Interdisciplinary Modeling and Dynamics of Archipelago Straits:

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1. **Research Goals and Objectives for this DRI Philippine Strait**
2. **Relevant Experience:**
   - **Straits of Sicily Features and Dynamics**
   - **Interdisciplinary DA and Modeling**
   - **Monterey Bay Research: LCS, Adaptive Sampling, Tides, MsEVA, Adaptive Modeling, Multi-Models**
3. **Conclusions**

http://web.mit.edu/pierrel/www

Stennis, Feb 14, 2007

Research Goal and Objectives

Long-Term Goal:

Explore and better understand interactive dynamics and variability of sub-mesoscale and mesoscale features and processes in the Philippine Straits region and their impacts on local ecosystems through

i. *Interdisciplinary physical-biogeochemical-acoustical data assimilation of novel multidisciplinary observations*
ii. *Adaptive, multi-scale physical and biogeochemical modeling*
iii. *Process and sensitivity studies based on a hierarchy of simplified simulations and focused modeling.*

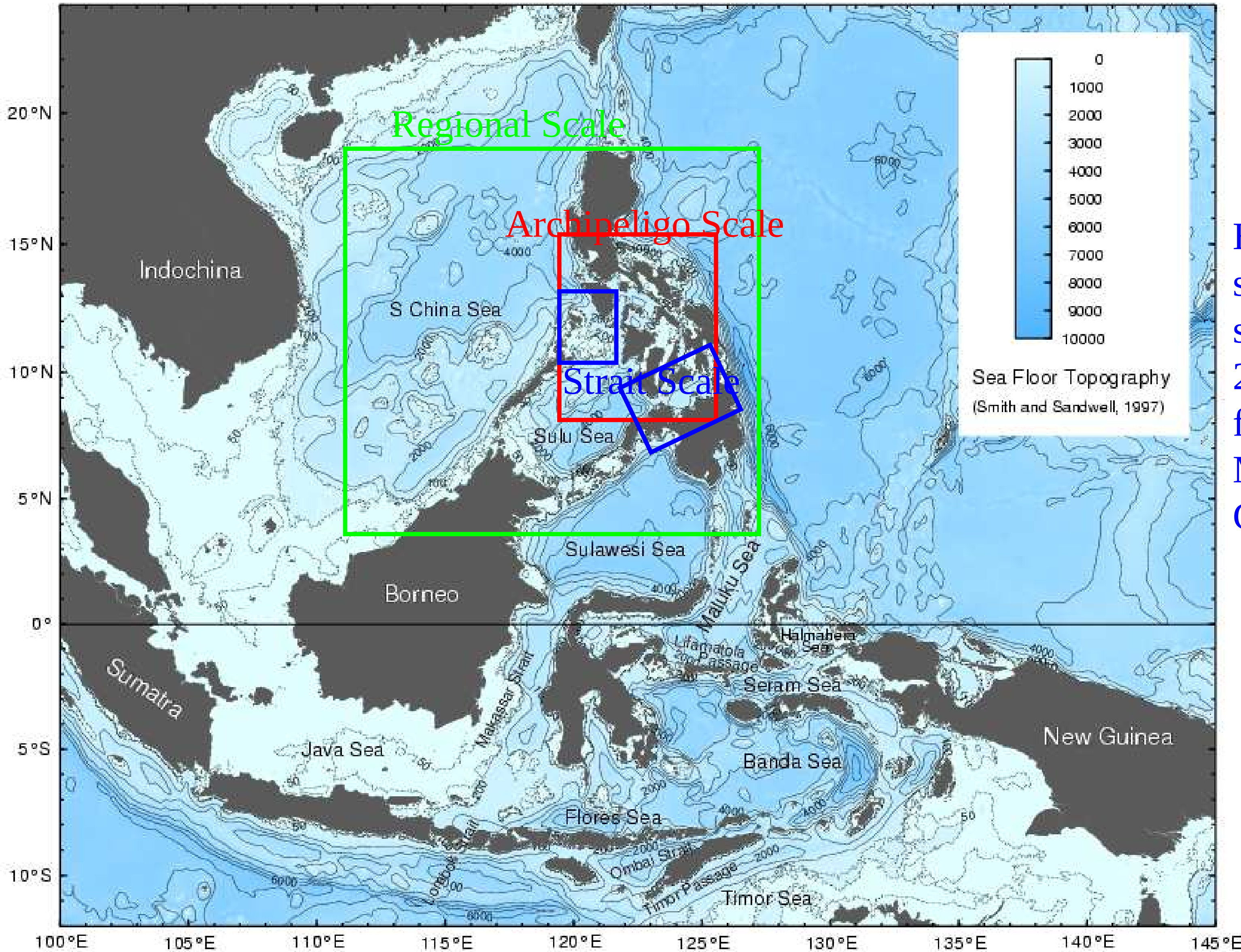
Specific objectives:

- Utilize and develop the Error Subspace Statistical Estimation (ESSE) system for interdisciplinary data assimilation and uncertainty estimation with the physical Primitive-Equation (PE) and generalized biogeochemical model of the Harvard Ocean Prediction System (HOPS)
- Study, describe and model the variability and dynamics of flow separations and associated eddies and filaments, of water mass evolutions and pathways, and of locally trapped waves
- Develop and implement schemes for parameter estimation and selection of model structures and parameterizations, and for high-resolution nested domains towards non-hydrostatic modeling

From Gordon *et al.*:

The observational nested approach [boxes are approximate]

From the R/V Melville in 2007 and 2008

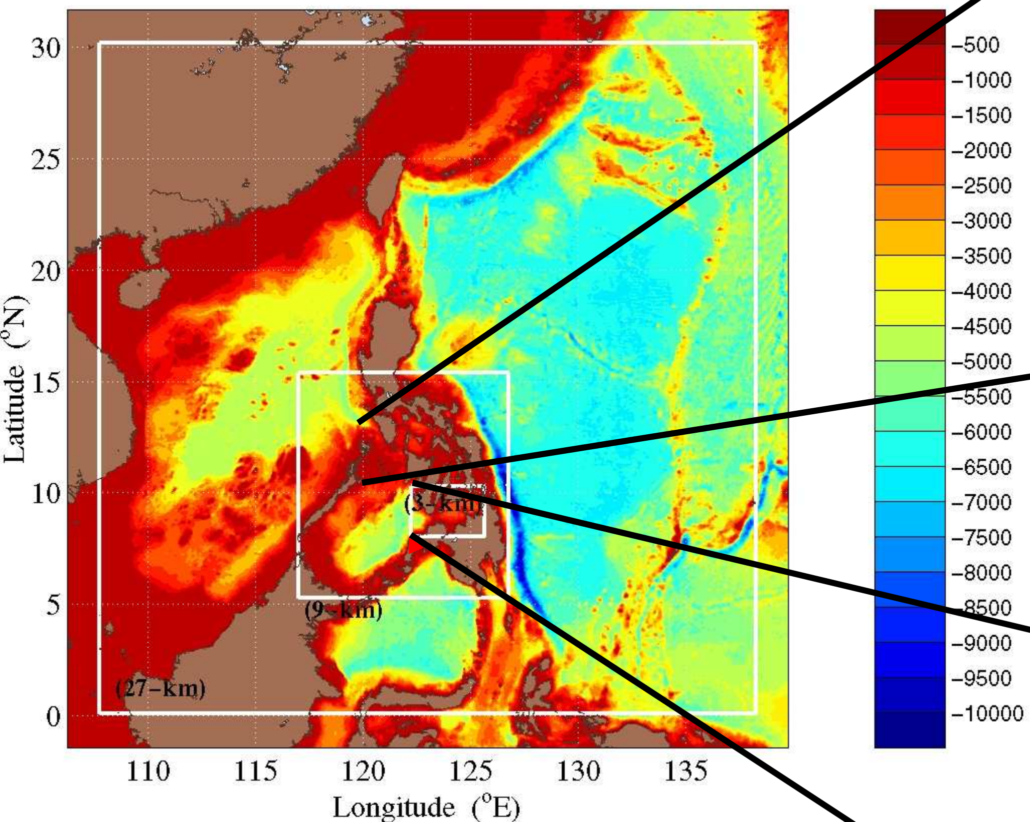


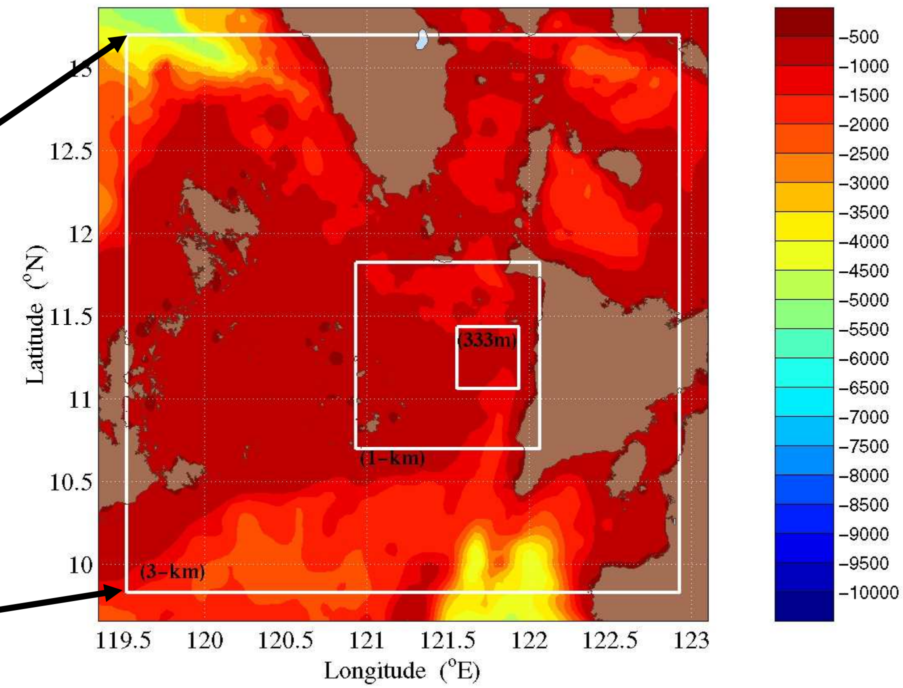
Red Box: Regional survey 2007 [June]

Blue Boxes: Detailed study of a specific strait environment 2008 [IOP, time frame: feb-mar; Aug-Sept] Mindoro or Mindanao Channels

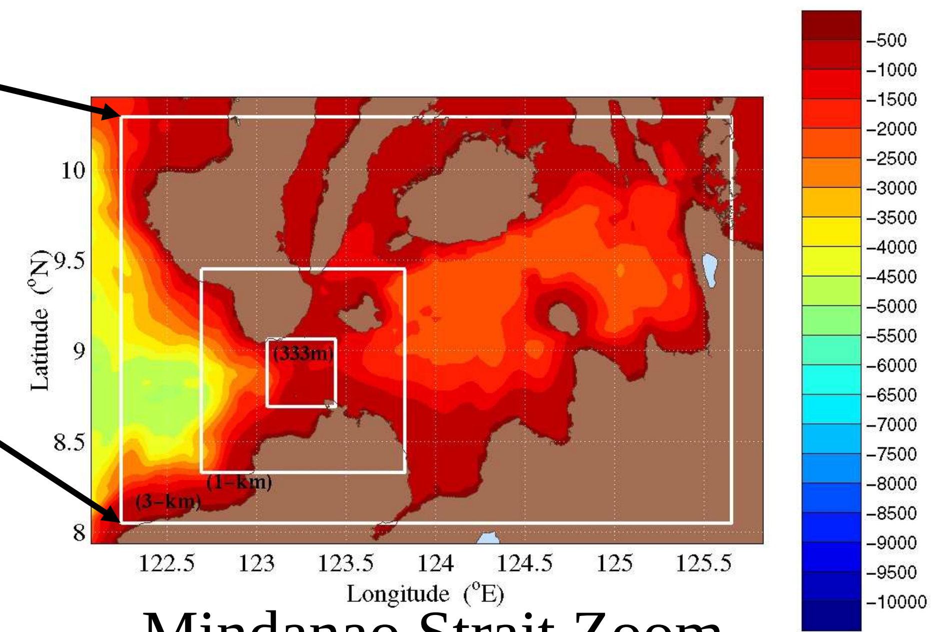
In addition: There will be a 2nd regional cruise in 2007 [August], for general survey work to be carried out by Philippine researchers

Our Ocean Modeling Nested Domains





Mindoro Strait Zoom



Mindanao Strait Zoom

Scientific Goals (to be finalized depending on observations)

Physical dynamical processes:

1. Flow separation occurring in and around Straits, and the associated formation of eddies and possibly persistent filaments (e.g. in collaboration with Larry Pratt and Karl Helfrich of WHOI, and others)
2. Water masses transformations, locally trapped waves and variability of three-dimensional flow patterns and water-pathways in the Philippines region, from sub-daily to monthly time-scales,
3. Effects of intense tidal forcing in Straits and the statistical properties of internal tides/waves and of interactions between tidal flows and buoyancy currents

Biological-geochemical-optical modeling:

1. Estimation of model parameters/parameterizations based on marine ecosystem observations
2. Study of impacts of the above 3 types of physical processes on the regional biology
3. Quantitative estimation of biogeochemical dynamics and dominant term balances

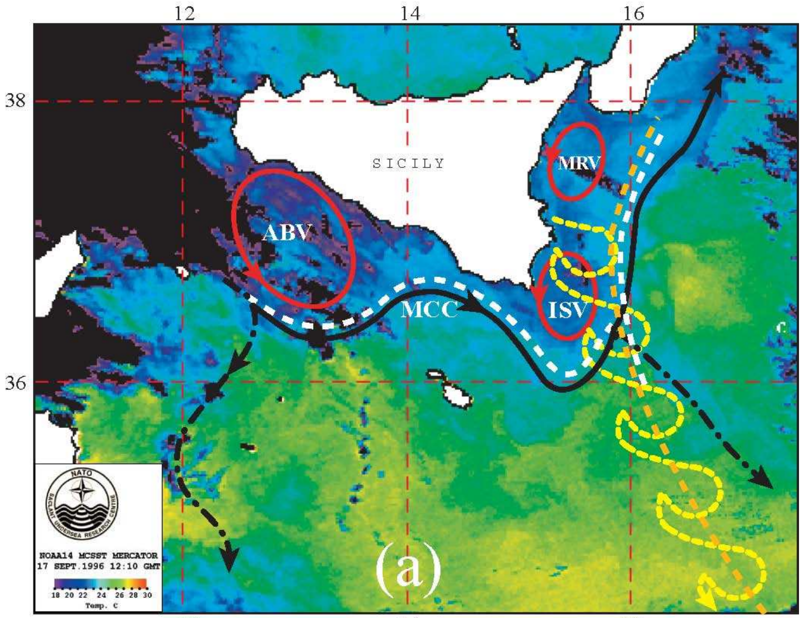
Technical Approach

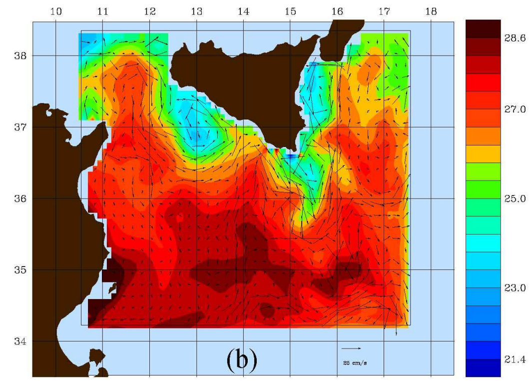
- **Physical and Interdisciplinary Data Assimilation of Novel Multidisciplinary Data Types**
  - *Measurement Models and Interdisciplinary DA:* e.g. new biogeochemical sensors, remote (HF radar, SST, SSH, SSC). Investigate combination of multi-grid DA with ESSE
  - *High-resolution DA*: assimilate sub-inertial processes & interactions without aliasing

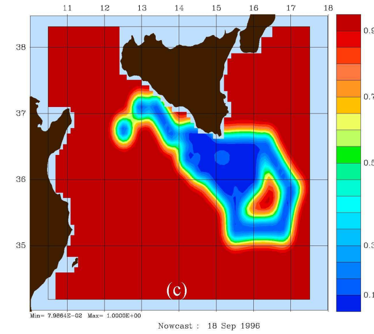
- **Scientific Process and Sensitivity Studies (to be prioritized based on DRI team inputs)**
  - *Processes*: variability and dynamics of flow; water pathways and transformation of water masses; tidal – buoyancy flow interactions; biological responses to these; blooms; biological accumulations
  - *Scientific model-based studies*: sensitivity studies; term and flux balances and transports; energy diagnostics; estimation of dominant scales of variability; predictability

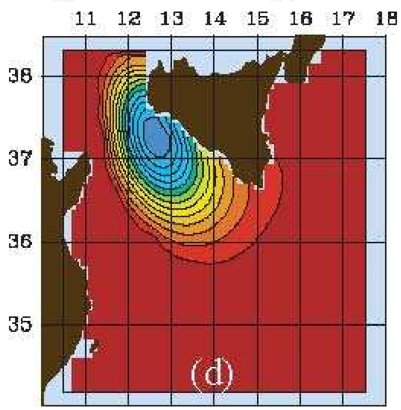
- **Adaptive Physical and Biogeochemical Modeling**
  - *Adaptive Modeling*: model structures & parameters quantitatively learn from observations, based on data-model misfits
  - *Tidal Modeling*: tidal inversion to combine global tides with data. Nesting with free surface PE. High-speed, tidal driven flows with (sub)-mesoscale interactions over steep terrain. Generation & propagation baroclinic tides & waves over mesoscale domains.
  - *Multi-dynamics nested domains and non-hydrostatic modeling*: boundary forcing from global model ; multi-model estimation; non-hydrostatic effects.

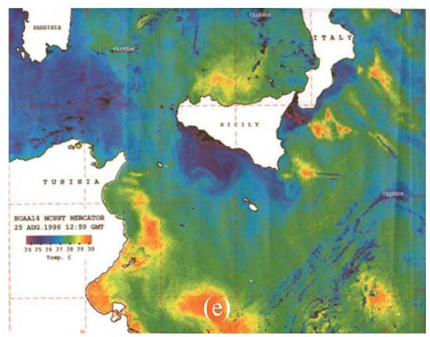
Selected ESSE oceanic results for the Strait of Sicily

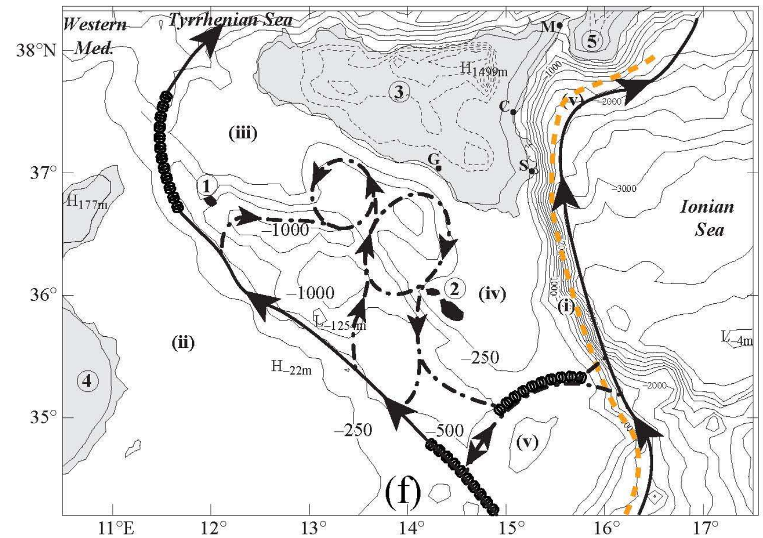






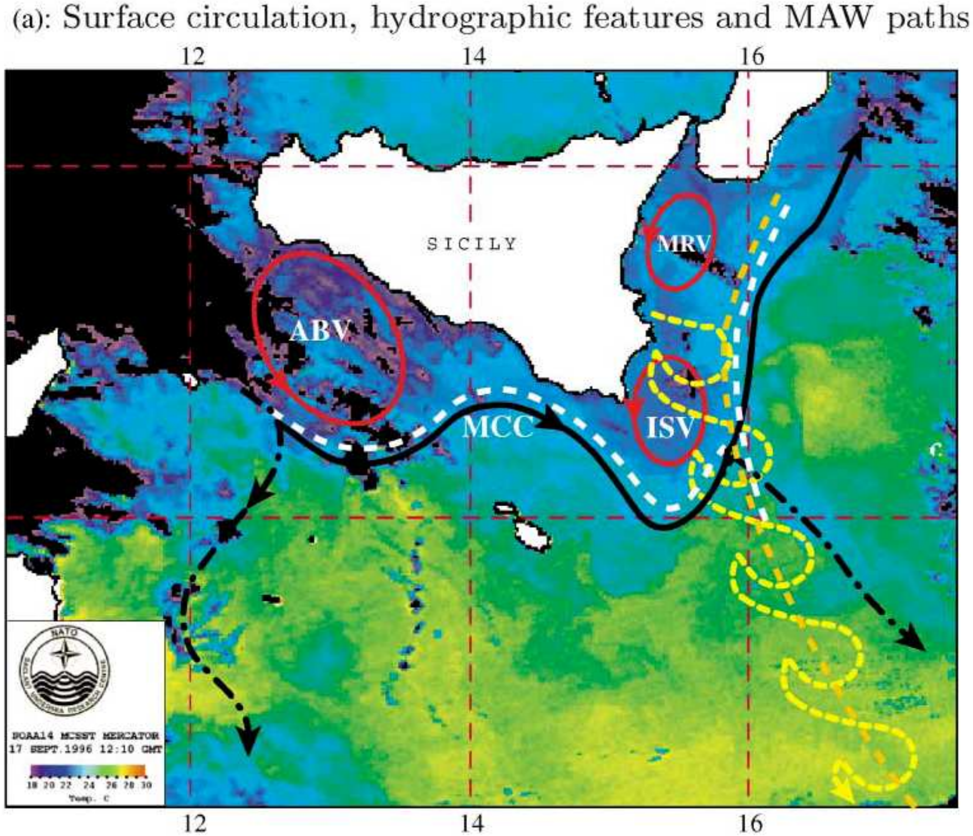






(a) Schematic of circulation features and dominant variabilities. (b) Forecast of the surface temperature for Aug. 25, 1996, overlaid with surface velocity vectors (scale arrow is 0.25 m/s). (c) Objectively analyzed surface standard error deviation associated with the aircraft sampling of Sep. 18, 1996 (normalized from 0 to 1). (d) Surface values of the first non-dimensional temperature variability mode. (e) Satellite SST distributions for Aug. 25, 1996. (f) Main LIW pathways, features and mixing on deep potential density anomaly iso-surface (σ_θ=29.05), over bottom topography.

(see: JMS, 99; DAO, 99; Deep Sea Res., 2001)



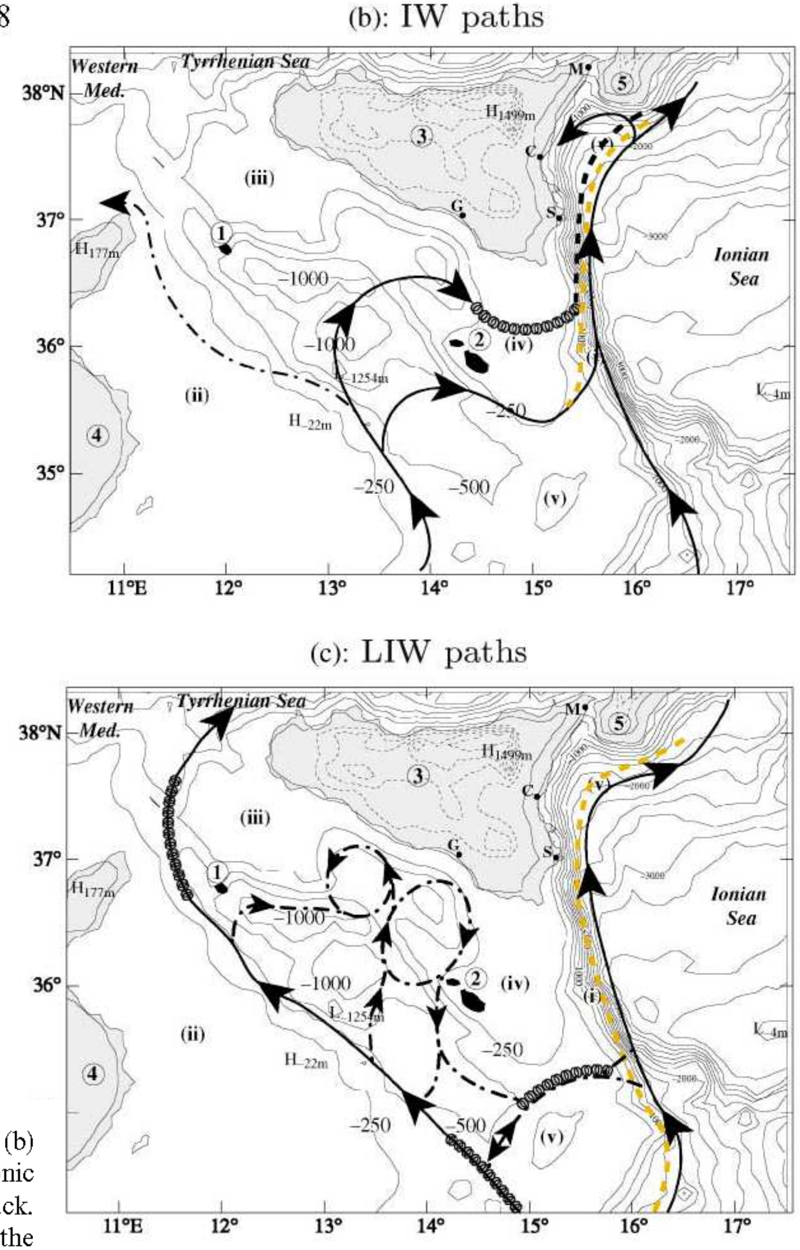


Fig. 16. Cartoons. (a) Main hydrographic and circulation features superposed on the satellite SST for Sep. 17, 1996. (b) Main IW pathways, superposed on the tography. (c) As (b), but for the LIW. On (a), the surface currents of cyclonic vortices (ABV, ISV and MRV) are schematized in red, those of the MCC and of the AIS and its branches are in black. These circulation patterns determine the main pathways of the upper-layer MAW. The sub-surface T and S fronts of the Ionian slope (ISFs) are dashed-white and dashed-orange, respectively (on b, the T front appears as dashed-black). The corresponding possible wave packets are dashed-yellow. For all Panels, dominant branches or pathways are solid lines, weaker or intermittent ones are dash-dotted. Important mixing regions are represented by corkscrews.

Even though cartoons purposely simplify reality, several properties are maintained. For example, since the S dominated Ionian slope front is tilted with depth, the largest upper-layer velocities are usually on its eastern side. The size of vortices, locations of AIS branches around Sep. 17 and dominant wavelength of possible Ionian slope wave packets are also respected (Panel a). Some properties are however not represented: e.g. compared to the MAW, the IW and LIW correspond to a broad overflow (see Figs. 12 and 13). In passing, note the agreement between the forecast for Sep. 18 (Fig. 10a) and the satellite SST.

Coupled Interdisciplinary Data Assimilation (DA)

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

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

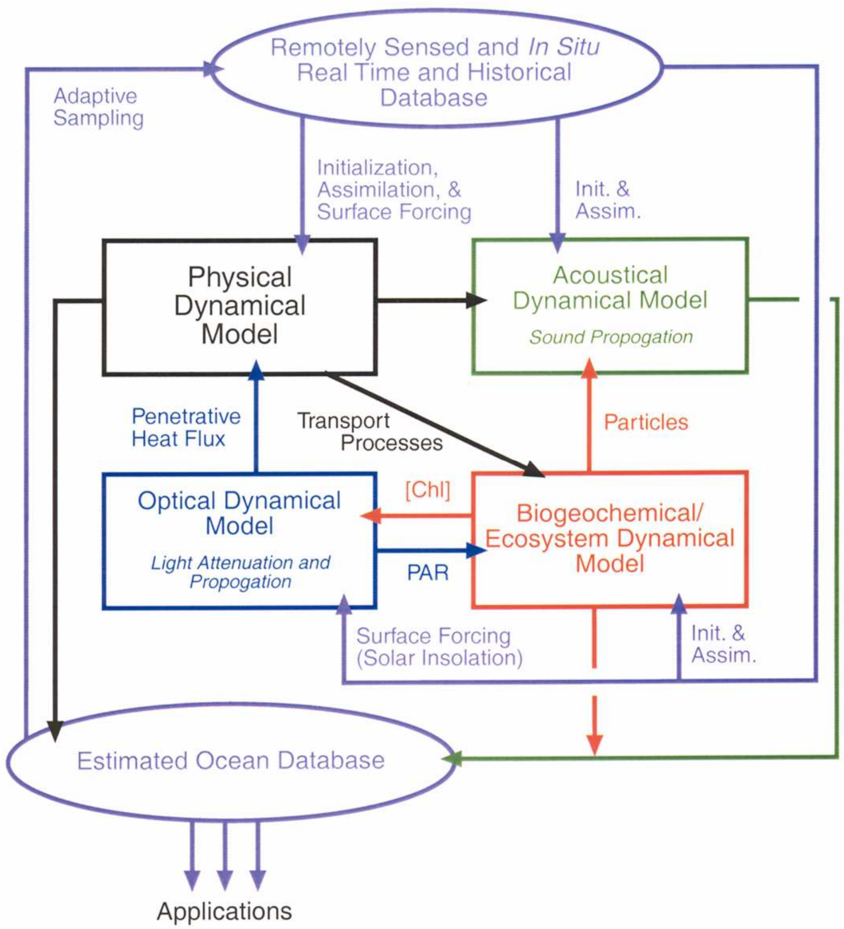
(can also include Seabed, Noise and Sonar Sys. models and variables)

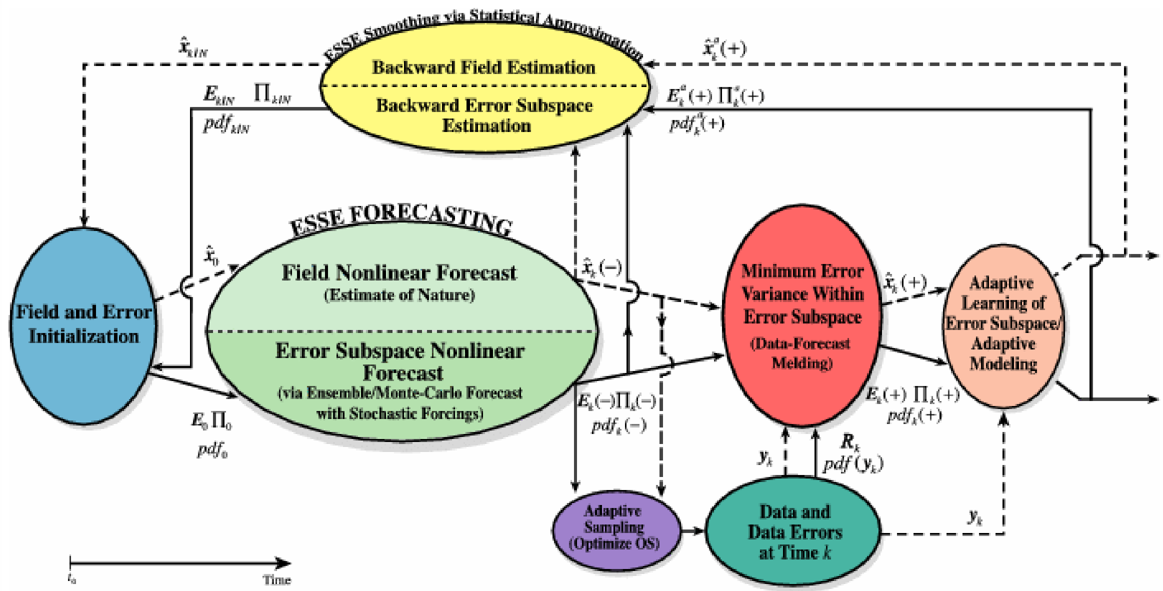
$$\boldsymbol{P} = \varepsilon \left\{ (\hat{\boldsymbol{x}} - \boldsymbol{x}^t)(\hat{\boldsymbol{x}} - \boldsymbol{x}^t)^T \right\}$$

Coupled error covariance with off-diagonal terms

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

Research Basis: HOPS/ESSE System





Harvard Ocean Prediction System

Free-surface PE, Generalized biological models, Coupled to acoustic models, XML schemes to check configuration

Error Subspace Statistical Estimation

Uncertainty forecasts, Ensemble-based, Multivariate DA, Adaptive sampling, Towards multi-model estimates

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

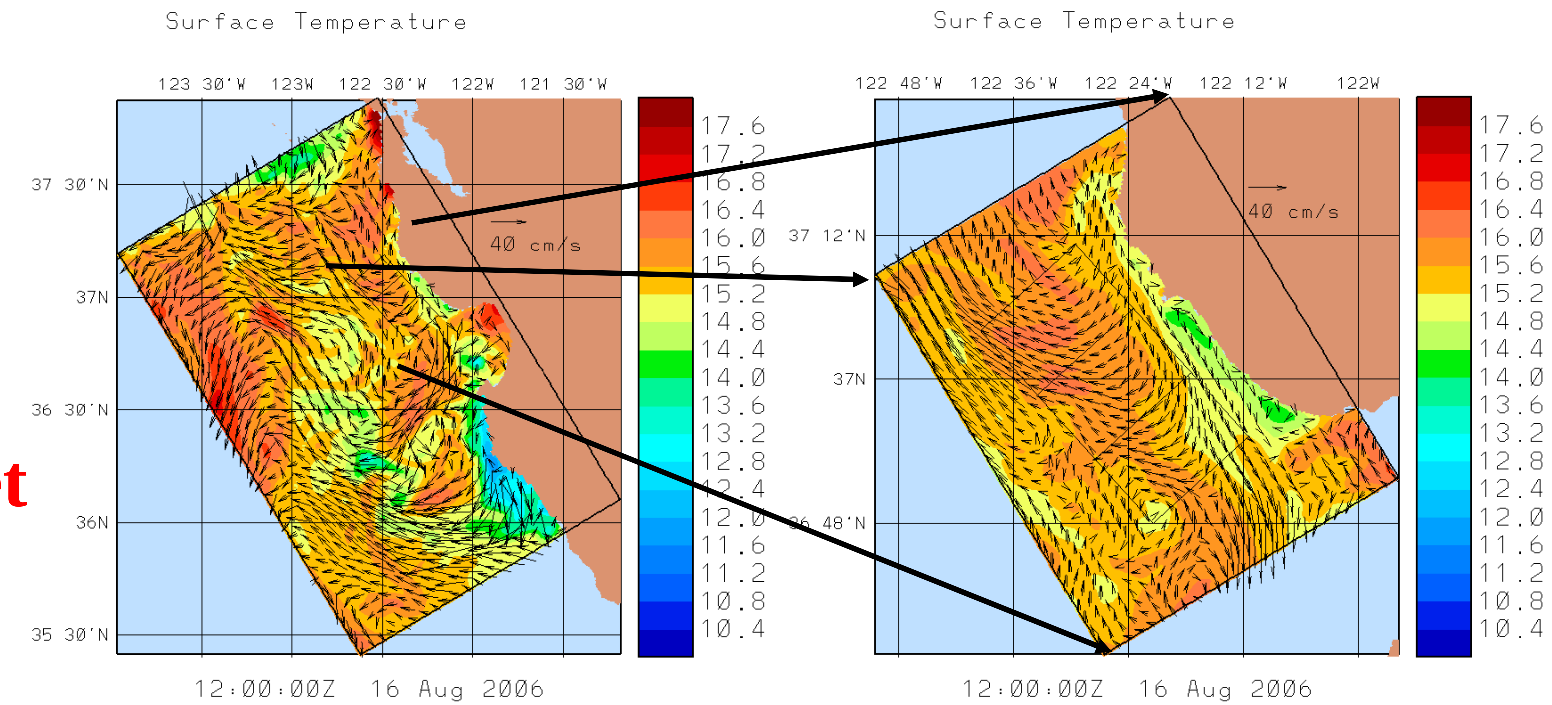
Nested Modeling with Grid-computing in Two Domains

- Monterey Bay/San Francisco Domain: 1.5 km resolution
- PLUSNet - Ano Nuevo Domain: 0.5 km resolution

Adaptive sampling recommendations for AN budget estimation, aiming to integrate coverage, dynamics and uncertainty.

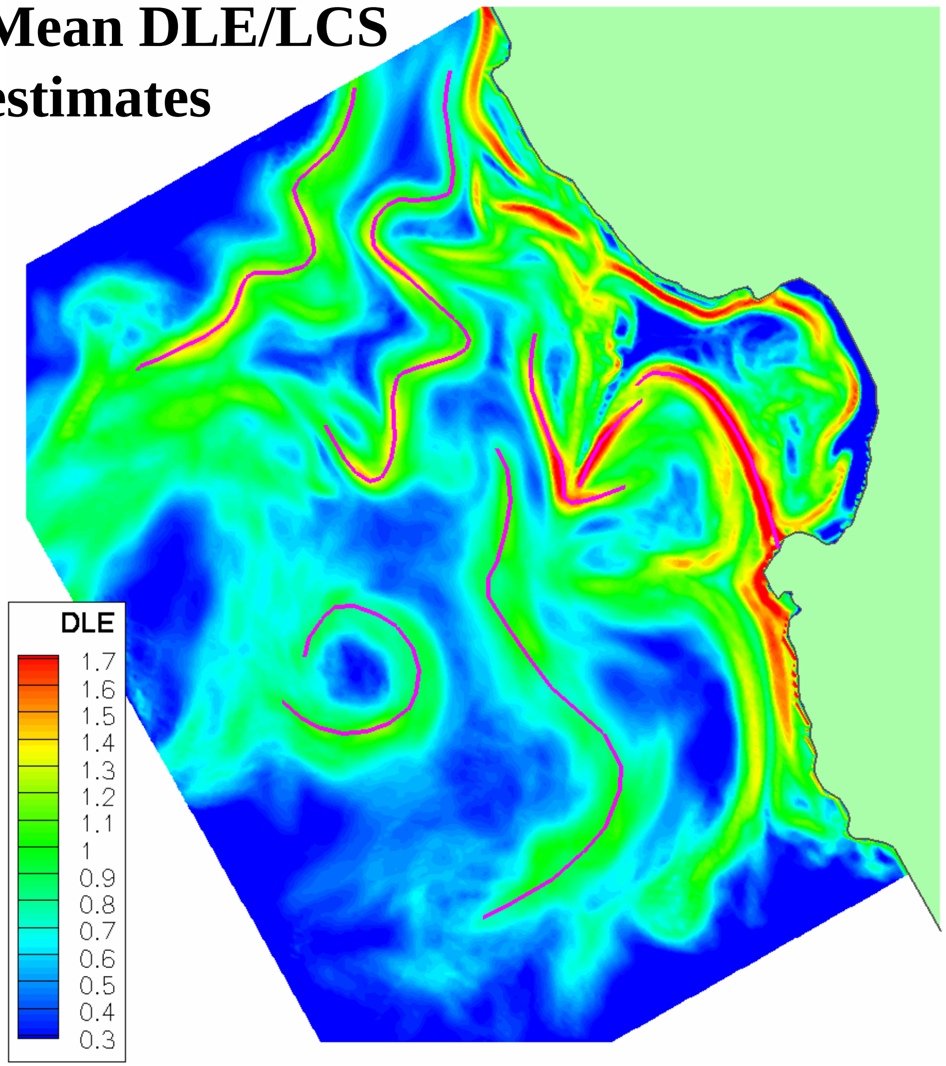
MB06:

- **ASAP**
- **PLUSNet**

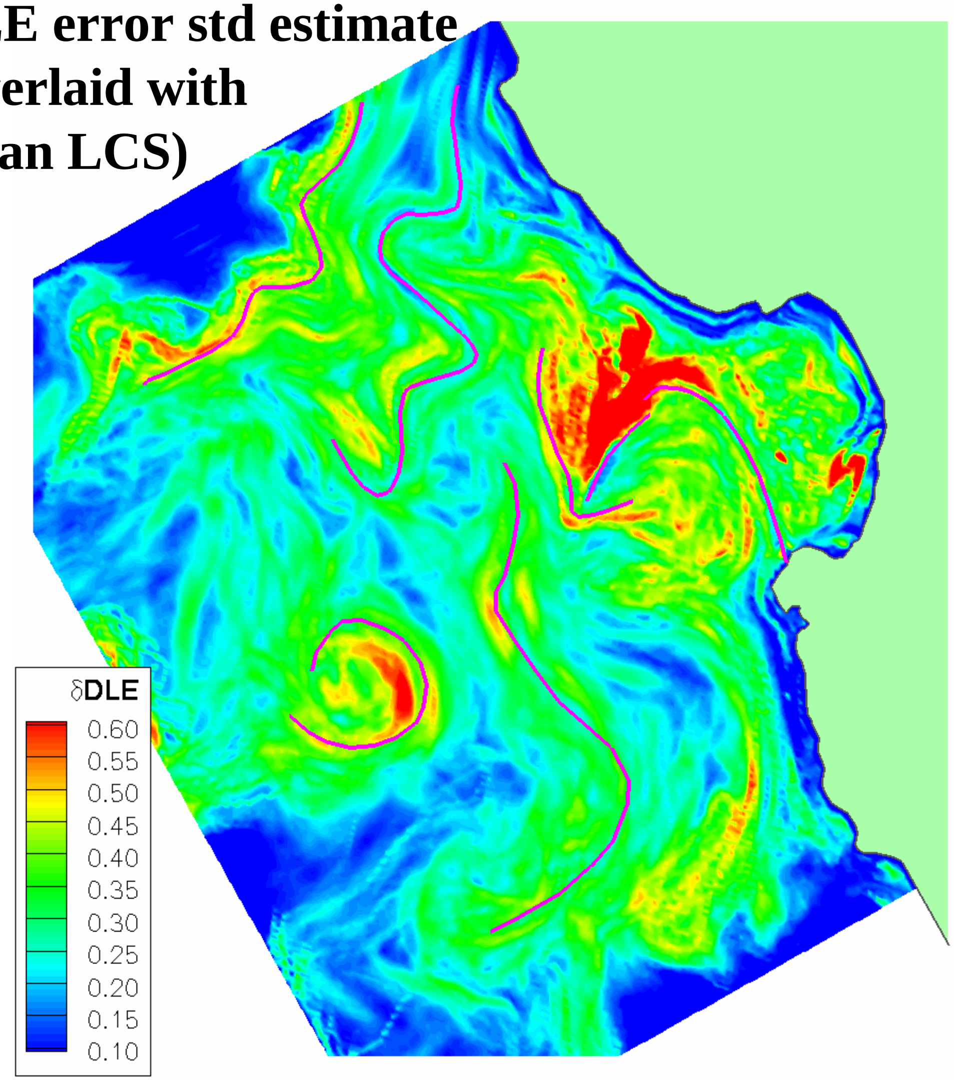


Lagrangian Coherent Structures and their Uncertainties for the Aug 26-29, 2003 Upwelling Period

Mean DLE/LCS estimates



DLE error std estimate (overlaid with mean LCS)



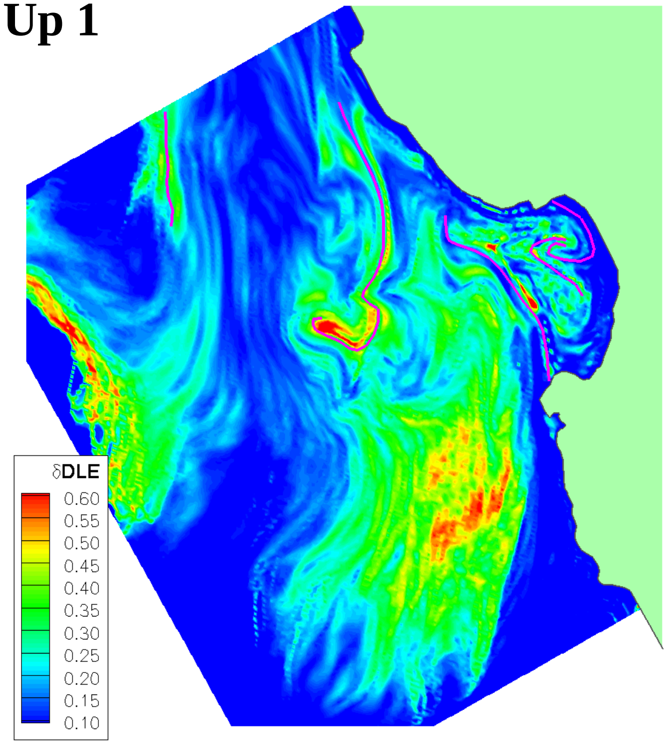
See: **Lermusiaux and Lekien**, Aug. 2005.
for “Dynamical System Methods in Fluid Dynamics”, Oberwolfach, Germany.

Mean LCSs overlaid on DLE error std estimate for 3 dynamical events

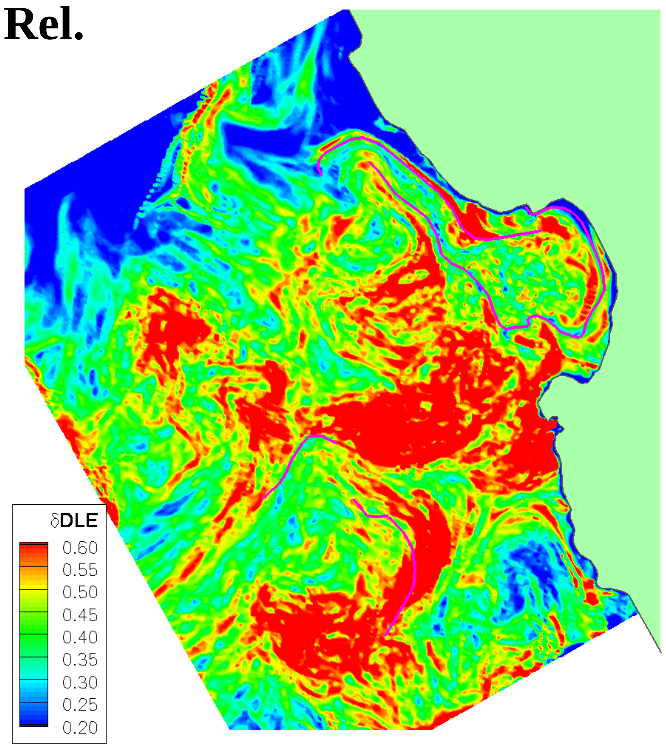
- Two upwellings and one relaxation
- Uncertainty estimates allow to identify most robust LCS (more intense DLE ridges are usually relatively more certain)
- Different oceanic regimes have different LCS uncertainty fields and properties

See: **Lermusiaux and Lekien**, 2005. In “Dynamical System Methods in Fluid Dynamics”,Oberwolfach, Germany.

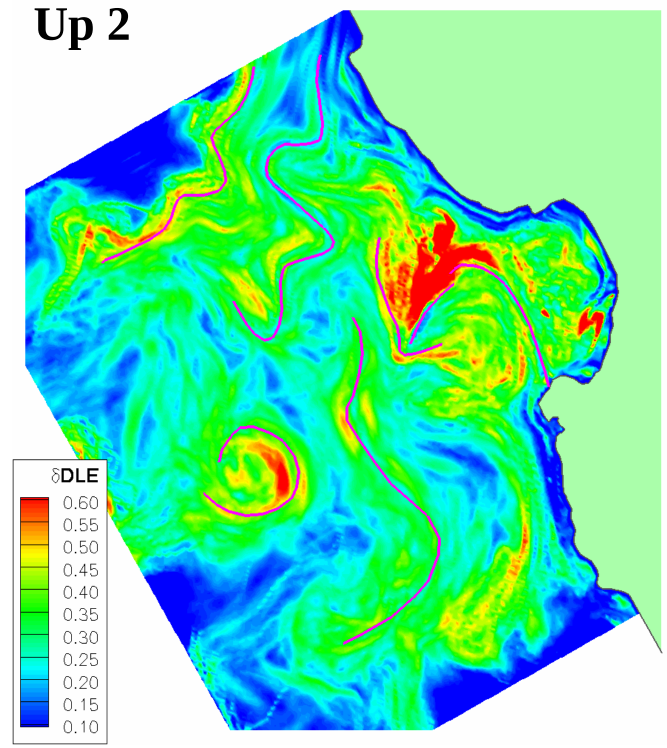
Up 1



Rel.

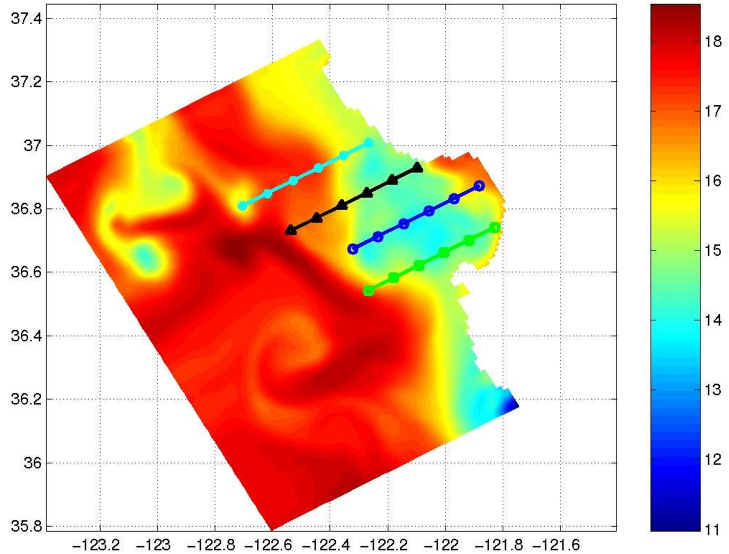


Up 2

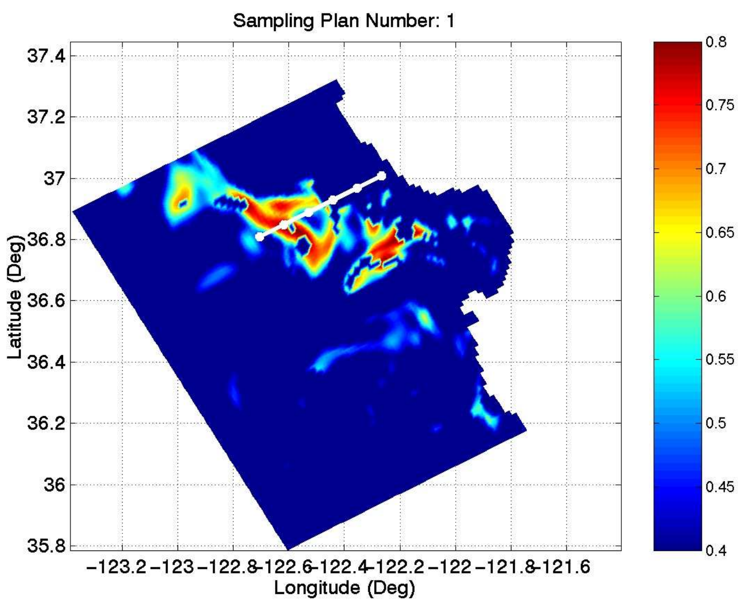


Adaptive Sampling Objectives and Methods

a) Which sampling tomorrow will reduce uncertainties the most the day after tomorrow?

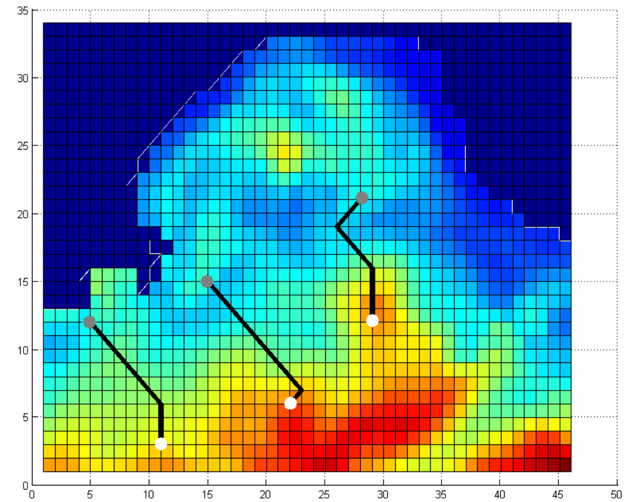


Four candidate tracks, overlaid on surface T fct for Aug 26. ESSE says best track is track 1.

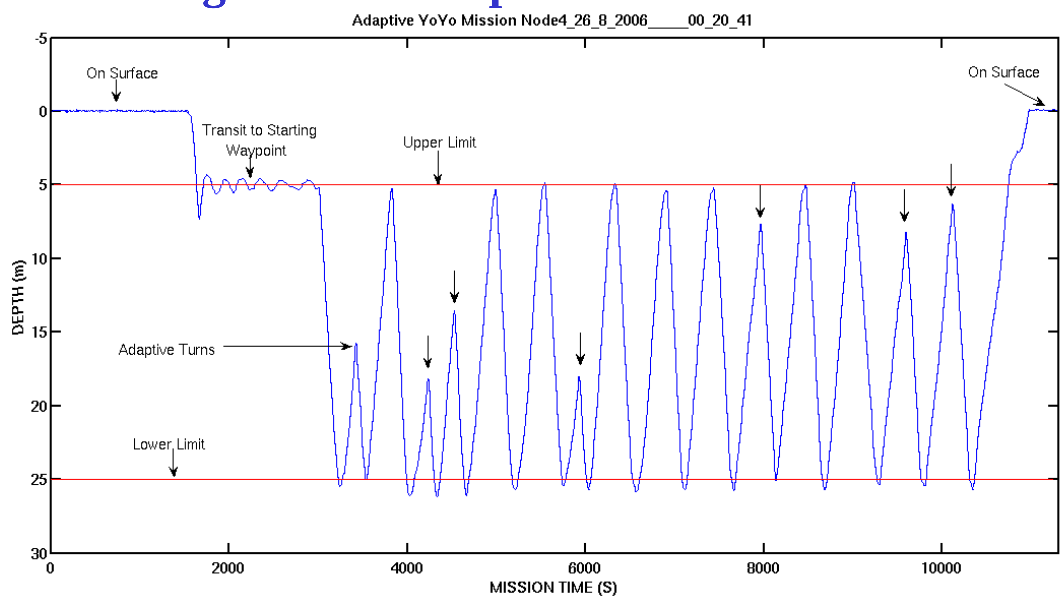


b) Optimal Paths Generation for "fixed" objective field via MIP

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?



c) Onboard Adaptive Sampling: Thermocline tracking for acoustic performance



Tidal Inversion

New HU code implemented in Matlab

Shallow water equations in the frequency domain

$$\nabla \cdot gH\Omega^{-1}\nabla\zeta - i\omega\zeta = 0$$

open boundary forcing:

$$\zeta|_{OBC} = \zeta_{TPXO_{GLOBAL}}$$

where $\Omega = \begin{bmatrix} i\omega + \kappa & -f \\ f & i\omega + \kappa \end{bmatrix}$

Inverse solution found as:

$$\zeta(x,y) = \zeta_0(x,y) + \boldsymbol{\beta}^T \mathbf{r}(x,y)$$

where

$$\mathbf{M}^* \boldsymbol{\alpha}_k = \boldsymbol{\delta}_k$$

$$\mathbf{M}\, \boldsymbol{r}_k = \mathbf{B}\, \boldsymbol{\alpha}_k$$

$$(\mathbf{C} + \mathbf{R})\boldsymbol{\beta} = \mathbf{y} - \mathbf{H}\zeta_0$$

$$\mathbf{C}_{m\times m} = \left[\mathbf{Hr}_1 | \mathbf{Hr}_2 | \ldots | \mathbf{Hr}_m\right]$$

Adjoint of dynamics

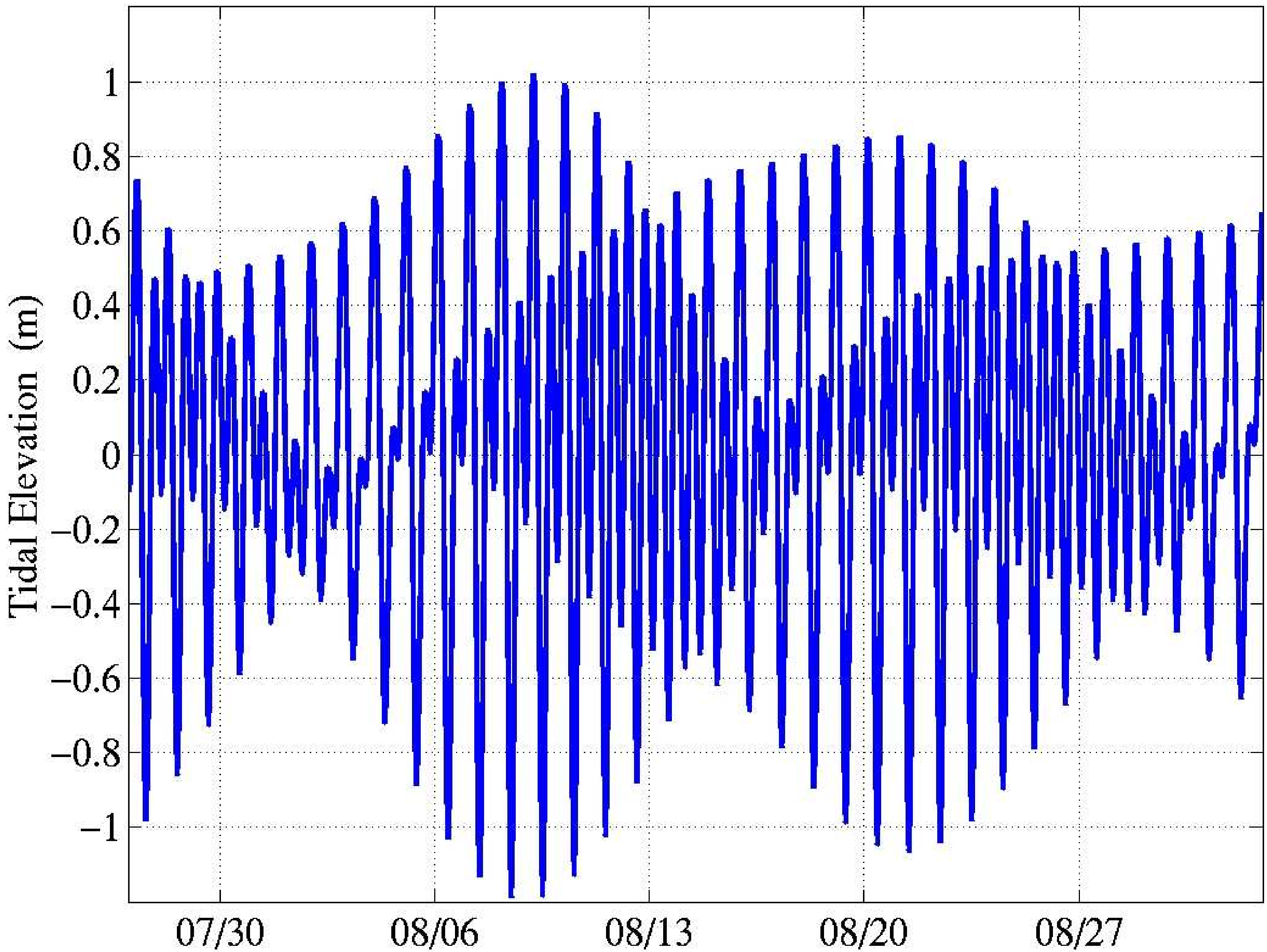
Dynamic error covariance

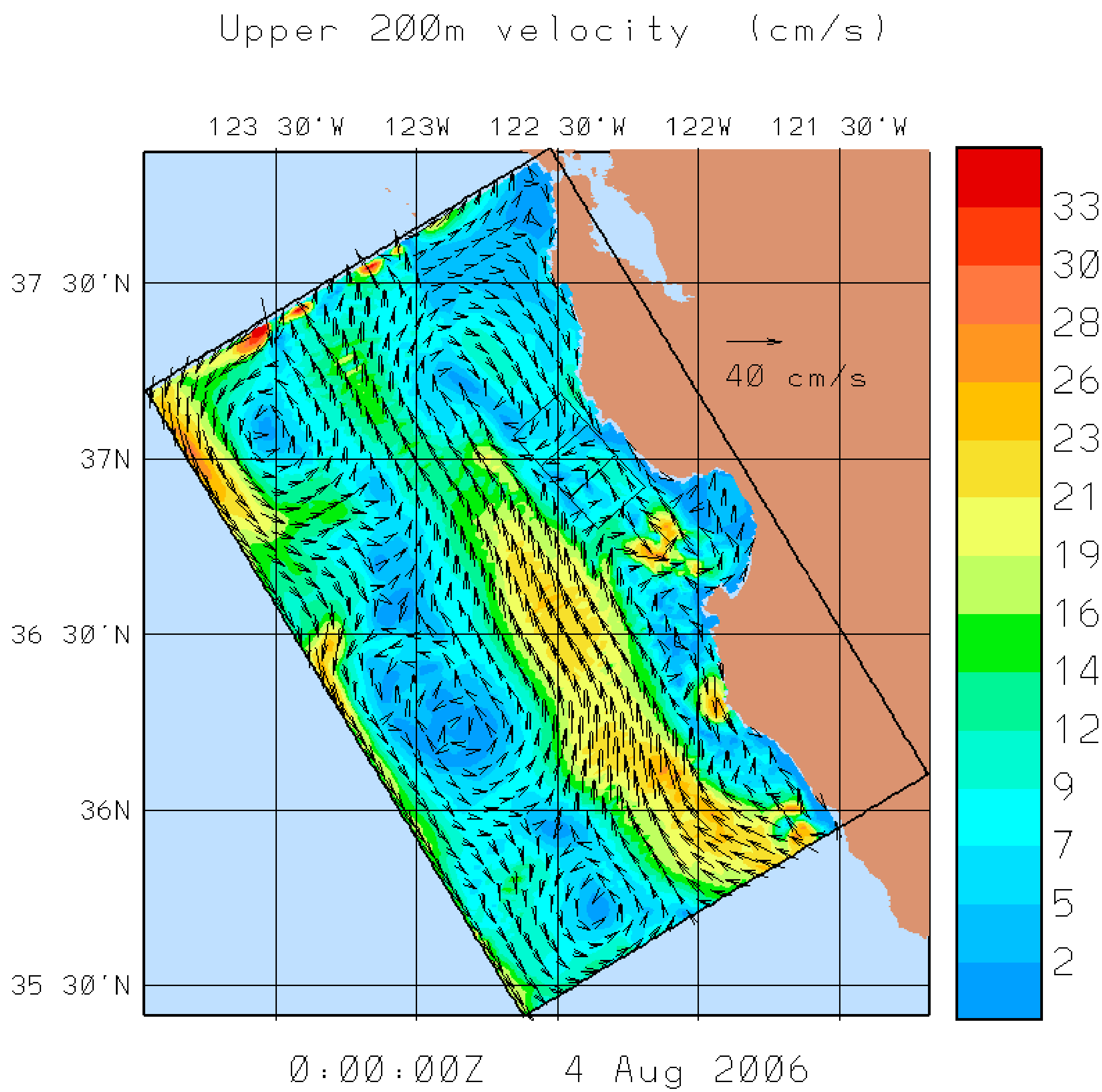
Observational error covariance

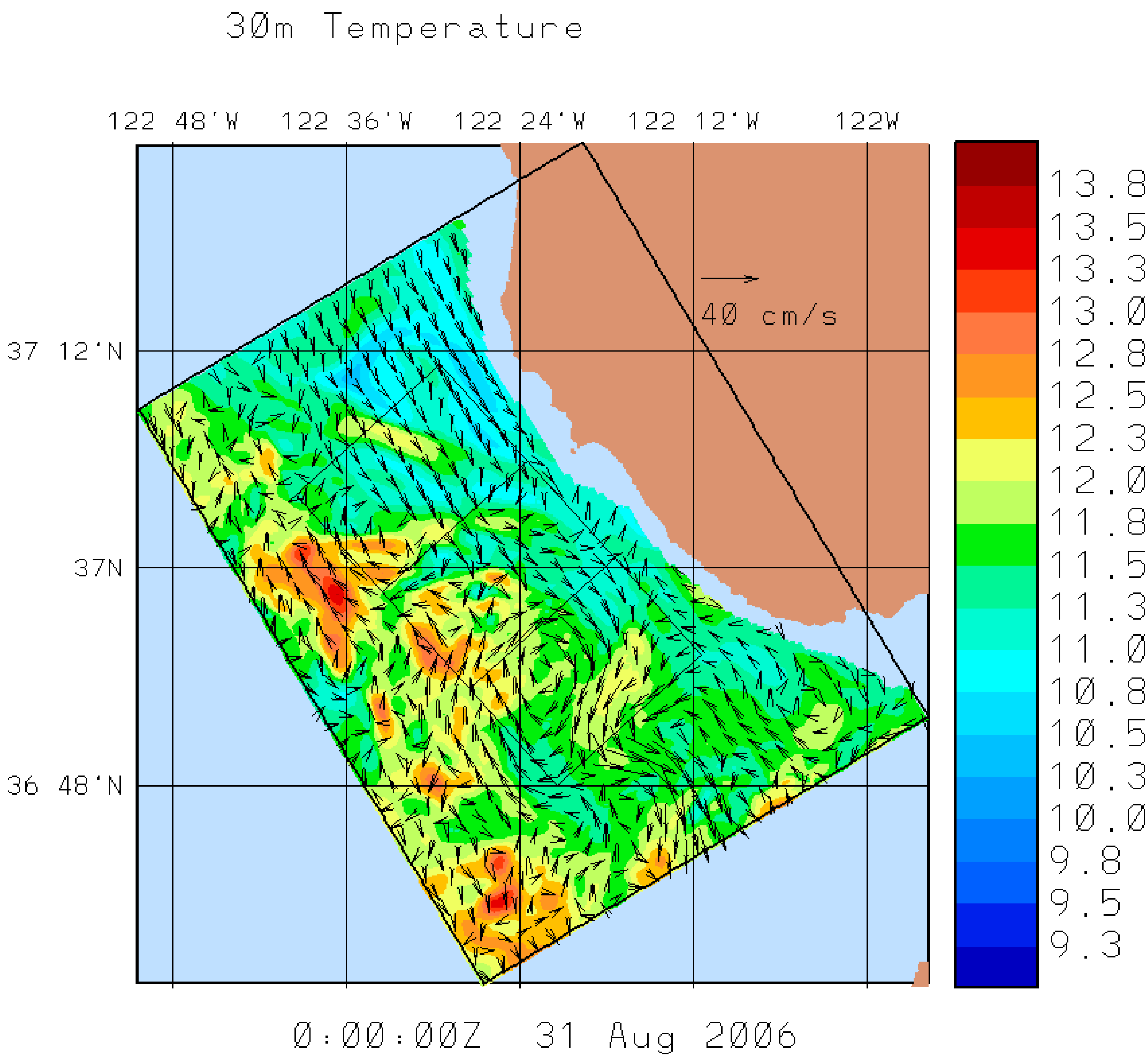
Reference: Egbert G.D. and S. Erofeeva (2002). Efficient Inverse Modeling of Barotropic Ocean Tides. J.Atm.Oc.Tech., Vol. 19, pp. 183-204.

HU Estimate of Barotropic Tidal Elevation on AN shelf

(with our new matlab Representer inversion of tide gauges on high-res. topo)

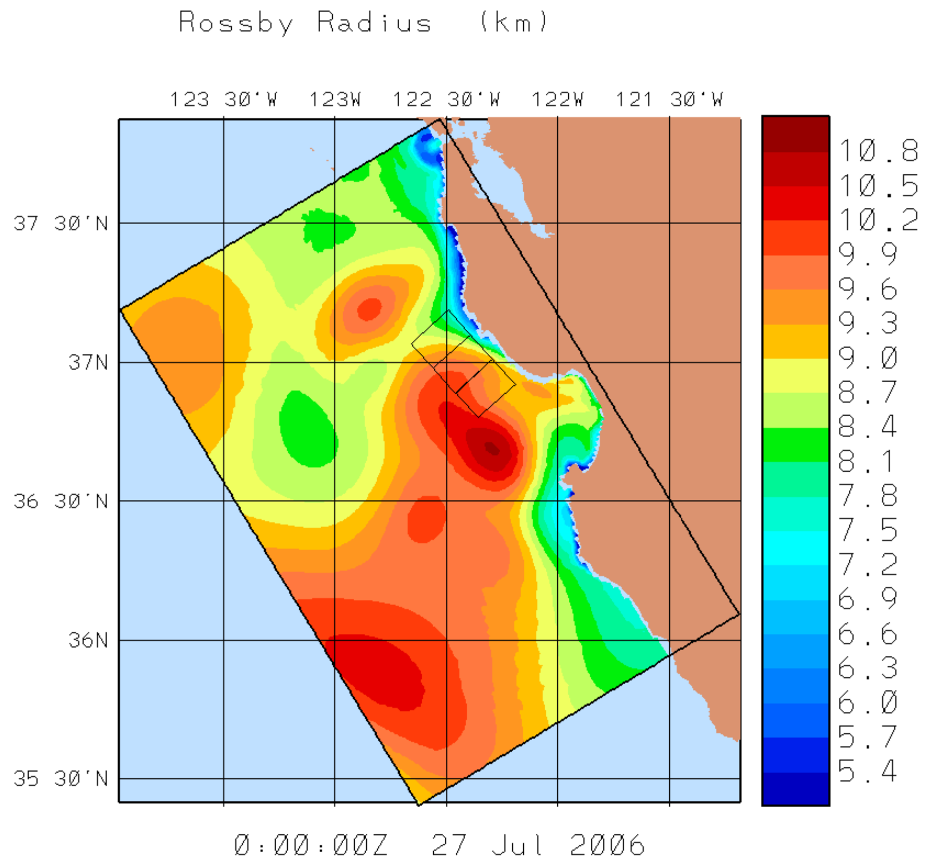



Upper 200m velocity (cm/s)
123 30'W
123W
122 30'W
122W
121 30'W
37 30'N
37N
36 30'N
36N
35 30'N
40 cm/s
33
30
28
26
23
21
19
16
14
12
9
7
5
2
0:00:00Z 4 Aug 2006



30m Temperature
122 48'W
122 36'W
122 24'W
122 12'W
122W
37 12'N
37N
36 48'N
40 cm/s
13.8
13.5
13.3
13.0
12.8
12.5
12.3
12.0
11.8
11.5
11.3
11.0
10.8
10.5
10.3
10.0
9.8
9.5
9.3
0:00:00Z 31 Aug 2006

Horizontal Length Scales
and the Rossby Radius of Deformation averaged over the thermocline

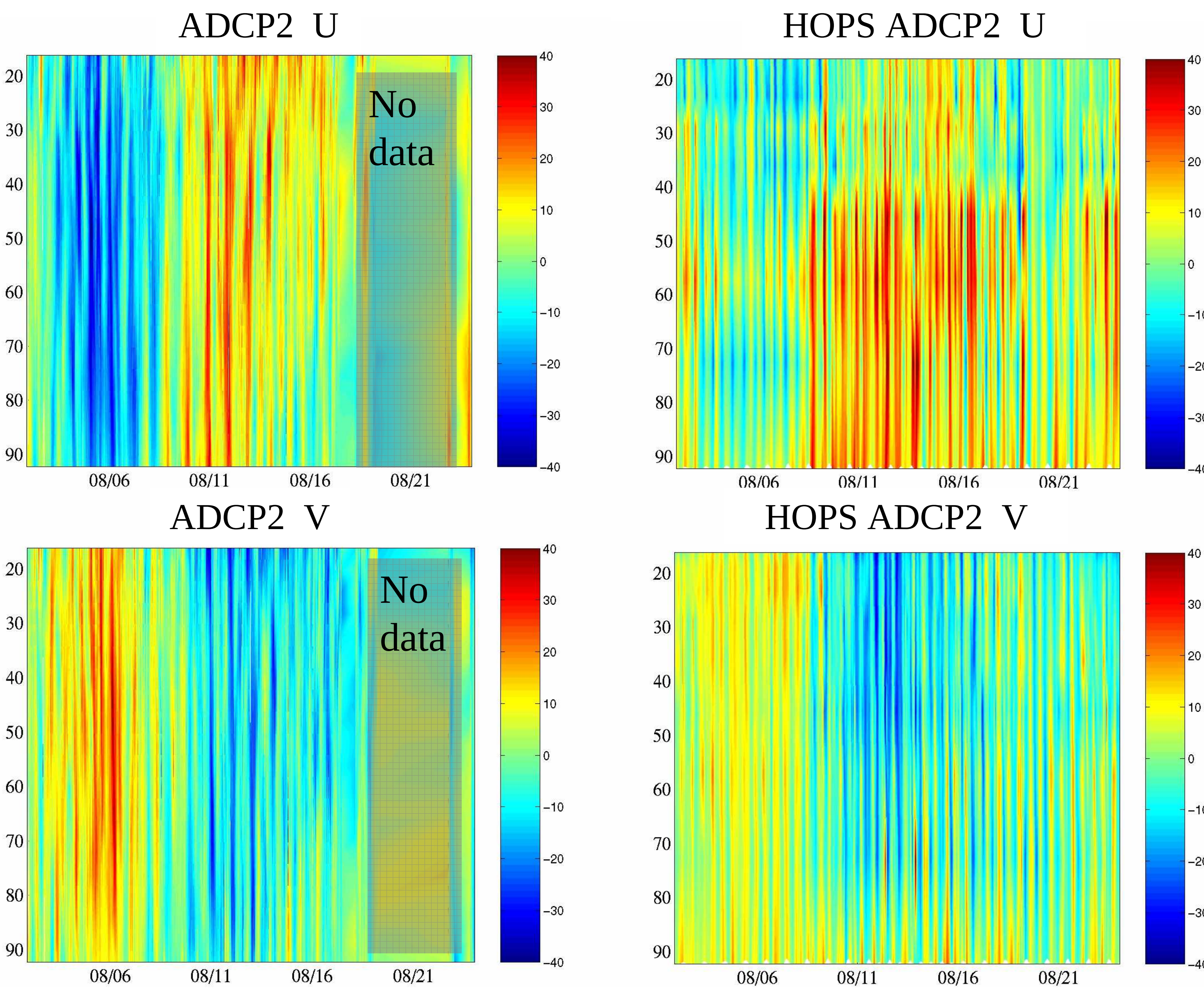


Rossby radius of deformation simply defined as $L_D = f^{-1} \tilde{N} D$ (Pedlosky, 1987), where:

- f is the Coriolis parameter
- $\tilde{N}$ a representative Brunt-Väisälä frequency, here vertical RMS of $N^2 = -(g/\rho_\theta)\, d\rho_\theta/dz$
- D the vertical length scale

L_D is evaluated over a vertical range [z_{top} z_{bot}], here 5m to 60m/bottom (thermocline)

The vertical length scale is chosen as $D = z_{top} - z_{bot}$


ADCP2 U
No data
HOPS ADCP2 U
ADCP2 V
No data
HOPS ADCP2 V
20
30
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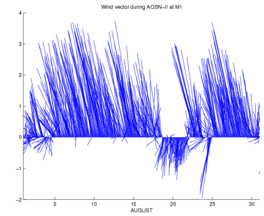
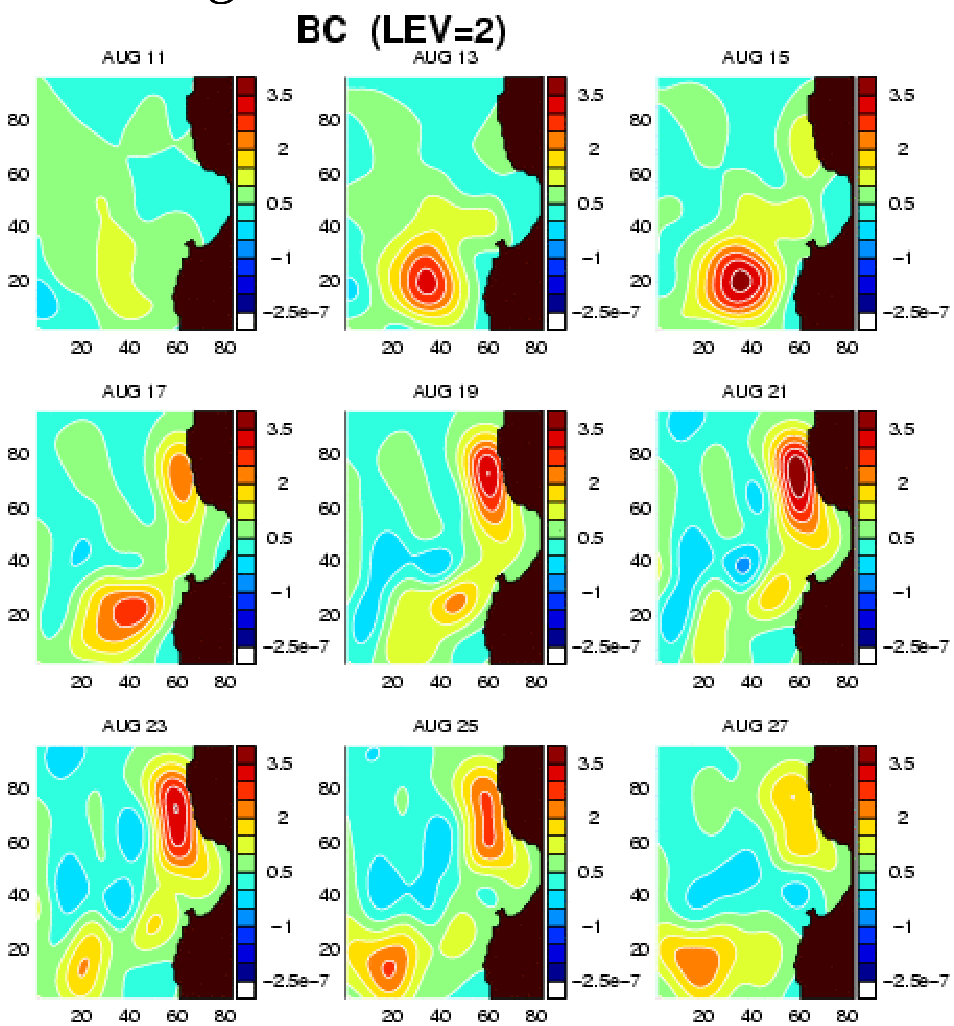
50
60
70
80
90
08/06
08/11
08/16
08/21
40
30
20
10
0
−10
−20
−30
−40

Multi-Scale Energy and Vorticity Analysis

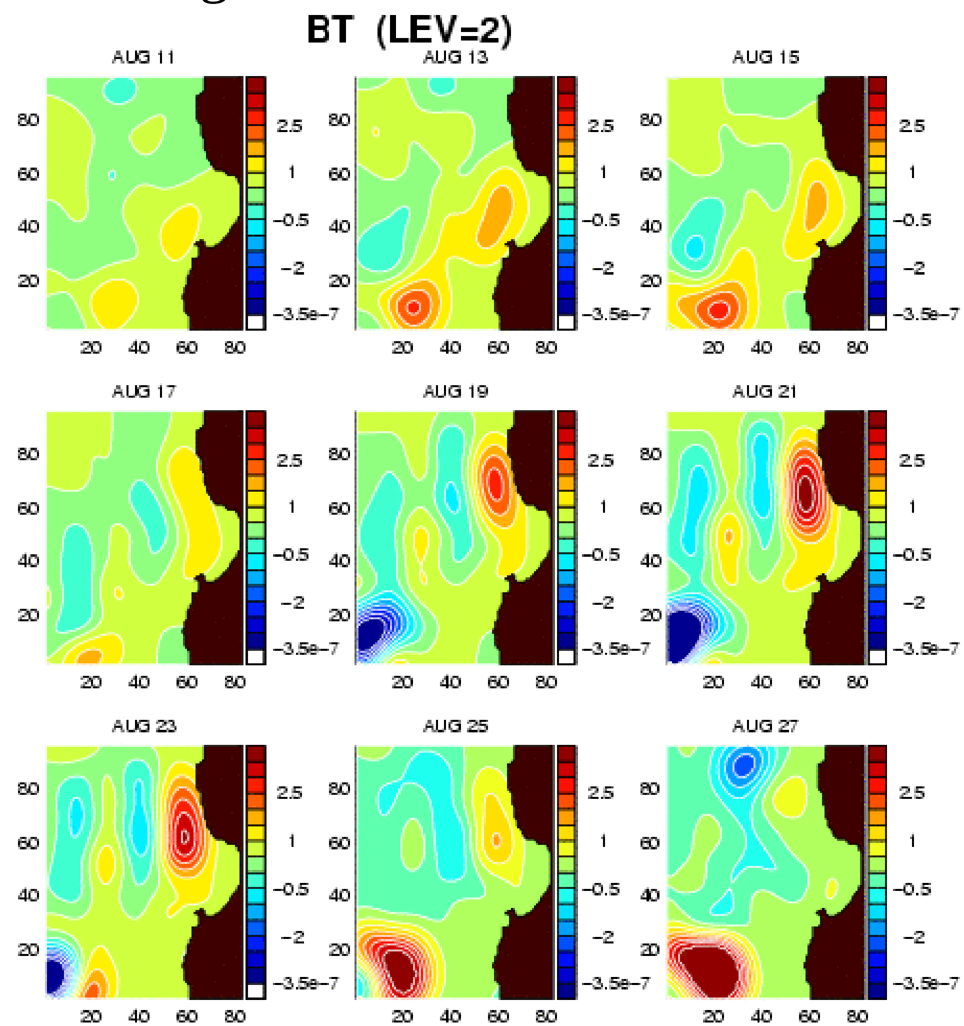
Two-scale window decomposition in space and time of energy eqns: 11-27 August 2003



Transfer of APE from large-scale to meso-scale



Transfer of KE from large-scale to meso-scale

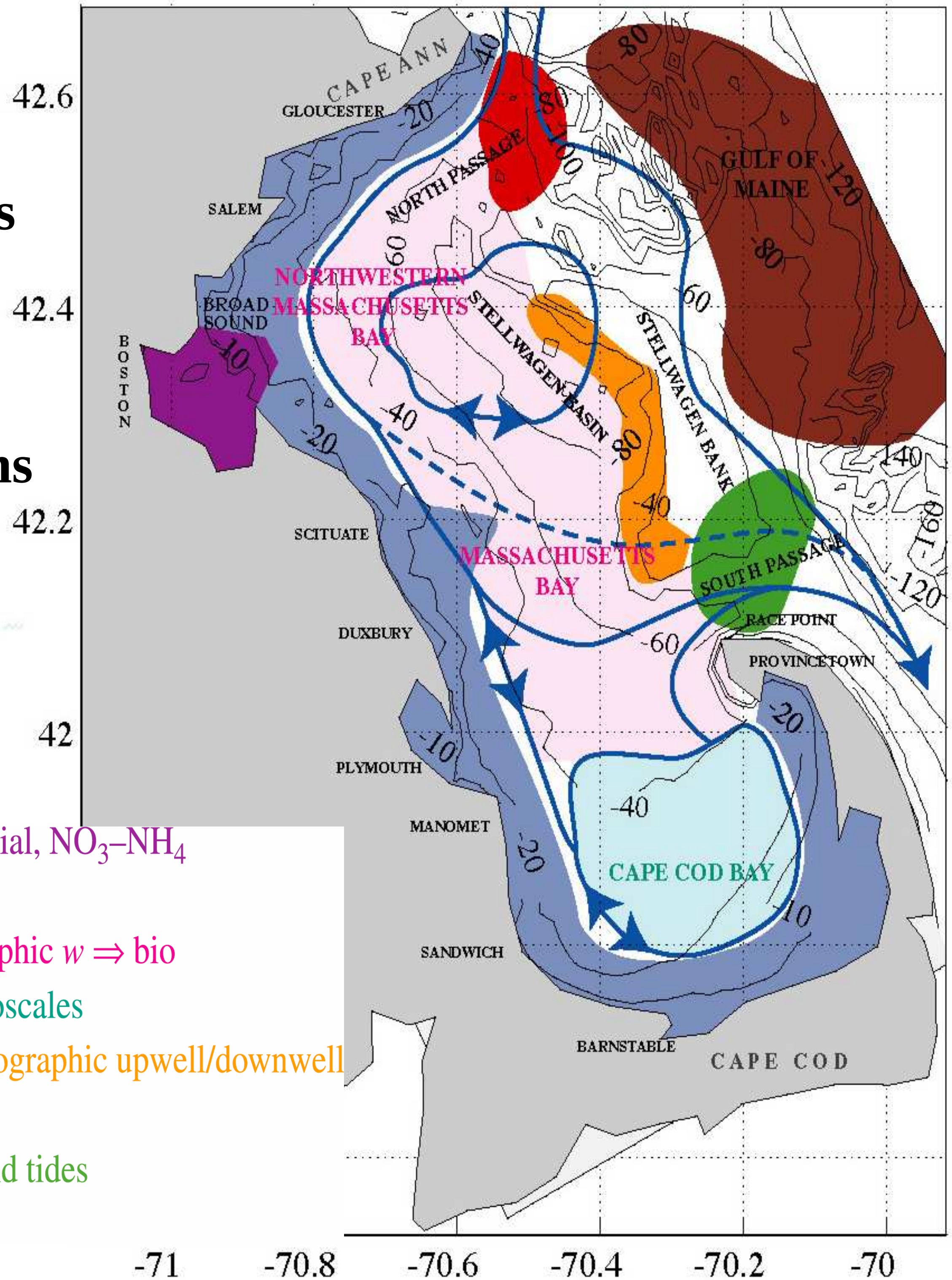


- Center west of Pt. Sur: winds destabilize the ocean directly.
- Center near the Bay: winds enter the balance on the large-scale window and release energy to the meso-scale window during relaxation.

X. San

Massachusetts Bay

Horizontal Circulation Patterns for stratified conditions (not present at all times) and Coupled bio-physical sub-regions in late summer (Dominant dynamics for trophic enrichment and accumulation)



Boston Harbor: Charles River, sediments, toxic material, NO_3–NH_4

Along Coast: upwelling/downwelling ⇒ bio ↑/↓

Open Bay: submesoscale/mesoscale eddies. Ageostrophic *w* ⇒ bio

Cape Cod Bay: Horizontal bio advection and submesoscales

West of Stellwagen Bank: GOM meanders, tides, topographic upwell/downwell

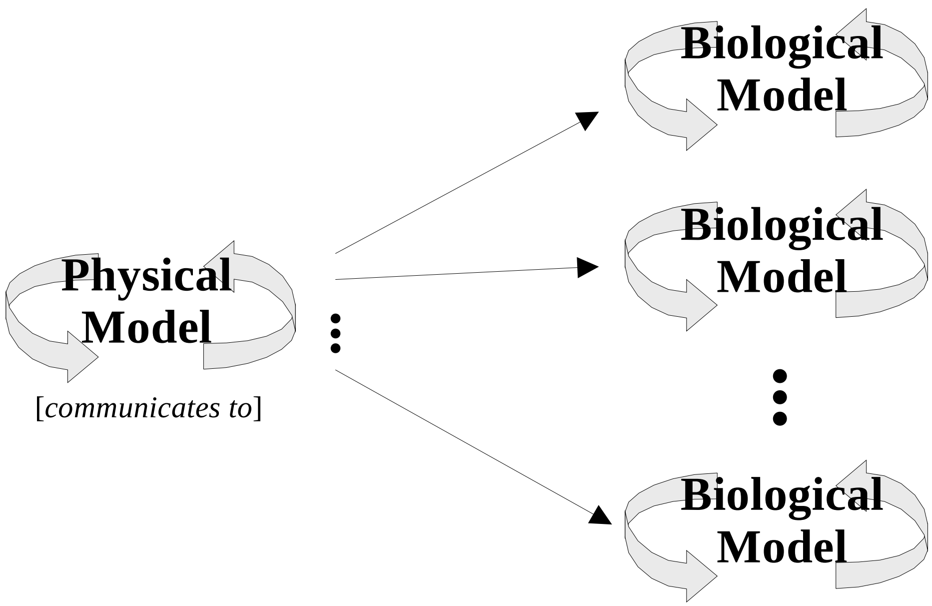
Offshore: GOM meanders

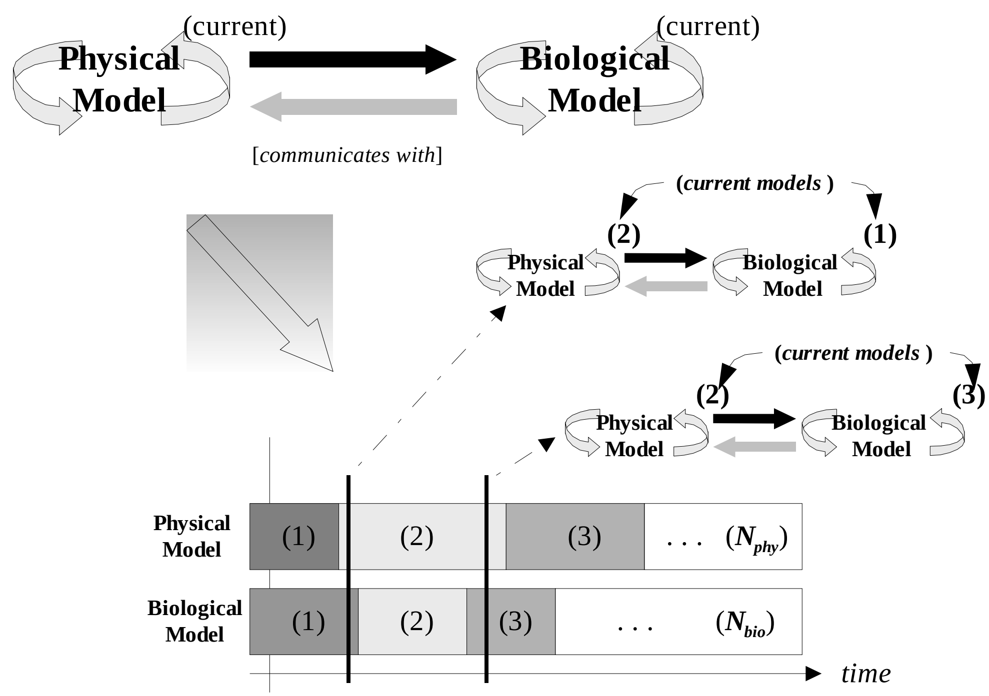
Race Point: Multiple bio advections, accumulation, and tides

Cape Ann: Physical instabilities at GOM inflow

Towards Real-time Adaptive Physical and Coupled Models

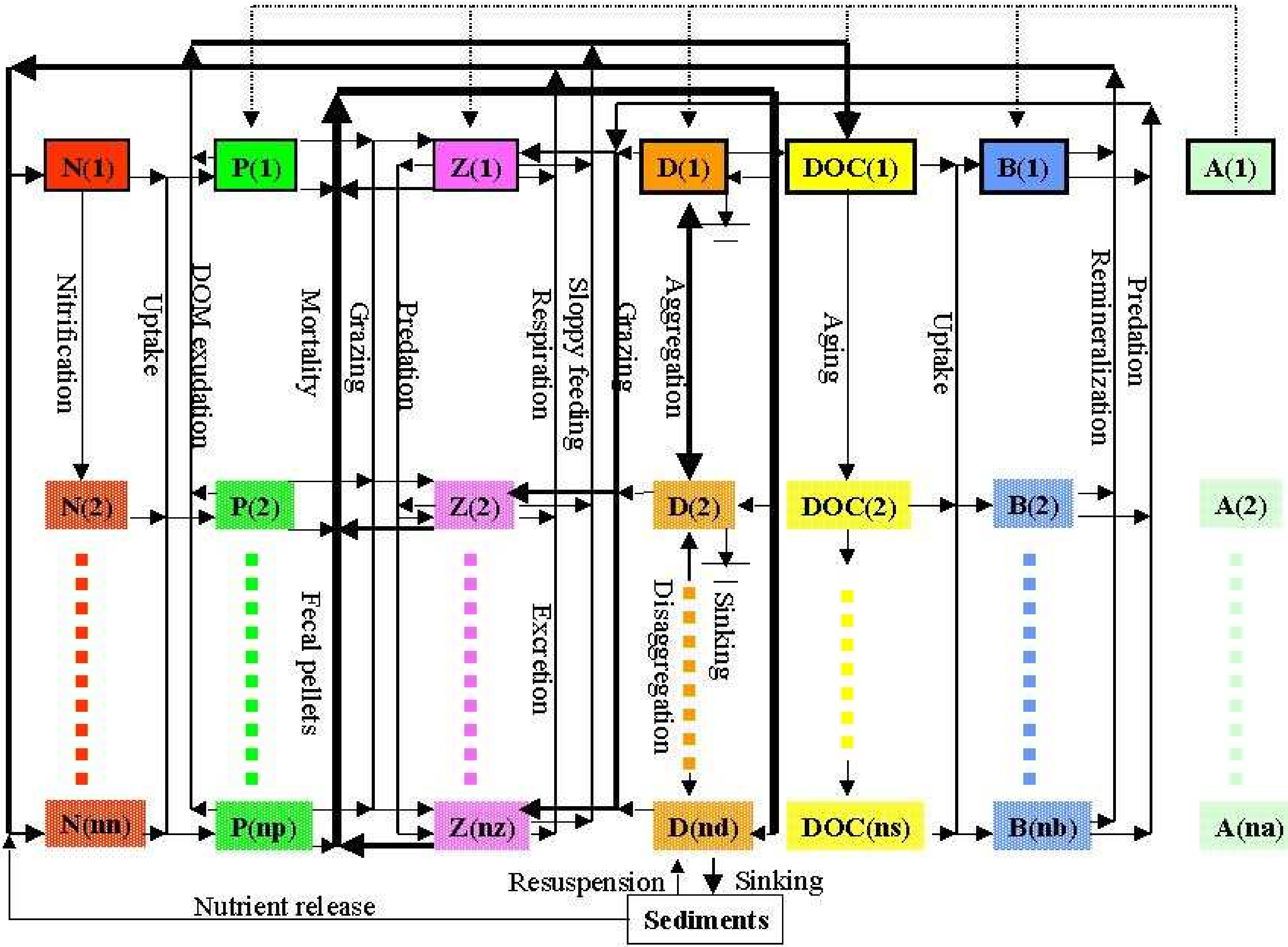
- Different Types of Adaptation:
  - Physical model with multiple parameterizations in parallel (hypothesis testing)
  - Physical model with a single adaptive parameterization (adaptive physical evolution)
  - Adaptive physical model drives multiple biological models (biology hypothesis testing)
  - Adaptive physical model and adaptive biological model proceed in parallel





- Model selection based on quantitative dynamical/statistical study of data-model misfits
- Mixed language programming (C function pointers and wrappers for functional choices) to be used for numerical implementation

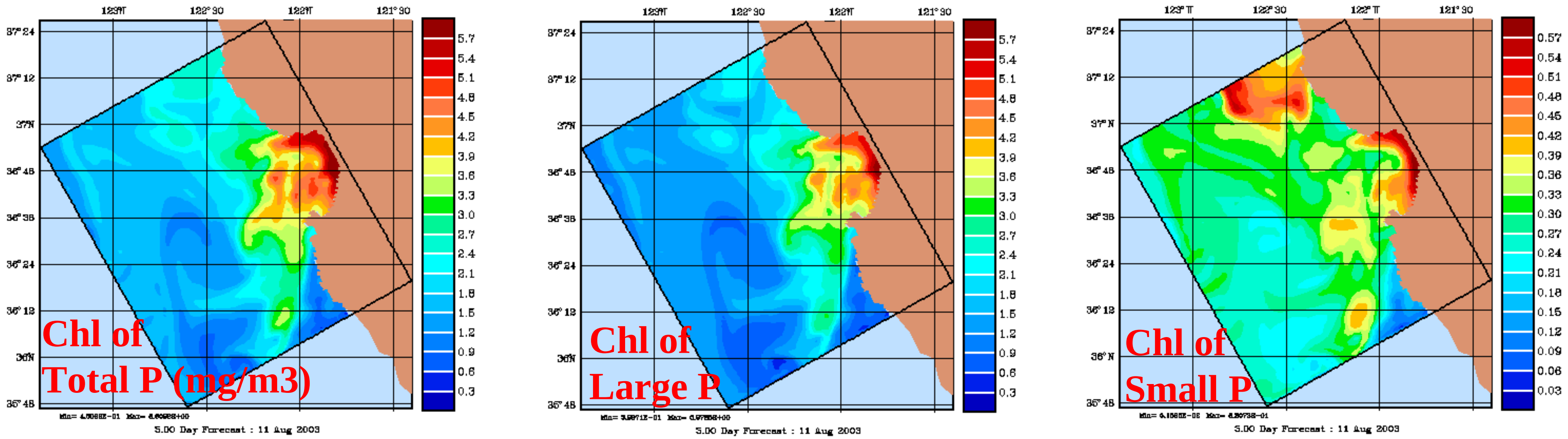
Generalized Adaptable Biological Model



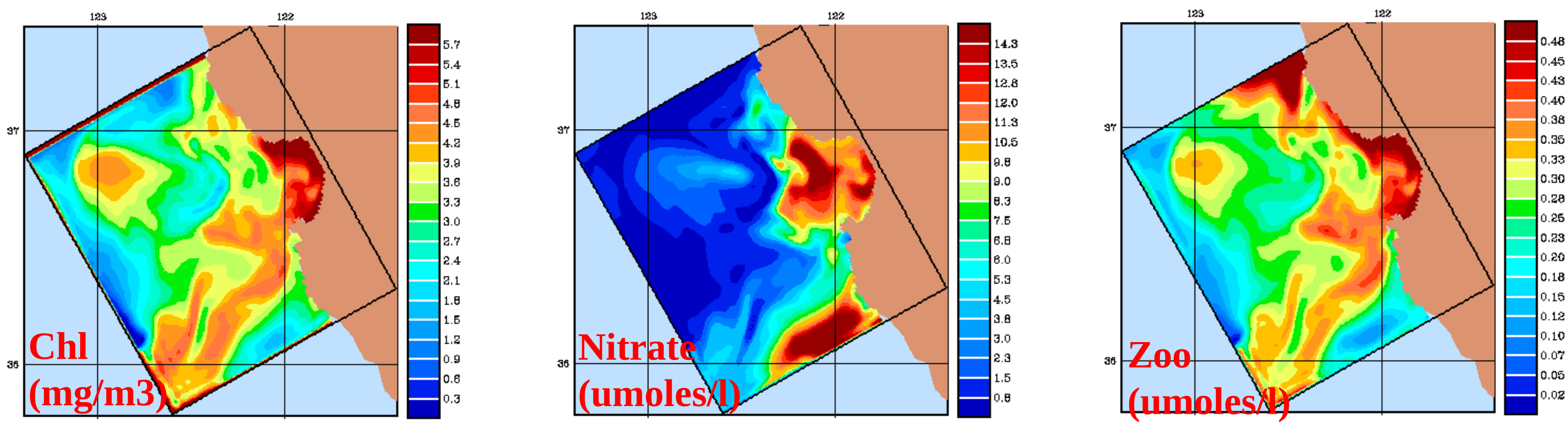
(R.C. Tian, P.F.J. Lermusiaux, J.J. McCarthy and A.R. Robinson, HU, 2004)

Towards automated quantitative model aggregation and simplification

A priori configuration of generalized model on Aug 11 during an upwelling event



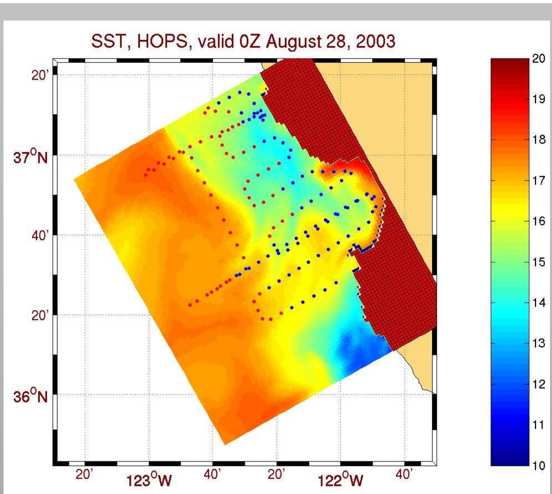
NPZ configuration of generalized model on Aug 11 during same upwelling event



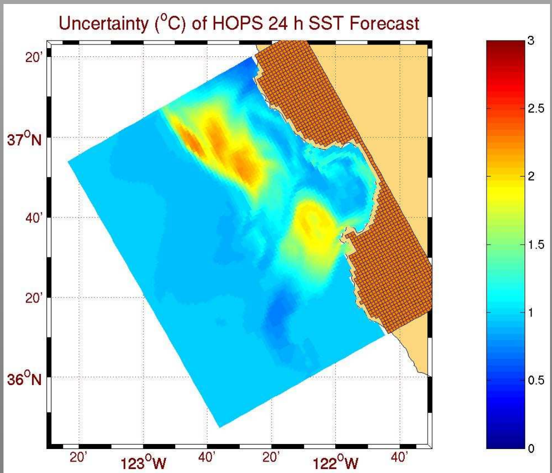
Dr. Rucheng Tian

Integrating Multiple Models into an Ocean Prediction System

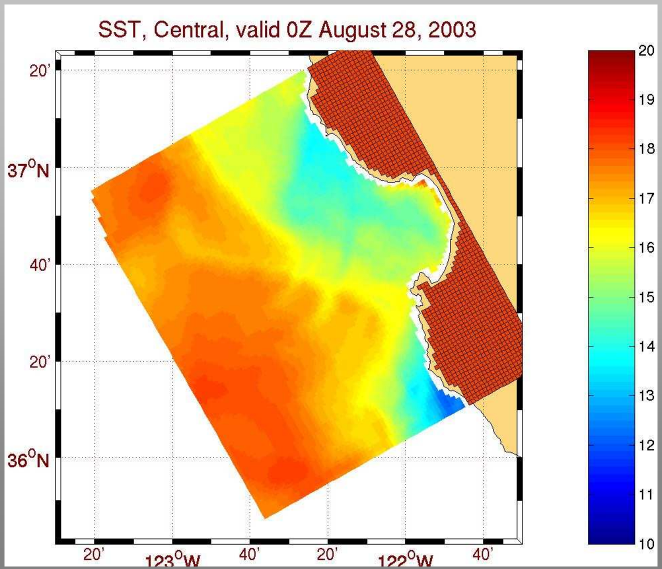
HOPS



Forecast, deg. C

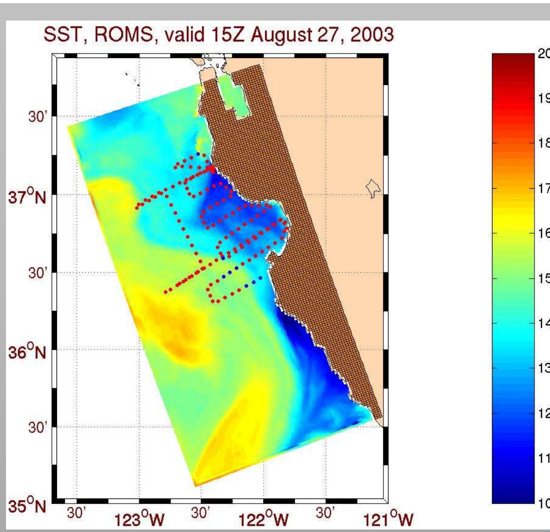


Uncertainty, deg. C

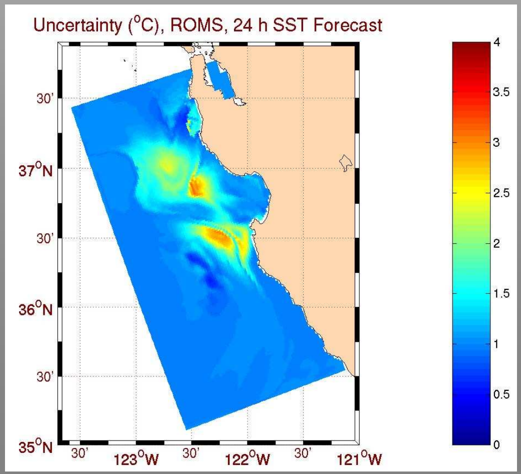


Central
Forecast, deg. C

ROMS



Forecast, deg. C



Uncertainty, deg. C

Example: 24 Hour HOPS/ROMS SST Forecast, valid Aug 28, 2003

Research Goal and Objectives

Long-Term Goal:

Explore and better understand interactive dynamics and variability of sub-mesoscale and mesoscale features and processes in the Philippine Straits region and their impacts on local ecosystems through

i. *Interdisciplinary physical-biogeochemical-acoustical data assimilation of novel multidisciplinary observations*
ii. *Adaptive, multi-scale physical and biogeochemical modeling*
iii. *Process and sensitivity studies based on a hierarchy of simplified simulations and focused modeling.*

Specific objectives:

- Utilize and develop the Error Subspace Statistical Estimation (ESSE) system for interdisciplinary data assimilation and uncertainty estimation with the physical Primitive-Equation (PE) and generalized biogeochemical model of the Harvard Ocean Prediction System (HOPS)
- Study, describe and model the variability and dynamics of flow separations and associated eddies and filaments, of water mass evolutions and pathways, and of locally trapped waves
- Develop and implement schemes for parameter estimation and selection of model structures and parameterizations, and for high-resolution nested domains towards non-hydrostatic modeling