Harvard Research and Plans:
Adaptive Sampling and Prediction (ASAP)
Persistent Littoral Undersea Surveillance Network (PLUSNet)

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MIT: **H. Schmidt, D. Wang et al.**

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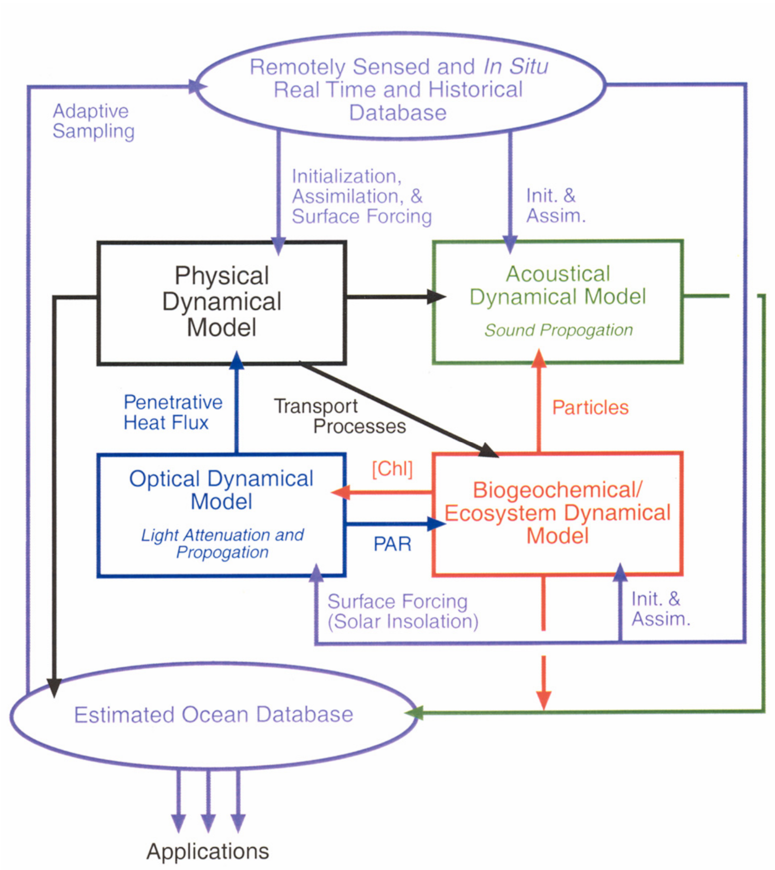
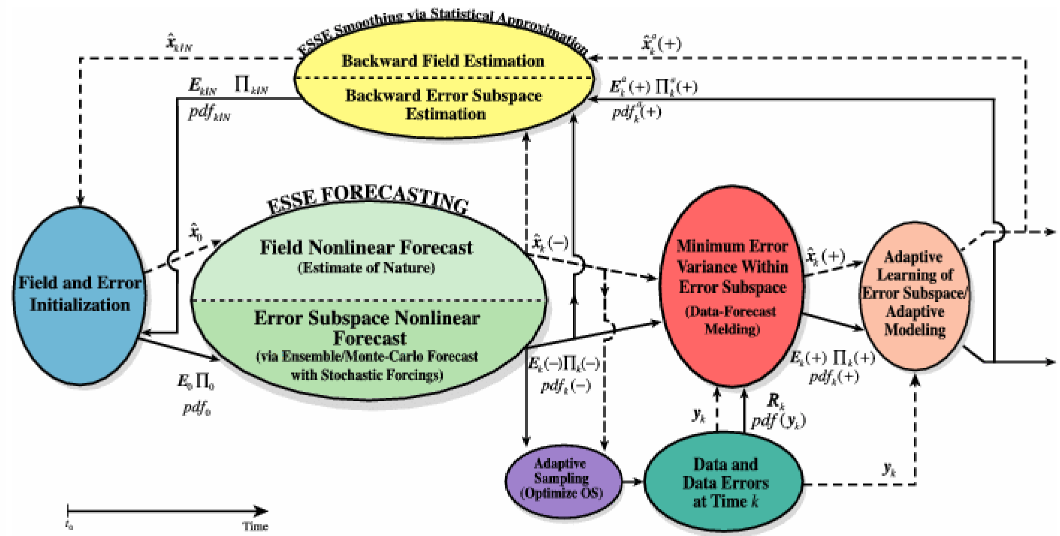
1. **ASAP** **http://oceans.deas.harvard.edu/ASAP/**
2. **PLUSNet** **http://oceans.deas.harvard.edu/PLUSNet/**
3. **Conclusions and AESOP collaborations**

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

Seattle - AESOP, June 7, 2006

HOPS/ESSE System





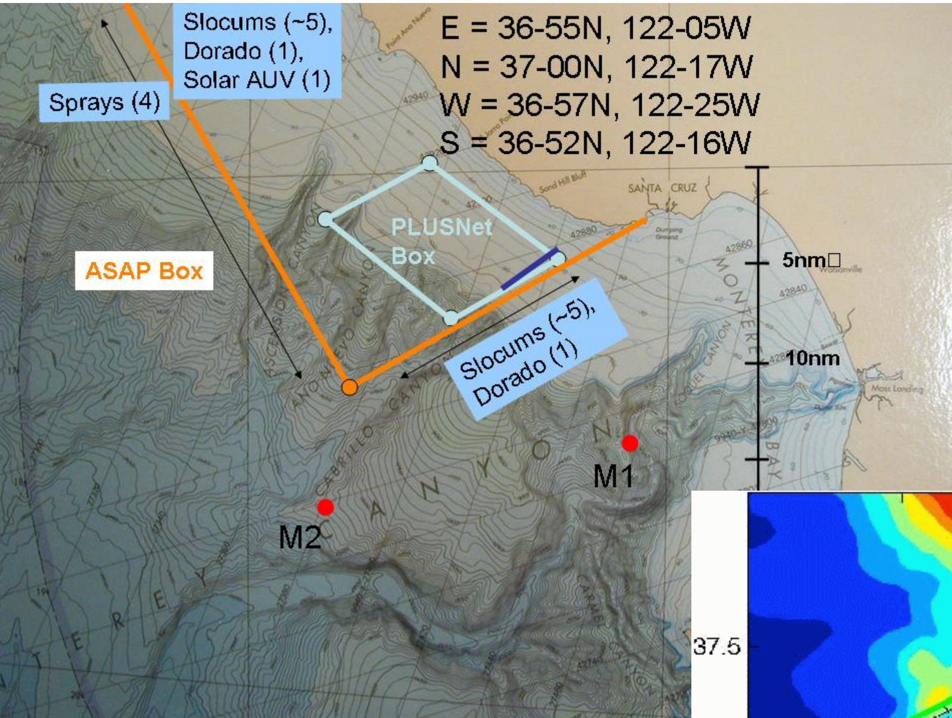
Harvard Ocean Prediction System

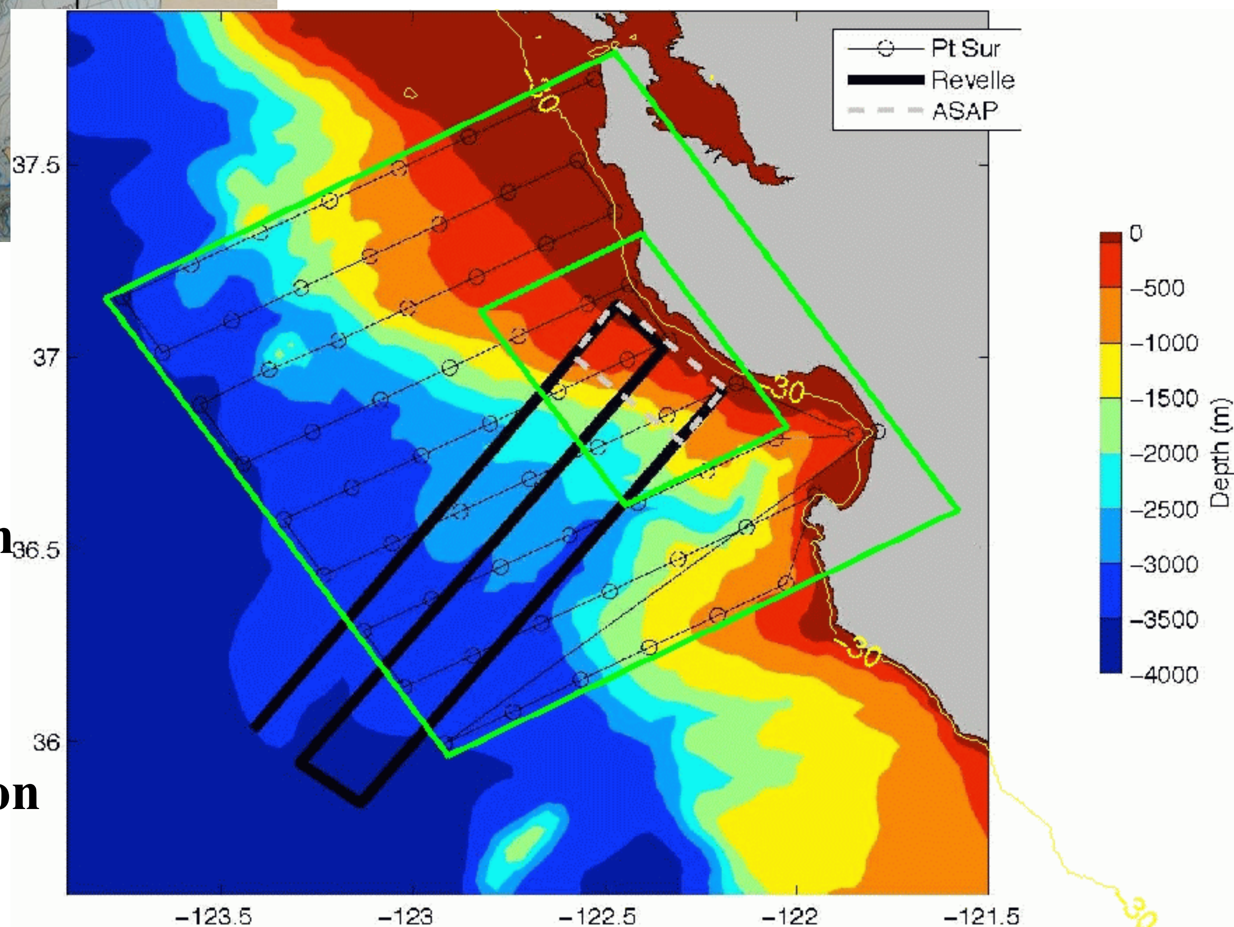
Free-surface PE, Generalized biological models, Coupled to acoustic models, XML schemes to check configuration

Error Subspace Statistical Estimation

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

ASAP and PLUSNet New Domains





Two nested HOPS domains

Resolution: 1.5 km and 500 m

Free-surface, Tidal forcing

OI and ESSE data assimilation

HU ASAP
Top Three Tasks to Carry Out/Problems to Address

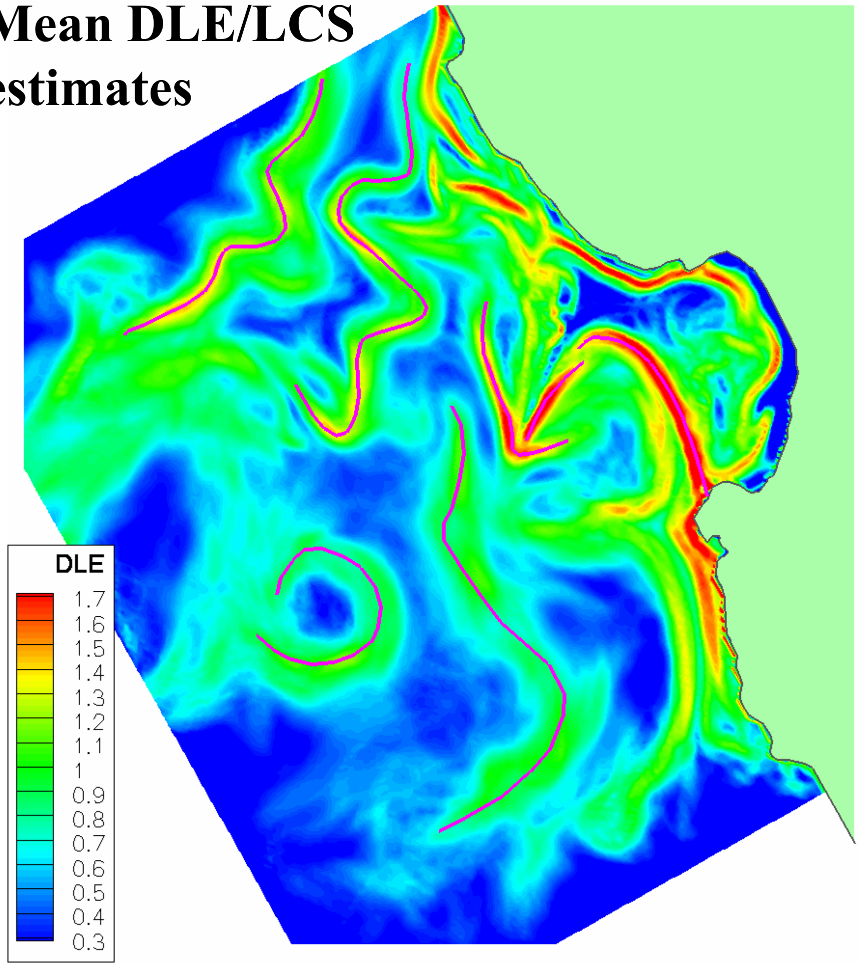
1. **Determine details of three metrics for adaptive sampling (coverage, dynamics, uncertainties) and develop schemes and exercise software for their integrated use**

2. **Carry out cooperative real-time (sub)-mesoscale data-driven predictions with adaptive sampling and research and evaluate skill measures**

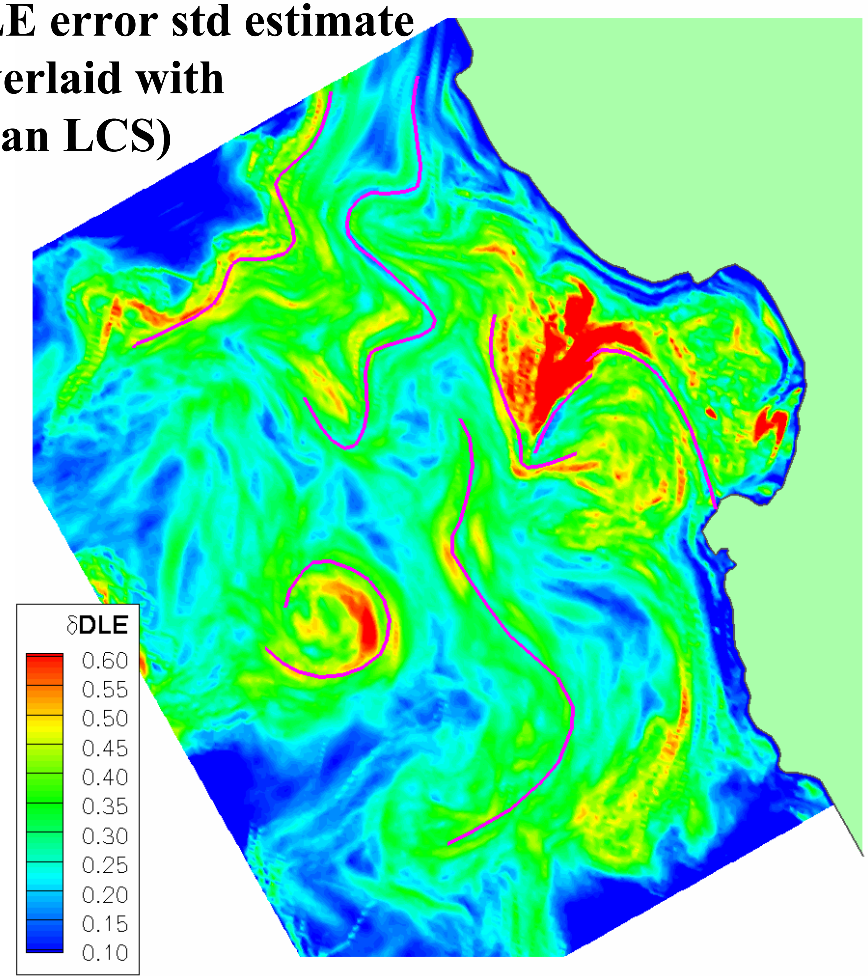
3. **Advance scientific understanding of 3D upwelling/relaxation dynamics and carry out budget analyses as possible (multi-balances, sensitivity studies, parameterizations, predictability)**

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

Mean DLE/LCS estimates



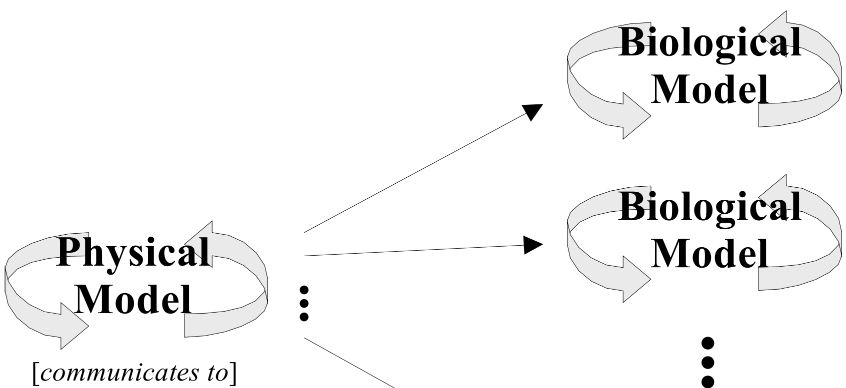
DLE error std estimate (overlaid with mean LCS)

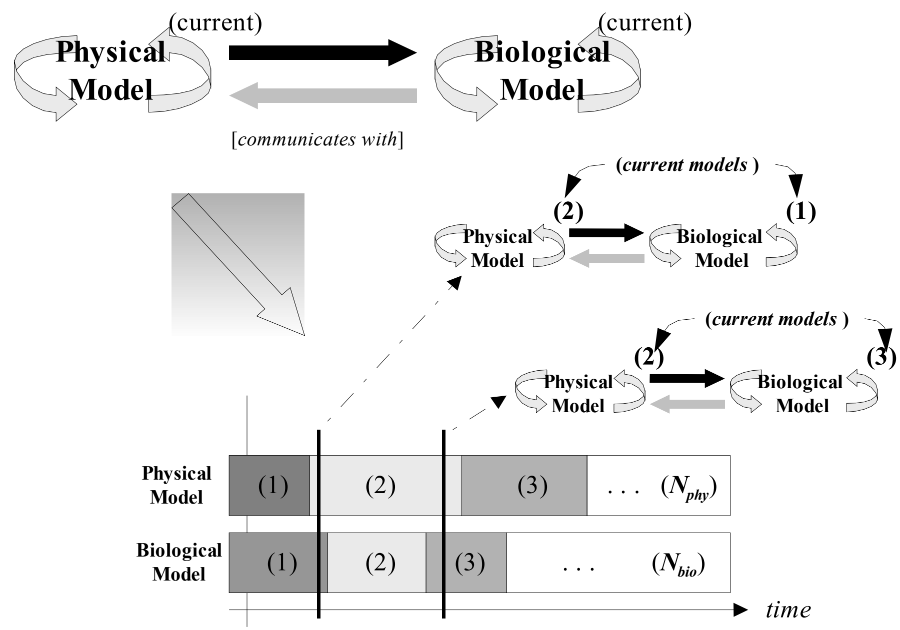


See: Lermusiaux and Lekien, Aug. 2005.
for "Dynamical System Methods in Fluid Dynamics", Oberwolfach, Germany.

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

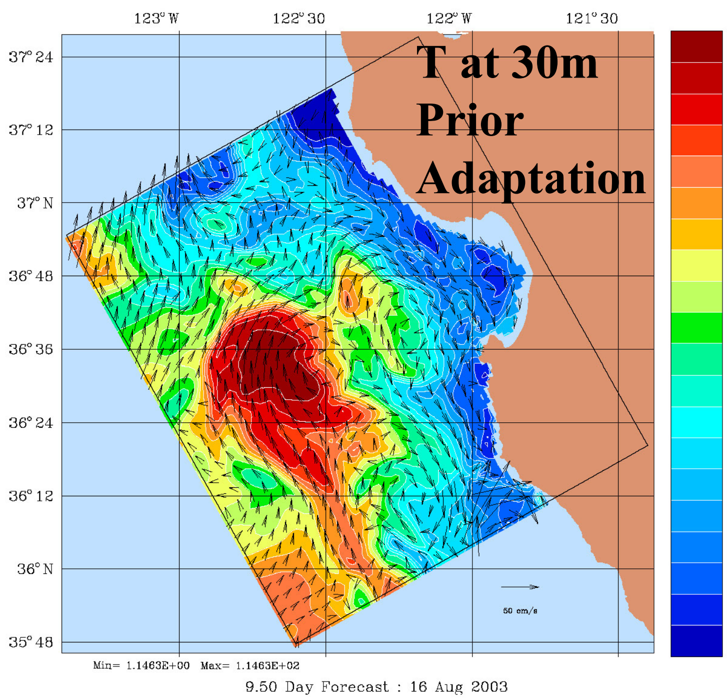


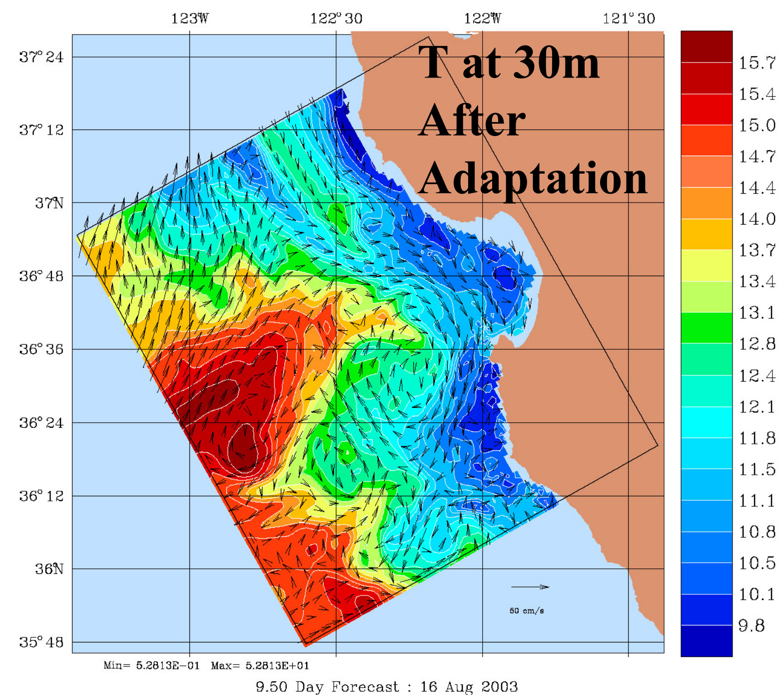


- Model selection based on quantitative dynamical/statistical study of data-model misfits
- Mixed language programming (C function pointers and wrappers for functional choices) to be used for numerical implementation

Semi-Automated Real-time Physical Adaptation during AOSN-II

- Prior to AOSN2, PE model calibrated to four historical conditions likely to be similar to the unknown August 2003 conditions
- Ten days in the experiment: Forecasts a bit too geostrophic/too warm in upper-layers and larger-scale OBCs needed
- Real-time Adaptation
  - SBL mixing parameters and Open Boundary Conditions (OBCs) adapted to new 2003 data
  - 49 sets of parameter values and OBC formulations evaluated
  - Configuration with smallest Bias/RMSE and highest PCC at data points selected
  - Improved upper-layer fields of Temp., Salinity and currents

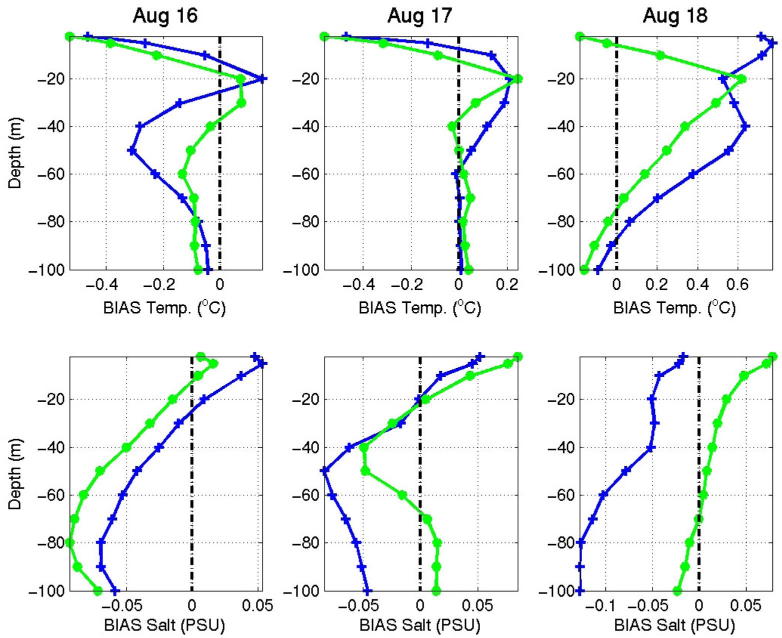




Bias, RMSE and PCC estimates for un-adapted (blue) and adapted (green) real-time physical models

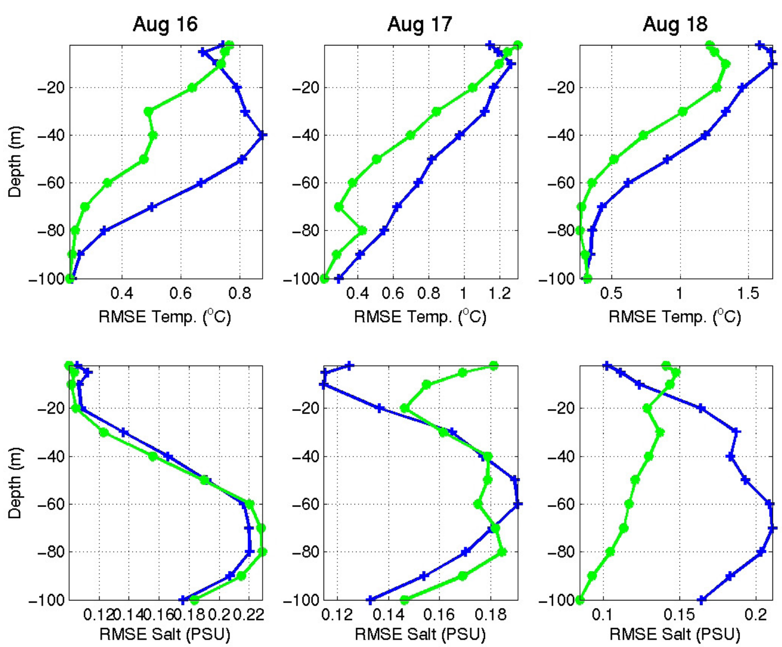
Bias

(a)



RMSE

(b)



PCC

(c)

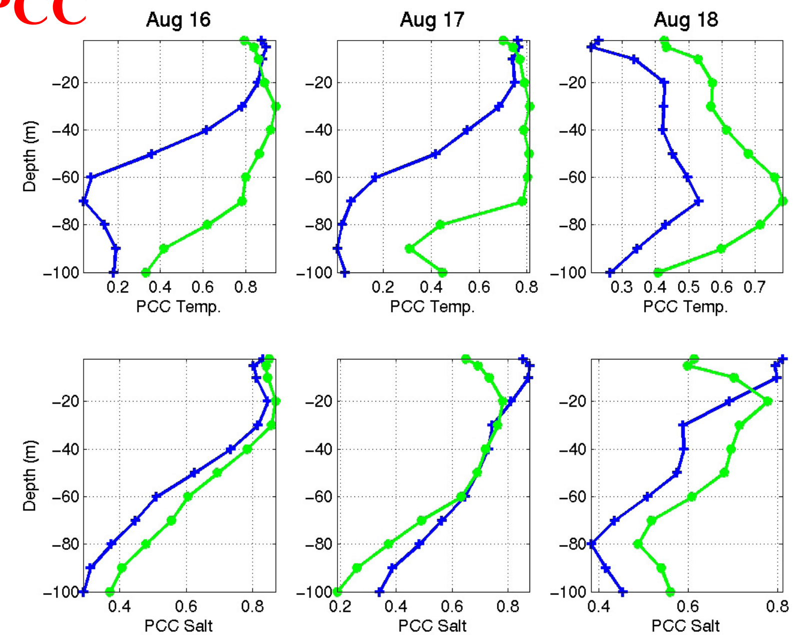


Fig. 2. Comparison between real-time un-adapted (blue lines with a plus at each data point) and real-time adapted (green lines with filled circles) physical ocean model. (a) Bias estimate (Model - OAed data) for temperature and salinity, as a function of depth (m) and time (day). (b) As (a), but for the Root-Mean-Square-Error (RMSE) estimate. (c) As (a), but for the mesoscale Pattern-Correlation-Coefficient estimate. Comparisons were made at 20 depths: 2, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 125, 150, 175, 200, 250, 300, 350 and 400 m (maximum data depth). However, only values for the first 100 m are shown for visibility.

a. Adaptive sampling via ESSE

- Objective: Minimize predicted trace of full error covariance (T,S,U,V error std Dev).
- Scales: Strategic/Experiment (not tactical yet). Day to week.
- Assumptions: Small number of pre-selected tracks/regions (based on quick look on error forecast and constrained by operation)
- Problem solved: e.g. Compute today, the tracks/regions to sample tomorrow, that will most reduce uncertainties the day after tomorrow.

- Objective field changes during computation and is affected by data to-be-collected

- Model errors ***Q*** can account for coverage term

Dynamics:	$dx = M(x)dt + d\eta$	$\eta \sim N(0, Q)$
Measurement:	$y = H(x) + \varepsilon$	$\varepsilon \sim N(0, R)$

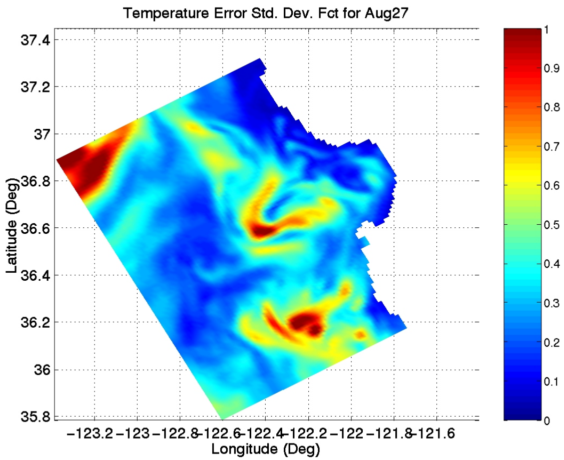
Non-lin. Err. Cov.:

$$dP / dt = <(x - \hat{x})(M(x) - M(\hat{x}))^T> + <(M(x) - M(\hat{x})(x - \hat{x})^T> + Q$$

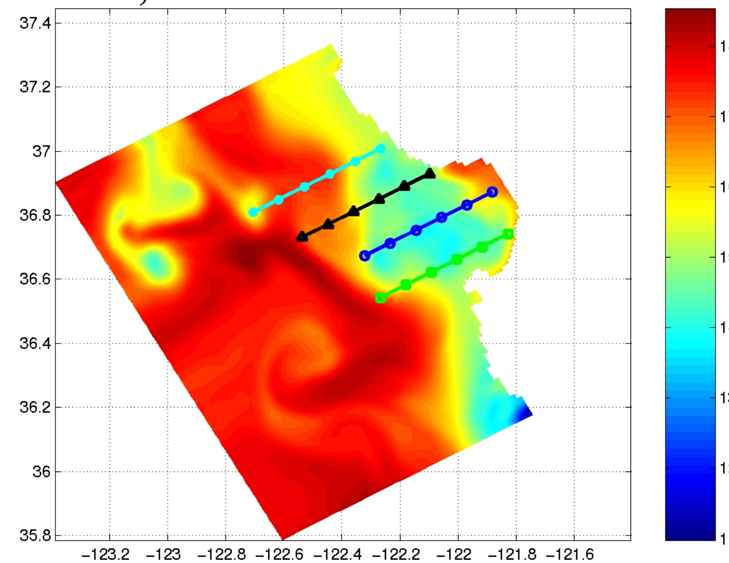
Metric or Cost function: e.g. Find future H_i and R_i such that

$$\underset{Hi,Ri}{Min} \quad tr(P(t_f)) \qquad or \qquad \underset{Hi,Ri}{Min} \int_{t_0}^{t_f} tr(P(t))\, dt$$

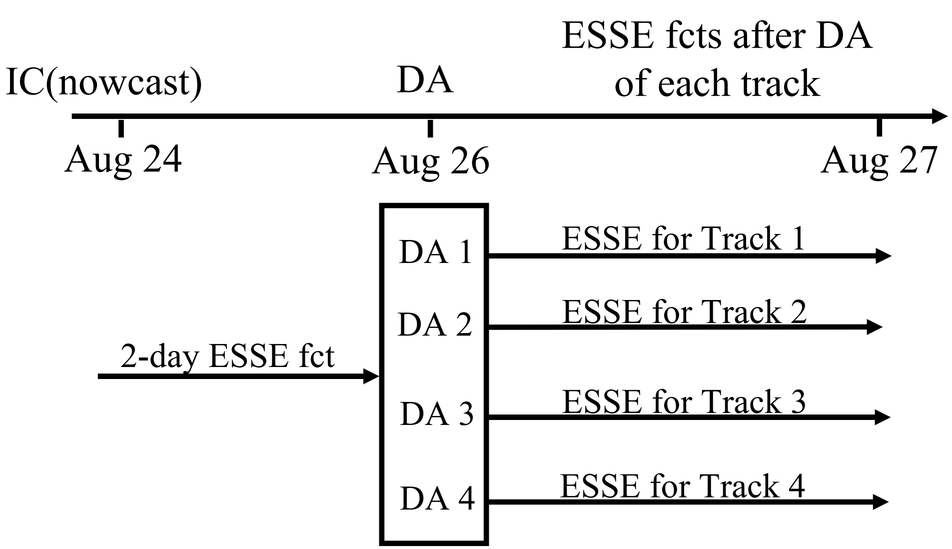
Which sampling on Aug 26 optimally reduces uncertainties on Aug 27?



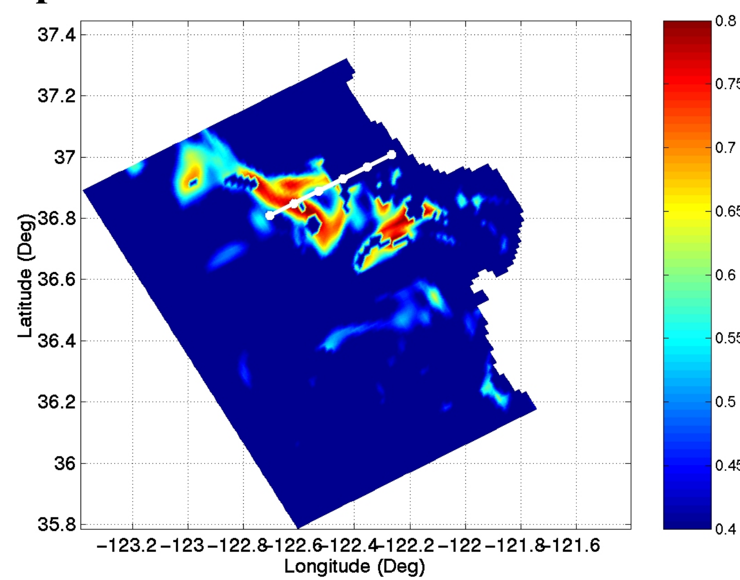
4 candidate tracks, overlaid on surface T fct for Aug 26



- **Based on nonlinear error covariance evolution**
- **For every choice of adaptive strategy, an ensemble is computed**



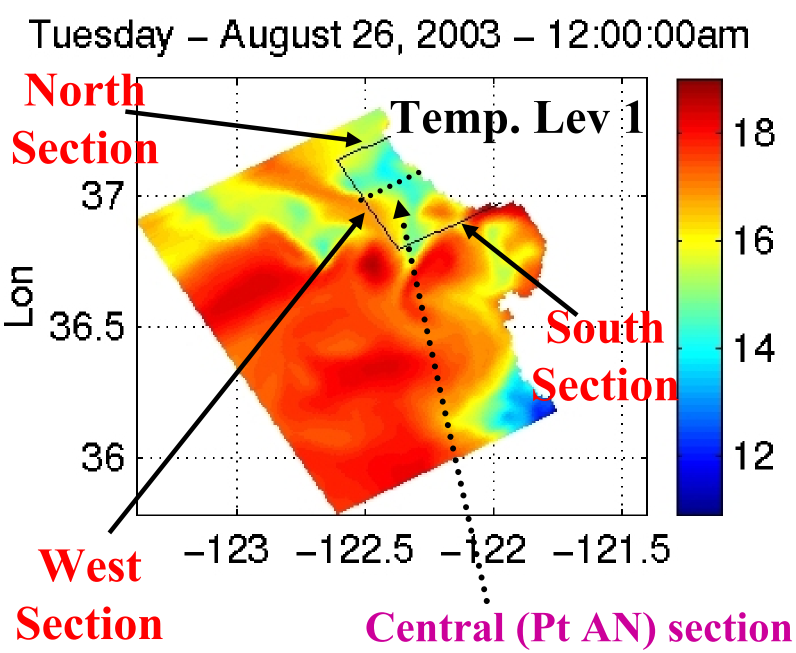
Best predicted relative error reduction: track 1



c. Different Objective Fields: e.g. Flux and/or Term-by-term Balances

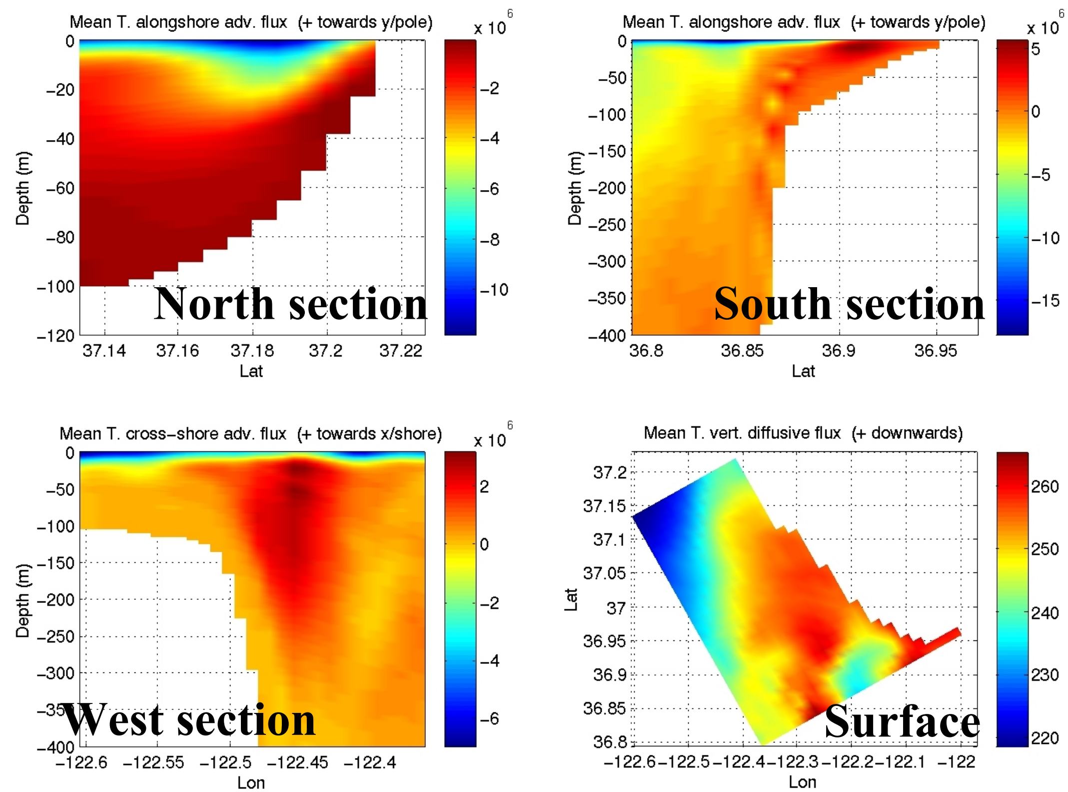
- **Physical model: Primitive-Equation (PDE, x, y, z, t: HOPS)**

Horiz. Mom.	$\frac{D\mathbf{u_h}}{Dt} + f\,\mathbf{e}_3 \wedge \mathbf{u}_h = -\frac{1}{\rho_0}\nabla_h p_w + \nabla_h \cdot (A_h \nabla_h \mathbf{u}_h) + \frac{\partial\, A_v\, \partial \mathbf{u}_h/\partial z}{\partial z}$
Vert. Mom.	$\rho g + \frac{\partial p_w}{\partial z} = 0$
Thermal en.	$\frac{DT}{Dt} = \nabla_h \cdot (K_h \nabla_h T) + \frac{\partial\, K_v\, \partial T/\partial z}{\partial z}$
Cons. of salt	$\frac{DS}{Dt} = \nabla_h \cdot (K_h \nabla_h S) + \frac{\partial\, K_v\, \partial S/\partial z}{\partial z}$
Cons. of mass	$\nabla \cdot \mathbf{u} = 0$
Eqn. of state	$\rho(\mathbf{r}, z, t) = \rho(T, S, p_w)$



Heat Flux Balances: 4 fluxes normal to each side averaged over first upwelling period

Mean Fluxes (W/m2) over: August 6, 2003 – 10:30:00pm -> August 13, 2003 – 4:30:00am GMT



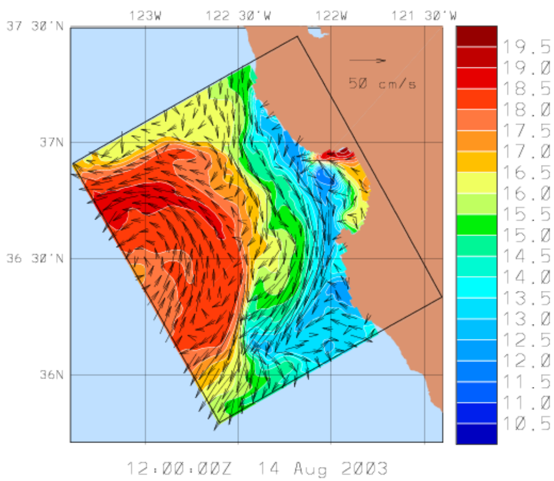
Adaptive Sampling and Prediction (ASAP): Virtual Pilot Study – March 2006

One of a sequence of virtual experiments to test software, data flow, methods, products, control room, etc. in advance of August 2006 experiment

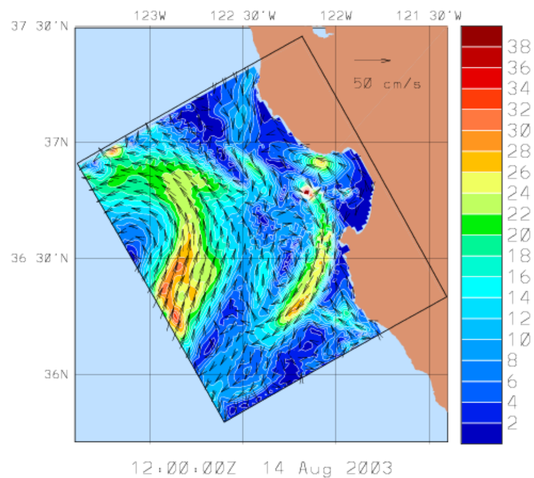
http://oceans.deas.harvard.edu/ASAP/index_ASAP.html

Example products for "14 August"

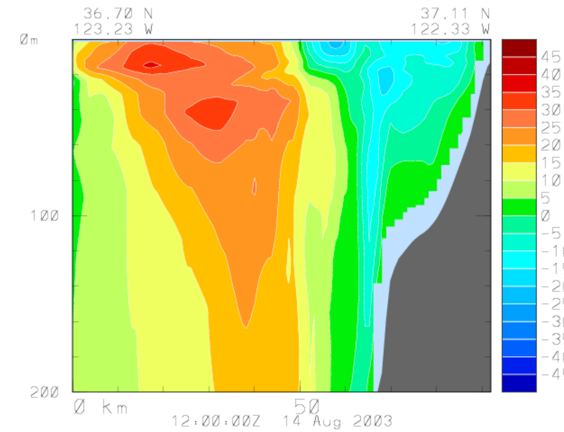
Surface Temperature



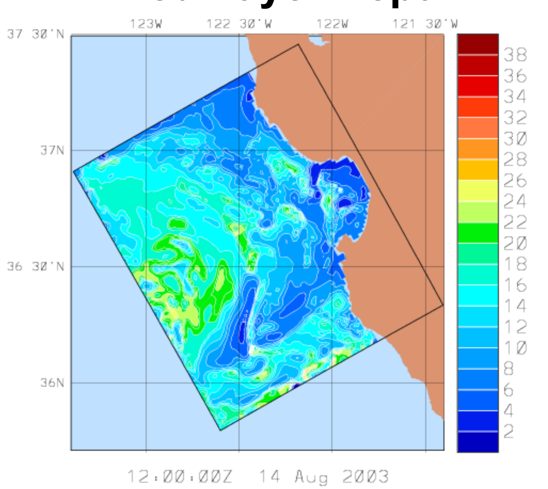
0-200m Ave. Velocity



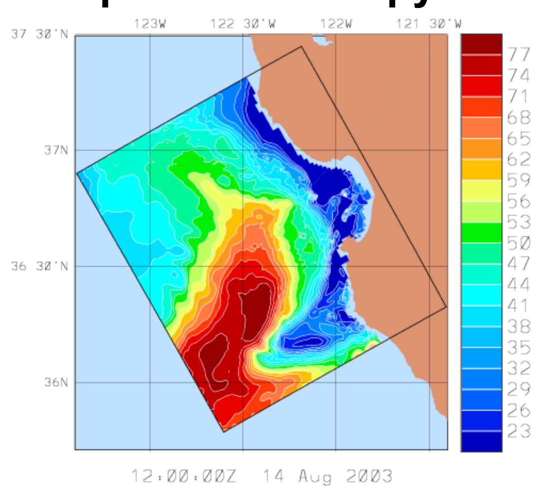
Velocity Section - AN



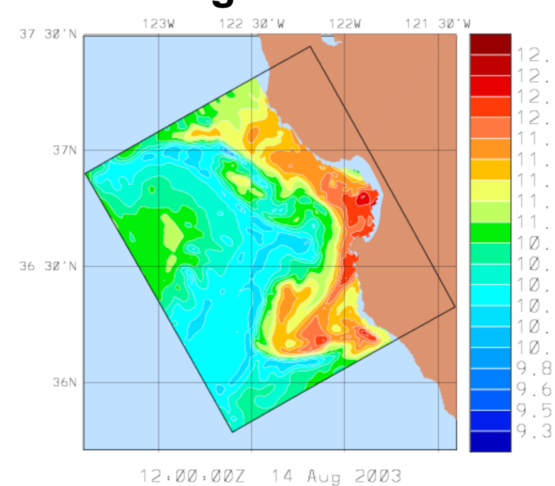
Mixed Layer Depth



Depth of 25.5 Isopycnal

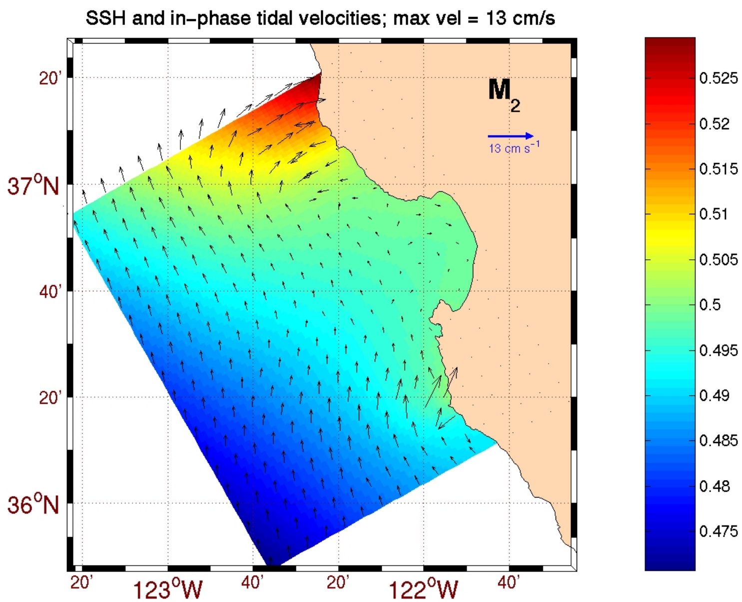


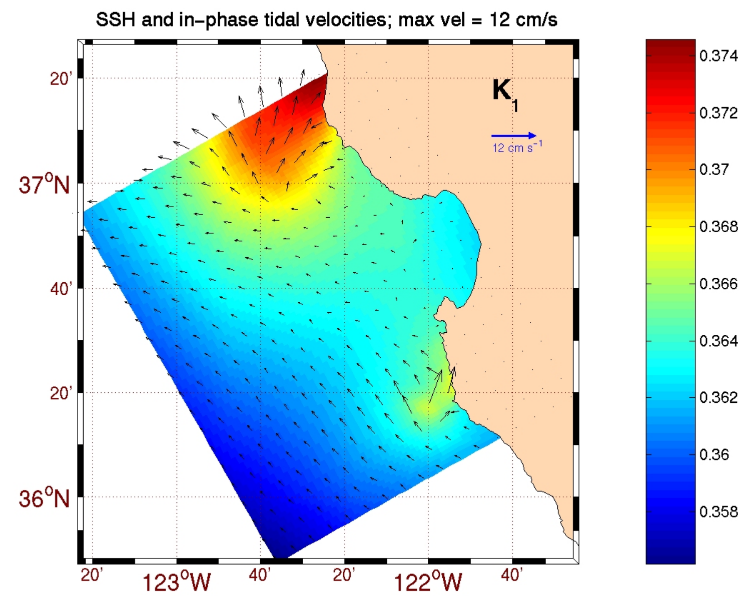
T on sigma-theta = 25.5



Modeling of tidal effects in HOPS

- Obtain first estimate of principal tidal constituents via a shallow water model
  1. Global TPXO5 fields (Egbert, Bennett et al.)
  2. Regional OTIS inversion with high-resolution bathy, using tidal-gauges and TPX05 at open-boundary, high-resolution bathy





- Used to estimate hierarchy of tidal parameterizations :
  i. Vertical tidal Reynolds stresses (diff., visc.) $K_T = \alpha \, ||\boldsymbol{u}_T||^2$ and $K = max(K_S, K_T)$
  ii. Modification of bottom stress $\tau = C_D \, ||\boldsymbol{u}_{S+} \boldsymbol{u}_T|| \, \boldsymbol{u}_S$
  iii. Horiz. momentum tidal Reyn. stresses Σ_ω (Reyn. stresses averaged over own T_ω)
  iv. Horiz. tidal advection of tracers ½ free surface
  v. Forcing for free-surface HOPS full free surface

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

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

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

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

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

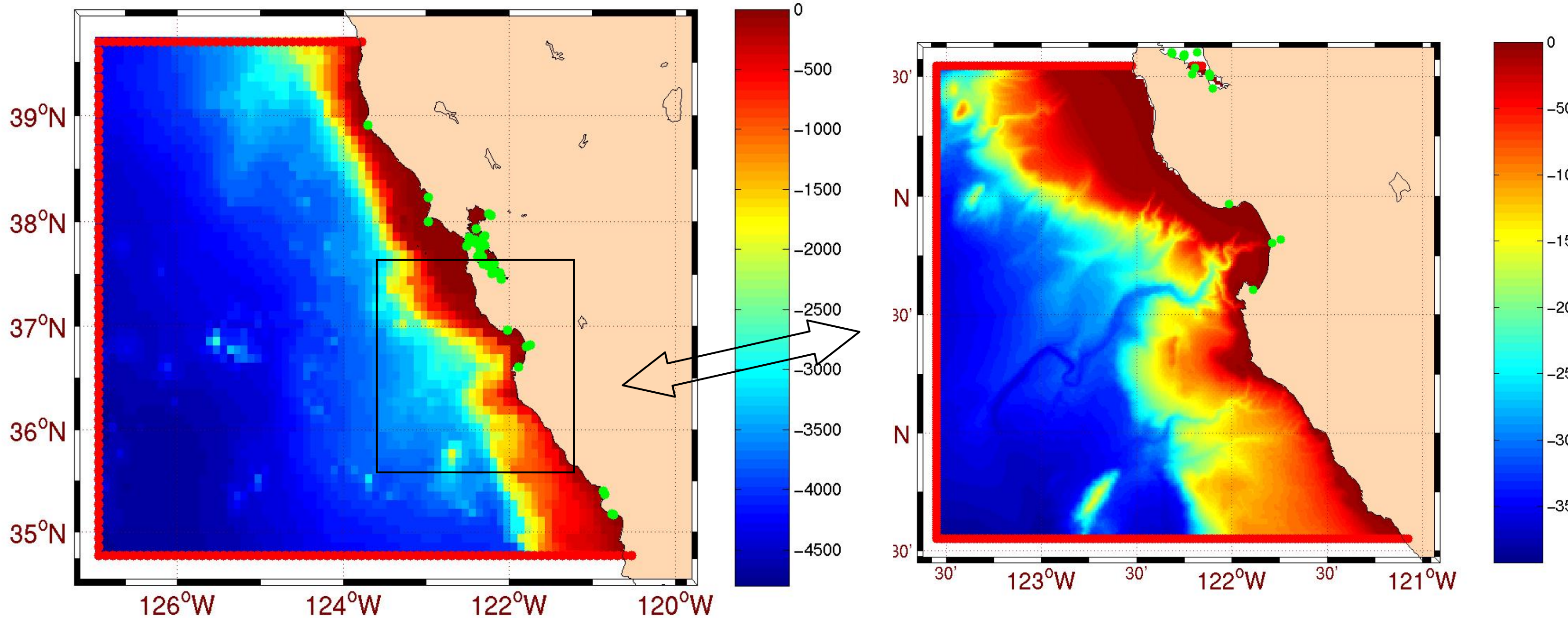
Adjoint of dynamics

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.

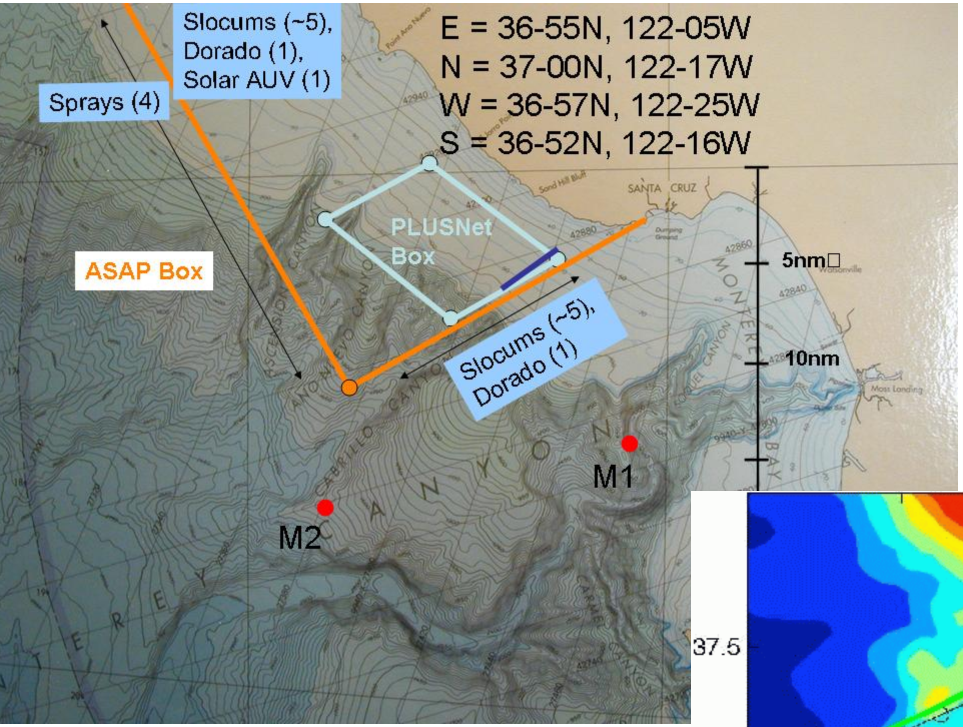
Available Tide Gauges

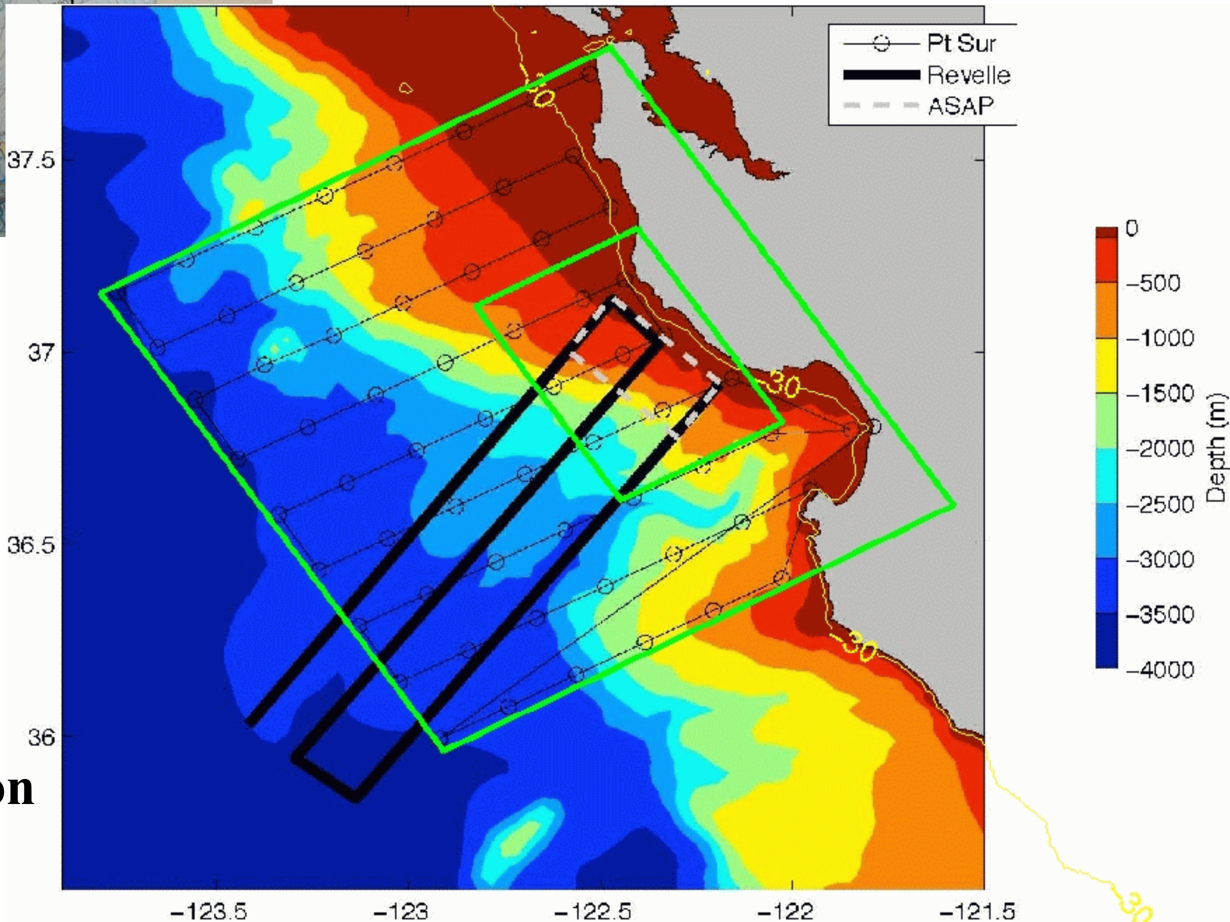


Bottom Topography [m]

Monterey Bay Area Pacific Basin

ASAP and PLUSNet Domains



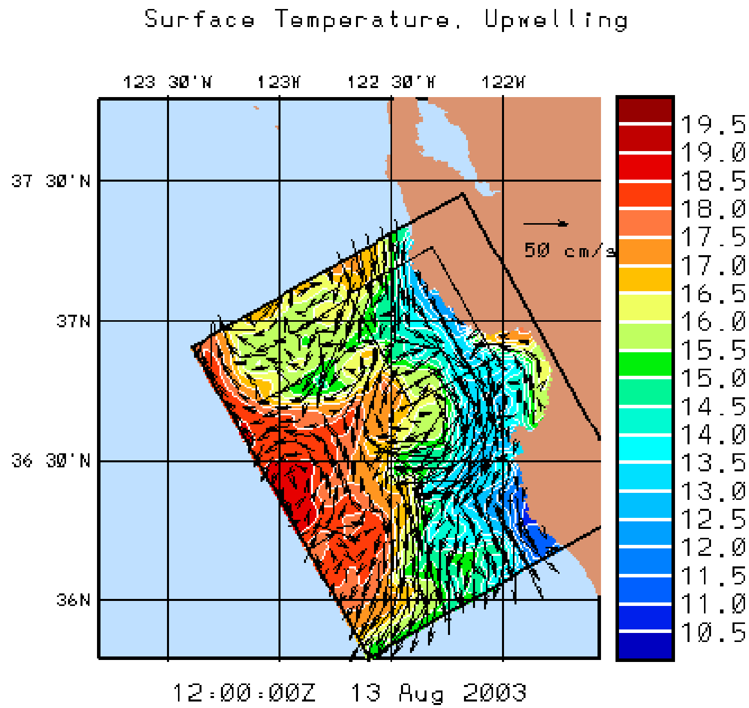


Two nested HOPS domains

Resolution: 1.5km and 500m

Free-surface, tidal forcing

OI and ESSE data assimilation


Surface Temperature, Upwelling
123 30'W
123W
122 30'W
122W
37 30'N
37N
36 30'N
36N
50 cm/s
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19.0
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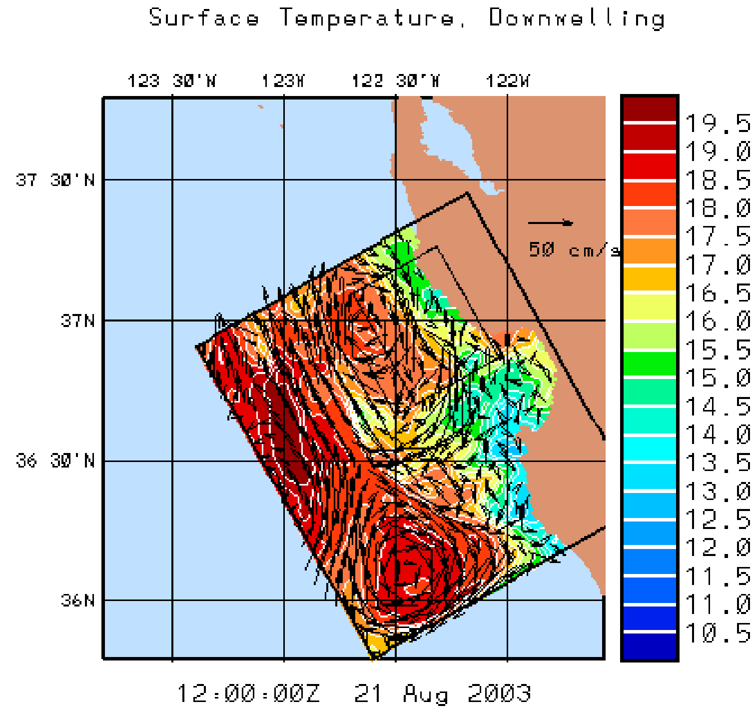
10.5
12:00:00Z 13 Aug 2003


Surface Temperature, Downwelling
123 30'W
123W
122 30'W
122W
37 30'N
37N
36 30'N
36N
50 cm/s
19.5
19.0
18.5
18.0
17.5
17.0
16.5
16.0
15.5
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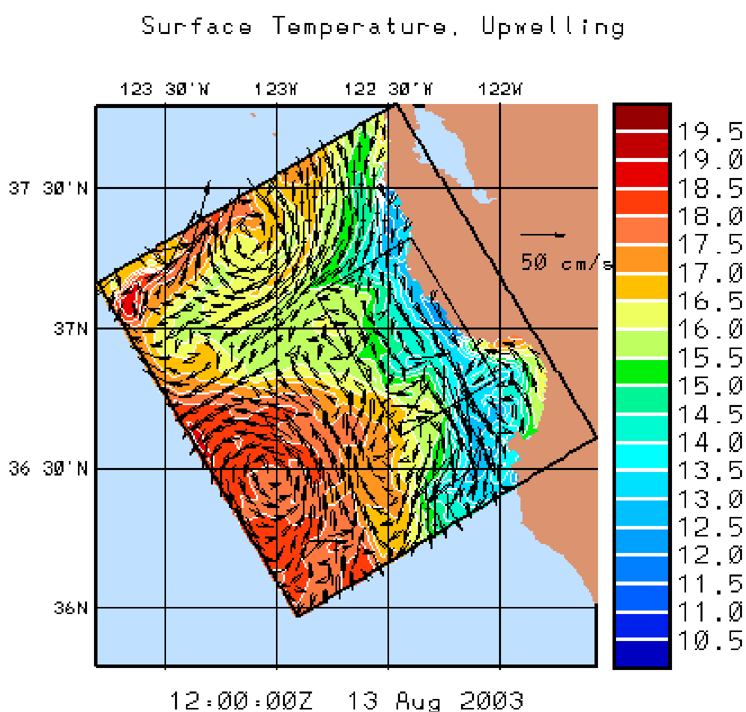
Surface Temperature, Upwelling
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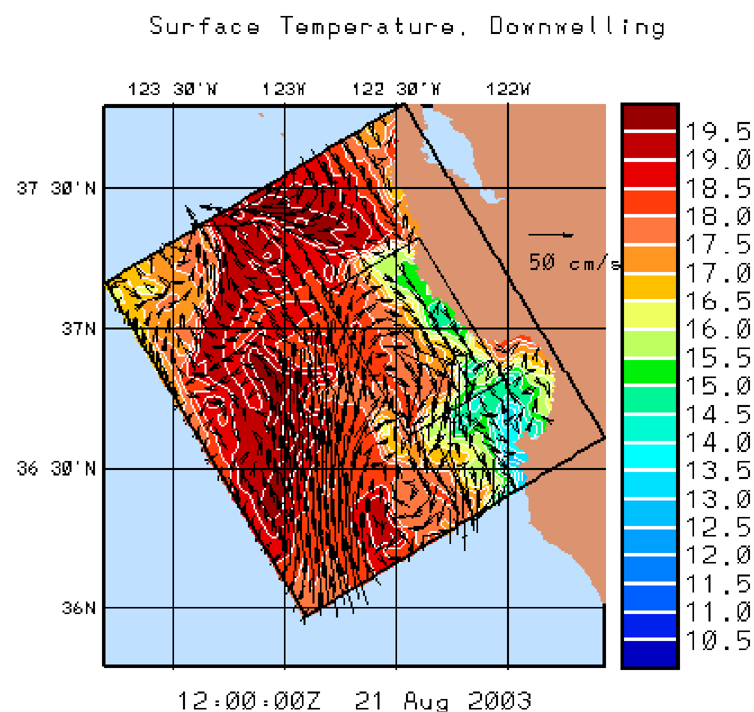
Surface Temperature, Downwelling
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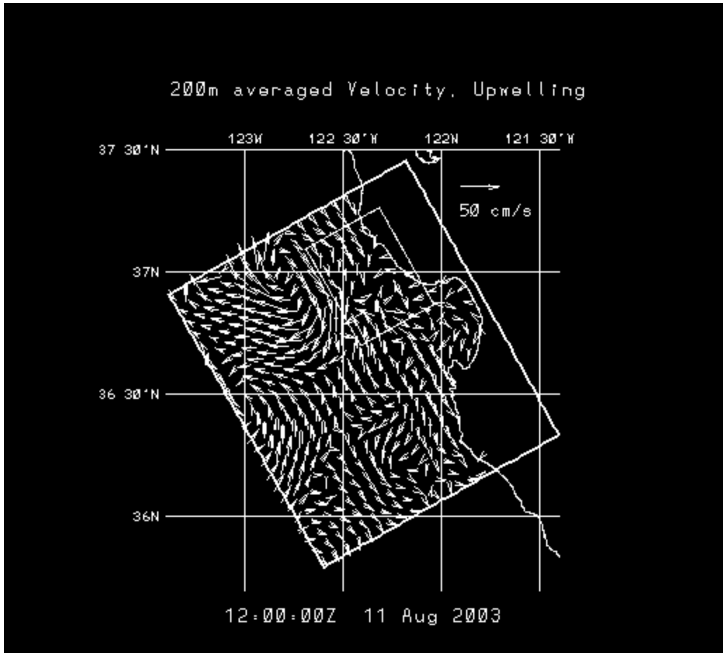
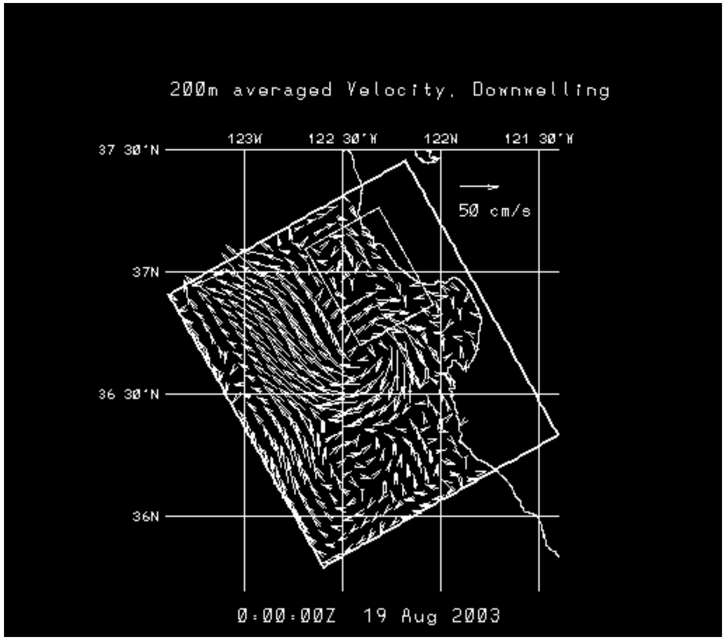
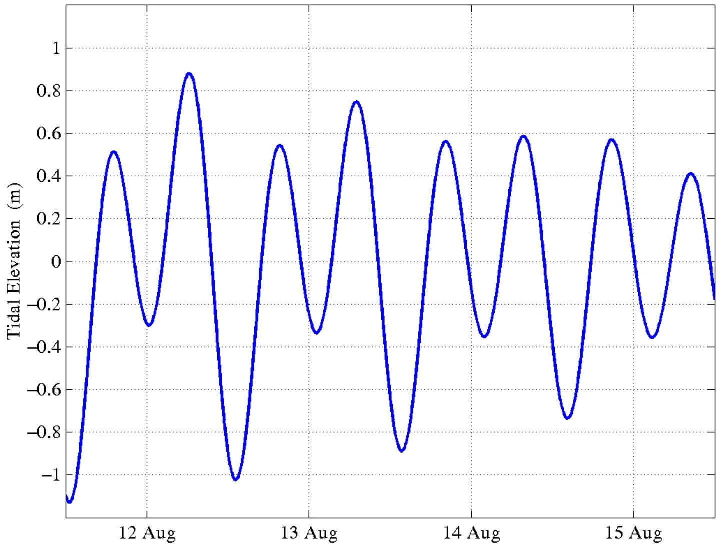
Upwelling and Relaxation States and Effects of Tidal Forcings

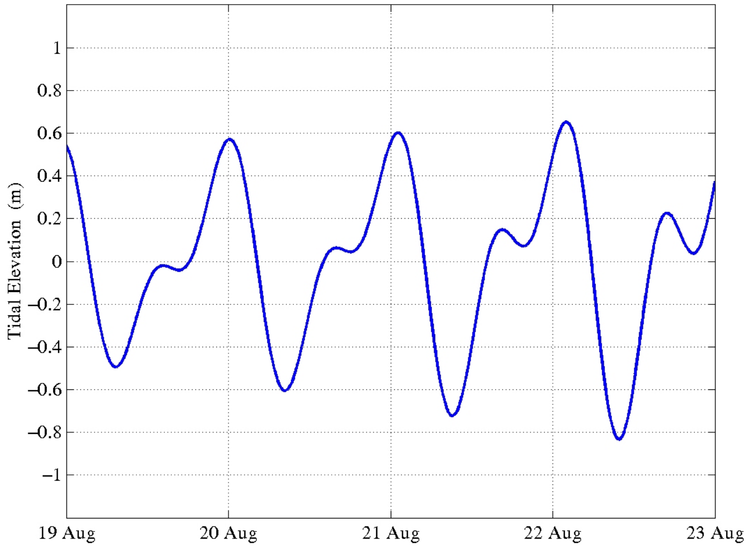
Upwel.

Relax.









Persistent Littoral Undersea Surveillance Network (PLUSNet)

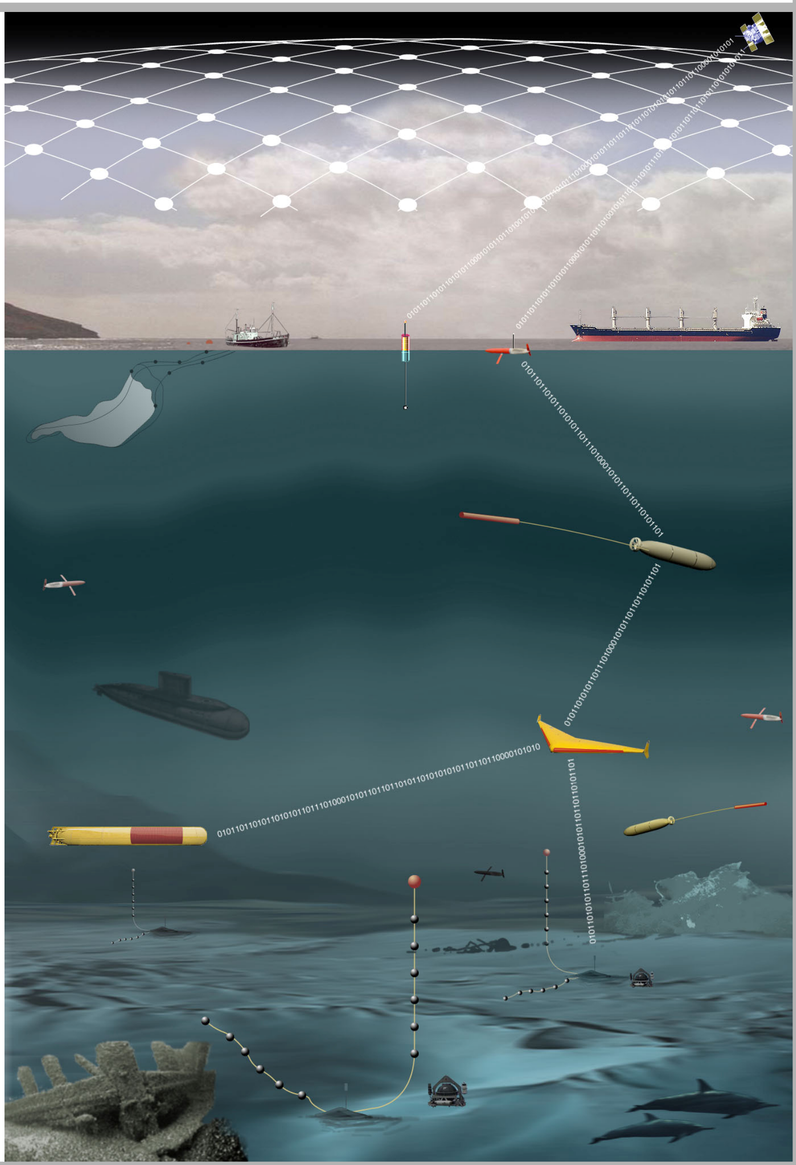
Lead: Kuperman, Schmidt et al.

End-to-end System components

- Adaptive Environmental and Tactical Assessment and Predictions with distributed network of fixed and mobile sensors for improved DCL
- Coordination via network control architecture and covert communications
- System level concept demonstration in three years

Harvard Research Thrusts

- Acoustical-physical nonlinear adaptive sampling with ESSE and AREA
- Multi-scale and (non)-hydrostatic nested ocean modeling
- Coupled physical-acoustical DA in real-time



Harvard Research Goals and Objectives

2.5 Environmentally Adaptive Sensing and Network Control

Goal: To provide (sub)-mesoscale environmental fields/picture to MIT and PLUSNet, using new multi-scale environmental data-driven forecasting systems and new HU-MIT physical-acoustical adaptive sampling schemes

Specific objectives are to:

(i) Research and develop a new nested sub-mesoscale (non)-hydrostatic ocean modeling system within coarser regional domains for improved acoustic predictions

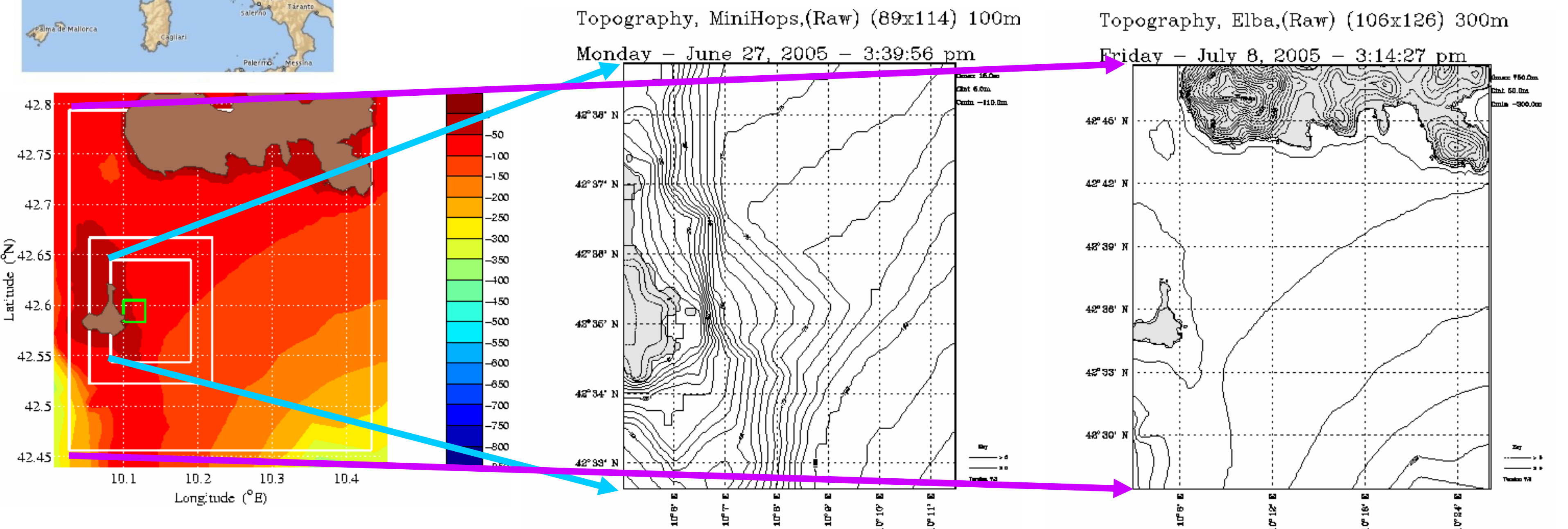
(ii) Investigate and carry out physical-acoustical-seabed estimation and data assimilation

(iii) Evaluate oceanic sub-mesoscale parameterizations and study selected sub-mesoscale/mesoscale interactions and their acoustical impacts

(iv) Collaborate with other efforts sponsored by ONR and NRL

(v) Lead the environmental PLUSNet scientific research, coordinating the HU and Scripps contributions (e.g. internal tide conversions, sub-mesoscale eddy mixing and atmospheric forcing)

FAF05: High-Resolution Nested Modeling Domains for Acoustical-Physical Adaptive Sampling

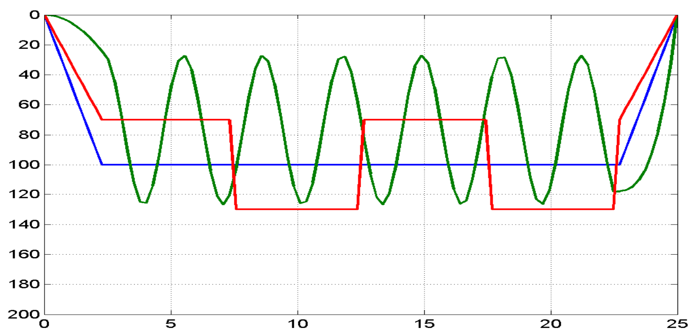


		Mini-HOPS	Elba
Resolution		**100m**	**300m**
Size	*nx × ny × nz*	89×114×21	106×126×21
	Extent	8.8×11.3 km	31.5×37.5 km
Domain center		42.59°N, 10.14°E	42.63°N, 10.24°E
Domain rotation		0°	0°
Speed	*dt=50s*	90 minutes/(model day)	120 minutes/(model day)
	dt=300s	15 minutes/(model day)	20 minutes/(model day)

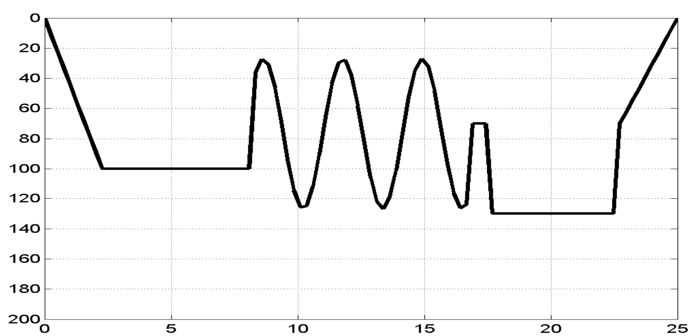
Acoustical-Physical Adaptive Sampling in Cross-Sections

AUV-Track Base Lines - For - Specific Sound-speed Features

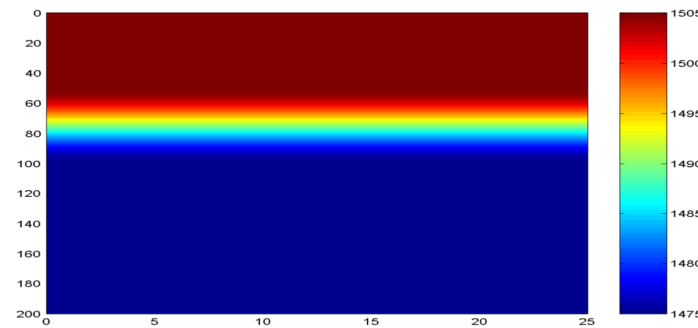
Base Lines



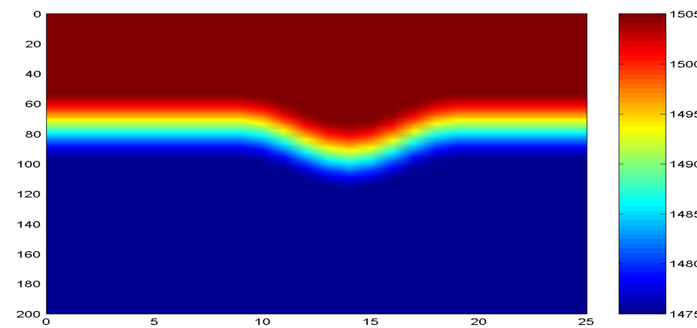
Composite Base Lines



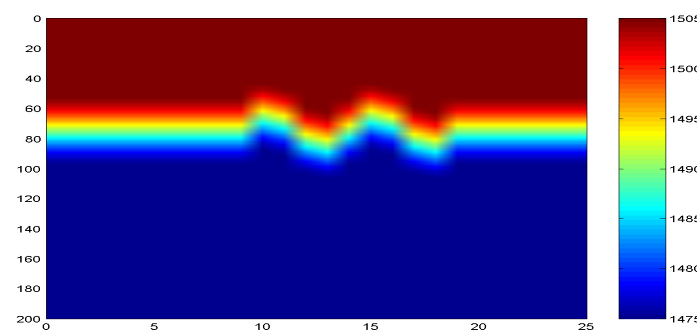
Thermocline



Eddy



Internal Wave



Capture the vertical variability of the thermocline (due to fronts, eddies, internal waves, etc)

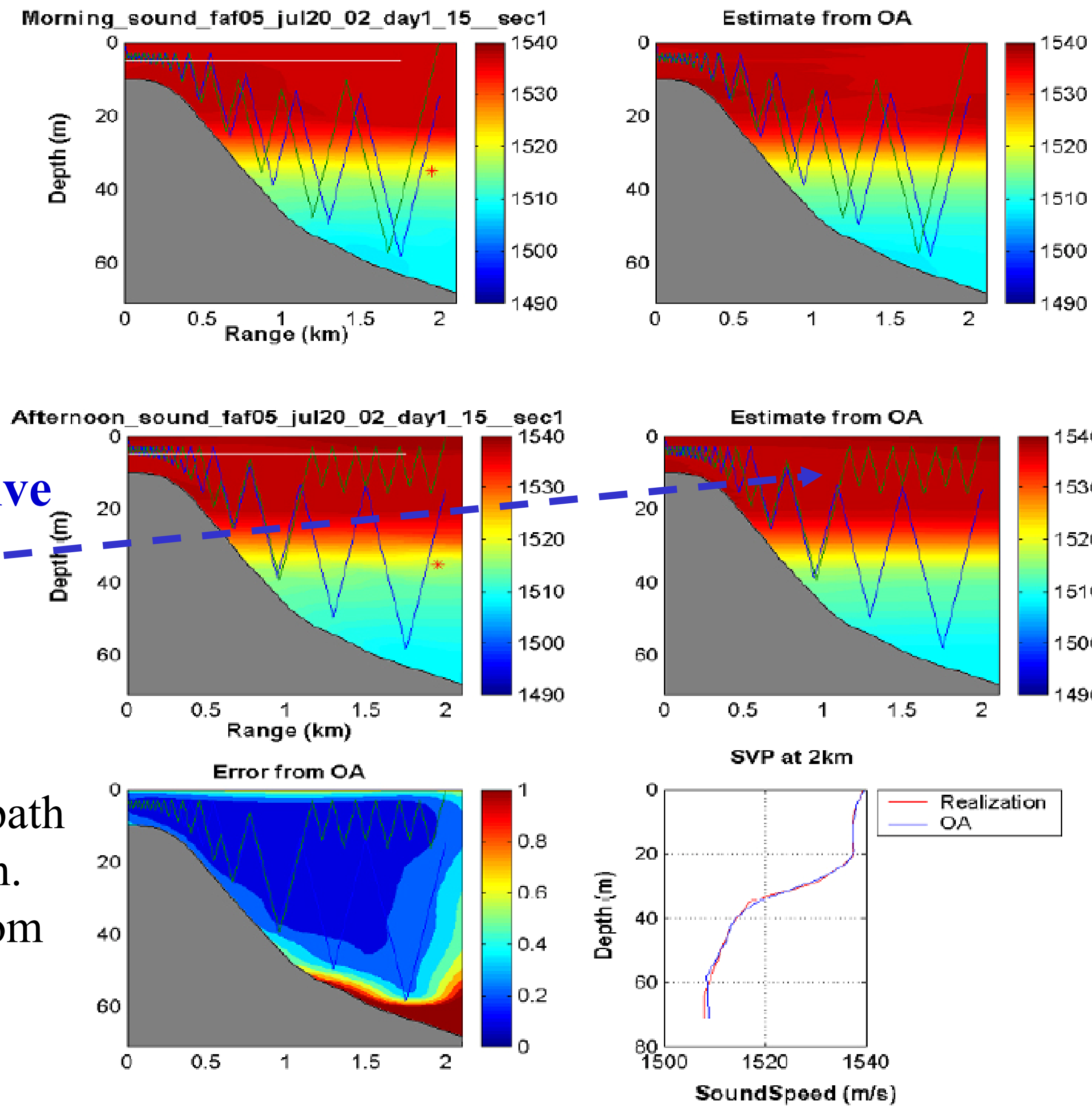
Minimize the corresponding uncertainties (ESSE)

Example of Results of Adaptive Yoyo Control (Jul 20-21)

Morning

Afternoon

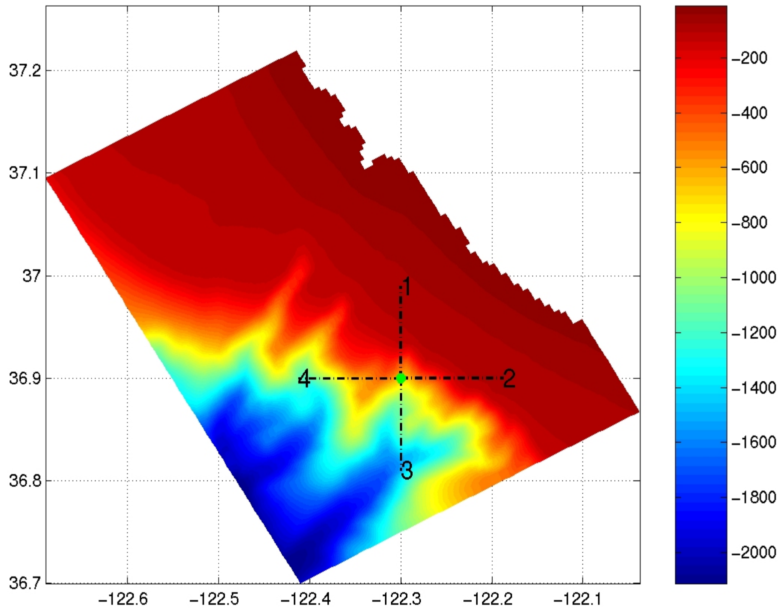
Shows Forecast, adaptive AUV capture of ``afternoon effects''



Legend:

- Blue line: forward AUV path
- Green line: backward path.
- AUV avoids surface/bottom by turning 5 m before surface/bottom

PLUSNet HU-MIT virtual Real-Time Experiment 1 (AREA-HOPS-ESSE)



The MIT-AUV is at center of the PLUSNet region to carry out its missions.

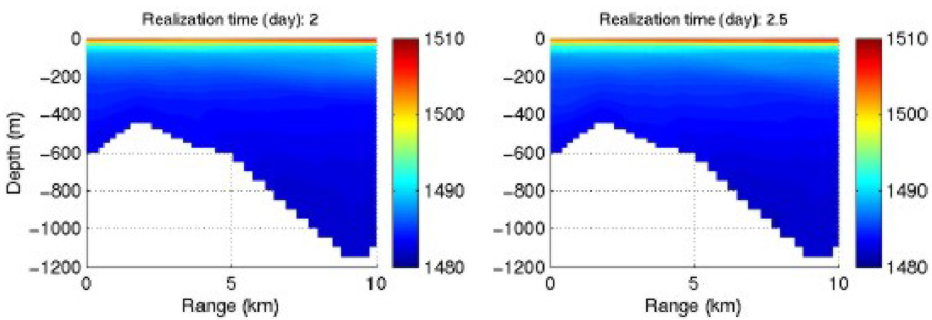
Four bearings are possible (0, 90, 180 and 270).

Question: "which bearing should it choose and which yoyo pattern should it follow along that bearing, so as to best sample the environment and optimize acoustic performance, including reduction of acoustic uncertainties".

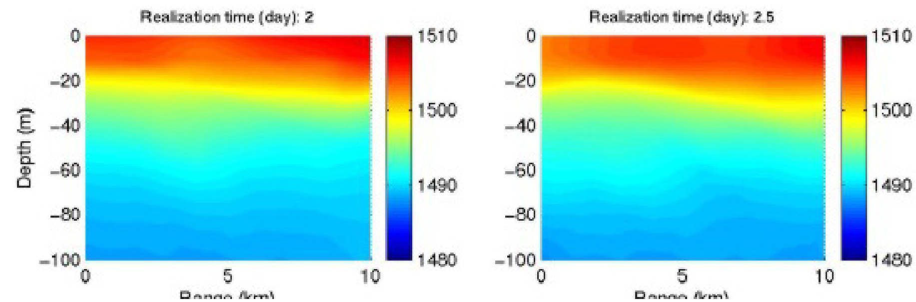
http://oceans.deas.harvard.edu/PLUSNet/Virtual1/plus_virtual1.html

PLUSNet HU-MIT virtual Real-Time Experiment 1 (AREA-HOPS-ESSE)

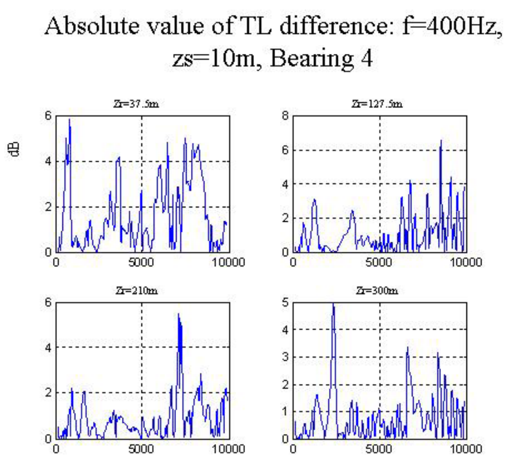
Bearing/path 4 chosen as this is where the acoustic variability and uncertainties are predicted to be largest, based on one source and signals at four receiver depths. The upwelling front is predicted to cross this path along bearing 4 (start of sustained upwelling conditions) and environmental uncertainties (ESSE) are largest there too.



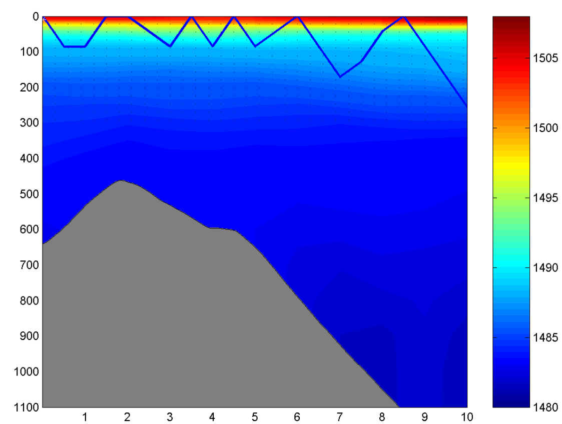
Sound-speed section predictions along path 4



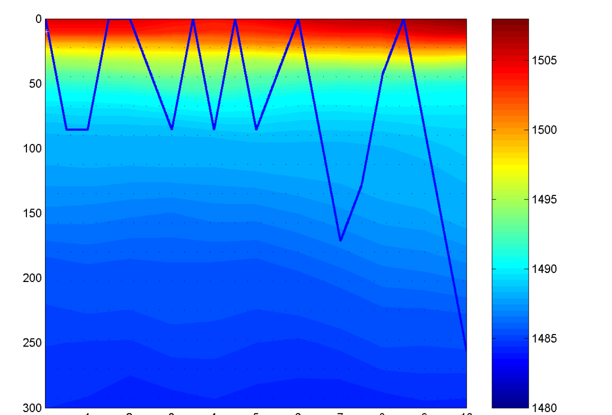
Same sections (upper 100m). Notice variations in thermocline properties (its slopes, advected plumes and eddies)



Differences in TL, for four receivers at 37.5, 127.5, 210 and 300 m depth



Optimized AUV path

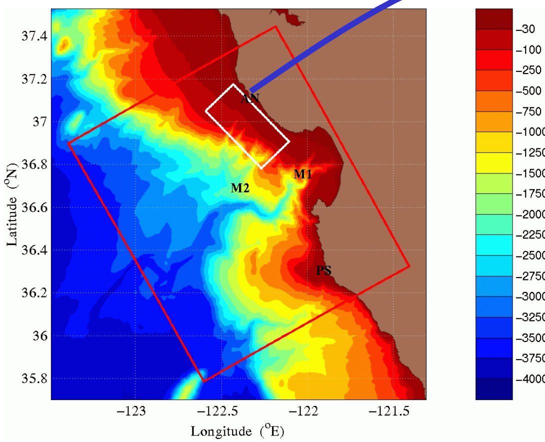


Optimized path (0-300m)

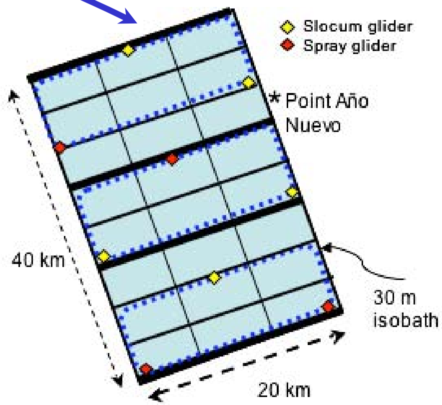
http://oceans.deas.harvard.edu/PLUSNet/Virtual1/plus_virtual1.html

MB06 AREA PLAN: HOPS-ESSE-AREA

ASAP Domains

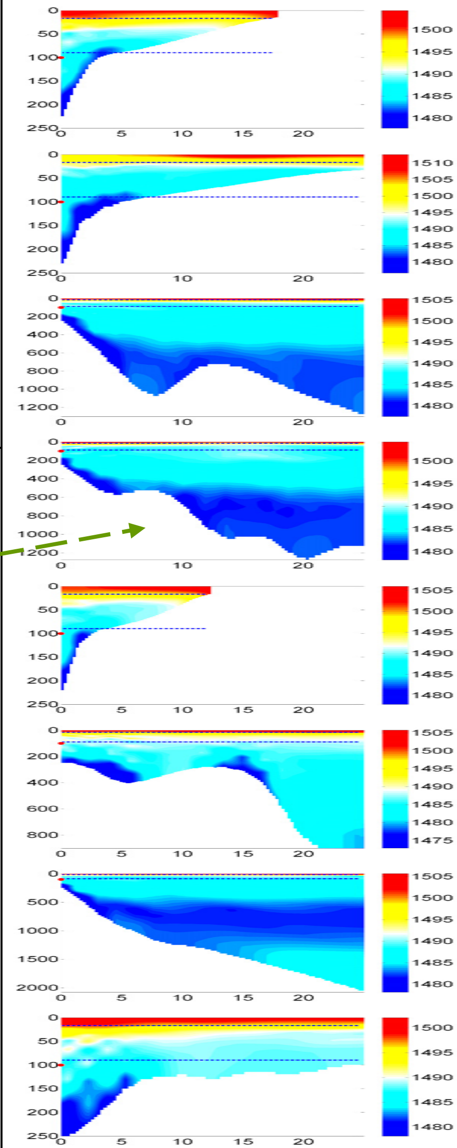


ASAP "Race-Tracks"

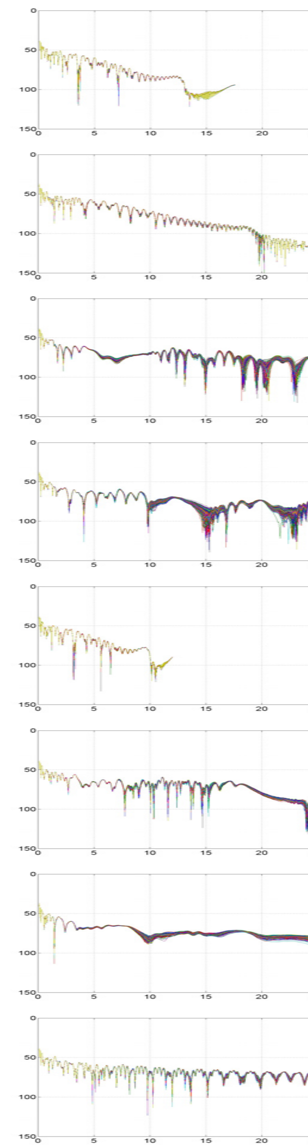


TL Forecast

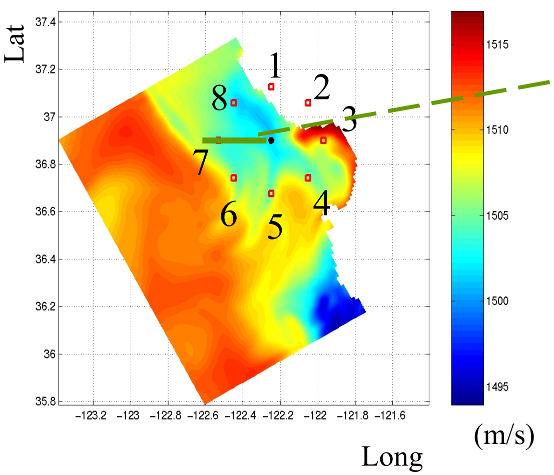
Sound Speed Profile



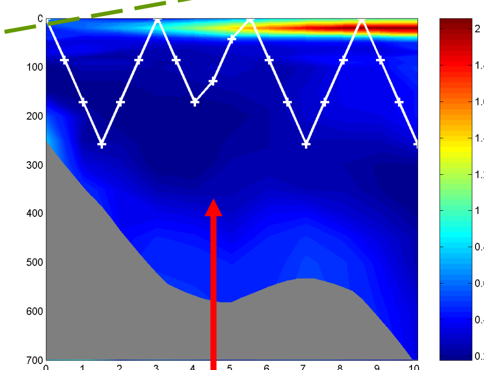
TL uncertainty



Surface Sound Speed Field



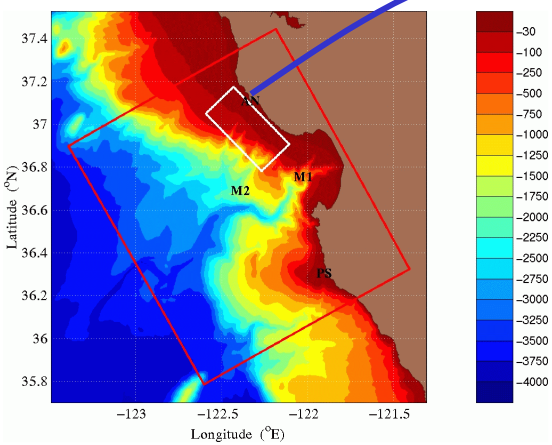
Optimal Sampling Track



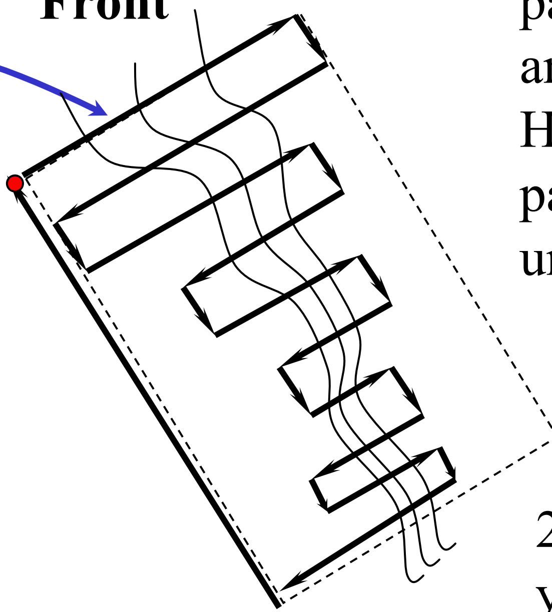
a priori SVP error field from ESSE

MB06: Capture upwelling fronts and eddies

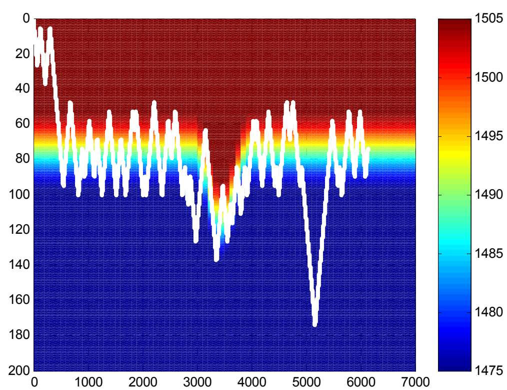
ASAP Domains



Front



1. Every day, plan the horizontal path adaptively based on ocean and uncertainty predictions from HOPS-ESSE. The horizontal paths focus on fronts/eddies and uncertainties.



2. Vertical path is an adaptive yoyo path. The two yoyo control parameters should be determined based on the ocean predictions from HOPS and experience.

3. After the above 2 steps, run the 3-D simulator for testing.

Major HU and MIT Accomplishments

- Integrated AREA Simulation Framework created.
- Interface is created for coupling HOPS/ESSE and AREASF.
- New nested HOPS free-surface re-analyses simulations issued for use as ``true ocean'' by both PLUSNet and ASAP teams
  - High-resolution 0.5 km and 1.5 km resolution domains, with full tidal forcing
  - ESSE for free-surface, tidal-forced HOPS code under development
  - HU web-page for integration and dissemination of HOPS, ESSE and AREA outputs being finalized
- Thermocline-oriented adaptive AUV path control developed and tested during FAF05 and March VPE-06.
- Path optimization and adaptive strategy schemes developed:
  - Rapid linear programming method and codes for AUV predetermined path optimization.
  - Real-time approximate dynamic programming method and codes being created for adaptive sampling strategy optimization.

Some Future Work and Challenges

- Initiate use of MIT-GCM for non-hydrostatic high-resolution ocean simulations, initialized based on HOPS-ESSE fields
- Investigate and carry out physical-acoustical-seabed estimation and data assimilation
- Fully coupled, four-dimensional acoustical-physical nonlinear adaptive sampling with ESSE and AREA
- Rapid non-linear programming method and codes for AUV predetermined path optimization.
- Rapid mixed-integer programming method and codes for AUV yoyo control parameters optimization.
- More approximate dynamic programming / machine learning / data mining methods for the adaptive sampling strategy optimization.

CONCLUSIONS and AESOP Collaborations

- **ASAP and PLUSNet provide multiple novel and challenging opportunities**:
  - Adaptive modeling and parameterizations
  - Adaptive sampling
  - Modern observation systems and their design (data, models, DA, IT)
  - Dominant dynamical balances for fundamental understanding and constraints
- **Possible HU Collaborations with AESOP**
  - HU provides HOPS/ESSE fields and other results to AESOP (directly or through MBARI)
  - HU provides Multi-model combinations (NCOM/HOPS)
  - Access to AESOP data as made available
- **Productive Collaborations requires time and energy**
- **Suggestions for AESOP research**
  - Background/Mean fields likely need to be accurate enough for evaluation of sub-grid-scale parameterizations
  - Modeling systems and Modelers: both have an impact