Harvard AOSN-II Research: Summary, Recent results and Writing plans

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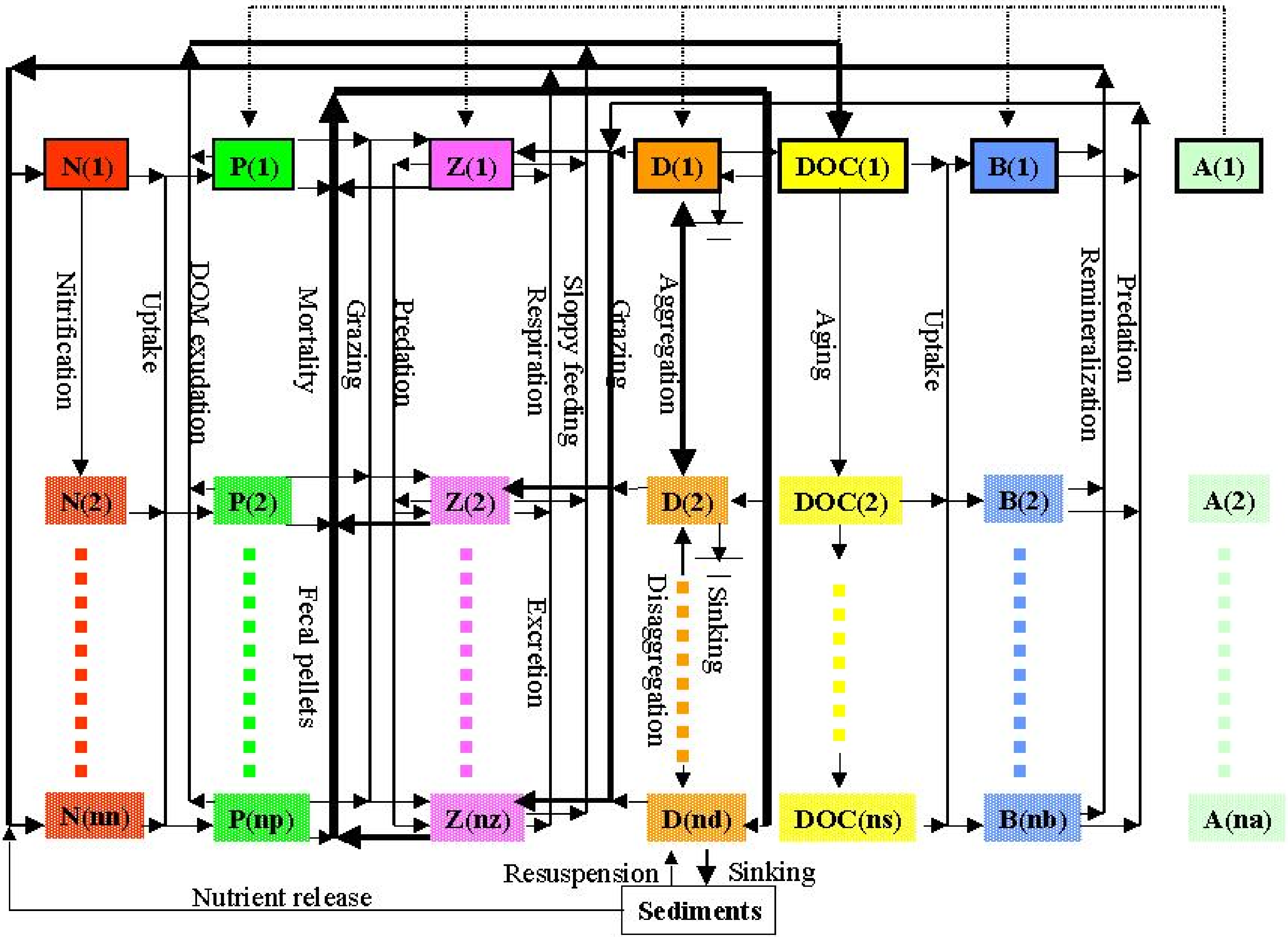
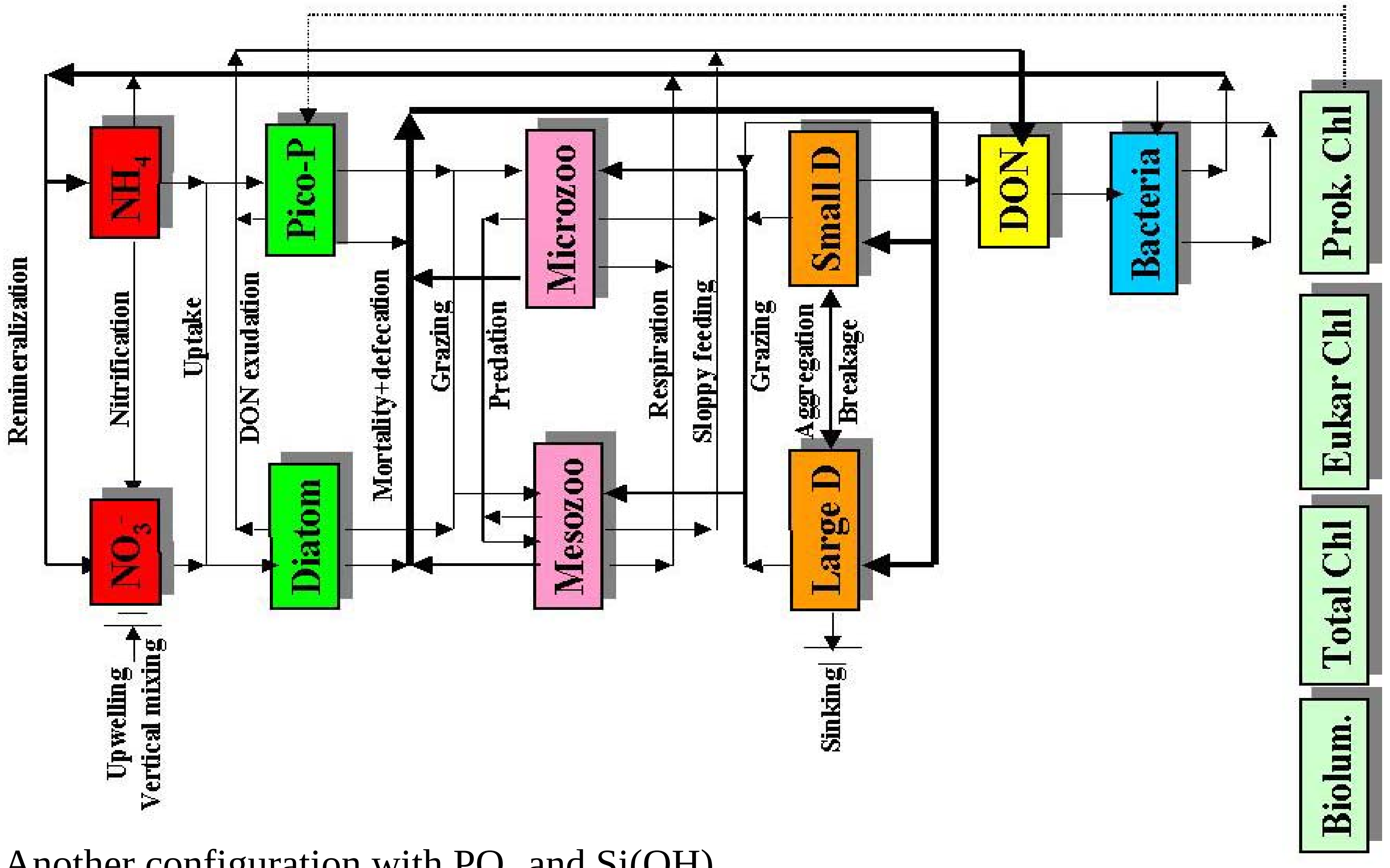
I. Generalized Adaptable Biological Model



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

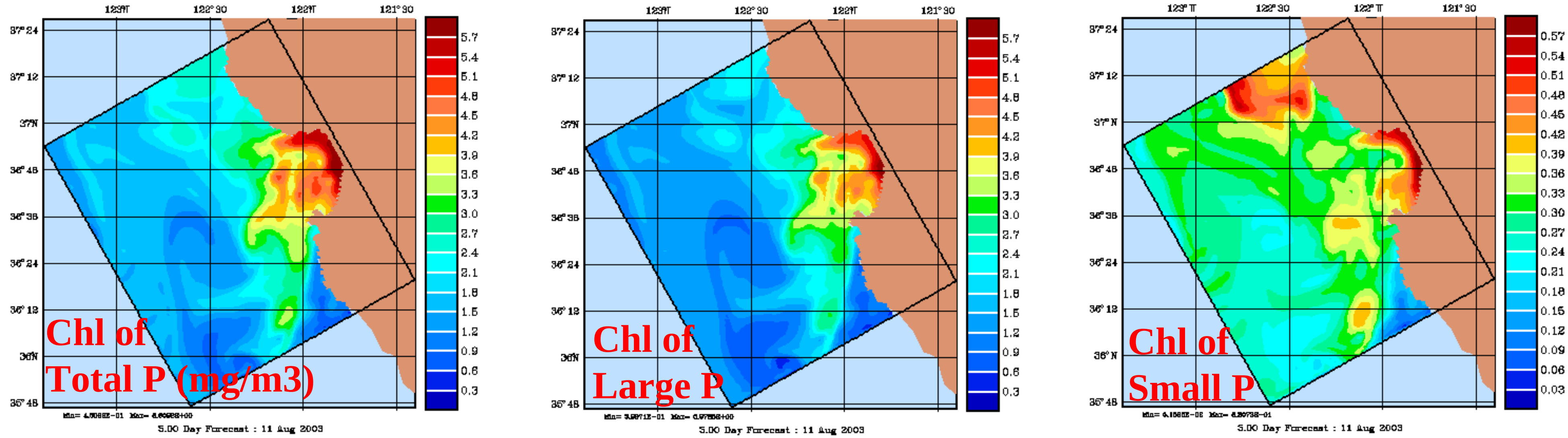
A Priori Biological Model for Monterey Bay



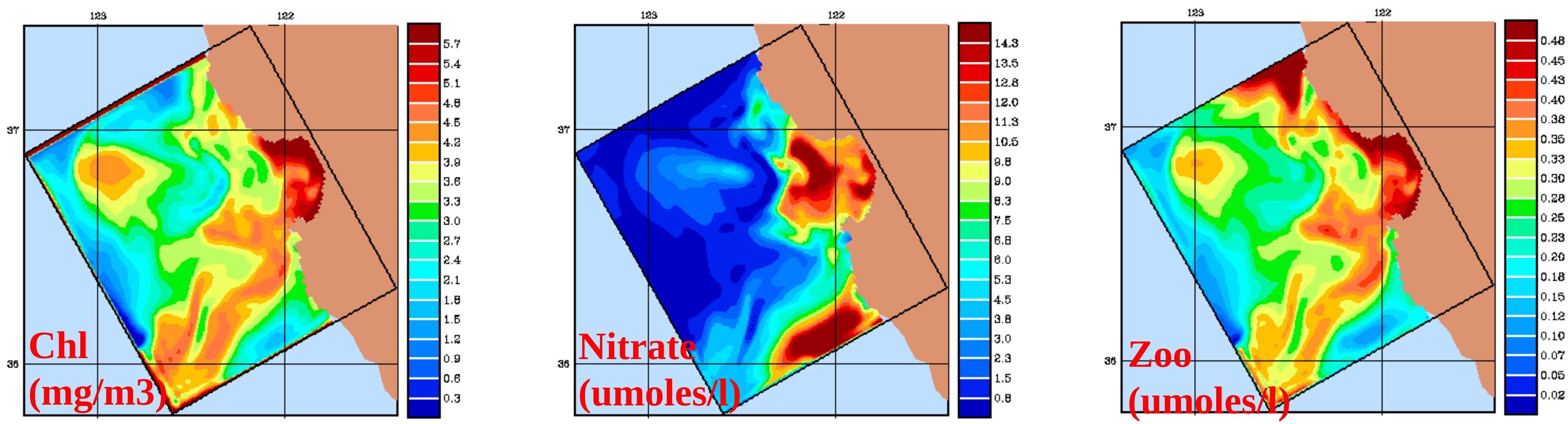
Another configuration with PO_4 and $Si(OH)_4$

Towards automated quantitative model aggregation and simplification (Older Simulations: done in Sep.-Oct. 2004)

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

A Priori Biological Modeling Set-Up

1) Field initialization

- Observed variables: Objective analysis of historical-July/Pt Sur data

Source	*Nb Profile*	*Parameters*	*Years*	*Note*
NODC	33	T, S, NO_3,Chlor	1978-1998	
CALCOFI	54	T, S, NO_3,Chlor	1964-1987	
CALCOFI	2	Mesozooplankton (monthly averaged)	1951-1985	<200m
MBARI	30	T, S, NO_3,Chlor(Monthly averaged at discrete depths & years)	1989-2002	<200m
MBARI	3	Microzooplankton (Season averaged)	1989-1998	C1, M1-2
Bauer 1998	3	DOC	1995	35°40'
Bard 1997	3	Bacteria	1993	
Ward 2001	9	Ammonium	1992-1993	Bronk 2001
AOSN II	318	Fluorescence Chlorophyll, Night casts	1-6/08/03	Haddock
AOSN II	98	Nitrate	4-6/08/03	Haddock

  - OA correlation scales: 15 km decay, 40 km zero-crossing

- Non-observed variables: Computed from statistical and dynamical (not yet) balances with observed variables (and chosen model)

2) Selection of model parameters and a priori structures/parameterizations

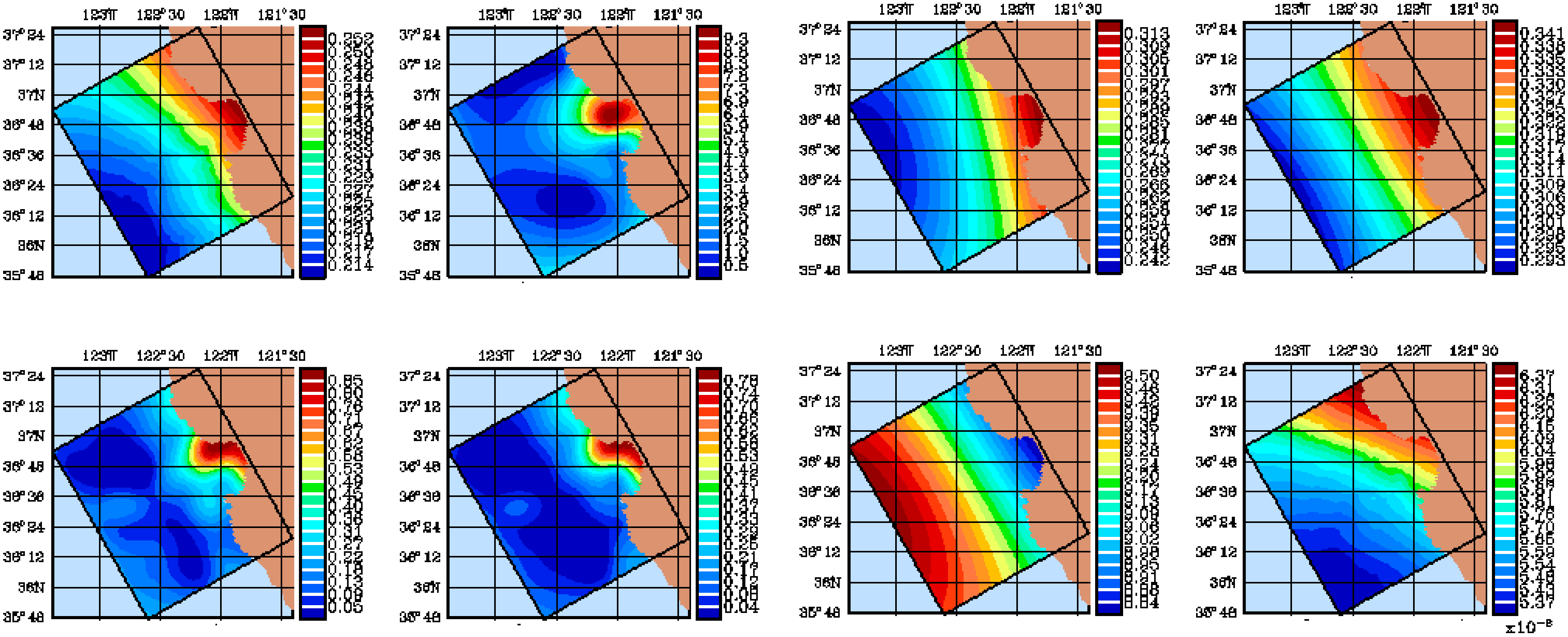
- A priori values chosen as in Olivieri and Chavez (2000) and rest of literature
- Tuning of values and functions by comparing model forecast to AOSN-II data

3) Estimation of 1) IC and 2) model parameters/structures not independent

4) Assimilation: Only physical data. No biological data assimilation yet

Initial Conditions

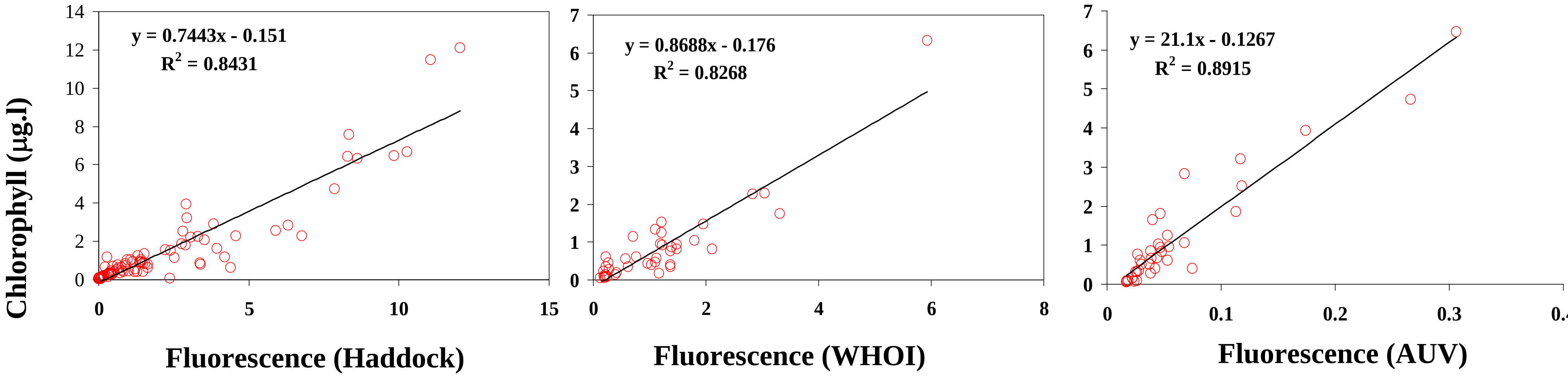
NH_4^+ **NO_3^-** **MicroZ** **MesoZ**



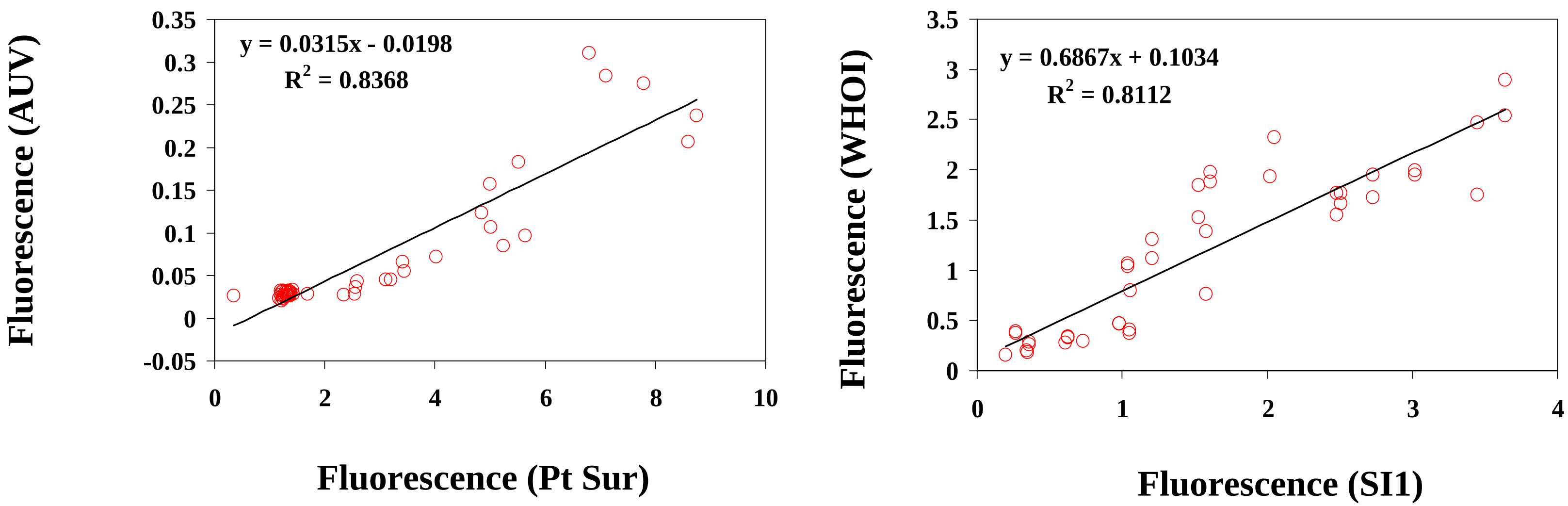
SP **LP** **DON** **Bacteria**

Determined through objective analysis (unit is in m M N m^{-3})

Chlorophyll-Fluorescence relationships

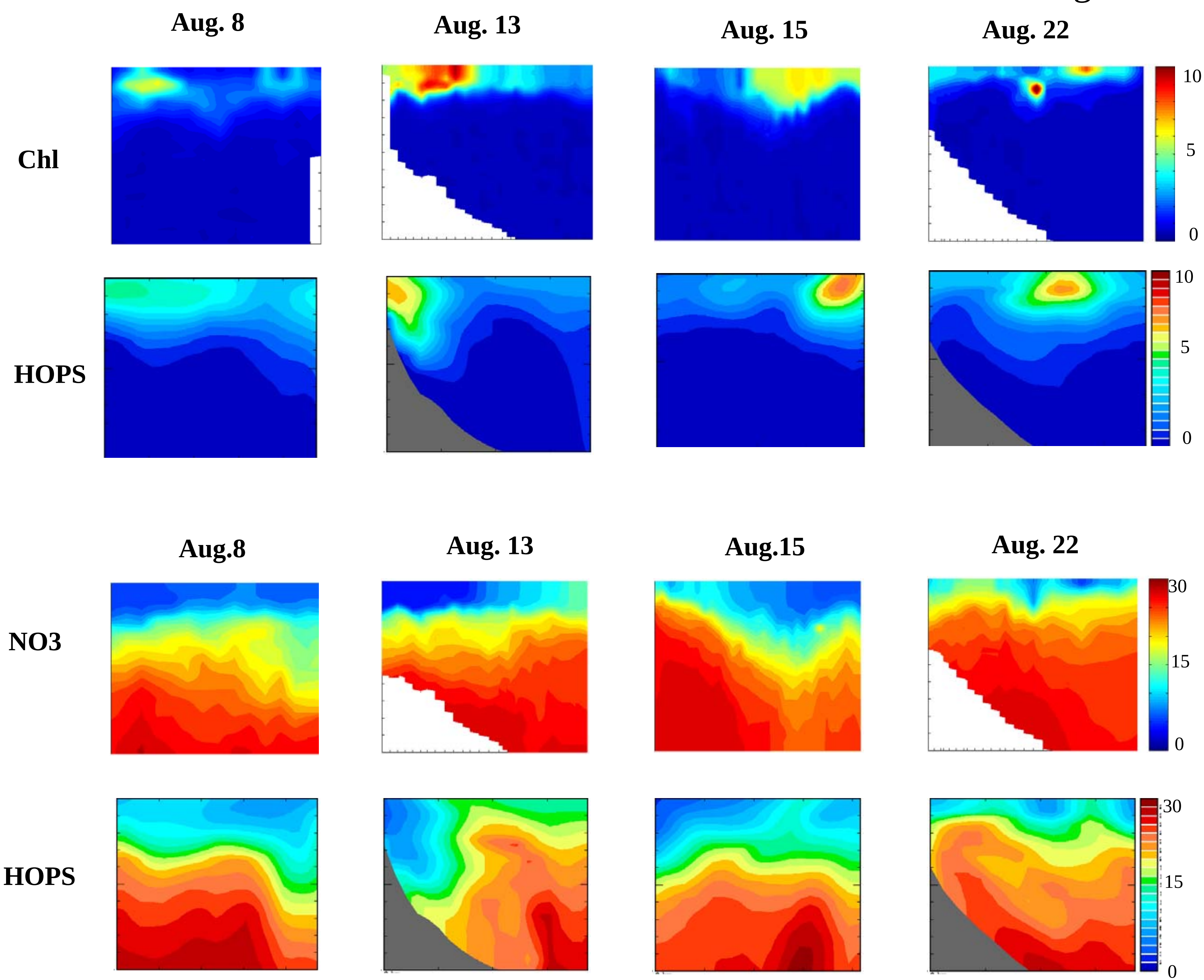


Fluorescence-Fluorescence relationships



Cross-Section in Chl μg/l and NO_3: Observations (S. Haddock et al) vs Simulations

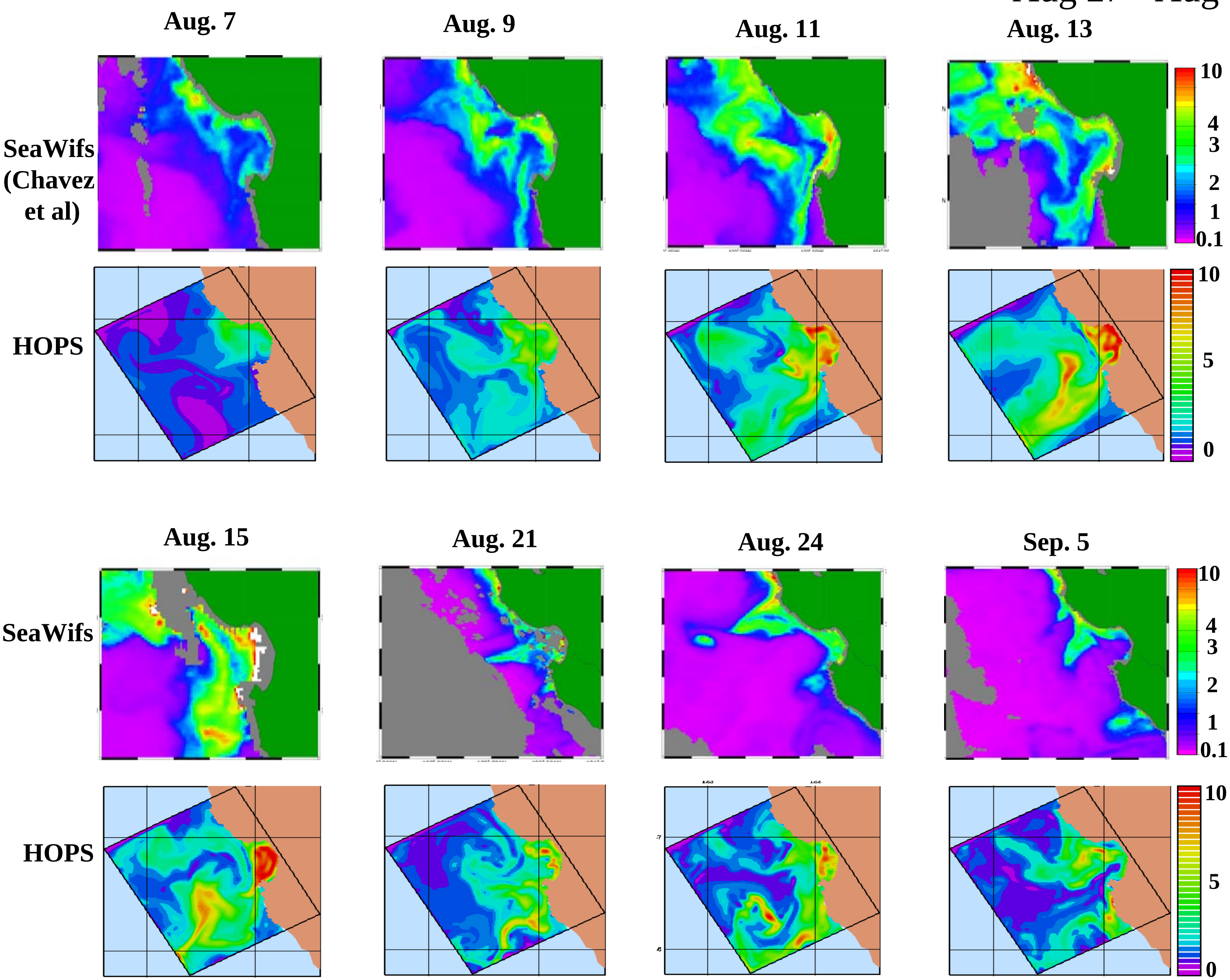
Aug 06 - Aug 18: Upwelling
Aug 19 - Aug 23: Relaxation
Aug 27 - Aug 30: Upwelling



- **Several Chl hot-spots position and amplitudes, and nutricline tilts, captured but bio. model vertical resolution not sufficient**
- **Deeper nutricline and stronger blooms during upwelling**
- **Much smaller scale hot-spots and shallower nutricline during relaxation (oceanic driven sub-mesoscales)**

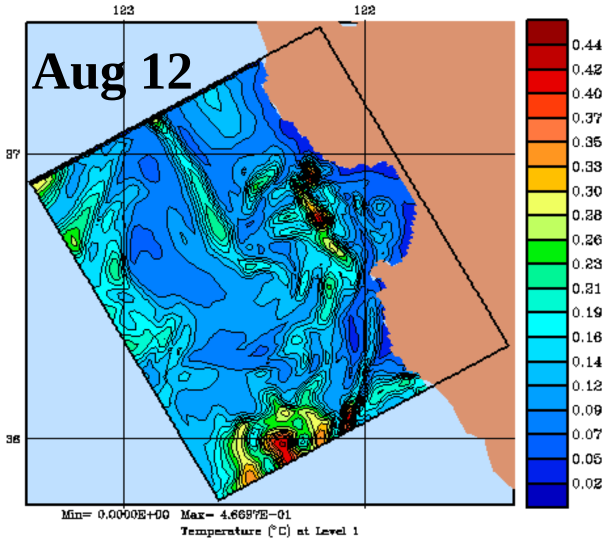
Surface Chlorophyll (μg/l): Observations versus Simulations

Aug 06 - Aug 18: Upwelling
Aug 19 - Aug 23: Relaxation
Aug 27 - Aug 30: Upwelling

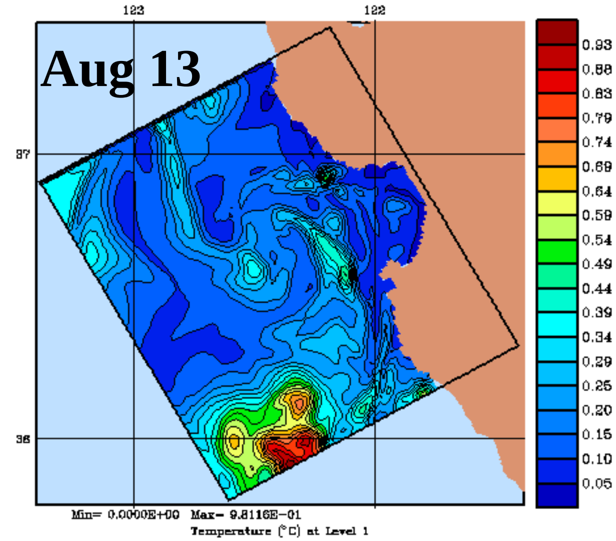


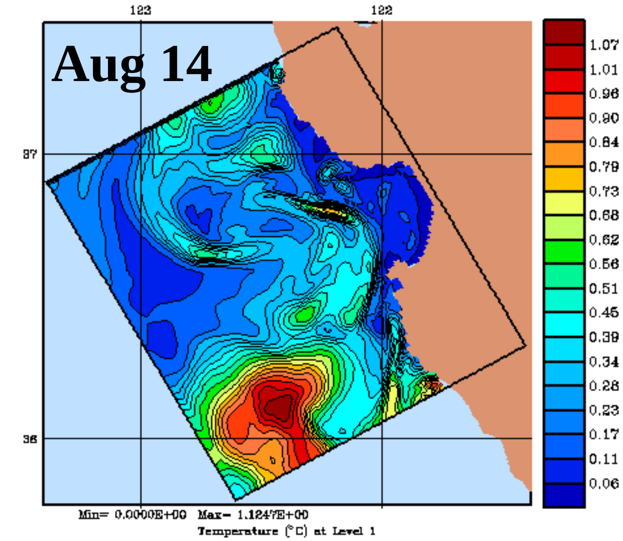
- **Several of main patterns captured but bio. production and advection offshore too strong**
- **Bio. blooms in response to establishment of cyclonic circ. in the Bay in strong or sustained upwelling both in data and model**
- **Details of biological-physical response in upwelling centers and filaments not ok**

ESSE Surface Temperature Error Standard Deviation Forecasts

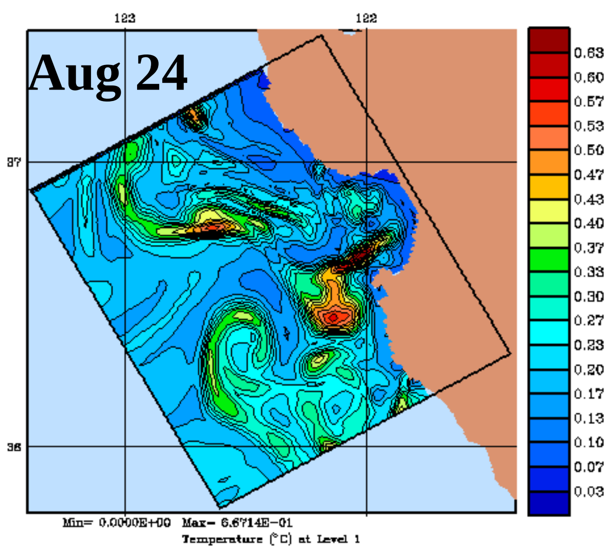


Start of Upwelling

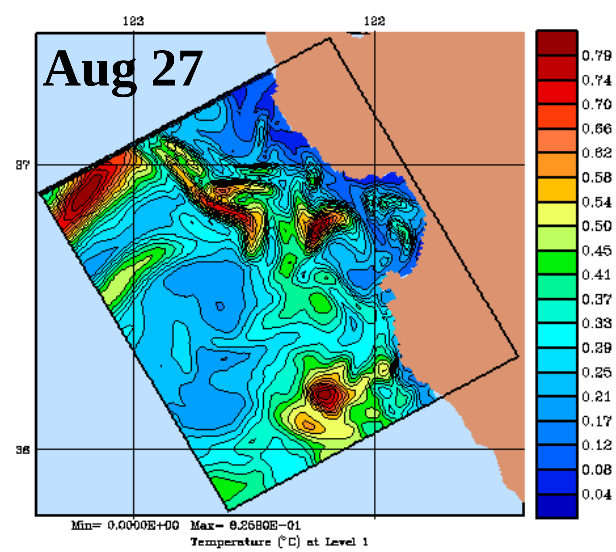


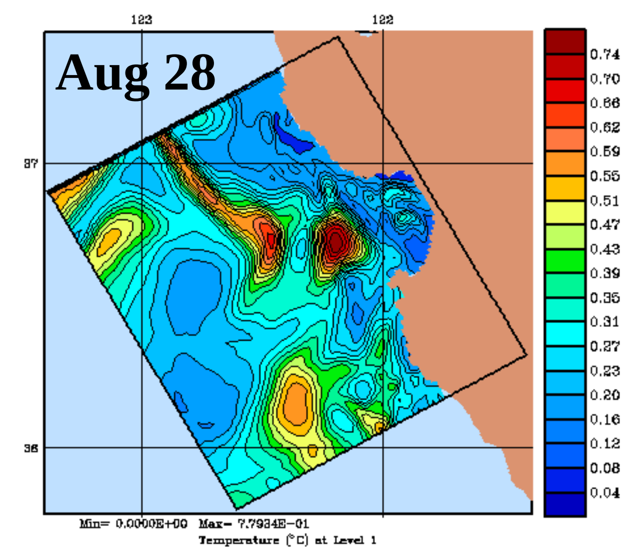


First Upwelling period



End of Relaxation





Second Upwelling period

- **Real-time consistent error forecasting, data assimilation and adaptive sampling (1 month)**
- **ESSE results described in details and posted on the Web daily (see Wayne's AOSN2 page)**

II.a Adaptive sampling via ESSE: evolving predicted objective field

- 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.

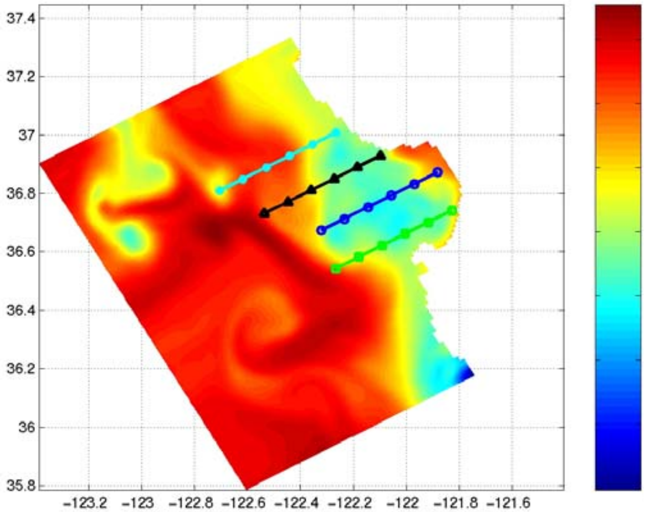
- Objective field changes during computation and is affected by data to-be-collected

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

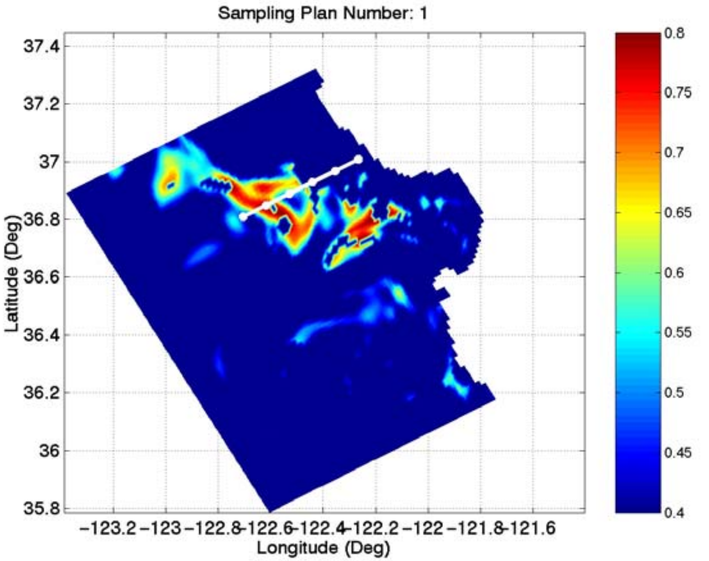
Example: Which sampling on Aug 26 optimally reduces uncertainties on Aug 27?

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

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



Best predicted relative error reduction: track 1



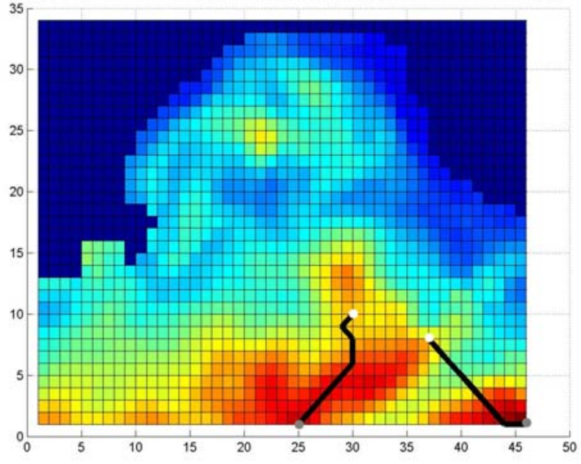
II.b Optimal Paths Generation for a "fixed" objective field

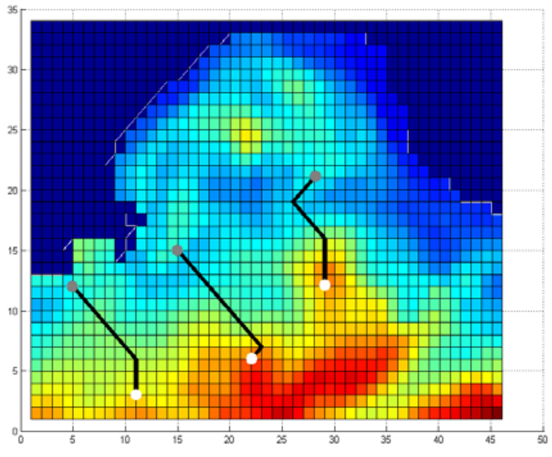
(Namik K. Yilmaz, P. Lermusiaux and N. Patrikalakis)

- 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 for Two and Three Vehicles, 2D objective field

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

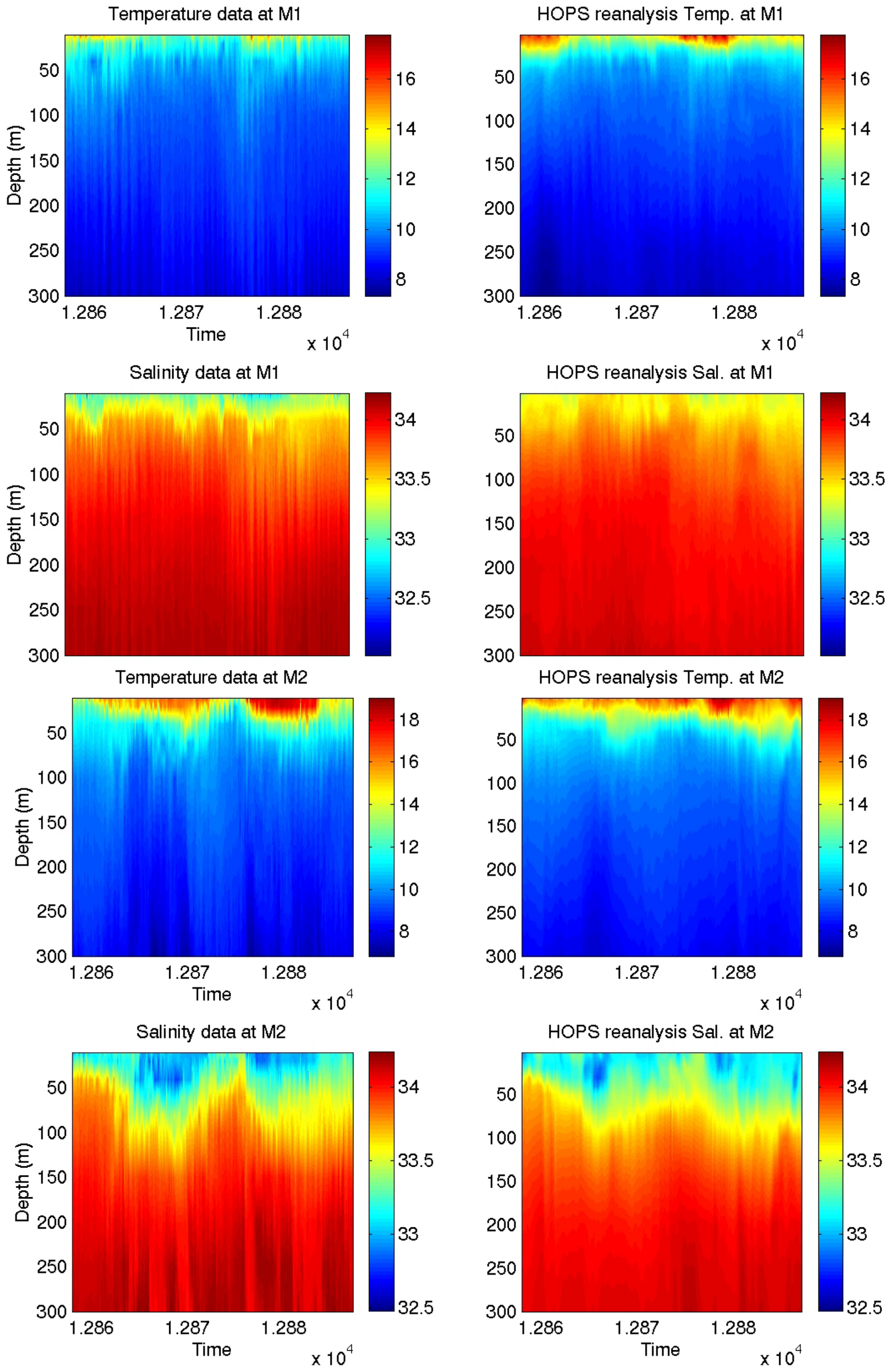


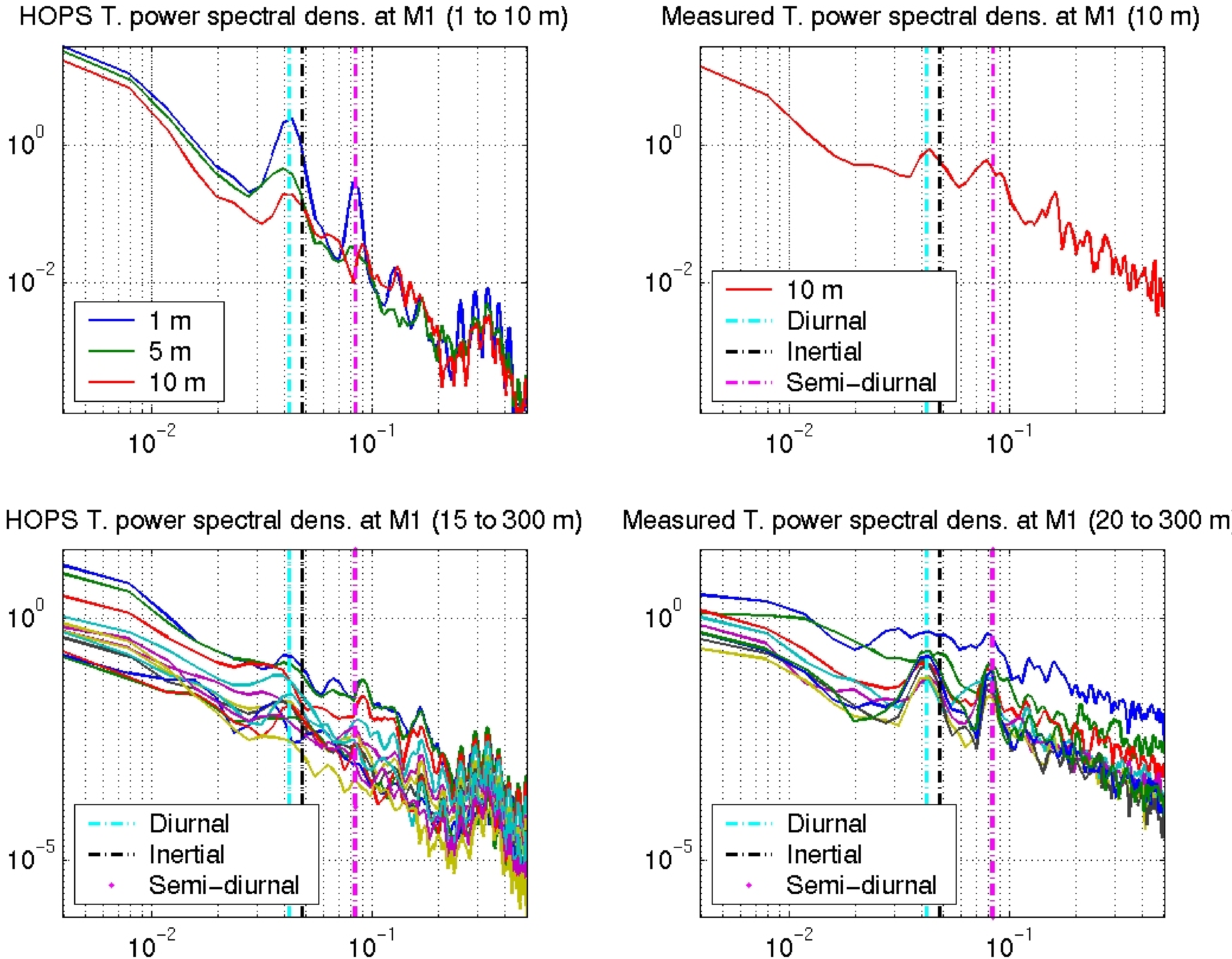


III. Progress towards near-inertial and tidal modeling for AOSN-II

- **Free surface HOPS**
  - Currently calibrated for MREA-03 (Elba-Corsican Channel) and MREA-04 (Portuguese coastal waters)
- **Hierarchy of tidal parameterizations**
  - Rigid-lid HOPS:
    - Reynolds stresses (vertical, horizontal)
    - Horiz. tidal advection of tracers (1/2 free surface)
  - Free-surface HOPS
  - ESSE stochastic forcings (estimate parameters from data)
- **Evaluation plans**
  - Compare models and data at M1/M2
  - Compare models and glider data
- **Initiate research towards**

  Optimal gliders patterns for sampling/filtering missing scales

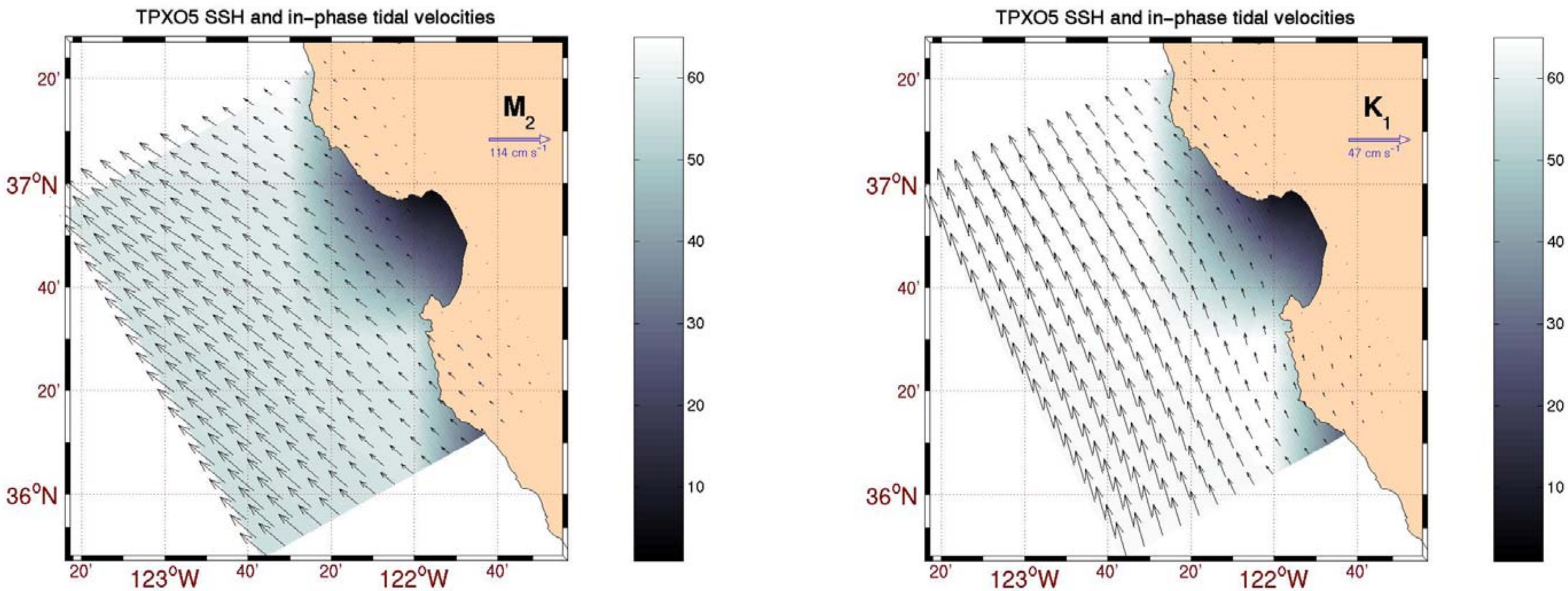




HOPS T. power spectral dens. at M1 (1 to 10 m)
Measured T. power spectral dens. at M1 (10 m)
HOPS T. power spectral dens. at M1 (15 to 300 m)
Measured T. power spectral dens. at M1 (20 to 300 m)
1 m
5 m
10 m
Diurnal
Inertial
Semi–diurnal
10^0
10^{-2}
10^{-5}
10^{-1}

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. Nested regional OTIS inversion using tidal-gauges and TPX05 at open-boundary



Need to cross-evaluate with Igor Shulman and Leslie Rosenfeld

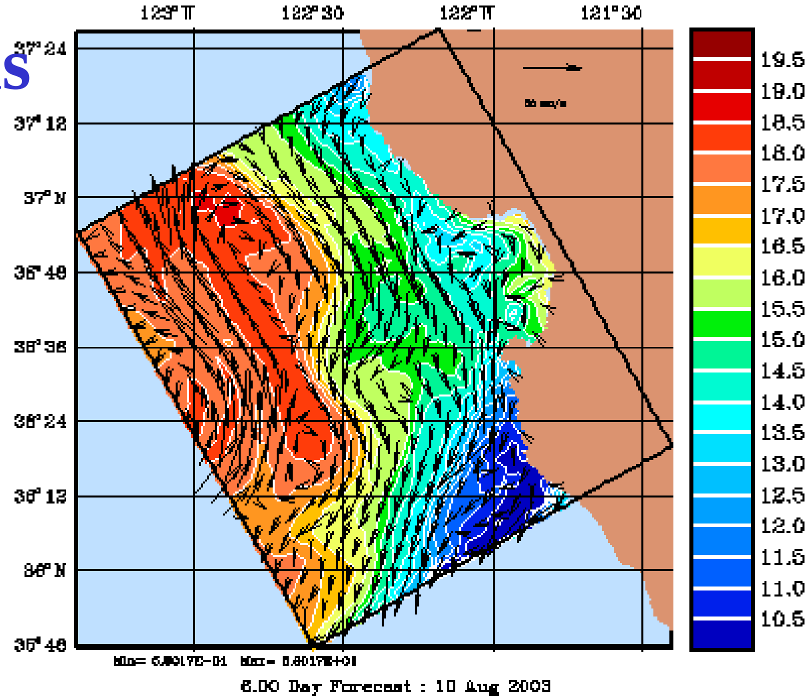
- Used to estimate hierarchy of tidal parameterizations :
  i. **Vertical tidal Reynolds stresses (diff., visc.)** $K_T = \alpha \, ||\boldsymbol{u}_T||^2$ and $K = max(K_S, K_T)$
  ii. **Modification of bottom stress** $\tau = C_D \, ||\boldsymbol{u}_{S+} \boldsymbol{u}_T|| \, \boldsymbol{u}_S$
  iii. **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

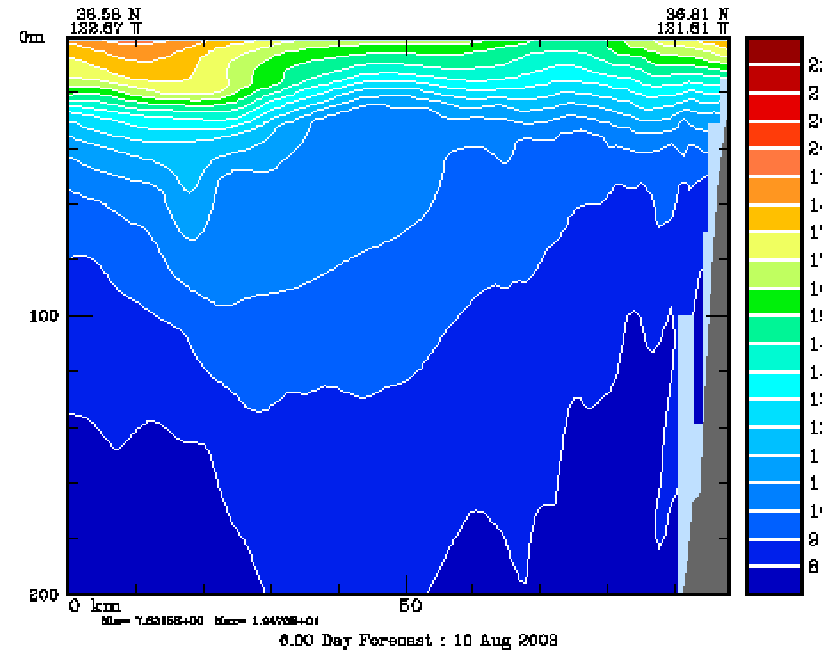
Two 6-day model runs

Temp. at 10 m

T section across Monterey-Bay

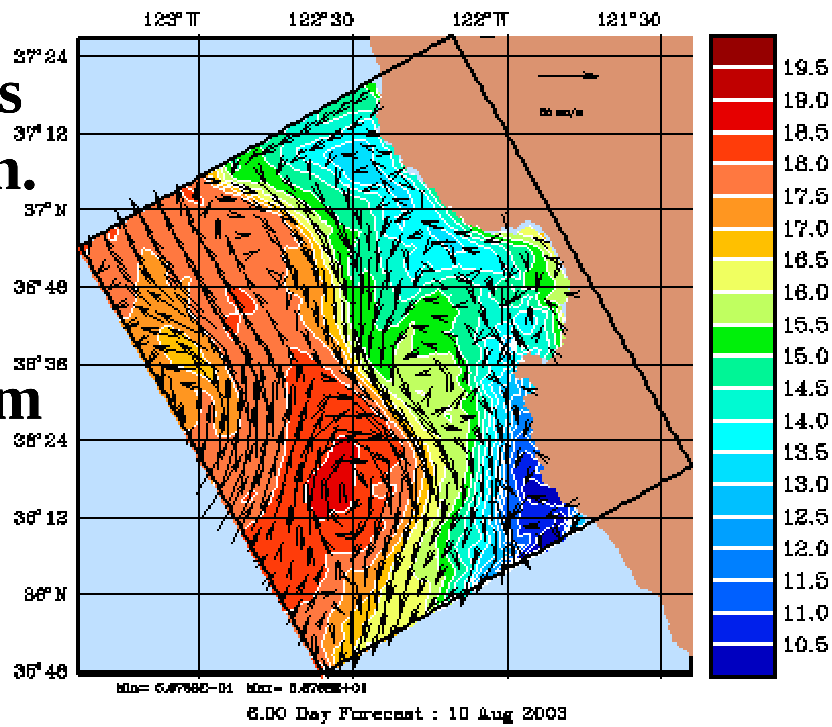
No-tides

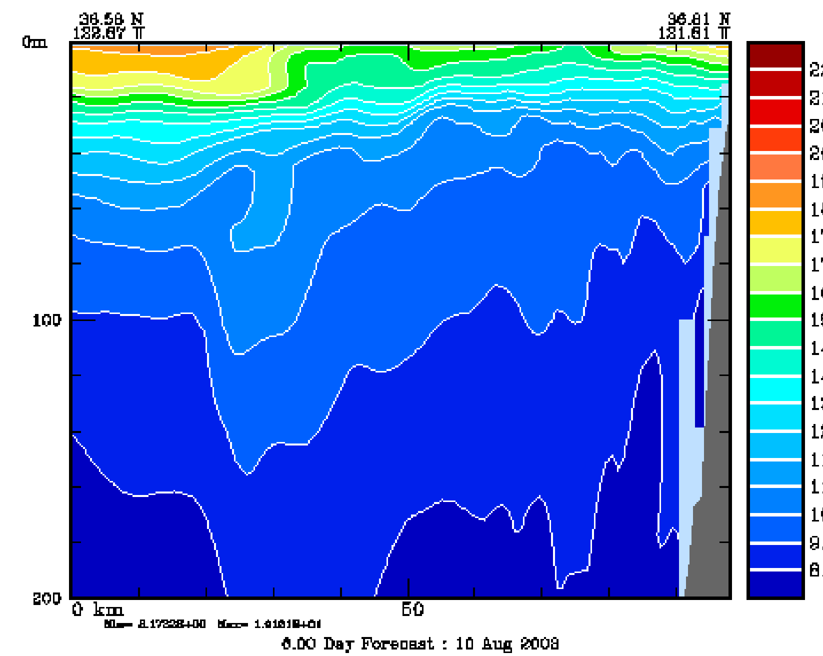




Tidal effects

- **Vert. Reyn. Stress**
- **Horiz. Momentum Stress**





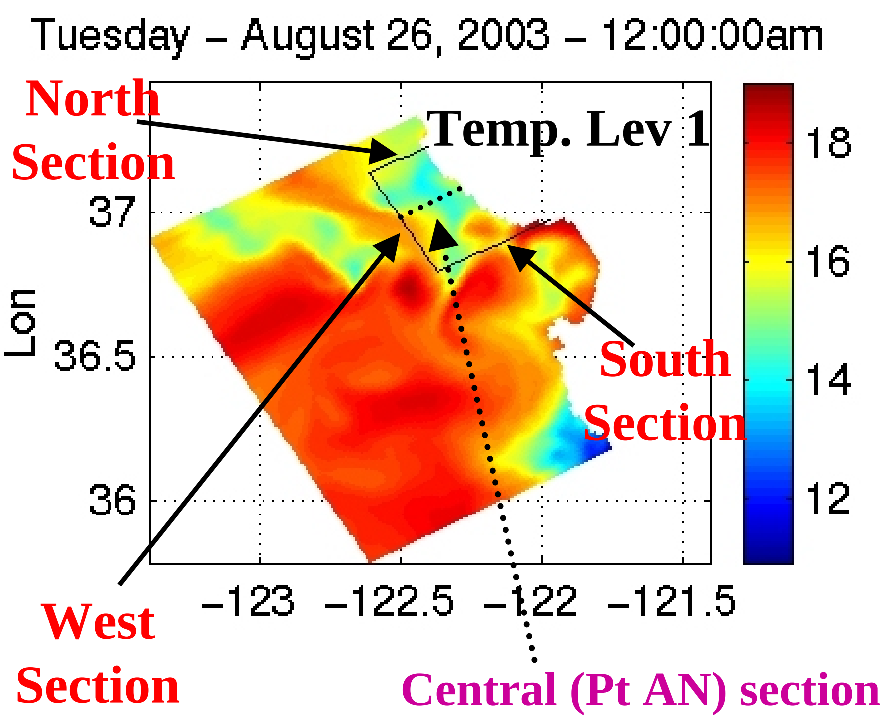
IV. Flux Balances and Term-by-term Balances

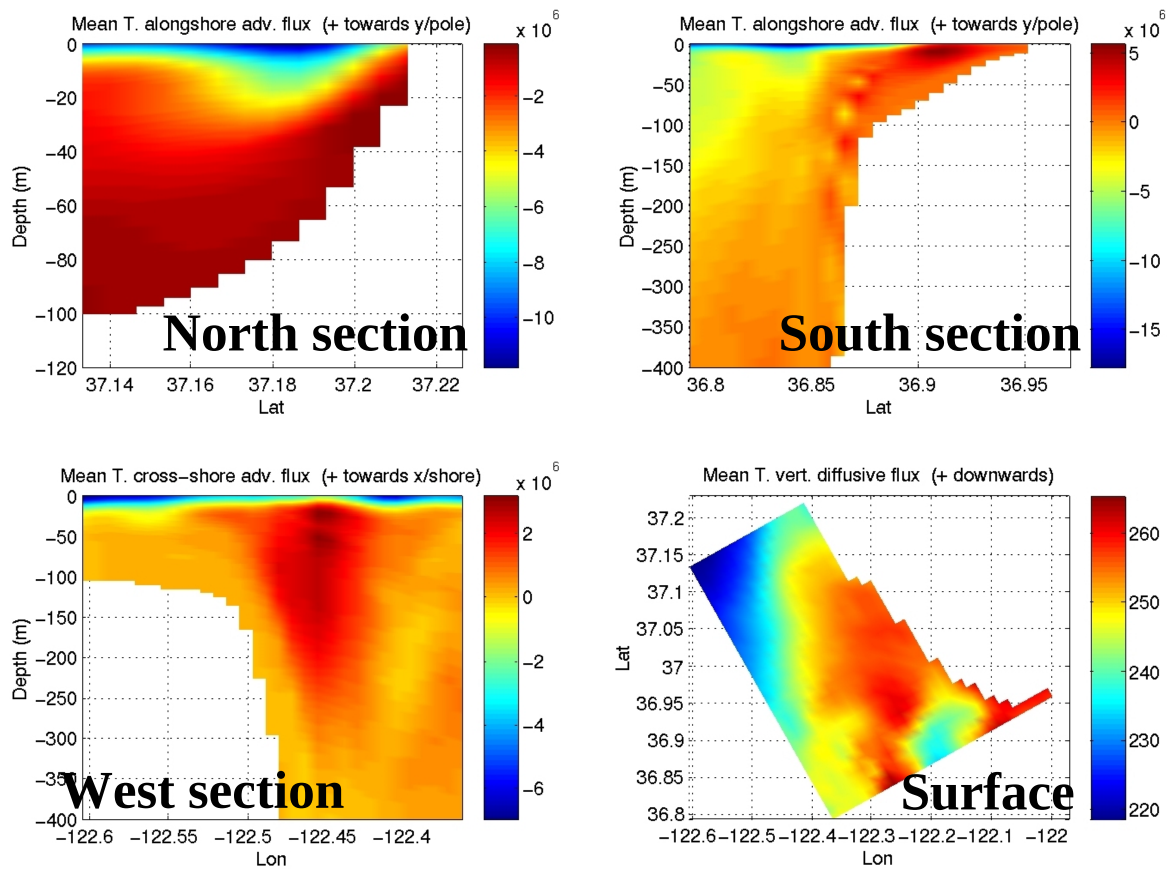
- **Physical model: Primitive-Equation (PDE, x, y, z, t: HOPS)**

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

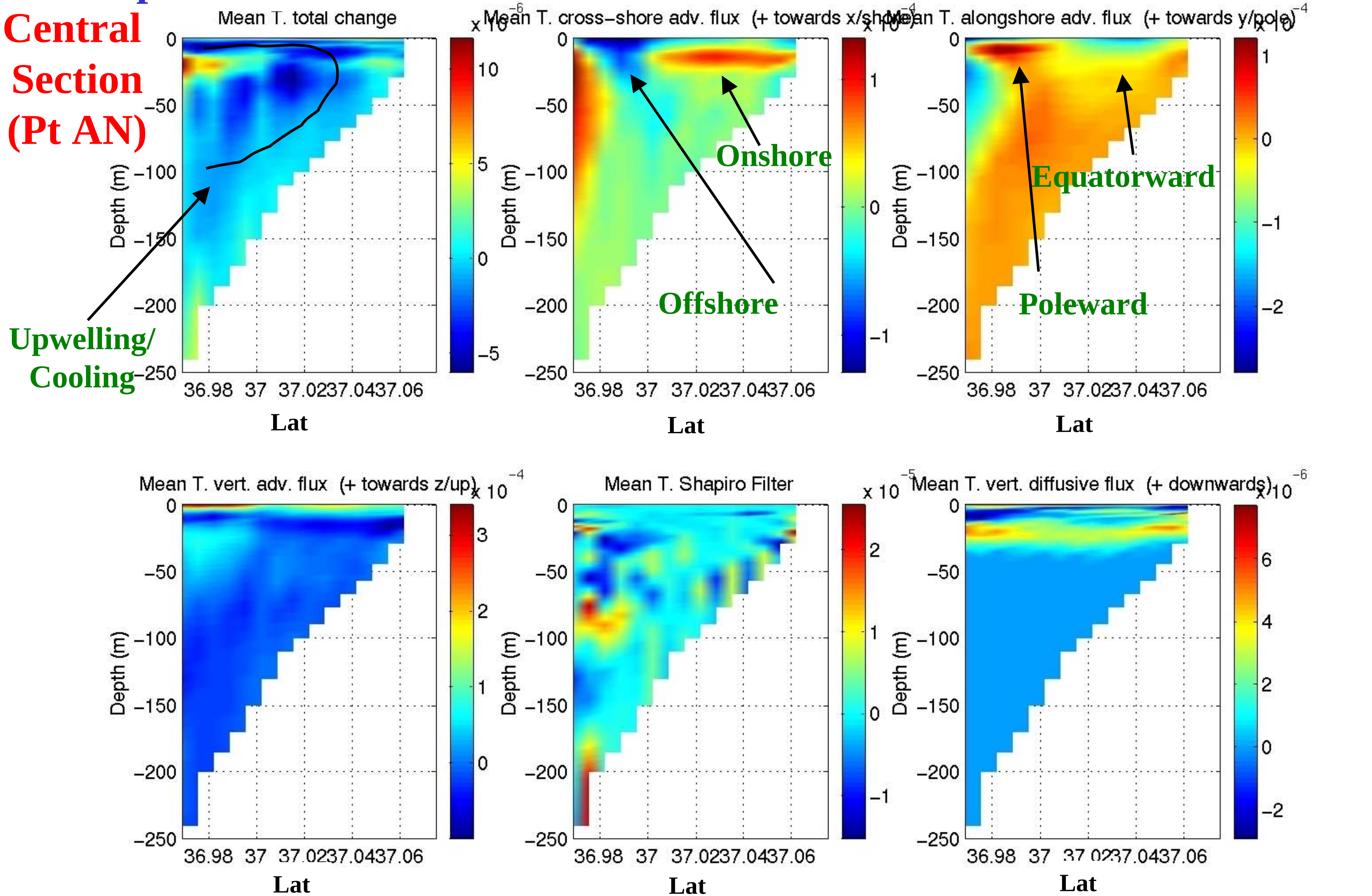
Mean Fluxes (W/m2) over: August 6, 2003 – 10:30:00pm -> August 13, 2003 – 4:30:00am GMT





Mean Term-by-Term Temp. balances

over: August 6, 2003 – 10:30:00pm –> August 17, 2003 – 1:30:00am GMT

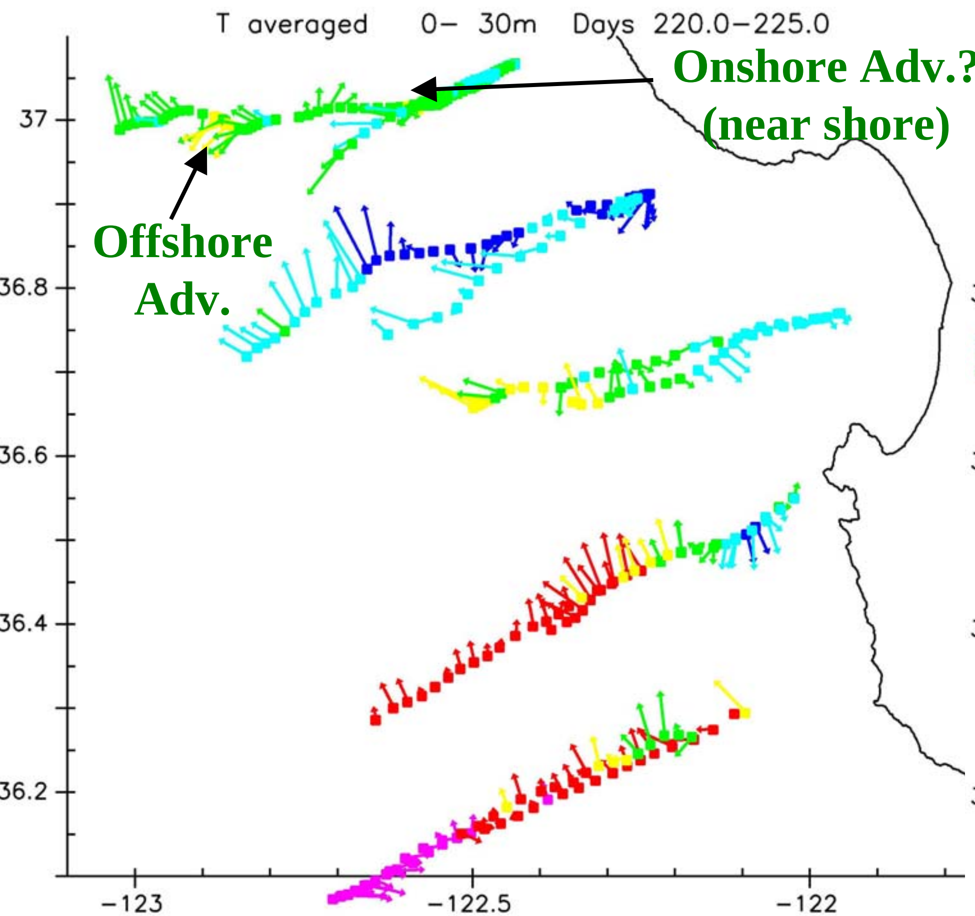


Mean Rate of change ≈ (Cross-shore +Alongshore +Vertical) Advection

What the Data Shows (Russ Davis et al.)

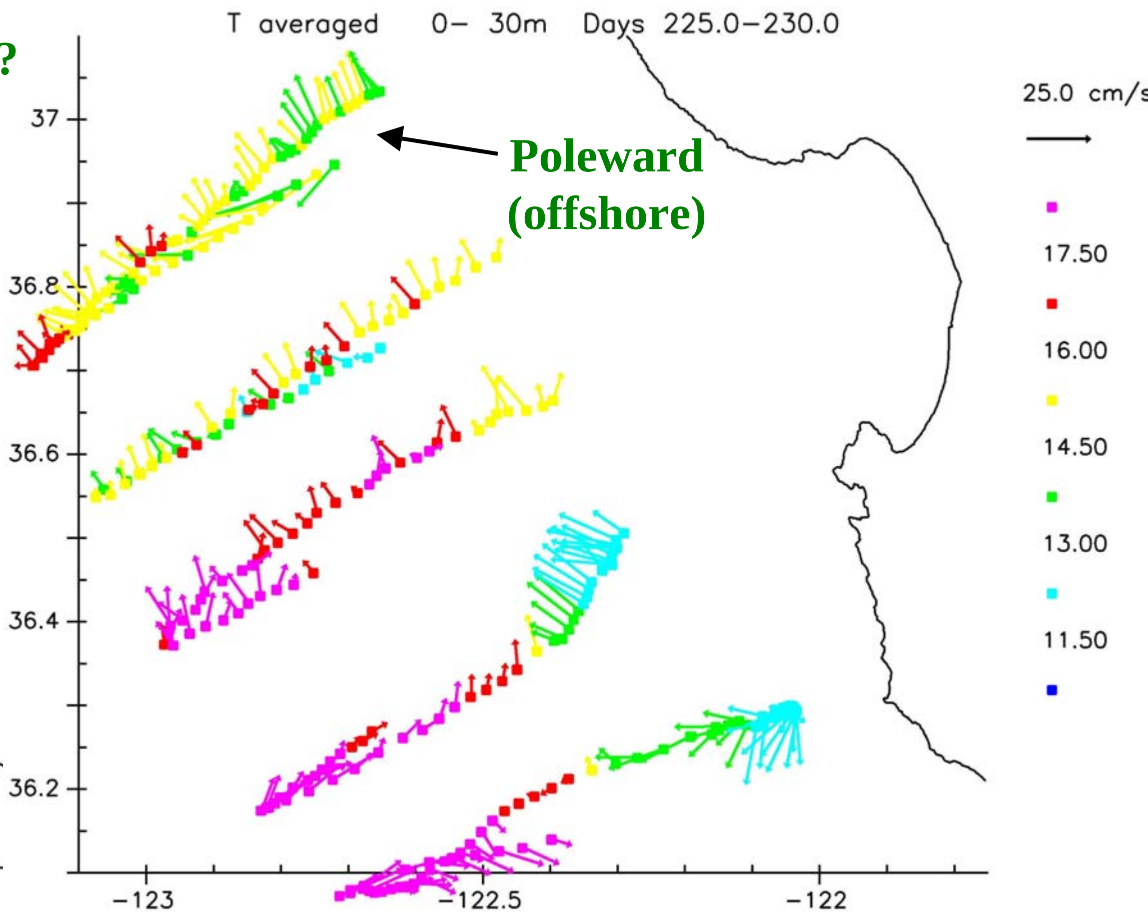
Days 220-230

08-13 Aug



Strong to moderate upwelling

13-18 Aug

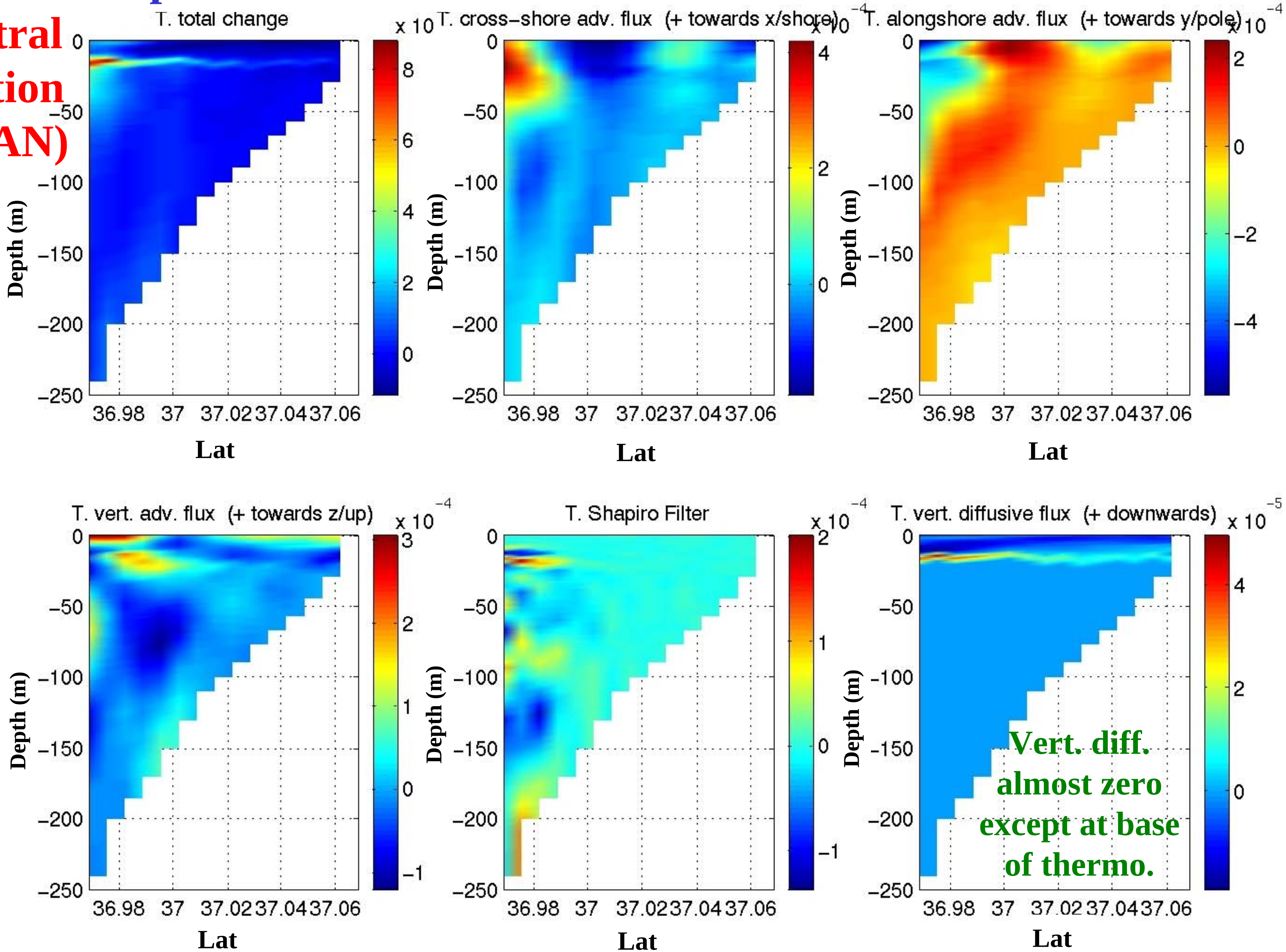


Strong sustained upwelling

Snapshot Term-by-Term Temp. balances

August 13, 2003 – 12:00:00pm GMT

Central Section (Pt AN)

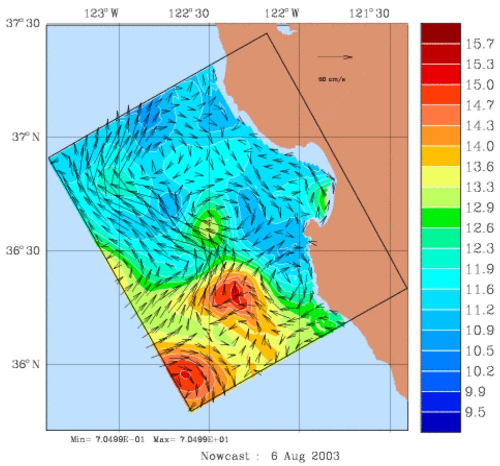


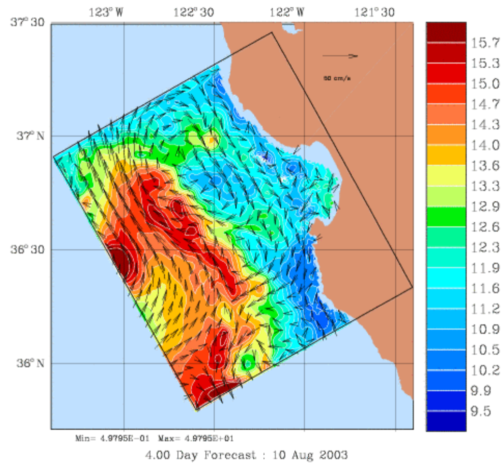
Vert. diff. almost zero except at base of thermo.

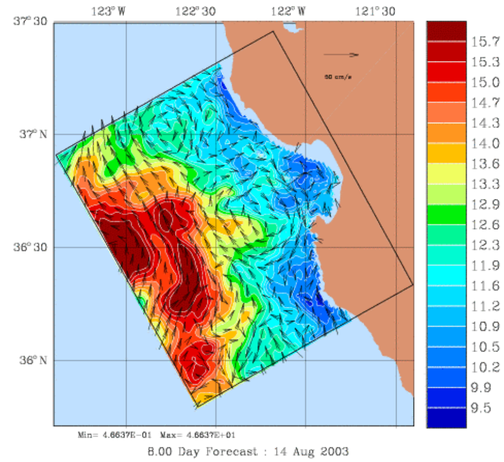
Mean Rate of change ≈ (Cross-shore +Alongshore +Vertical) Advection

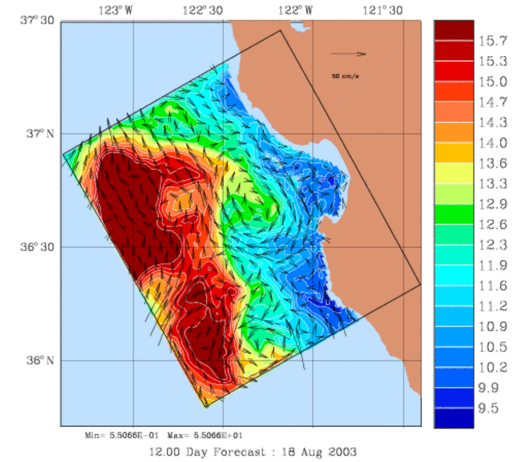
HOPS Re-Analysis

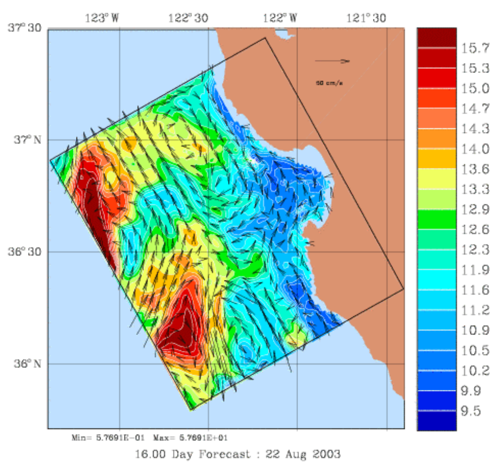
30m Temperature: 6 August – 3 September (4 day intervals)

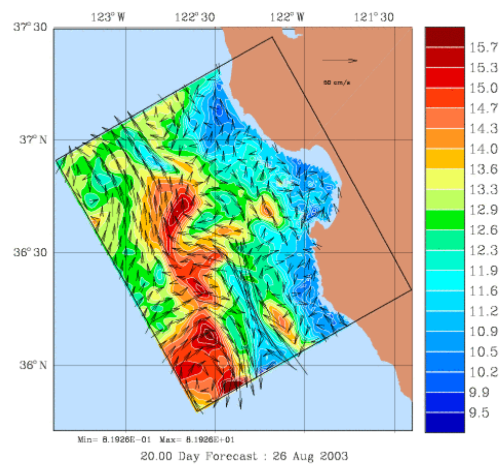


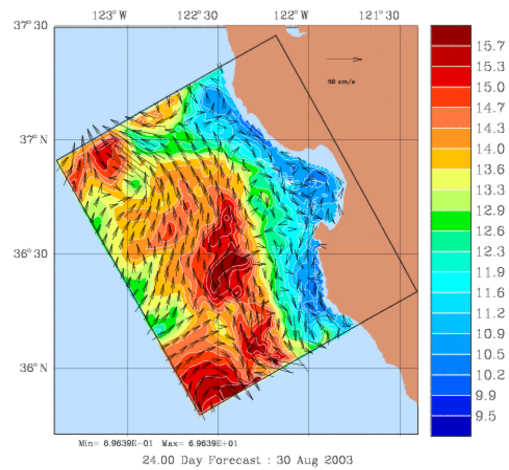


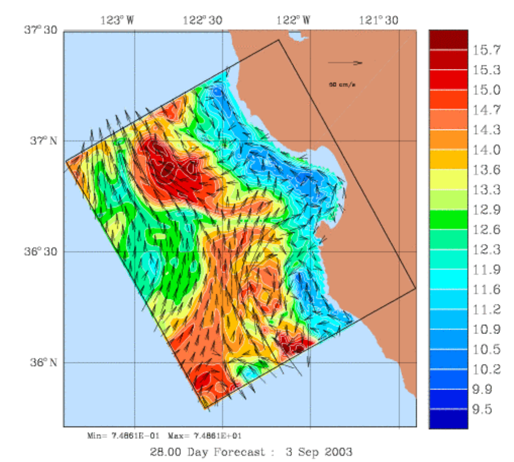








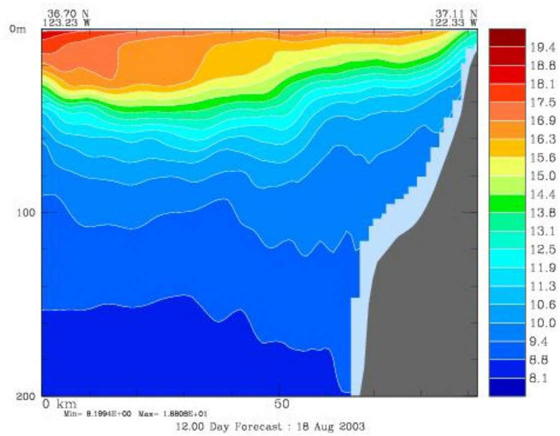


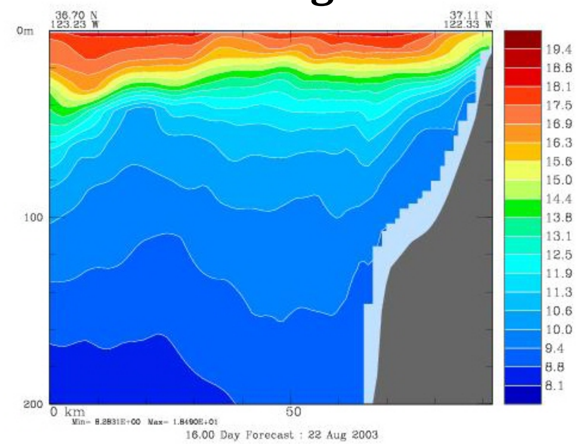


HOPS Re-Analysis

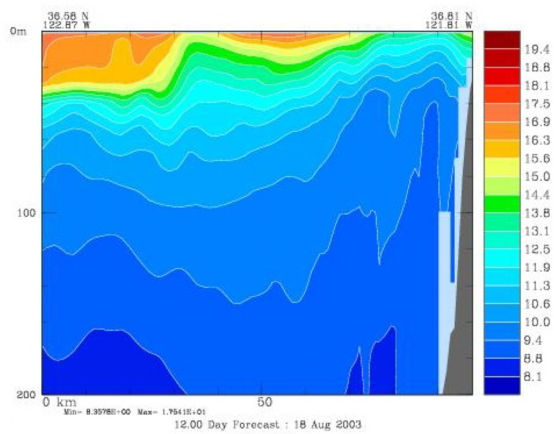
18 August | **22 August**

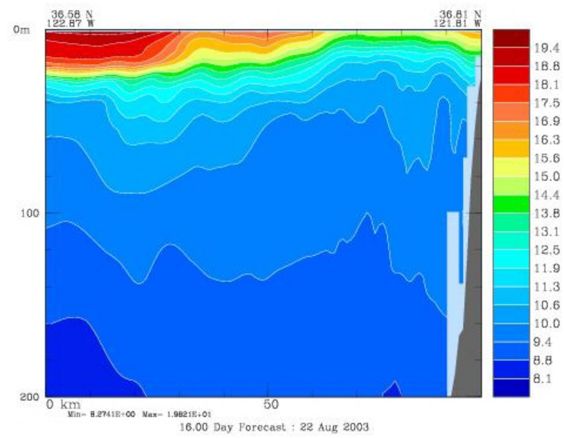
Ano Nuevo



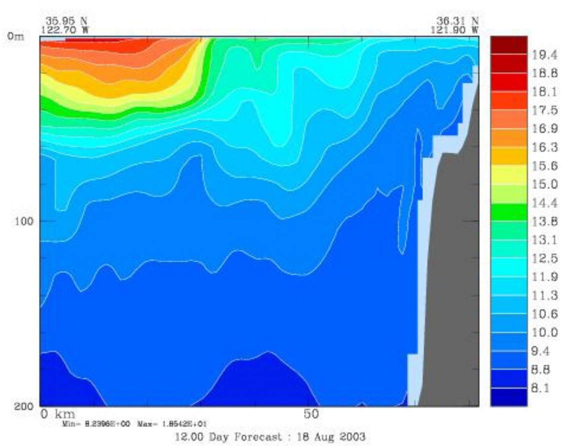


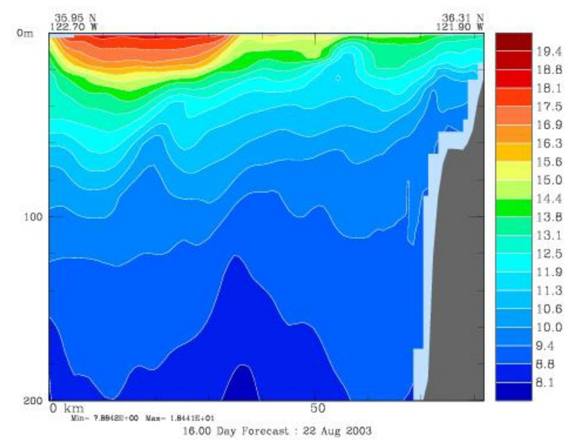
Monterey Bay





Point Sur





HOPS Re-Analysis

The reanalysis simulation is a 35 day simulation spanning 0000Z August 6, 2003 through 0000Z September 10, 2003. The simulation is initialized with and/or assimilates Pt. Sur, John Martin and Pt. Lobos CTDs; WHOI and SIO gliders; and NPS aircraft SST for the period Aug. 2 - Sept. 6, 2003. The model is forced with wind stress, net heat flux and E-P derived from the hourly 3km COAMPS fields.

Two data files are available containing the gzipped netcdf formatted fields. Both files are from the same re-analysis PE run and are on the HOPS horizontal grid.

File 1 has output on the flat levels: 0, -5, -10, -15, -20, -30, -40, -50, -60, -75, -100, -125, -150, -200, -250, -300 with an output frequency of 90 minutes, spanning 0000Z August 6, 2003 through 0000Z September 7, 2003.
File 2 has output on the flat levels: -1, -5, -10, -15, -20, -30, -40, -50, -60, -75, -100, -125, -150, -200, -250, -300, -400, -500, -600, -700, -800, -900, with an output frequency of 3 hours, spanning 0000Z August 6, 2003 through 0000Z September 10, 2003.

HOPS Re-Analysis

Initialization/Boundary Conditions

The initialization field was created by an objective analysis of the August 2-6, 2003 Point Sur CTD + WHOI and SIO glider + NPS SST data (thinned for speed).

The fields were created with the following correlation scales:

XZERO = YZERO = 37.5 (km);
XDCAY = YDCAY = 15.0 (km);
TDCAY = 10.0 (days);
XZEROM = YZEROM = 112.5 (km)
XDCAYM = YDCAYM = 45.0 (km)
TDCAYM = 1000.0 (days)
OADAY = 12858.0 (06 Aug. 2003 - 0:00:00)

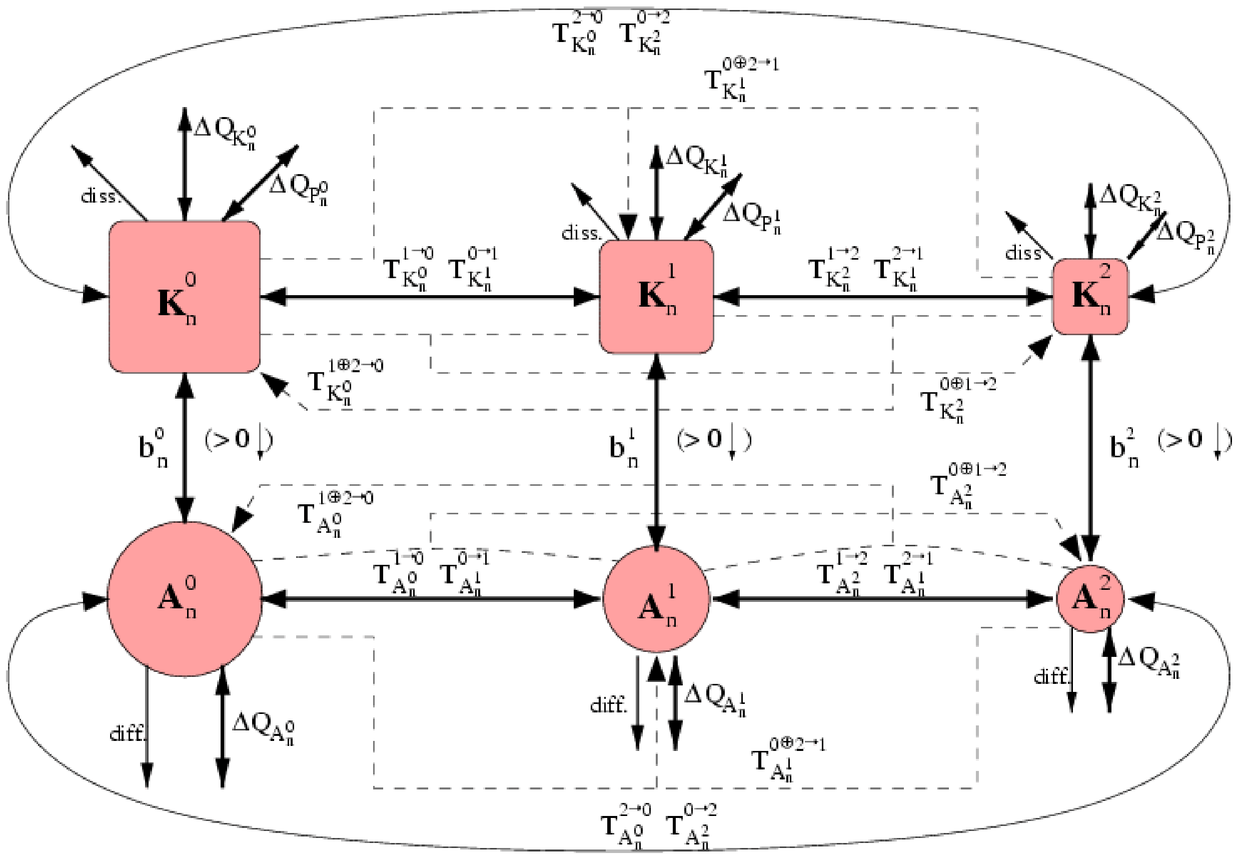
Time evolving boundary values were obtained by objective analysis of data concurrent with the remaining Pt. Sur Surveys.

http://people.deas.harvard.edu/~leslie/AOSNII/REANALYSIS/index.html

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 and
- energy and enstrophy
  - transfers
  - transports, and
  - conversions

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

Window-Window Interactions:
MS-EVA-based Localized Instability Theory

Perfect transfer:

A process that exchanges energy among distinct scale windows which does not create nor destroy energy as a whole.

In the MS-EVA framework, the perfect transfers are represented as field-like variables. They are of particular use for real ocean processes which in nature are non-linear and intermittent in space and time.

Localized instability theory:

BC: Total perfect transfer of APE from large-scale window to meso-scale window.

BT: Total perfect transfer of KE from large-scale window to meso-scale window.

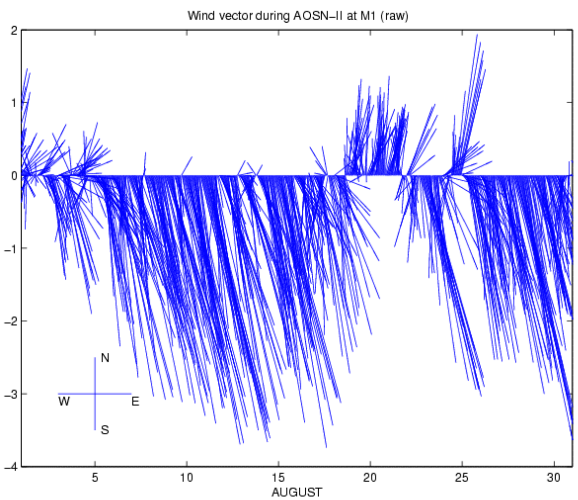
$BT + BC > 0$ => system locally unstable; otherwise stable

If $BT + BC > 0$, and

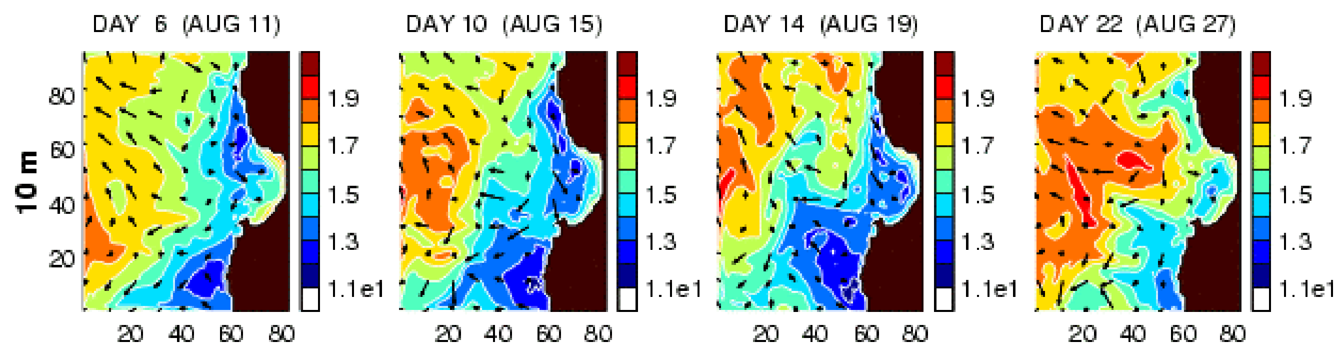
- $BC \leq 0$ => barotropic instability;
- $BT \leq 0$ => baroclinic instability;
- $BT > 0$ and $BC > 0$ => mixed instability

Multi-Scale Energy and Vorticity Analysis

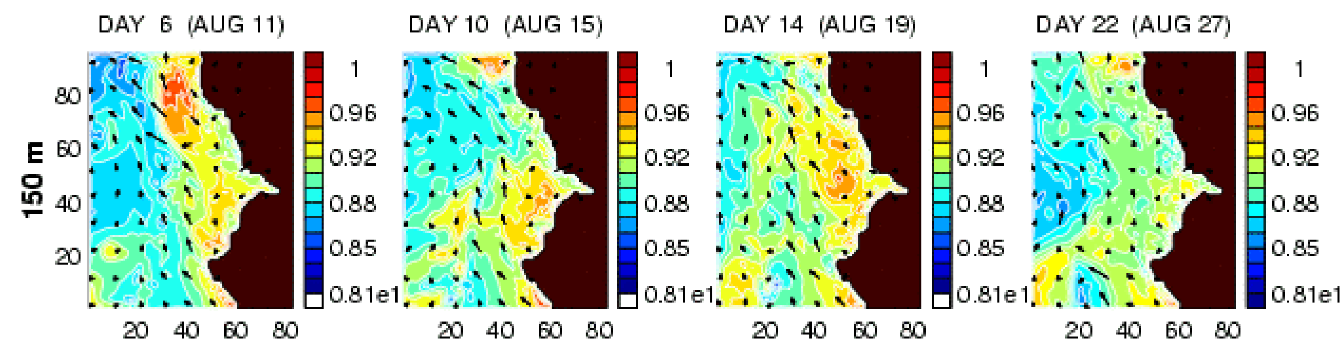
AOSN-II



M1 Winds



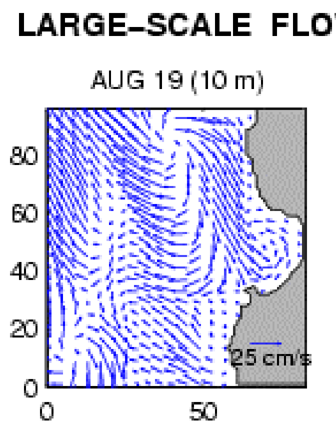
Temperature at 10m



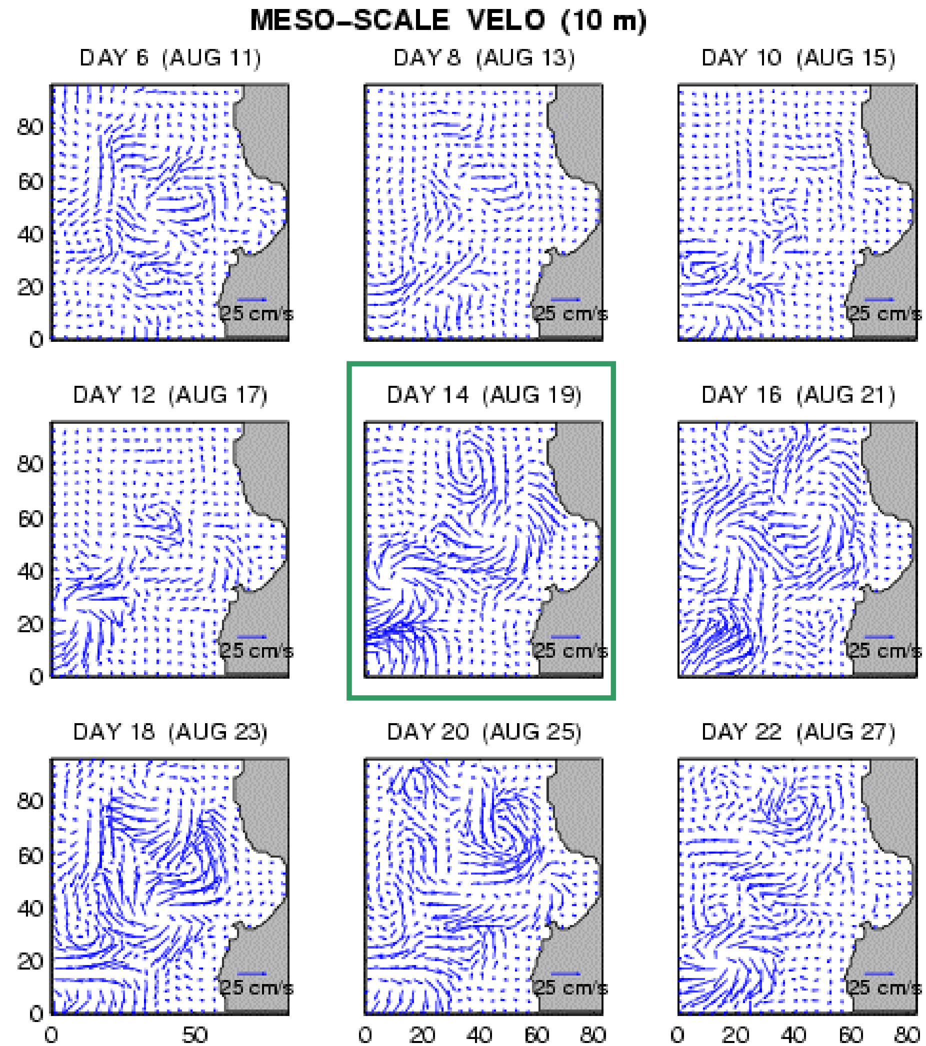
Temperature at 150m

Multi-Scale Energy and Vorticity Analysis

Multi-Scale Window Decomposition in AOSN-II Reanalysis



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



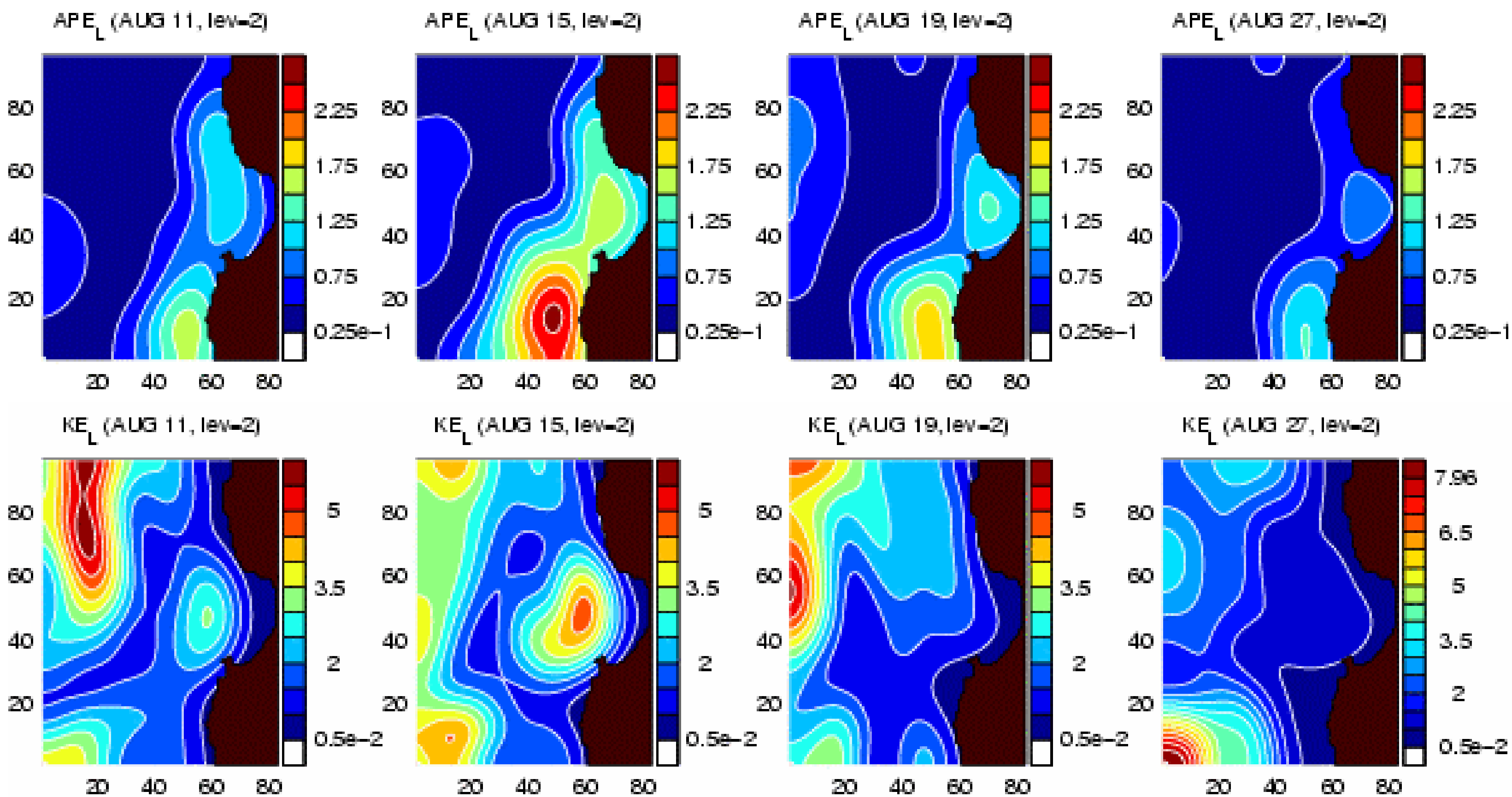
Time windows
Large scale: > 8 days
Meso-scale: 0.5-8 days
Sub-mesoscale: < 0.5 day

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

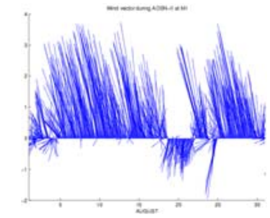
• Transfer from large-scale window to mesoscale window occurs to account for decrease in large-scale energies (as confirmed by transfer and mesoscale terms)

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

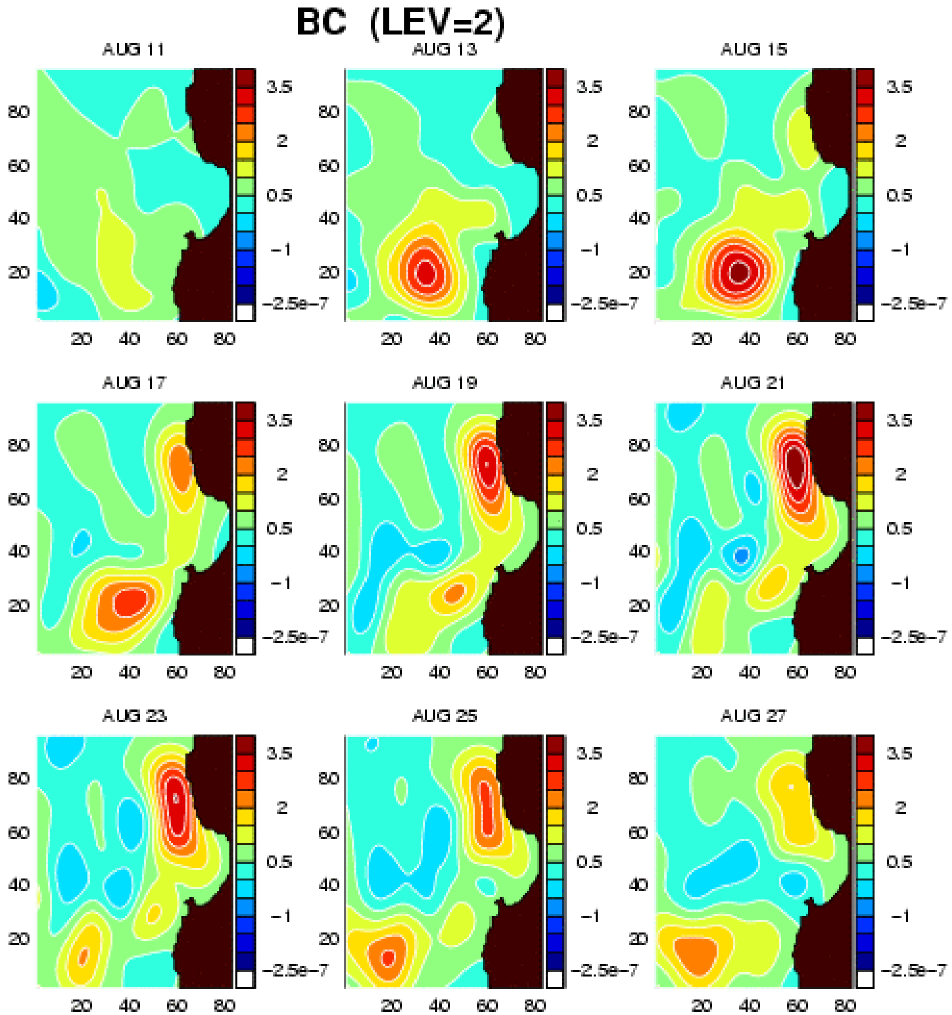
Dr. X. San Liang

Multi-Scale Energy and Vorticity Analysis

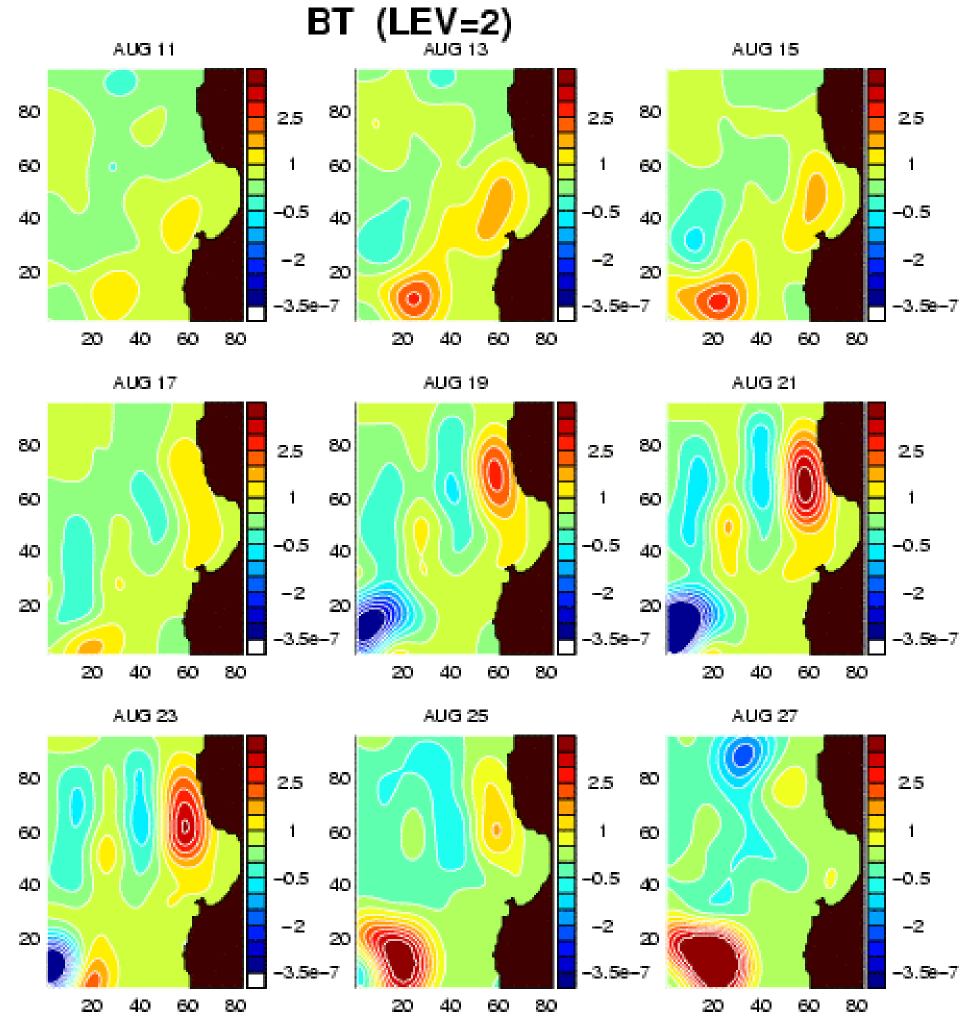
MS-EVA Analysis: 11-27 August 2003



Transfer of APE from large-scale to meso-scale



Transfer of KE from large-scale to meso-scale

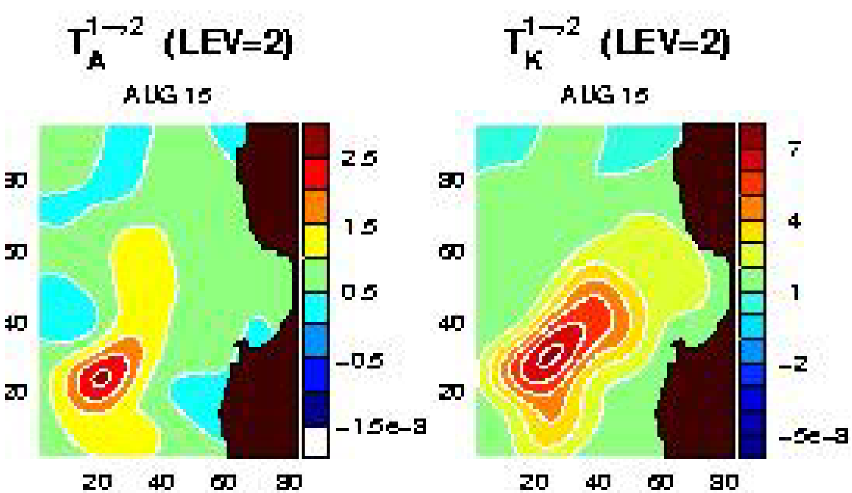


Multi-Scale Energy and Vorticity Analysis

Multi-Scale Dynamics

- 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.

- Sub-mesoscale processes and their role in the overall large, mesoscale, sub-mesoscale dynamics are under study.



Energy transfer from meso-scale window to sub-mesoscale window.

Error Analyses and Optimal (Multi) Model Estimates

Strategies For Multi-Model Adaptive Forecasting

- Error Analyses: *Learn individual model forecast errors in an on-line fashion from model-data misfits based on Maximum-Likelihood*
- 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 via Maximum-Likelihood based on the current estimates of error parameters

O. Logoutov

Error Analyses and Optimal (Multi) Model Estimates

Forecast Error Parameterization

Limited validation data motivates use of few free parameters

- Approximate forecast error covariances and biases as some parametric family, e.g. homogeneous covariance model:

$$\mathbf{B}_m(i,j) = \sigma(\mathbf{x}_i)\sigma(\mathbf{x}_j)\rho\left(||\mathbf{x}_i - \mathbf{x}_j||\right); \quad \rho(r) = \exp\left(\frac{-r^2}{2L^2}\right)$$

  – Choice of covariance and bias models $\tilde{\mathbf{B}}$ and $\tilde{\boldsymbol{\mu}}$ should be sensible and efficient in terms of $\tilde{\mathbf{B}}\mathbf{v}, \tilde{\mathbf{B}}^{-1}\mathbf{v}$ and storage
    - * functional forms (positive semi-definite), e.g. isotropic
      - facilitates use of Recursive Filters and Toeplitz inversion
    - * feature model based
      - sensible with few parameters. Needs more research.
    - * based on dominant error subspaces
      - needs ensemble suite, complex implementation-wise

Error Analyses and Optimal (Multi) Model Estimates

Error Parameter Tuning

Learn error parameters in an on-line fashion from model-data misfits based on Maximum-Likelihood

- We estimate error parameters via Maximum-Likelihood by solving the problem:

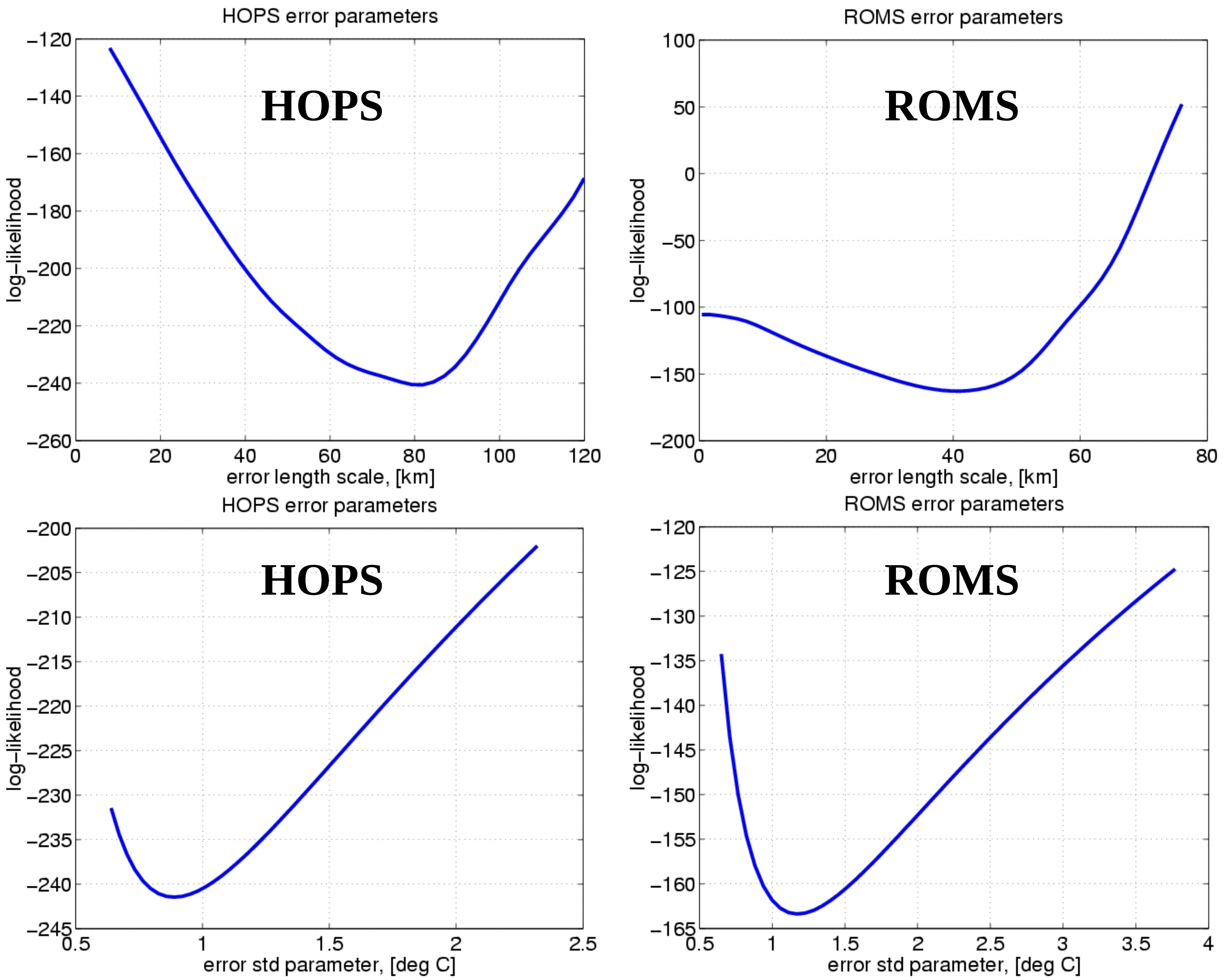
$$\mathbf{\Theta}^* = \arg\max_{\mathbf{\Theta}} p(\boldsymbol{\mathcal{Y}}|\mathbf{\Theta}) \tag{1}$$

Where $\boldsymbol{\mathcal{Y}} = \{\mathbf{y}_1^o, \mathbf{y}_2^o, \ldots, \mathbf{y}_T^o\}$ is the observational data, $\mathbf{\Theta} = \{\boldsymbol{\theta}_1, \boldsymbol{\theta}_2, \ldots, \boldsymbol{\theta}_M\}$ the forecast error covariance parameters of the M models

- (1) implies finding parameter values that maximize the probability of observing the data that was, in fact, observed
- By employing a randomized algorithm, we solve (1) relatively efficiently

Error Analyses and Optimal (Multi) Model Estimates

Log-Likelihood functions for error parameters



Length Scale

Variance

Error Analyses and Optimal (Multi) Model Estimates

Model Fusion

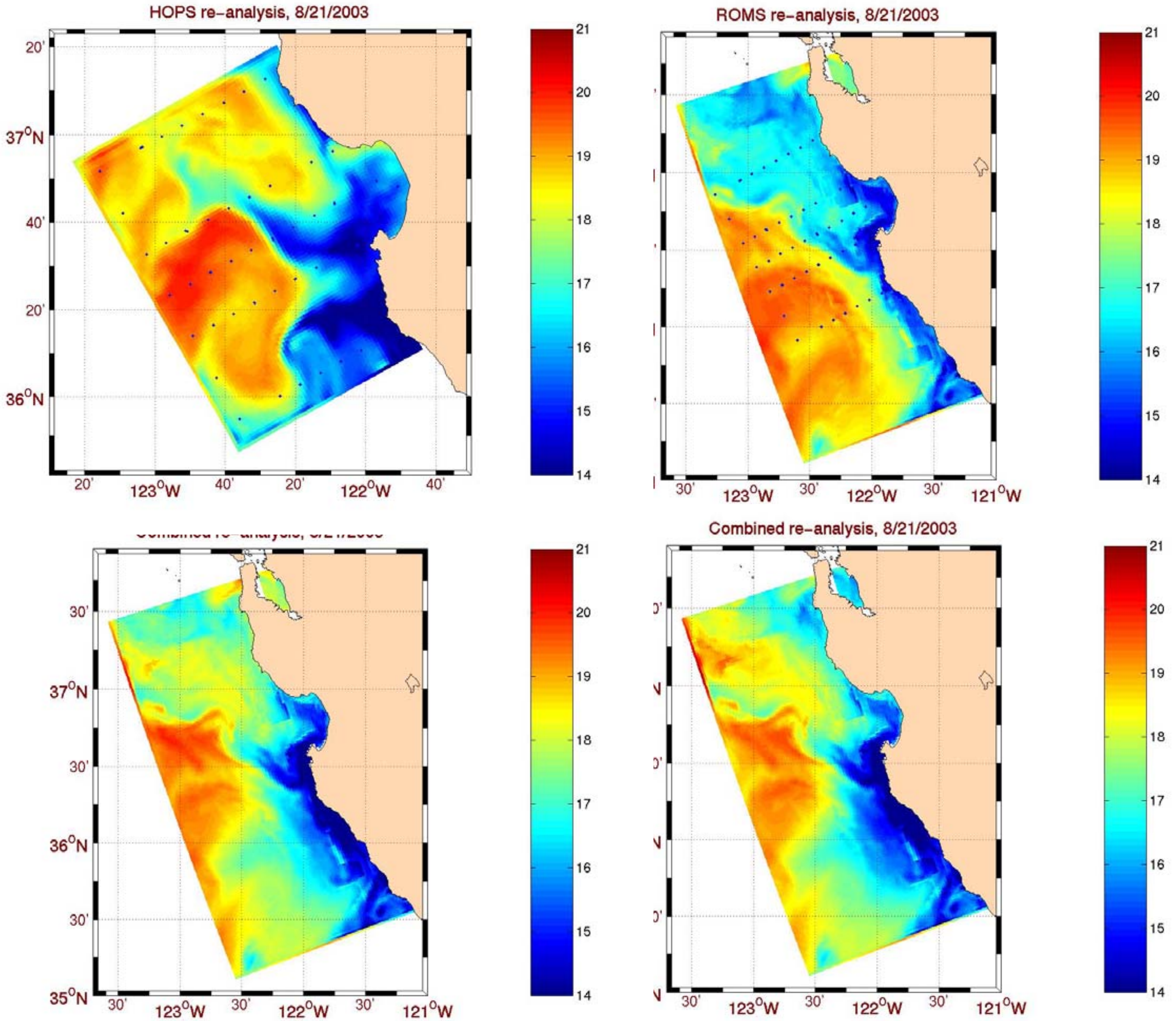
combine based on relative model uncertainties

- **Model Fusion**: once error parameters $\boldsymbol{\Theta}^*$ are available, combine forecasts $\mathbf{x}_m$ based on their relative uncertainties as:

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

Error Analyses and Optimal (Multi) Model Estimates

Two-Model Forecasting Example



HOPS and ROMS SST forecast

Left – HOPS (re-analysis)

Right – ROMS (re-analysis)

Combined SST forecast

Left – with *a priori* error parameters

Right – with Maximum-Likelihood error parameters

AOSN-II Papers – In Preparation or Planned

- **Real-Time Forecasting and Re-Analysis Fields – A.R. Robinson, *et al*.**
- **Real-Time Error Prediction and Data Assimilation with ESSE – P.F.J. Lermusiaux, *et al*.**
- **Multi-Scale Dynamical Processes, Mesoscale and Sub-Mesoscale Dynamics – X.S. Liang and A.R. Robinson et al. (in draft form)**
- **Models Errors Parameter Estimation and Multi-Model Estimation – O. Logoutov and A.R. Robinson.**
- **A generalized biological model and application in Monterey Bay, California – R. Tian, P.F.J. Lermusiaux *et al.***

- **Adaptive Sampling in Oceanography and Meteorology: ESSE and ETKF. Lermusiaux and Majumdar**
- **Model Comparisons and Multi-Model Estimates – (A.R. Robinson, Y. Chao, I. Schulman, *et al.?*)**
- **Data and model comparisons (authorship?)**
- **Comparison of observed and modeled biology – S. Haddock, C. Herren, R. Tian, P.F.J. Lermusiaux, *et al.***

Monterey Bay / CCS – Planned Research

- **Descriptive Dynamical and Statistical Interpretation of Reanalysis**
- **Monterey Bay / CCS Research**
  - Free surface HOPS reanalysis
    - Hierarchy of tidal forcing effects
  - Domain revisions
    - Placement of southern boundary, Vertical discretization, Horizontal resolution
  - 2-way Nesting (including Temperature & Salinity based Feature Model)
  - Additional data: AUV, AXBT, CODAR, AVHRR, SSH
  - Diurnal assimilation
- **Continue with Multi-Model Estimates**
- **Continue Multi-Scale Energy and Vorticity Analyses**
  - Conclude MS-EVA study of relaxation event
  - Apply MS-EVA to onset and maintenance of upwelling
  - Determine sampling requirements of full multi-scale fields to test dynamical processes predicted by MS-EVA
- **Continue with Balance of Terms Studies**
  - Primary Term by Term balances
  - Heat, Salt and Momentum Flux balance;
  - Energy and Vorticity balances
  - For each case: balances during onset, maintenance and transition of upwelling and relaxation events

Monterey Bay /CCS – Planned Research (Cont.)

- **ESSE**
  - Quantitative evaluation of real-time uncertainty predictions
  - Study of ESSE correlation and covariance functions (local, vertical average, along-shore average, etc)
  - Evaluation of details of assimilation scheme
  - Descriptive dynamical interpretation of uncertainty fields
  - Quantitative OSSEs and coupled studies with Princeton, SIO, WHOI, Cal Tech, etc
- **Generalized Biological Modeling and Coupled Physical-Biological Simulations**
  - Improve biological initial conditions (dynamical field and parameter balances)
  - Check all parameters with S. Haddock and others; Finalize conversion of Fluorescence to Chl
  - Higher-vertical resolution in upper-layers
  - Continue to compare data and model; quantify biological forecast skill; improve biological model
  - Assimilate biological data
  - Descriptive dynamical interpretation of the simulated fields

EXTRA VUGRAFS