Adaptive Modeling and Adaptive Sampling Research For Coupled Air-Sea Predictions

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Main collaborators for the material presented

HU: **A. Robinson**, **P. Haley, W. Leslie, J. McCarthy, O. Logoutov and X. Liang**

PLUSNet-FAF05**: H. Schmidt, D. Wang (E. Coehlo, E. Nacini, A. Cavanna, M. Tudor)**

AOSN2-MURI: **N. Leonard, J. Marsden, F. Lekien, S. Ramp, R. Davis, D. Fratantoni**

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

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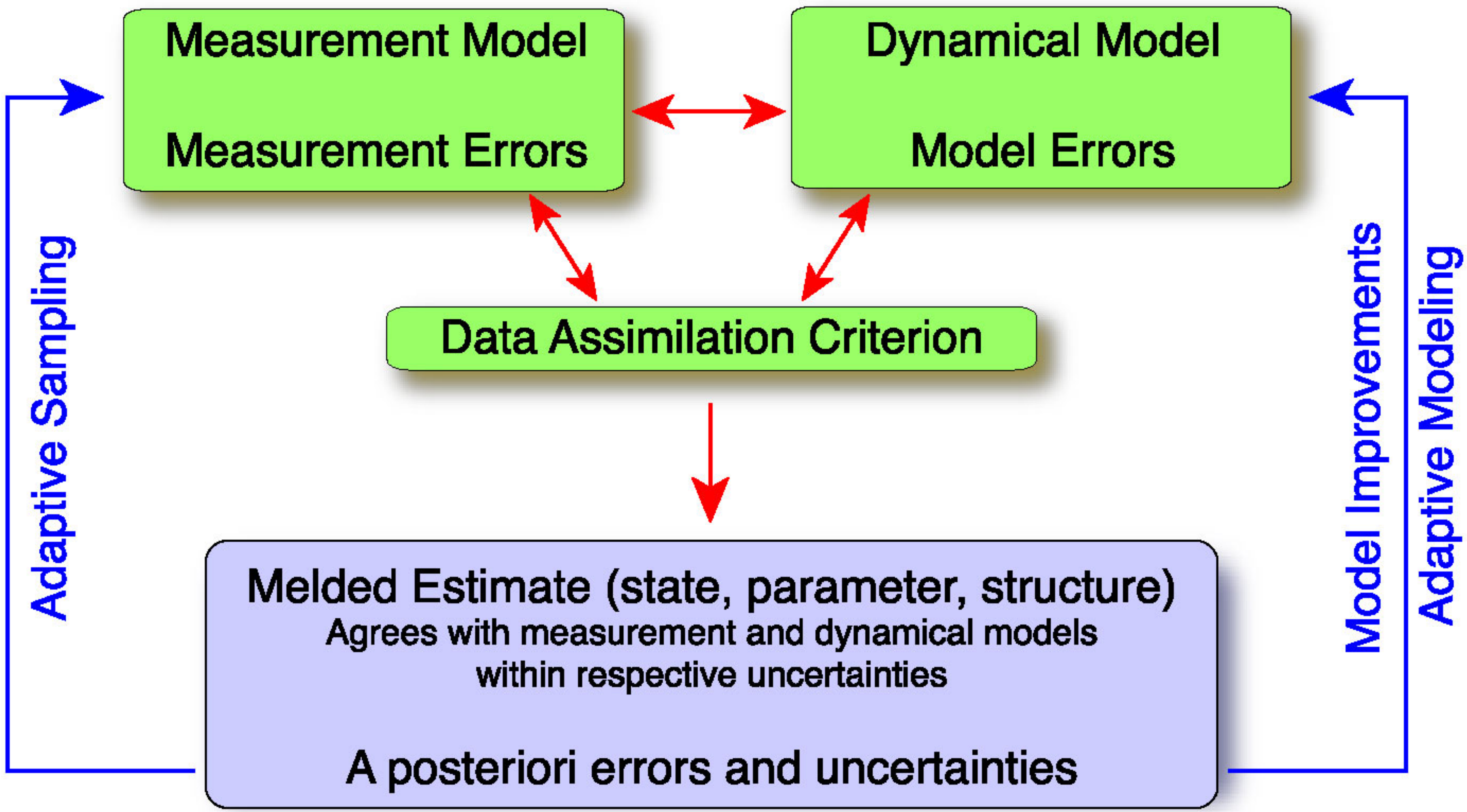
1. **Adaptive Modeling (Monterey Bay and California Current System region)**
2. **Adaptive Sampling**
3. **PLUSNet Research during FAF-05: Coupled Acoustical-Physical Adaptive Sampling**
4. **Conclusions**

NURC High-resolution Coupled Coastal Prediction Workshop

November 29, 2005

WHAT IS DATA ASSIMILATION?

A Melded Estimate of Data and Dynamics



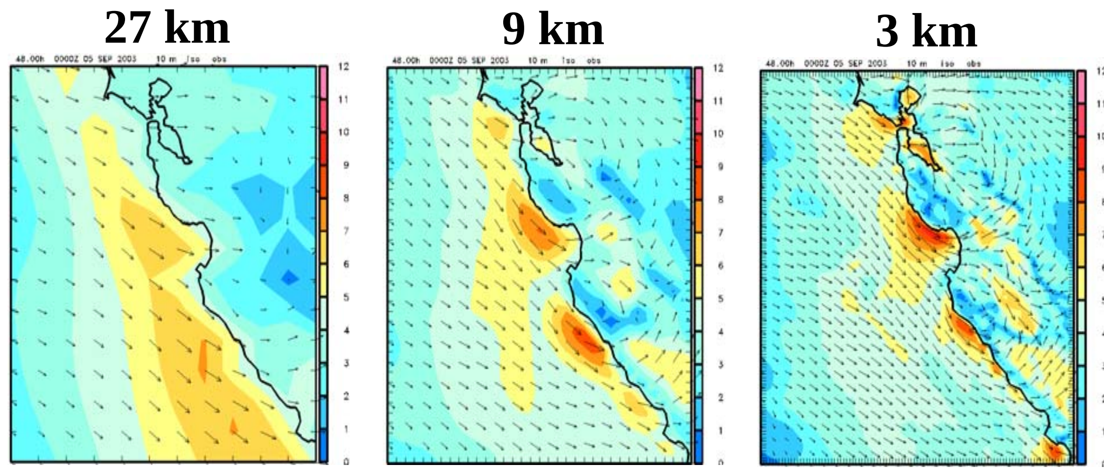
e.g. Robinson A.R., P.F.J. Lermusiaux and N.Q. Sloan, III (1998). *Data Assimilation*. The Sea, Vol. 10.

Robinson A.R. and P.F.J. Lermusiaux (2002). *DA for physical-biological interactions*. The Sea, Vol.12.

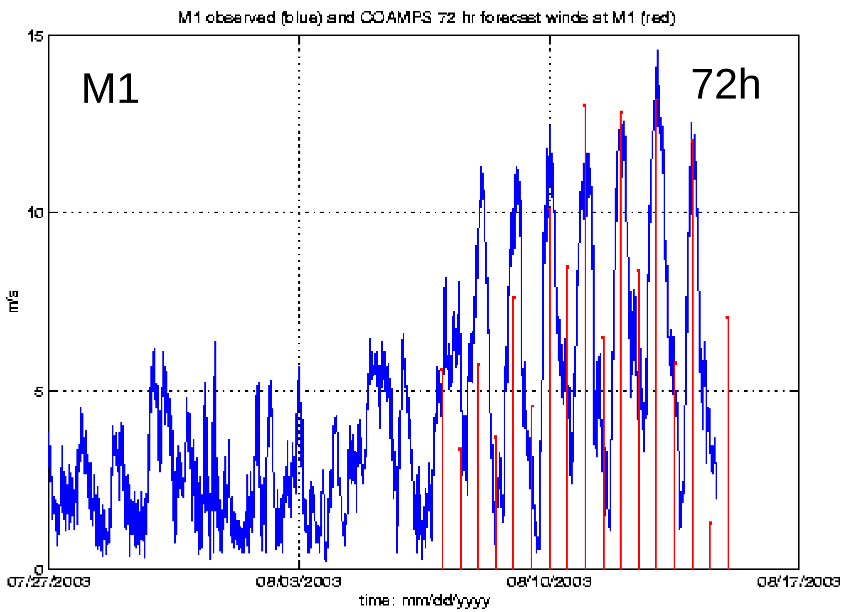
Atmospheric fluxes from 3km and hourly COAMPS (J. Doyle, NRL): Winds

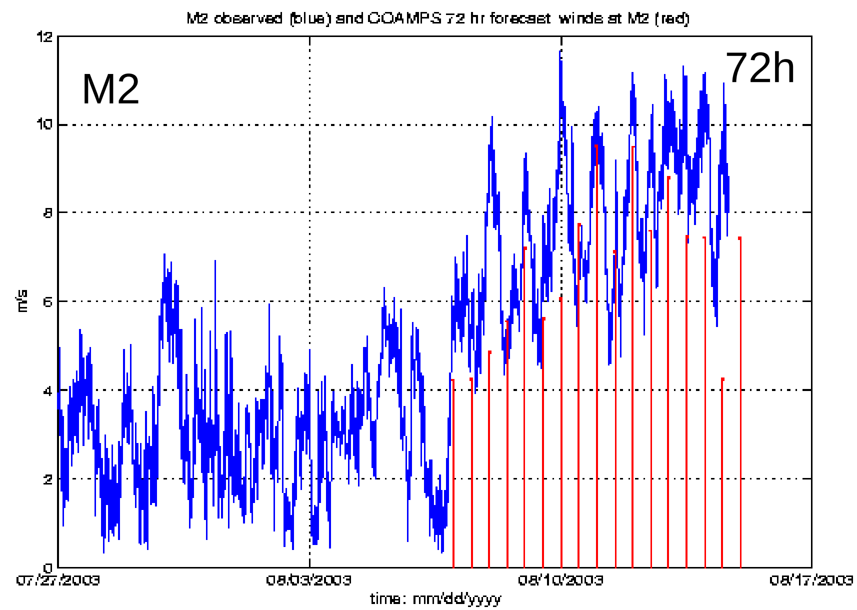
Sensitivity to horizontal resolution

3 km improves Representation of Coastal Jets & Coastal Shear Zone



Our evaluations: e.g. Buoy winds (blue) vs COAMPS 72h forecasts (red dots)



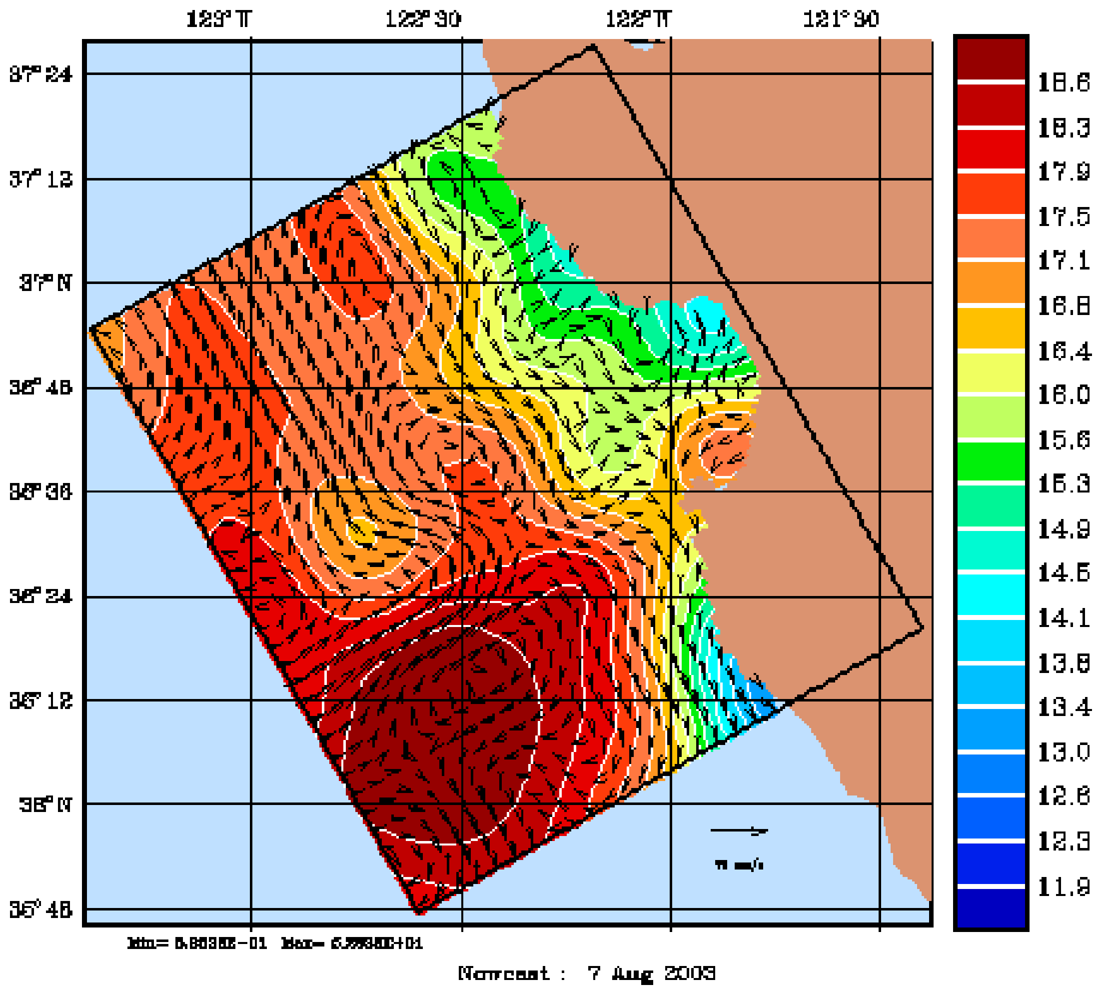


But: Wind-stress curl (for ocean upwelling)?, Long-wave radiations (cloud effects)?

Surface Temperature: 7 August-23 August

Illustrates

- Daily cycle
  - Night/day T sequence
  - Daily variability of rim currents
- Onset and maintenance of first upwelling state (Aug 7-18)
- Relaxation (Aug 19-23)



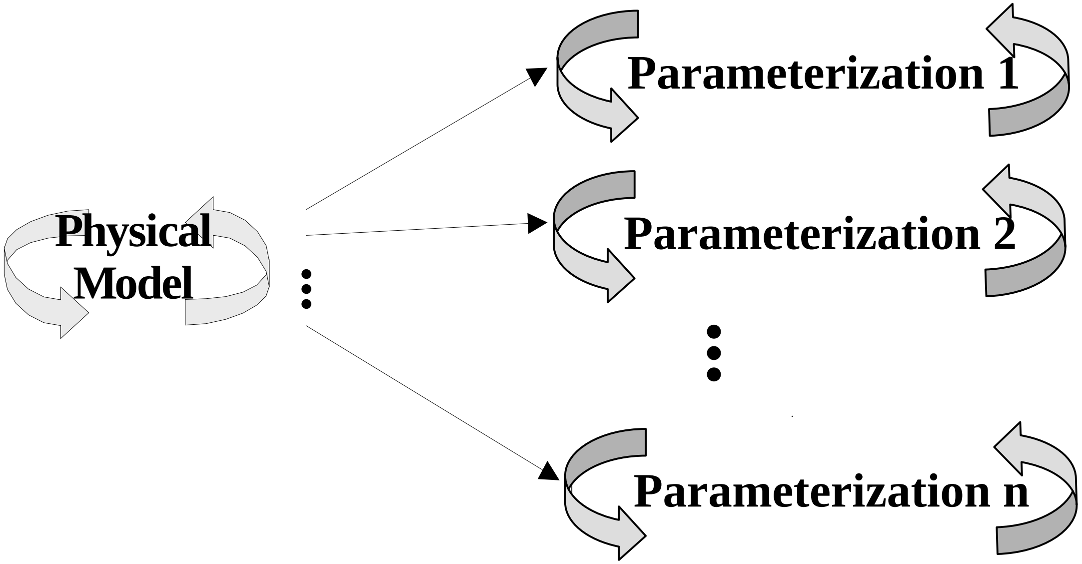
Adaptive Modeling: Motivations and Concepts

- **Atmospheric and oceanic dynamics can be intermittent and highly variable, and can involve interactions on multiple scales**
- **In general, fields and interactions that matter vary in time and space**
- **Model uncertainties can be (very) large (e.g. for biogeochemical processes)**

- **For efficient forecasting, model structures and parameters should evolve and respond quantitatively to new data injected into the running prediction system**
  - Quantitative correction of model biases
  - Quantitative automated evolution of model structures as a function of model-data misfits
  - Quantitative comparison of competing models and better scientific understanding
  - Multi-model data assimilation

- **Model quantity (parameters, structures, state-variables) said to be adaptive if its formulation, classically assumed constant, is made a function of data values**
  - Physical regime transition (e.g., well-mixed to stratified) and evolving/unknown turbulent mixing parameterizations
  - Variations of biological assemblages with time and space (e.g., variable zooplankton dynamics, summer to fall phytoplankton populations, etc) and evolving biogeochemical rates and ratios

Towards Real-time Physical Adaptive Models



Grey arrows schematize data feedbacks and evolving simulations

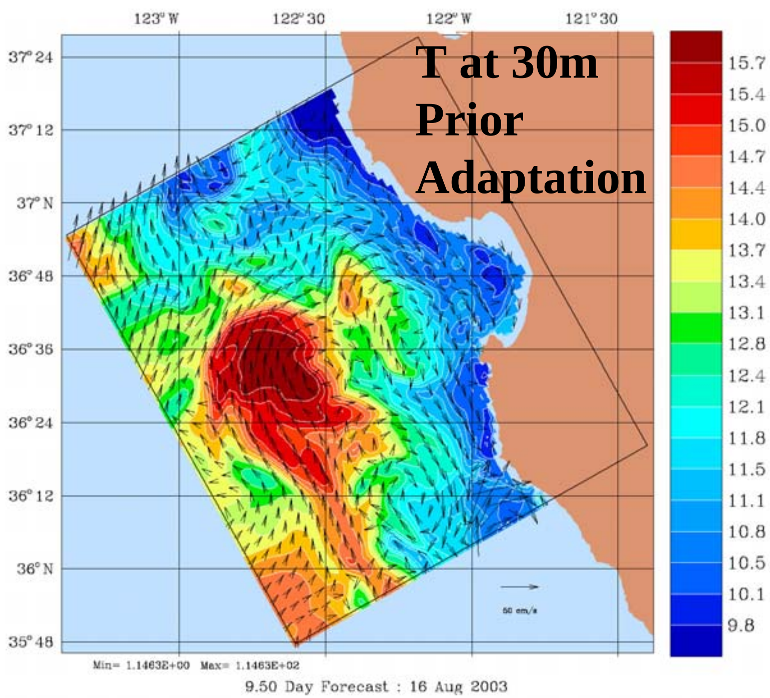
- Different Types of Adaptation:
  - Physical model with multiple parameterizations evaluated in parallel (hypothesis testing)
  - Physical model with a single adaptive parameterization (adaptive evolution). Not sketched.

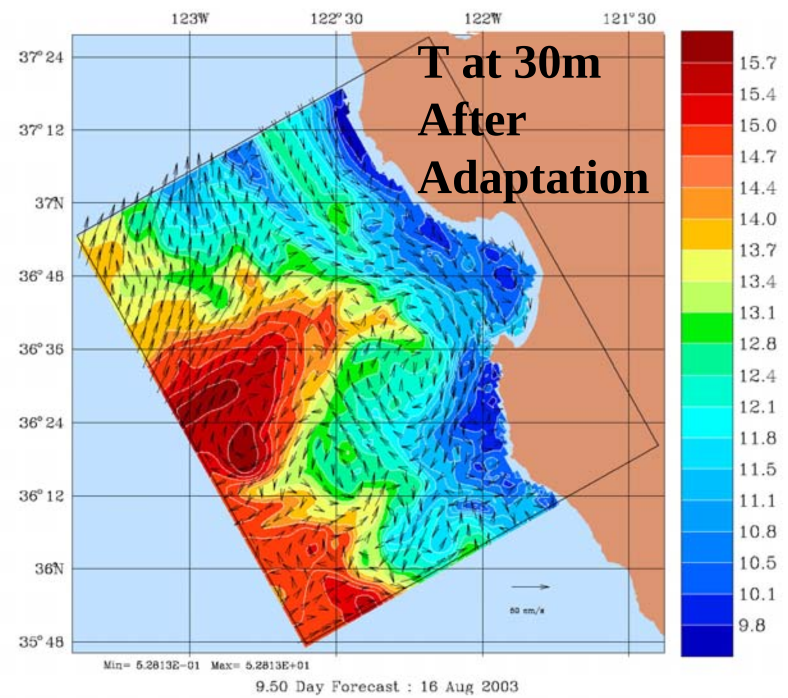
- Model selection based on quantitative dynamical/statistical study of data-model misfits

- Multi-model estimates: adaptive learning of errors of each model and combination based on maximum likelihood (examples carried out for SST of HOPS and ROMS)

Semi-Automated Real-time Physical Adaptation during AOSN2

- 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





Parameters/Parameterizations Selected for Possible Improvement/Adaptation

i. Initial condition parameters and simulation restart time

ii. SBL: parameters in vertical mixing and dissipation of atmospheric fluxes

iii. Horizontal viscosities

iv. Formulations of OBCs:

$$\frac{\partial T_i}{\partial t} \pm c_n \frac{\partial T_i}{\partial n} = -\beta_i \frac{(T_i - T_i^\ell(x,y,z,t))}{\tau_i(z)}$$

$$\frac{\partial u_i}{\partial t} \pm c_n \frac{\partial u_i}{\partial n} = -\beta_i \frac{(u_i - u_i^\ell(x,y,z,t))}{\tau_i(z)}$$

Adaptation Procedure

i. Parameter/parameterizations modified one at a time, then in groups

ii. In total, 49 simulations ran in parallel in real time
(starting from Aug 5 or 7, with DA up to Aug 15 and forecasts beyond (for Aug. 16, 17 and 18)

iii. Bias, RMSE and PCC estimates computed at data points (glider data)

iv. Model chosen: the one with smallest weighted sum of Bias/RMSE/PCCs

Result

	IC/Re-start date	ν_0	K_v^e	E_k	Boundary Relaxation				
Non-adapted	OA on Aug. 7 of Aug. 2-7 data	50.0	5.0	0.15	None				
Adapted	”	”	6.0	0.22	Bnd i	y/n	τ_i^b	τ_i^s	h_i
					West	1	1.5	4.5	50
					South	1	1.0	2.0	50
					East	0	-	-	-
					North	1	1.0	2.0	50

Table 1
Parameters and parameterization before and after adaptation. Units: ν_0 (cm^2/s), K_v^e (cm^2/s), E_k (non-dim), τ_i^b and τ_i^s (days), and h_i (m) (see also App. A.1).

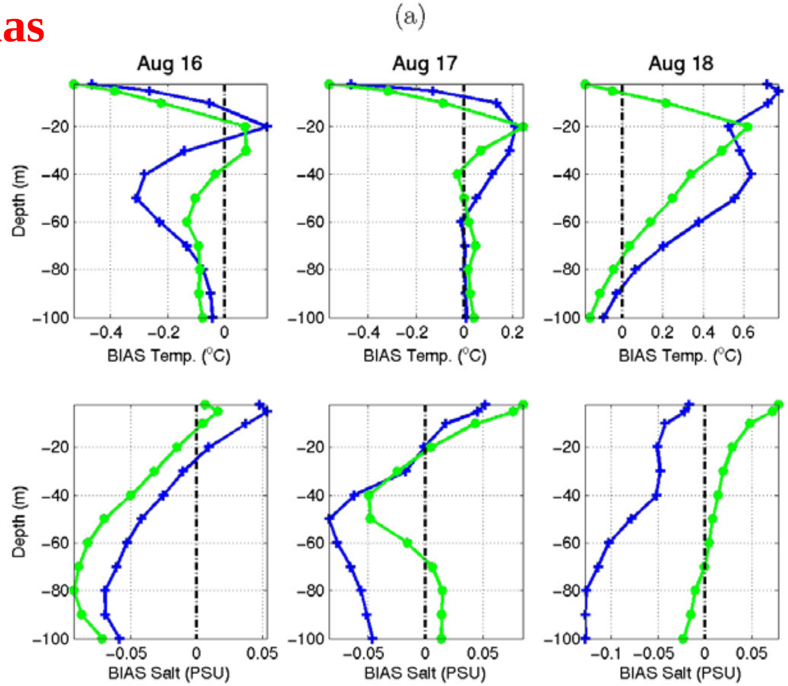
ν_0: shear viscosity at zero local gradient Richardson number (cm^2/s)

K_v^e: eddy diffusion for tracers within the wind-mixing depth h^e (cm^2/s)

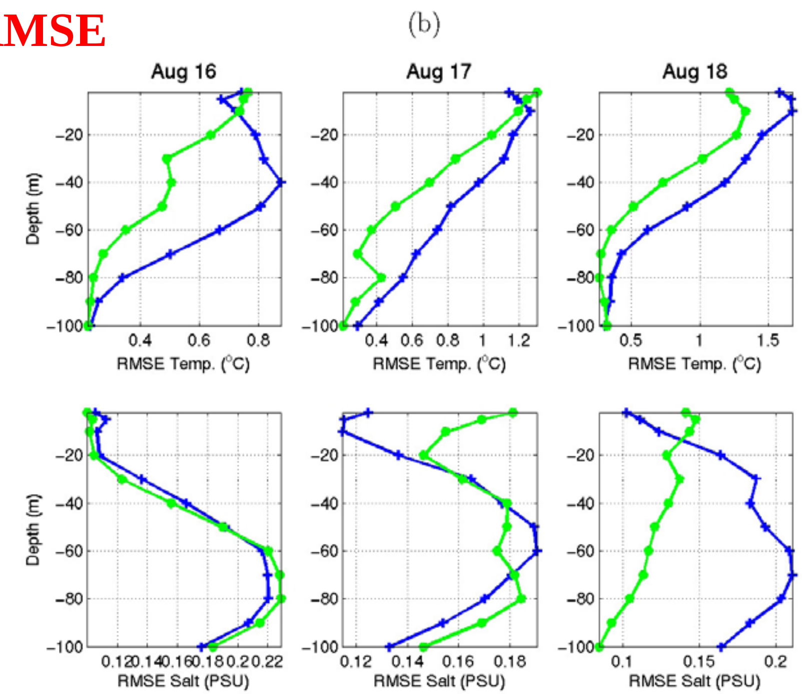
E_k: Ekman depth factor

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

Bias



RMSE



PCC

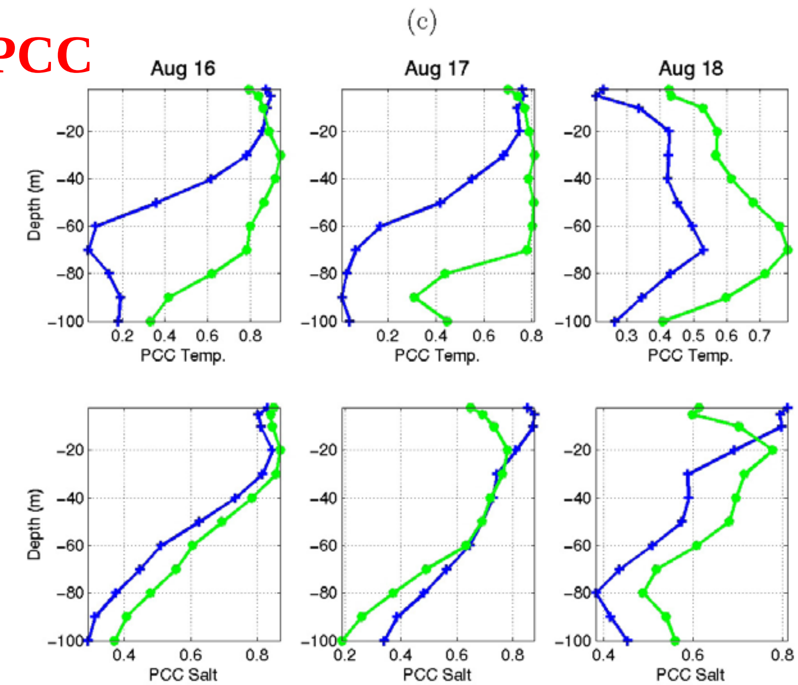


Fig. 2. Comparison between real-time un-adapted (blue lines with a plus at each data point) and real-time adapted (green lines with filled circles) physical ocean model. (a) Bias estimate (Model - OAed data) for temperature and salinity, as a function of depth (m) and time (day). (b) As (a), but for 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.

Fig. 3. Differences between the objectively analyzed (OAed) temperature data and the real-time un-adapted (left column) and real-time adapted (right column) temperature forecasts at 30 m, for Aug 16 (top), 17 (middle) and 18 (bottom), 2003. Differences are shown only where the expected error standard deviation of the OAed data is less then 30%. The region plotted varies from day to day, following glider motions.

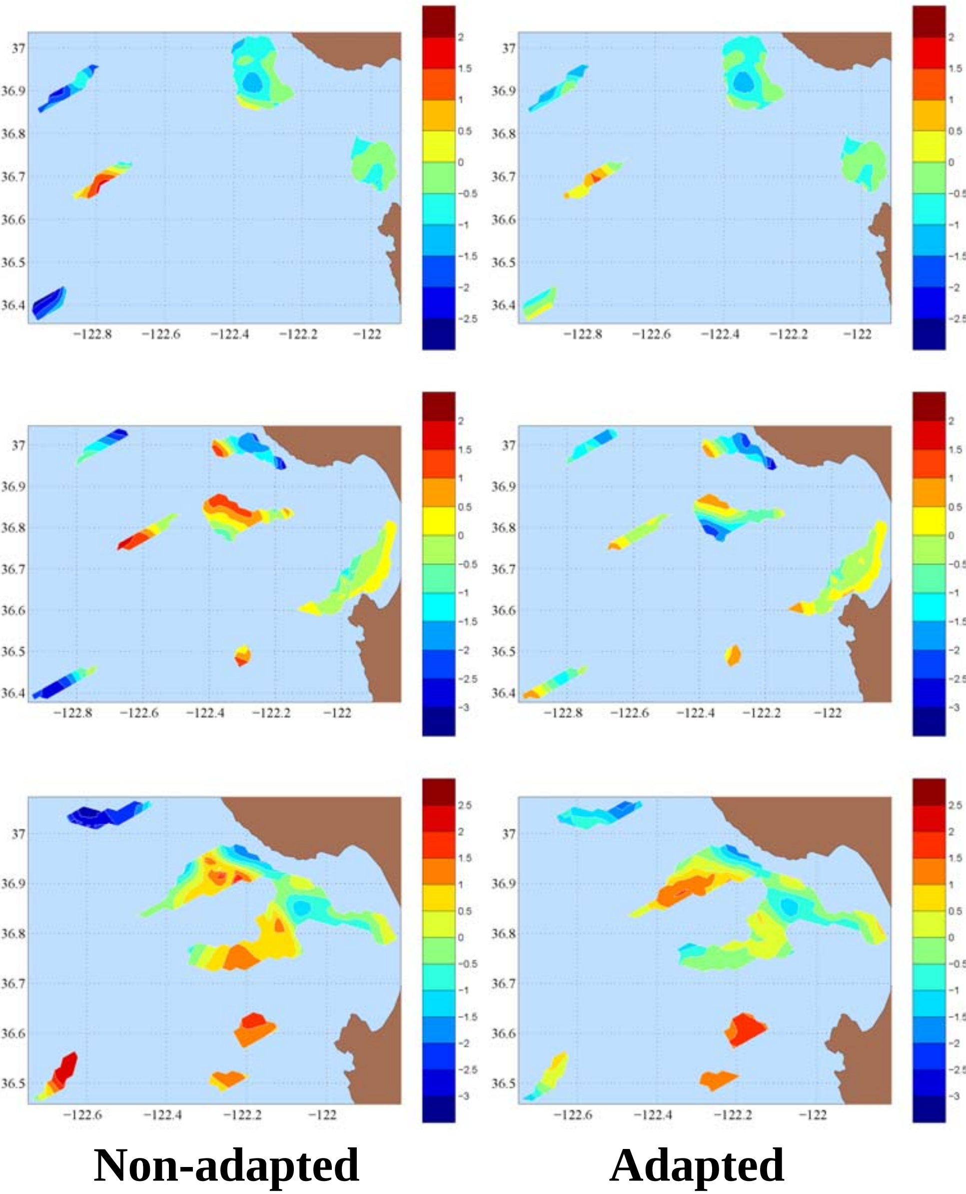
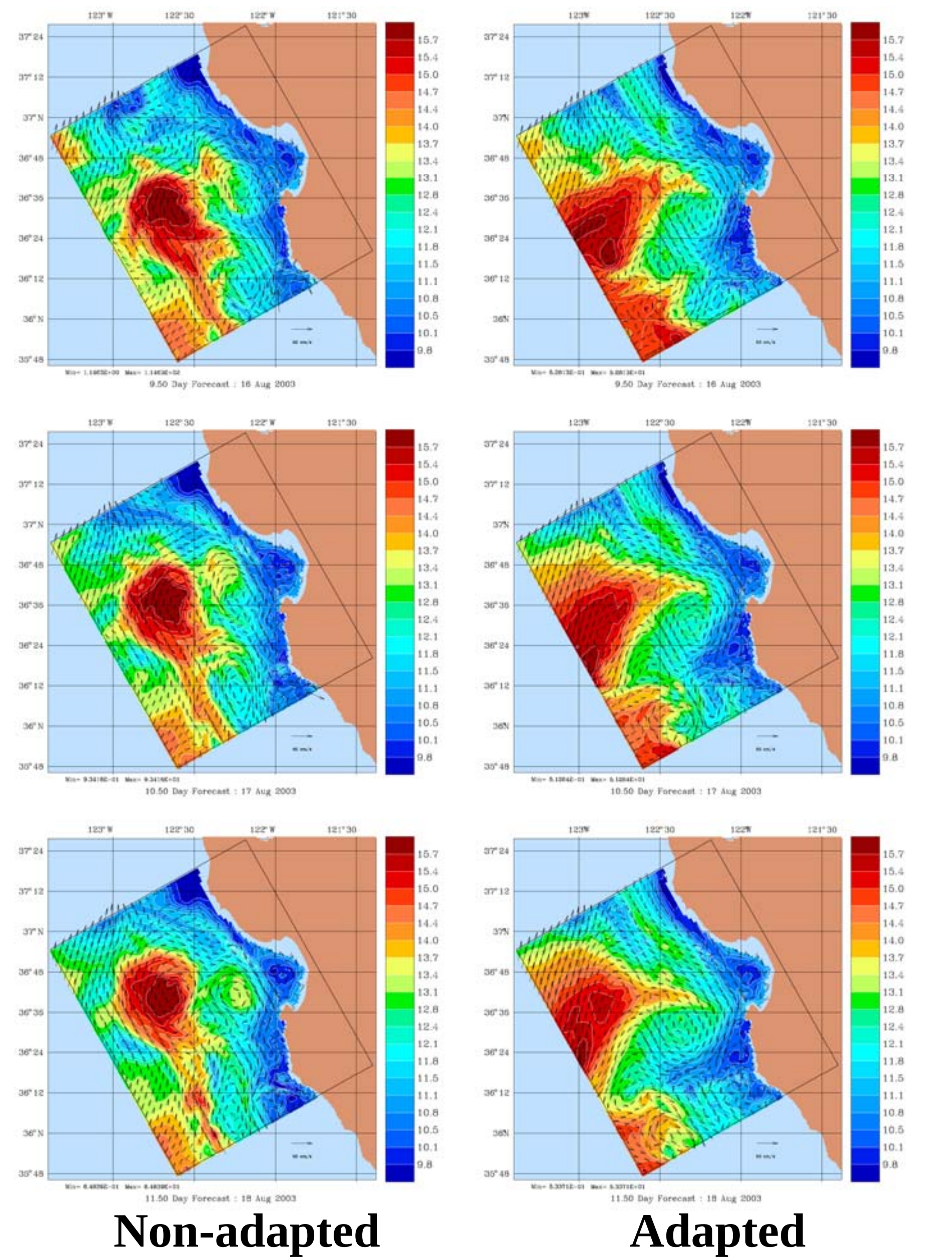
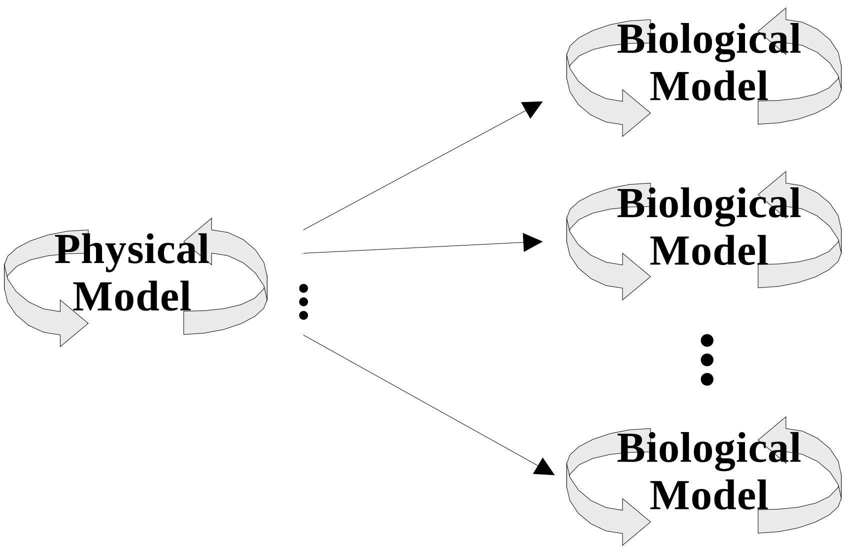
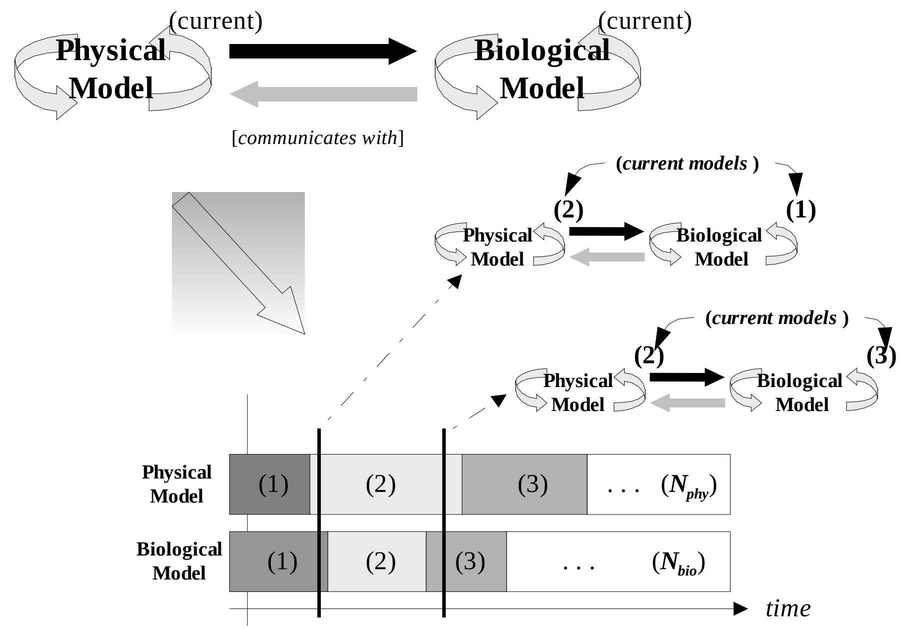


Fig. 4. Real-time un-adapted (left column) and real-time adapted (right column) temperature forecasts at 30 m, for Aug 16 (top), 17 (middle) and 18 (bottom), 2003.



Towards Real-time Adaptive Coupled Models





- Different Types of Adaptive Couplings:
  - Adaptive physical model drives multiple biological models (biology hypothesis testing)
  - Adaptive physical model and adaptive biological model proceed in parallel, with some independent adaptation
- Ongoing and Future Numerical Implementation
  - For performance and scientific reasons, both modes are being implemented using message passing for parallel execution
  - Mixed language programming (using C function pointers and wrappers for functional choices)

Oceanic Adaptive Sampling: Multiple Facets

Foci	- Optimal ocean science (Physics, Acoustics and/or Biology) - Demonstration of adaptive sampling value, etc.
Objective Fields	i. Maintain synoptic accuracy (e.g. upwelling, atmos.-ocean boundary layer) ii. Minimize uncertainties (e.g. uncertain ocean estimates), or iii. Maximize the sampling of expected events (e.g. start of upwelling/ relaxation, dynamics of upwelling filament, small scales/model errors) Multidisciplinary or not Local, regional or global, etc.
Time and Space Scales	i. Tactical scales (e.g. minutes-to-hours adaptation by each glider/AUV) ii. Strategic scales (e.g. hours-to-days adaptation for glider/AUV group/cluster) iii. Experiment scales
Assumptions	- Fixed or variable environment (w.r.t. asset speeds) - Objective field depends on the predicted data values or not - Operational, time and cost constraints, or not, etc.
Methods	Bayesian-based, Nonlinear programming, (Mixed)-integer programming, Simulated Annealing, Genetic algorithms, Neural networks, Fuzzy logics

For each of the 5 categories, there are multiple choices (only a few listed here)
Choices set the type of adaptive sampling research

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:	$y = H(x) + \varepsilon$	$\varepsilon \sim N(0, R)$

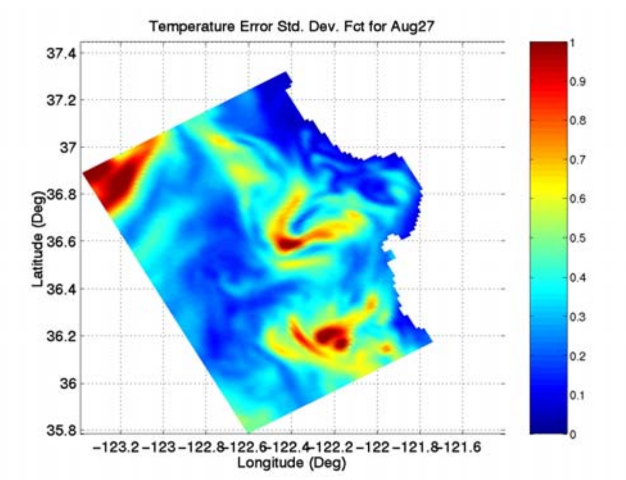
Non-lin. Err. Cov.:

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

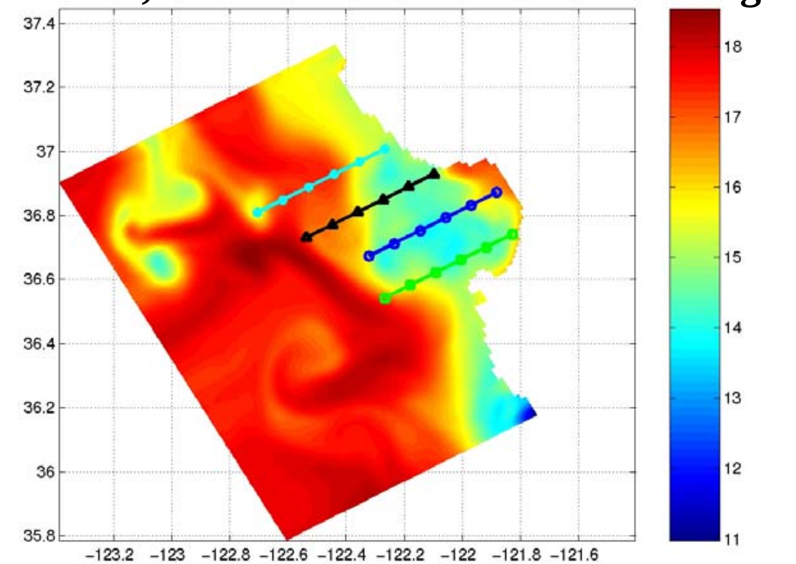
Metric or Cost function: e.g. Find future H_i and R_i such that

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

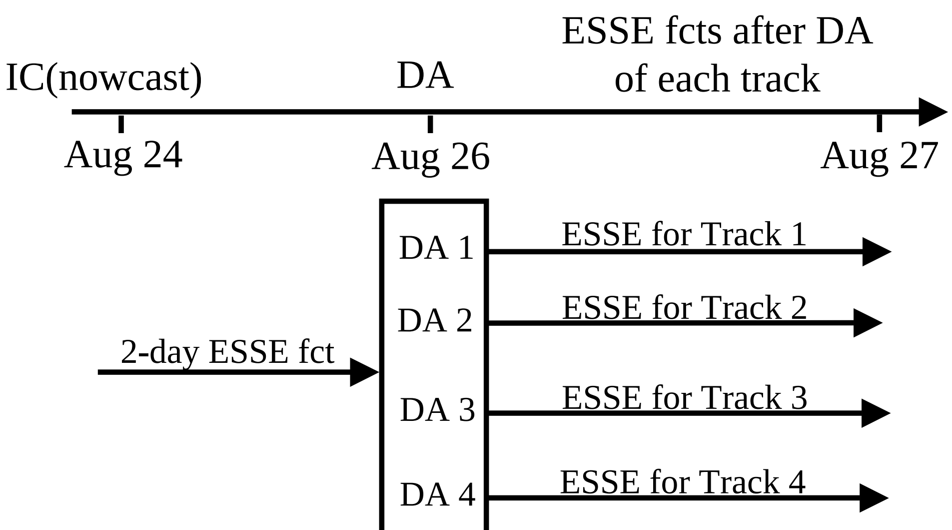
Which sampling on Aug 26 optimally reduces uncertainties on Aug 27?



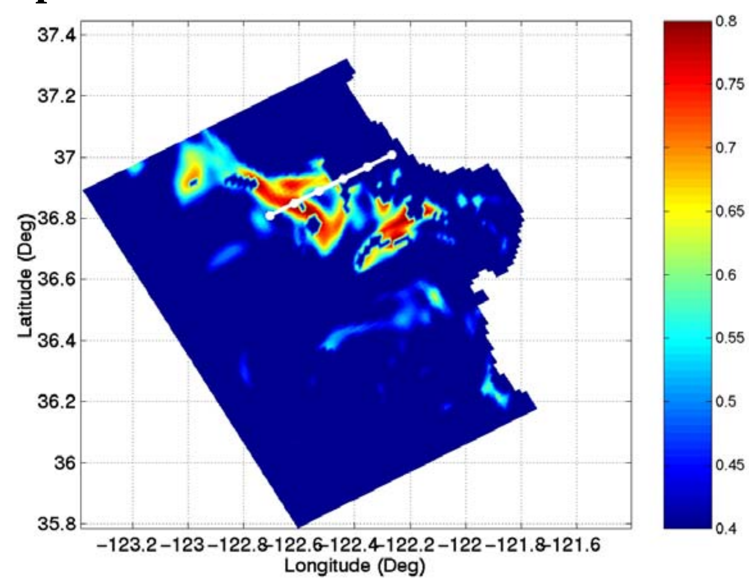
4 candidate tracks, overlaid on surface T fct for Aug 26



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



Best predicted relative error reduction: track 1



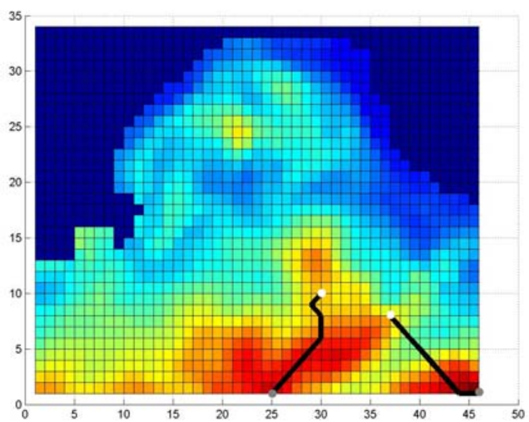
b. Optimal Paths Generation for a "fixed" objective field

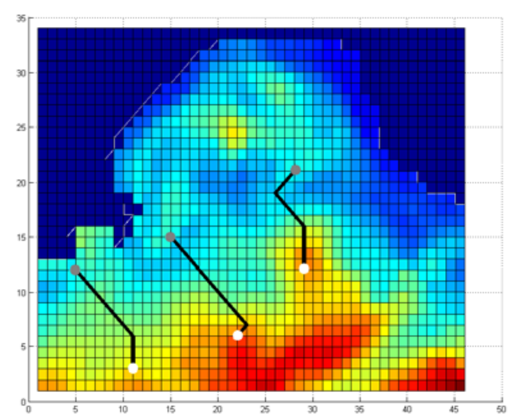
(Namik K. Yilmaz, P. Lermusiaux and N. Patrikalakis)

- 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

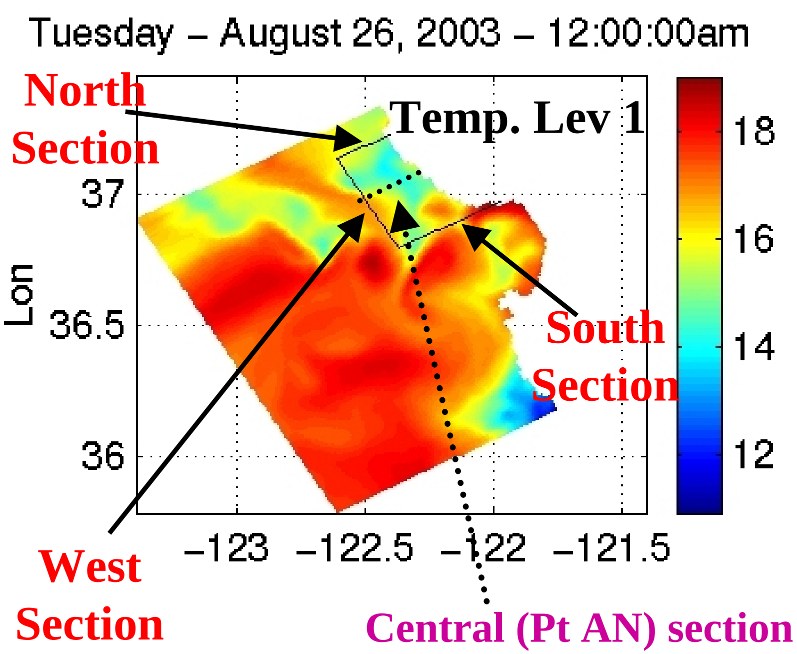




c. Dynamics Objective Fields: Flux and/or Term-by-term Balances

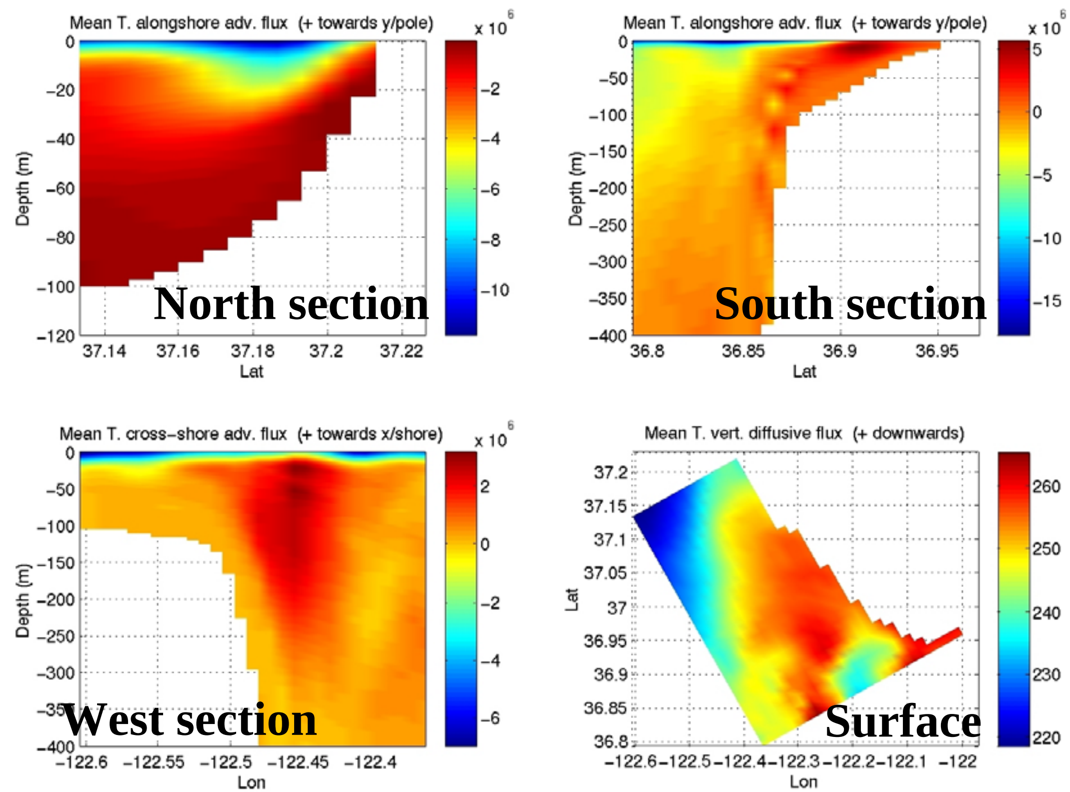
- **Physical model: Primitive-Equation (PDE, x, y, z, t: HOPS)**

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	$\rho(\mathbf{r}, z, t) = \rho(T, S, p_w)$



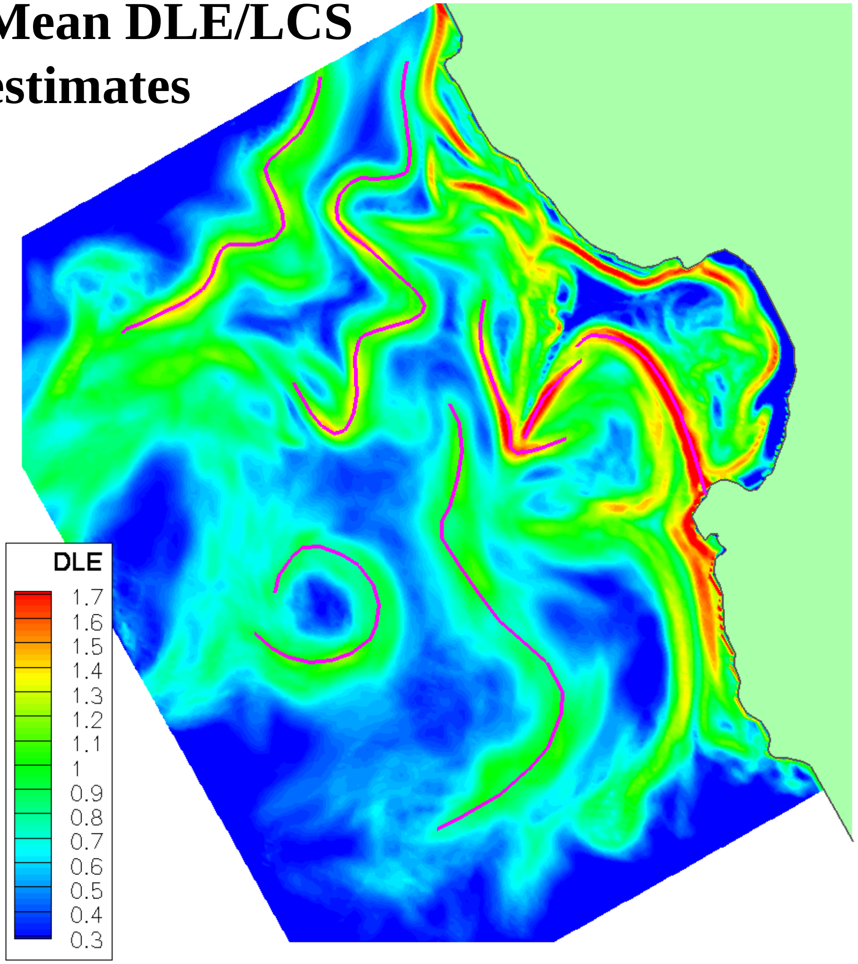
Heat Flux Balances: 4 fluxes normal to each side averaged over first upwelling period

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

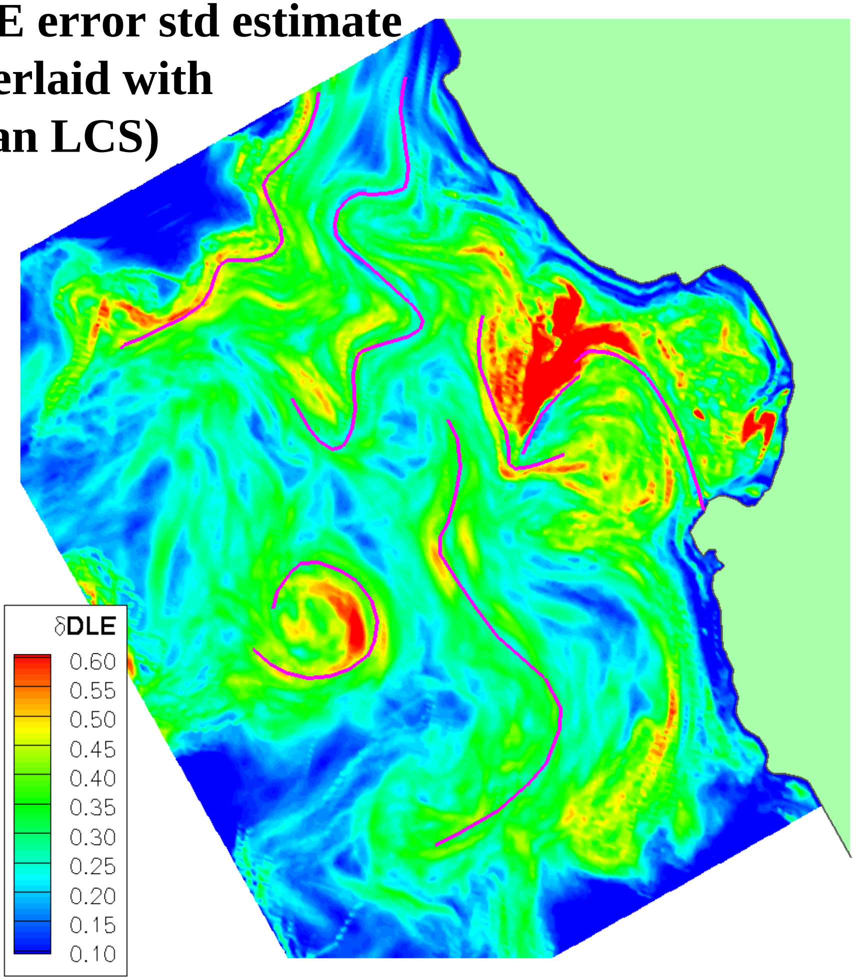


d. Dynamics Objective Fields: Lagrangian Coherent Structures and their Uncertainties for the Aug 26-29, 2003 Upwelling Period

Mean DLE/LCS estimates



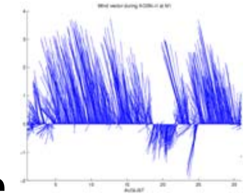
DLE error std estimate (overlaid with mean LCS)



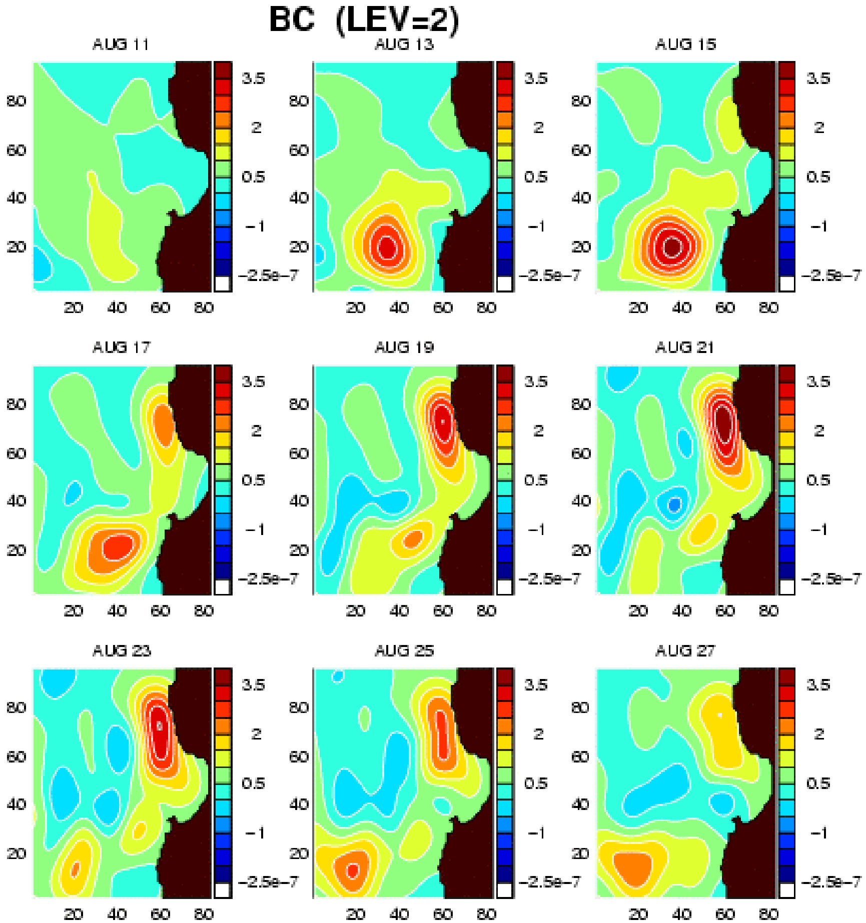
See: Lermusiaux and Lekien, Aug. 2005, In press.
for "Dynamical System Methods in Fluid Dynamics", Oberwolfach, Germany.

e. Dynamics Objective Field: M-S. Energy and Vorticity Analysis

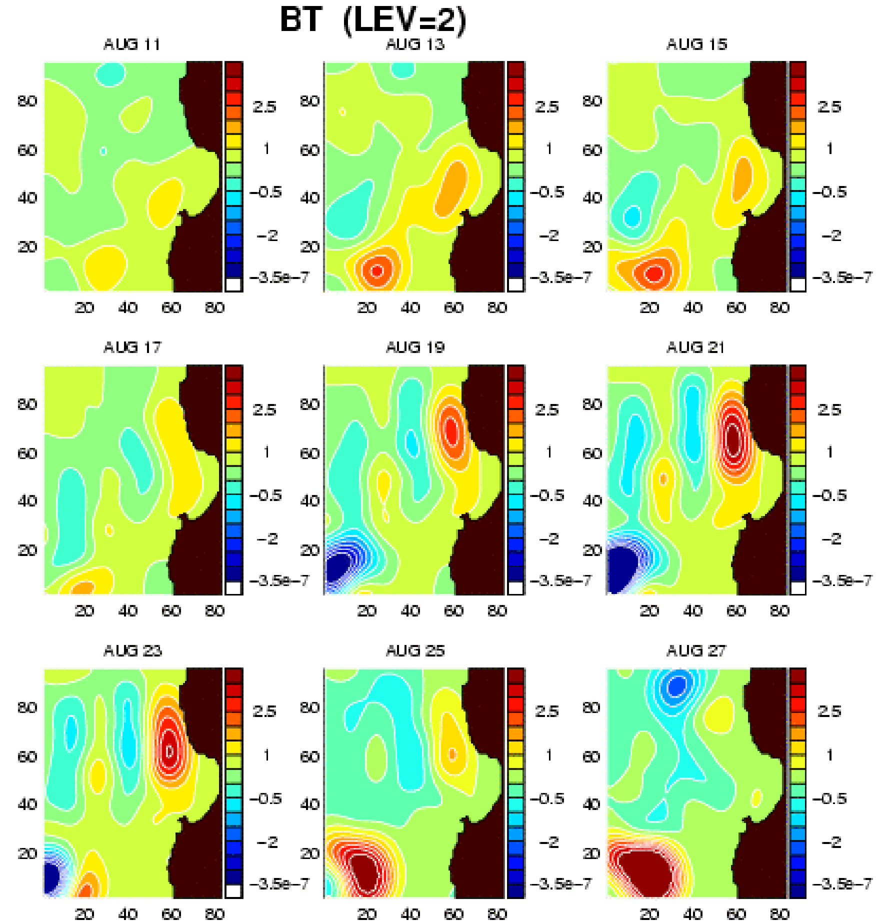
Two-scale window decomposition in space and time of energy eqns: 11-27 August 2003



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 Liang

Undersea Surveillance Seascape

Tom Curtin et al, ONR

ONR 31/32/33/35/NRL Team Efforts

Sensors
Energy
Comms
Navigation
Control
Modeling

6.1 *Adaptive Mobile Networks*

Targeted observations
Cooperative behavior

Adaptive gain
Clutter/Noise suppression

Four dimensional target discrimination
Mobile sensor environmental adaptation

Adaptive Sampling and Prediction Using Mobile Sensing Networks (ASAP)

Autonomous Wide Aperture Cluster for Surveillance (AWACS)

Undersea Persistent Surveillance (UPS-PLUSNet)

6.2 *Adaptive Mobile nodes*

Undersea Persistent Glider Patrol / Intervention (Sea Sentry)

Target interdiction with mobile sensors

Undersea Bottom-stationed Network Interdiction (CAATS)

Fixed surface nodes

Persistent Ocean Surveillance (POS)

Congressional Plus-ups

Component technologies

ONR/DARPA/NAVSEA SBIR efforts

6.3 *Trip wires, track and trail*

Littoral Anti-Submarine Warfare (FNC)

Fixed bottom nodes

Autonomous Operations (FNC)

Adaptive path planning

Persistent Littoral Undersea Surveillance (PLUS) (INP)

Prototype system integration and testing

ONR Team-Efforts (co-PI: Harvard U.)

ONR
DARPA
NAVSEA
Italics: potential new program

PMS-403
PEO-LMW
Submarine T&T

Task Force ASW
PEO-IWS
Theater ASW BAA

Persistent Littoral Undersea Surveillance Network (PLUSNet)

Lead: Kuperman, Schmidt et al.

End-to-end System components

- Adaptive Tactical and Environmental 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

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

Physical-Acoustical Predictions and Adaptive Sampling

P.F.J. Lermusiaux, D. Wang (MIT)
P.J. Haley, Jr., W.G. Leslie,
H. Schmidt et al.

FAF'05:
July 11-29, 2005
Isola di Pianosa, Italy

Thanks to:

NURC: **E. Coelho, E. Nacini, A. Cavanna, P. Ranelli**

Cro. Met. Service: **M. Tudor**

HU: **A. Robinson**

FAF05 Goals and Accomplishments

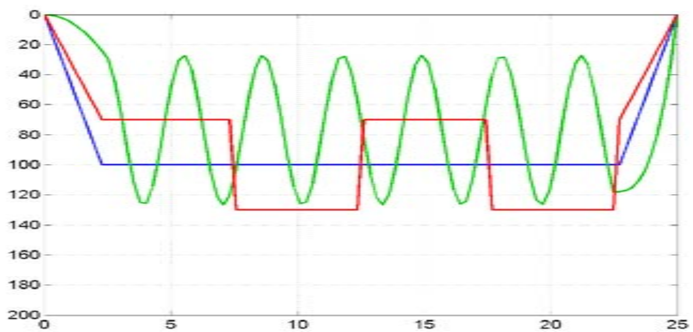
1. **Initiate and test the coupling of HOPS, ESSE (HU) and AREA (MIT)**
2. **Issue physical-acoustical adaptive sampling recommendations every day**
   - Capture the vertical variability of the thermocline (due to fronts, eddies, internal waves, etc)
   - Minimize the corresponding uncertainties.

Adaptive sampling plans computed based on 1-to-2 days forecasts of physical-acoustical fields and uncertainties

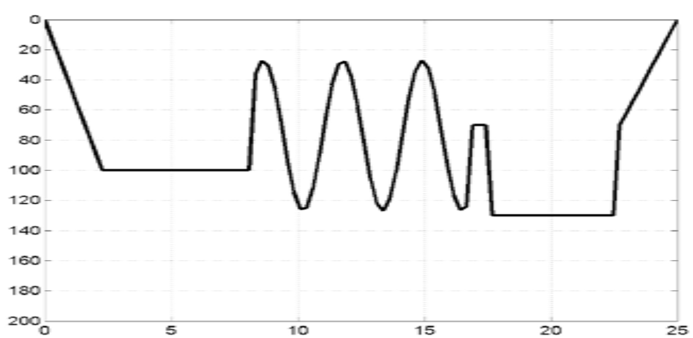
Adaptive Sampling in Vertical Cross-Sections

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

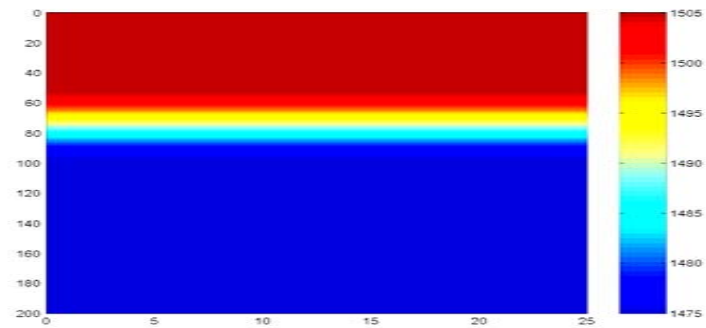
Base Lines



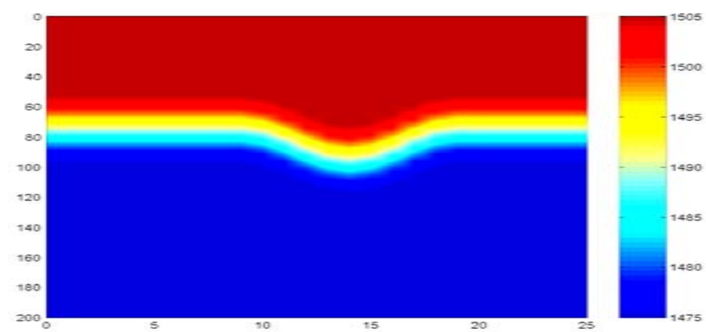
Composite Base Lines



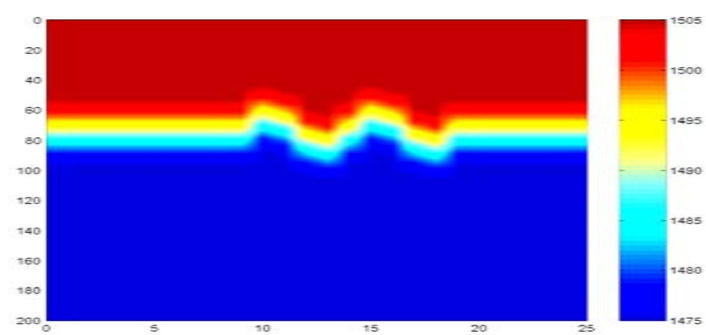
Thermocline



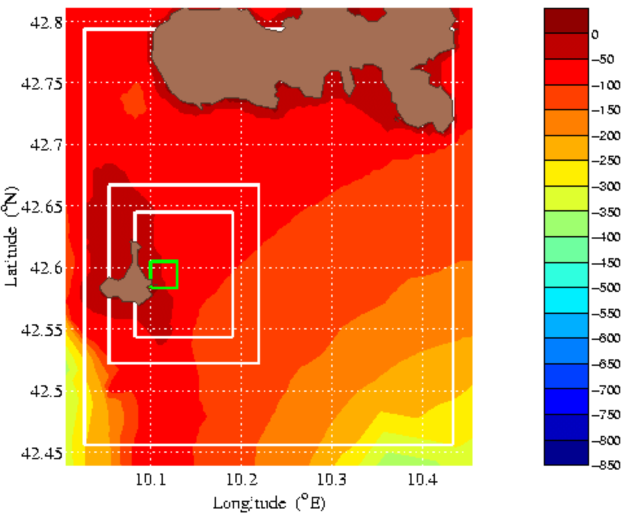
Eddy

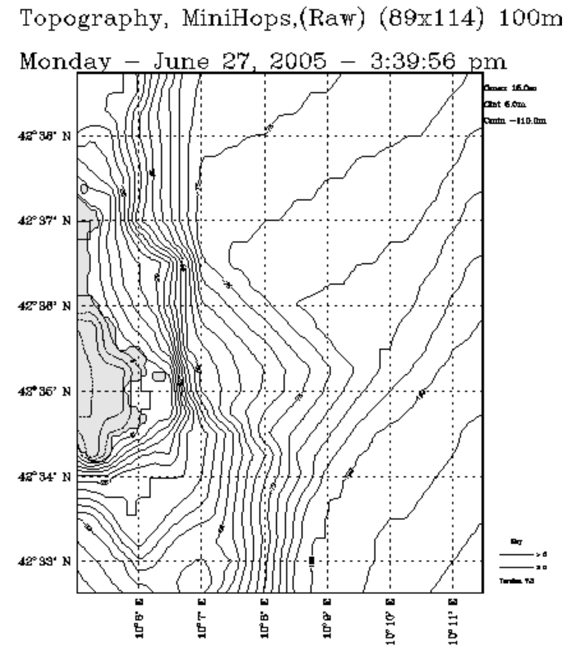


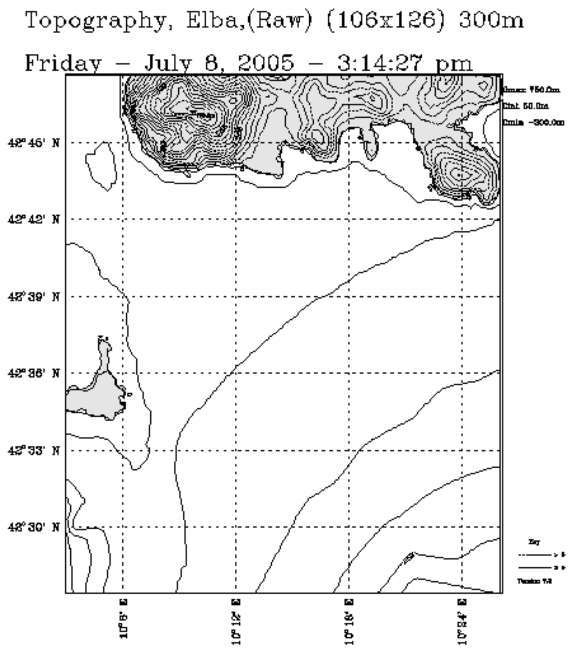
Internal Wave



High-Resolution Nested Ocean Modeling Domains

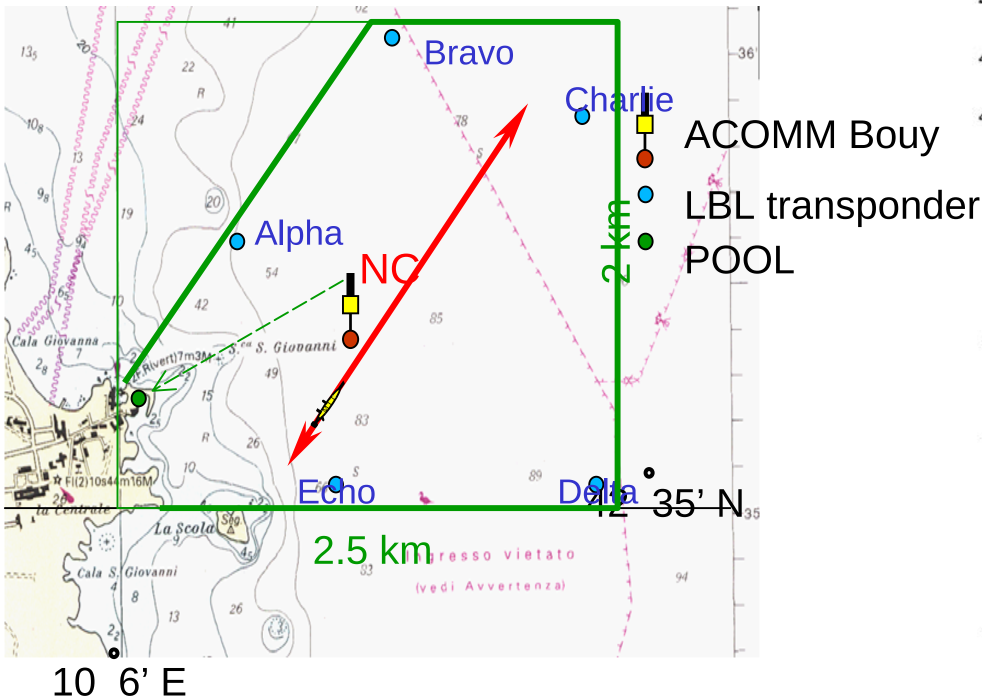


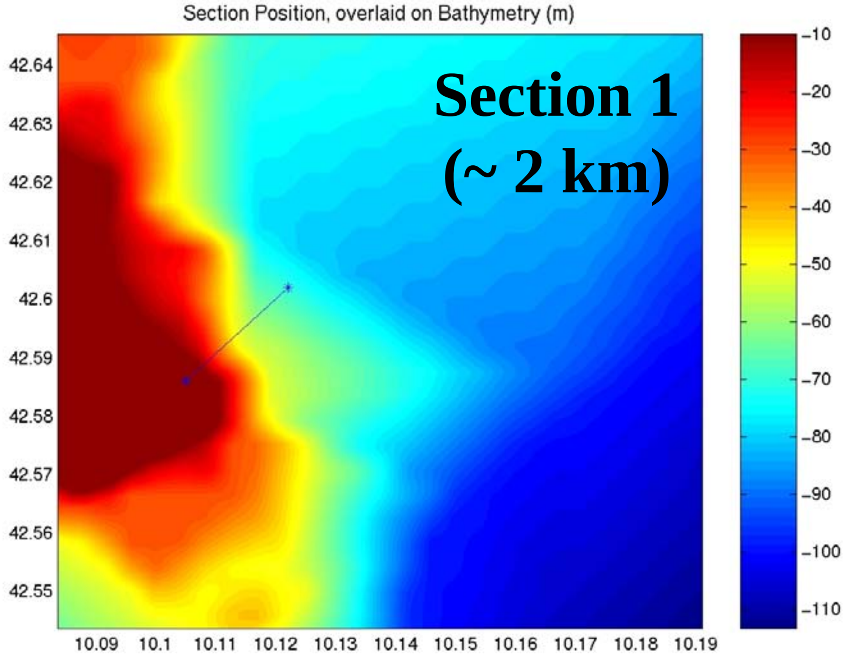


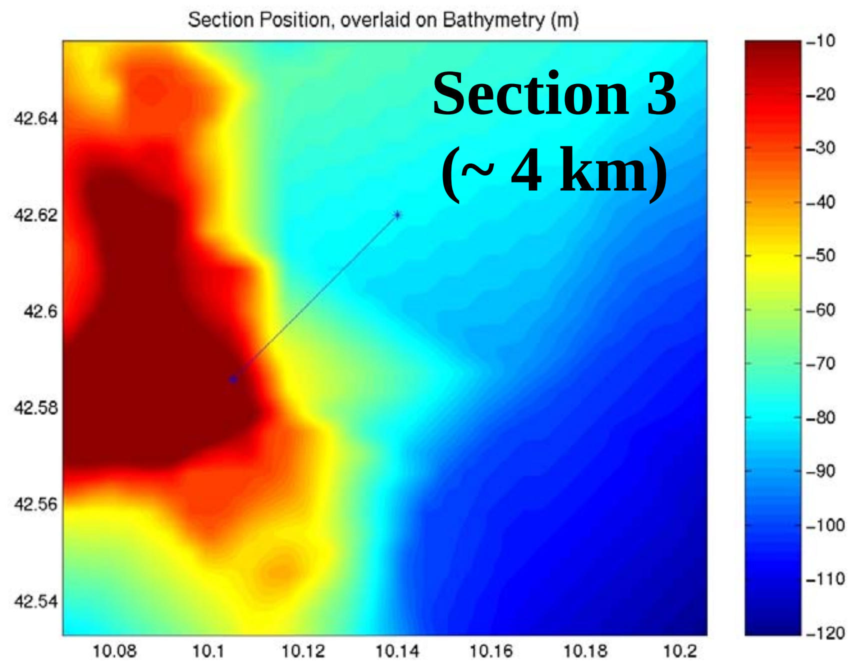


		Mini-HOPS	Elba
Resolution		**100m**	**300m**
Size	*nx × ny × nz*	89×114×21	106×126×21
	Extent	8.8×11.3 km	31.5×37.5 km
Domain center		42.59°N, 10.14°E	42.63°N, 10.24°E
Domain rotation		0°	0°
Speed	*dt=50s*	90 minutes/(model day)	120 minutes/(model day)
	dt=300s	15 minutes/(model day)	20 minutes/(model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

Characteristic Acoustic Sections





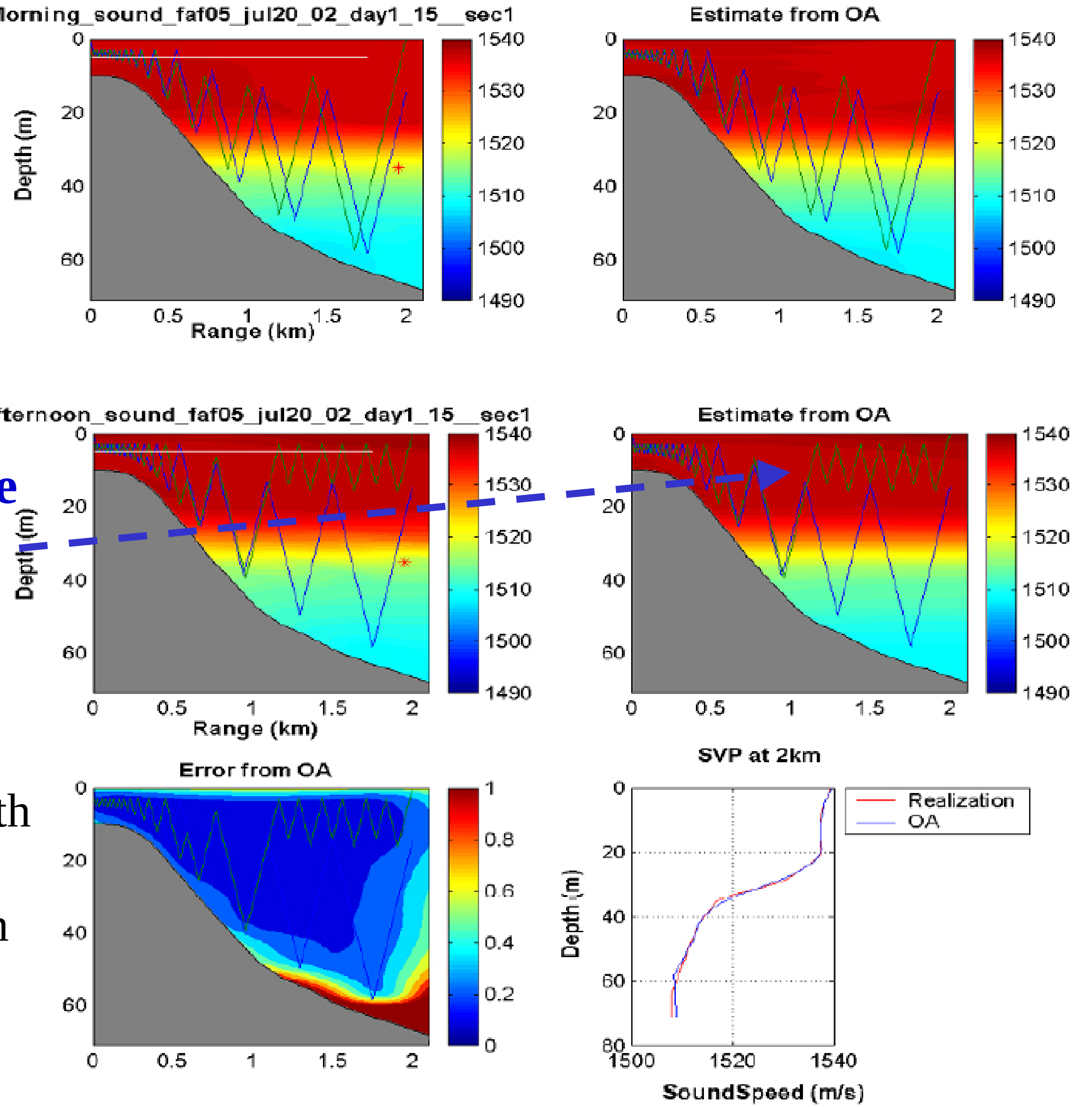


Example of Results of Adaptive Yoyo Control (Jul 20-21)

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

Multiscale Dependences of Coupled Ocean-Atmosphere Processes

- On atmos. large-scale, ocean SST usually negatively correlated to surface winds
- On atmos. mesoscales (100-3000 km), “ positively “ (Chelton et al, 2004)
- On atmos. sub-mescocales, ???

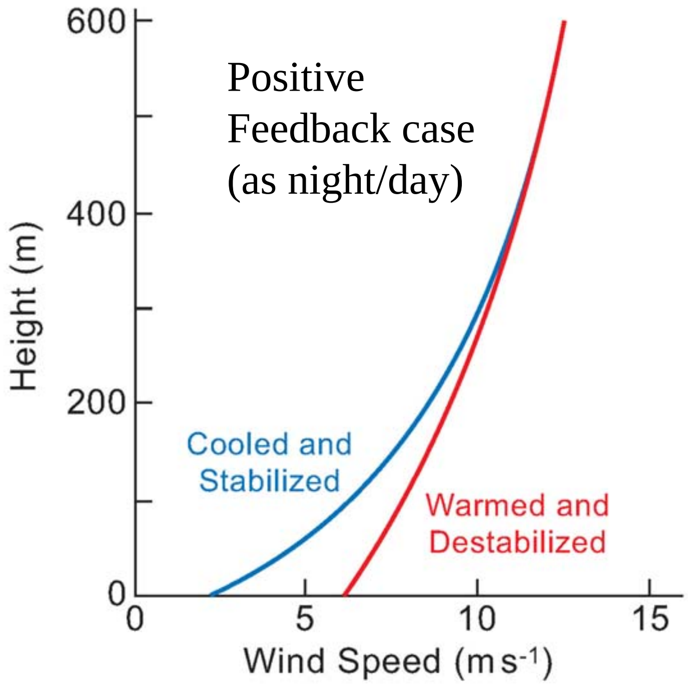


Fig. S5. Schematic illustration of wind variations in the marine atmospheric boundary layer (MABL) induced by small-scale features in the SST field (*S2-S4*). Cooling over cool water increases stratification and stabilizes the MABL, inhibiting vertical mixing by turbulence and convection. This decouples the surface winds from the winds aloft and increases the wind shear near the sea surface (blue curve). Heating over warm water decreases stratification and destabilizes the MABL, enhancing vertical turbulent mixing and convection. This deepens the MABL and mixes momentum downward from aloft, decreasing the wind shear near the sea surface (red curve). Deepening of the MABL over warm water has been observed directly (*S5, S6*) and inferred from satellite measurements of increased low-level cloudiness (*S7–S9*). Cooling and warming of the MABL also create an enhanced pressure gradient in the direction of the SST gradient (*S10–S12*). Small imbalances between the pressure gradient force and frictional effects from vertical turbulent mixing accelerate the flow in regions of strong downwind SST gradients, resulting in higher surface wind speeds over warm water and lower surface wind speeds over cool water.

D. Chelton et al, Science, 2004

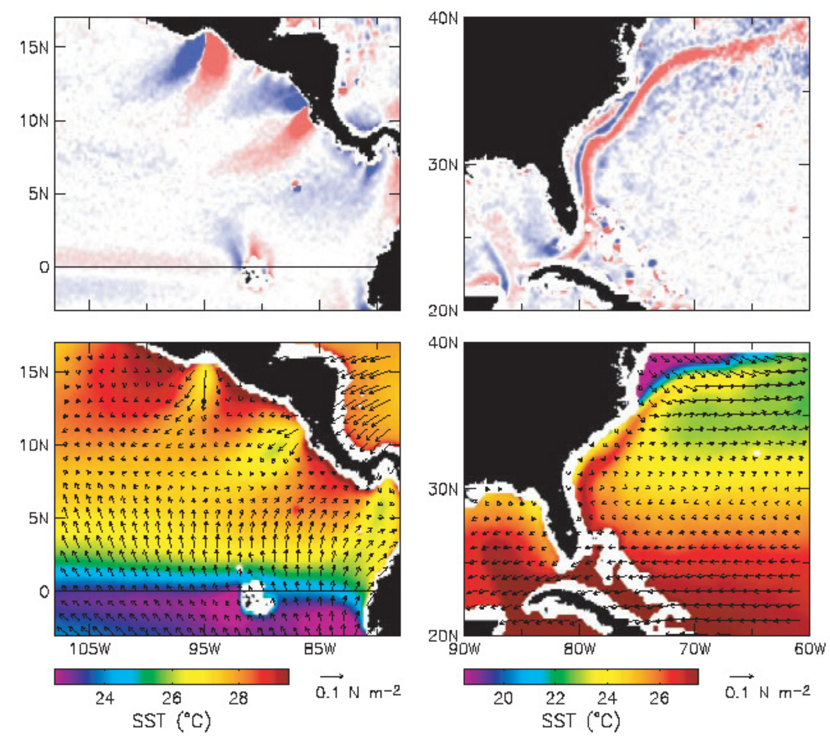


Fig. 5. Four-year averages (August 1999–July 2003) of the spatial high-pass–filtered curl of the wind stress (top) from Fig. 3 and of the SST and vector-average wind stress (bottom) for the eastern tropical North Pacific (left panels) and the western North Atlantic (right panels). The color scale for the wind stress curl is the same as in Figs. 1 to 3. The 4-year average SST fields were derived from satellite measurements by the TRMM (Tropical Rainfall Measuring Mission) Microwave Imager (TMI) (*45*). For clarity, the 25-km wind stress vectors are displayed with reduced resolution on a 1° by 1° grid. The white fringes along the continental margins are gaps in the satellite coverage (about 25 km for QuikSCAT and about 75 km for TMI) owing to land contamination of the microwave signals.

Conclusions for Coupled Air-Sea Predictions

- **Coupled Adaptive Sampling**
  - Data sets dedicated to coupled modeling are needed
  - Both -comprehensive- data sets and -targeted- data sets for specific processes
  - Can be optimized with adaptive sampling
- **Coupled Adaptive Modeling**
  - Hierarchy of modeling options need to be evaluated/tuned
  - From simple linear feedback to full fledged-models
  - Multiple types/scales of coupling: from waves to atmos. mesoscale/large-scale
  - Computational issues/research
- **Coupled atmospheric-oceanic-acoustic effects important**
  - Waves and sea surface
  - Daily cycle can be very significant, including for coastal currents and hydrography
  - Wind-curl most important for ageostrophic properties
  - Long-wave radiation
  - Impacts on multiple littoral fields: physics, biology, seabed