Ocean Prediction Systems:
Concepts and Advanced Research Issues

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Ocean Prediction System Concept

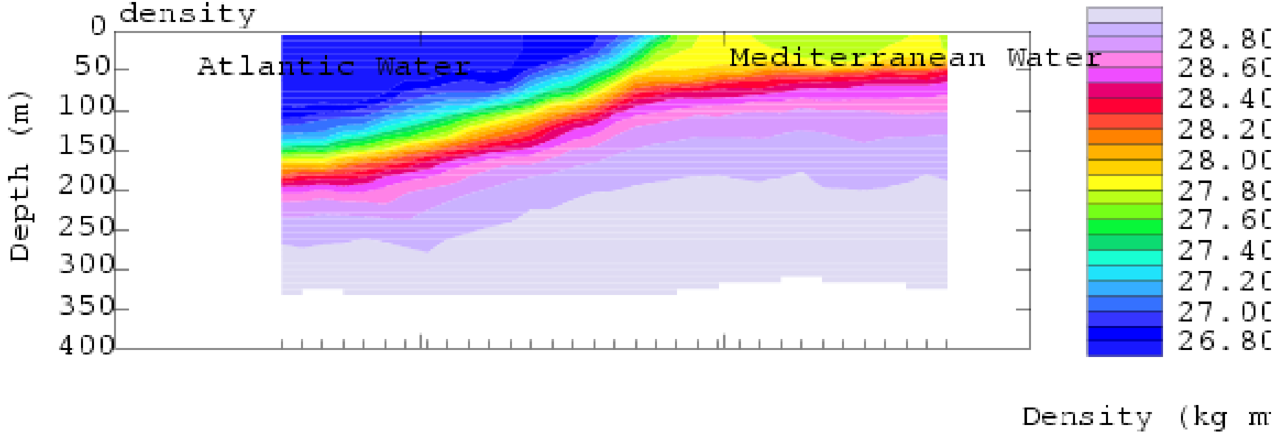
- Interdisciplinary ocean science research underway on coupled physical, biological, chemical, sedimentological, acoustical, optical non-linear, multi-scale, interdisciplinary processes intermittent in space and time
- Ocean Observing and Prediction Systems for science and operational applications have been initiated on basin, regional and coastal scales and consist of three major components
  - An observational network: a suite of platforms and sensors for specific tasks
  - A suite of interdisciplinary dynamical models
  - Data assimilation schemes

Interdisciplinary Data Assimilation

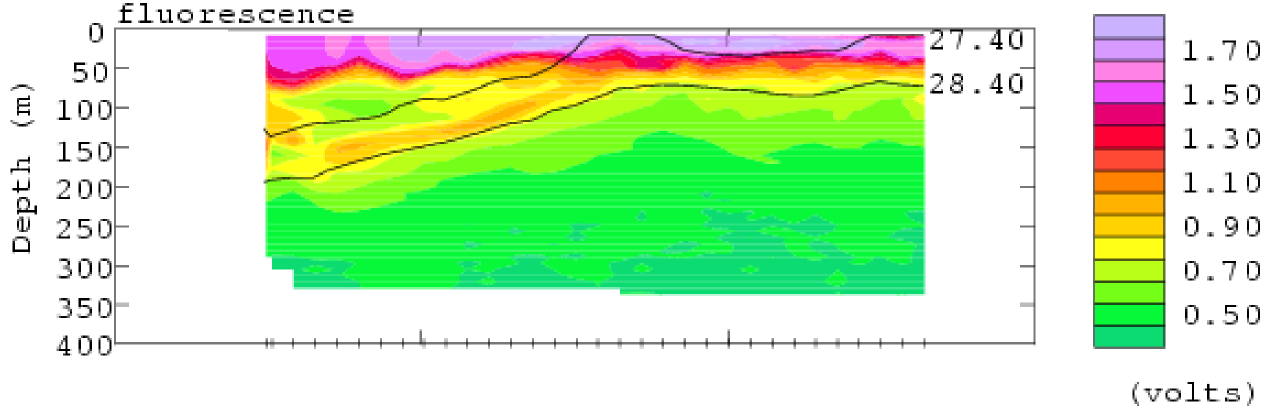
- **Data assimilation can contribute powerfully to understanding and modeling physical-acoustical-biological processes and is essential for ocean field prediction and parameter estimation**

- **Model-model, data-data and data-model compatibilities are essential and dedicated interdisciplinary research is needed**

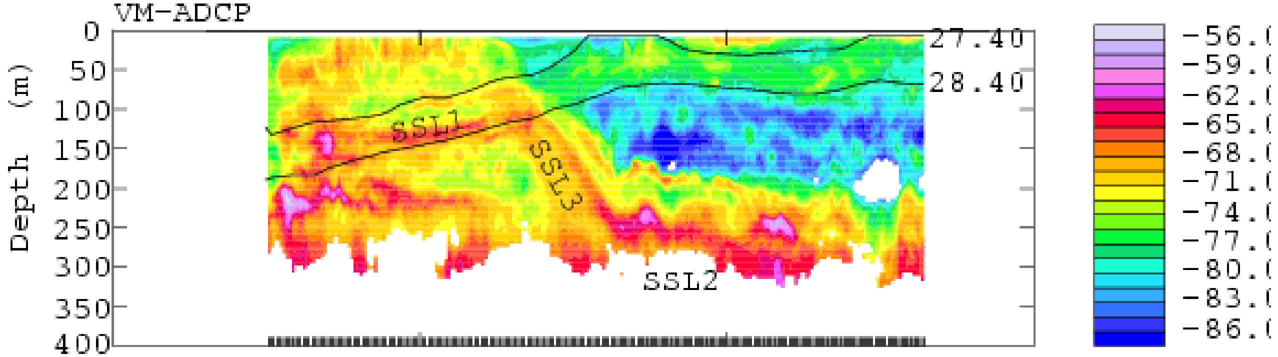
Interdisciplinary Processes - Biological-Physical-Acoustical Interactions



Physics - Density



Biology –
Fluorescence
(Phytoplankton)



Acoustics –
Backscatter
(Zooplankton)

Almeira-Oran front in Mediterranean Sea
Fielding *et al*, JMS, 2001

Griffiths *et al*,
Vol 12, THE SEA

Coupled Interdisciplinary Data Assimilation

$\boldsymbol{x} = [\boldsymbol{x}_A \;\; \boldsymbol{x}_O \;\; \boldsymbol{x}_B]$ **Unified interdisciplinary state vector**

Physics: $\boldsymbol{x}_O = [T, S, U, V, W]$

Biology: $\boldsymbol{x}_B = [N_i, P_i, Z_i, B_i, D_i, C_i]$

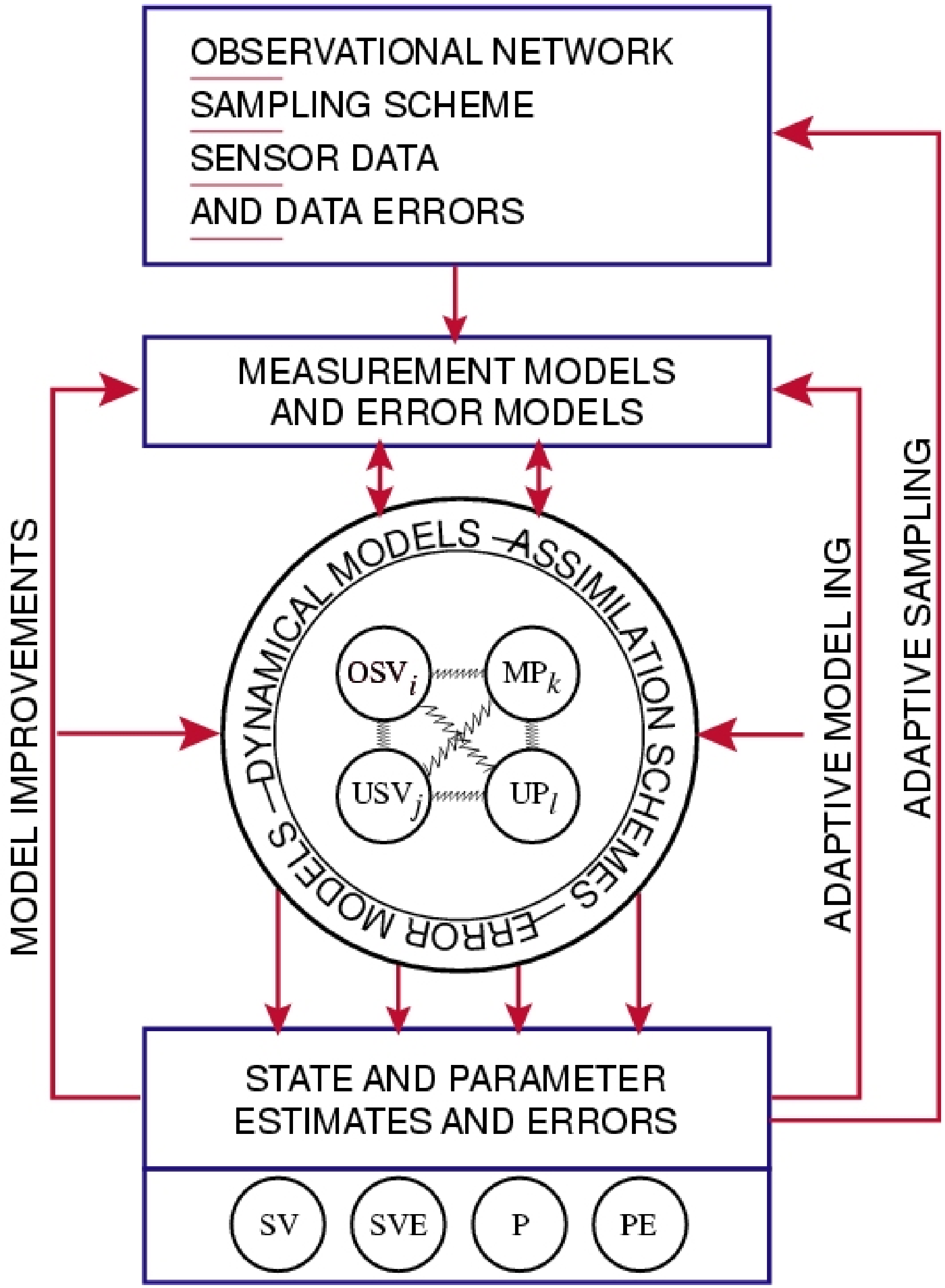
Acoustics: $\boldsymbol{x}_A = [\text{Pressure } (p), \text{Phase } (\varphi)]$

$$\boldsymbol{P} = \varepsilon \left\{ (\hat{\boldsymbol{x}} - \boldsymbol{x}^t)(\hat{\boldsymbol{x}} - \boldsymbol{x}^t)^T \right\}$$

Coupled error covariance with off-diagonal terms

$$\boldsymbol{P} = \begin{pmatrix} P_{AA} & P_{AO} & P_{AB} \\ P_{OA} & P_{OO} & P_{OB} \\ P_{BA} & P_{BO} & P_{BB} \end{pmatrix}$$

Data Assimilation in Advanced Ocean Prediction Systems



OBSERVATIONAL NETWORK
SAMPLING SCHEME
SENSOR DATA
AND DATA ERRORS

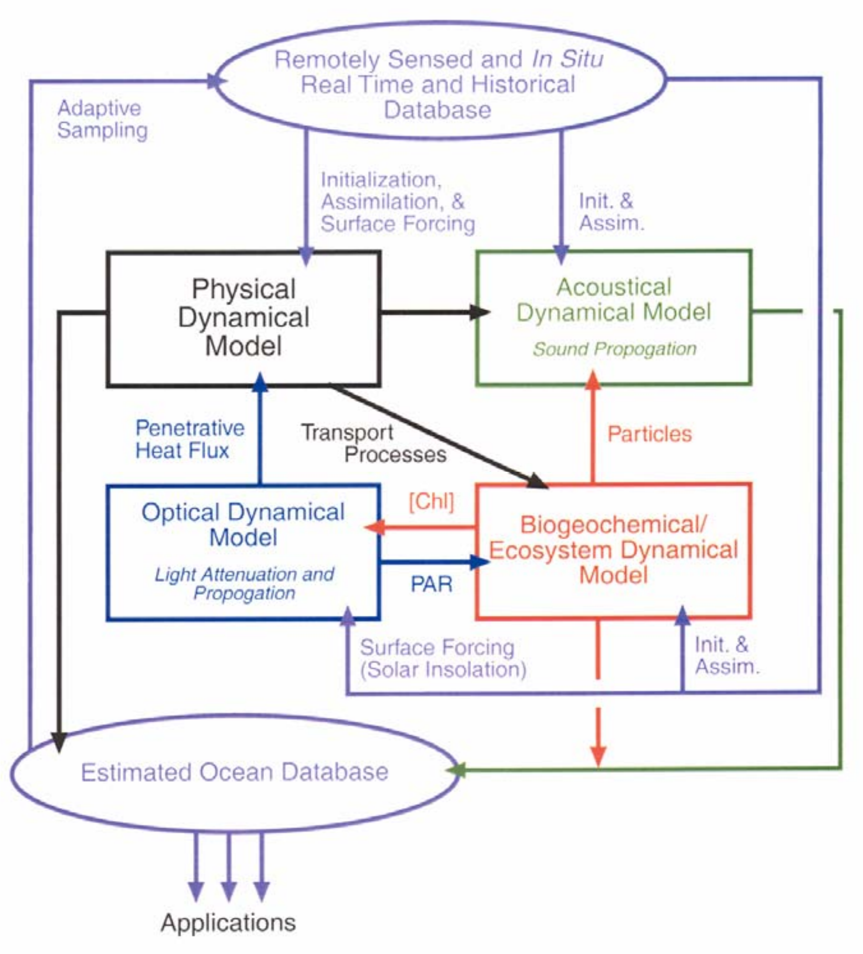
MEASUREMENT MODELS
AND ERROR MODELS

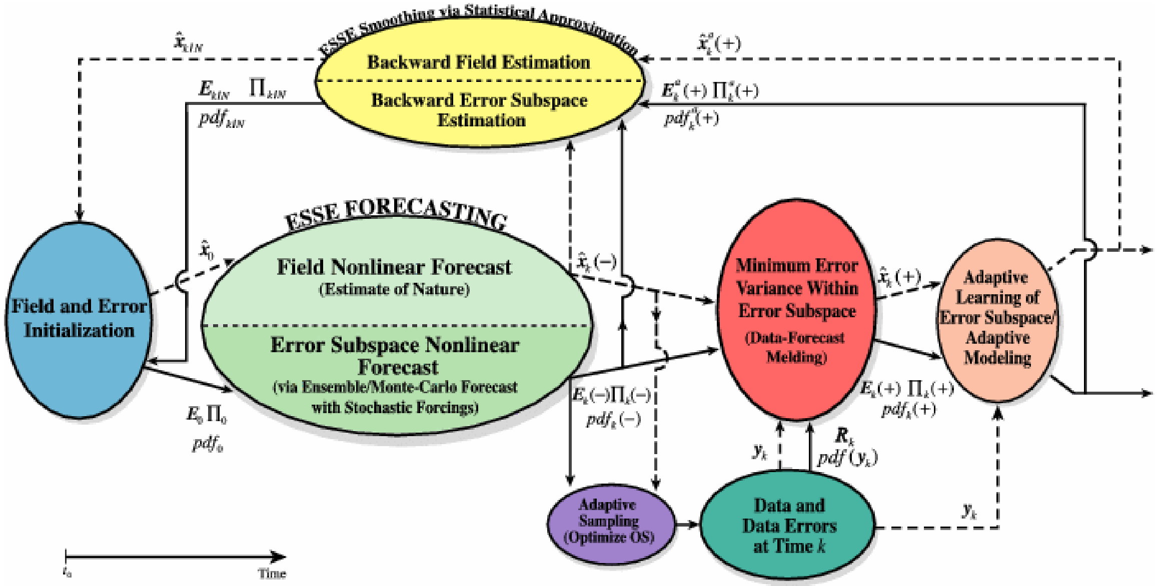
DYNAMICAL MODELS – ASSIMILATION SCHEMES – ERROR MODELS

STATE AND PARAMETER
ESTIMATES AND ERRORS

SV: STATE VARIABLE
P: PARAMETER
O: OBSERVED
M: MEASURED
U: UNOBSERVED OR UNMEASURED
E: ERROR
⁓⁓: DYNAMICAL LINKAGES

HOPS/ESSE System





Harvard Ocean Prediction System

Error Subspace Statistical Estimation

HOPS/ESSE Long-Term Research Goal

To develop, validate, and demonstrate an advanced
relocatable regional ocean prediction system
for real-time ensemble forecasting and simulation of
interdisciplinary multiscale oceanic fields and their
associated errors and uncertainties,
which incorporates both
autonomous adaptive modeling and
autonomous adaptive optimal sampling

Approach

To achieve regional field estimates as realistic and valid as possible:

- **every effort is made to acquire and assimilate both remotely sensed and *in situ* synoptic multiscale data from a variety of sensors and platforms in real time or for the simulation period, and a combination of historical synoptic data and feature models are used for system initialization**

- **"fine-tune" the model to the region, processes and variabilities: *examine model output*, modify set-up (e.g. grids, etc.) and alter structure and values of parameters (e.g. SGS, boundary conditions, etc.)**

- **continuously evaluate and iterate tuning as necessary**

Mini-HOPS

- Designed to locally solve the problem of accurate representation of sub-mesoscale synopticity
- Involves rapid real-time assimilation of high-resolution data in a high-resolution model domain nested in a regional model
- Produces locally more accurate oceanographic field estimates and short-term forecasts and improves the impact of local field high-resolution data assimilation
- Dynamically interpolated and extrapolated high-resolution fields are assimilated through 2-way nesting into large domain models

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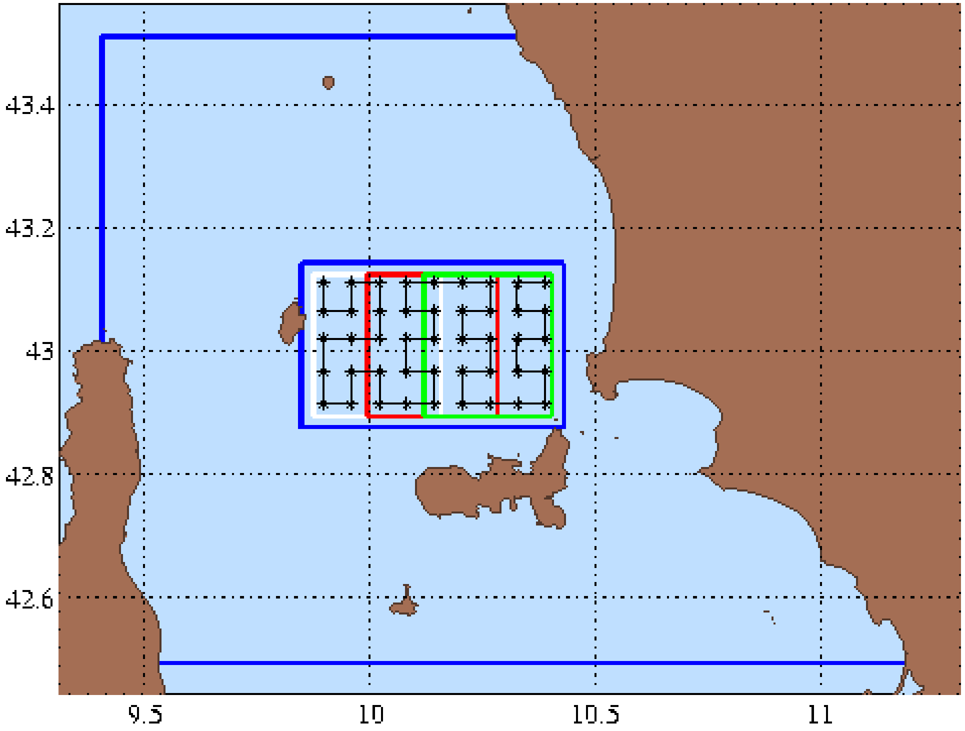
In collaboration with Dr. Emanuel Coelho (NATO Undersea Research Centre)

MREA-03 Mini-HOPS Protocol

- Regional Domain (1km) run at Harvard in a 2-way nested configuration with a super-mini domain.
  - Super mini has the same resolution (1/3 km) as the mini-HOPS domains and is collocated with them
- From the super-mini domain, initial and boundary conditions were extracted for all 3 mini-HOPS domains for the following day and transmitted to the NRV Alliance.
- Aboard the NRV Alliance, the mini-HOPS domains were run the following day, with updated atmospheric forcing and assimilating new data.

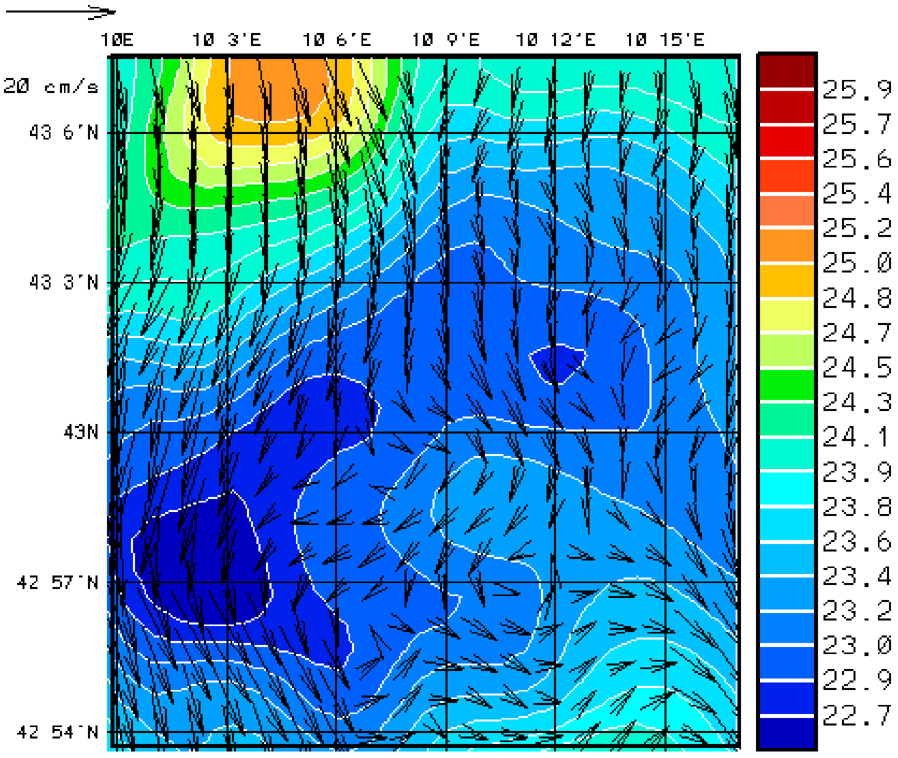
MREA-03 Domains



Mini-HOPS for MREA-03

Prior to experiment, several configurations were tested leading to selection of 2-way nesting with super-mini at Harvard

- During experiment:
  - – Daily runs of regional and super mini at Harvard
  - – Daily transmission of updated IC/BC fields for mini-HOPS domains
  - – Mini-HOPS successfully run aboard NRV Alliance

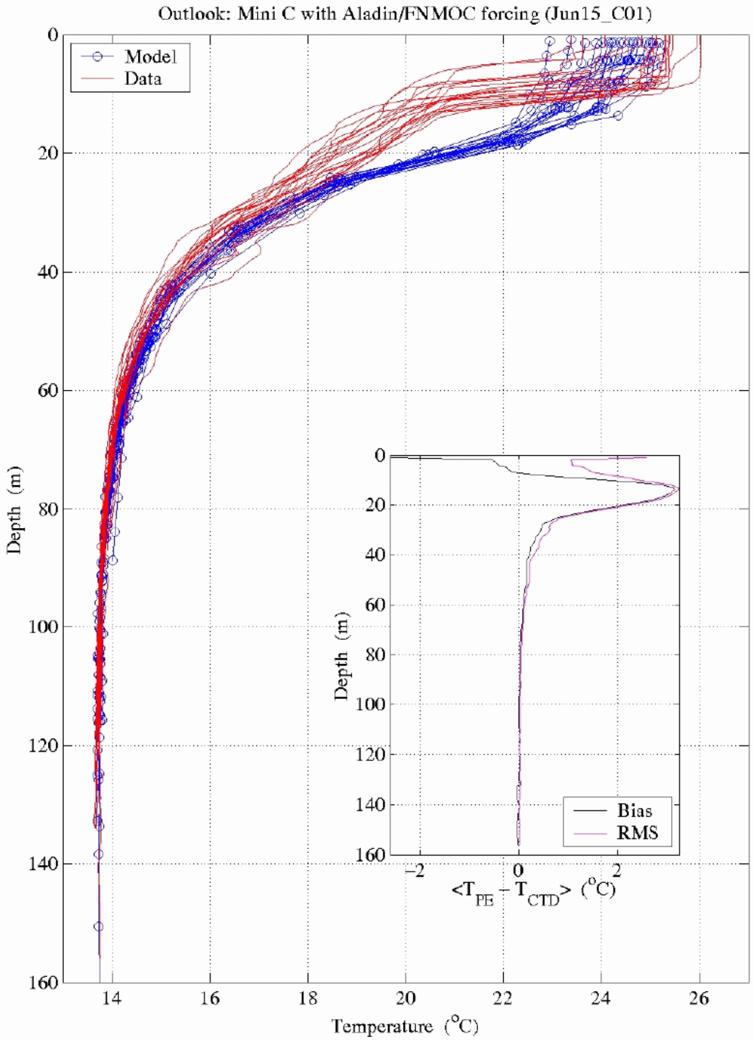


Nowcast : 15 Jun 2003

Mini-HOPS simulation run aboard NRV Alliance in Central mini-HOPS domain (surface temperature and velocity)

Results of MREA03 Re-analysis and Model Tuning

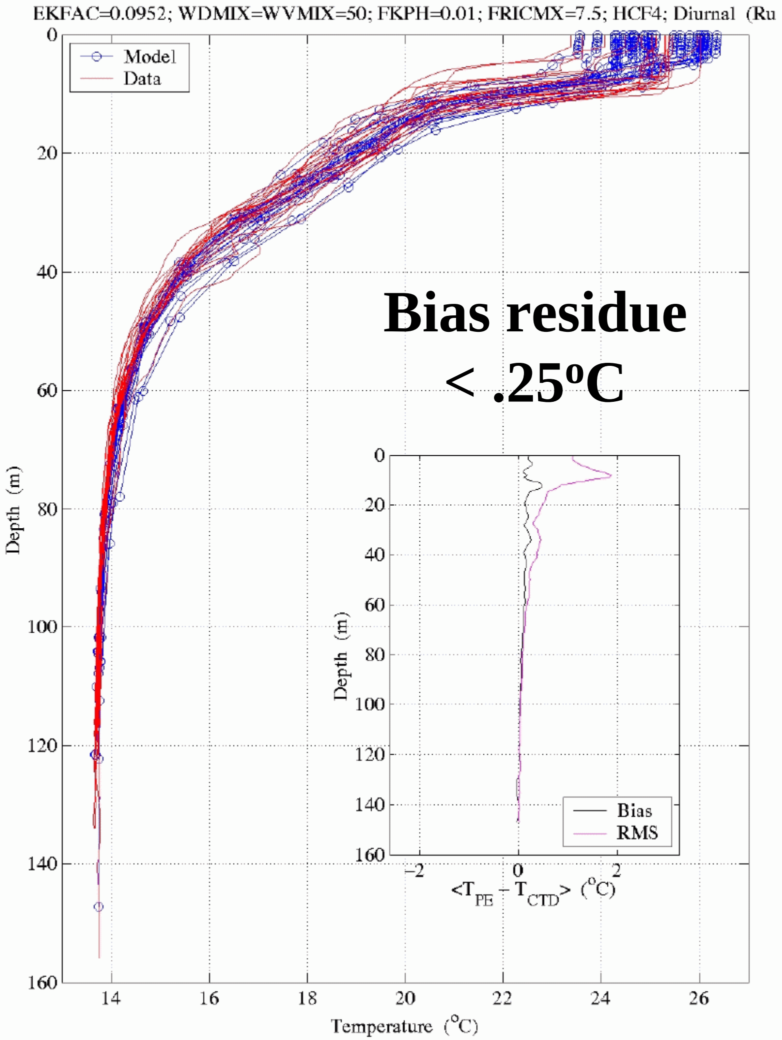
Real-time Model/Data Comparison



Model Temp.

Observed Temp.

Re-analysis Model/Data Comparison



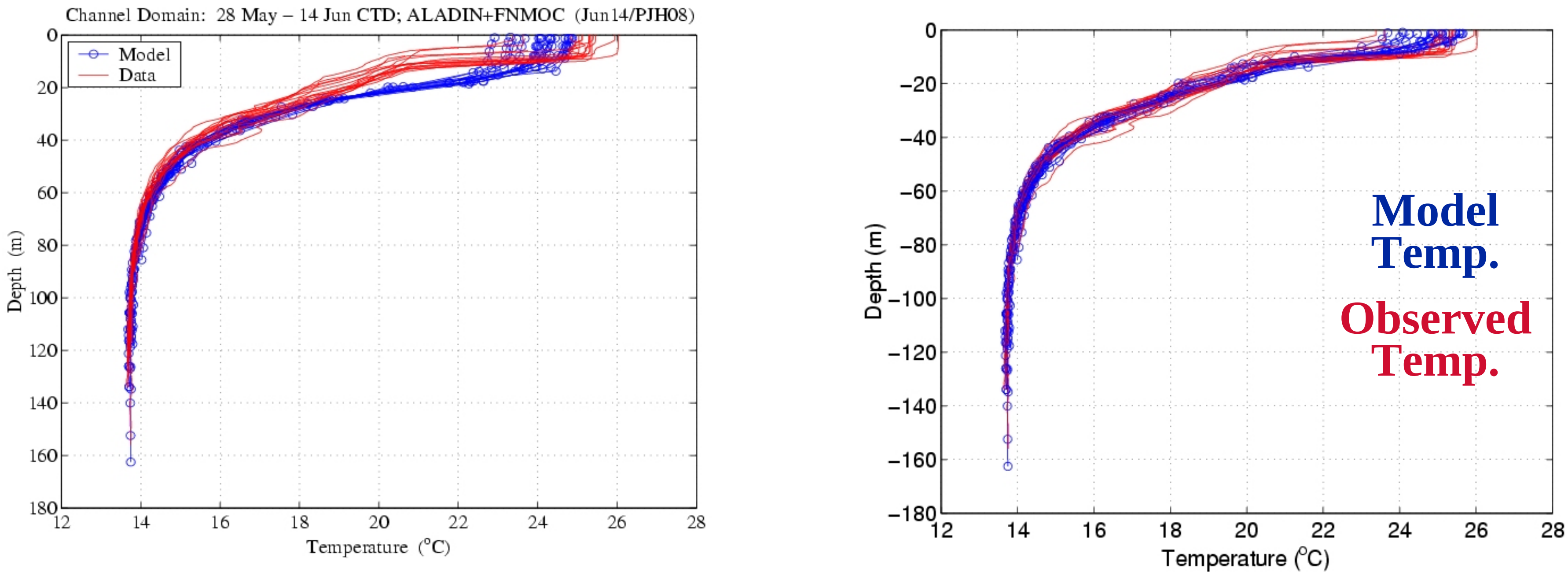
Bias residue < .25°C

- Tuned parameters for stability and agreement with profiles (especially vertical mixing)
- Improved vertical resolution in surface and thermocline
- Corrected input net heat flux
- Improved initialization and synoptic assimilation in dynamically tuned model

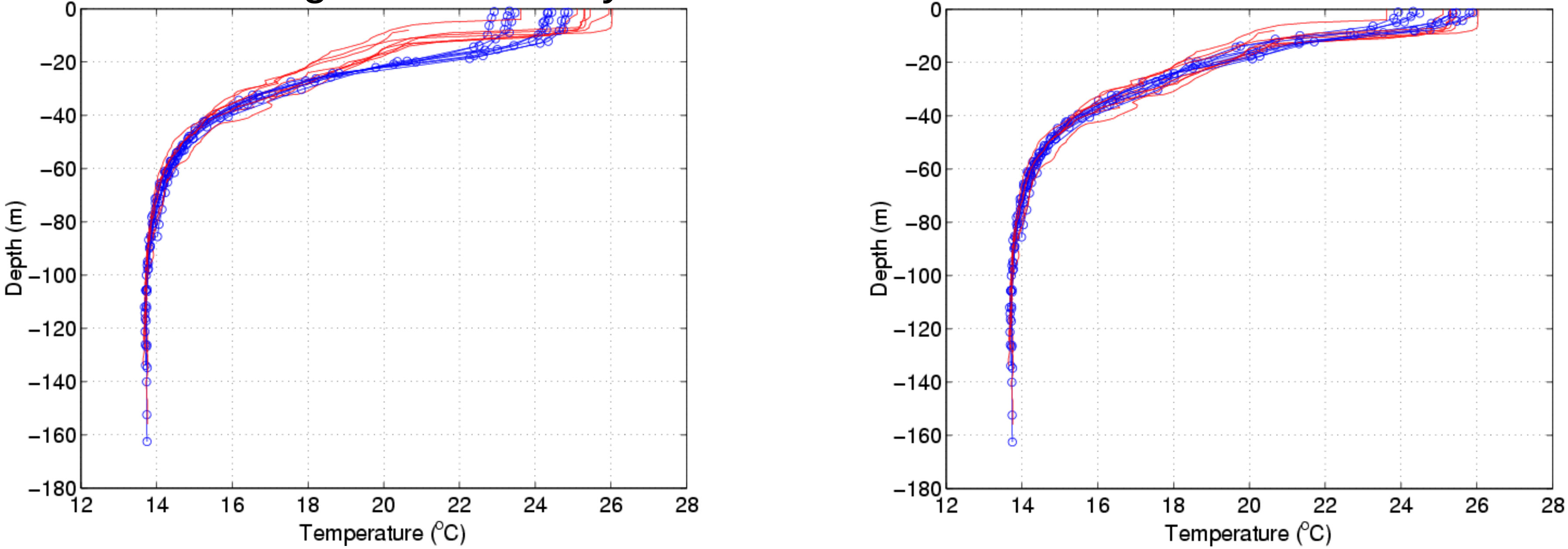
Error Analyses and Optimal (Multi) Model Estimates

Maximum-Likelihood Correction of Real-Time Forecast

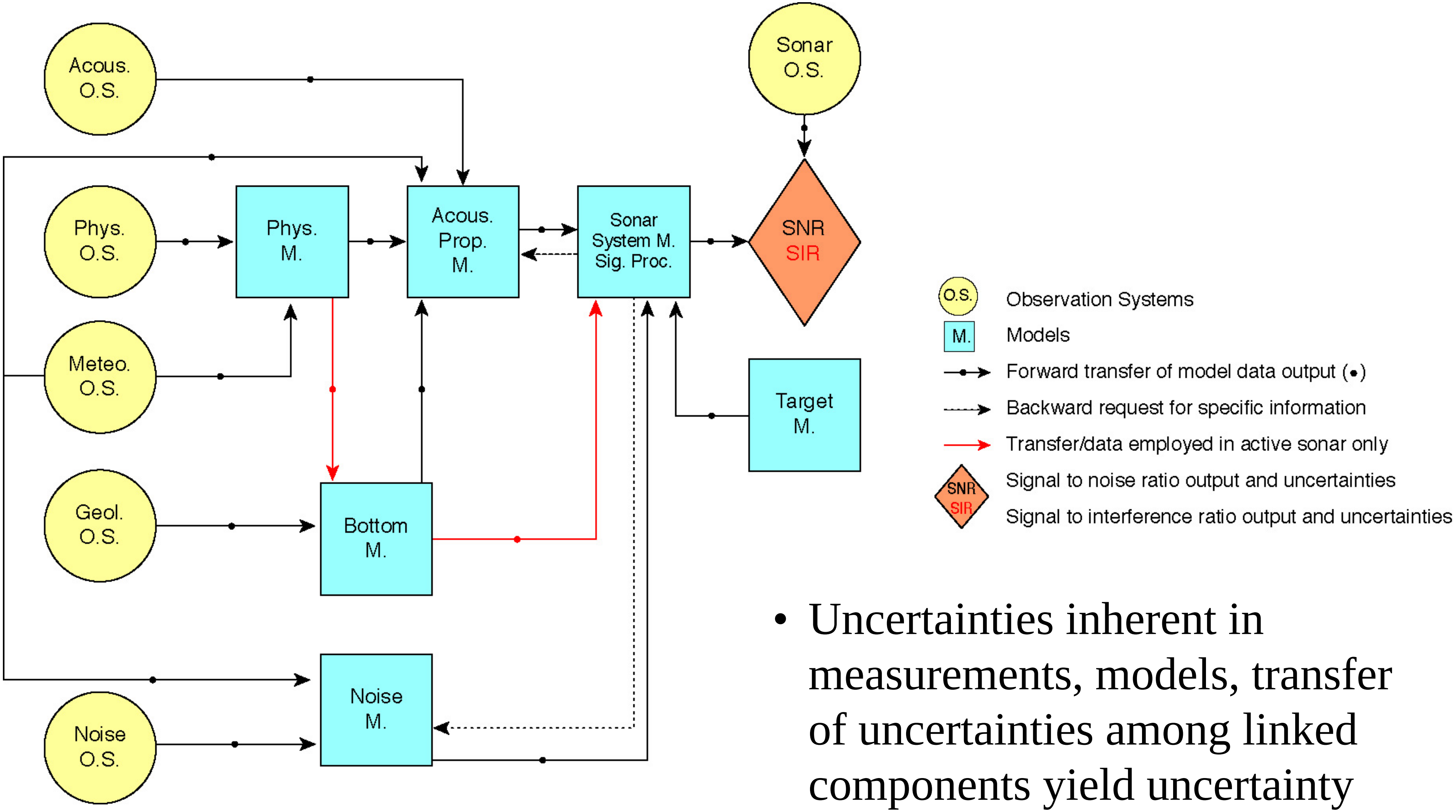
Training via Full Data Set



Training with Today's Data for Tomorrow's Forecast

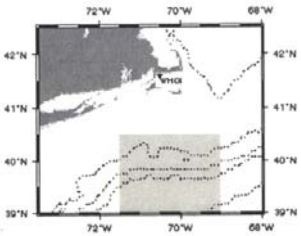


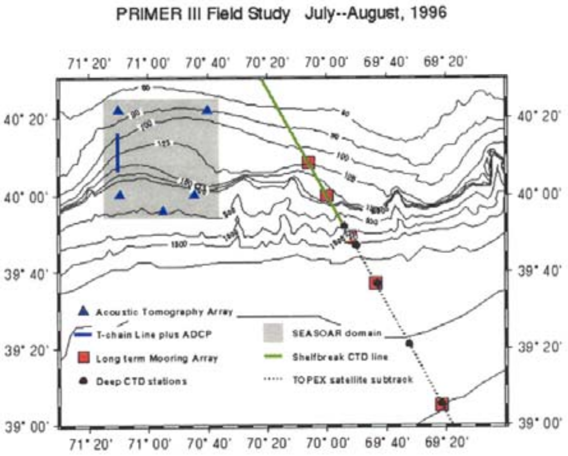
End-to-End System Concept

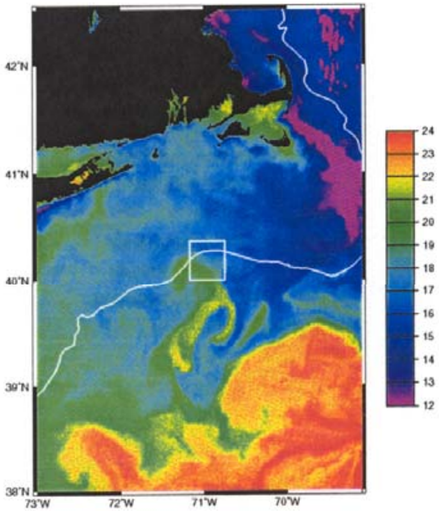


- Uncertainties inherent in measurements, models, transfer of uncertainties among linked components yield uncertainty in sonar performance prediction

PRIMER End-to-End Problem
Initial Focus on Passive Sonar Problem







***Location**:* Shelfbreak PRIMER Region

***Season**:* July-August 1996

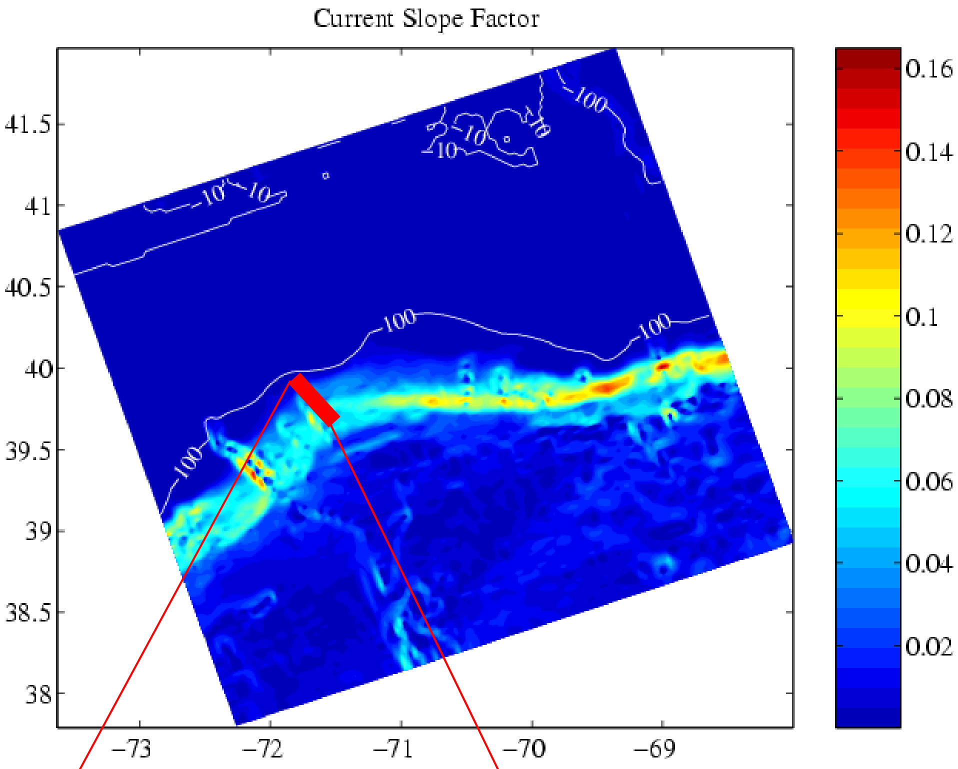
***Sonar System** (Receiver):* Passive Towed Array

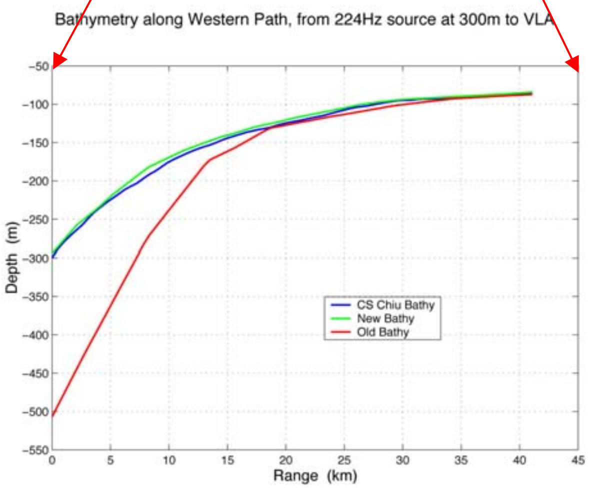
***Target**:* Simulated UUV (with variable source level)

***Frequency Range**:* 100 to 500 Hz

***Geometries**:* Receiver operating on the shelf shallow water;
target operating on the shelf slope (deeper water than receiver)

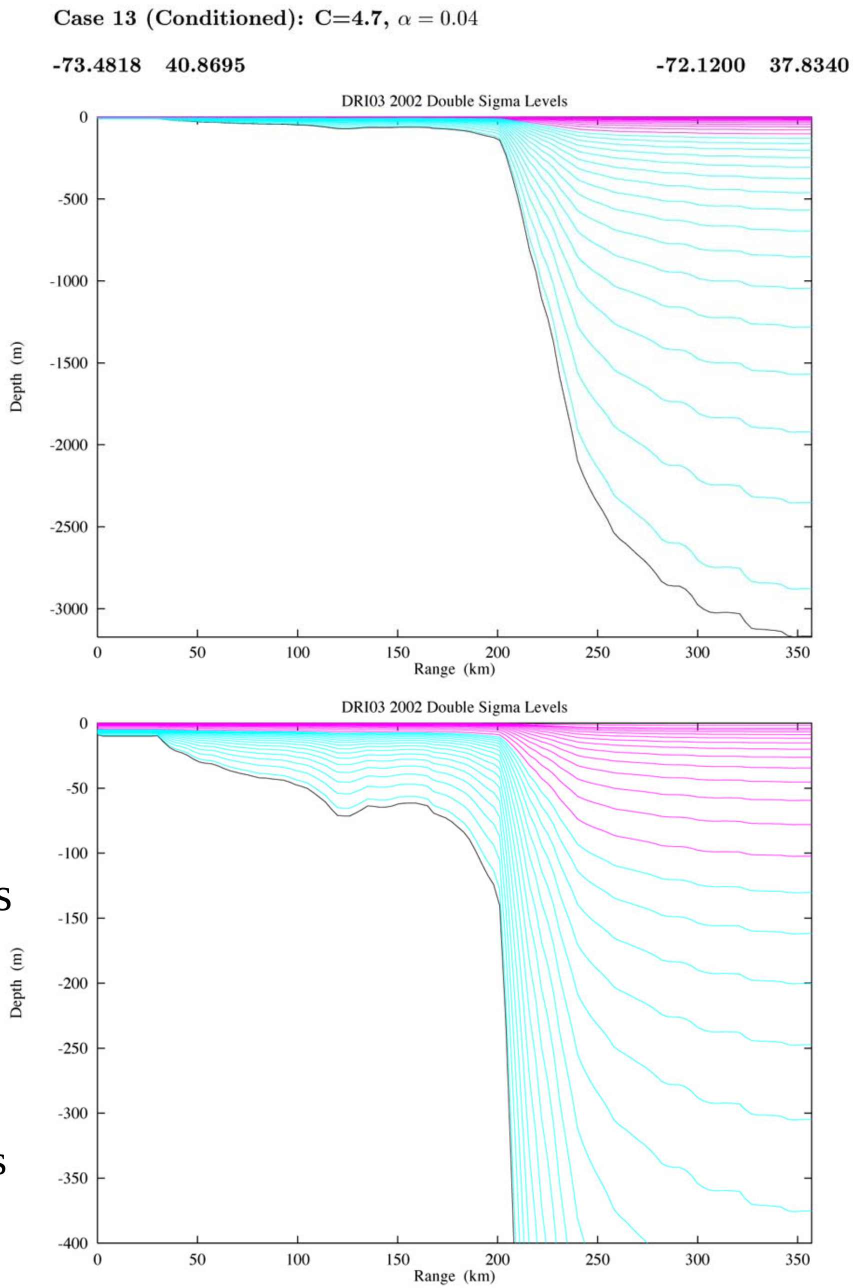
Numerical tuning of ocean bathymetry and model levels for accurate acoustics





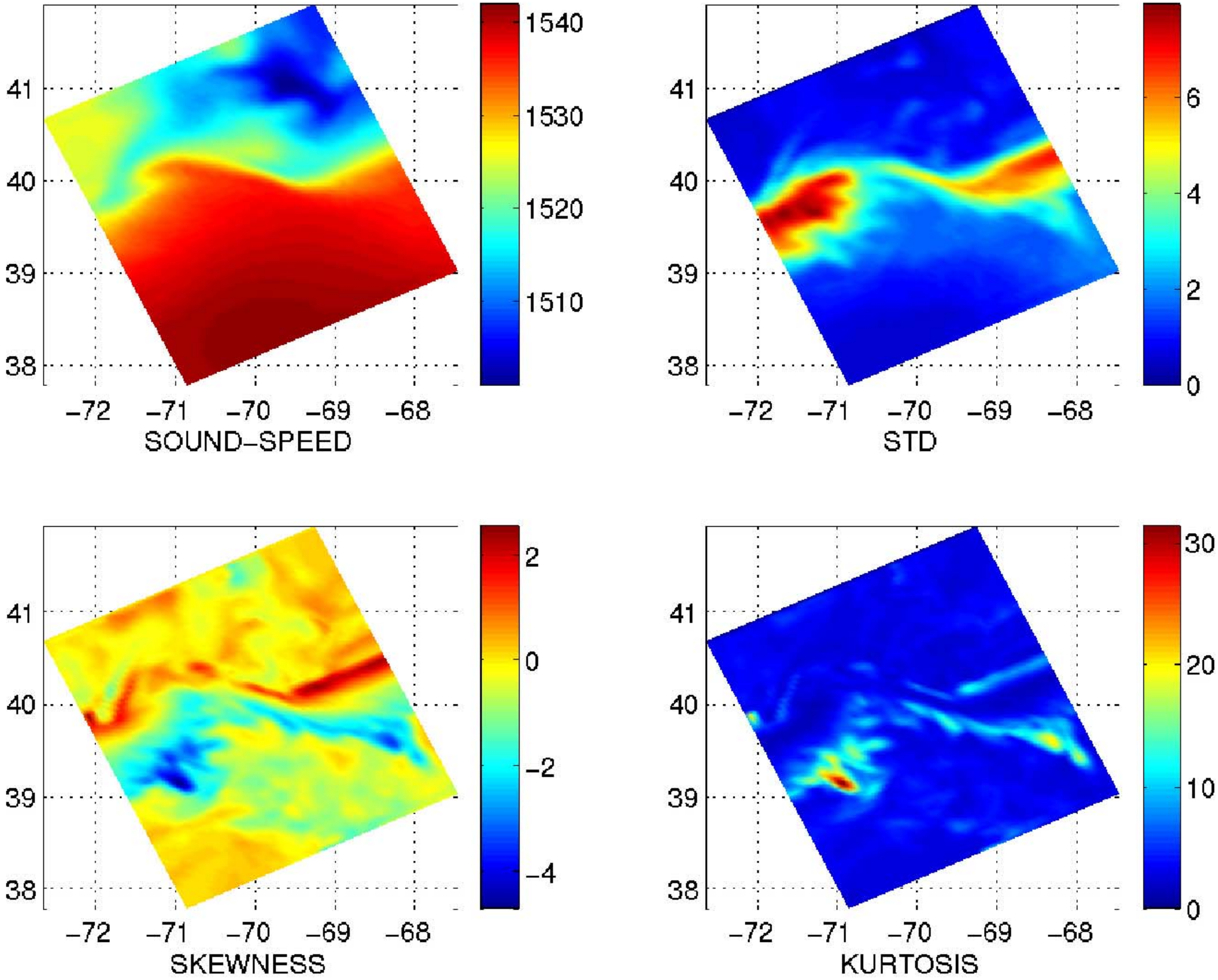
Bottom slope, and depth at acoustic section

- Ocean model runs on unchanged absolute slope
- Minimize numerical errors from:
  - steep topog./pressure gradient
  - squeezing model levels
  - distortion of vertical boxes
  - inadequate vertical resolution for dynamics



Optimised model levels

Environmental-Acoustical Uncertainty Estimation and Transfers, Coupled Acoustical-Physical DA and End-to-End Systems in a Shelfbreak Environment



Note the front

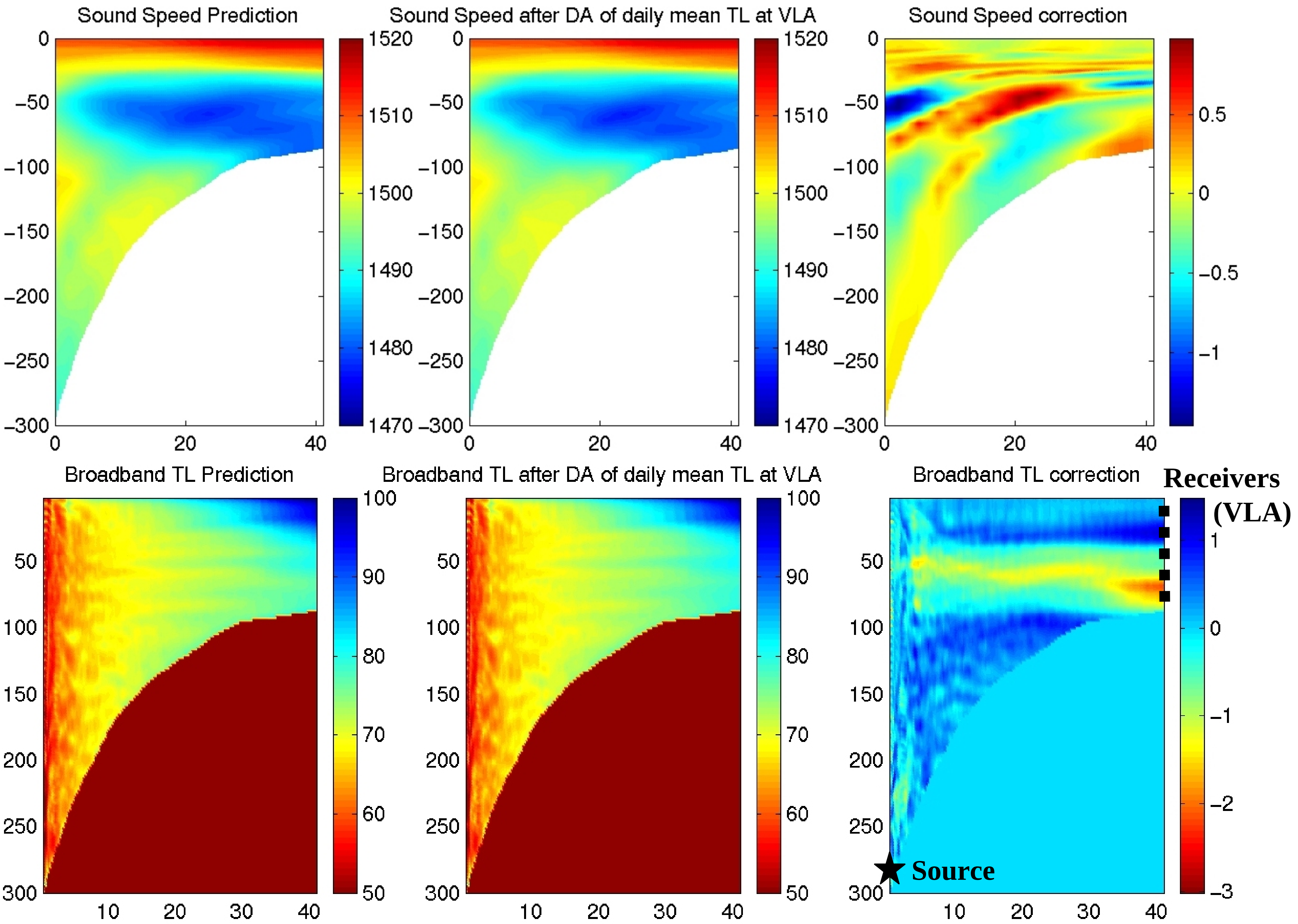
Variability at the front

Warm/cold events on each side

Extreme events

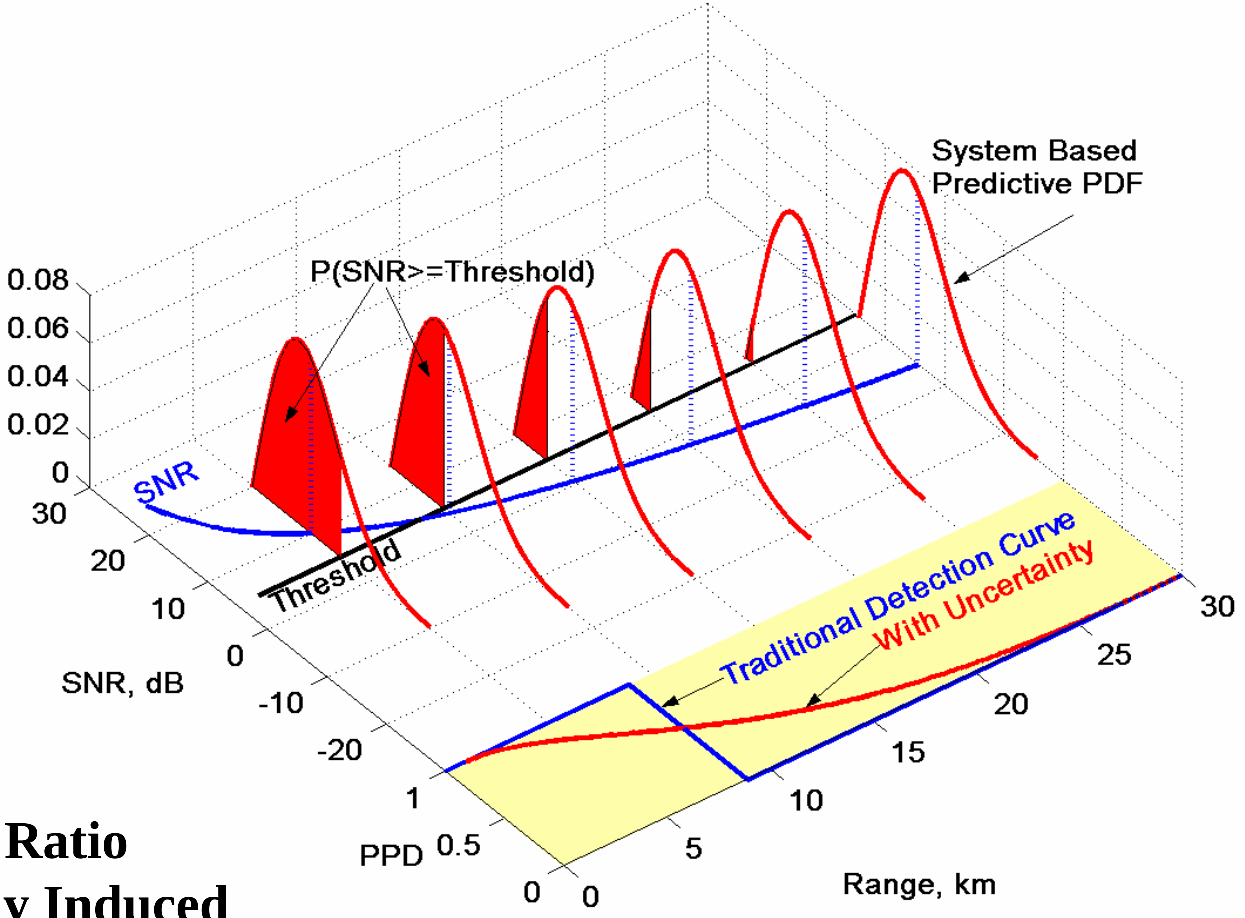
Coupled Physical-Acoustical Data Assimilation of real TL-CTD data:

TL measurements affect TL and C everywhere.



Determination of PPD (Predictive Probability Of Detection) using SNRE-PDF

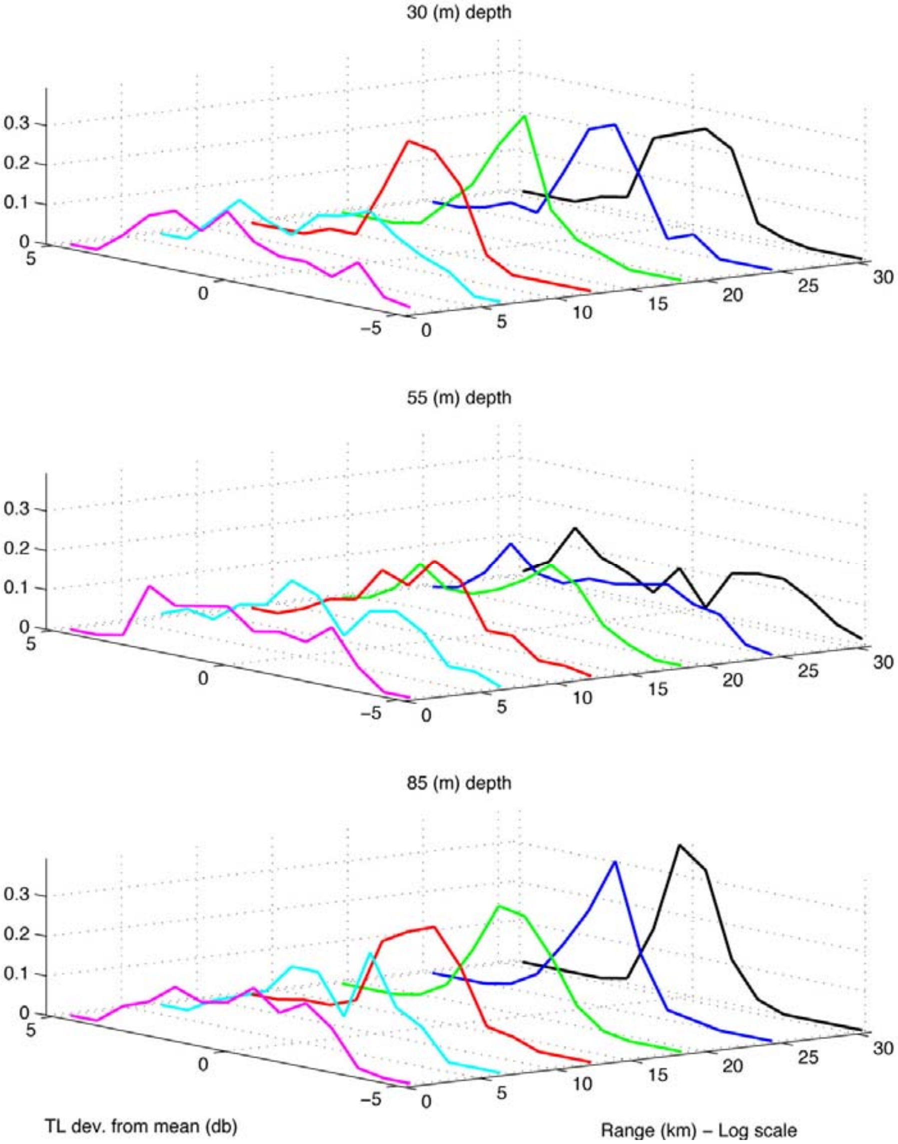
Systems - based PDF (incorporates environmental and system uncertainty)



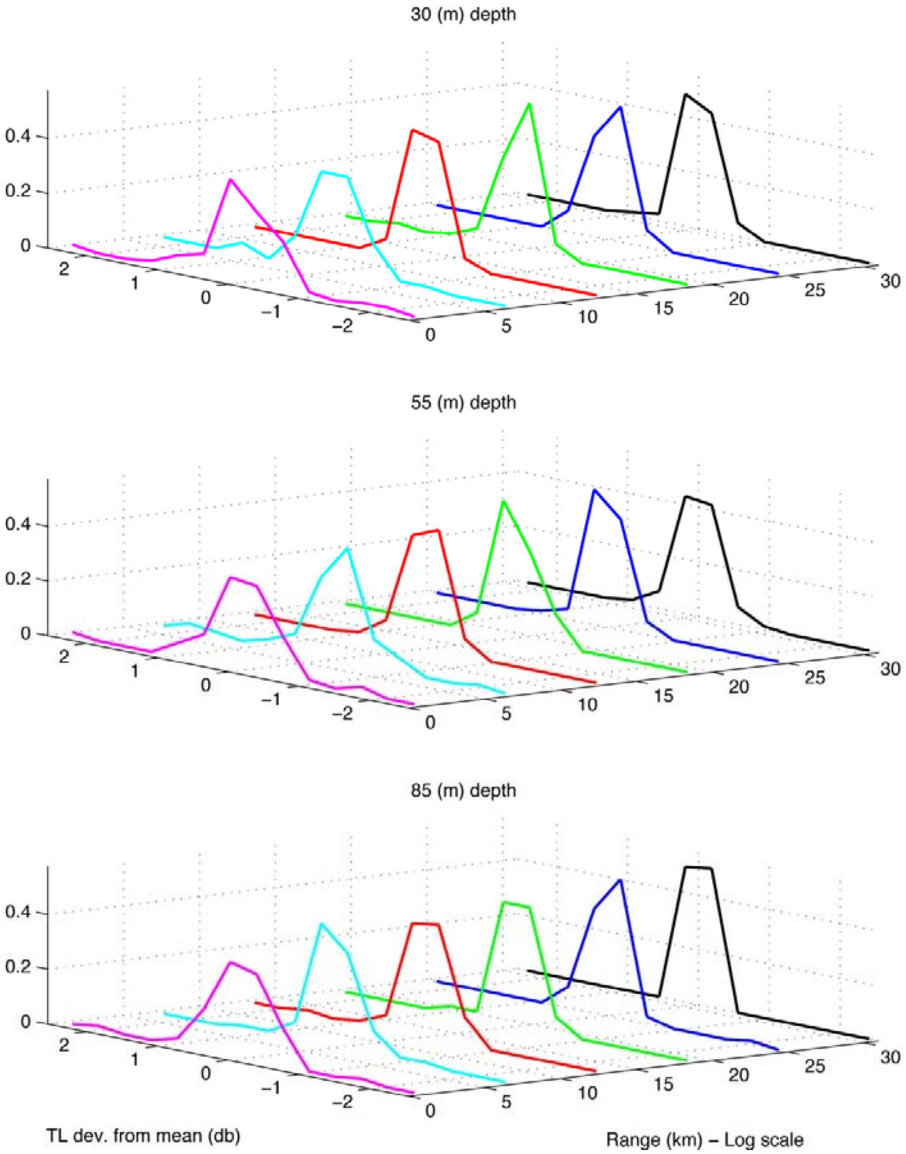
SNRE =
Signal-to-Noise Ratio
Environmentally Induced

Used by UNITES to characterize and transfer uncertainty from environment through end-to-end problems

Predicted PDF of broadband TL



After Assimilation PDF of broadband TL



Coupled HOPS/ESSE/NPS Physics/Acoustics Assimilation

- Oceans physics/acoustics data assimilation: carried-out as a single multi-scale joint estimation for the first time

- ESSE nonlinear coupled assimilation recovers fine-scale TL structures and mesoscale ocean physics from real daily TL data and CTD data

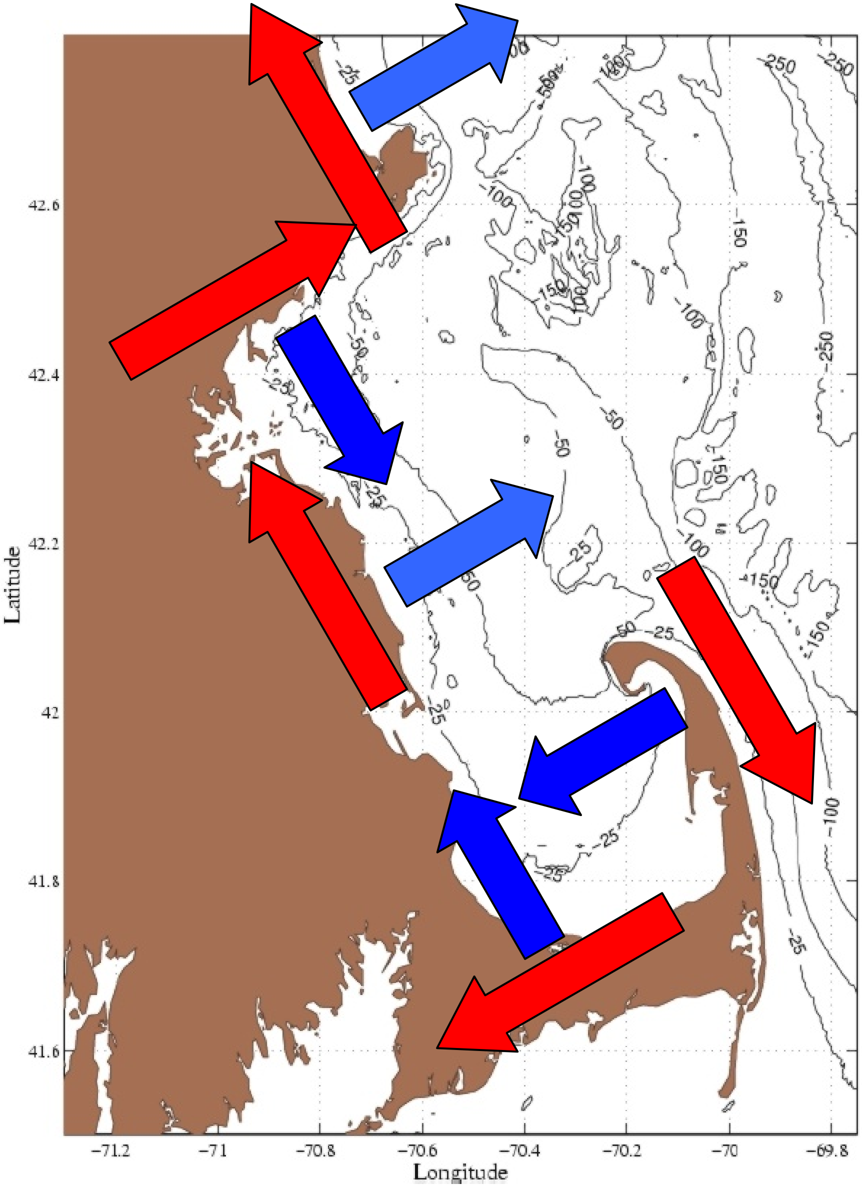
- Shifts in the frontal shape (meander, etc.) leads to more/less in acoustic waveguide (cold pool on the shelf)

- Broadband TL uncertainties predicted to be range and depth dependent

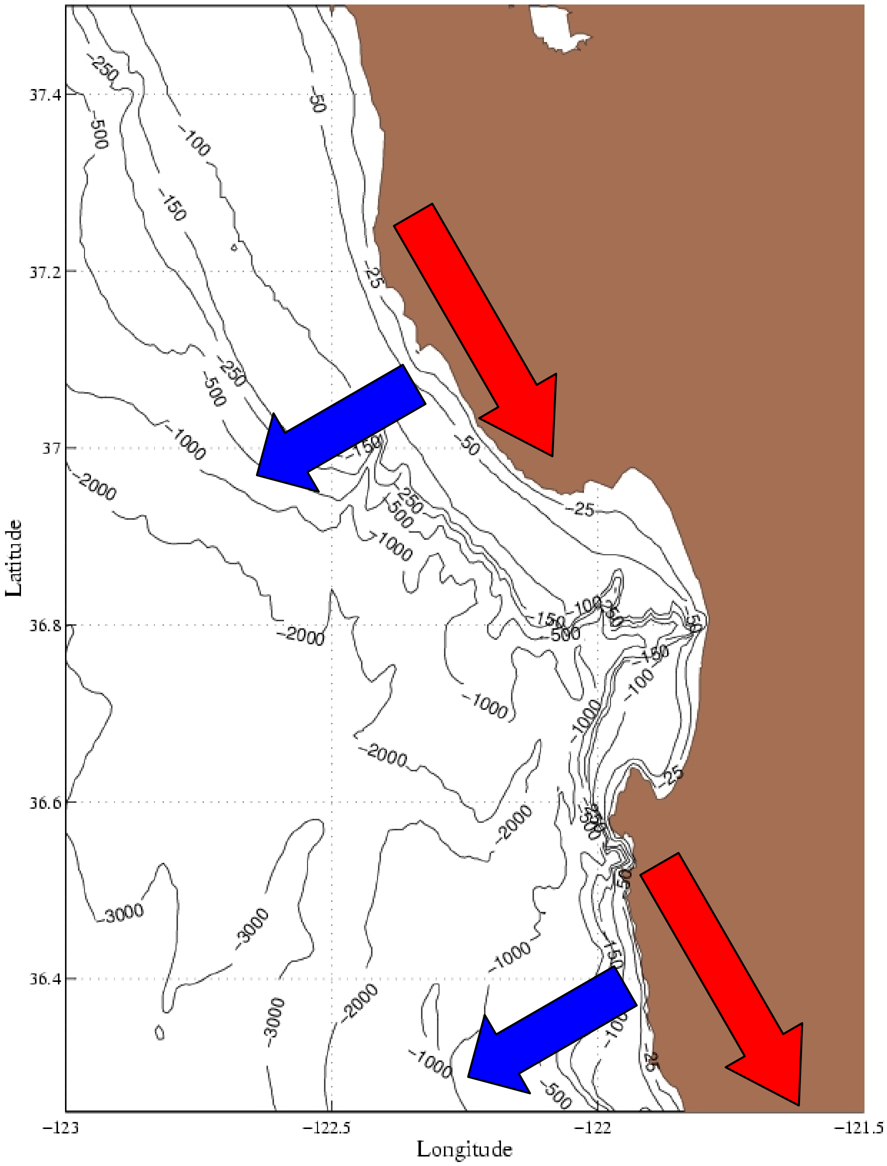
- Coupled DA sharpens and homogenizes broadband PDFs

Wind-Induced Upwelling

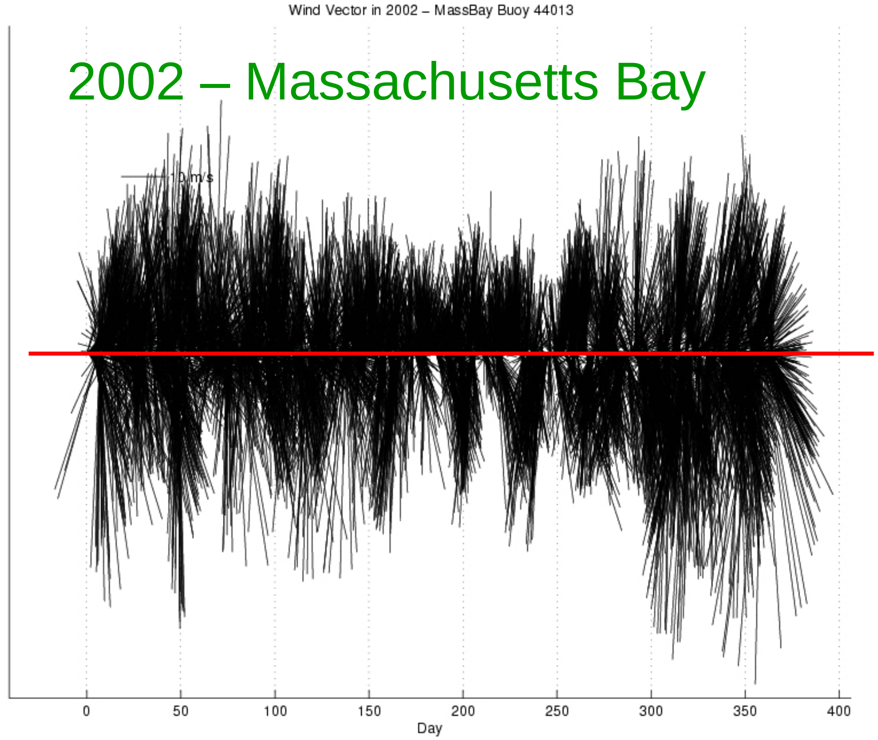
Massachusetts Bay
Episodic upwelling



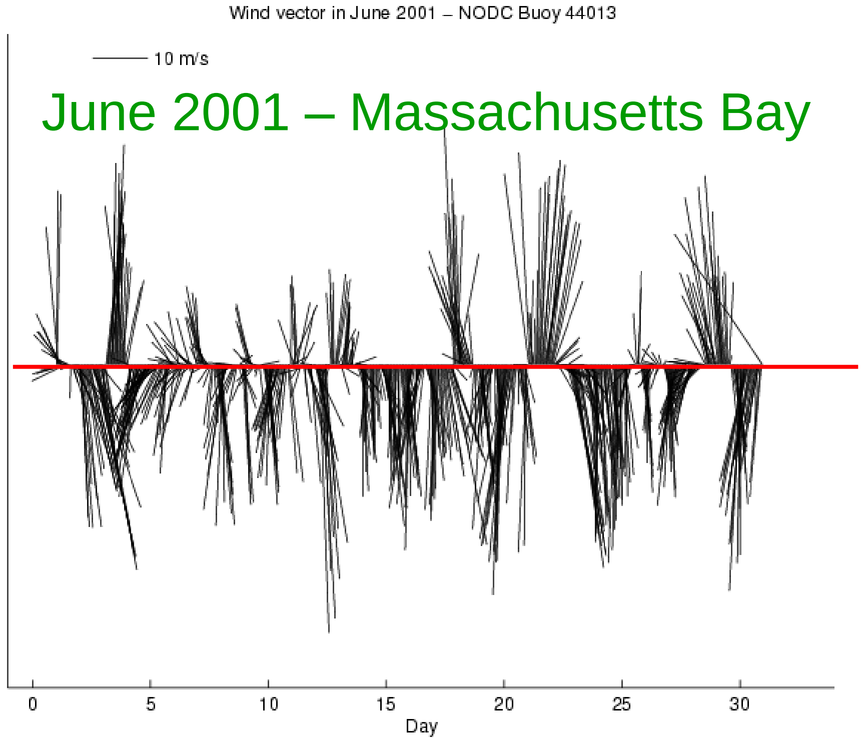
Monterey Bay
Sustained Upwelling



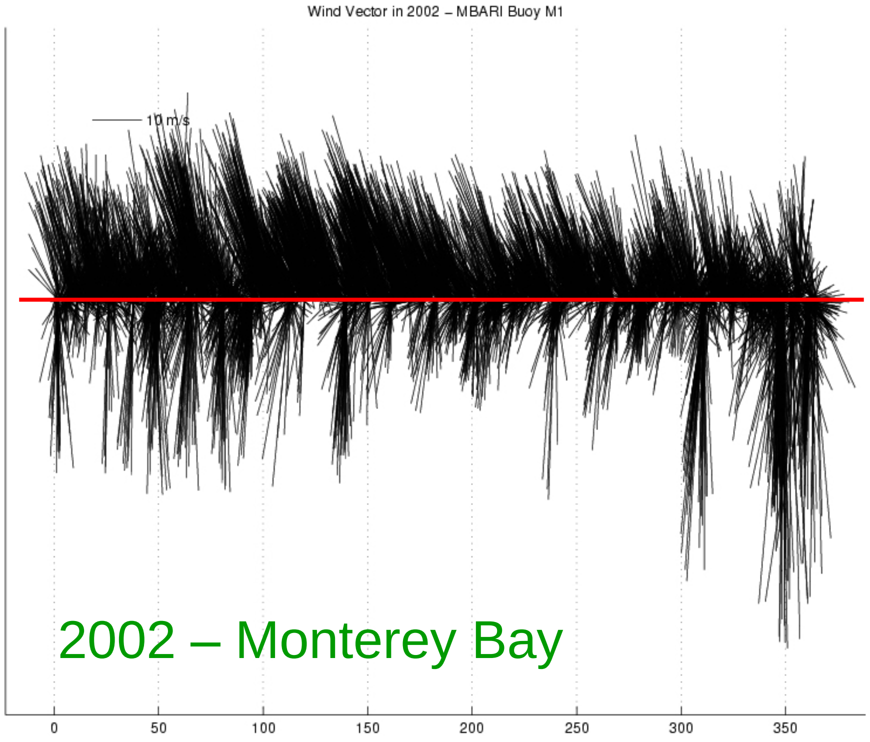
Red = Wind, Blue = Upwelling


Wind Vector in 2002 – MassBay Buoy 44013

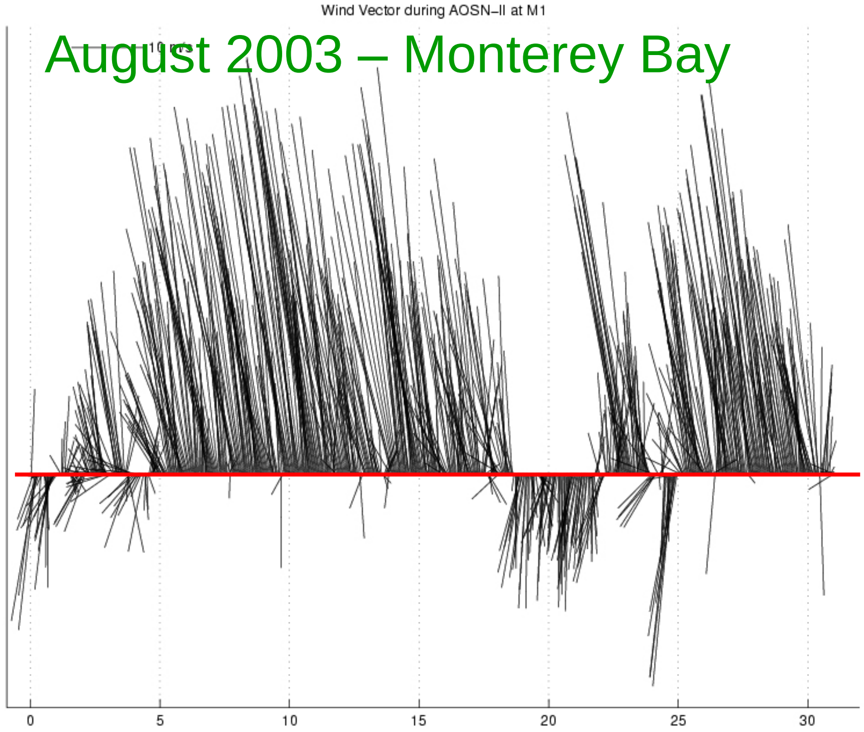
2002 – Massachusetts Bay


Wind vector in June 2001 – NODC Buoy 44013

June 2001 – Massachusetts Bay

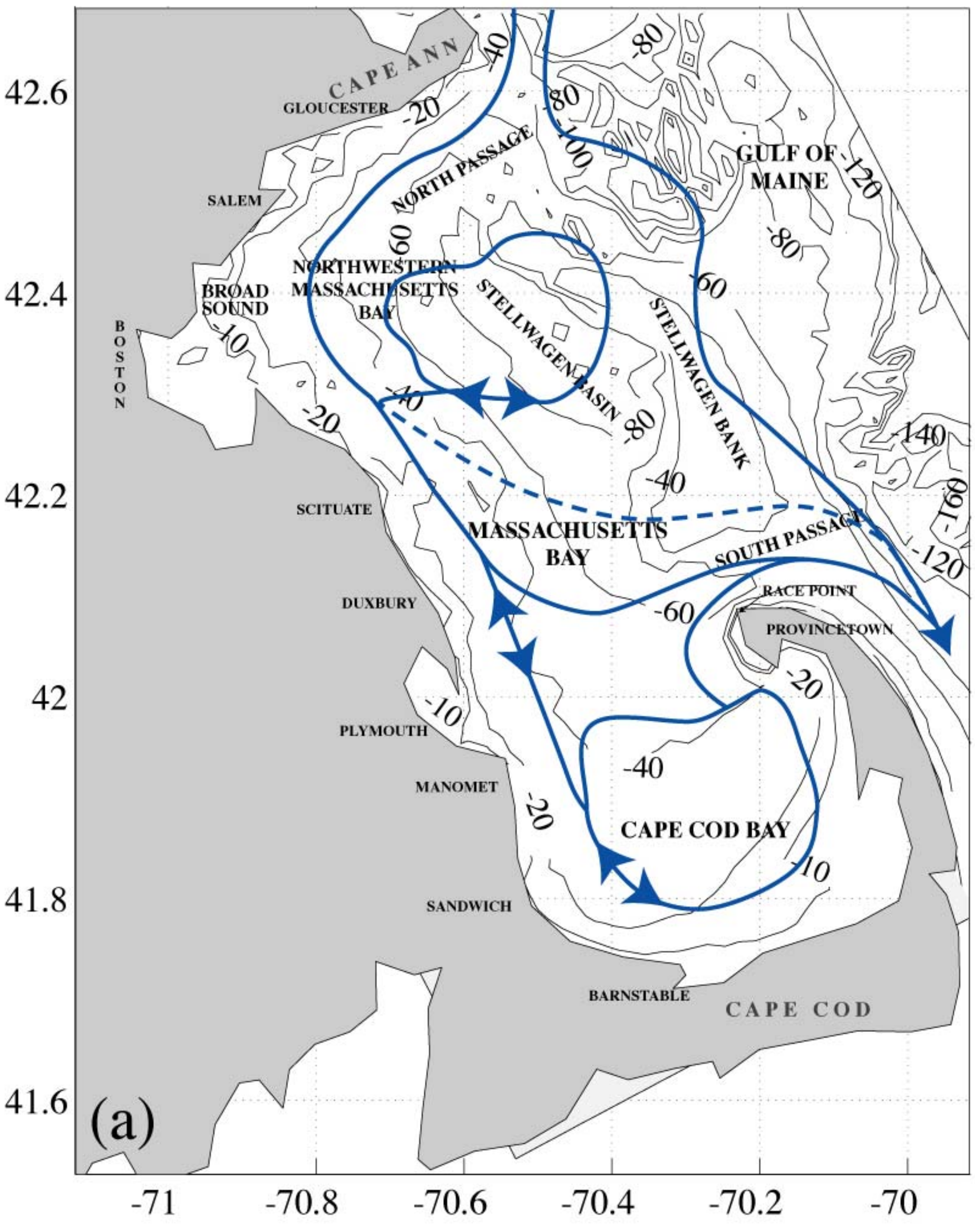

Wind Vector in 2002 – MBARI Buoy M1

2002 – Monterey Bay


Wind Vector during AOSN–II at M1

August 2003 – Monterey Bay

HORIZONTAL CIRCULATION PATTERNS IN MASSACHUSETTS BAY

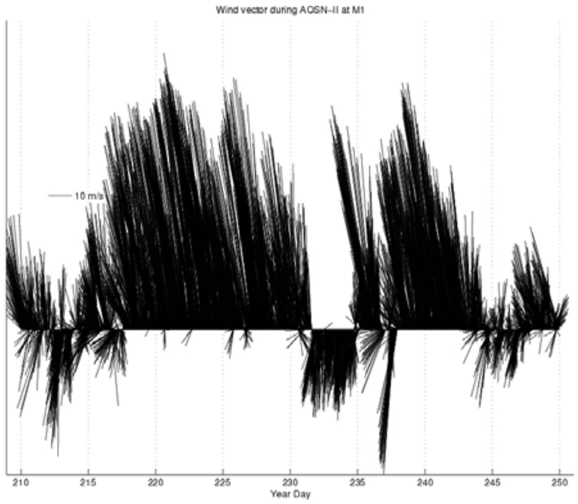


Cartoon of horizontal circulation patterns for stratified conditions in Massachusetts Bay, overlying topography in meters (thin lines).

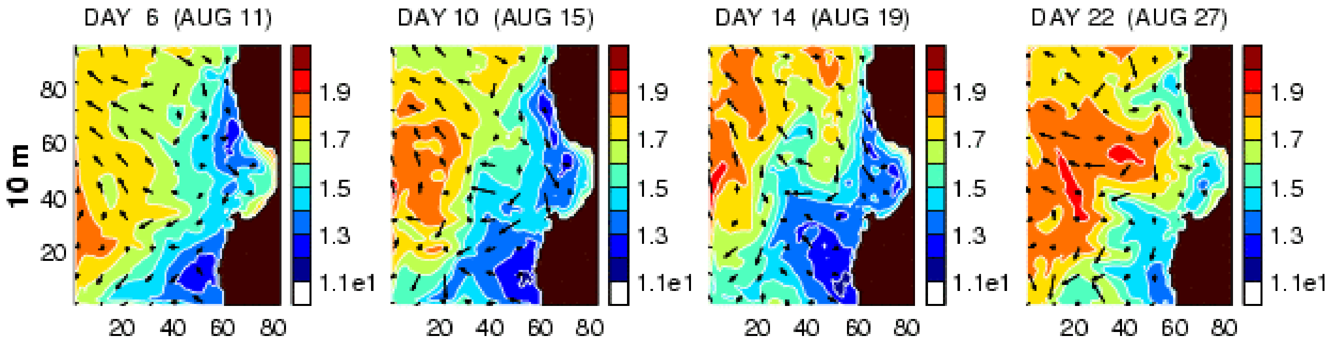
- **Patterns are not present at all times**
- **Most common patterns (solid), less common (dashed)**
- **Patterns drawn correspond to main currents in the upper layers of the pycnocline where the buoyancy driven component of the horizontal flow is often the largest**

Coastal upwelling system: sustained upwelling – relaxation – re-establishment

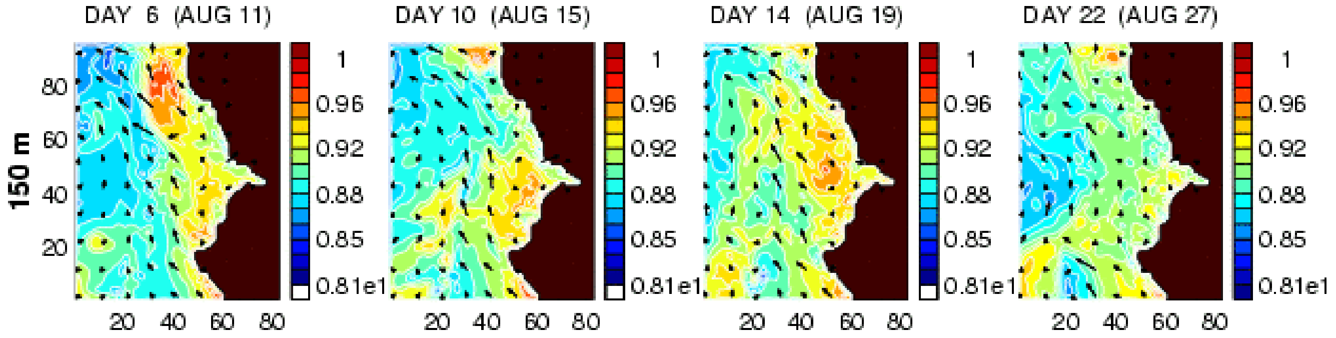
Monterey Bay and California Current System August 2003



M1 Winds

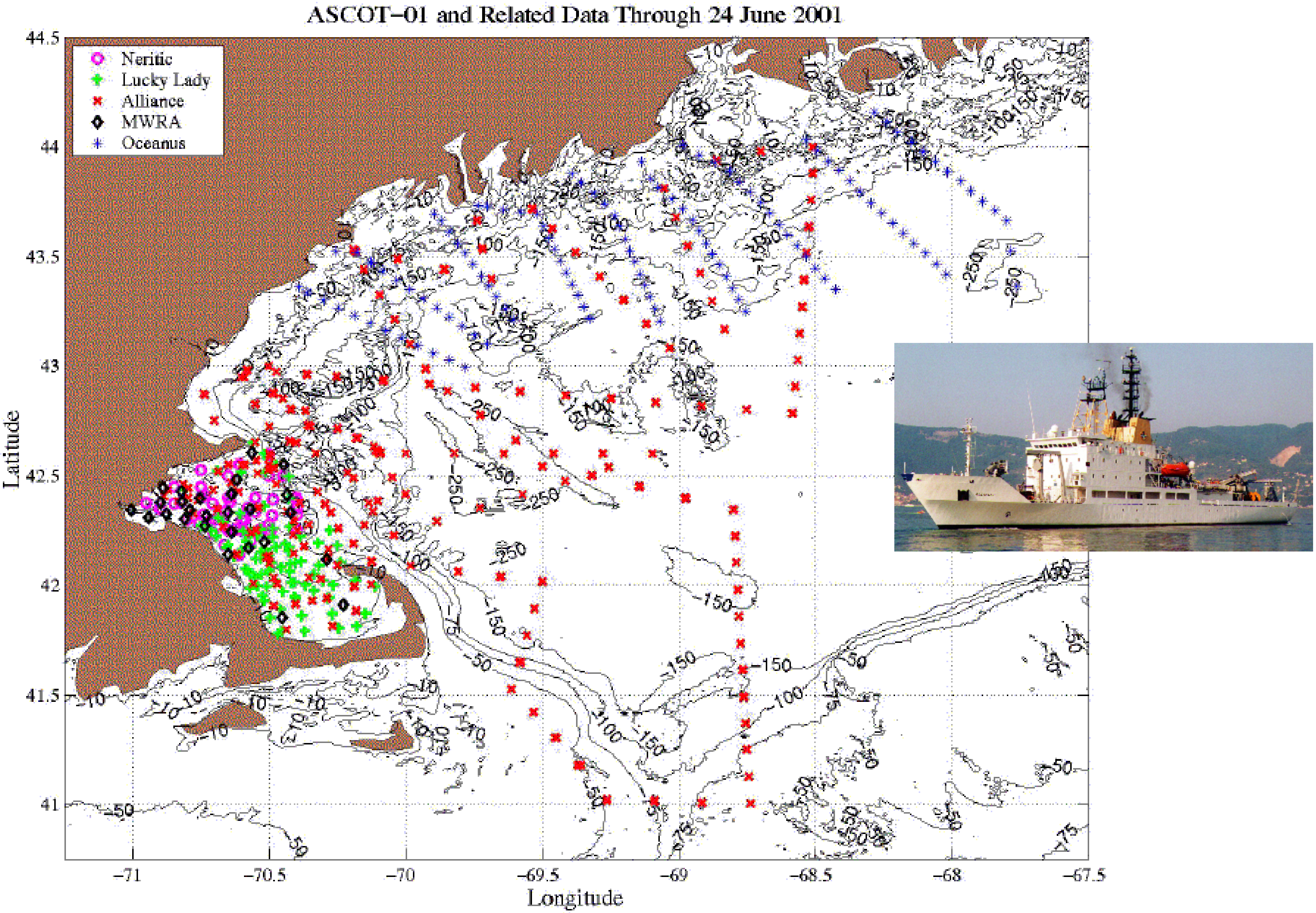


Temperature at 10m



Temperature at 150m

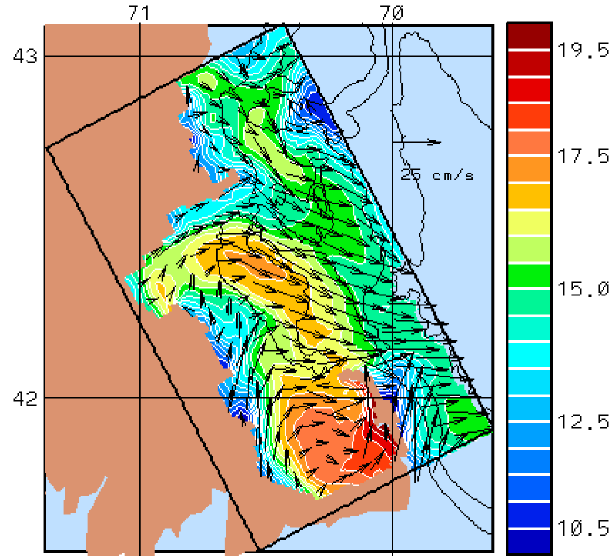
ASCOT-01 (6-26 June 2001):
Positions of data collected and fed into models



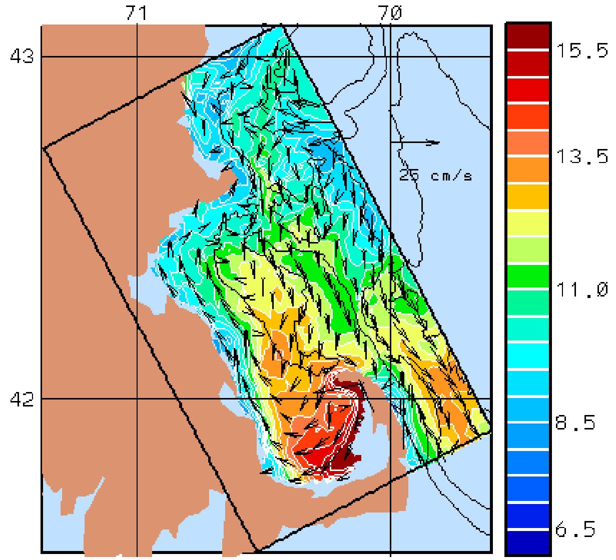
ASCOT-01: Sample Real-Time Forecast Products

Massachusetts Bay

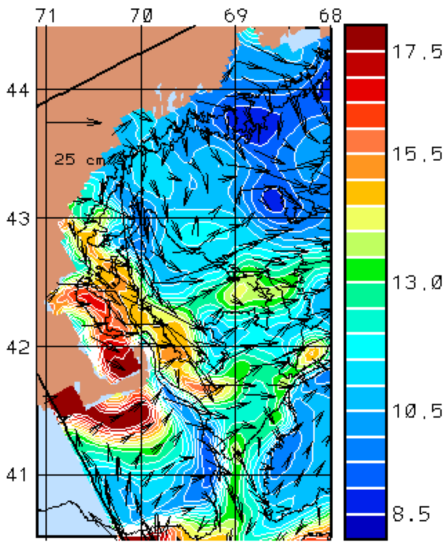
Gulf of Maine



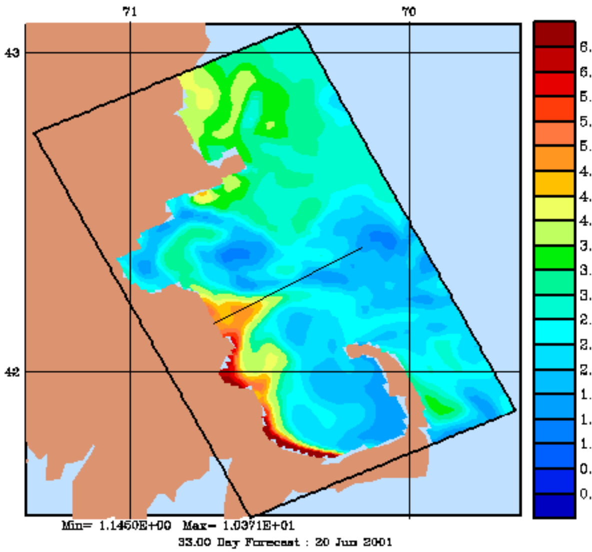
2m Temp.



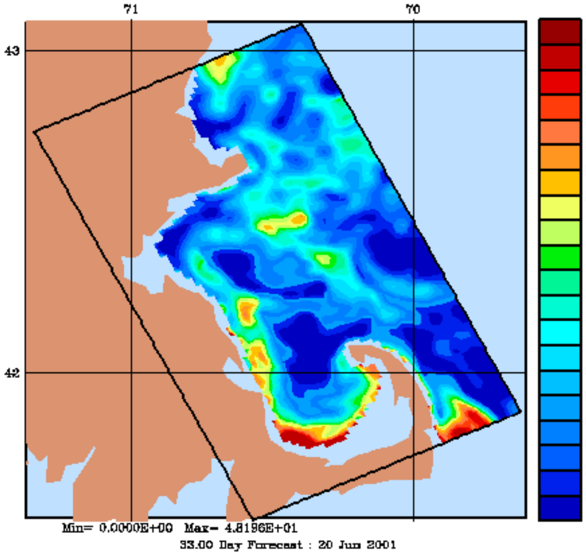
10m Temp.



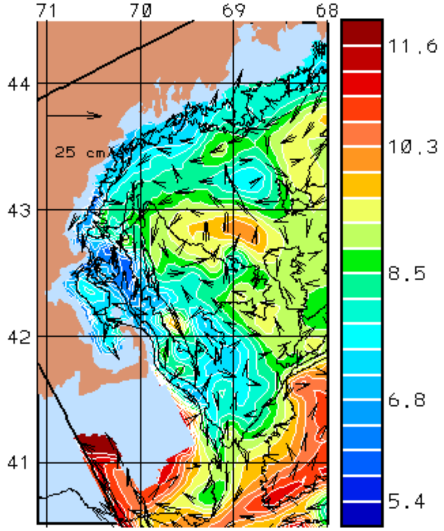
3m Temp.



5m Chlorophyll



15m Nitrate

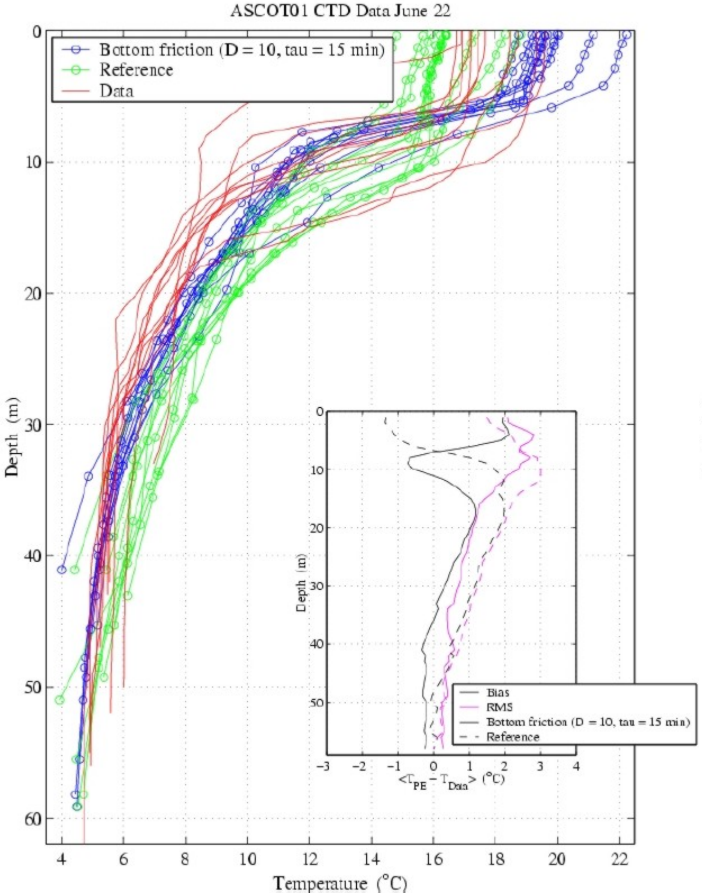


25m Temp.

Successive Tuning of Physical Parameters

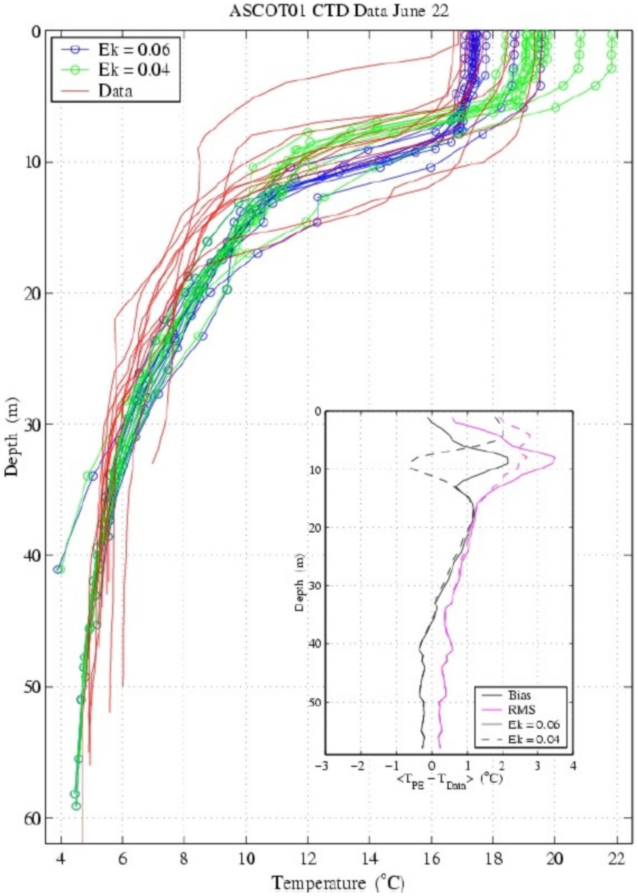
Green – prior parameters; Blue – latest parameters

Stronger bottom friction – body force



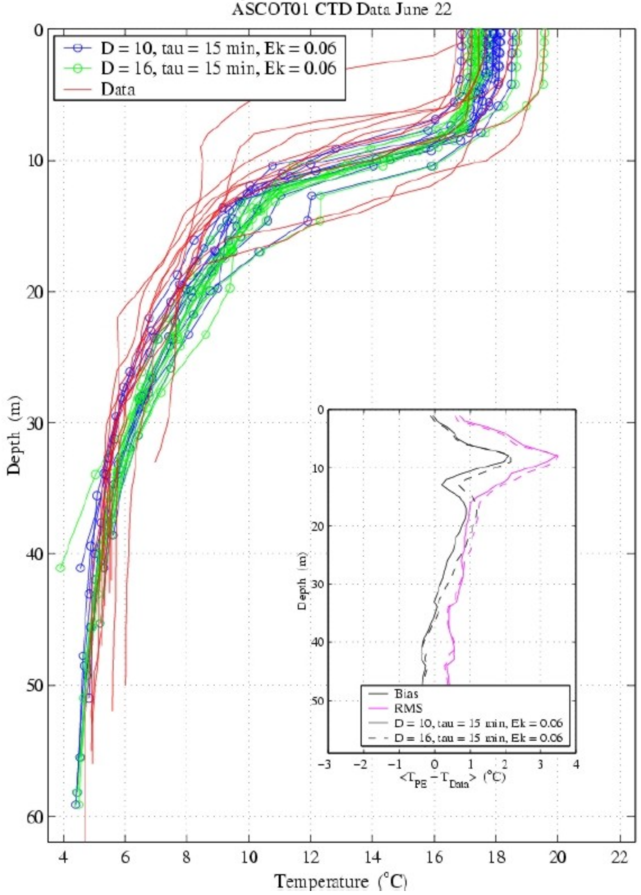
- Improvement in thermocline
- Mixed layer temperature too high

Larger Ekman Factor – wind-mixed surface layer



- Improvement in mixed layer
- Worse match at top of thermocline

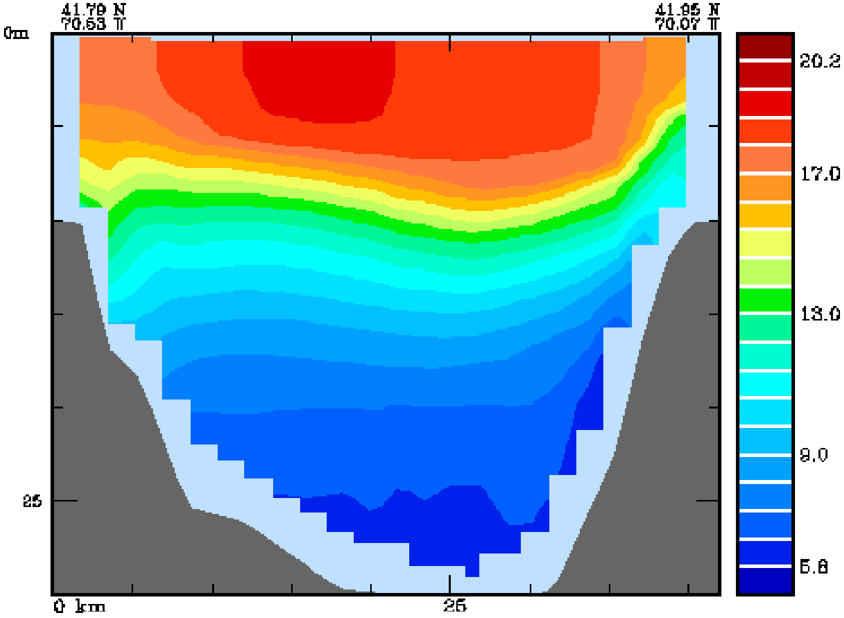
Larger Ekman factor and even stronger bottom friction



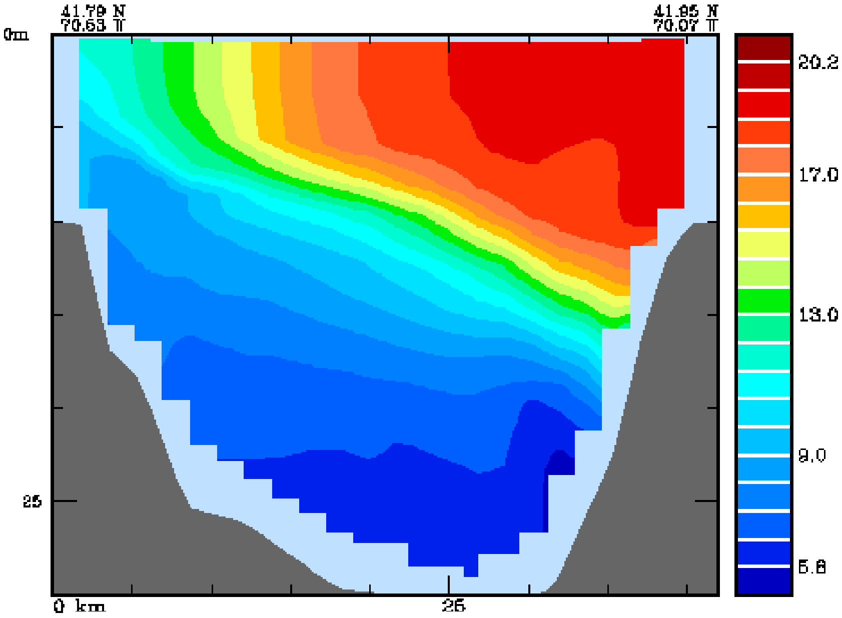
- Further improvement in thermocline and mixed layer
- Lower bias in thermocline

In shallow Bay, surface and bottom effects interact

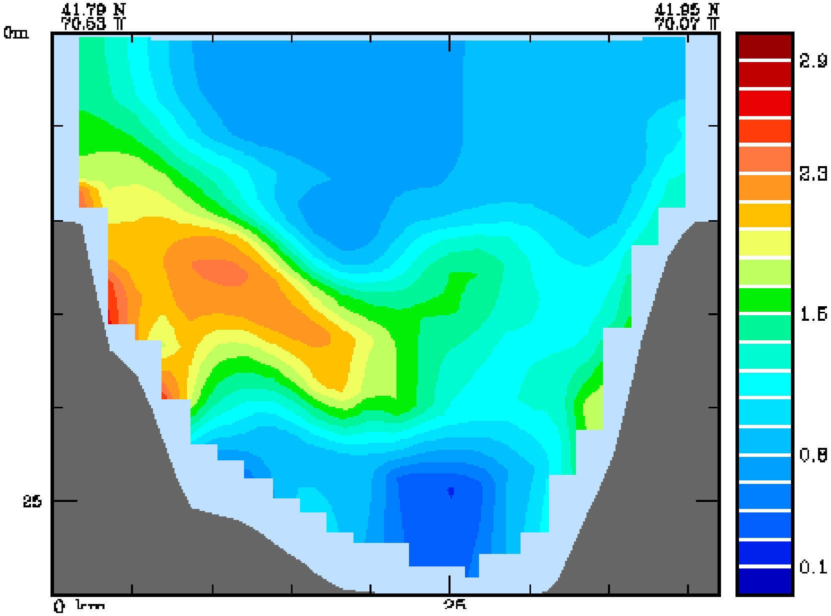
Coupled Biological-Physical DA for Dynamics of Upwelling Event



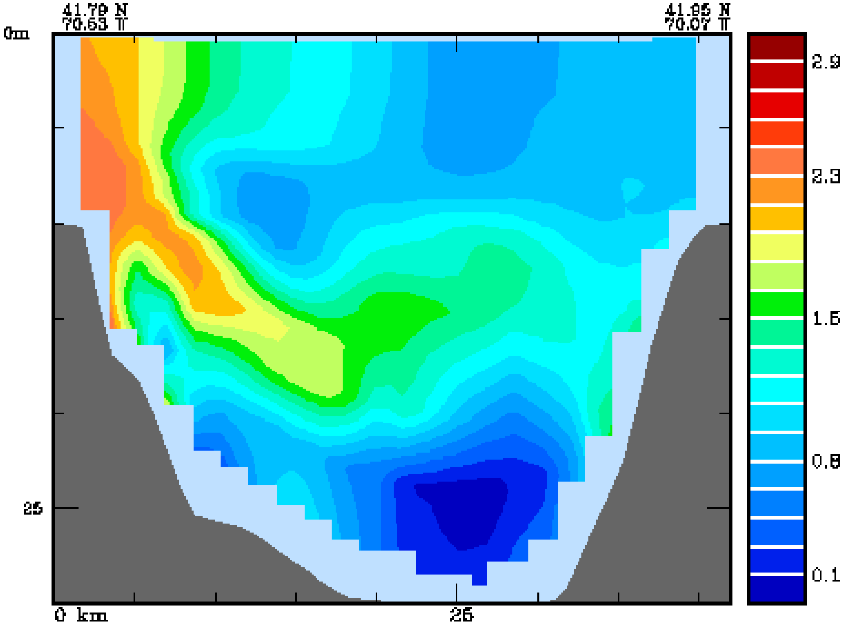
Temperature – 22 June



Temperature – 24 June



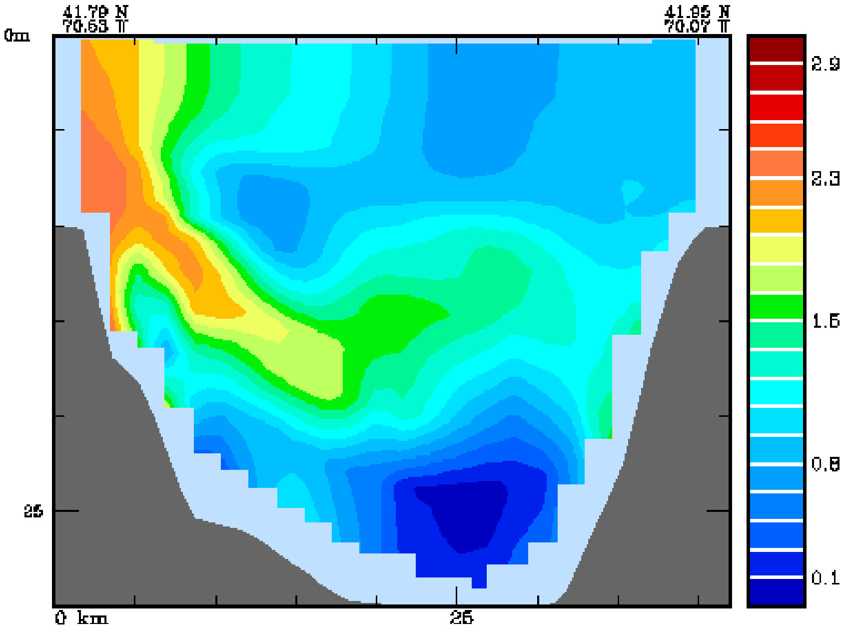
Chlorophyll – 22 June



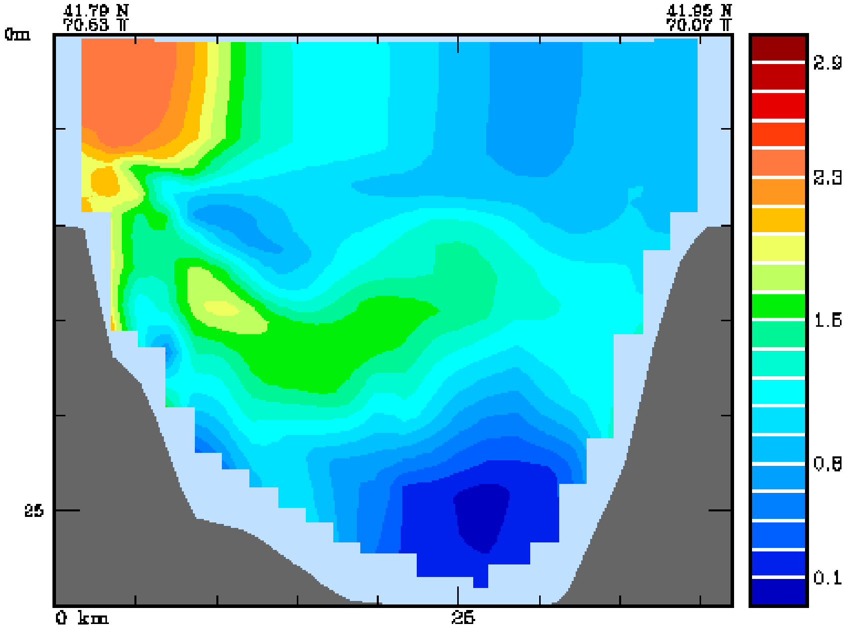
Chlorophyll – 24 June

Patricia Moreno

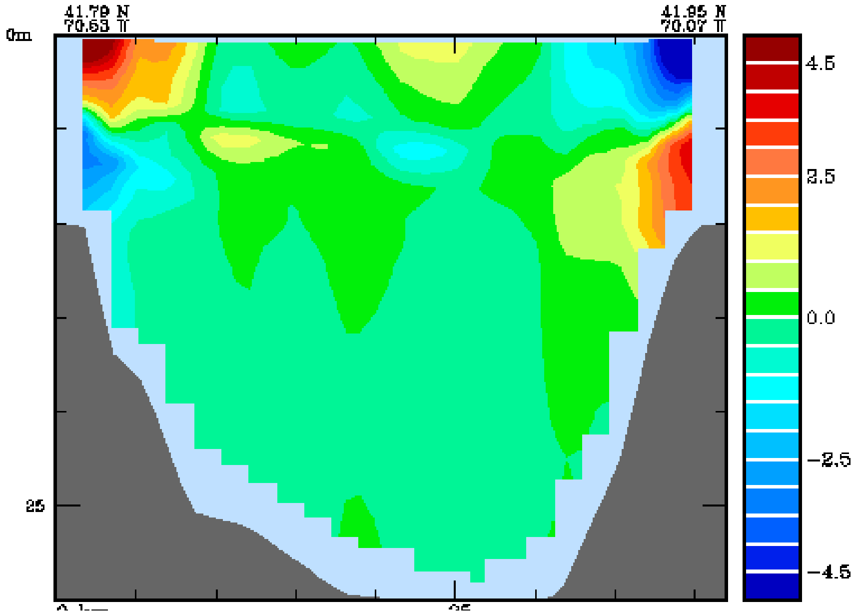
Upwelling Event in Massachusetts Bay



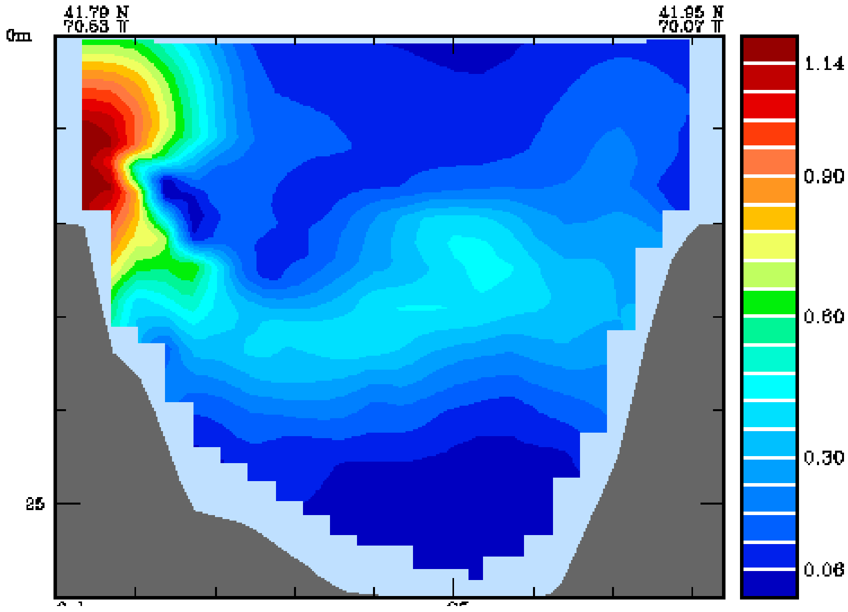
Chlorophyll – 24 June



Chlorophyll – 24.5 June



Total Chl Advection – 24.5 June



Primary Production – 24.5 June

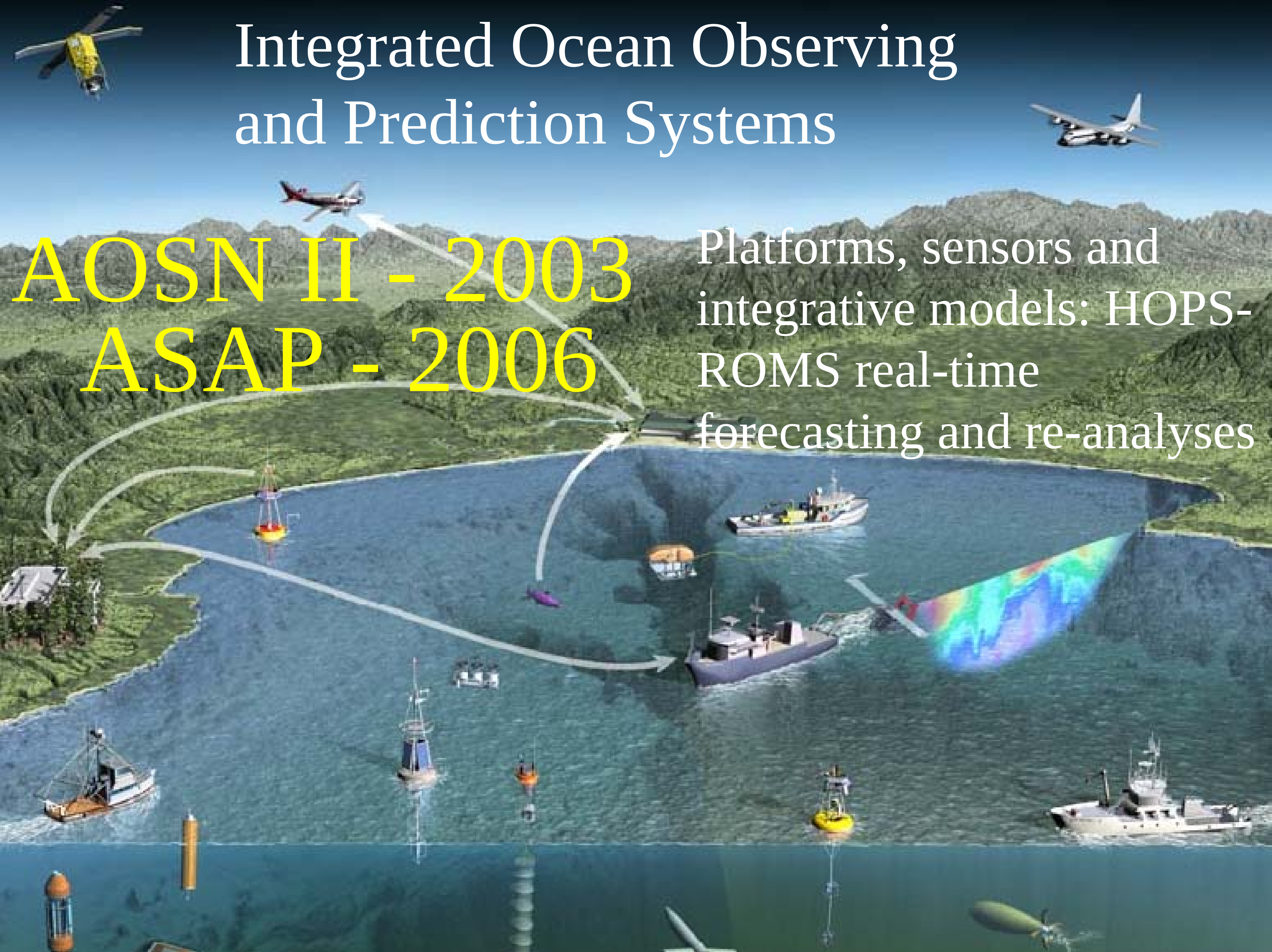
Upwelling Event in Massachusetts Bay

- Strong southerly winds lead to upwelling on the western side of Cape Cod Bay
- Near the surface temperature decreases from 17°C to 12°C
- Near the surface chlorophyll increases from 1.4 mg Chl/m^3 to 2.3

- One-half day later, chlorophyll
  - continues to increase near the surface
  - decreases between 5-10m
- Between 3-10m there is maximum primary production
- Advective effects are stronger, bringing the newly produced chlorophyll closer to the surface

- Primary production during the upwelling event is mainly due to ammonium uptake
- Nitrate acts as a passive tracer

Integrated Ocean Observing and Prediction Systems

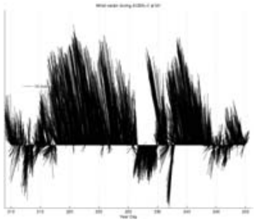


AOSN II - 2003

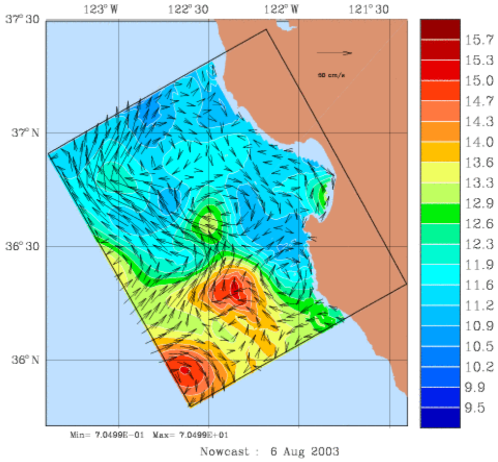
ASAP - 2006

Platforms, sensors and integrative models: HOPS-ROMS real-time forecasting and re-analyses

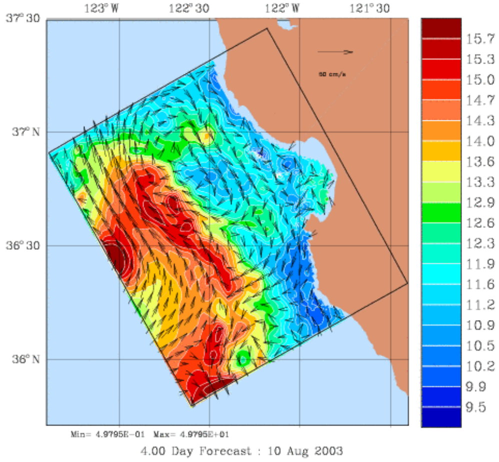
HOPS AOSN-II Re-Analysis



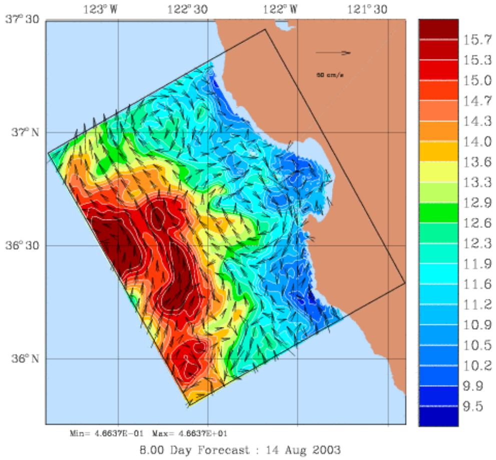
30m Temperature: 6 August – 3 September (4 day intervals)



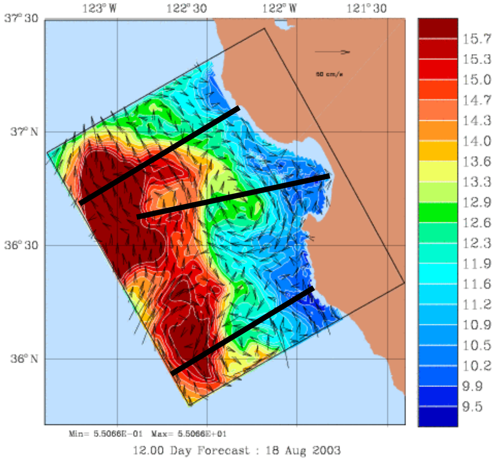
6 Aug



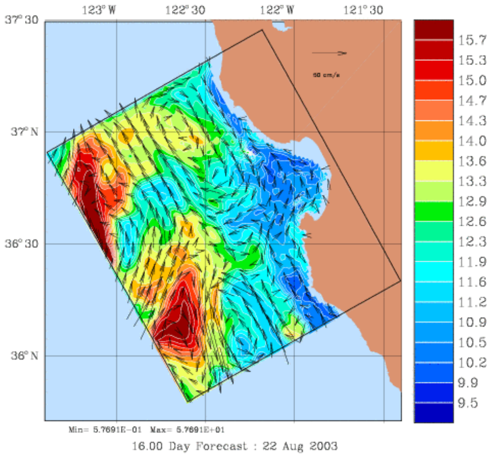
10 Aug



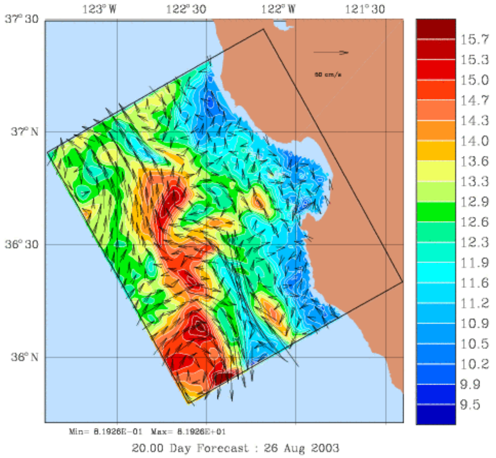
14 Aug



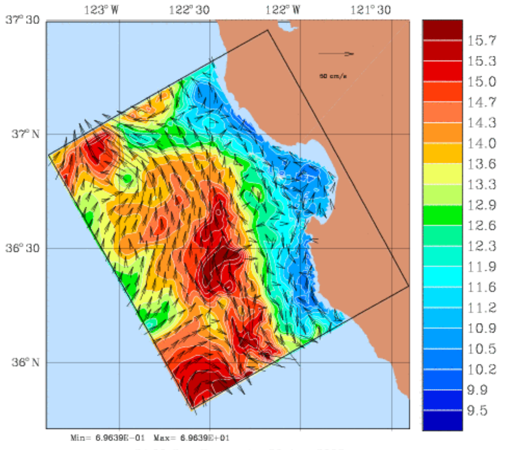
18 Aug



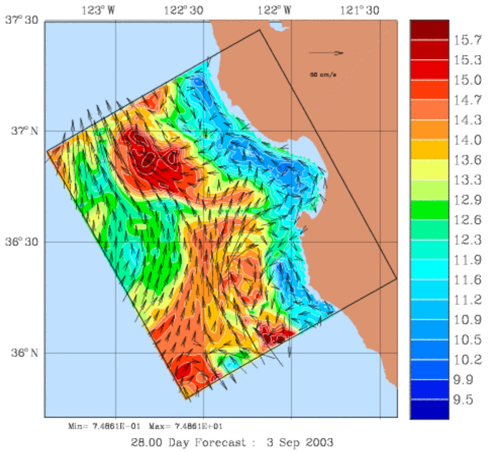
22 Aug



26 Aug



30 Aug

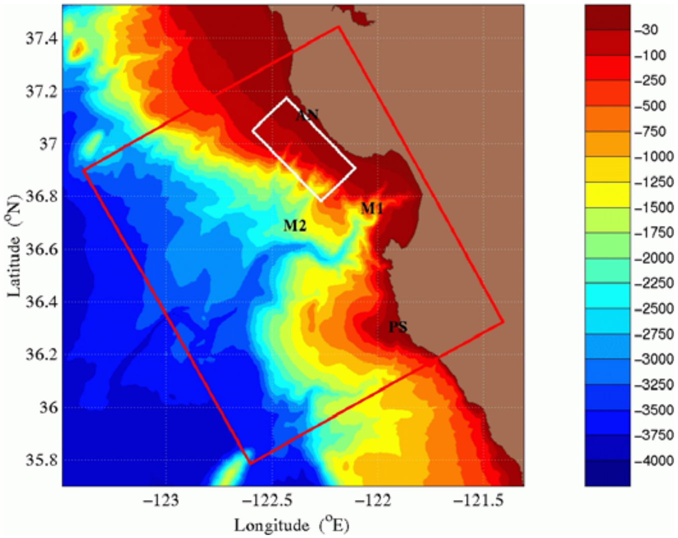


3 Sep

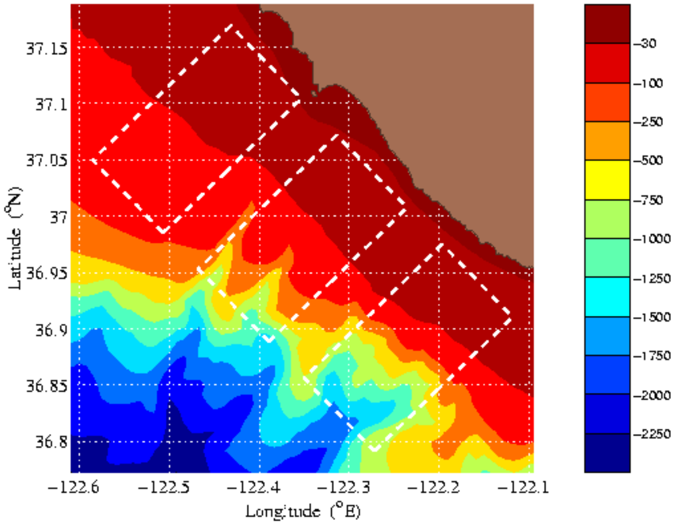
Descriptive oceanography of re-analysis fields and and real-time error fields initiated at the mesoscale.

Description includes: Upwelling and relaxation stages and transitions, Cyclonic circulation in Monterey Bay, Diurnal scales, Topography-induced small scales, etc.

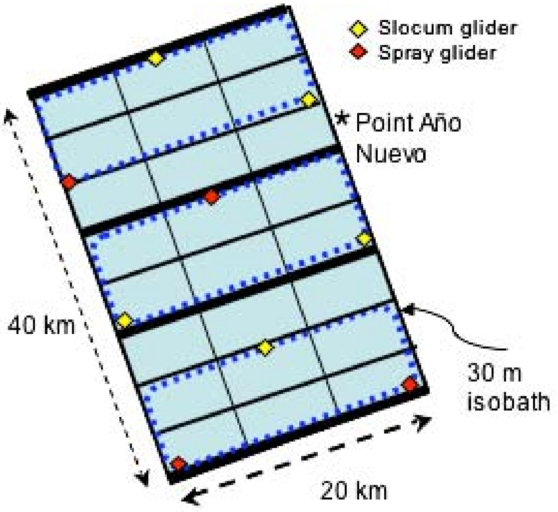
Adaptive Sampling and Prediction (ASAP)
Monterey Bay 2006



AOSN2 and ASAP Modeling Domains



ASAP Glider tracks for nominal sampling



Close-up view of nominal sampling

Adaptive sampling to:

- maintain nominal sampling array
- investigate special features

http://oceans.deas.harvard.edu/AOSN2/OSSE2005/Exp0001/

ASAP OSSE #1 – *N Gliders per Track*

OSSE Definition

- Ability of N gliders to quantitatively represent a simulated “true” ocean with and without melding with dynamics

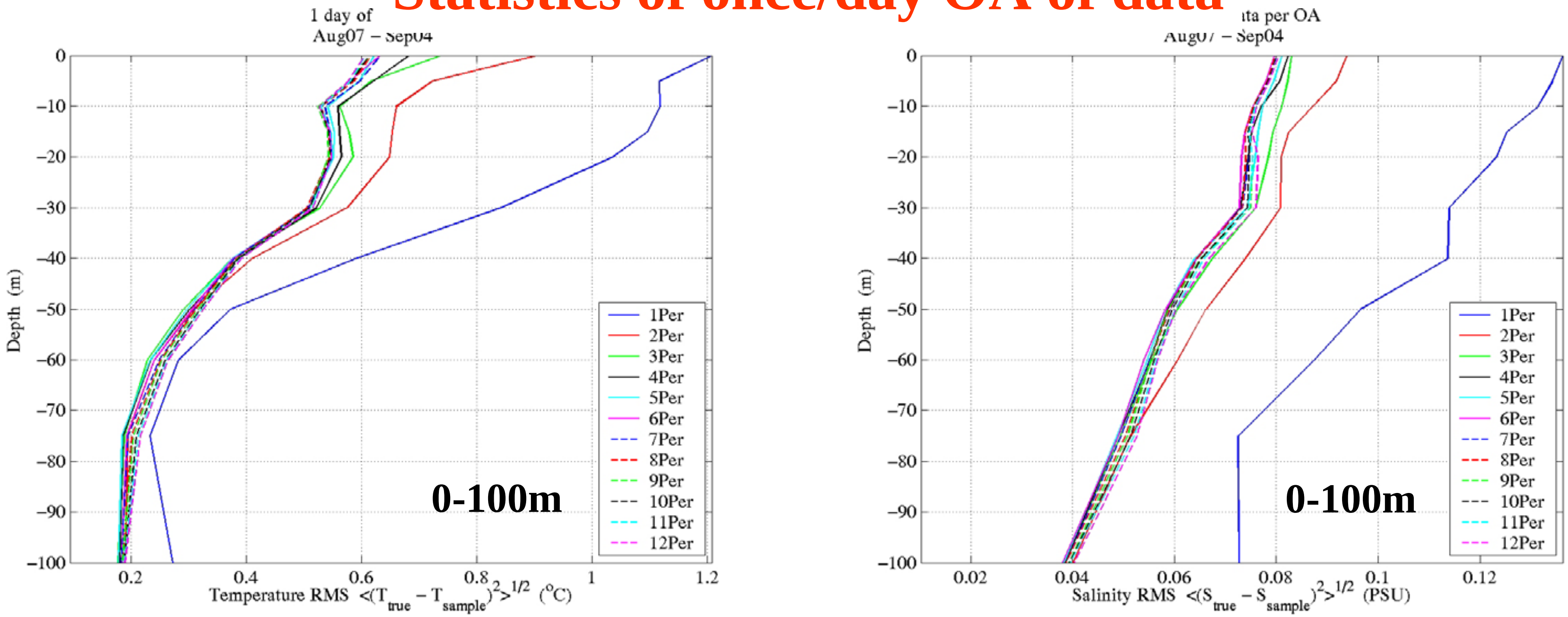
- Without dynamics: objectively analyze
  i. OA of glider data once per day

- With dynamics: assimilate data once per day and compare
  i. *A priori* estimate
  ii. *A posteriori* estimate

  Compare these estimates with once a day OA’s above

- OSSE fields for ASAP
  i. Preliminary results from – 1.5km, free surface, no tides
  ii. In preparation – 0.5km, free surface, tides

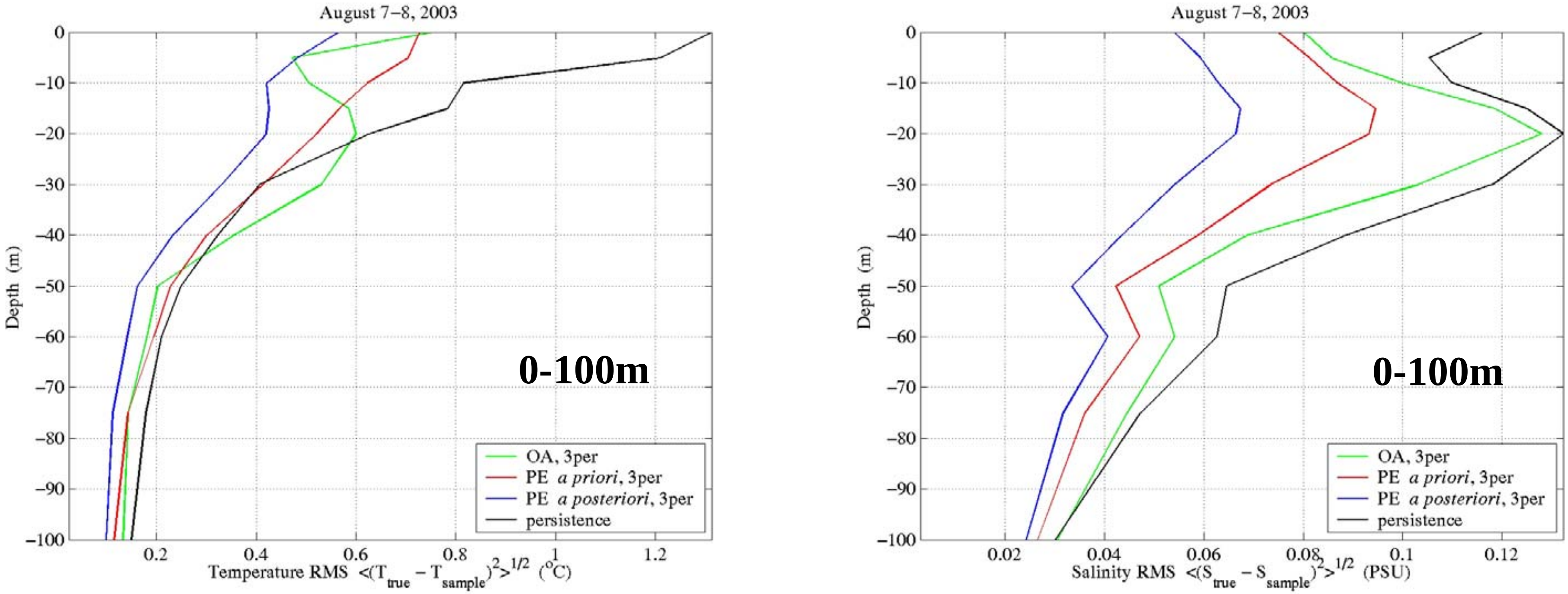
Statistics of once/day OA of data



Temperature RMS

Effect of Dynamics

Salinity RMS



Multi-Model Ensemble Estimates of Fields and Errors

Strategies For Multi-Model Adaptive Forecasting

- Error Analyses: *Learn individual model forecast errors in an on-line fashion through developed formalism of multi-model error parameter estimation*
- Model Fusion: *Combine models via Maximum-Likelihood based on the current estimates of their forecast errors*

3-steps strategy, using model-data misfits and error parameter estimation

1. Select forecast error covariance $\mathbf{B}$ and bias $\boldsymbol{\mu}$ parameterization $\boldsymbol{\alpha}, \boldsymbol{\beta}$

$$\mathrm{B} \approx \tilde{\mathrm{B}}(\boldsymbol{\alpha}); \qquad \boldsymbol{\mu} \approx \tilde{\boldsymbol{\mu}}(\boldsymbol{\beta}); \qquad \boldsymbol{\Theta} = \{\boldsymbol{\alpha}, \boldsymbol{\beta}\}$$

2. Adaptively determine forecast error parameters from **model-data misfits** based on the Maximum-Likelihood principle:

$\boldsymbol{\Theta}^* = \arg\max_{\boldsymbol{\Theta}} p(\boldsymbol{\mathcal{Y}}|\boldsymbol{\Theta})$ Where $\boldsymbol{\mathcal{Y}} = \{\mathbf{y}_1^o, \mathbf{y}_2^o, \ldots, \mathbf{y}_T^o\}$ is the observational data

3. Combine model forecasts $\mathbf{x}_i$ via Maximum-Likelihood based on the current estimates of error parameters (Bayesian Model Fusion)

O. Logoutov

$$\mathbf{x}^* = \arg\min_{\mathbf{x}} \sum_{m=1}^{M} \left(\mathbf{x} - \mathbf{H}_m \mathbf{x}_m\right)^T \mathcal{B}^{-1}_{(\boldsymbol{\Theta}_m)} \left(\mathbf{x} - \mathbf{H}_m \mathbf{x}_m\right)$$

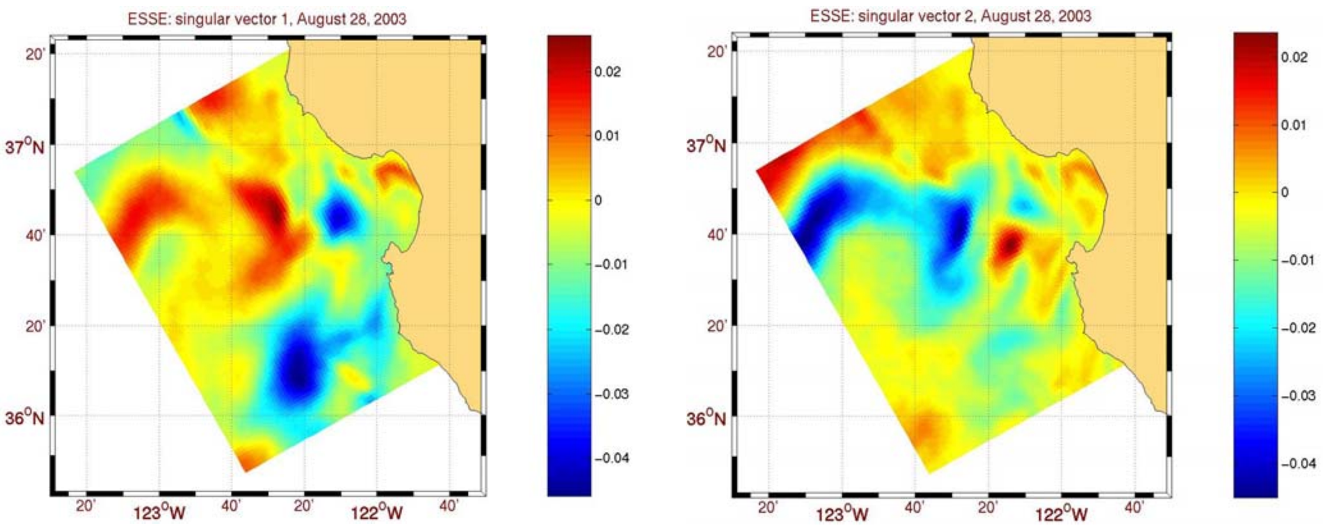
Error Subspaces and ESSE Tuning Prior to Assimilation

- ESSE 1st and 2nd dominant error subspaces on August 28, 2003 (AOSN2)

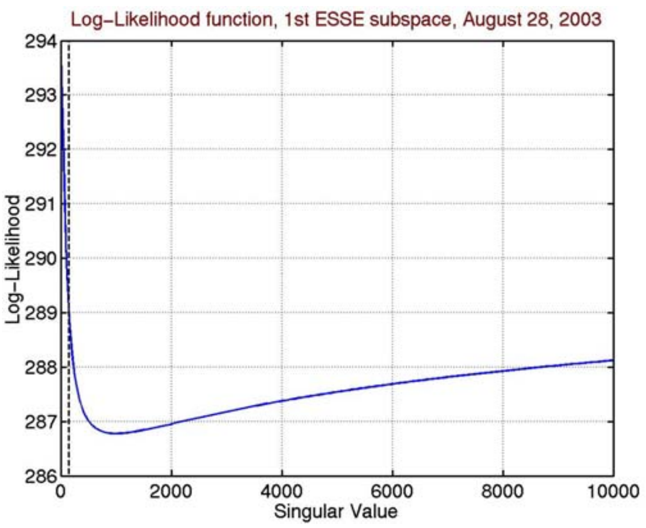
  ESSE seeks a low-rank error covariance representation: $\mathbf{B}(\hat{\boldsymbol{\alpha}}) = \mathbf{U}\mathbf{S}(\hat{\boldsymbol{\alpha}})\mathbf{U}^T$

  New Approach: use error subspace singular values as tunable parameters. The likelihood function for ESSE singular values:

  $$\log \mathcal{L}(\boldsymbol{\alpha}|\mathcal{D}) \propto (\boldsymbol{\alpha}-\boldsymbol{\alpha}_0)^T \boldsymbol{\Sigma}^{-1} (\boldsymbol{\alpha}-\boldsymbol{\alpha}_0) + \log \prod \mathrm{diag}\, \mathbf{S}(\hat{\boldsymbol{\alpha}}) + \mathbf{d}^T \left(\mathbf{B}(\boldsymbol{\alpha}) + \mathbf{R}\right)^{-1} \mathbf{d}$$



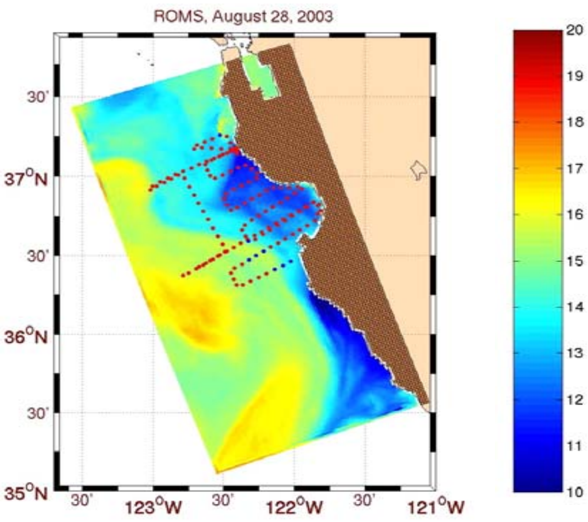
First (left) and second (right) dominant error subspaces (First and second columns of **U**)

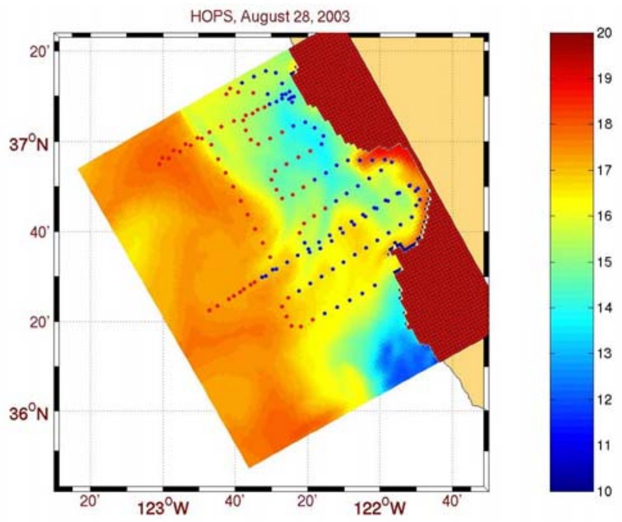


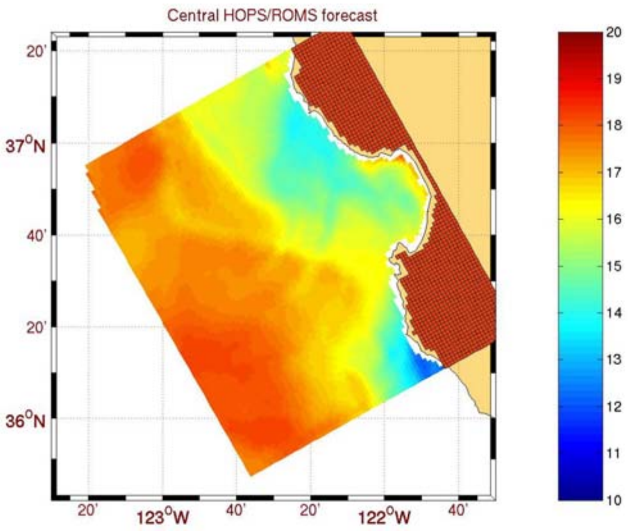
Log-likelihood function of the 1st ESSE subspace singular value

Two Models and Data Combined via Bayesian Fusion

ROMS and HOPS individual SST forecasts and the NPS aircraft SST data are combined based on their estimated uncertainties to form the central forecast







A new batch of model-data misfits and priors on uncertainty parameters determine via the Bayesian principle uncertainty parameter values that are employed to combine the forecasts.

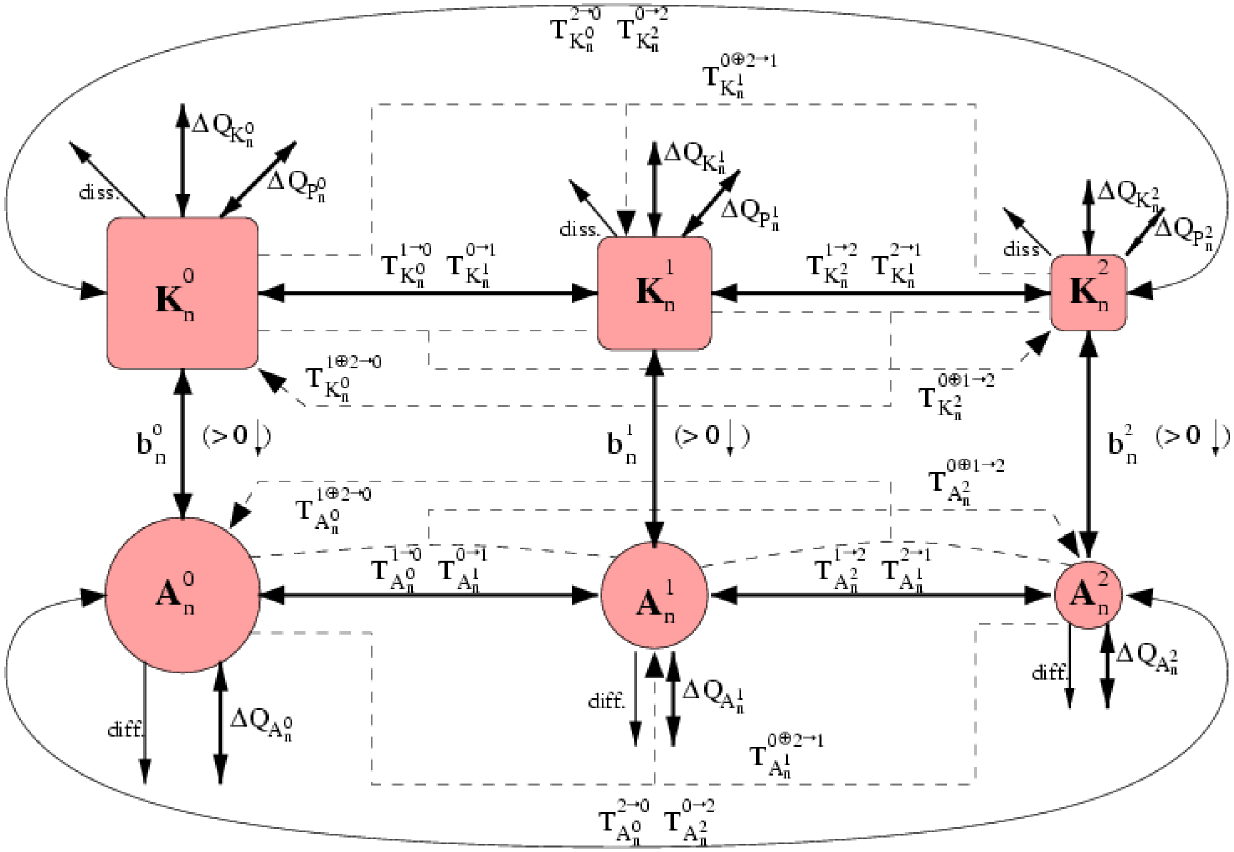
Multi-Scale Energy and Vorticity Analysis

MS-EVA is a new methodology utilizing multiple scale window decomposition in space and time for the investigation of processes which are:

- multi-scale interactive
- nonlinear
- intermittent in space
- episodic in time

Through exploring:

- pattern generation
- energy and enstrophy transfers, transports, and conversions
- perfect transfer fields

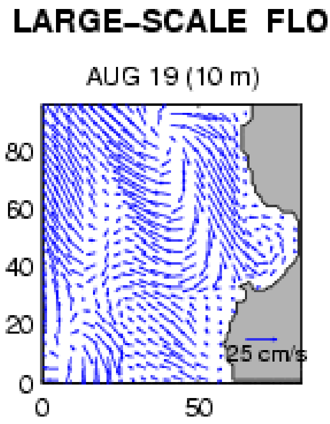


MS-EVA helps unravel the intricate relationships between events on different scales and locations in phase and physical space.

Dr. X. San Liang

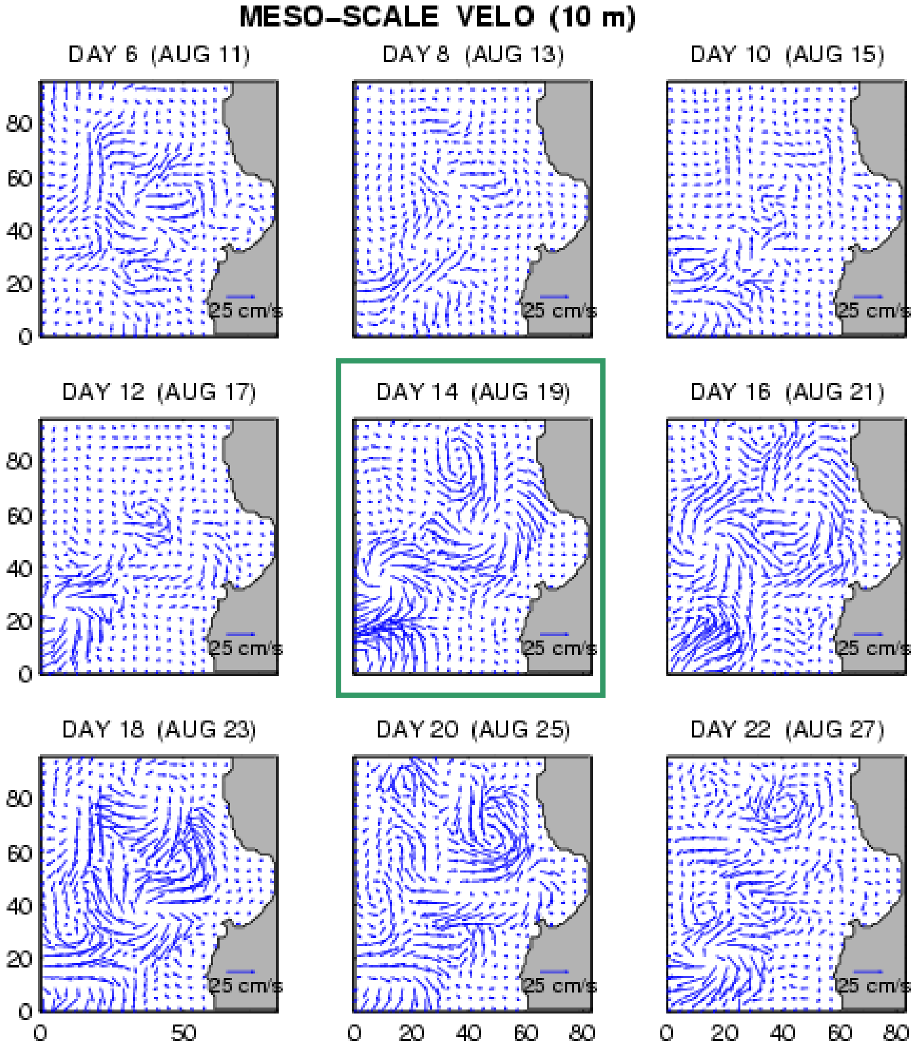
Multi-Scale Energy and Vorticity Analysis

Multi-Scale Window Decomposition in AOSN-II Reanalysis


LARGE-SCALE FLOW

The reconstructed large-scale and meso-scale fields are filtered in the horizontal with features < 5km removed.

Time windows
Large scale: > 8 days
Meso-scale: 0.5-8 days
Sub-mesoscale: < 0.5 day

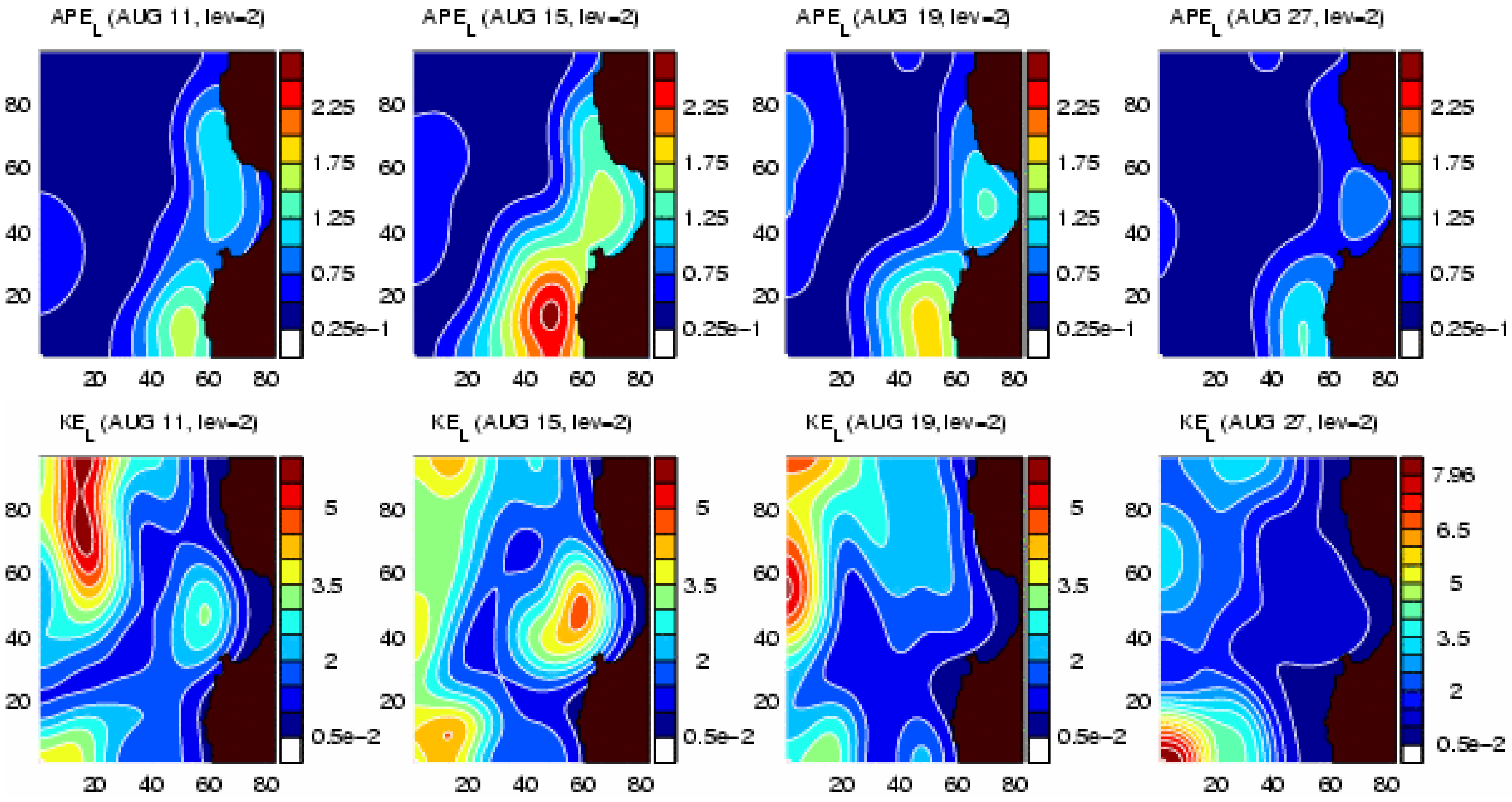

MESO-SCALE VELO (10 m)

Question: How does the large-scale flow lose stability to generate the meso-scale structures?

Multi-Scale Energy and Vorticity Analysis

- Decomposition in space and time (wavelet-based) of energy/vorticity eqns.

Large-scale Available Potential Energy (APE)



Large-scale Kinetic Energy (KE)

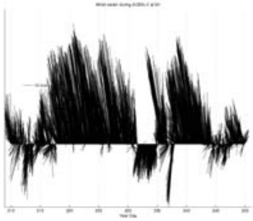
- Both APE and KE decrease during the relaxation period
- Transfer from large-scale window to mesoscale window occurs to account for decrease in large-scale energies (as confirmed by transfer and mesoscale terms)

Windows: Large-scale (>= 8days; > 30km), mesoscale (0.5-8 days), and sub-mesoscale (< 0.5 days)

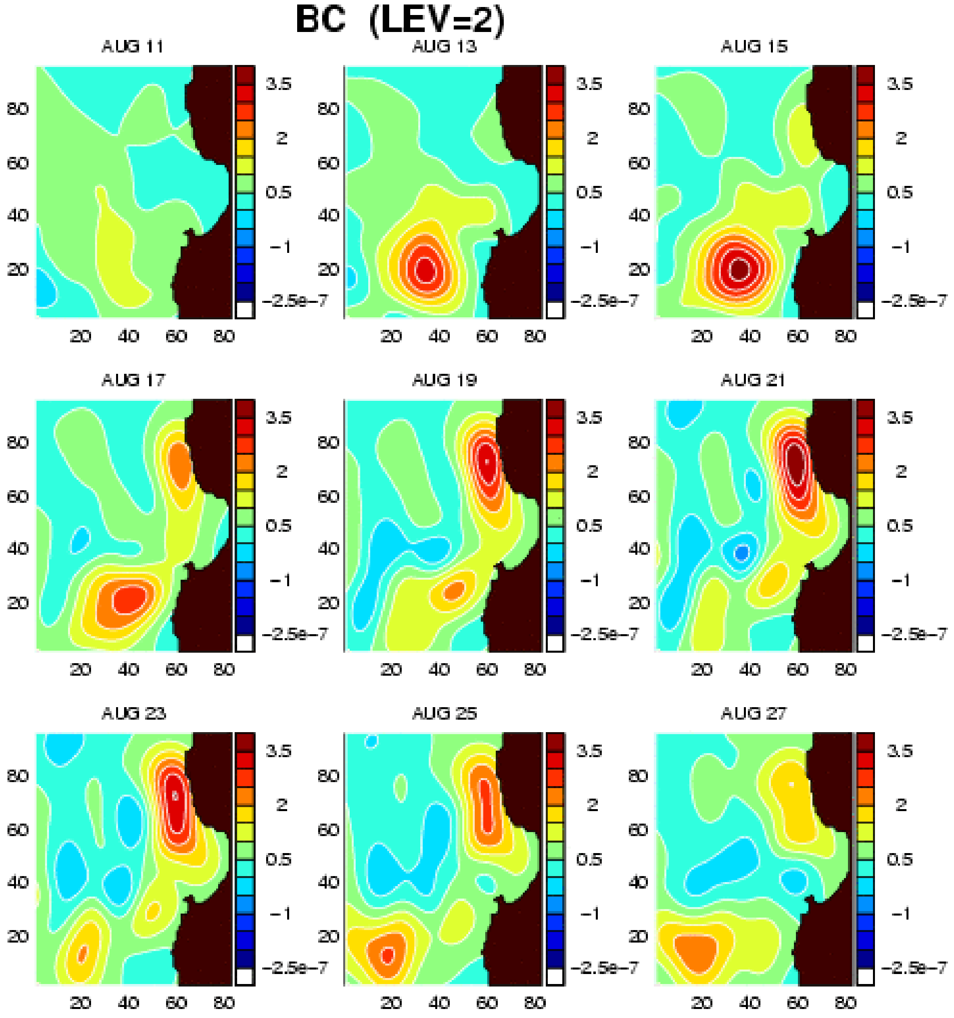
Dr. X. San Liang

Multi-Scale Energy and Vorticity Analysis

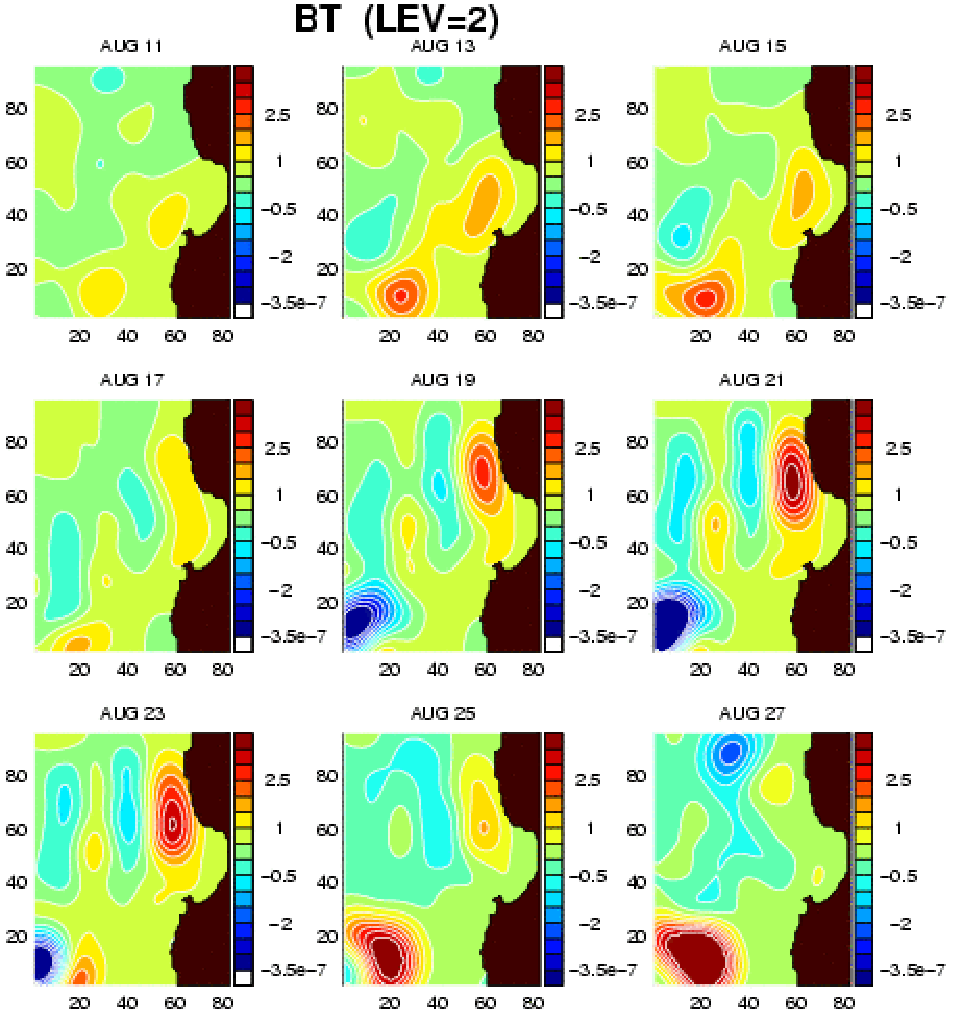
MS-EVA Analysis: 11-27 August 2003



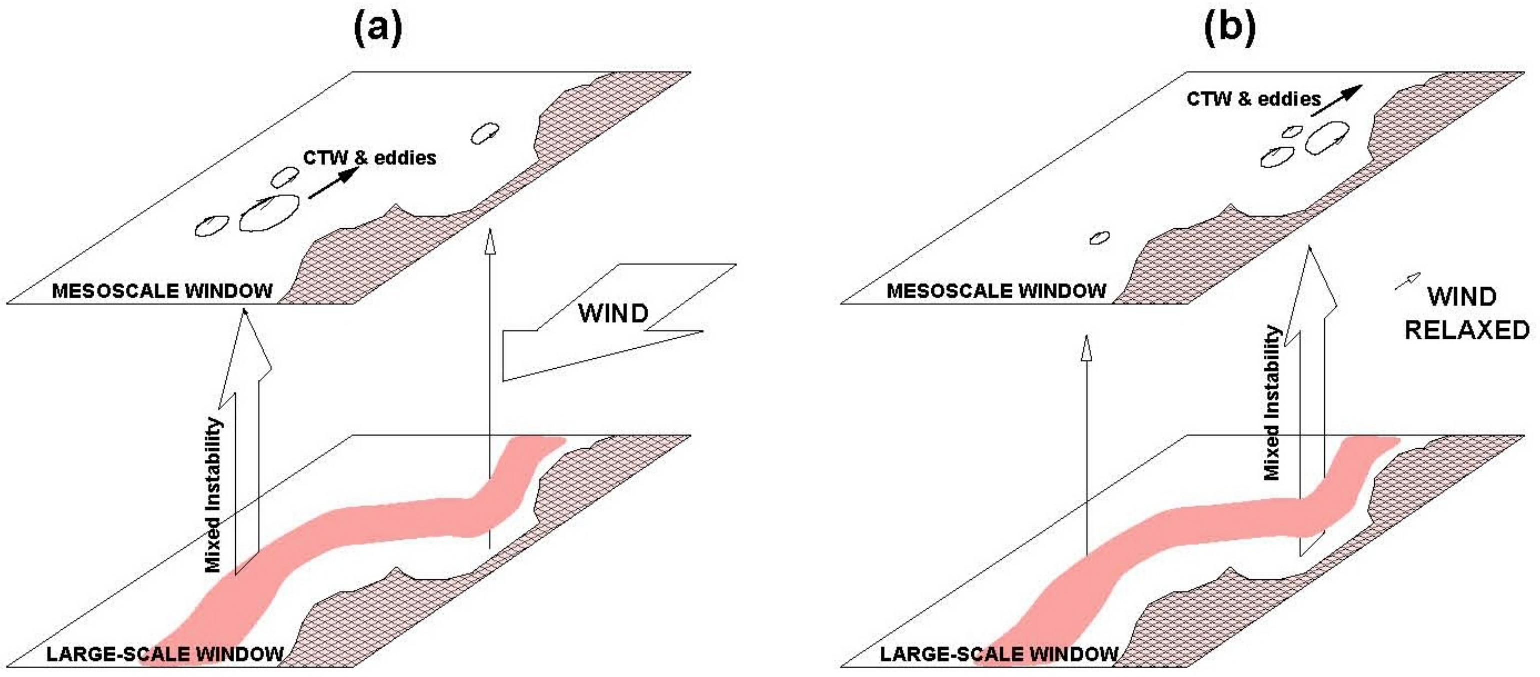
Transfer of APE from large-scale to meso-scale



Transfer of KE from large-scale to meso-scale



Multi-Scale Energy and Vorticity Analysis



- Two distinct centers of instability: both of mixed type but different in cause.
- Center west of Pt. Sur: winds destabilize the ocean directly during upwelling.
- Center near the Bay: winds enter the balance on the large-scale window and release energy to the mesoscale window during relaxation.
- Monterey Bay is source region of perturbation and when the wind is relaxed, the generated mesoscale structures propagate northward along the coastline in a surface-intensified free mode of coastal trapped waves.

CONCLUSIONS

- Entering a new era of fully interdisciplinary ocean science: physical-biological-acoustical-biogeochemical

- Advanced ocean prediction systems for science, operations and management: interdisciplinary, multi-scale, multi-model ensembles

- Interdisciplinary estimation of state variables and error fields via multivariate physical-biological-acoustical data assimilation

http://www.deas.harvard.edu/~robinson