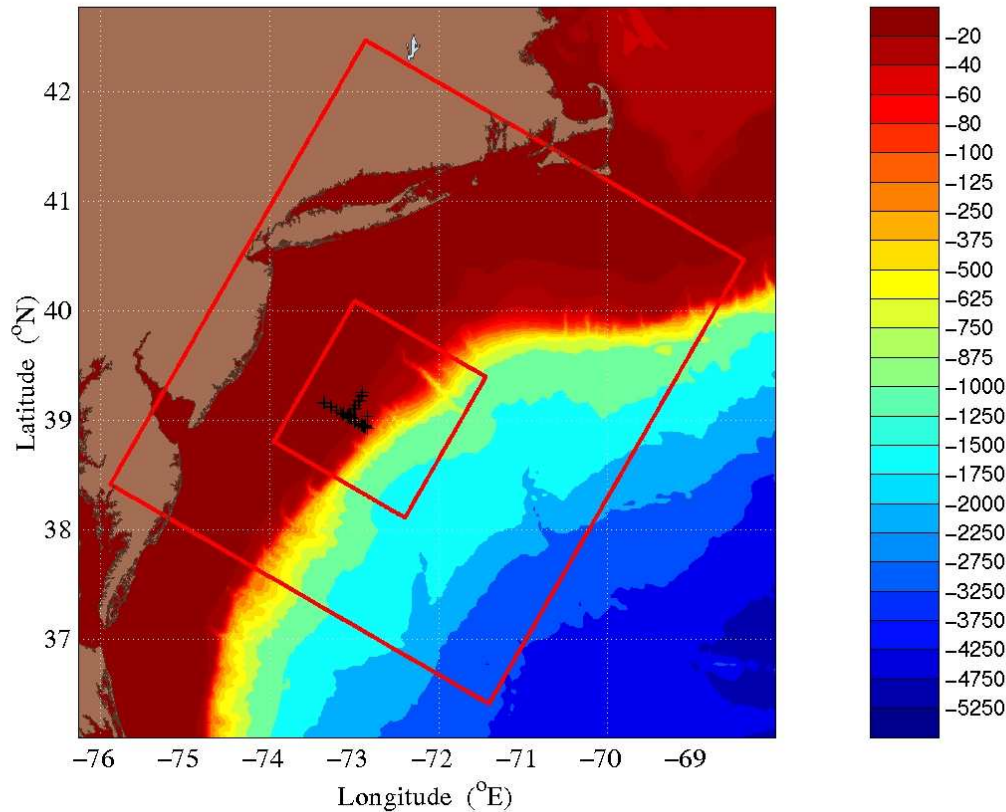

Fig 1. Two-way nested modeling domains (1km and 3km res.), overlaid on bathymetry (m) and SW06 mooring positions. Bathymetry based on NOAA coastal soundings combined with Smith&Sandwell

Fig 2. Barotropic Tidal velocities (u and v) at 39N and 73W, from August 31 to September 11 2006, as estimated by a new MIT-OTIS inversion (Matlab code). This variability impacts internal tides/waves.

Model coastal surface velocities compared and tuned to Rutgers' CODAR velocities in real-time. Show relatively good agreement.
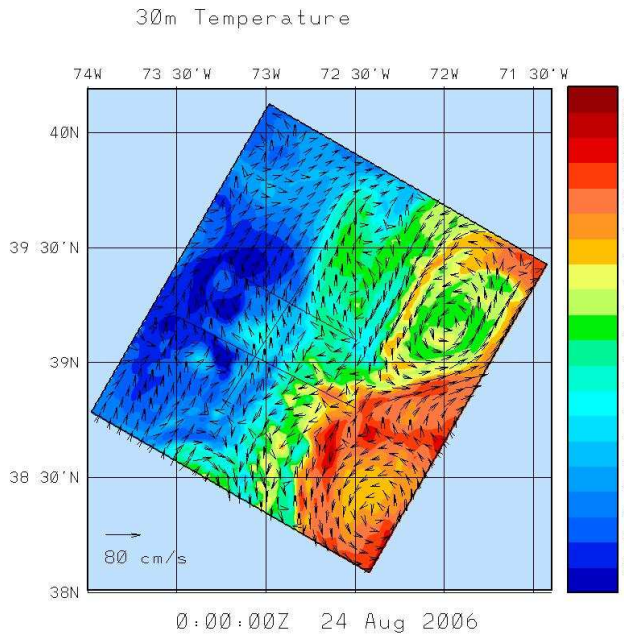
Fig. 3. Horizontal temperature maps in the nested 3km SW06 (top) and 1km AWACS (bottom) modeling domains, on Aug 24, 2006 (left), prior to the Tropical Storm Ernesto, and on Sep 3, 2006 (right), after Tropical Storm Ernesto. The temperature fields shown are at different depths: surface (0m) estimates are shown in the large SW06 domain, while thermocline (30m) estimates are shown in the AWACS domain (bottom).
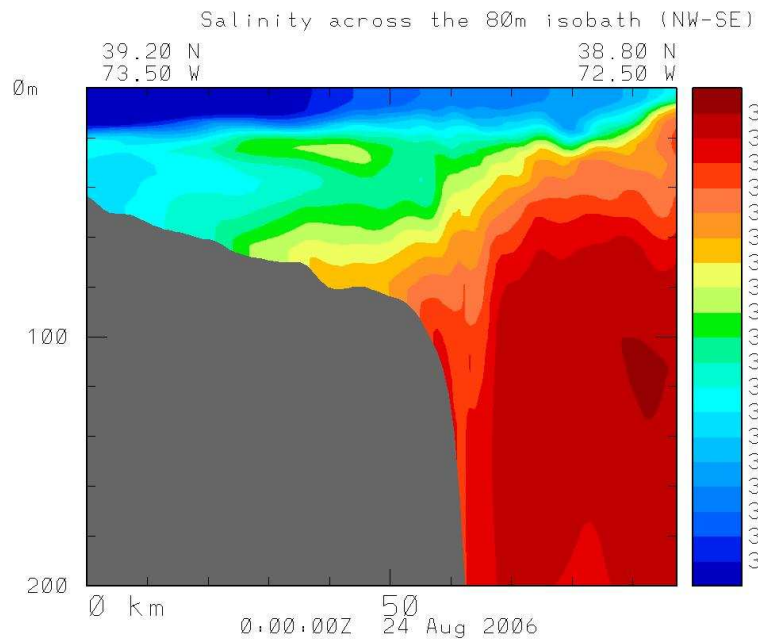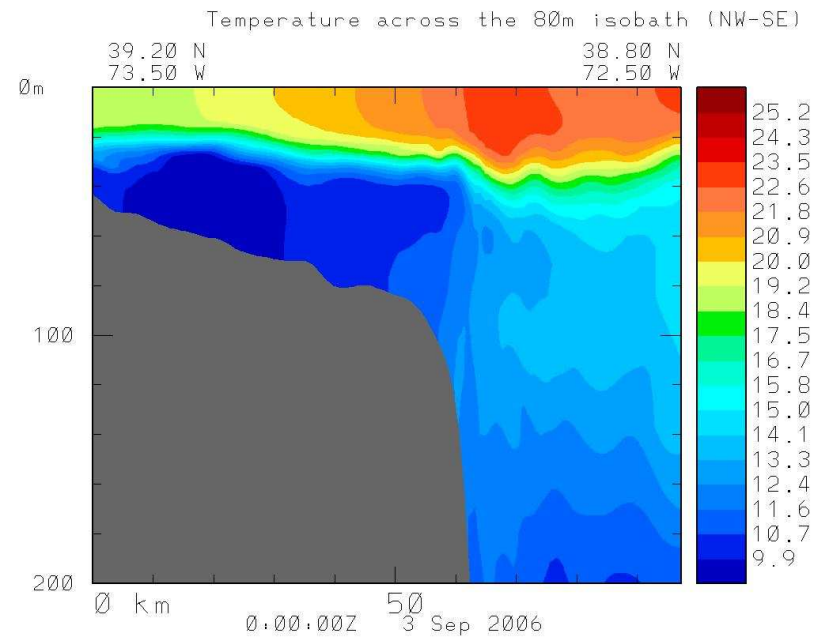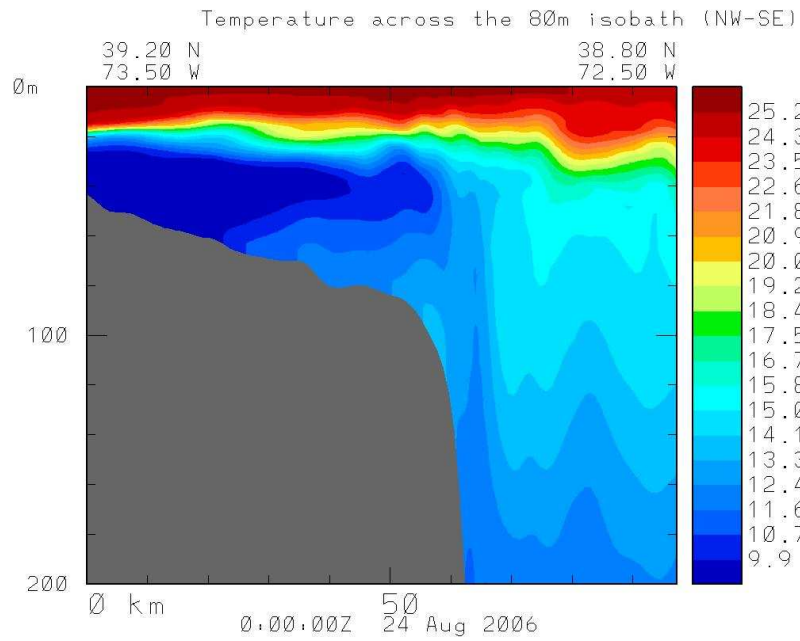
Figure 4. Cross-sections across the 80m isobath, along the main SW06 mooring line. Shown are temperature (top) and salinity (bottom) estimates on Aug 24, 2006 (prior to the Tropical Storm Ernesto) and on Sep 3 (after Tropical Storm Ernesto).
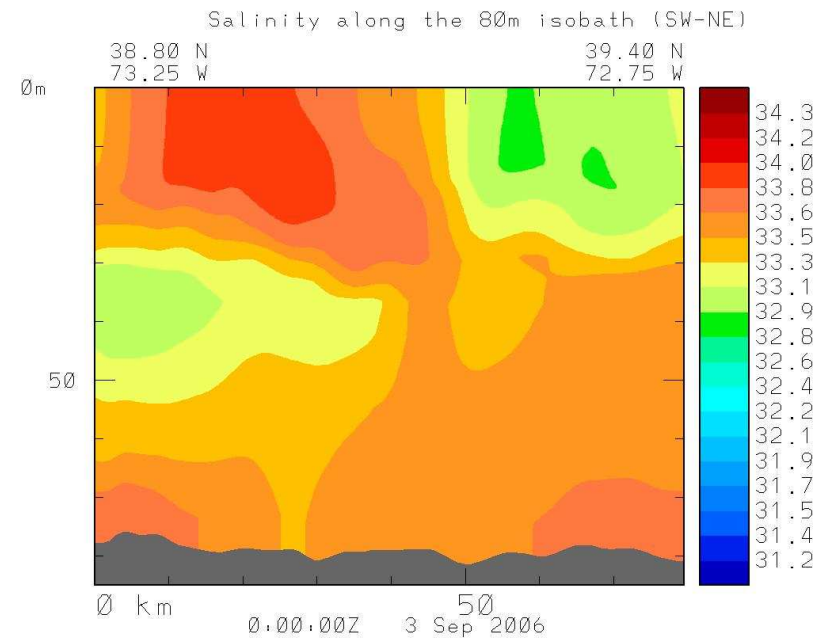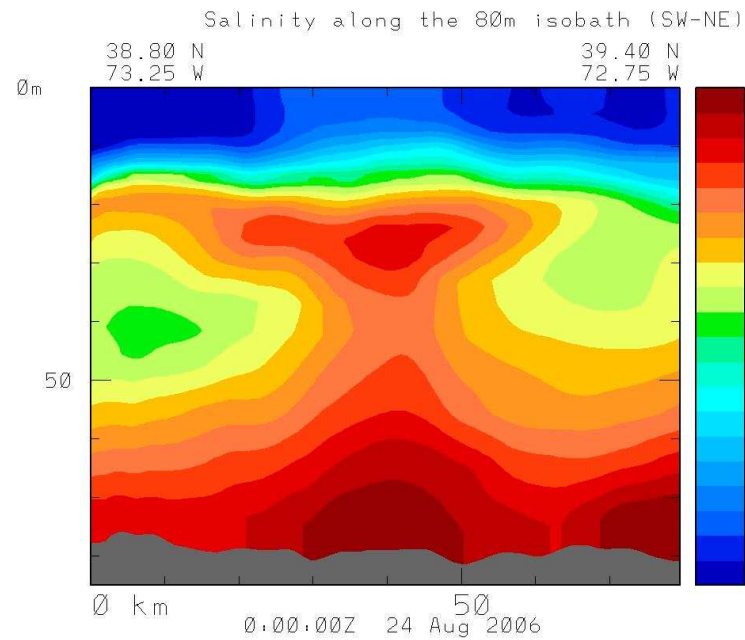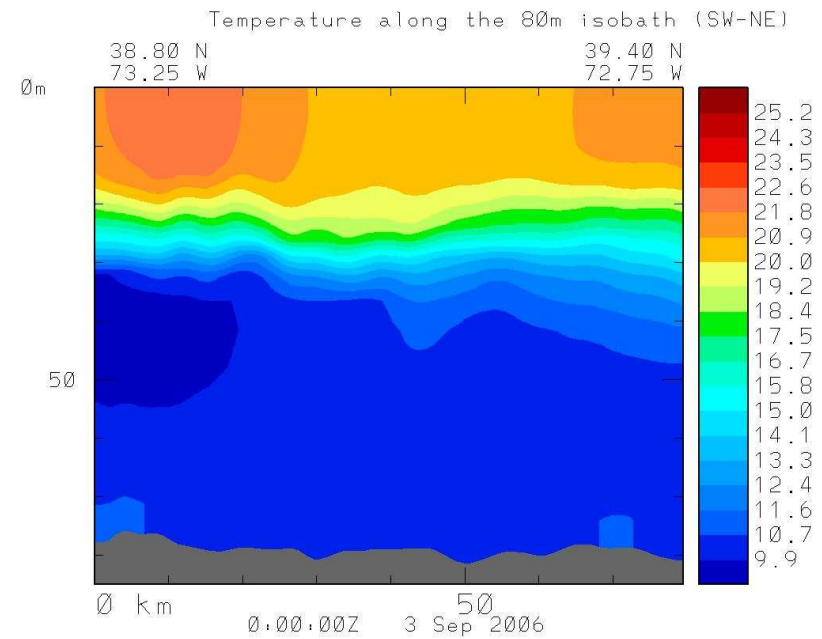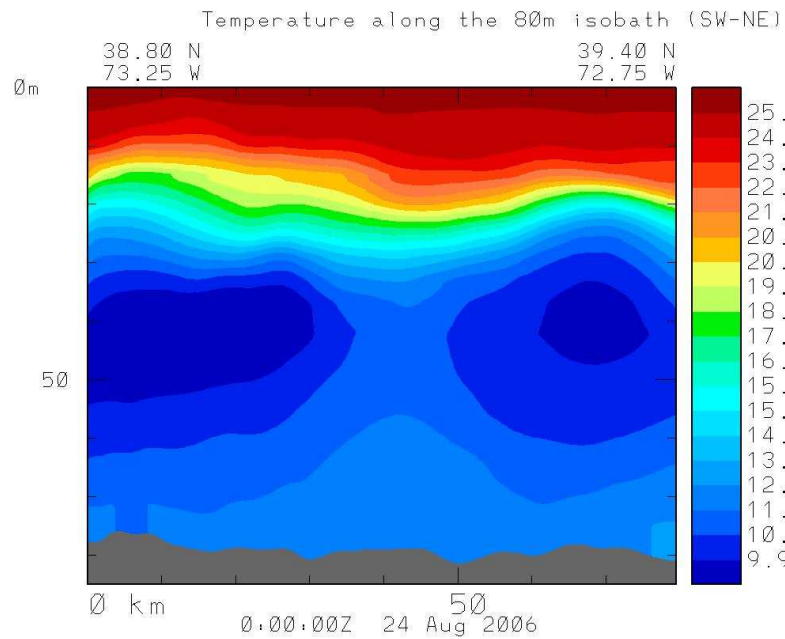
Figure 5. Cross-sections along the 80m isobath in the AWACS domain. Shown are temperature (top) and salinity (bottom) estimates on Aug 24, 2006 (prior to the Tropical Storm Ernesto) and on Sep 3 (after Tropical Storm Ernesto).

Summary of MIT work carried out so far in 2007

❖ **Model - Data comparisons and skill evaluations**

- SST
- Rutgers CODAR
- SW06 Moorings (Tim Duda)

❖ **Large number of model parameter sensitivity studies**

- Re-analyses runs: data-assimilative model simulations with different model parameters (bottom friction, mixing, nesting/stand-alone, etc)
- Compare all runs to each other and to ocean data

❖ **Numerical Modeling studies**

- Complete review of all tidal modeling, from barotropic tides to free-surface primitive-equations model (bottom friction, enforcement of B-grid continuity in barotropic tidal forcing)
- Evaluation/Improvements of Nested Modeling in idealized setting (special issue of Ocean Dynamics)
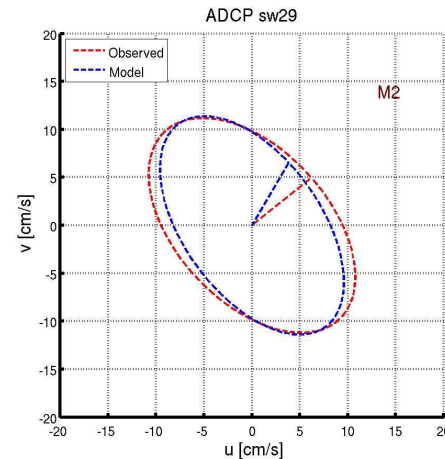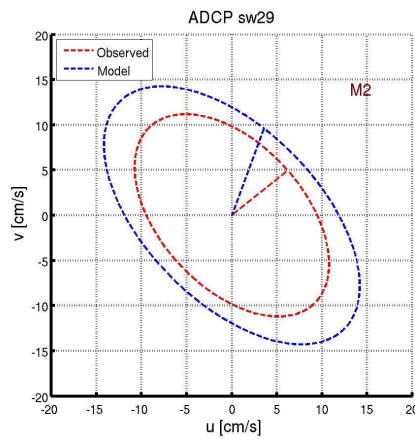
❖ **Adaptive Sampling OSSEs for Kevin Heaney and Tim Duda**
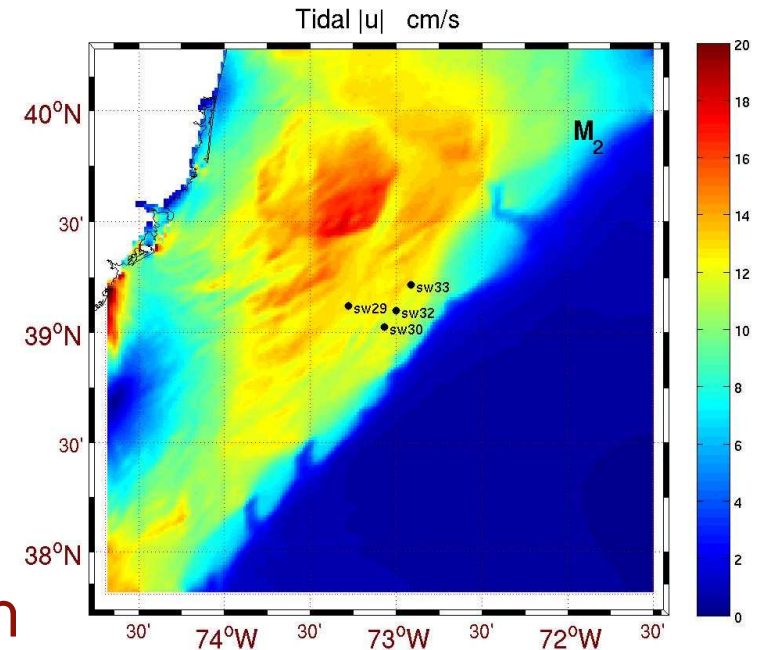
- Ran simulations and prepared fields, see:

http://modelseas.mit.edu/Research/AWACS/index.html

Improvements to barotropic tidal estimates/codes

- Sensitivities to bottom topographies. High Resolution Topo is now employed

Lower Res
Topo (5 min)

Hi Res
Topo (1 min)

M2 Tidal Velocity (max)
at 1 min resolution
(black dots show ADCP locations)

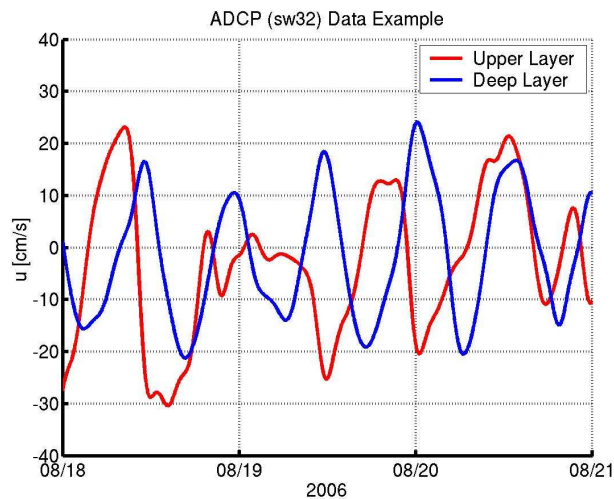- Work in progress close to completion
  - Optimal corrections to open boundary conditions based on tide gauge SSH data
  - Assimilation of velocity data
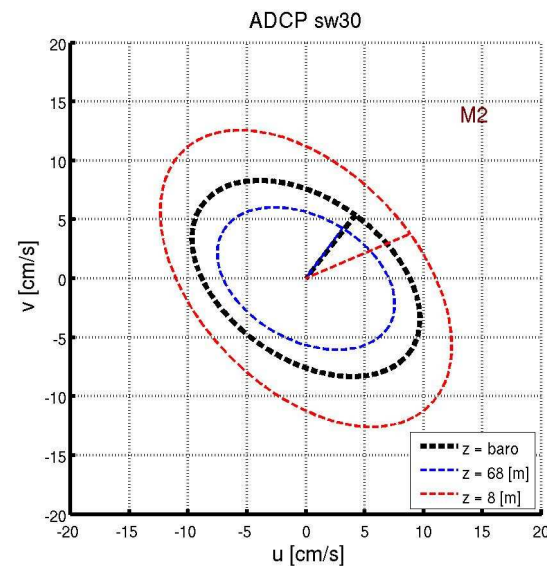 - Bottom friction parameters through adjoint method

Internal Tides / Internal Waves

- **Significant baroclinic structure is observed, including tidal velocities**

An Example of **Observed** Upper and Deep layer velocities: ADCP sw32

Observed Upper, Deep and **Baro** tidal velocity ellipses: note baroclinic structure

- **Internal tide/ internal wave generation/evolution must be captured**
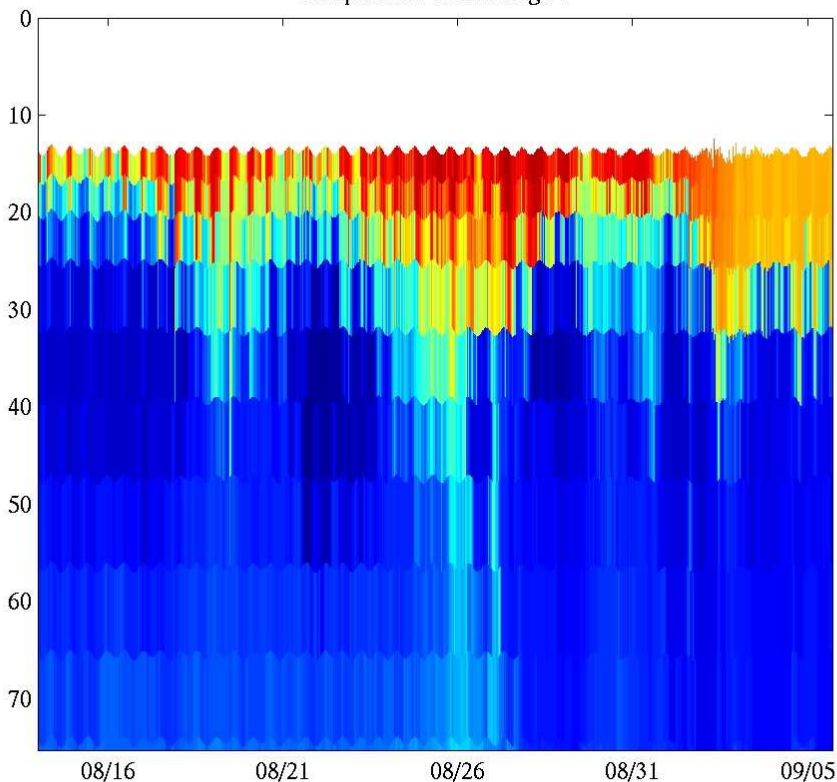
Towards Modeling and Scientific studies of Tides/internal tides and their interactions with mesoscales

- ❖ Most of the MIT-AWACS 2007 work so far (with model-data comparisons)

- ❖ Approach: Model estimates sampled at ½ hr intervals at selected mooring locations and compared to mooring data by Tim Duda (WHOI)

- ❖ Even though results are encouraging, fine scale needs improvement
    - ○ 1 km resolution insufficient (internal tides)
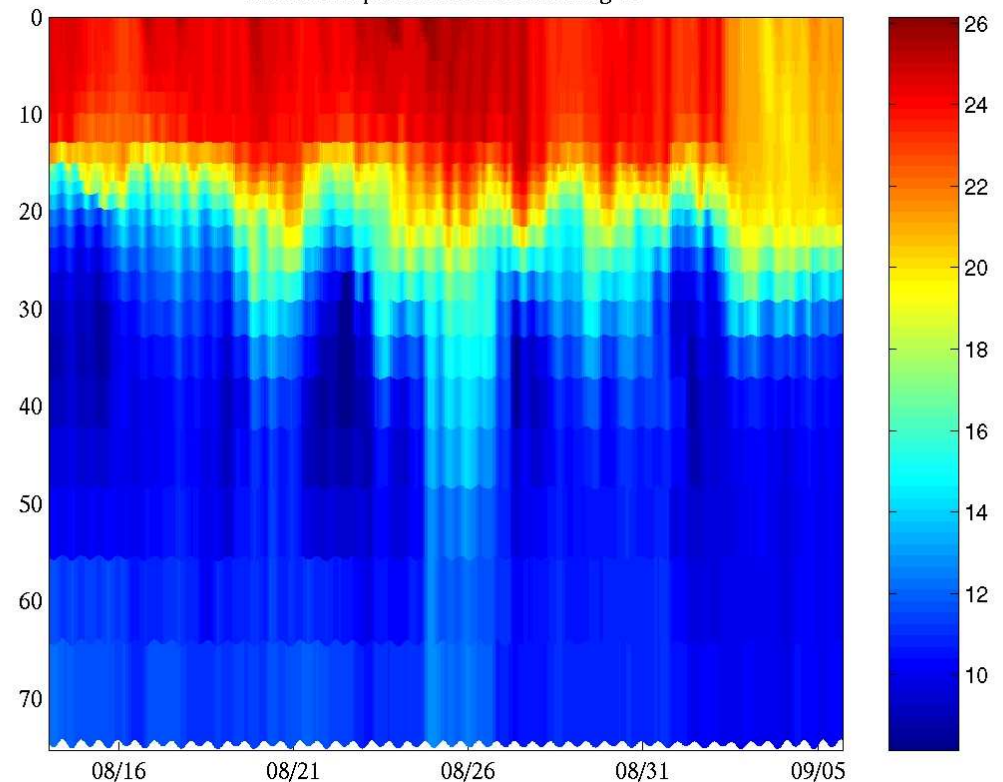   - ○ We are researching new adaptive sub-mesoscale parameterizations

T data

T Model

Temperature at Mooring 30
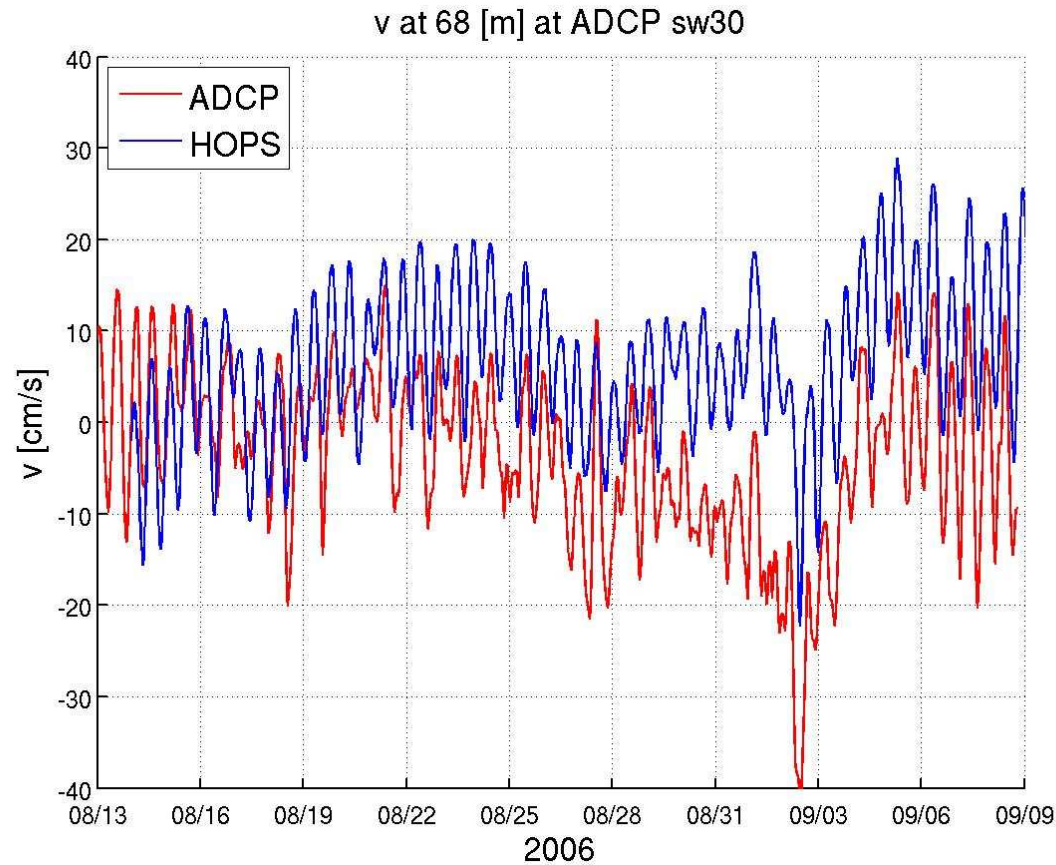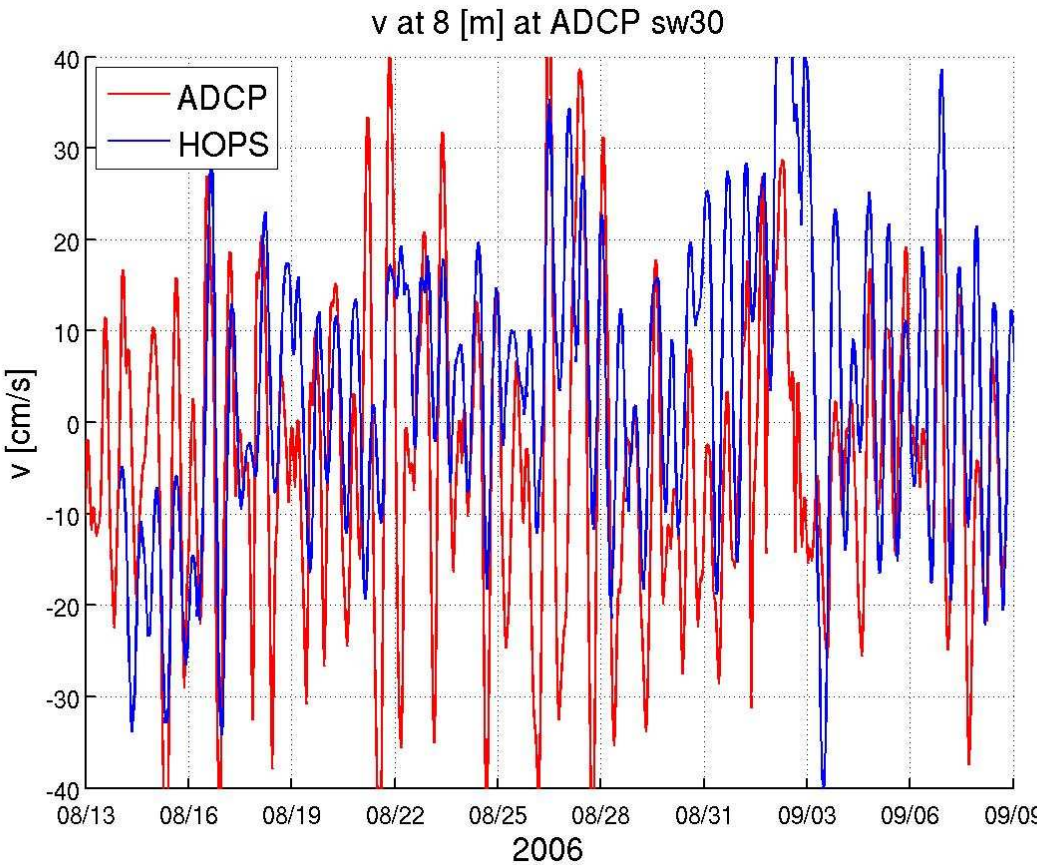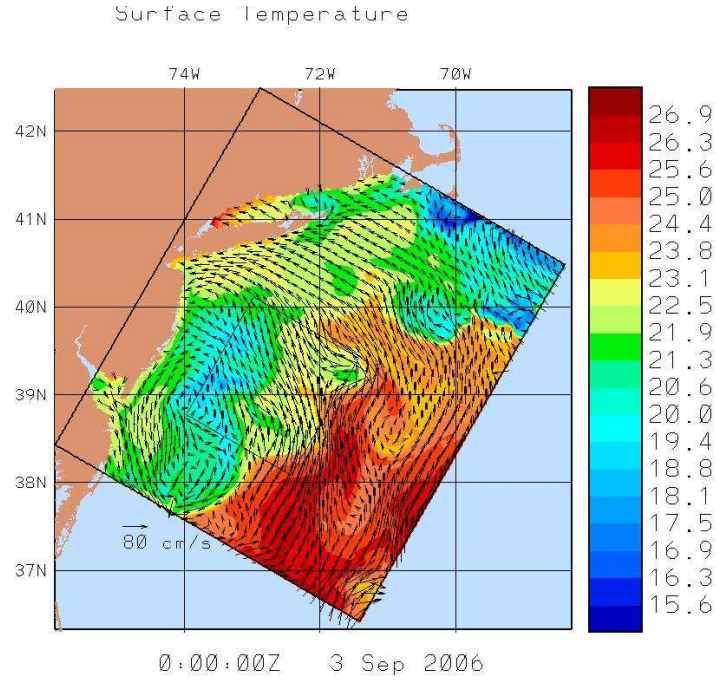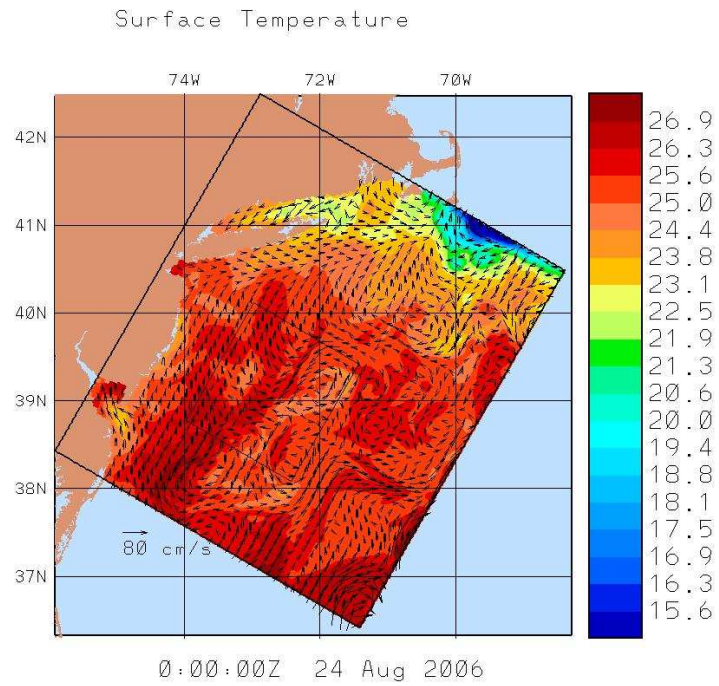
Model Temperature nearest Mooring 30

Towards Modeling and Scientific studies of Tides/internal tides and their interactions with mesoscales

Hourly meridional velocities (v) at 8m depth (left) and 68m depth (right) at the location of mooring SW30, as measured by the moored ADCP (red curve) and as estimated by a 3-km grid resolution HOPS re-analysis (blue curve) with atmospheric and barotropic tidal forcing. No mooring data are assimilated in HOPS.
Parameter sensitivity study shows importance of bottom friction.

Model coastal surface velocities compared and tuned to Rutgers' CODAR velocities in real-time. Show relatively good agreement.
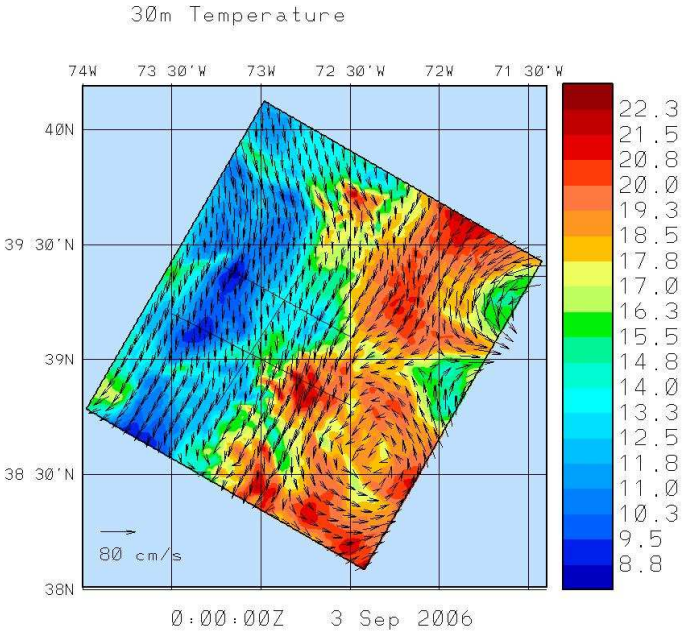
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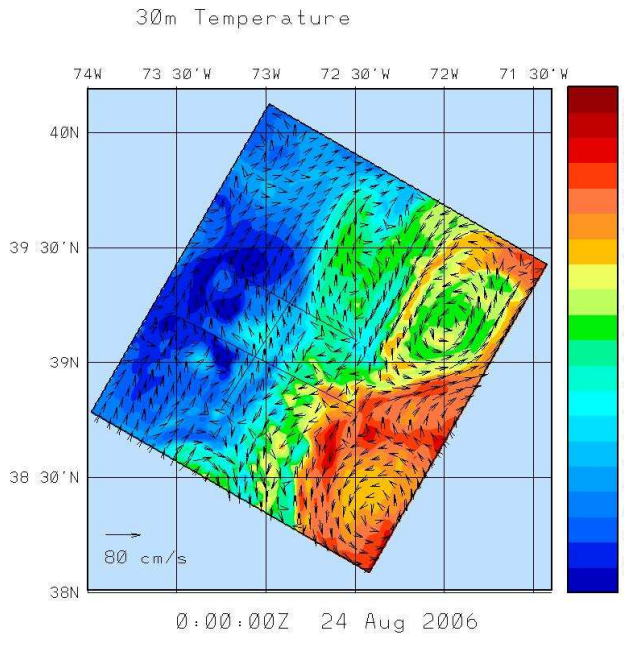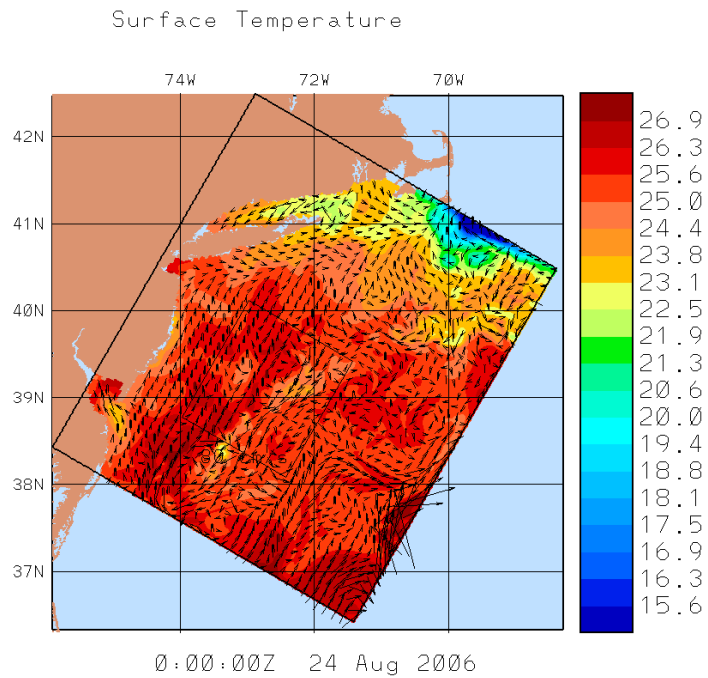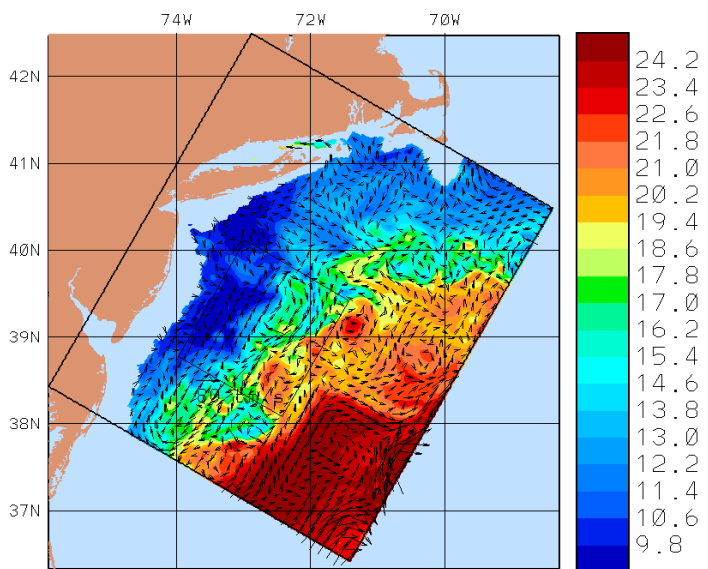
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HOPS 2-way Nested Modeling Domains and Grid Computing

New Free-Surface Primitive-Equation Ocean Model of HOPS
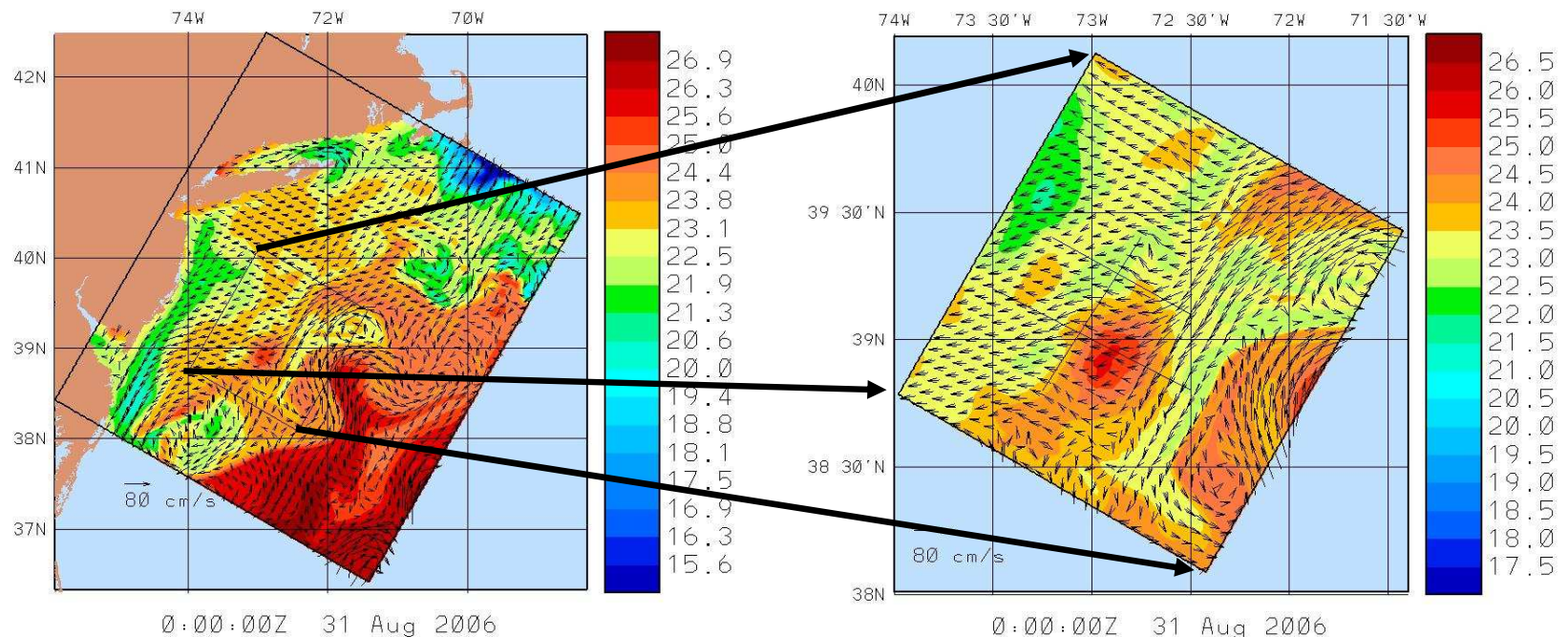
- Tidal and atmospheric forcing
- Twice-daily data assimilation

Nested Modeling with Grid-computing in Two Domains

- SW06 Domain: 3 km resolution
- AWACS Domain: 1 km resolution

Adaptive sampling recommendations, aiming to integrate coverage, dynamics and uncertainty (with K. Heaney and T. Duda).

Numerical Testing of 2-way Nesting: Idealized Studies

Issue: barotropic velocities in 2-way nested domains show discrepancy that slowly grows in time under the free-surface formulation

Goal: Test and improve nesting in simplified set-up.

- Large domain: 1000km x 1000km, periodic (East-West) channel, flat bottom (5000m)
- Small domain: 333km x 333km open domain centered in channel, flat bottom (5000m)
- ICs: sinusoidal jet, smoothed Gulf Stream mass field, quiescent outside of jet.

Model Output Files from Control Forecast Runs (for OSSE)
In collaborations with Kevin Heaney and Tim Duda

http://modelseas.mit.edu/Research/AWACS/RunCompOsse/Control/

Here we provide the output netCDF files from a series of forecast runs for two different time periods:

Prior to tropical storm Ernesto (24-27 Aug 2007)

   Central Simulation

After tropical storm Ernesto (4-7 Sep 2007)

   Central Simulation

Outputs are hourly. Each file contains temperature (℃), salinity (PSU) and horizontal velocity (cm/s, aligned East-West and North-South) fields, every hour, on the following constant depth levels (in m):

0 -5 -10 -15 -20 -25 -30 -40 -50 -60 -80 -100 -125 -150 -200 -250 -300 -400 -500 -600 -800 -1000 -1250 -1500 -2000 -2500 -3000

Optimal Paths Generation for a "fixed" objective field
(Namik K. Yilmaz, P. Lermusiaux, C. Evangelinos and N. Patrikalakis)

- Objective: Minimize ESSE error standard deviation of temperature field

- Scales: Strategic/Tactical

- Assumptions
  - Speed of platforms >> time-rate of change of environment
  - Objective field fixed during the computation of the path and is not affected by new data

- Problem solved: assuming the error is like that now and will remain so for the next few hours, where do I send my gliders/AUVs?

- Method: *Combinatorial optimization (Mixed-Integer Programming, using Xpress-MP code)*
  - Objective field (error stand. dev.) represented as a piecewise-linear: solved *exactly* by MIP
  - Possible paths defined on discrete grid: set of possible path is thus finite (but large)
  - Constraints imposed on vehicle displacements dx, dy, dz for meaningful path

**Example:
Two and Three
Vehicles,
2D objective field (3D
examples also done)**

Grey dots: starting points
White dots: MIP optimal end points