Development of a Regional Coastal and Open Ocean Forecast System

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Long-Term Goal

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

Objectives

To extend the HOPS-ESSE assimilation, real-time forecast and simulation capabilities to a single interdisciplinary state vector of ocean physical-acoustical-biological fields.

To continue to develop and to demonstrate the capability of multiscale simulations and forecasts for shorter space and time scales via multiple space-time nests (Mini-HOPS), and for longer scales via the nesting of HOPS into other basin scale models.

Objectives

To evaluate quantitatively fields and parameterizations and to model errors adequately for adaptive sampling, adaptive modeling and multi-model ensemble combinations.

To extend the conceptual, algorithmic and software structure of HOPS-ESSE to facilitate the exchange and sharing of components with other models and systems and importantly to evolve HOPS into a multi-model ensemble system with web-based infrastructure.

Approach

To achieve regional field estimates as realistic and valid as possible, an effort is made to acquire and assimilate both remotely sensed and *in situ* synoptic multiscale data from a variety of sensors and platforms in real time or for the simulation period, and a combination of historical synoptic data and feature models are used for system initialization.

Approach

Real time exercises and predictive skill experiments in various regions are carried out to provide fields for operational and scientific purposes and to test methodology in collaboration with other institutions and scientists including, the NATO Undersea Research Centre (NURC) and ONR multi-institutional projects.

A careful step-by-step approach to the research is maintained, so as to contribute successfully to our complex system objectives.

Approach

Forecasting and regional dynamics are intimately linked and several scientists are supported both under our 6.2 (operational system development) and 6.1 (fundamental dynamics) projects, including:

the PI, Dr. Pierre F.J. Lermusiaux, Dr. Patrick J. Haley, Jr., Mr. Wayne G. Leslie, post-doctoral fellow Dr. X. San Liang (now at Courant Institute, NYU) and graduate student Oleg G. Logoutov.

Ongoing work is in close collaboration with "Physical and Interdisciplinary Regional Ocean Dynamics and Modeling Systems (Dr. Pierre F.J. Lermusiaux, PI).

Outline

1. **Adaptive Sampling and Adaptive Modeling**
2. **Flux and Term-by-Term Balances**
3. **Near-Inertial and Tidal Modeling**
4. **AOSN-II Re-analysis Fields**
5. **Free Surface HOPS**
6. **Multi-Scale Energy and Vorticity Analysis**
7. **Multi-Model Estimates**
8. **Harvard/NURC Collaborative Research**
9. **Mini-HOPS and Real-time Exercises**

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.

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

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

Dynamics: $dx = M(x)dt + d\eta \qquad \eta \sim N(0, Q)$

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

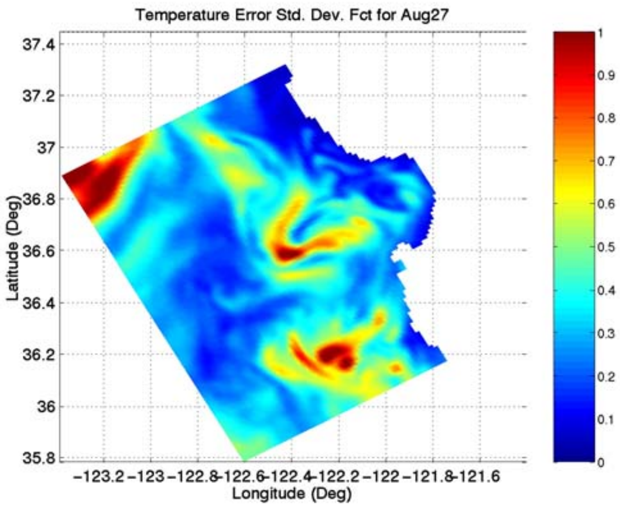
Non-lin. Err. Cov.:

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

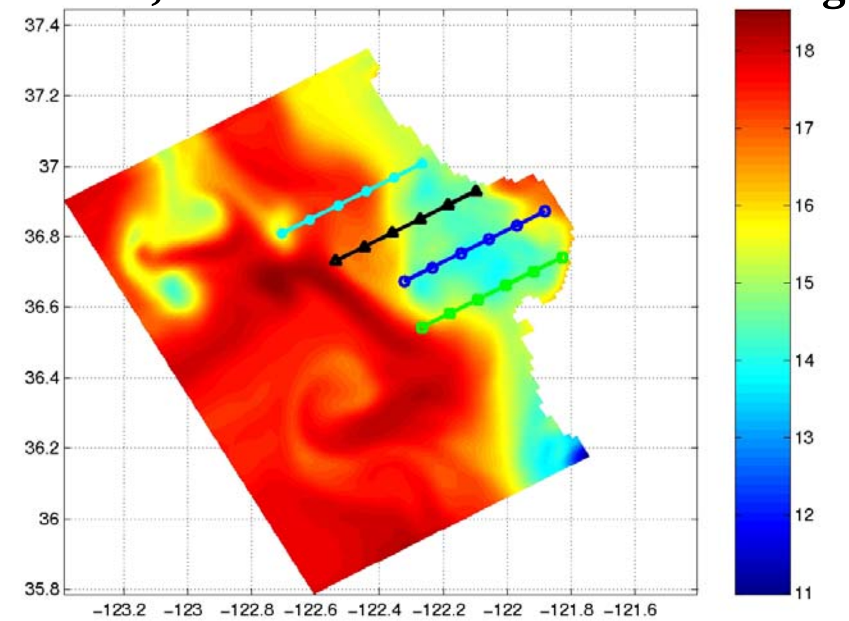
Metric or Cost function: e.g. Find future H_i and R_i such that

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

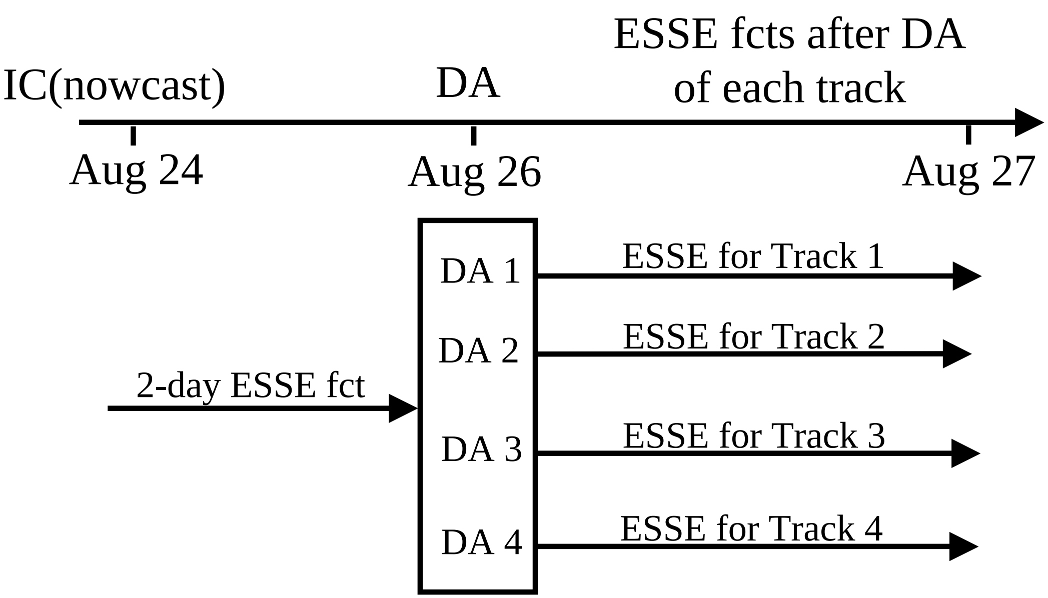
Which sampling on Aug 26 optimally reduces uncertainties on Aug 27?



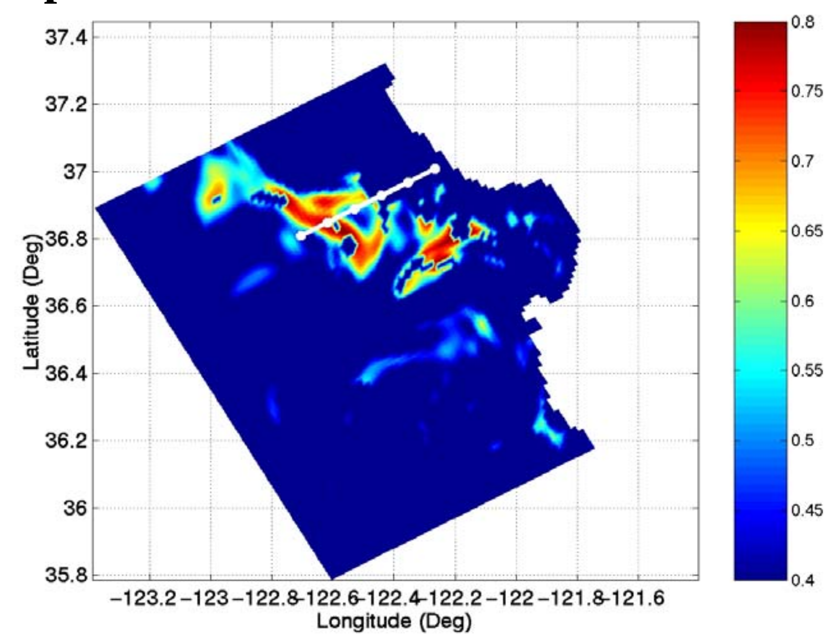
4 candidate tracks, overlaid on surface T fct for Aug 26



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



Best predicted relative error reduction: track 1



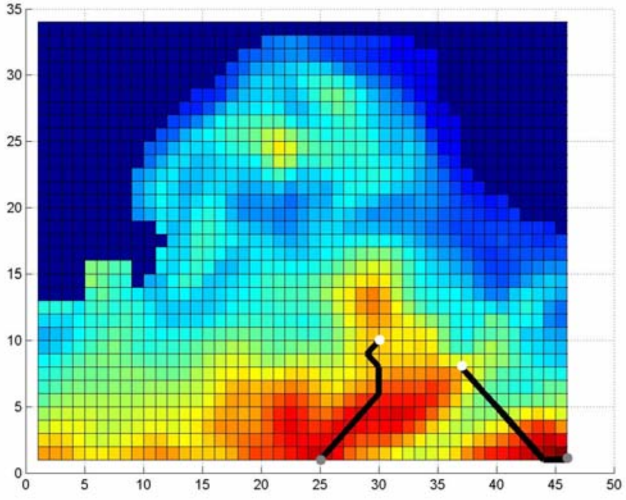
Optimal Paths Generation for a “fixed” objective field

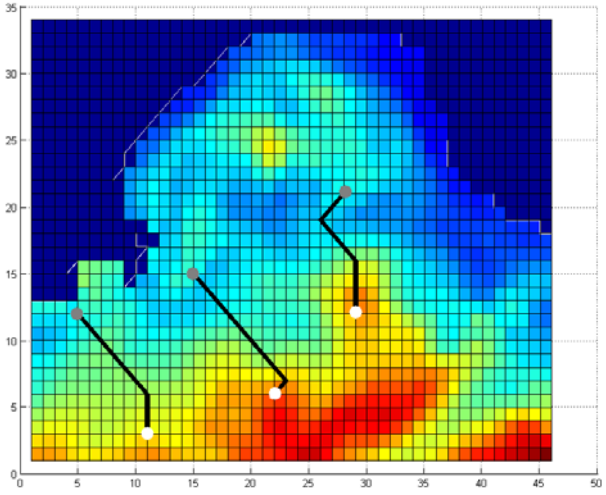
(Namik K. Yilmaz, P. Lermusiaux and N. Patrikalakis)

- 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 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 (err. stand. dev.) represented as discrete piecewise-linear fct: solved *exactly* by MIP
  - 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

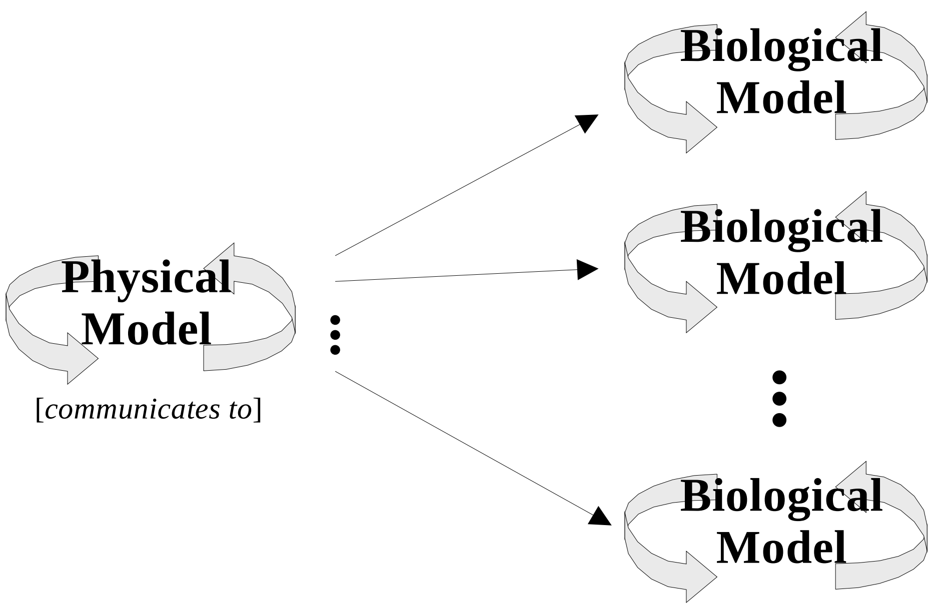


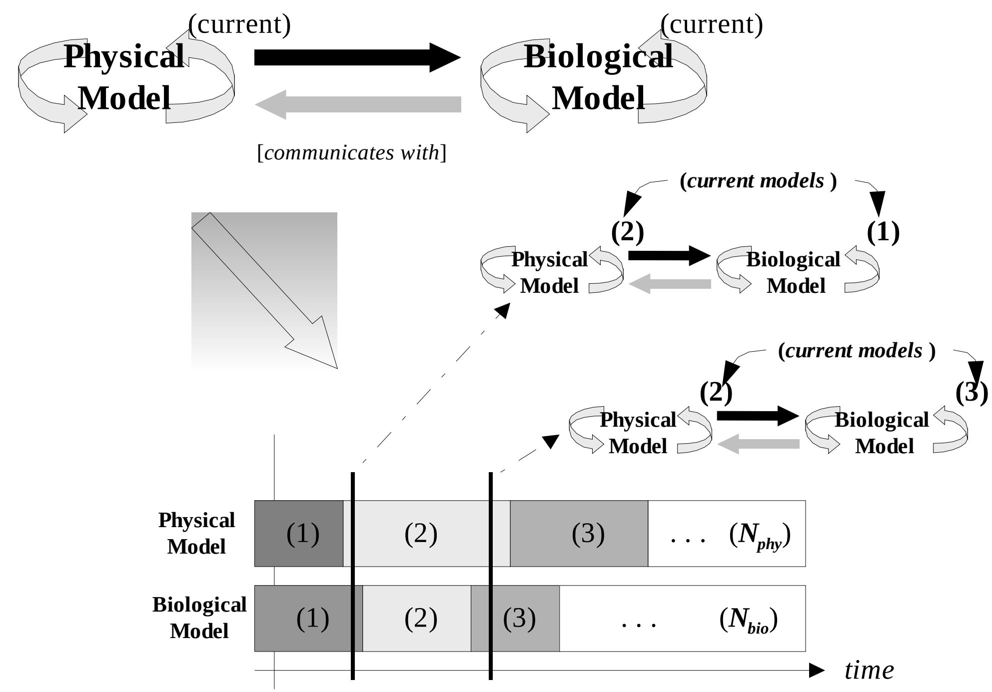


Towards Real-time Adaptive Physical and Coupled Models

- 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





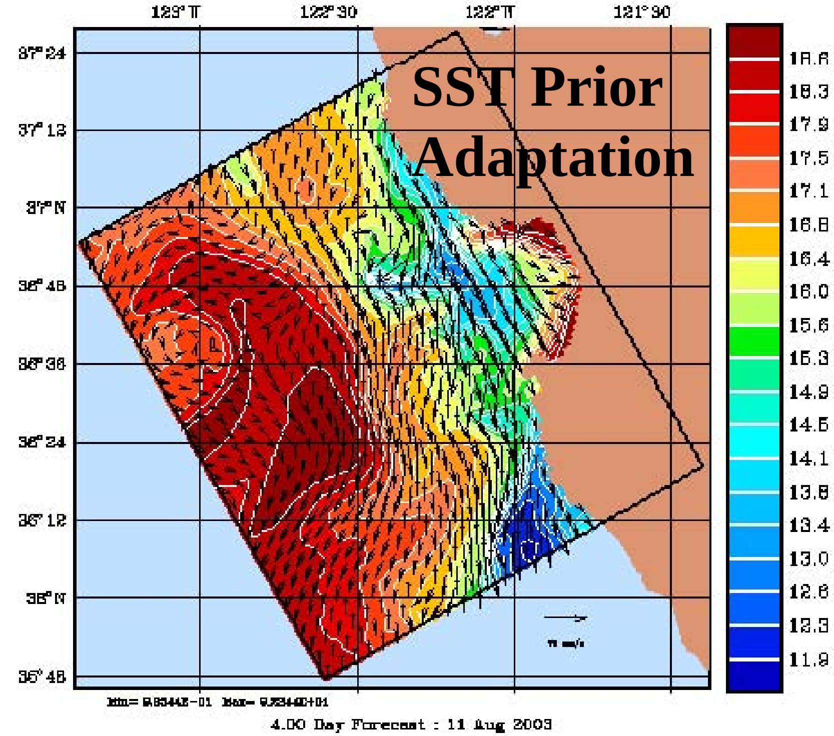
- Model selection based on quantitative dynamical/statistical study of data-model misfits
- Mixed language programming (C function pointers and wrappers for functional choices) to be used for numerical implementation

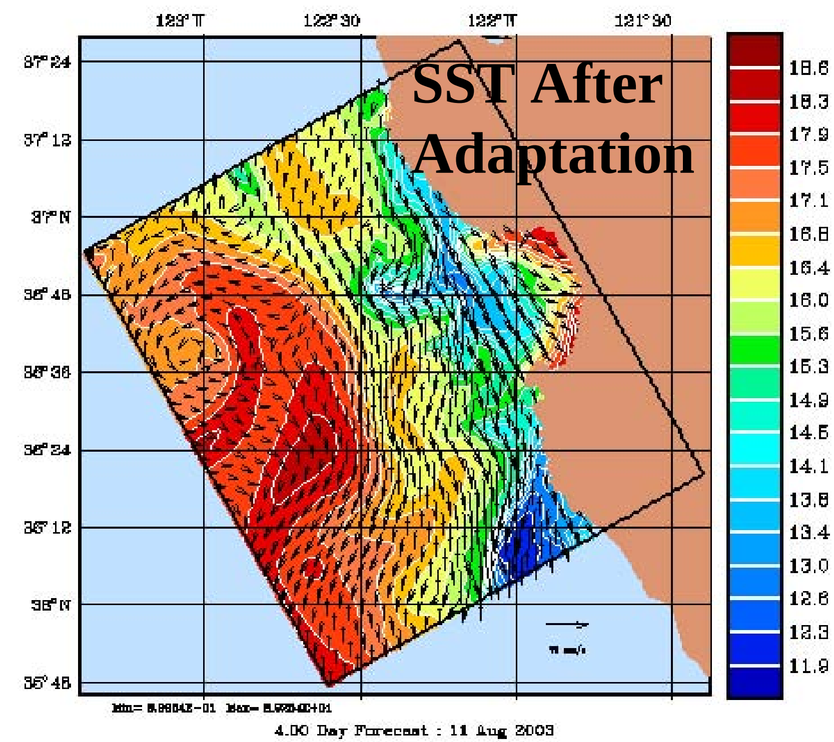
Quasi-Automated Real-time Physical Calibration during AOSN-II

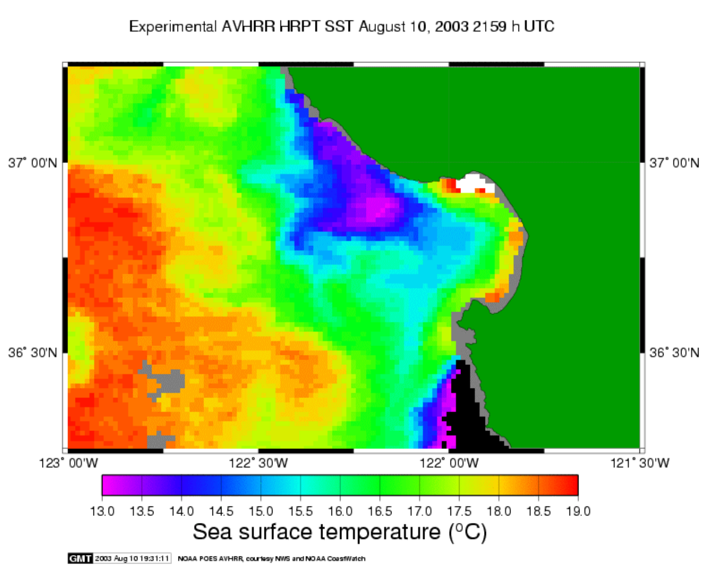
Prior to AOSN-II, ocean models calibrated to historical conditions judged to be similar to these expected in August 2003.

Ten days in the experiment:

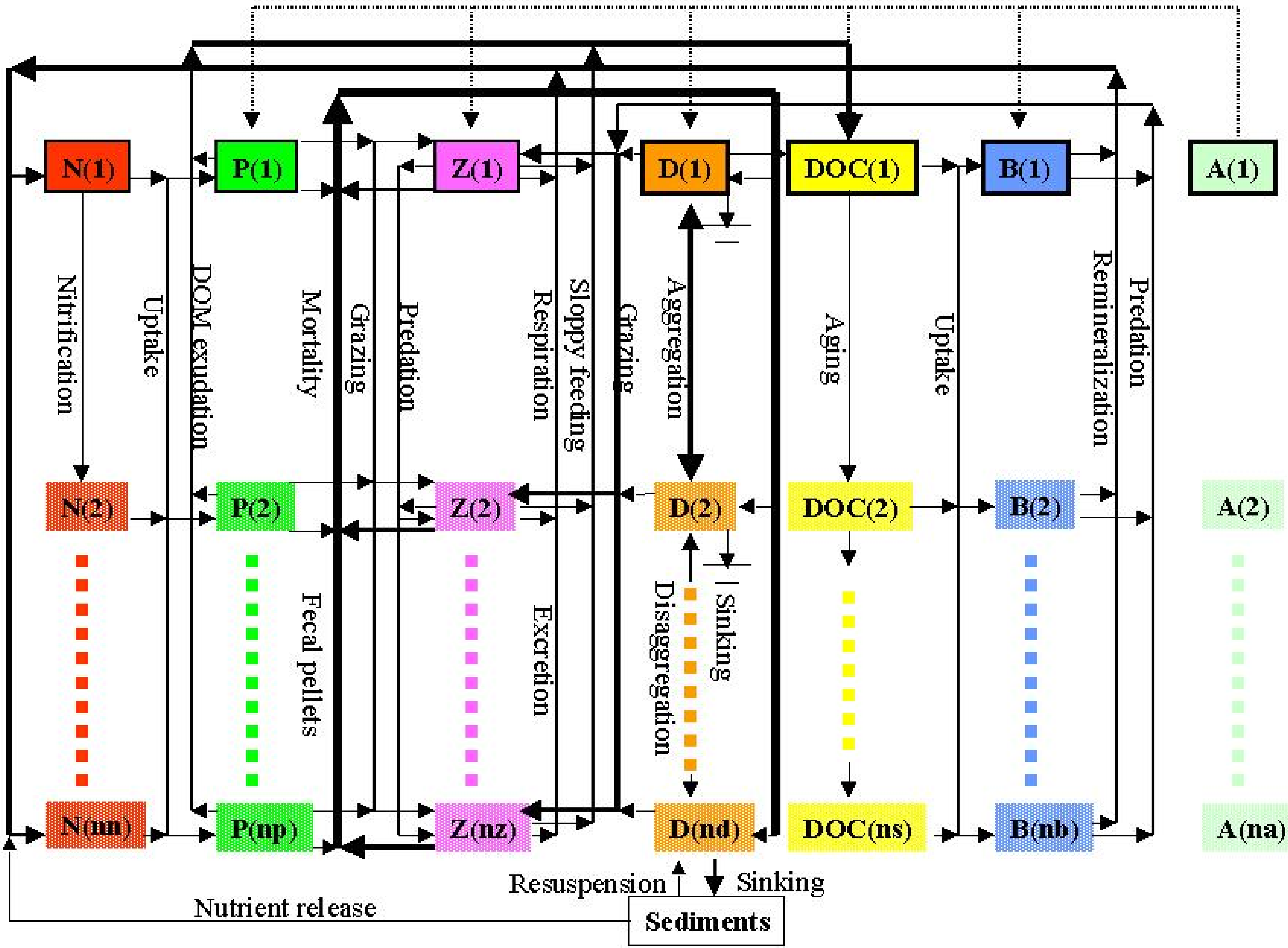
- Parameterization of the transfer of atmos. fluxes to upper layers (SBL mixing) adapted to new 2003 data
- 20 sets of parameter values and 2 mixing models tested
- Configuration with smallest RMSE/higher PCC improved upper-layer T and S fields, and currents





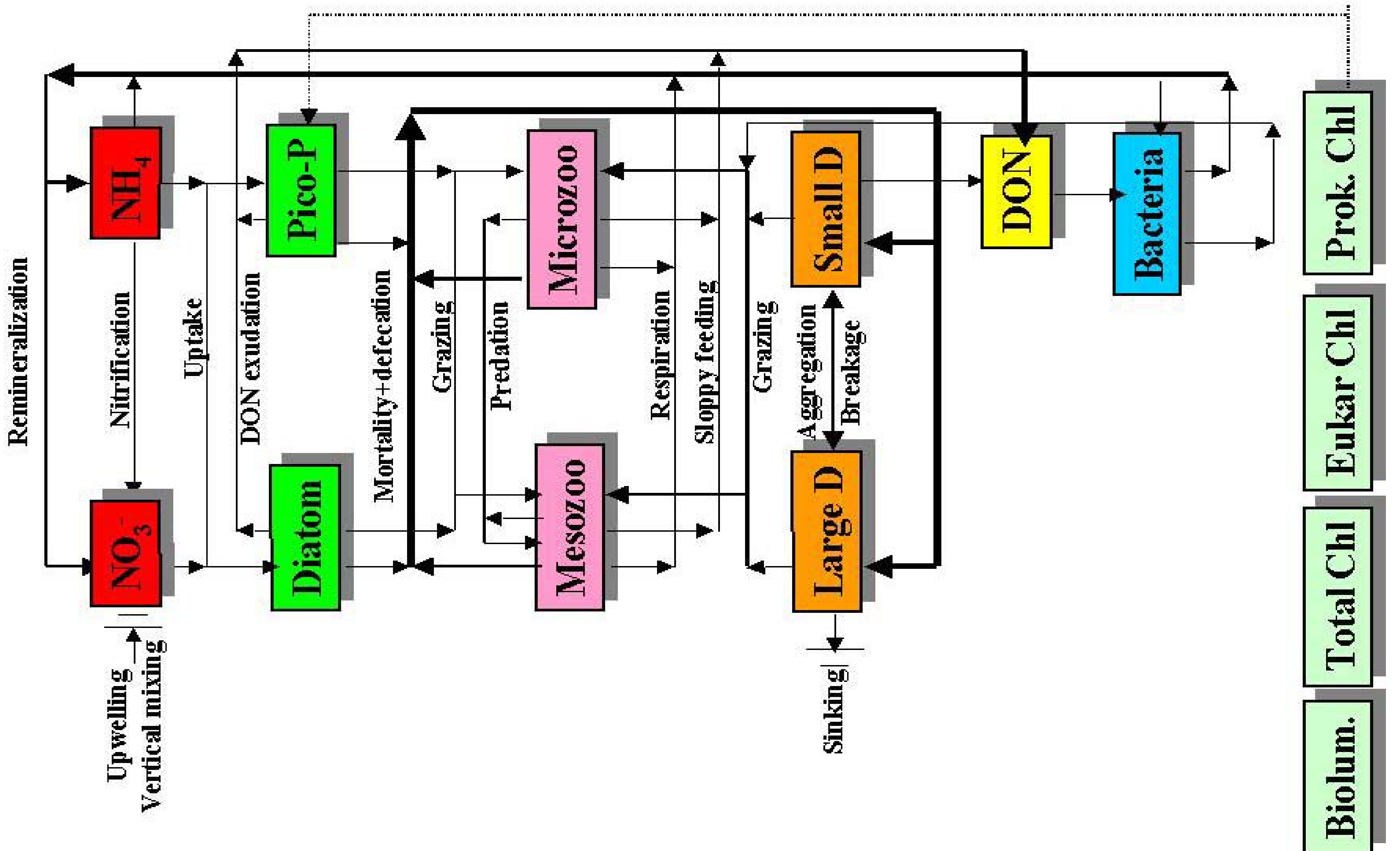


Harvard Generalized Adaptable Biological Model



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

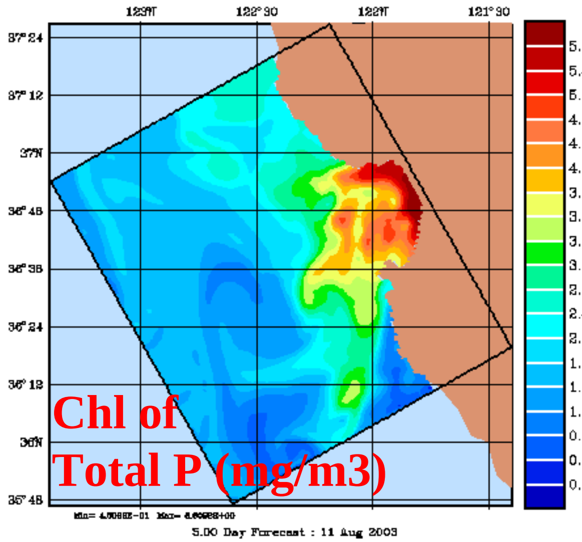
A Priori Biological Model for Monterey Bay

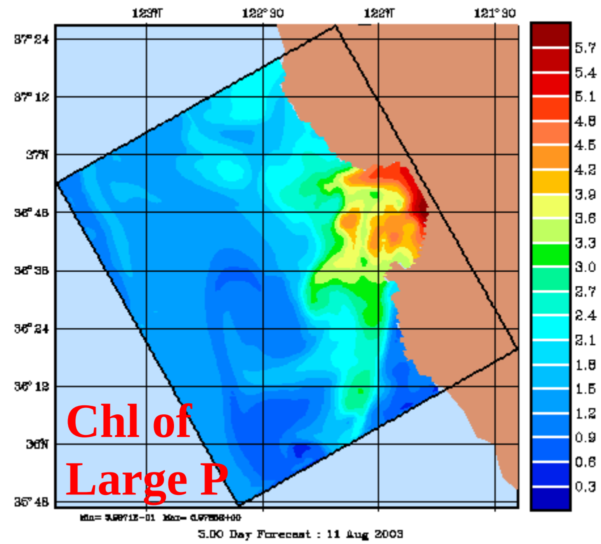


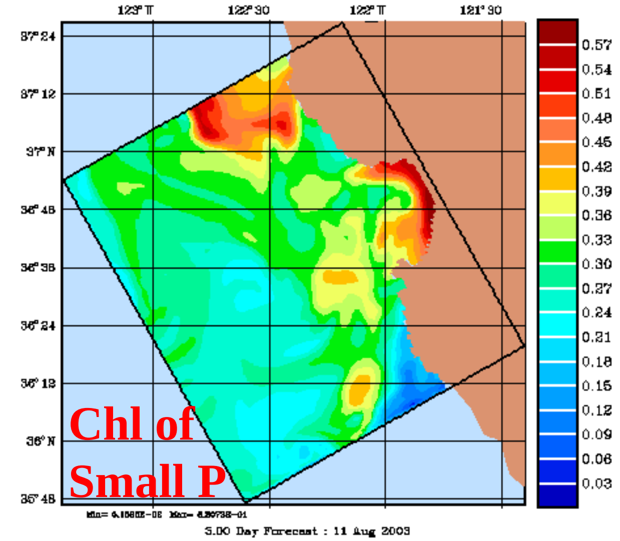
Another configuration with PO_4 and $Si(OH)_4$

Towards automated quantitative model aggregation and simplification

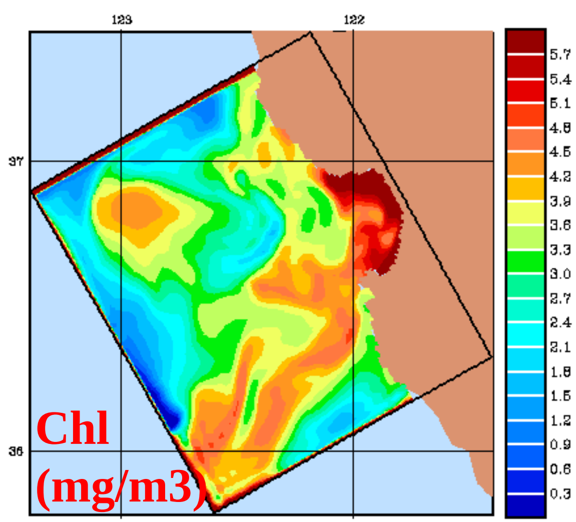
A priori configuration of generalized model on Aug 11 during an upwelling event

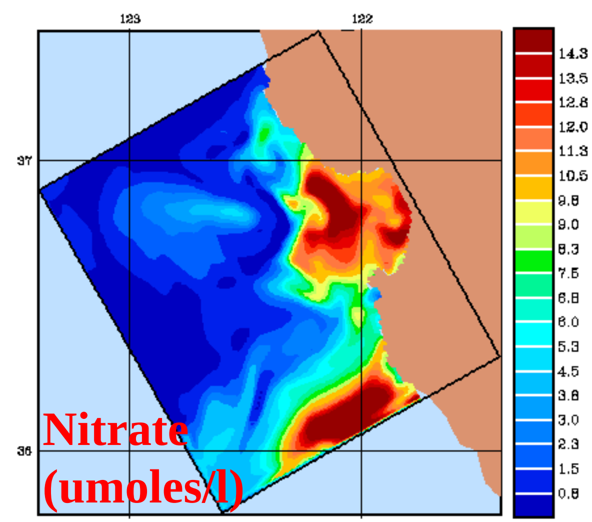


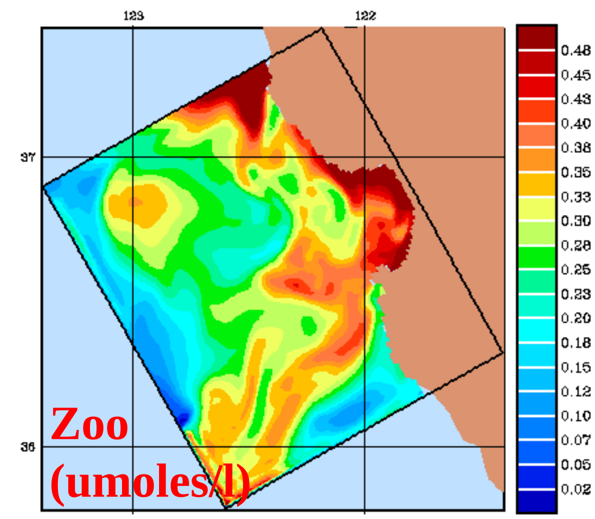




Simple NPZ configuration of generalized model on Aug 11 during same upwelling event



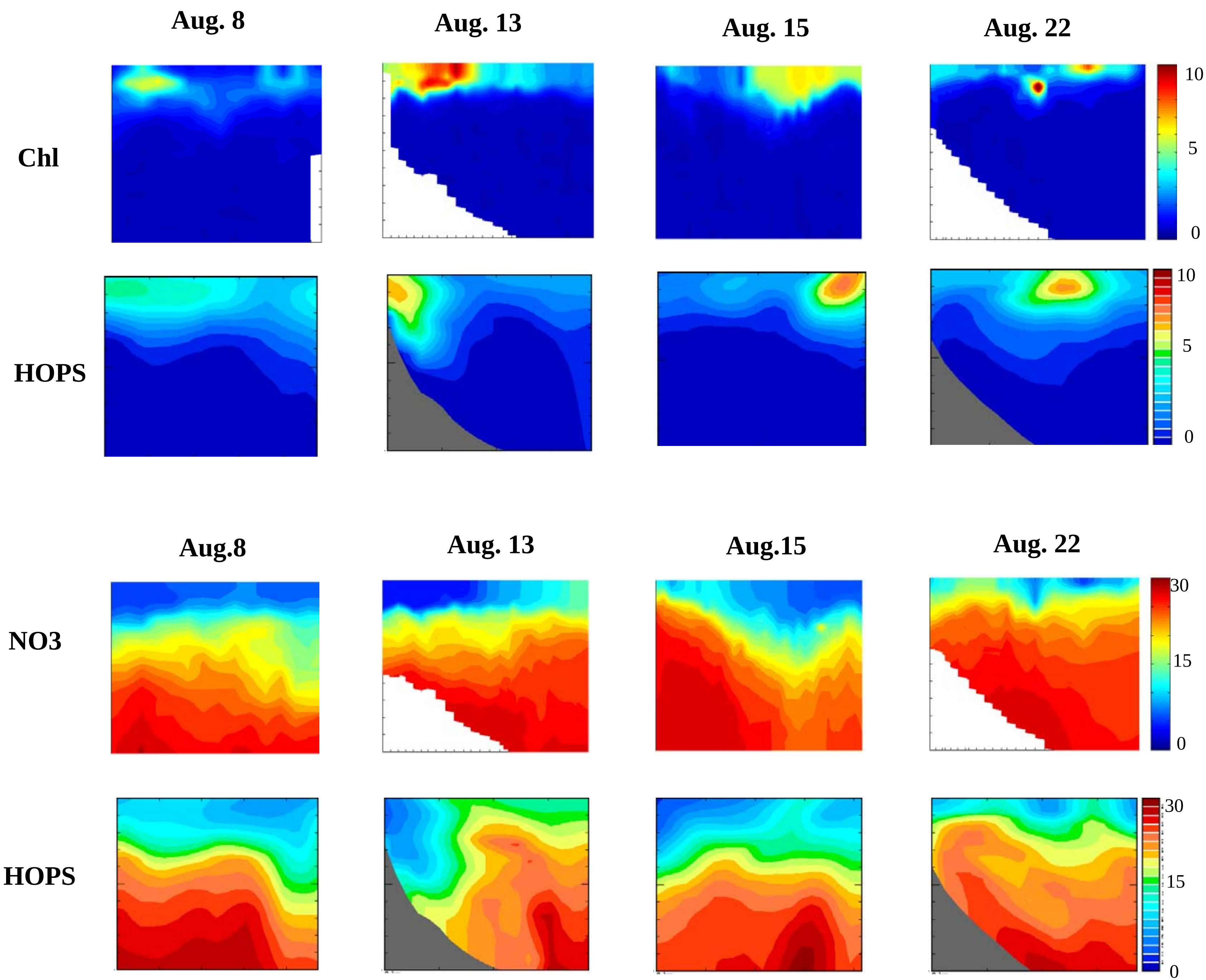




Dr. Rucheng Tian

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**

PROCESSES

1. **Deeper nutricline and stronger blooms during upwelling**
2. **Much smaller scale hot-spots and shallower nutricline during relaxation (oceanic driven sub-mesoscales)**

Flux Balances and Term-by-term Balances

- Flux: Rate at which quantity flows through a surface
  [Quantity * m/s] or [(Quantity *m^3/s) /m^2]
  For heat: W/m^2 through any surface

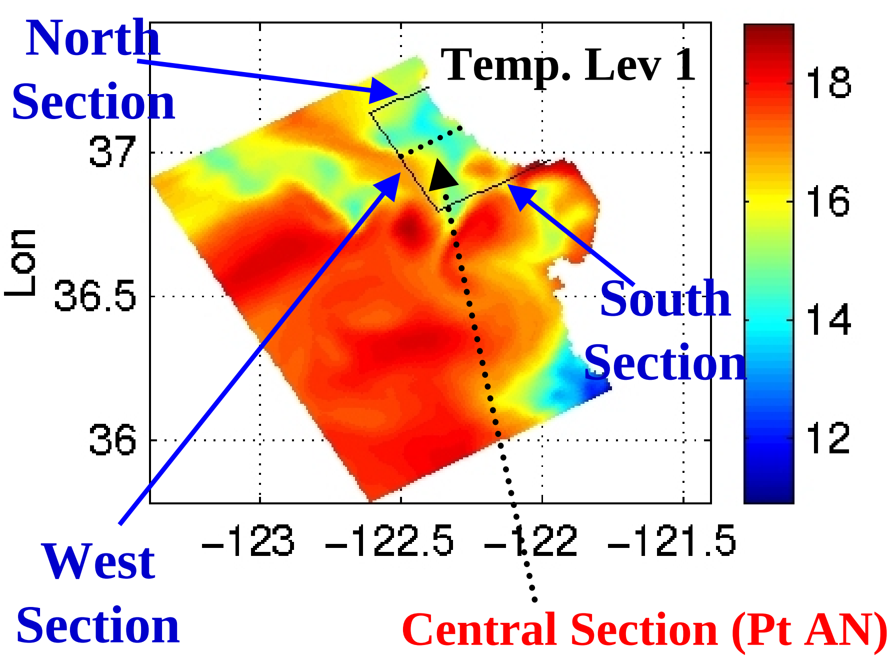
- Term: Rate of change of single term in PE
  [Quantity/sec]
  For Temp.: ^{o}C/s

Thermal en. $$\frac{DT}{Dt} = \nabla_h \cdot (K_h \nabla_h T) + \frac{\partial\ K_v\, \partial T/\partial z}{\partial z}$$

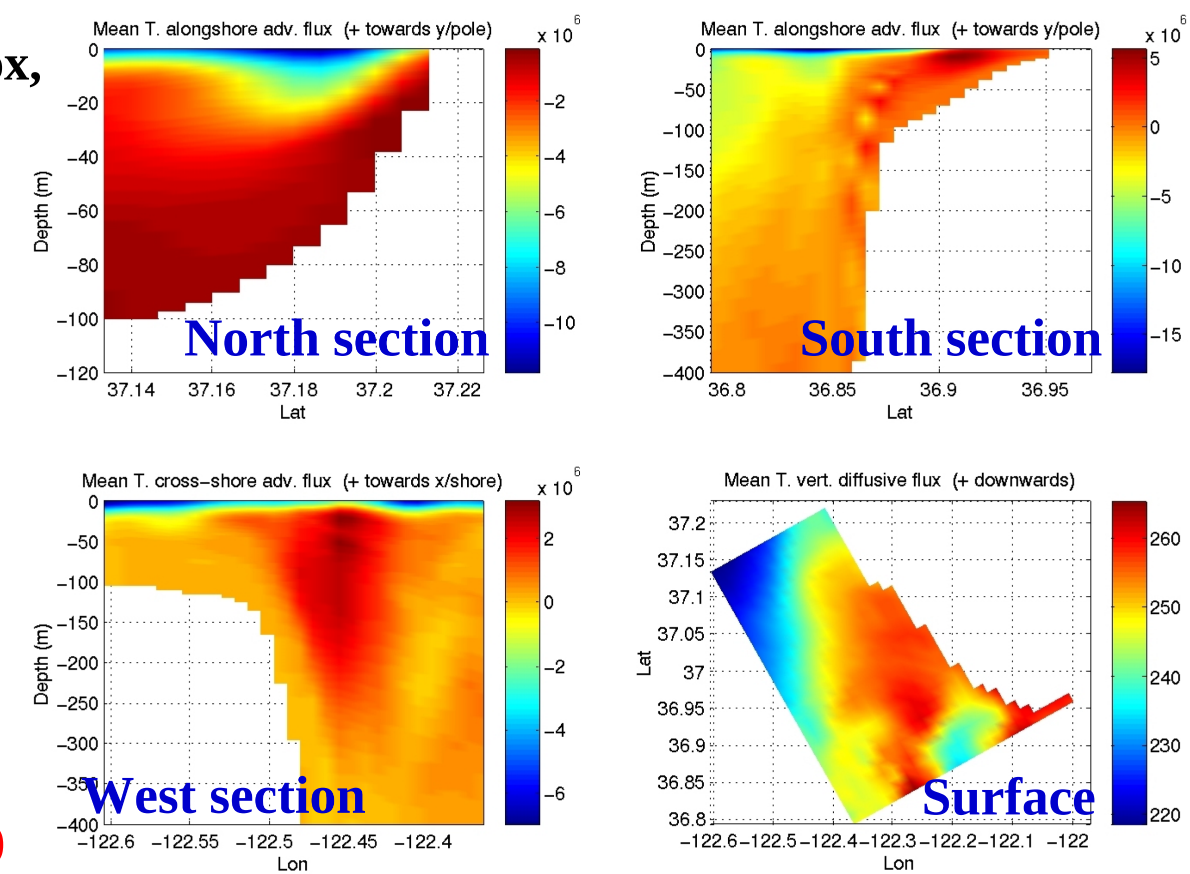
Cons. of salt $$\frac{DS}{Dt} = \nabla_h \cdot (K_h \nabla_h S) + \frac{\partial\ K_v\, \partial S/\partial z}{\partial z}$$

1) Heat Flux Balances:

4 fluxes normal to each side of Pt. AN box, averaged over first upwelling period

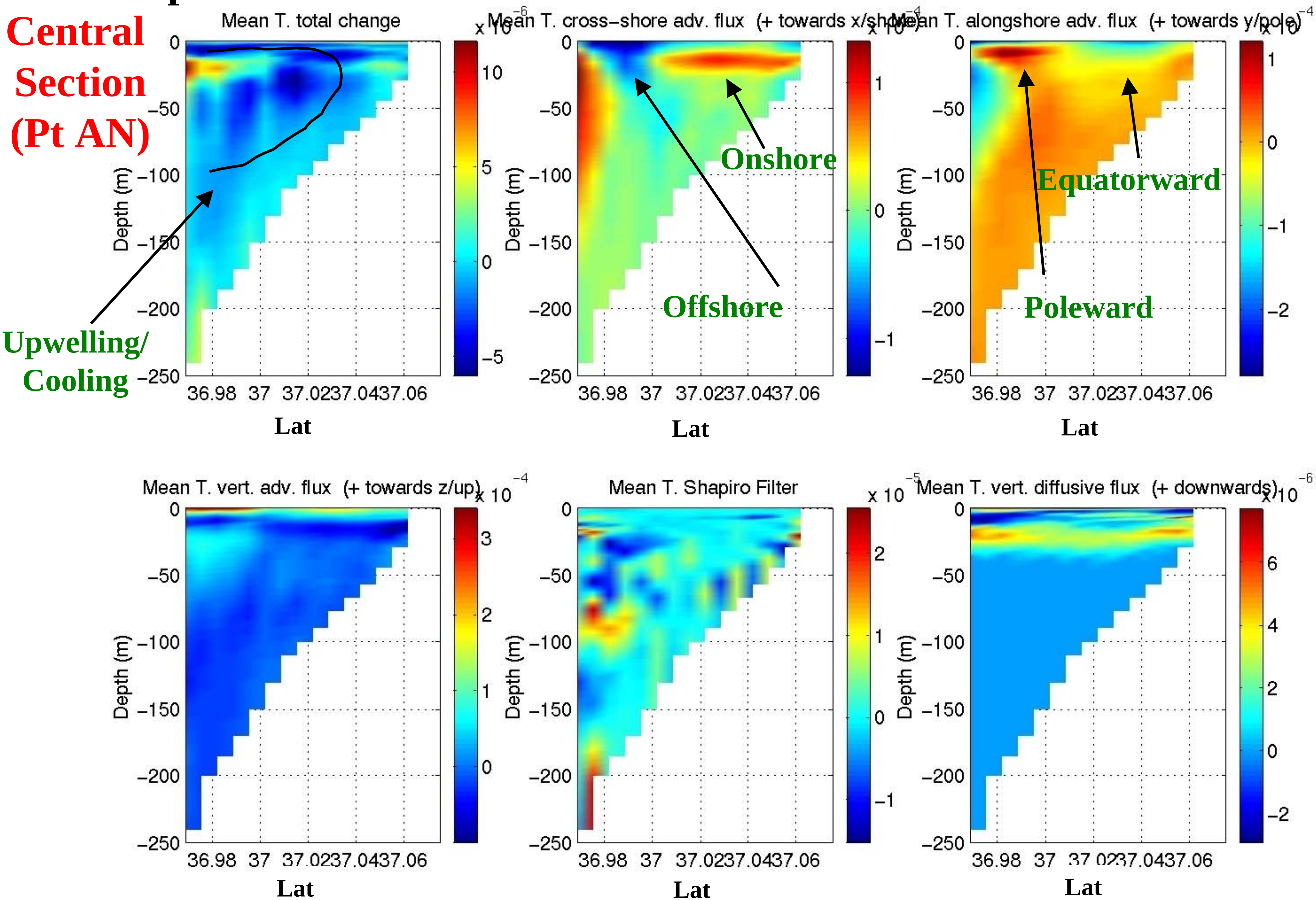


Mean Fluxes (W/m2) over: August 6, 2003 – 10:30:00pm -> August 13, 2003 – 4:30:00am GMT



2) Mean Term-by-Term Temp. balances

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



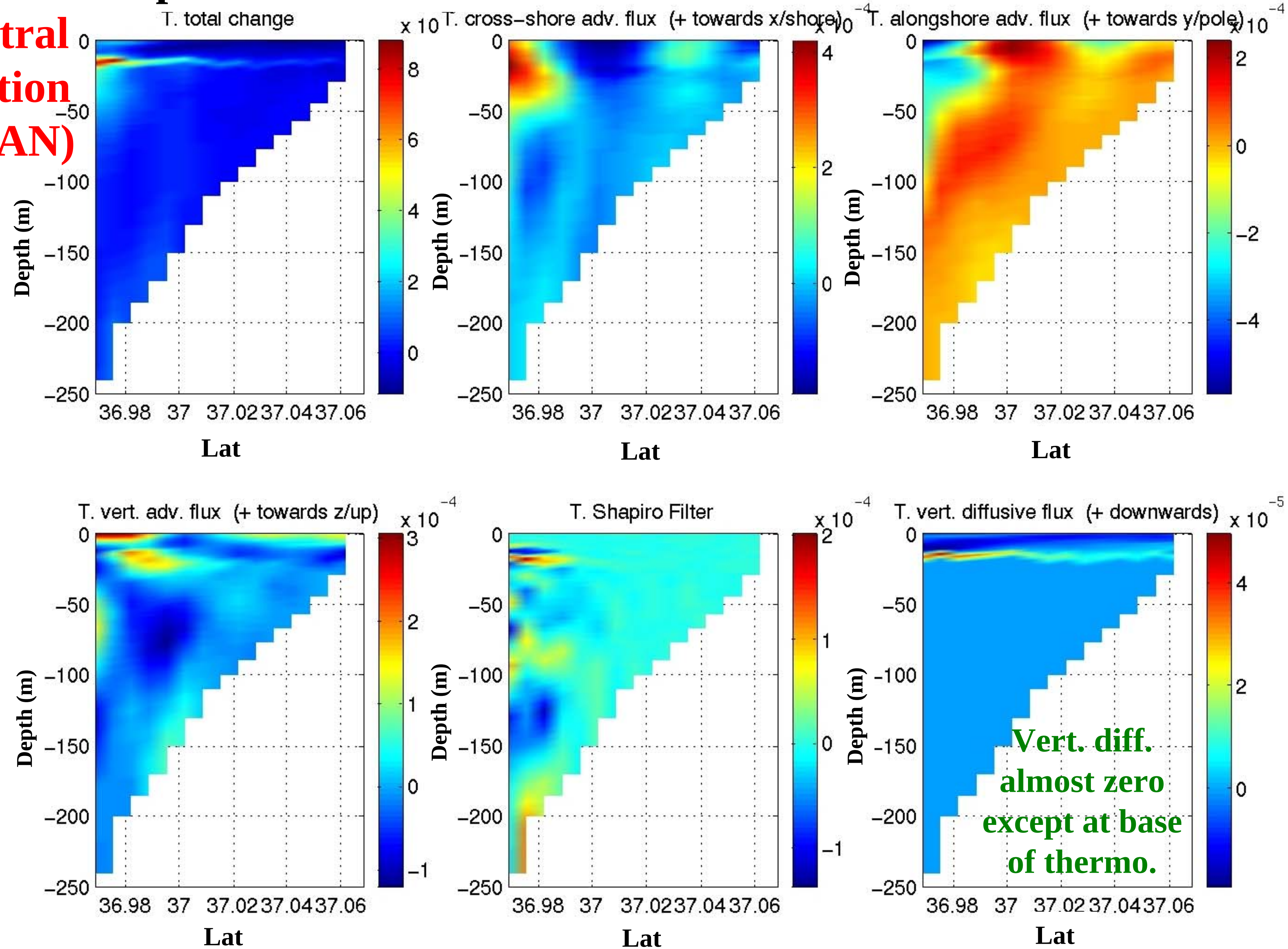
Mean Rate of change ≈ (Cross-shore +Alongshore +Vertical) Advection

Snapshot Term-by-Term Temp. balances

August 13, 2003 – 12:00:00pm GMT

Complex 3D non-homogenous upwelling (eddies, meanders of upwelling current and jets, etc)

Central Section (Pt AN)

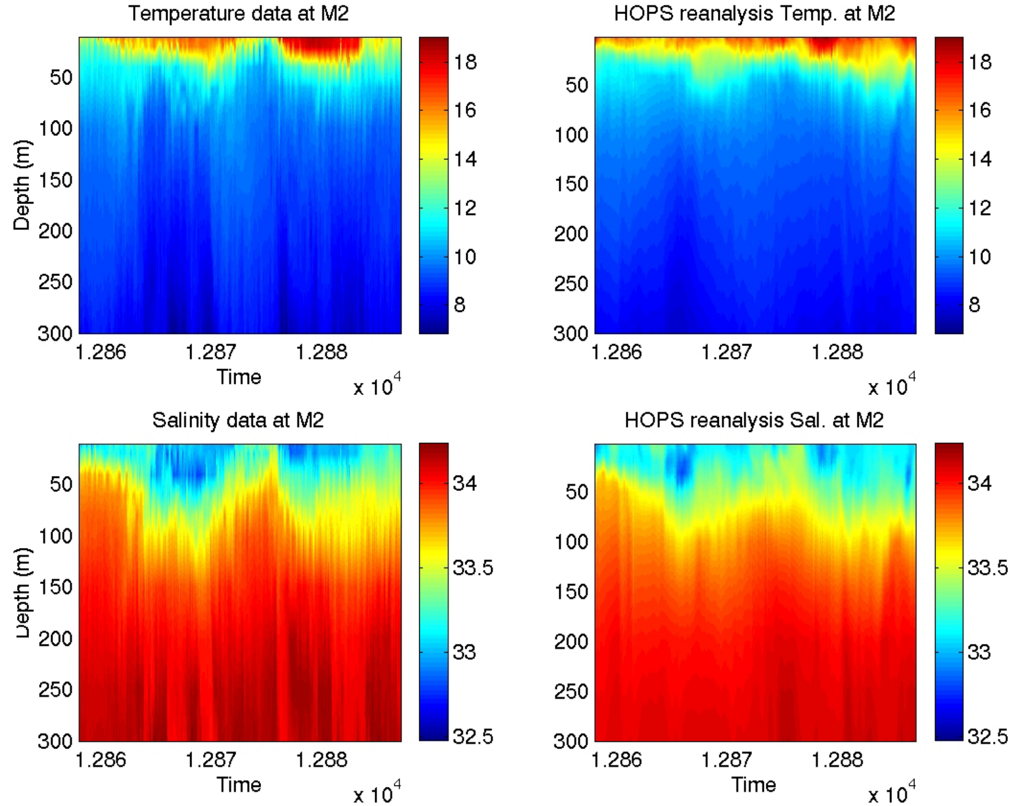


Mean Rate of change ≈ (Cross-shore +Alongshore +Vertical) Advection

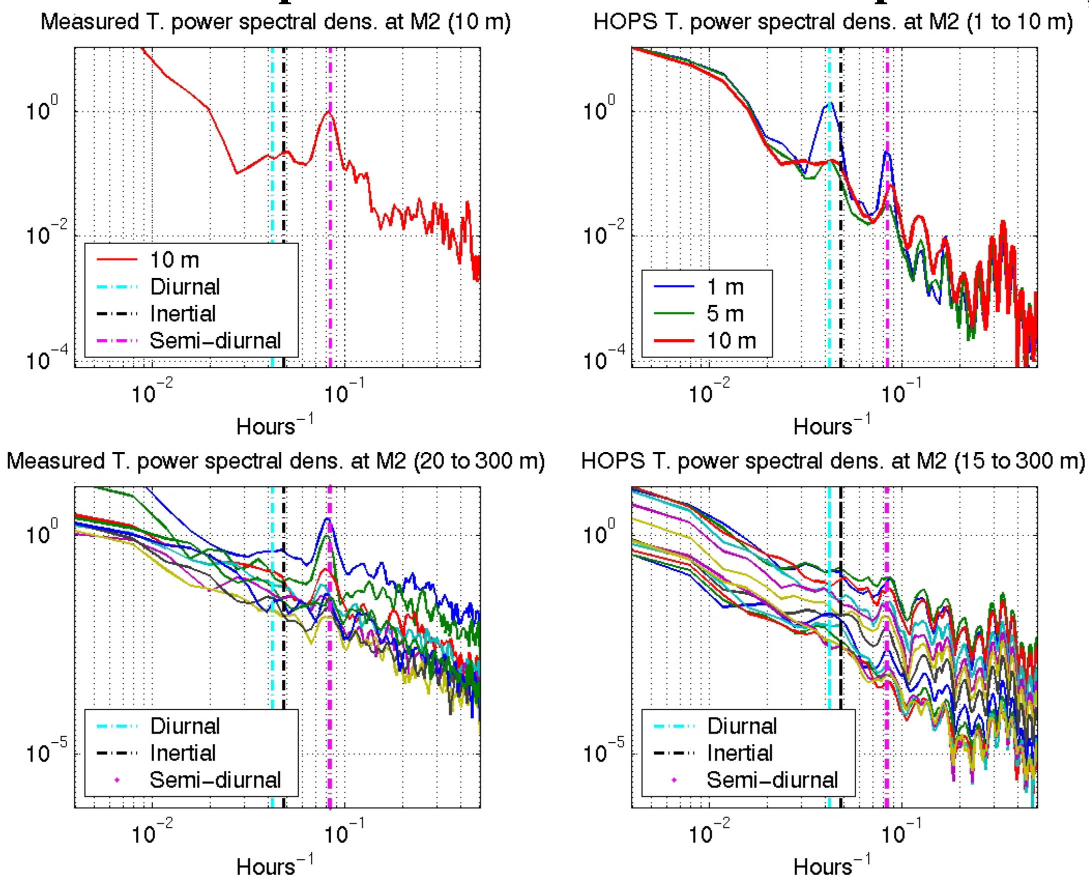
AOSN-II Motivations for Near-Inertial and Tidal Modeling

- **Model-Data Comparisons**
  - Data-driven model with no tides vs. Data at M1/M2 (T,S,U,V)

M2 Data Time series / M2 HOPS Time Series



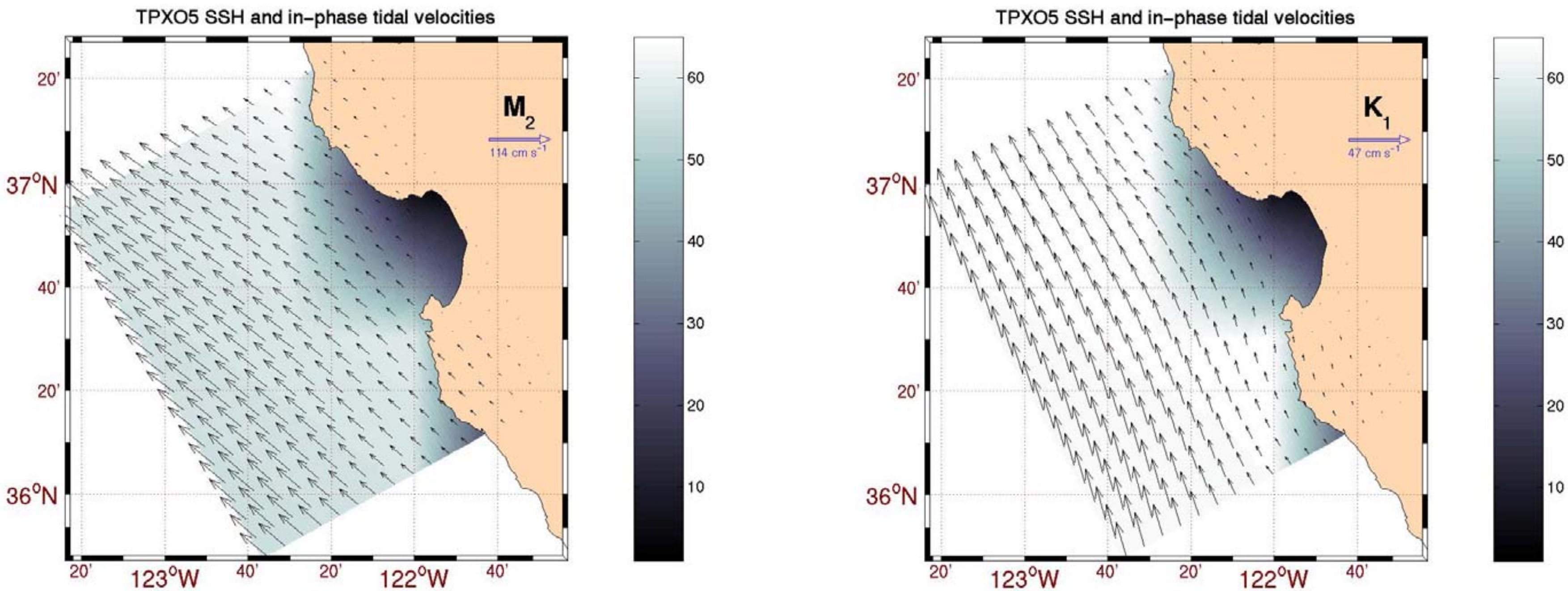
M2 Data Spectra / M2 HOPS Spectra



- **Spectra Results**
  - Diurnal band obvious in 1-5m HOPS (not measured by M2)
  - Spectra similar within mesoscale to inertial band.
  - Semi-diurnal in HOPS forced by wind
  - Too low energy for sub-inertial scales: add deterministic (tides) and/or stochastic forcing (ESSE)

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



To be cross-evaluated with Leslie Rosenfeld and Igor Shulman

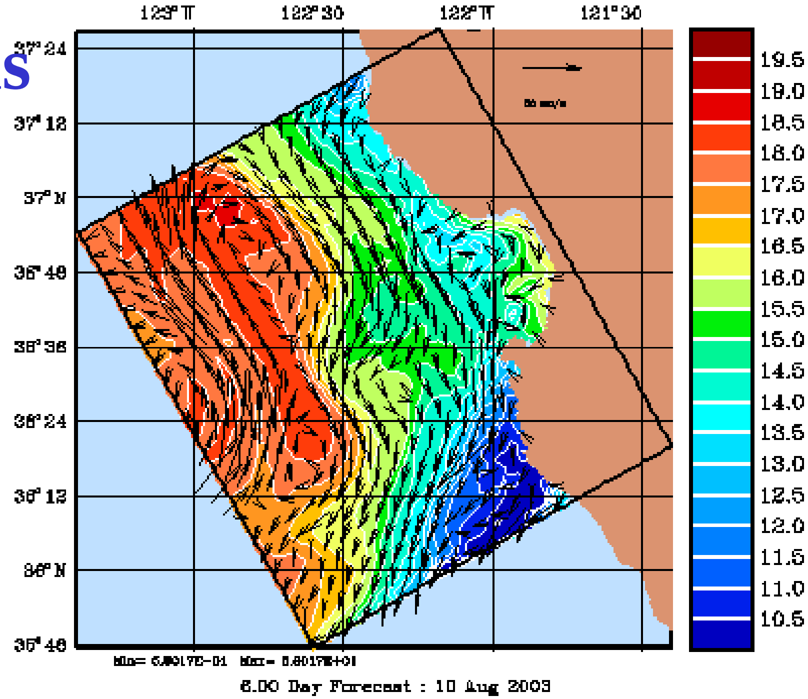
- Used to estimate hierarchy of tidal parameterizations :
  - **i. Vertical tidal Reynolds stresses (diff., visc.)** $K_T = \alpha \, ||\boldsymbol{u}_T||^2$ and $K = max(K_S, K_T)$
  - **ii. Modification of bottom stress** $\tau = C_D \, ||\boldsymbol{u}_{S+} \, \boldsymbol{u}_T|| \, \boldsymbol{u}_S$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

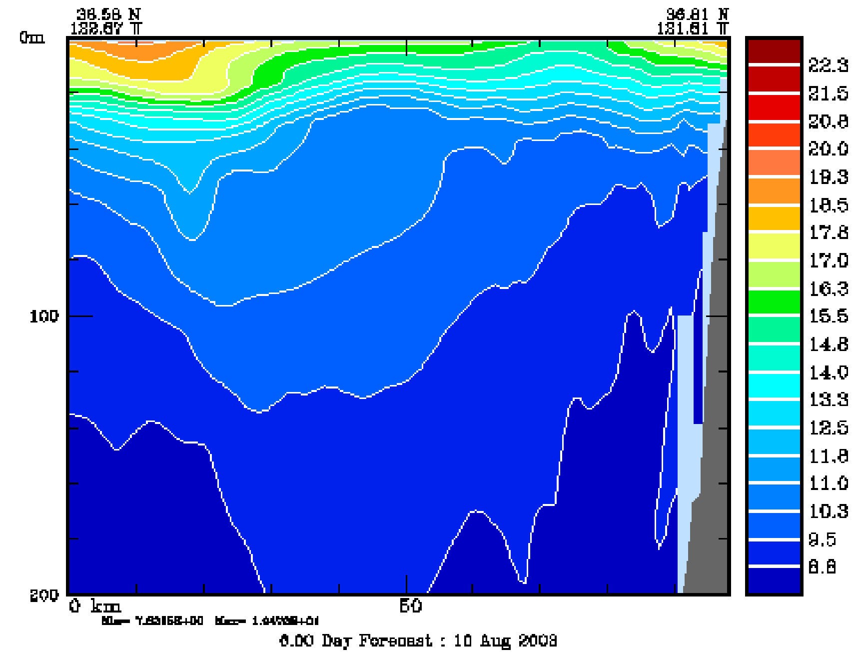
Two 6-day model runs

Temp. at 10 m

T section across Monterey-Bay

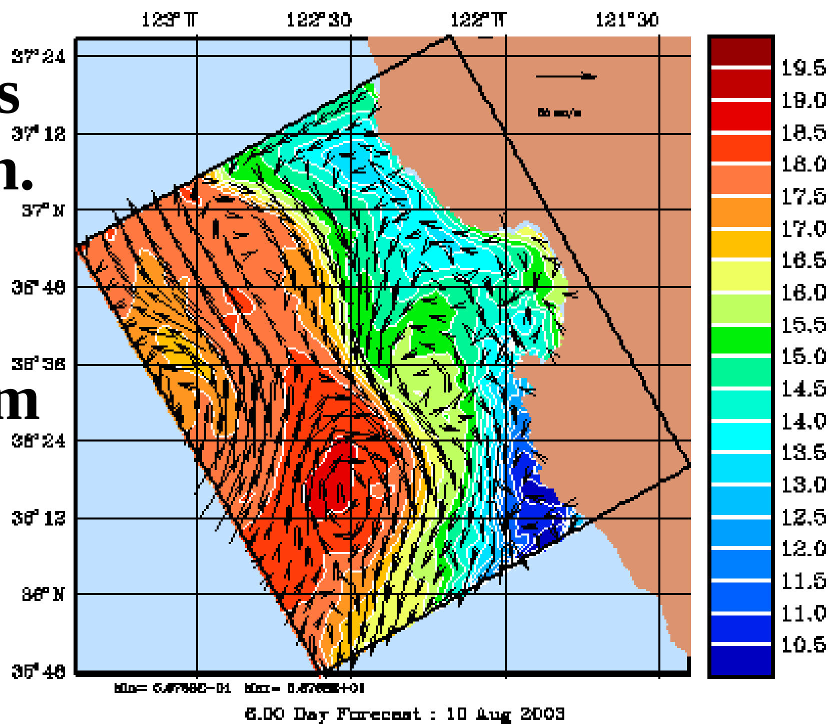
No-tides

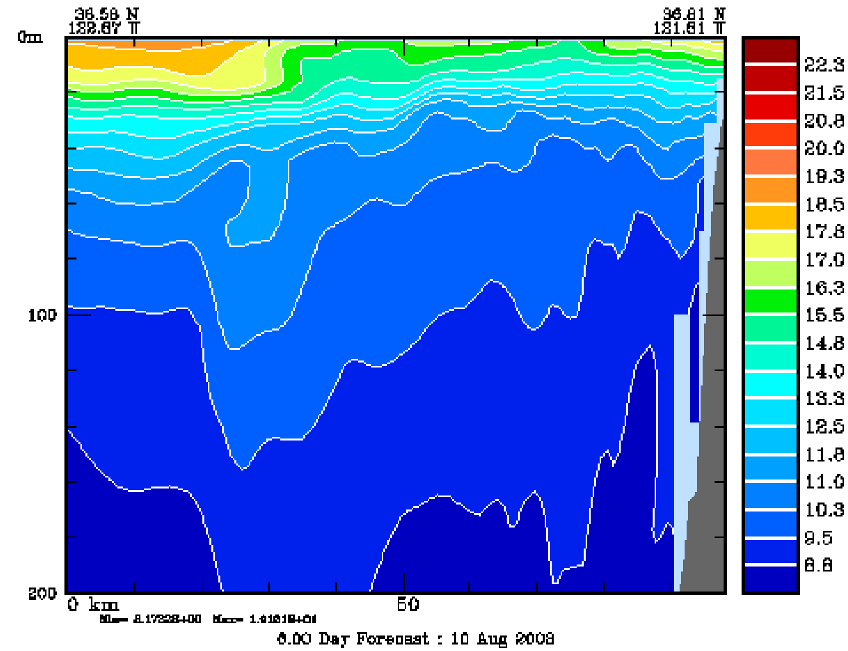




Tidal effects

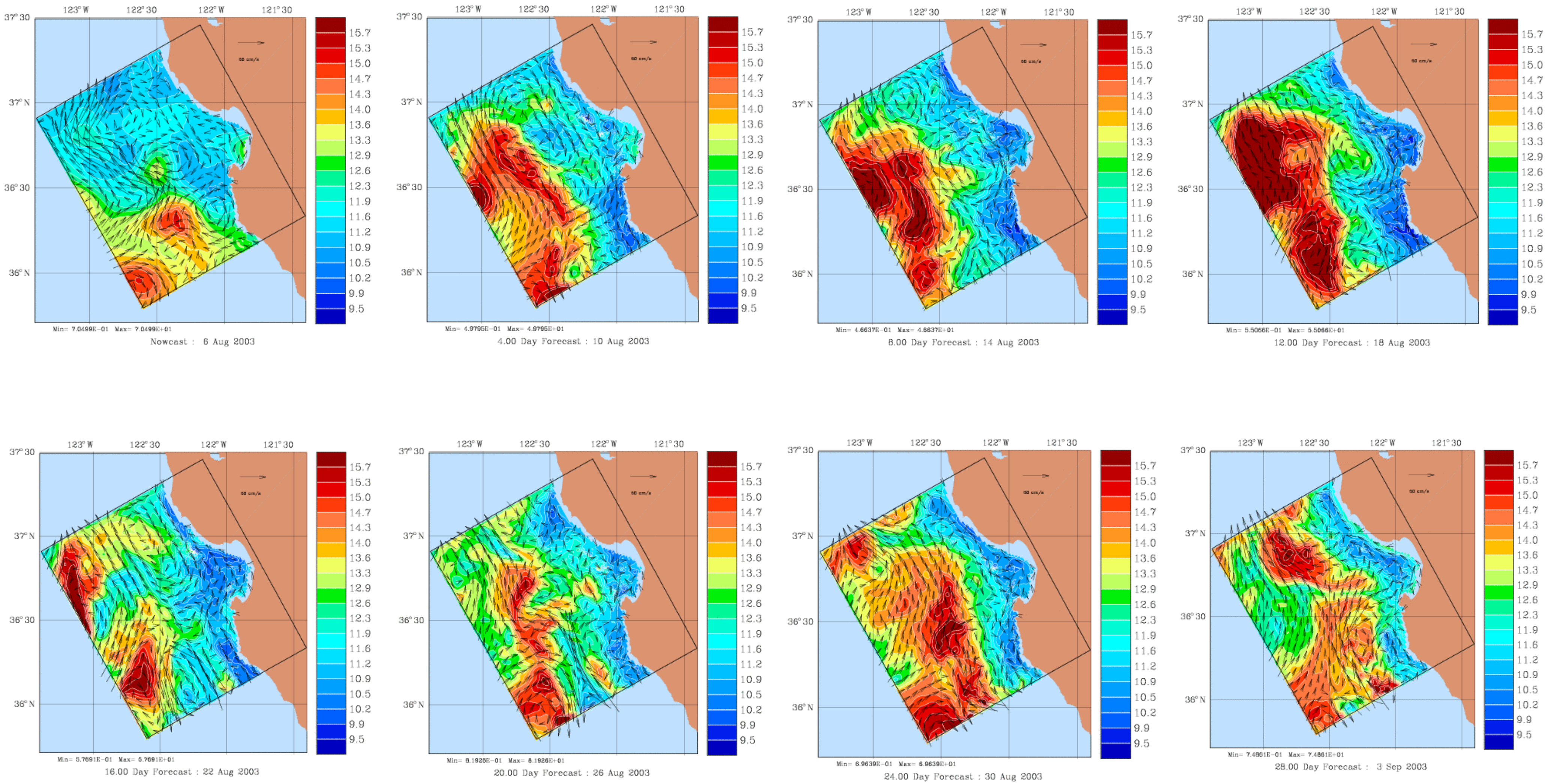
- Vert. Reyn. Stress
- Horiz. Momentum Stress





AOSN-II Re-Analysis

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



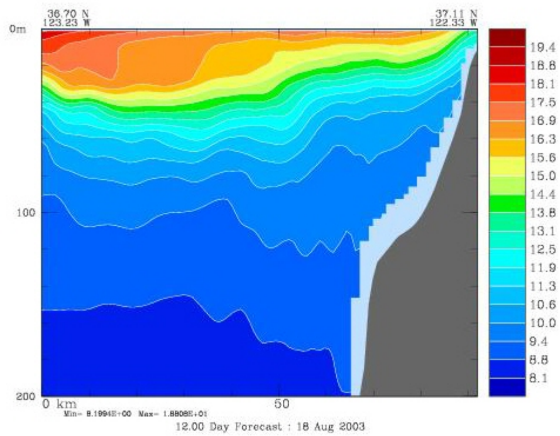
Descriptive oceanography of re-analysis fields and and real-time error fields initiated at the mesoscale.

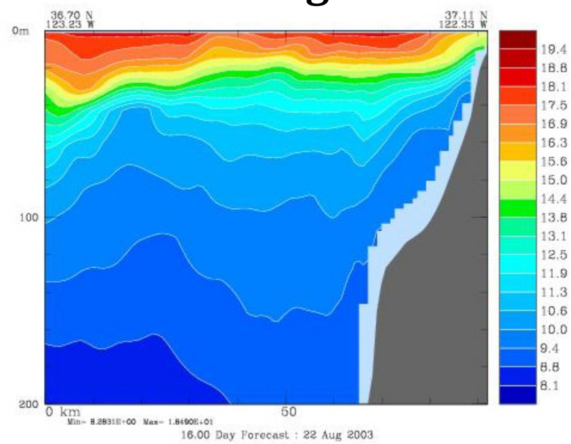
Description includes: Upwelling and relaxation stages and transitions, Cyclonic circulation in Monterey Bay, Diurnal scales, Topography-induced small scales, etc.

AOSN-II Re-Analysis

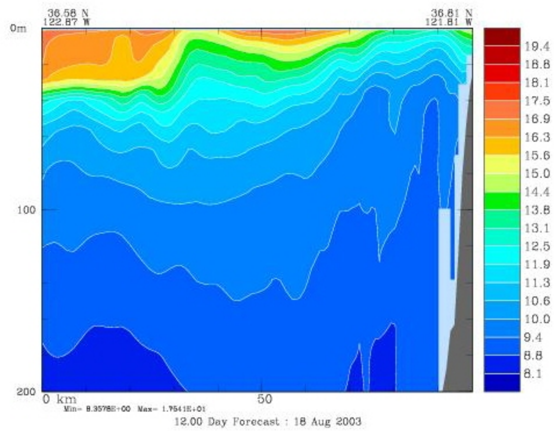
18 August | **22 August**

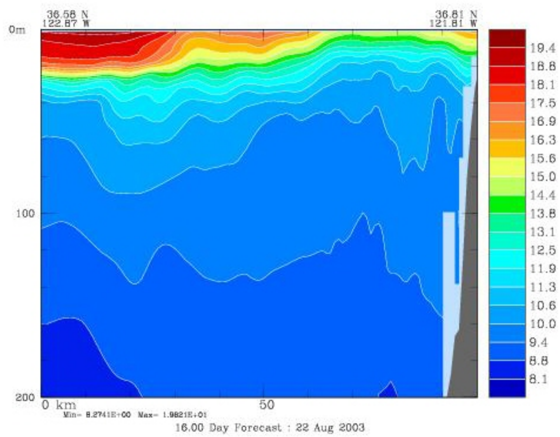
Ano Nuevo



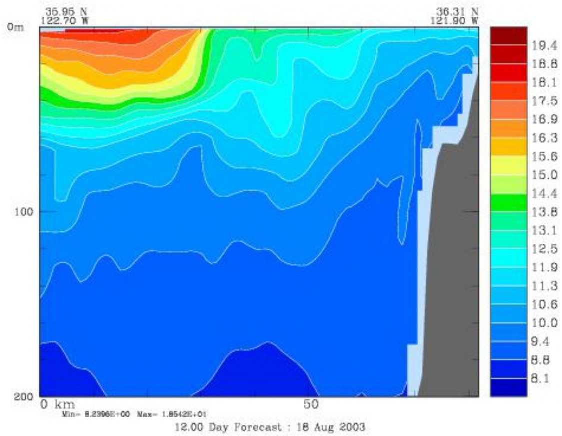


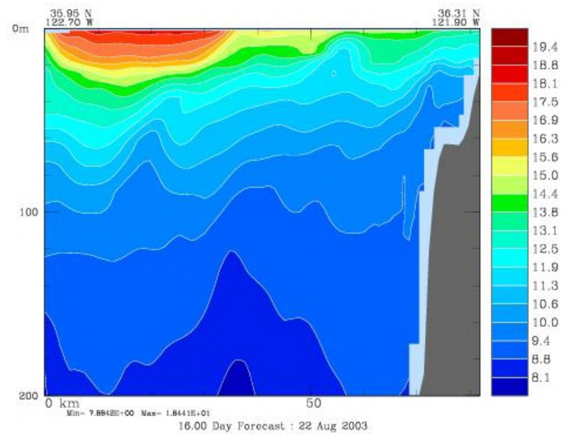
Monterey Bay





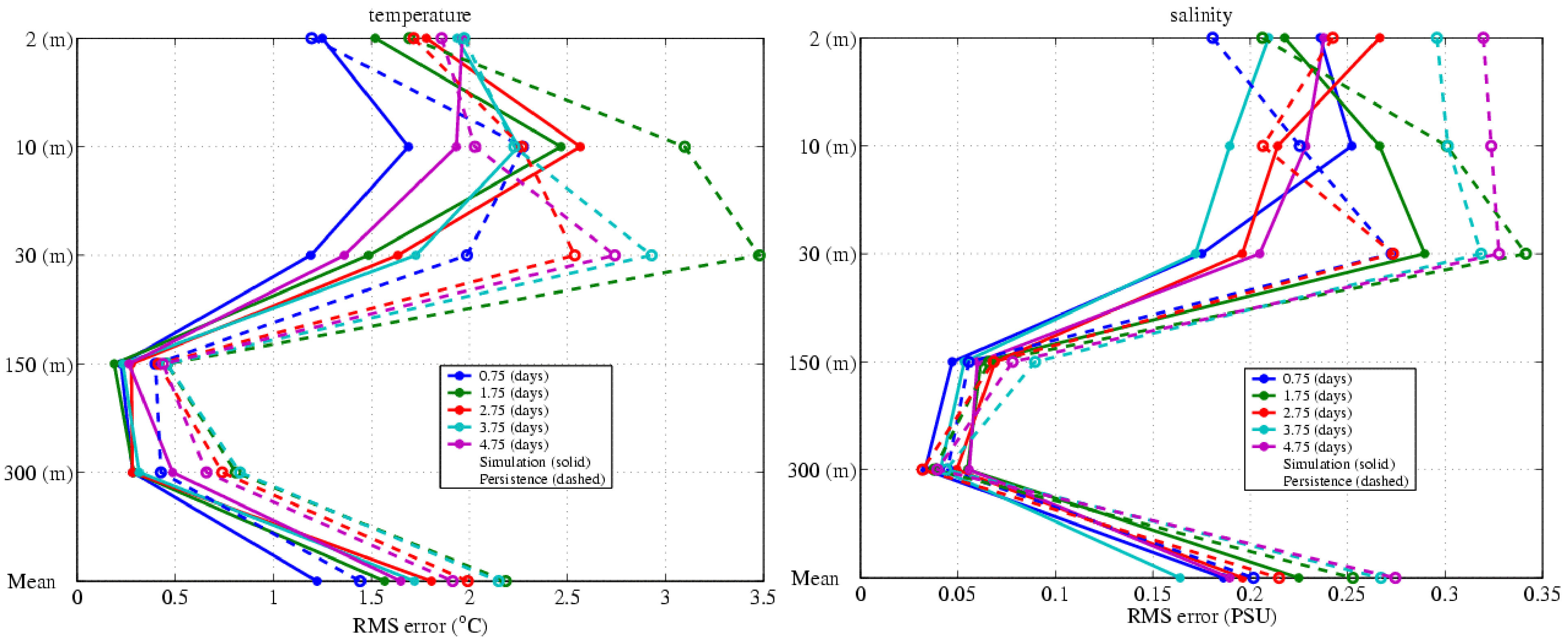
Point Sur





AOSN-II – Skill Metrics

These metrics were generated from a simulation reproducing the reanalysis but only using data from August 2-20, 2003, prior to the second Pt Sur Survey. The forecast fields for the second Pt Sur Survey (Aug 21-26, 2003) were compared to all the data collected during the survey. The data persistence fields, used for comparison, were created from an OA of all AOSN-II data prior to the second Pt Sur Survey.



Implementation of Free Surface in HOPS

Explicitly maintain surface pressure

Allow vertical levels to deform according to free surface, related to surface pressure via $p_s = g\rho_0\eta$

Compute surface pressure with Dukowicz and Smith algorithm

- implicit in time for greater stability
- split-time algorithm to enable use of efficient conjugate gradient solvers

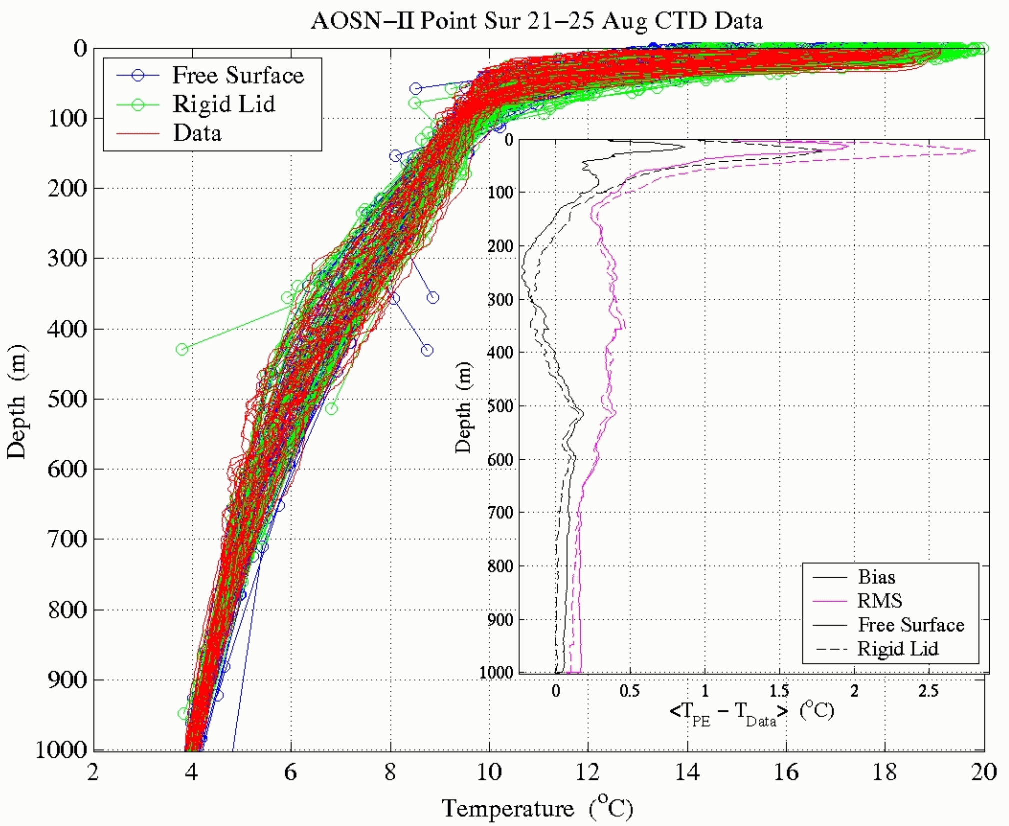
Adaptations for use in HOPS

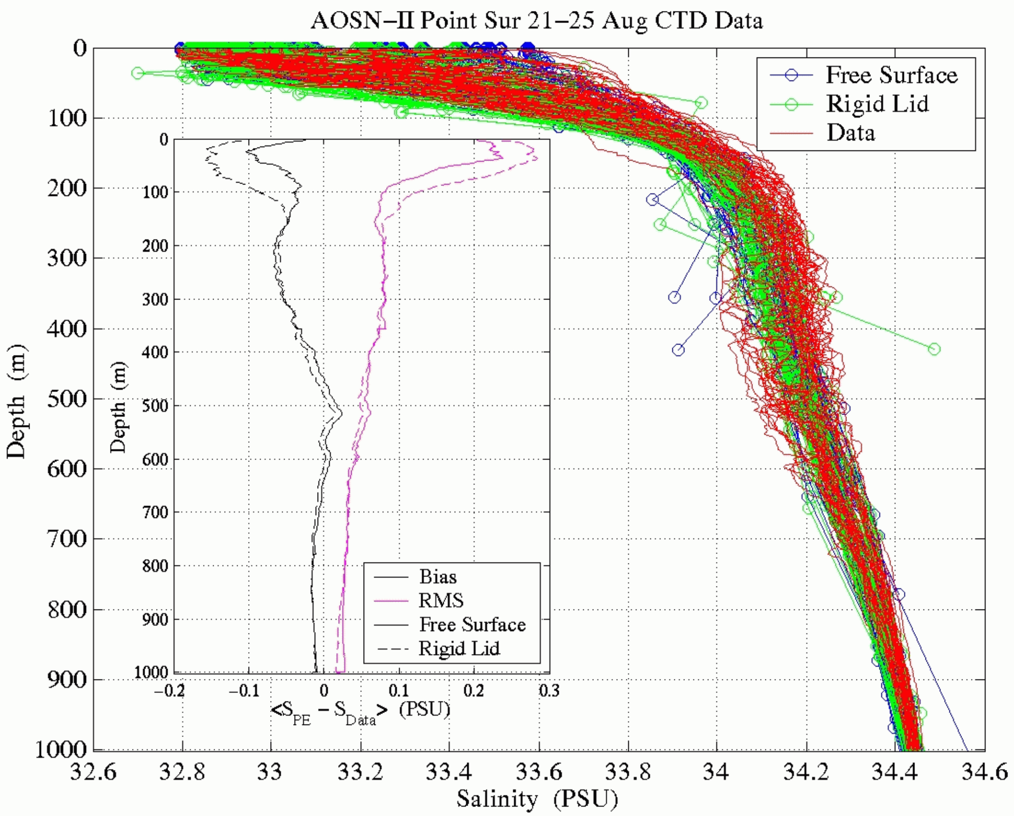
- synoptic initialization
- open boundary conditions
  –including barotropic tidal forcing
- assimilation
- two-way nesting (ongoing)

Validated for MREA-03 and AOSN-II

Implementation of Free Surface in HOPS

AOSN-II Validation





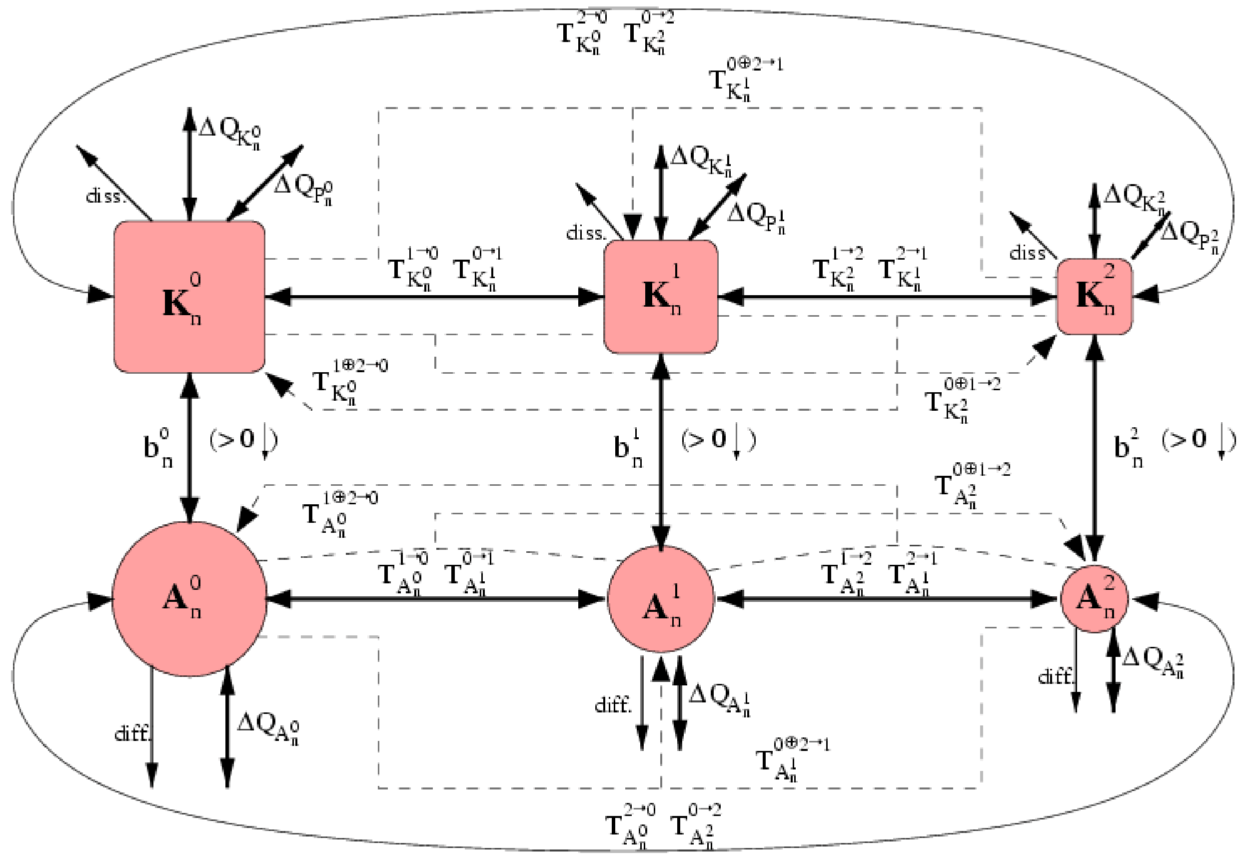
20 day simulation spanning Aug 6-26, 2003
Assimilate CTDs, gliders and aircraft SST from Aug 7-20, 2003
Compare to Pt Sur CTDs from Aug 21-25, 2003

- **Overall comparable skill**
- **Significant improvement in main thermocline**

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.

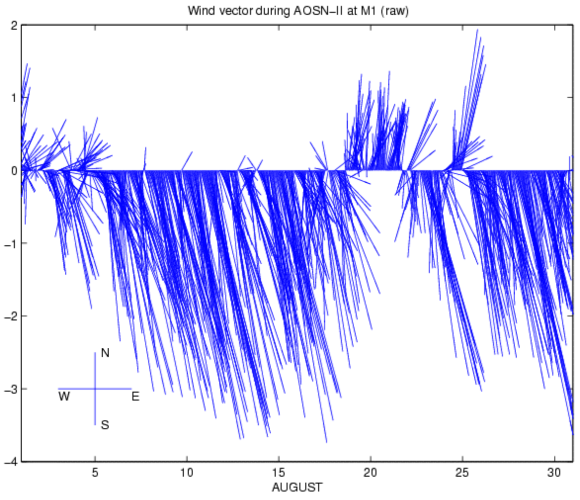
$BT + BC > 0$ => system locally unstable; otherwise stable

If $BT + BC > 0$, and

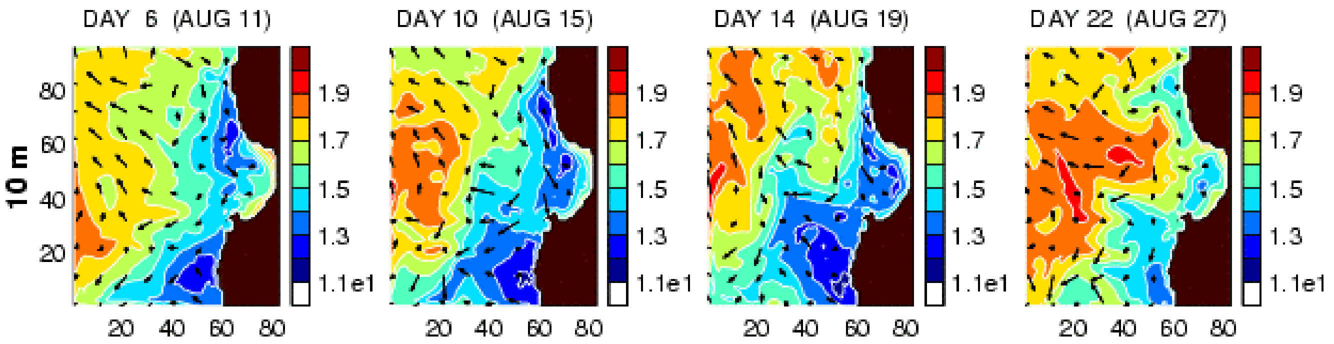
- $BC \leq 0$ => barotropic instability;
- $BT \leq 0$ => baroclinic instability;
- $BT > 0$ and $BC > 0$ => mixed instability

Multi-Scale Energy and Vorticity Analysis

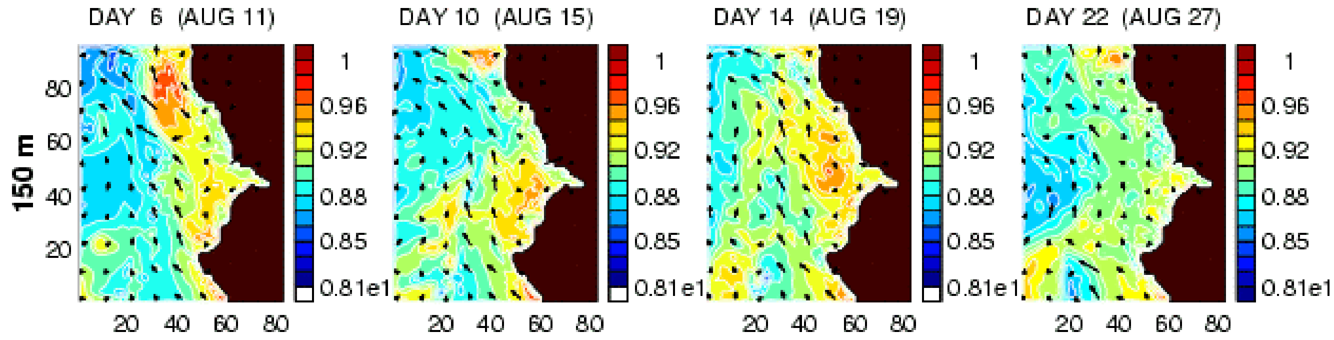
AOSN-II



M1 Winds

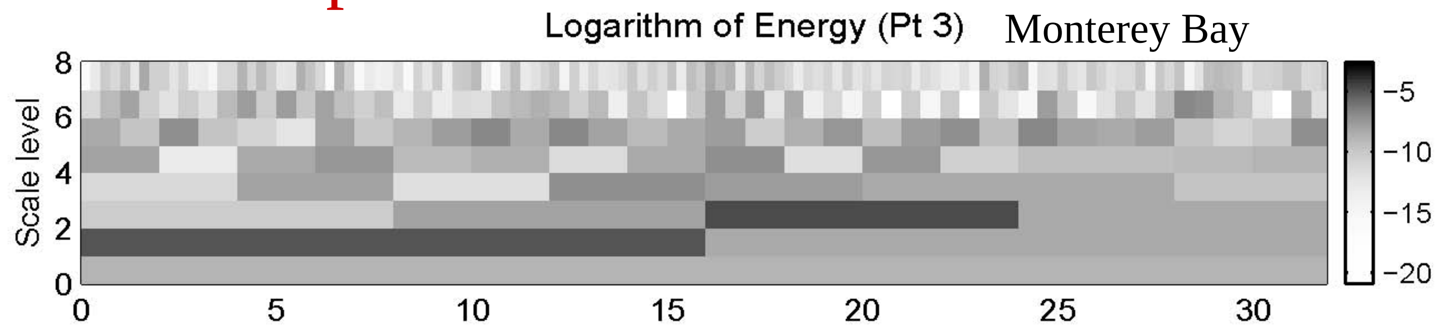


Temperature at 10m

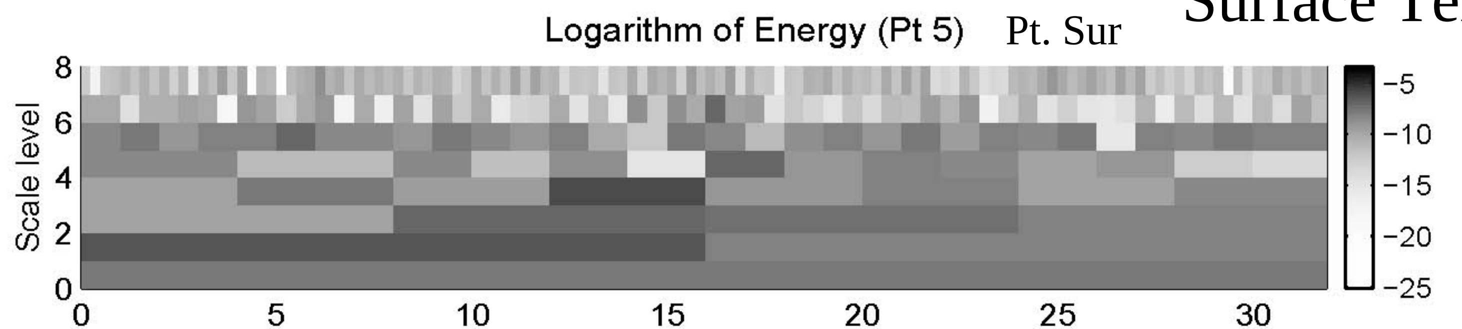


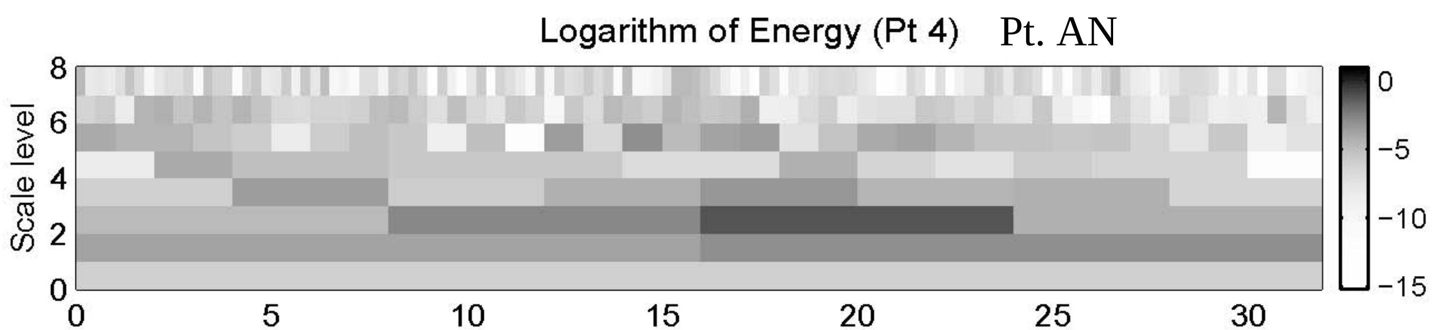
Temperature at 150m

Wavelet Spectra

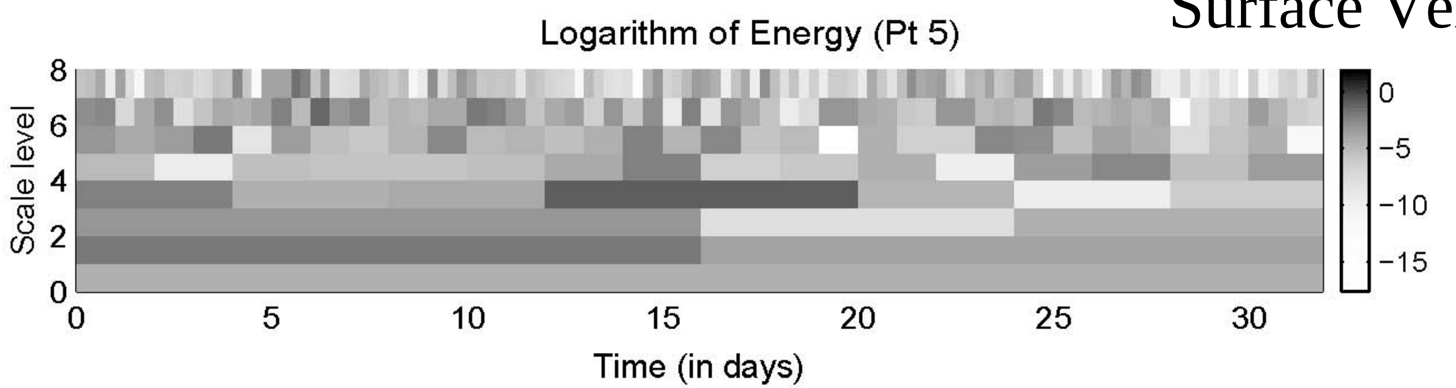


Surface Temperature



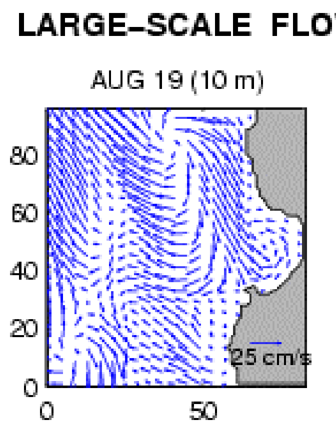


Surface Velocity



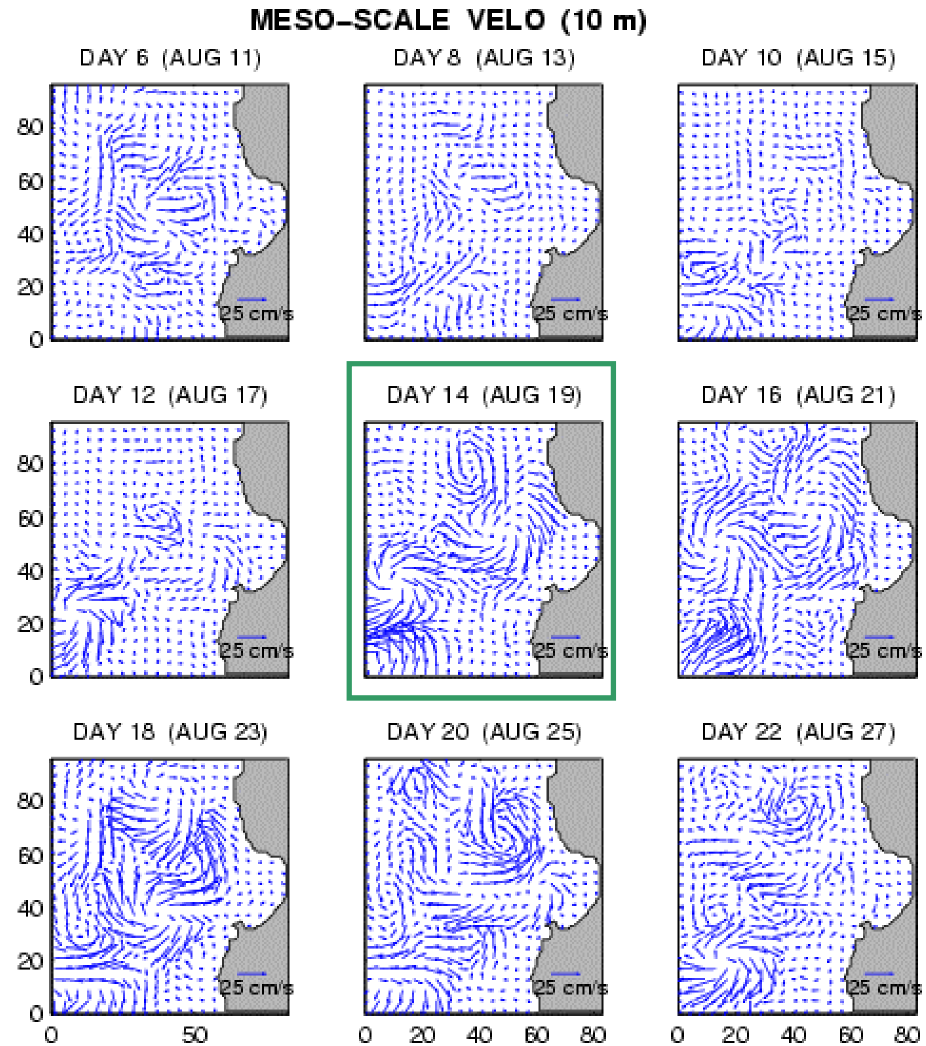
Multi-Scale Energy and Vorticity Analysis

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

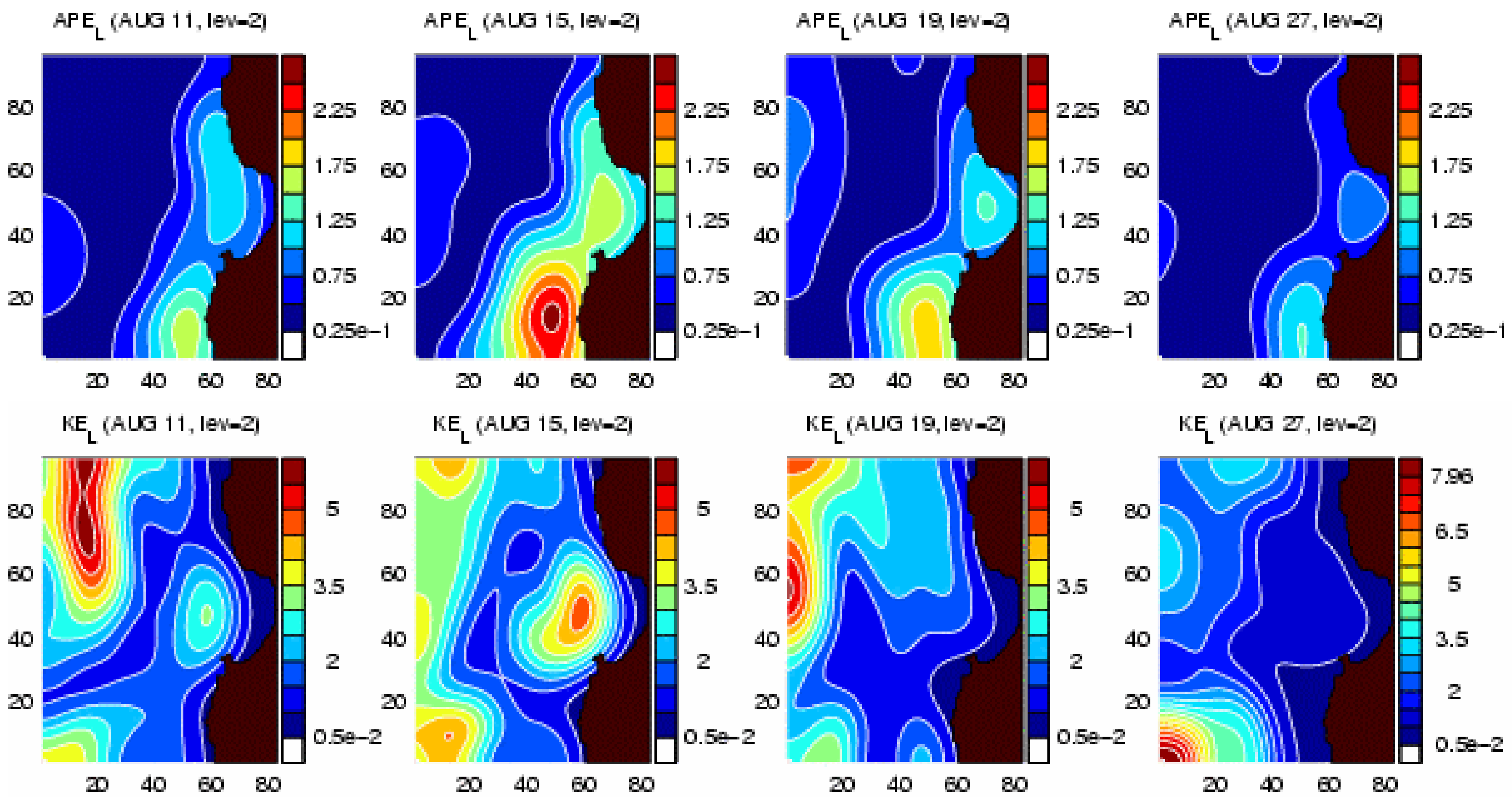


Question: How does the large-scale flow lose stability to generate the meso-scale structures?

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)

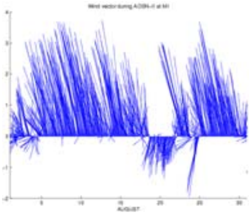
- Both APE and KE decrease during the relaxation period
- Transfer from large-scale window to mesoscale window occurs to account for decrease in large-scale energies (as confirmed by transfer and mesoscale terms)

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

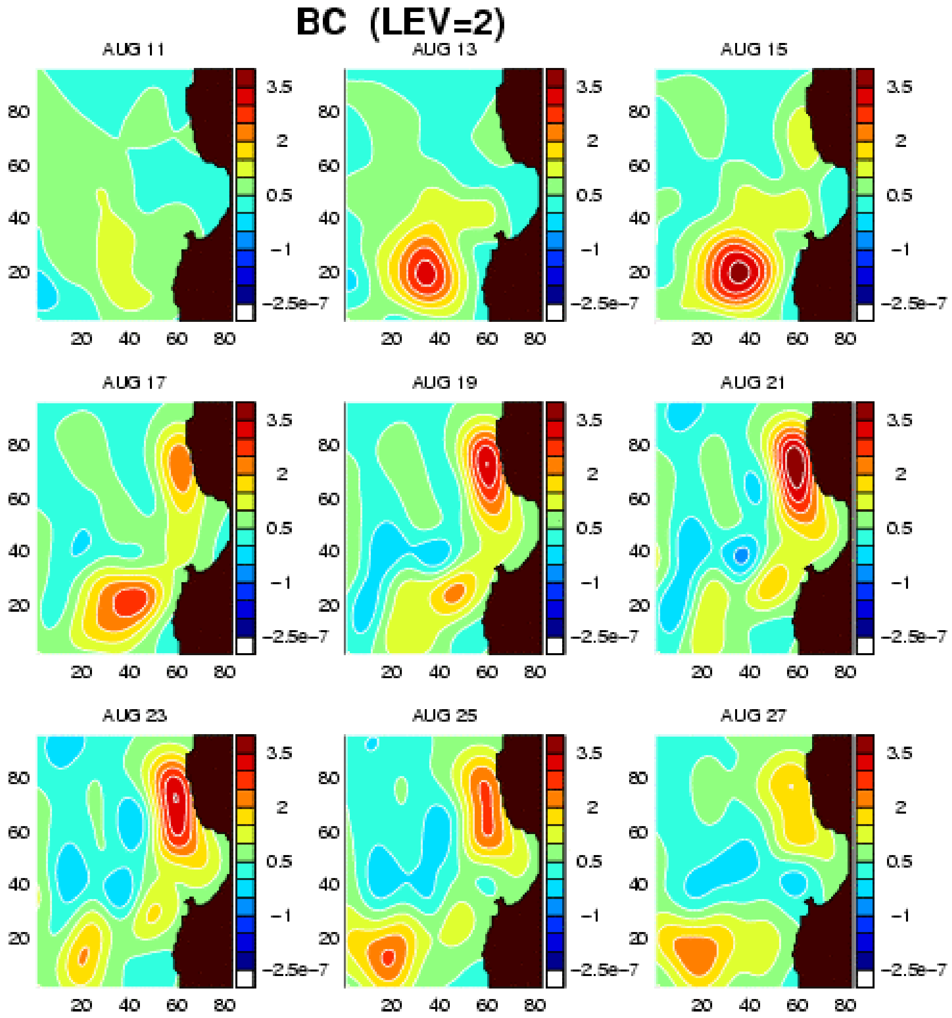
Dr. X. San Liang

Multi-Scale Energy and Vorticity Analysis

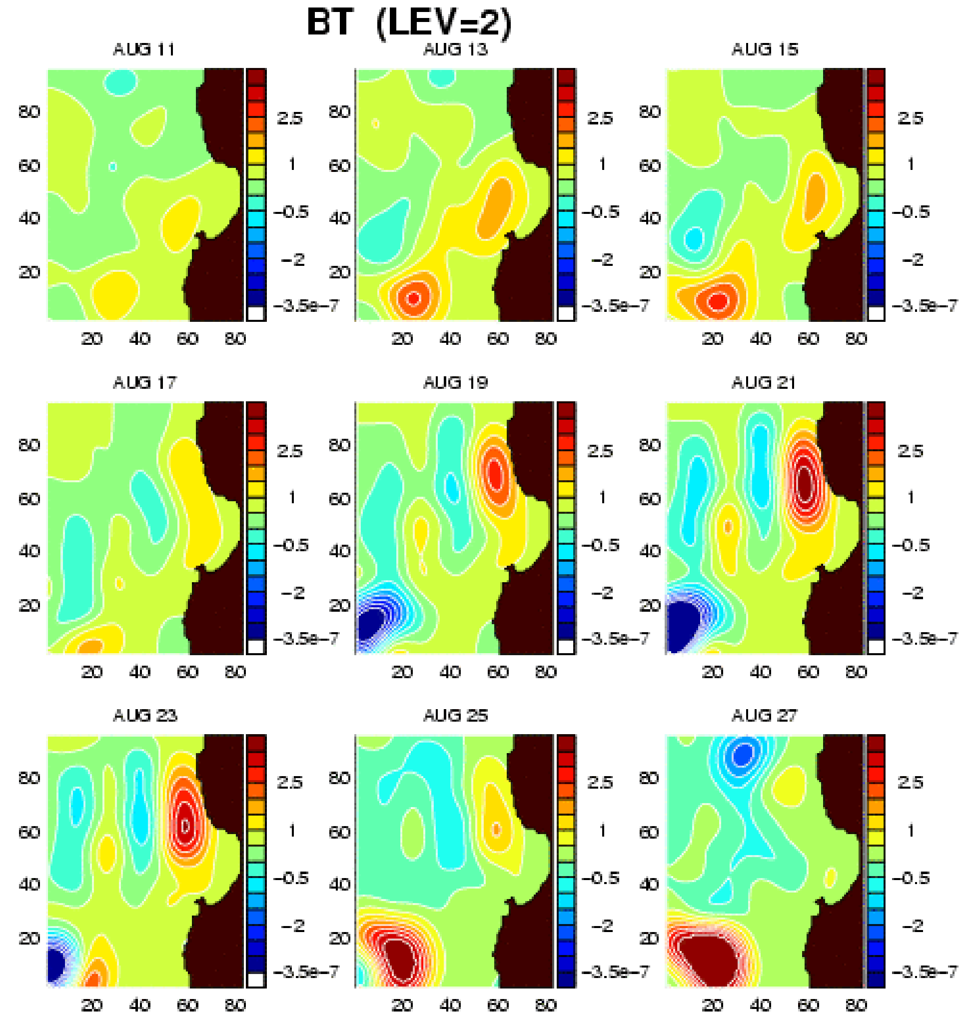
MS-EVA Analysis: 11-27 August 2003



Transfer of APE from large-scale to meso-scale



Transfer of KE from large-scale to meso-scale

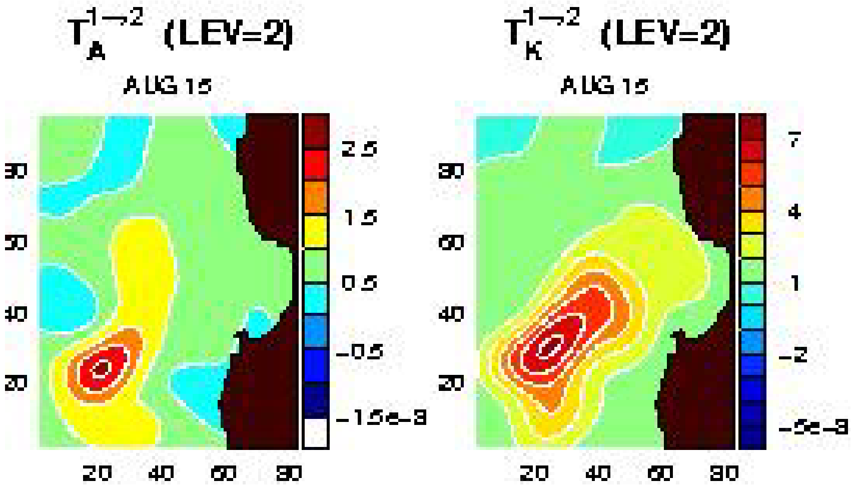


Multi-Scale Energy and Vorticity Analysis

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 through developed formalism of multi-model error parameter estimation*
- Model Fusion: *Combine models via Maximum-Likelihood based on the current estimates of their forecast errors*

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

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

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

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

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

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

O. Logoutov

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

Error 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. isotropic 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:

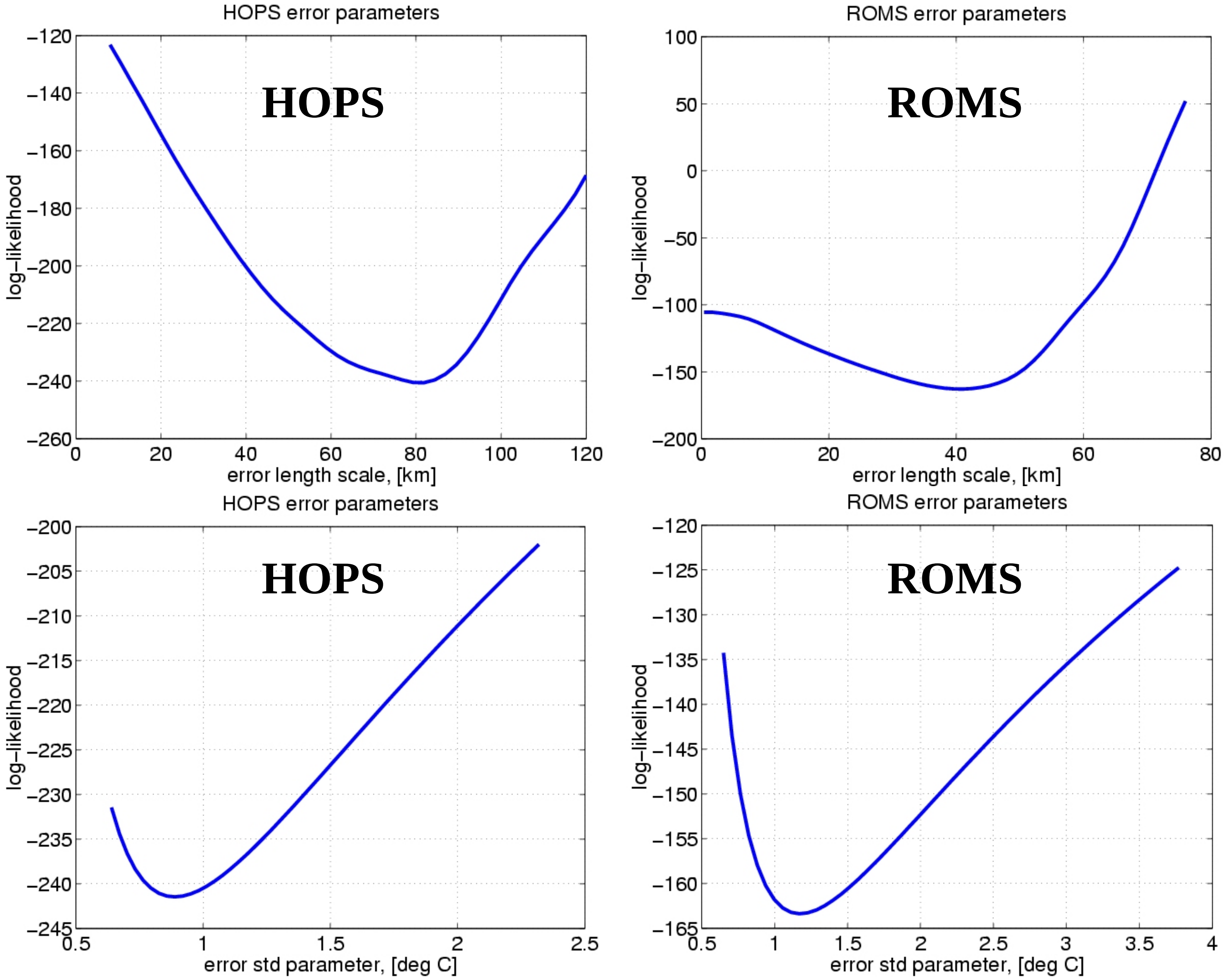
$$\boldsymbol{\Theta}^* = \arg\max_{\boldsymbol{\Theta}} p(\boldsymbol{\mathcal{Y}}|\boldsymbol{\Theta}) \tag{1}$$

Where $\boldsymbol{\mathcal{Y}} = \{\mathbf{y}_1^o, \mathbf{y}_2^o, \ldots, \mathbf{y}_T^o\}$ is the observational data, $\boldsymbol{\Theta} = \{\boldsymbol{\theta}_1, \boldsymbol{\theta}_2, \ldots, \boldsymbol{\theta}_M\}$ 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 the Expectation-Maximization methodology, we solve (1) relatively efficiently

Error Analyses and Optimal (Multi) Model Estimates

An Example of Log-Likelihood functions for error parameters

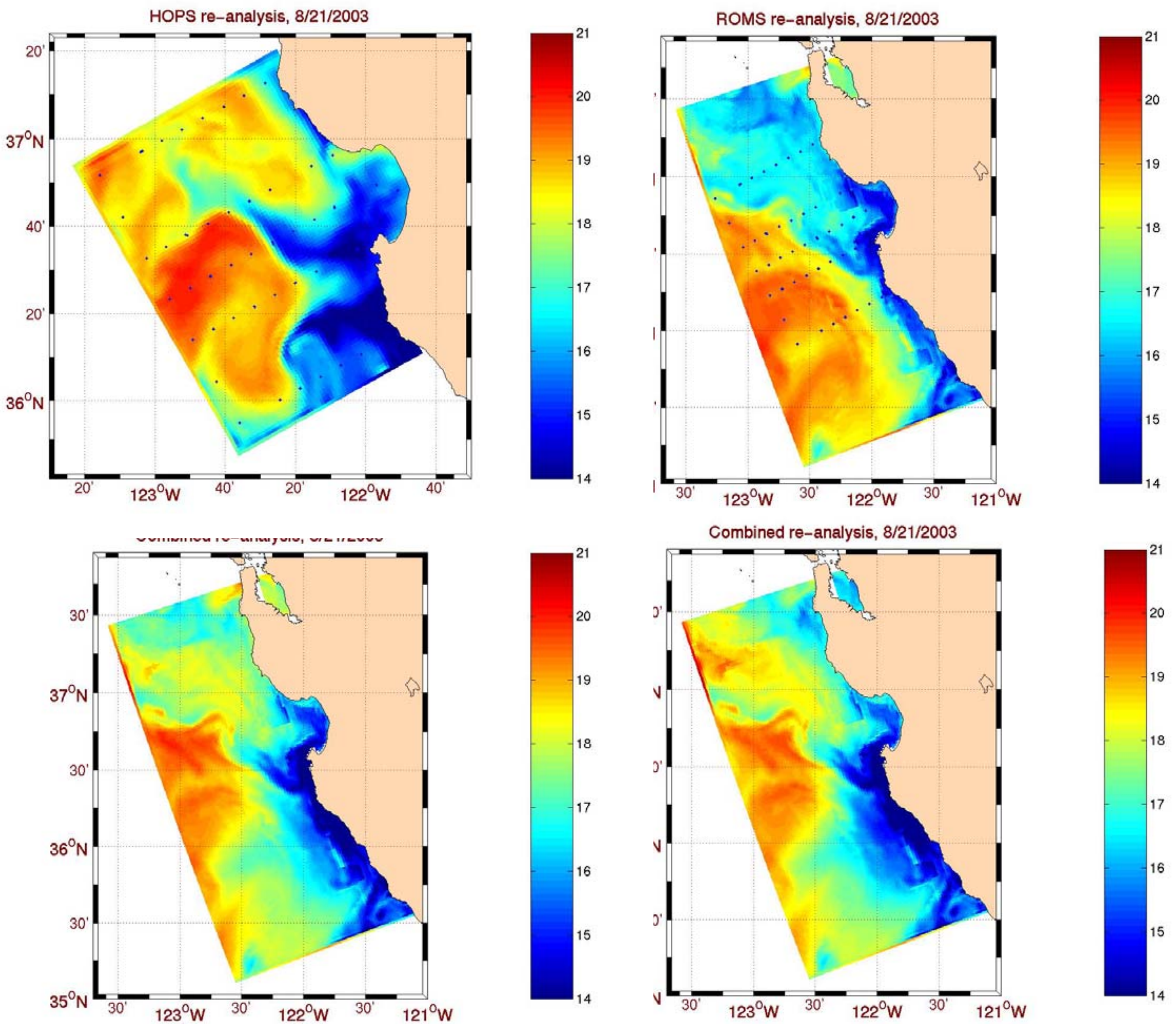


Length Scale

Variance

Error Analyses and Optimal (Multi) Model Estimates

Two-Model Forecasting Example



Model Fusion

combine based on relative model uncertainties

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

Harvard/NURC Collaborative Research: Real-time Field Exercises

1. **HOPS/ESSE transitioned with updates routinely used by Centre and Joint Research Project 2005-2008**
   a) JRP Deterministic and Stochastic Regional Forecasting

2. **Current Collaboration Topics**
   a) Multi-Scale Energy and Vorticity Analysis
   b) Error Analyses and Optimal (Multi) Model Estimates
   c) Mini-HOPS

3. **Recent and Upcoming Field Exercises**
   a) MREA03 – Corsican Channel
   b) MREA04 – Portuguese Coastal Waters
   c) DART05 – Adriatic Sea
   d) 2006 – Demonstration of Mini-HOPS concept for harbor protection – series of day cruises with NRV Leonardo

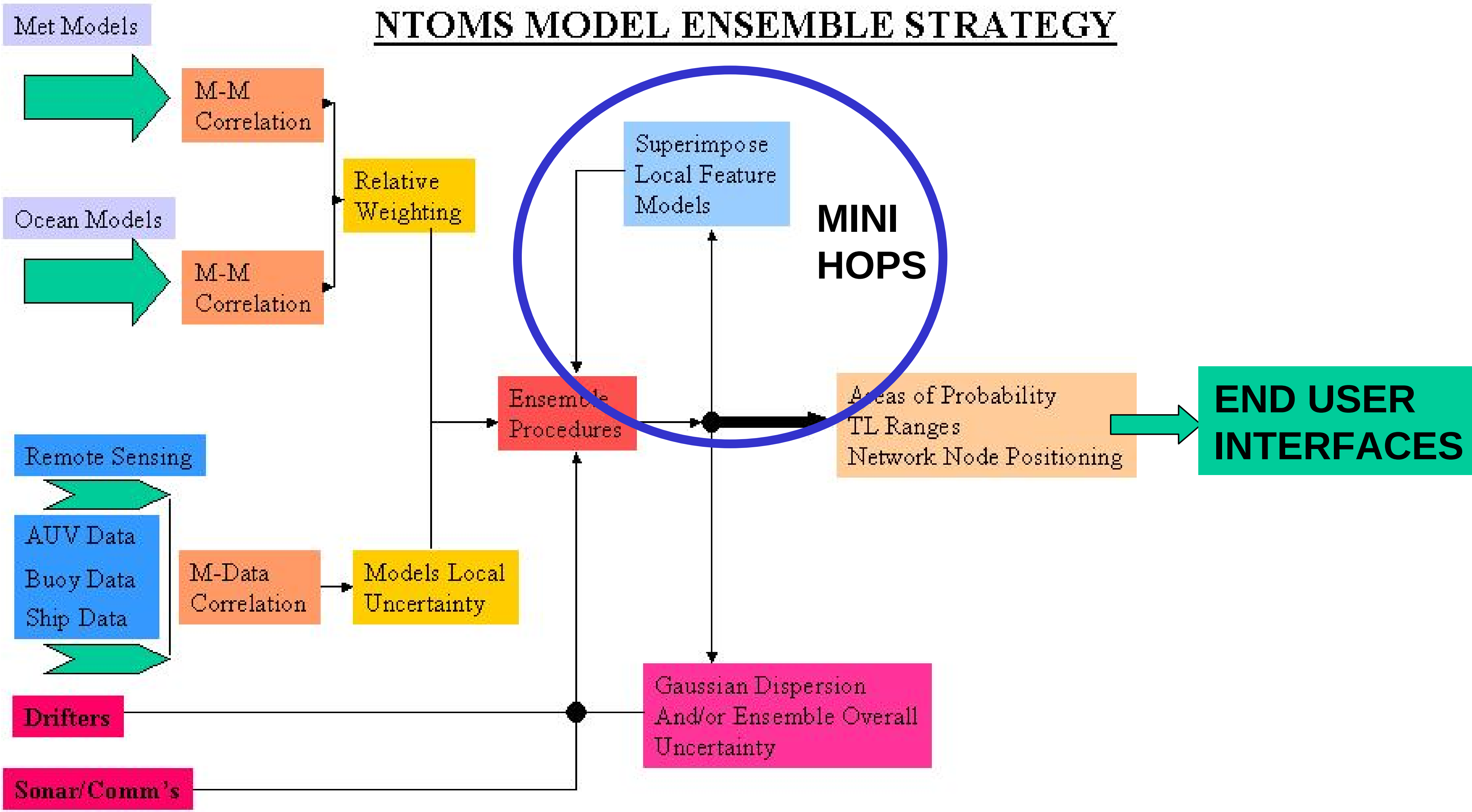
Mini-HOPS

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

NATO Tactical Ocean Modeling System (NTOMS)

E. Coelho

NTOMS MODEL ENSEMBLE STRATEGY

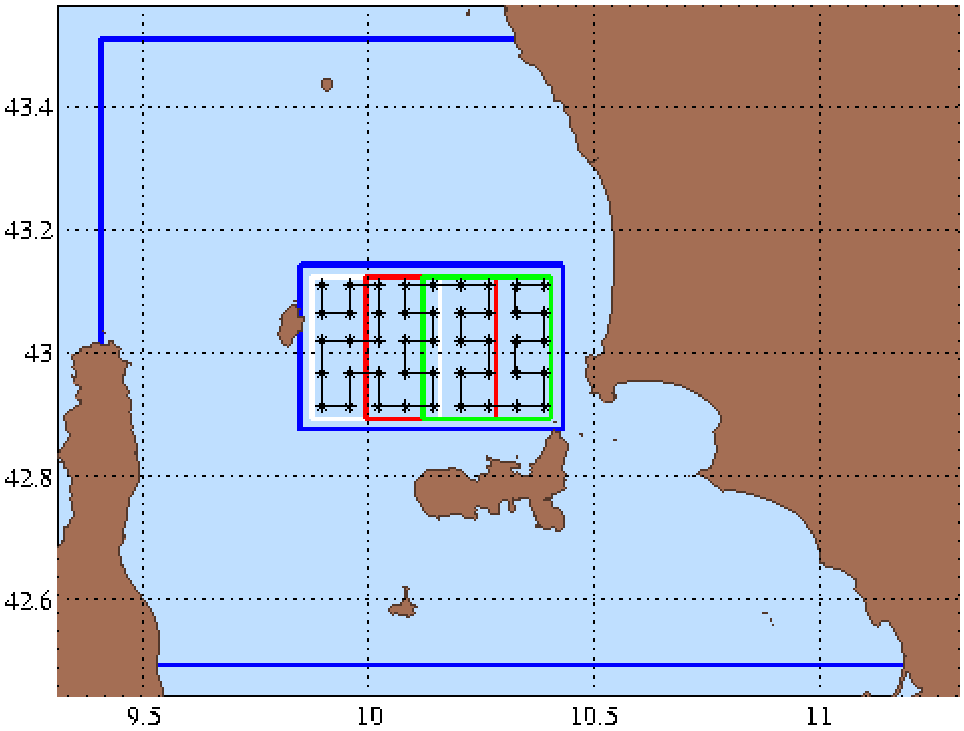


NOTE: the uncertainty of final estimates will be limited by the skills of the existing models and data to characterize the true multiple scale ocean states and by the uncertainty cascade

MREA-03 Mini-HOPS Protocol

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

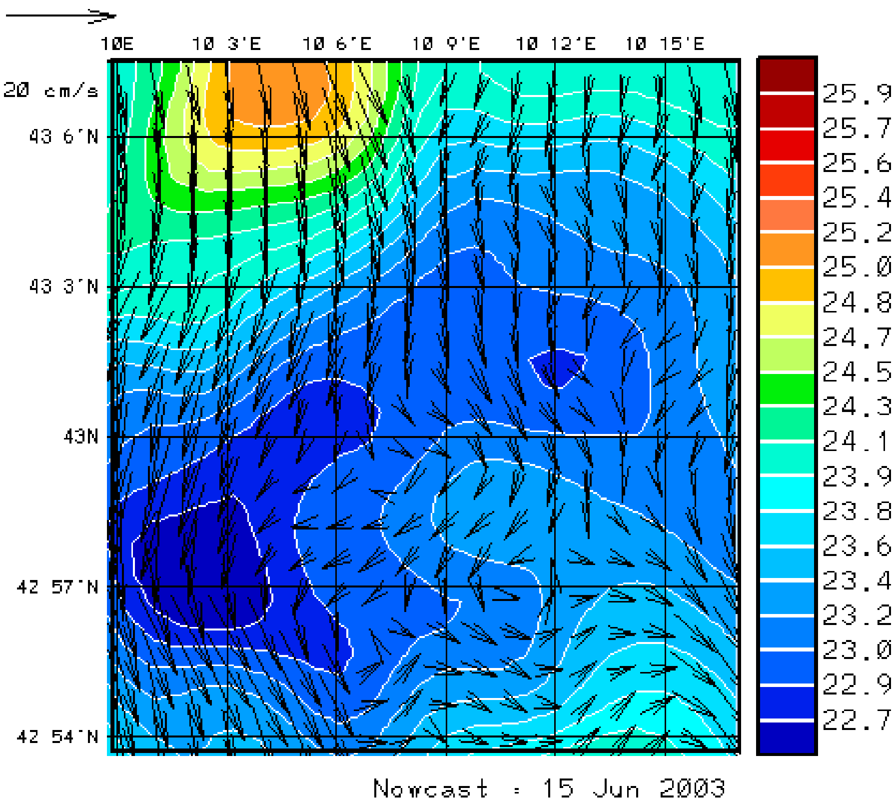
MREA-03 Domains



Mini-HOPS for MREA-03

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

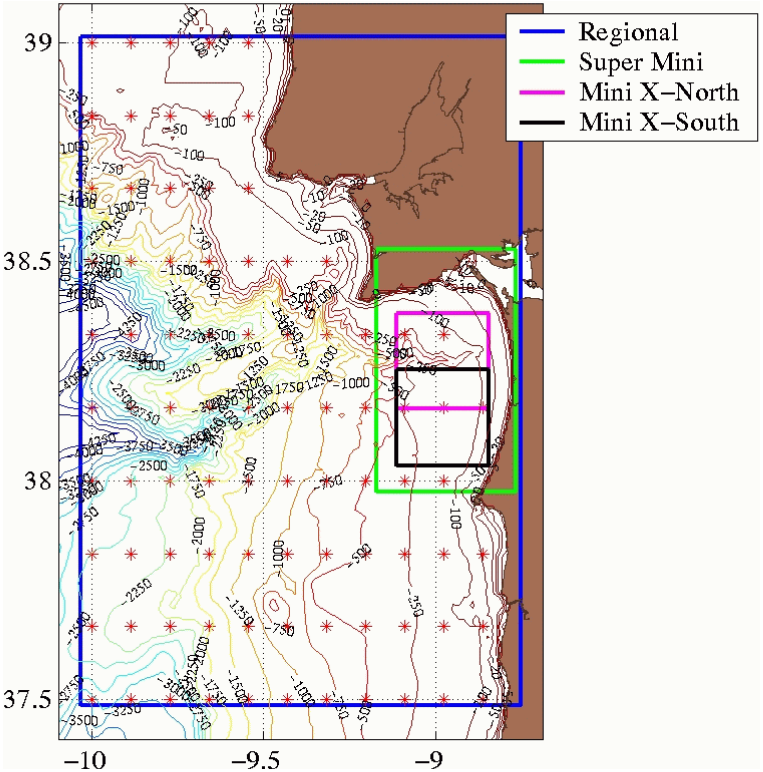
- During experiment:
  - Daily runs of regional and super mini at Harvard
  - Daily transmission of updated IC/BC fields for mini-HOPS domains
  - Mini-HOPS successfully run aboard NRV Alliance

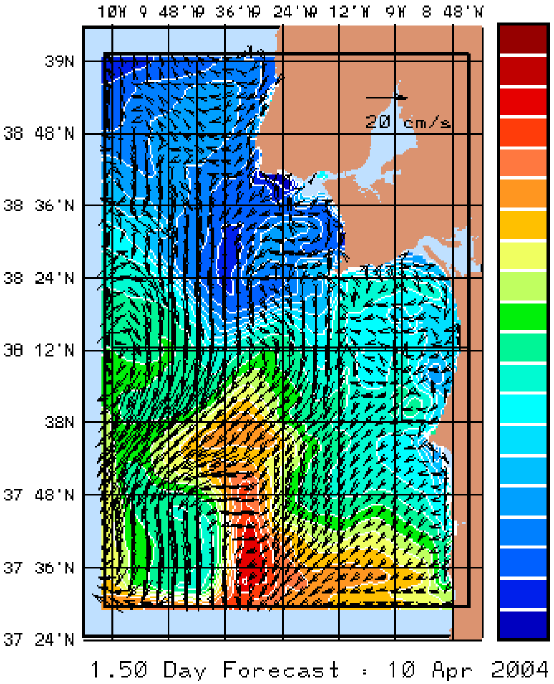


Mini-HOPS simulation run aboard NRV Alliance in Central mini-HOPS domain (surface temperature and velocity)

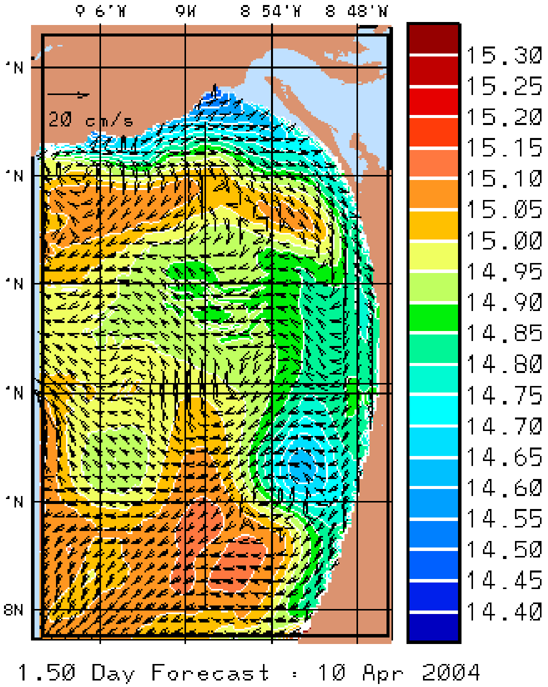
Mini-HOPS for MREA-04

- Daily runs of regional and super mini at Harvard
- Daily transmission of updated IC/BC fields for mini-HOPS domains
- Alliance manpower constraints prevented running of Mini-HOPS at sea



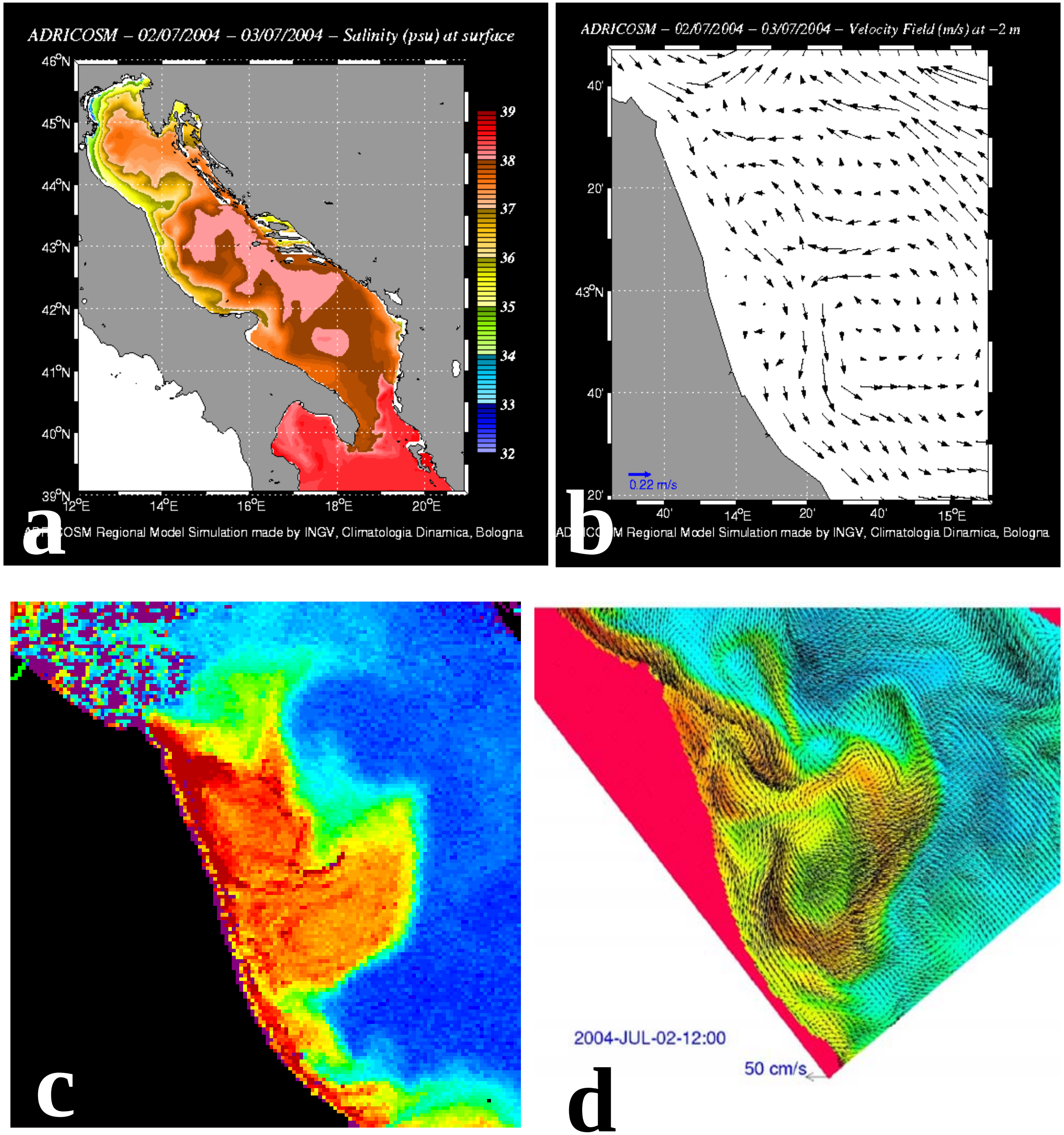


Regional Domain
1km resolution



Super Mini Domain
1/3 km resolution

DART-05 – Adriatic Sea – Aug/Sep 2005



DART - Dynamics of the Adriatic in Real-Time

Mesoscale, sub-mesoscale dynamics of coastal currents and eddies shedding from head of Gargano Peninsula.

NRL/NURC JRP – J. Book/M. Rixen

with HOPS forecasting for high-resolution dynamics and adaptive sampling

Improvement of forecasting accuracy with high resolution relocatable ocean models: a successful experiment in the western Adriatic Sea (June-July 2004): A. RUSSO, et al.

a) AREG surface salinity; b) zoom of the AREG surface velocity; c) surface chlorophyll-a map from SeaWIFS (same colour scale as Fig. 3); d) zoom of HOPS surface salinity (colour scale going from 35 –orange– to 38.8 –cyan) and velocity fields; all maps for July 2, 2004.

Hypothesis being tested

- Available operational numerical model fields contain multi-scale physics with different statistic properties

  (e.g. higher resolution grids do not imply lower uncertainty)

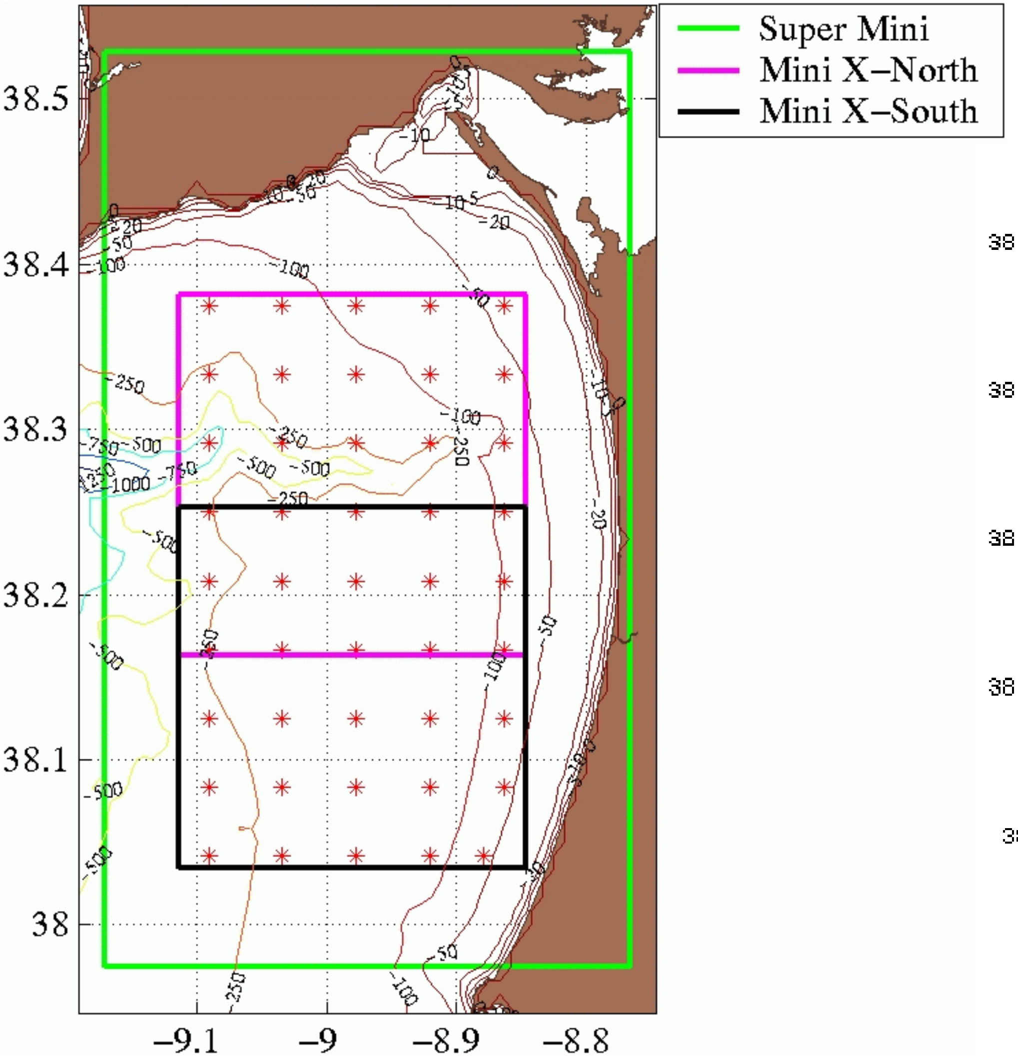
  - *MS-EVA efforts*
  - *Mini-HOPS efforts*
- Available operational model fields and observations can be used to span a domain containing most of the true ocean-meteo-wave states
  - *Hyper-ensemble techniques*
- Available operational model fields, when combined with observations, can be used to forecast pdf's for the output variables, that will be piecewise smooth in both time and space.
  - *Stochastic tactical modeling*

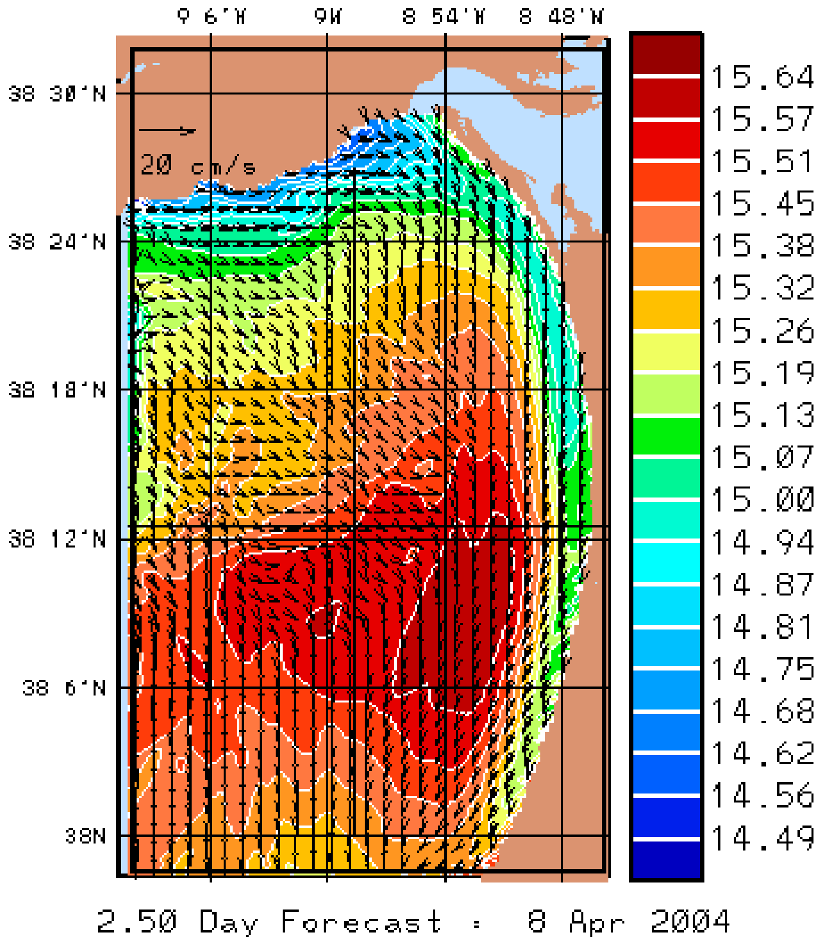
E. Coelho

EXTRA VUGRAFS

Mini-HOPS for MREA-04

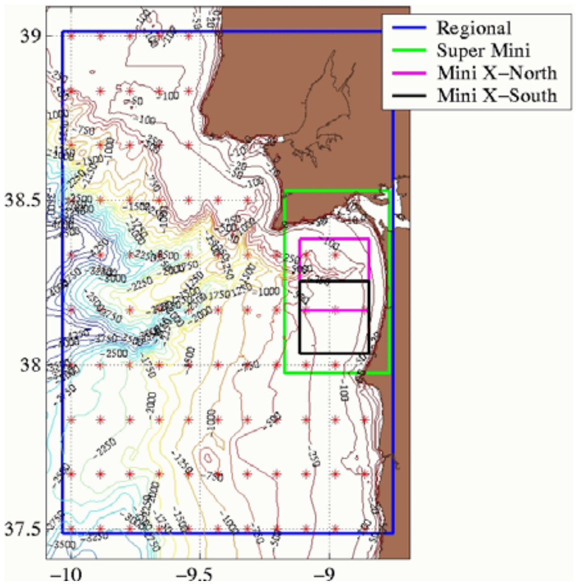
- Daily runs of regional and super mini at Harvard
- Daily transmission of updated IC/BC fields for mini-HOPS domains
- Alliance manpower constraints prevented running of Mini-HOPS at sea

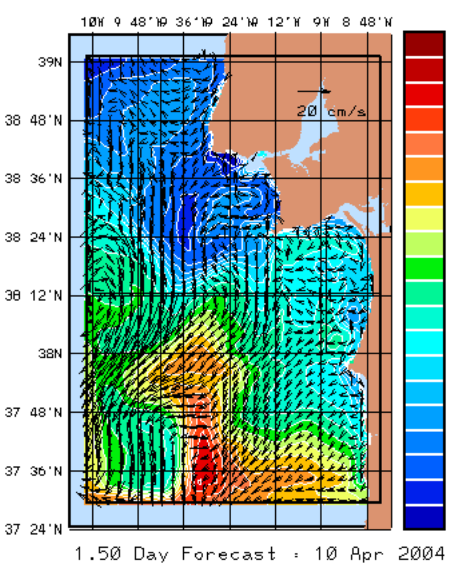




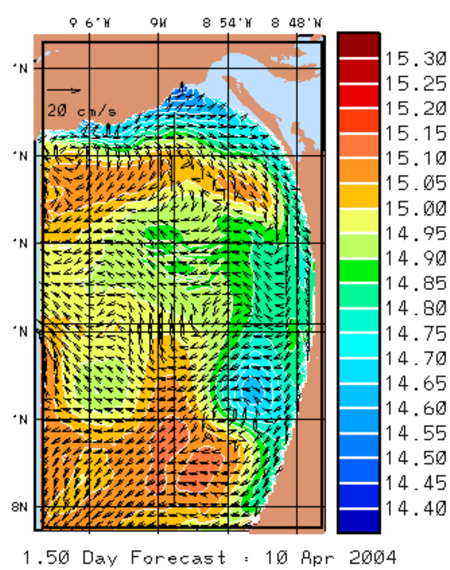
Real-time Regional Applications

MREA04 – Portuguese Atlantic Coast
March/April 2004





Regional Domain



Super Mini Domain

HOPS provided real-time forecasts during the period 6-10 April 2004. A regional survey during 31 March - 6 April 2004 provided the initial state. HOPS performed real-time forecasting and ocean and model data transfers were carried out between the NRV Alliance and Harvard University. The Mini-HOPS concept was utilized in real-time to locally solve the problem of accurate representation of sub-mesoscale synopticity. This concept involves rapid real-time assimilation of high-resolution data in a high-resolution locally nested model domain around observational platforms. HOPS provided 2-way nested output in regional and sub-regional domains. These outputs provided initial and boundary data for shipboard Mini-HOPS simulations. Real-time forecasts included an evaluation of model bias and RMS error every day, in routine fashion and were also used for onboard acoustic calculations

Mini-HOPS

Future work

BCs more compatible with assimilation
Incorporation of coasts in Mini Domains

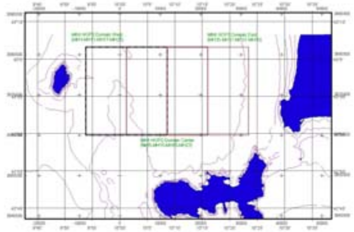
Future experiments in collaboration with NURC:

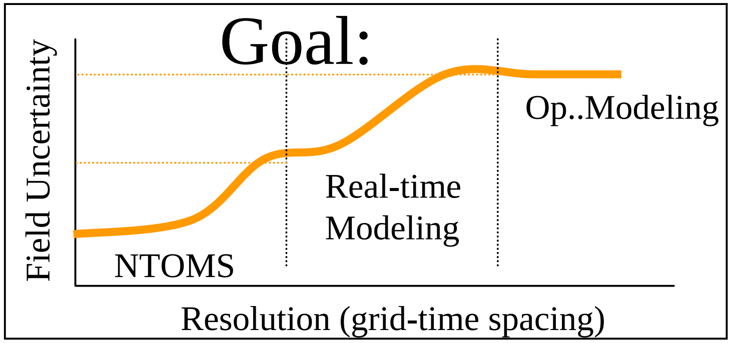
Implementation of Mini-HOPS in Harbor protection initiatives

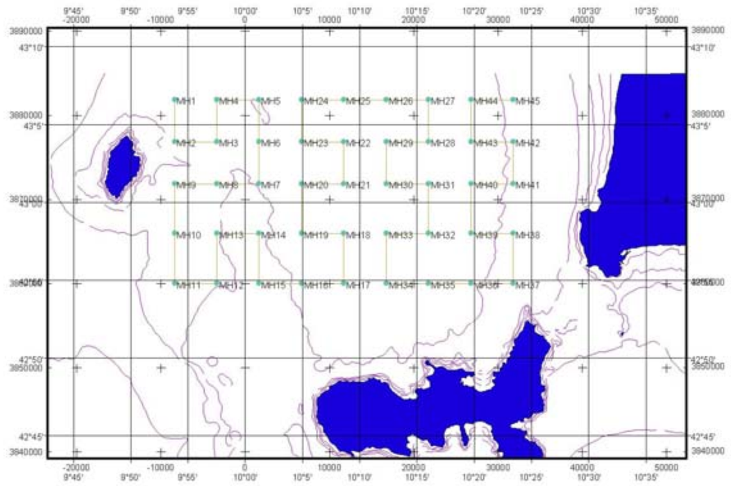
Locations: Italy-Black Sea-Baltic

Type: The Italy and Black Sea will be more related with DAT and homeland protection initiatives. The Baltic sea will be in conjunction with a MCM exercise.

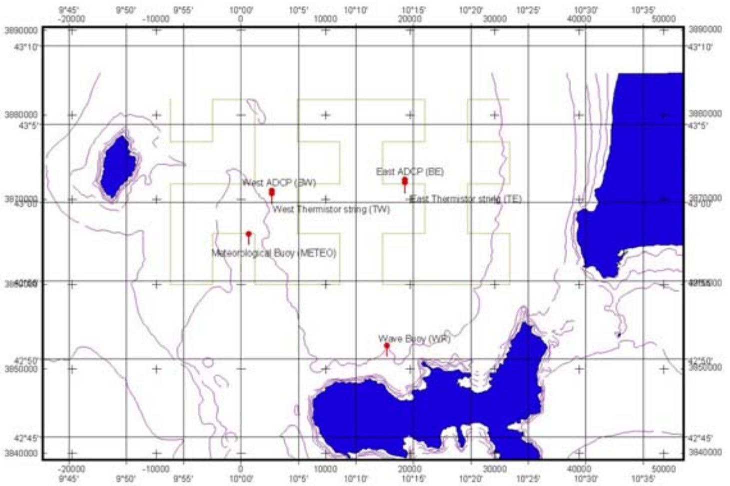
MREA03







Local high resolution data collection



- **Start with an operational model run**
- **Nest three 20x20Km 50% superimposed domains on a regional HOPS domain**
- **Perform assimilation cycles within one inertial period**
- **Provide and monitor hourly outputs for 24-48 hours forecasts**

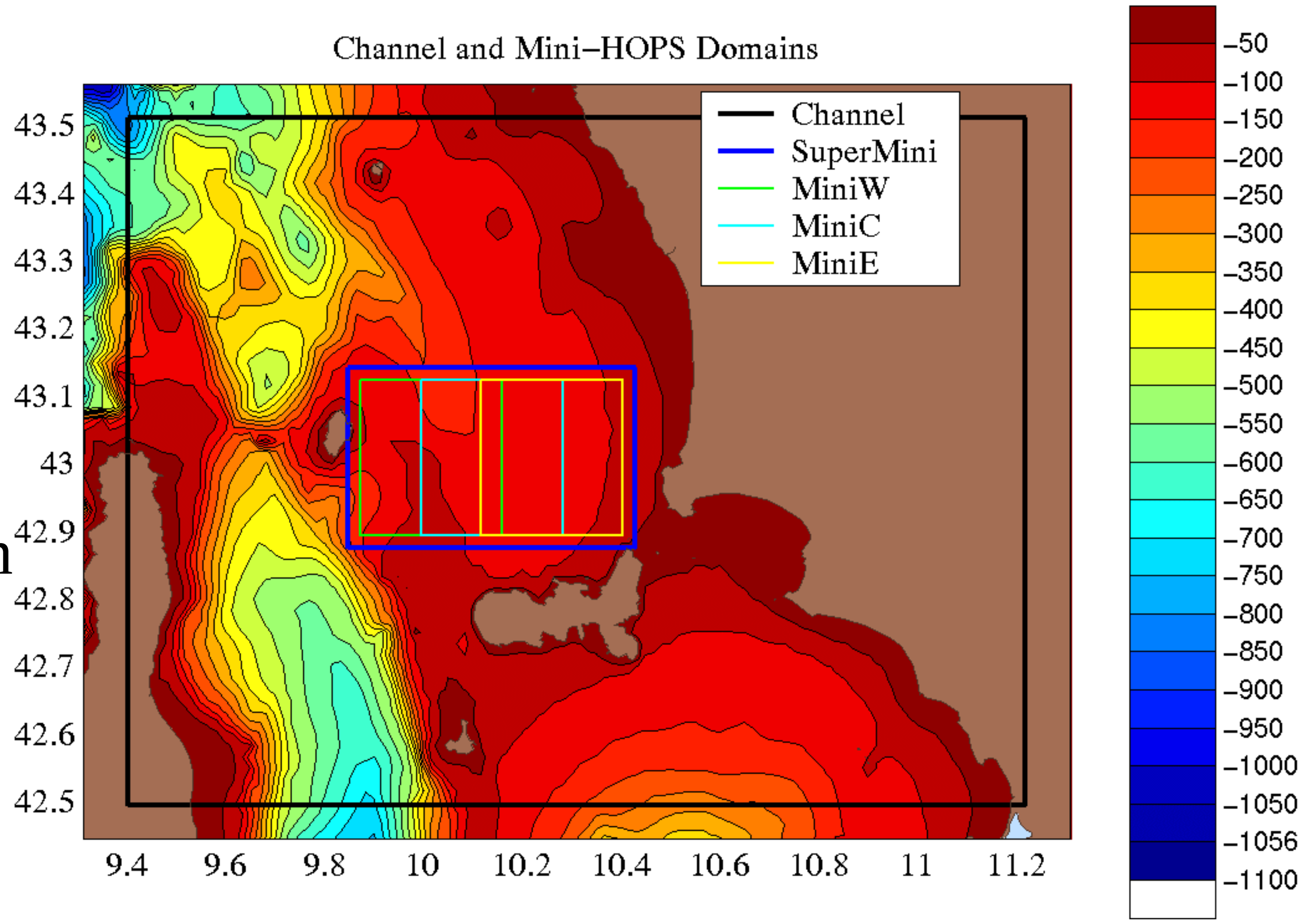
E. Coelho

MREA03 Modeling Domains

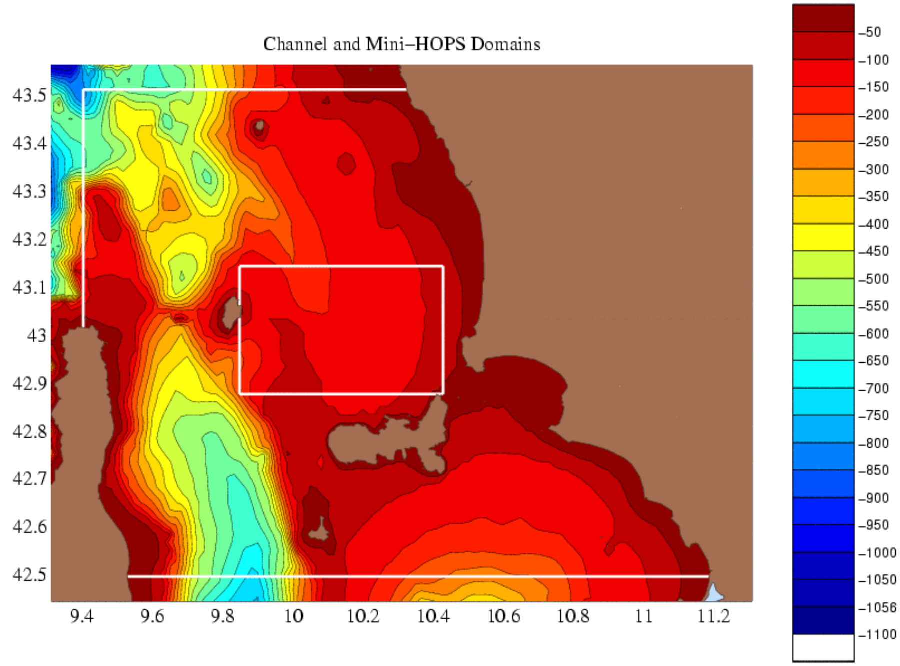
Channel domain
- 1 km resolution
- Spans initialization survey

Mini-HOPS
- 1/3 km resolution
- Span high-resolution survey

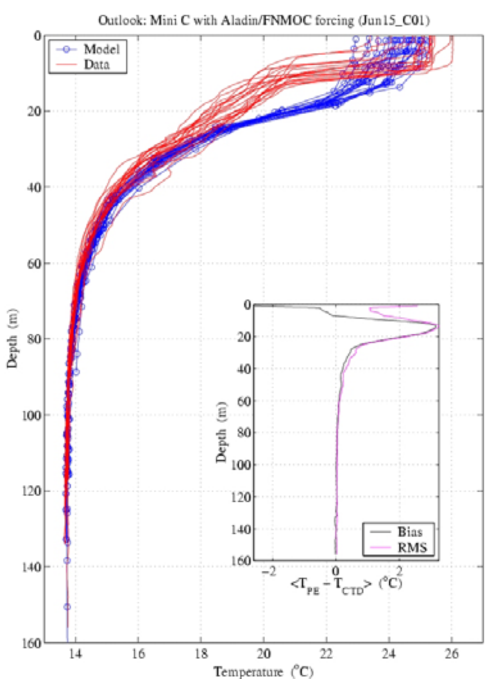
Super Mini-HOPS
- 1/3 km resolution
- 2 km buffer

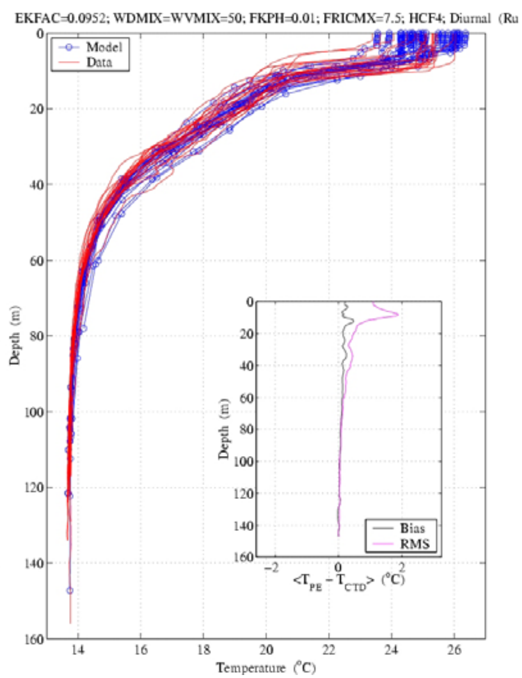


MREA03 – Ligurian Sea – May/June 2003



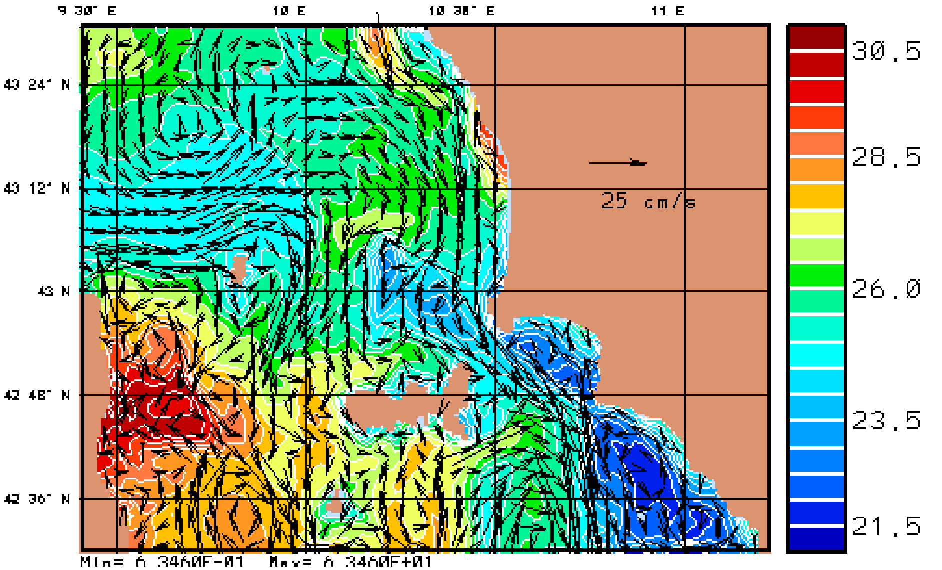
Prior to the MREA04 exercise, a re-analysis of the HOPS forecasts of the May-June 2003 MREA03 exercise was performed. This led to dramatically improved detailed agreement of model results with observed profiles. This re-analysis was motivated by observations of recurring mismatches between HOPS near surface structure and that observed in the CTD profiles. The general stability of the simulations was first improved with parameter tuning and slight modifications to the filtering and open boundary algorithms. Sensitivity studies on the model parameters (especially vertical mixing) produced a moderate improvement in the bias and RMS error between the simulation fields and a set of generally troublesome profiles. A much larger improvement was obtained by redistributing the vertical model levels to better resolve the near surface fields. Moderate improvement came by correcting the pre-processing of atmospheric fields to construct the net heat flux. A final, smaller, improvement came by revising the initialization procedures.

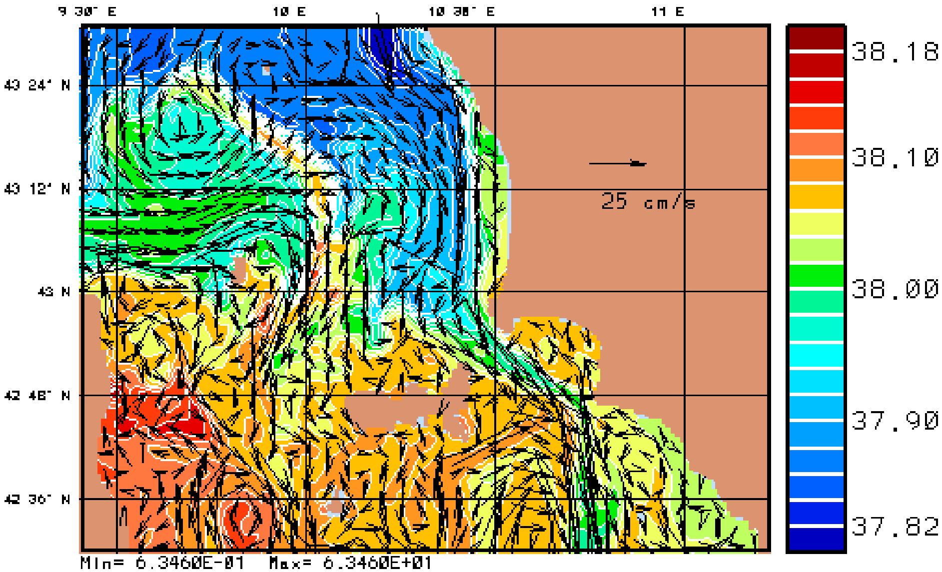




HOPS and mini-HOPS in MREA03

T_0, S_0 on 17 June 2003





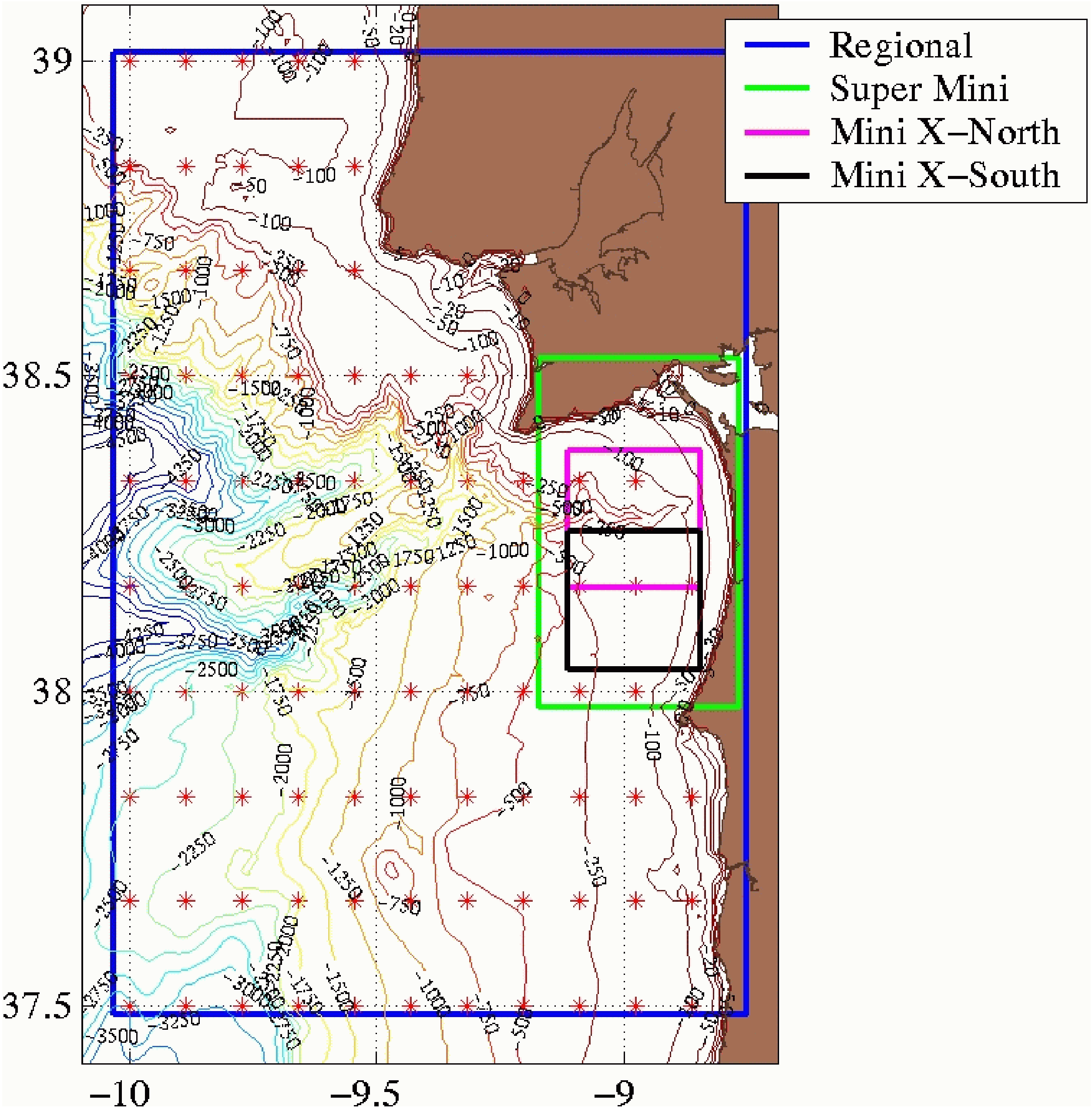
- Web-distributed nowcasts and forecasts 11-17 June 2003
- Web-distributed mini-HOPS domain initial and boundary conditions 11-17 June 2003
- Channel domain forecasts run at Harvard
- Mini-HOPS domain forecasts run aboard NRV Alliance – real-time, in the field, demonstration of concept
- Post-experiment re-analysis and model tuning to improve model/data profile comparisons

MREA04 Modeling Domains

Regional domain
- 1 km resolution
- Spans initialization survey

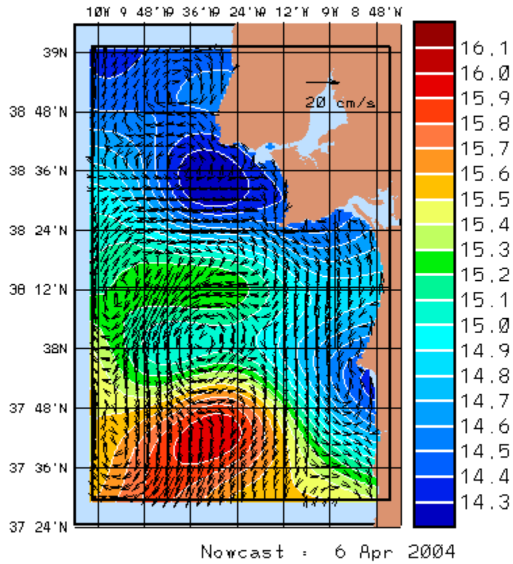
Super Mini-HOPS
- 1/3 km resolution
- Extended to coasts (reducing coastal currents)
- 5 km buffer

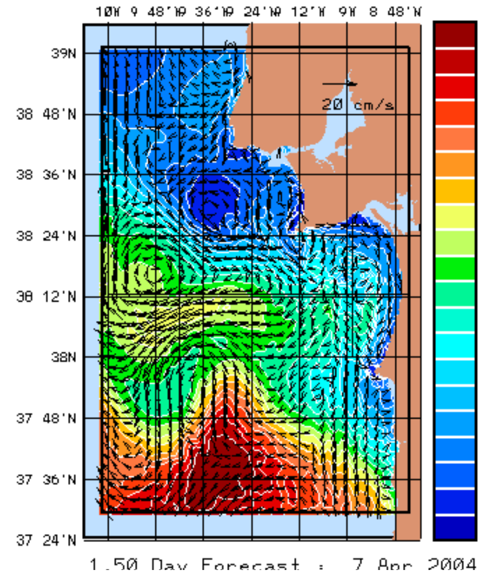
Mini-HOPS
- 1/3 km resolution
- Span high-resolution survey

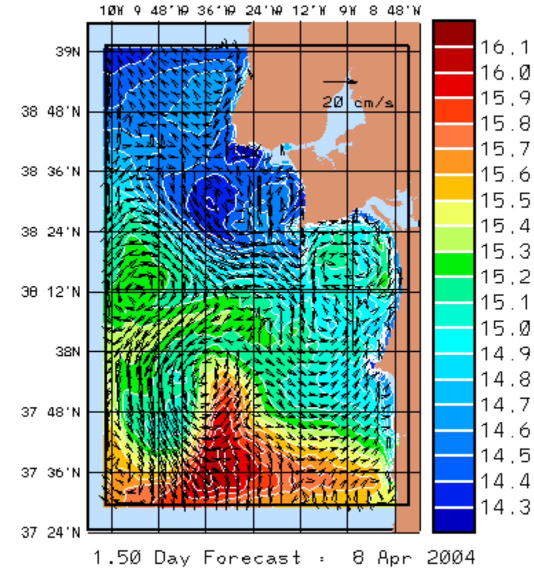


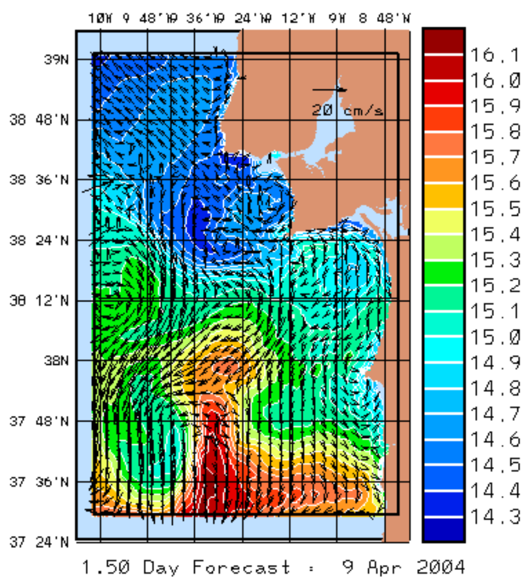
HOPS and mini-HOPS in MREA04

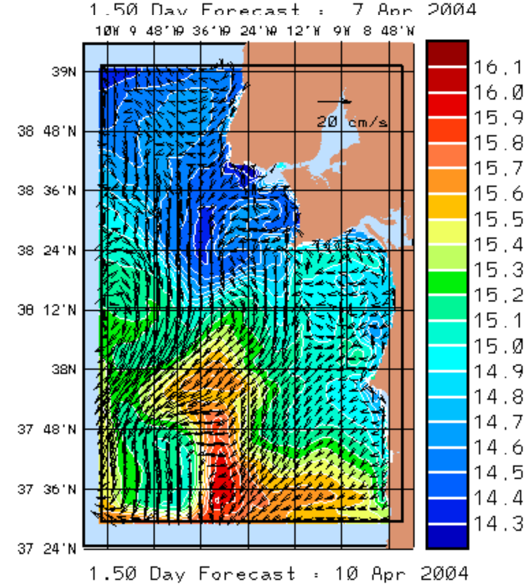
Daily evolution of temperature at 10m from 6 April – 10 April.
Superimposed upon the temperature field are vectors of sub-tidal velocity.

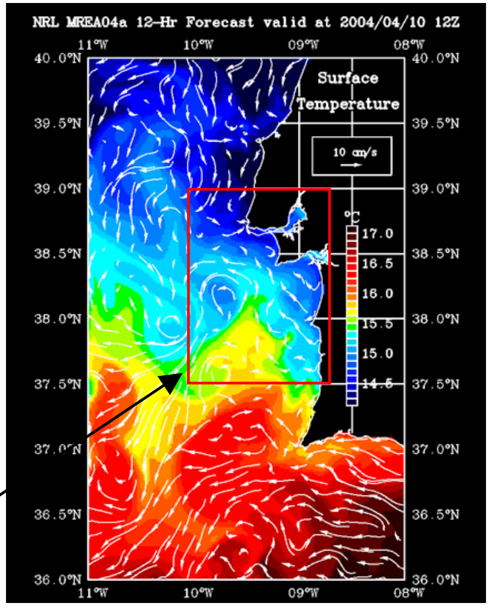












NRL Nowcast 10 Apr.

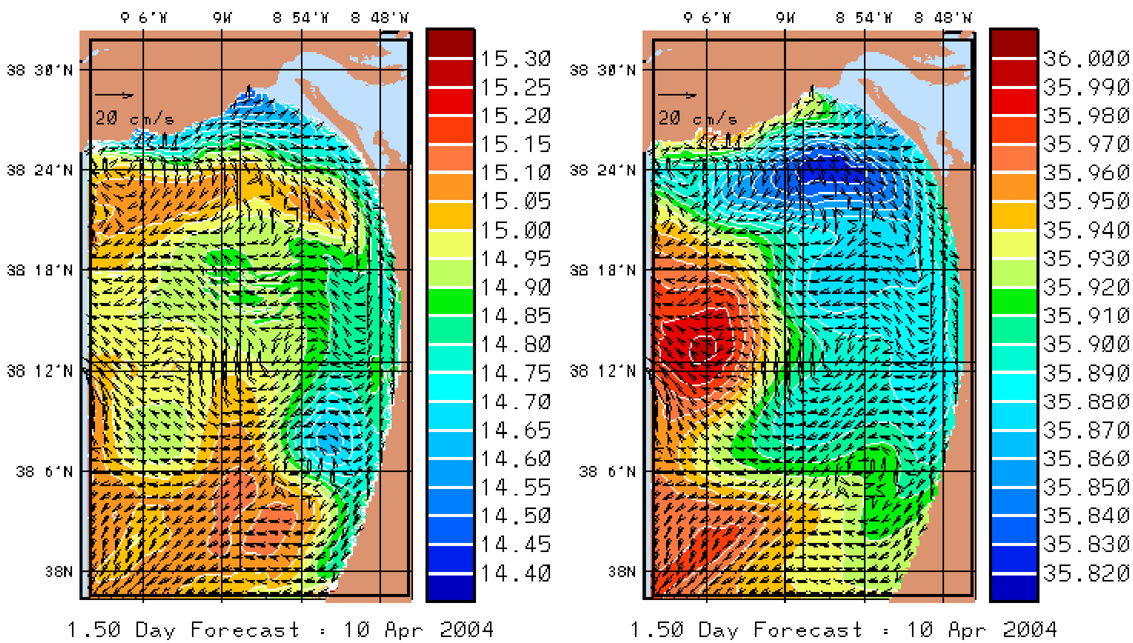
HOPS Regional Domain

HOPS and mini-HOPS in MREA04

- Web-distributed regional domain nowcasts and forecasts 6-10 April 2004
- Web-distributed mini-HOPS domain initial and boundary conditions 6-10 April 2004
- Web-distributed model/data profile comparisons 7-10 April 2004

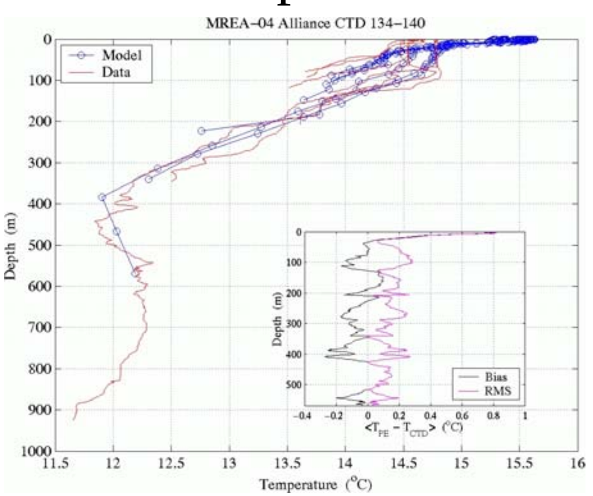
- Regional domain and super-mini-HOPS domain forecasts run at Harvard
- Regional domain acoustic calculations run aboard NRV Alliance

T_0, S_0 on 10 April 2004



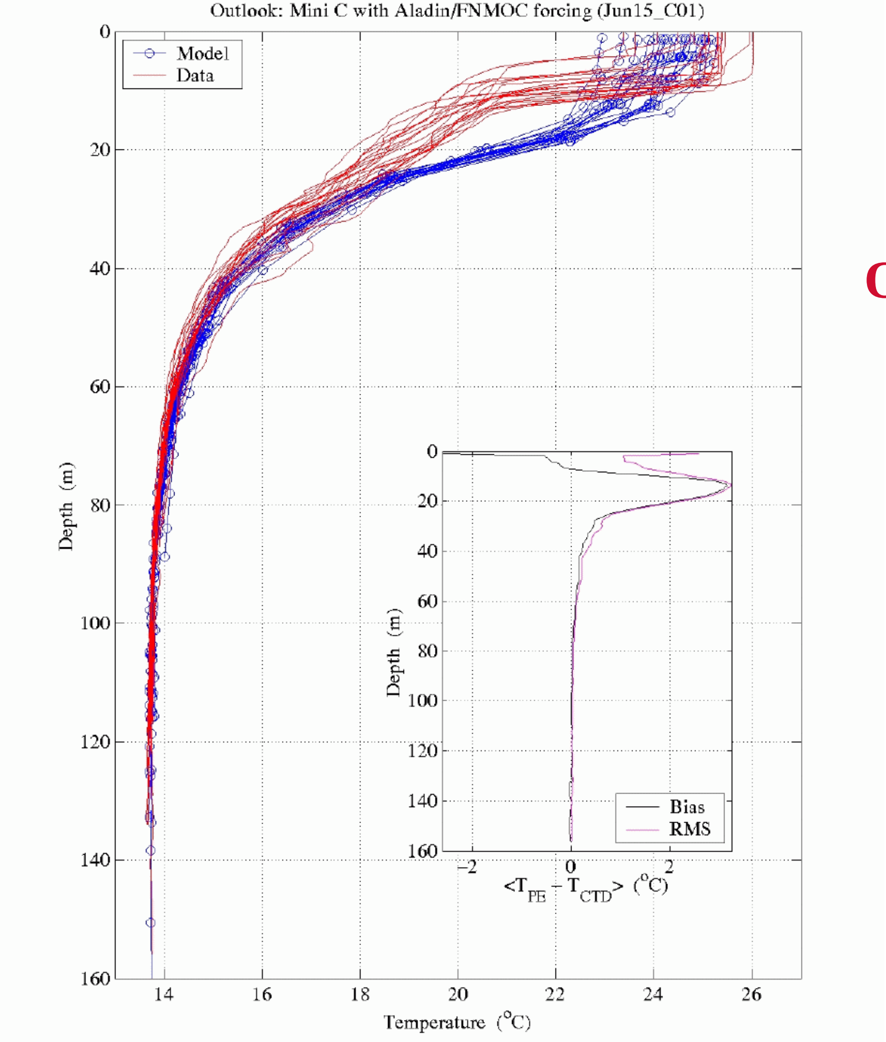
Super Mini-HOPS domain

Real-time model/data comparison



Results of Re-analysis and Dynamical Model Tuning

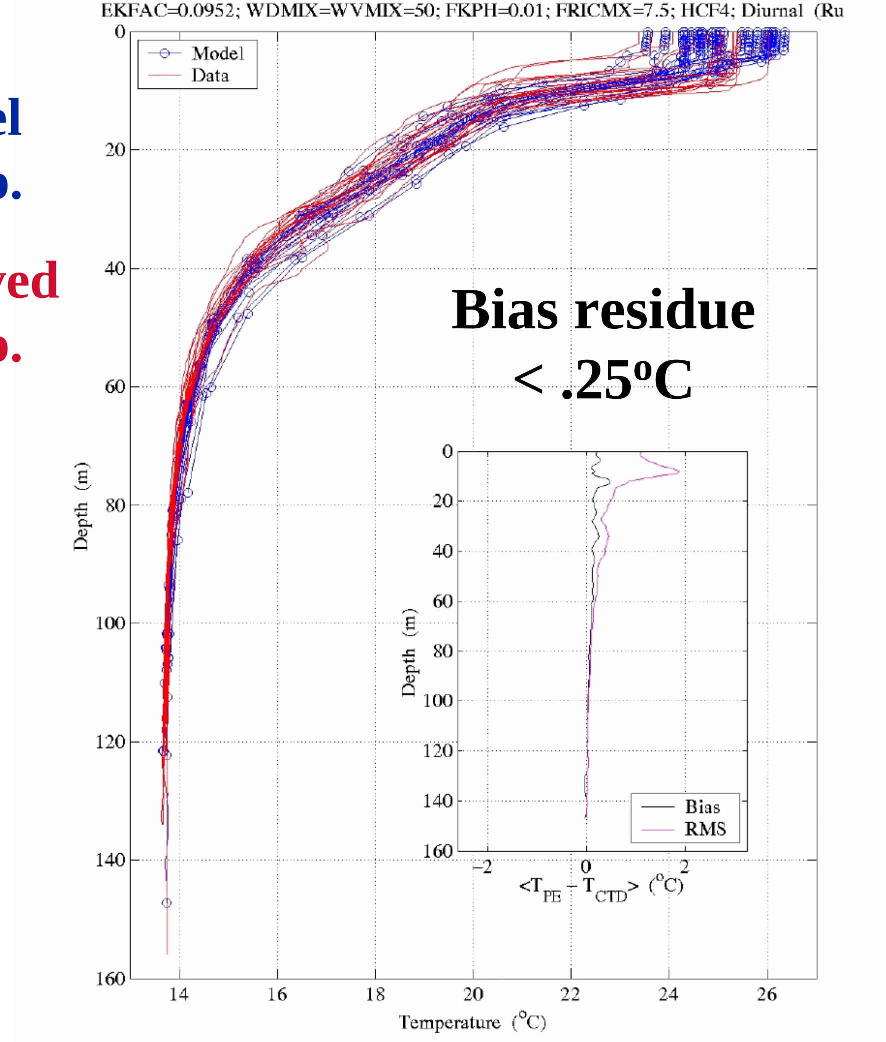
Real-time Model/Data Comparison



Model Temp.

Observed Temp.

Re-analysis Model/Data Comparison

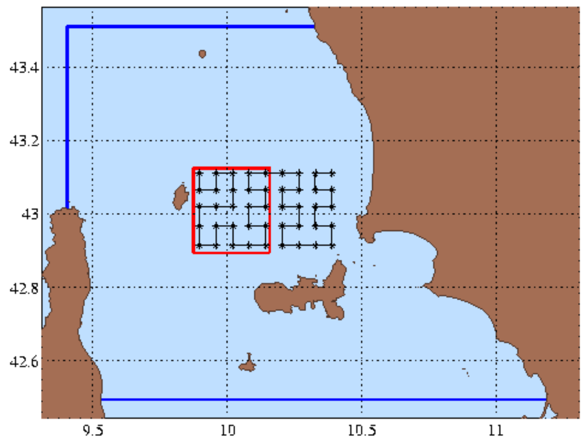


- Tuned parameters for stability and agreement with profiles (especially vertical mixing)
- Improved vertical resolution in surface and thermocline
- Corrected input net heat flux
- Improved initialization and synoptic assimilation in dynamically tuned model

Mini-HOPS

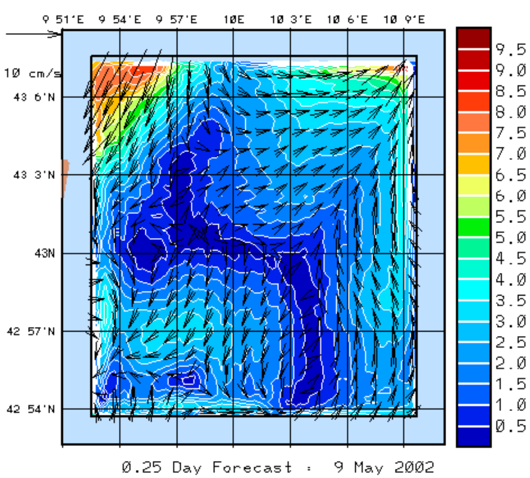
MREA03 – “OSSE”

Direct

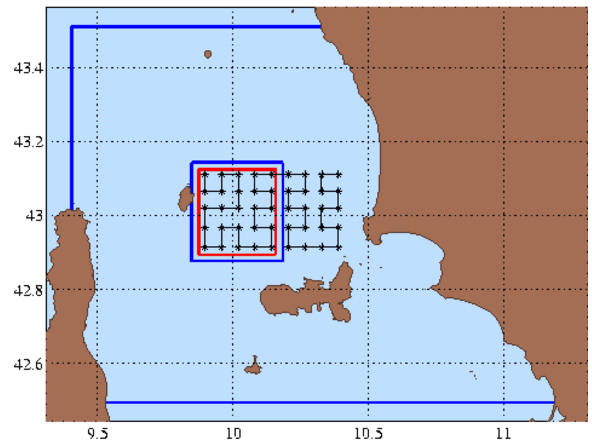


Simplest Configuration

Boundary mismatch
Maintenance Uclin

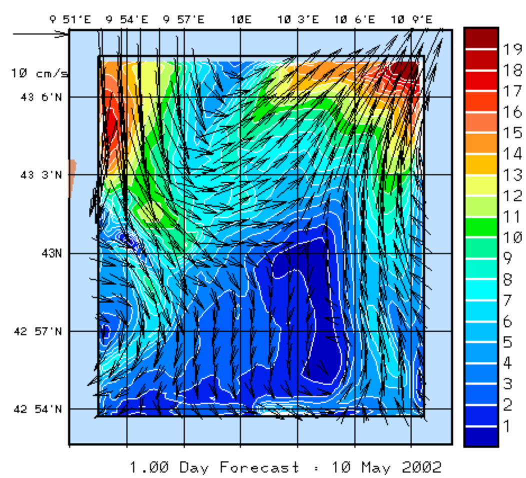


Extended Minis

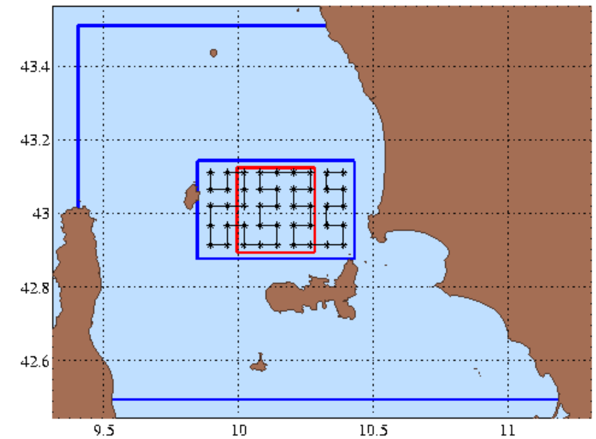


IC/BC’s at proper scales

Most complex configuration

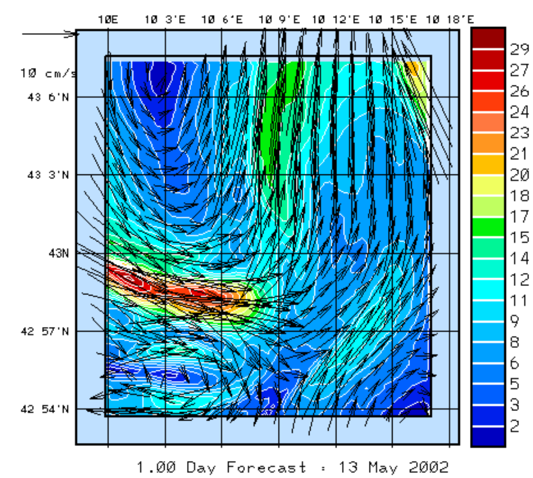


Super Mini



IC/BC’s at proper scales
Fine scale data “memory”

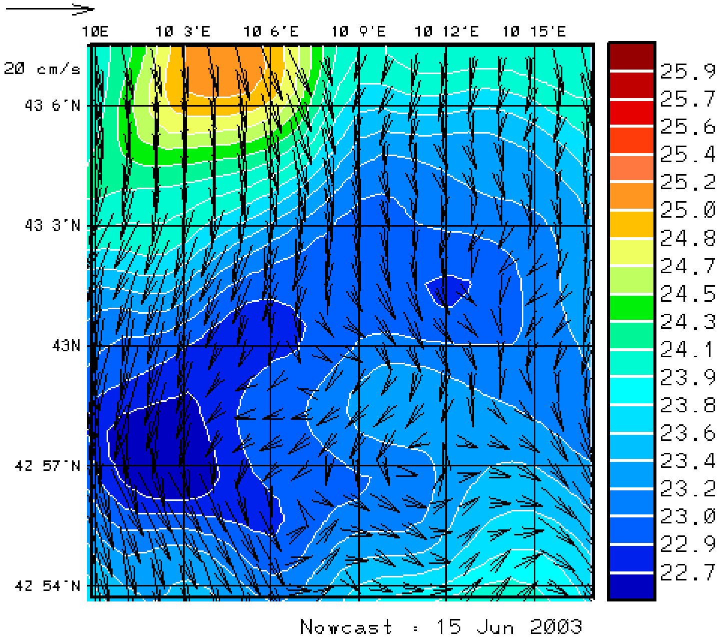
Intermed. complex
Not generalizable



Mini-HOPS

MREA03

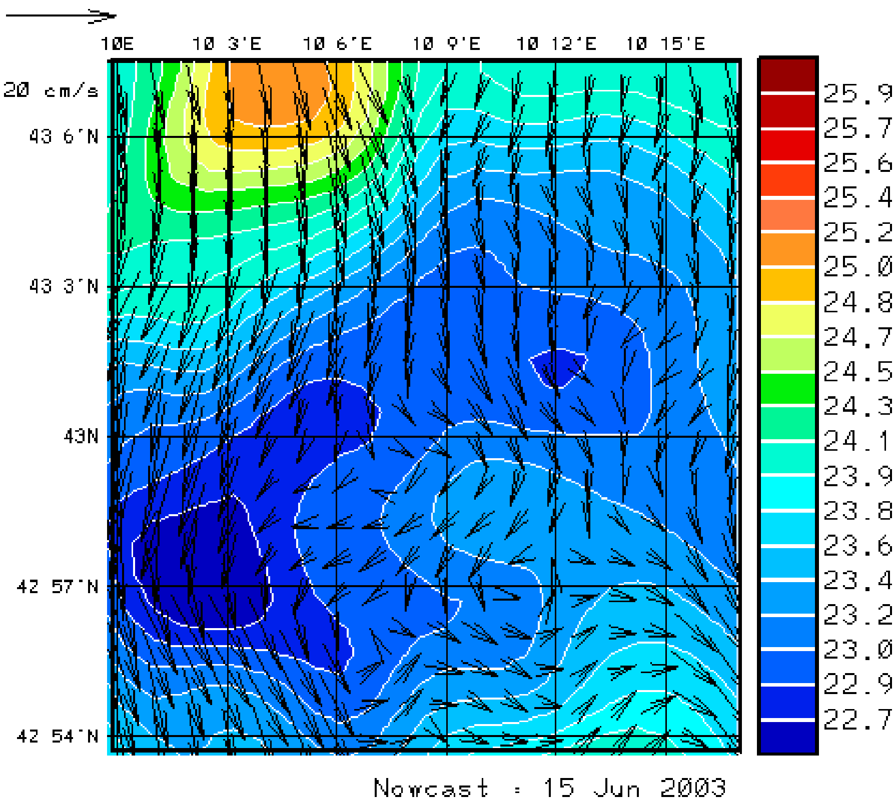
- Successfully run aboard NRV Alliance
- Near-surface mismatch of model to profiles ⇒ 2004 re-analysis in regional domain
- Assimilation/boundary mismatch



Mini-HOPS for MREA-03

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

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



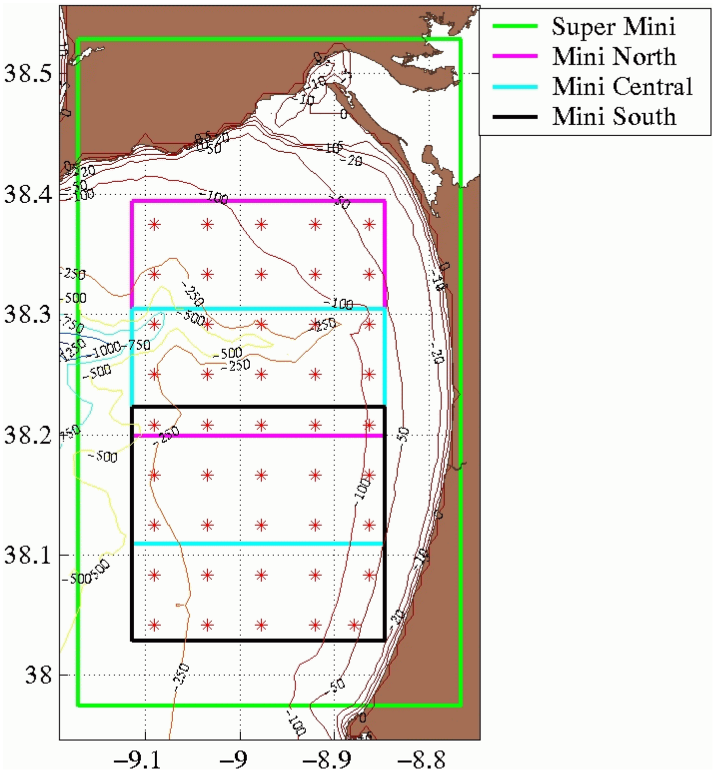
Mini-HOPS simulation run aboard NRV Alliance in Central mini-HOPS domain

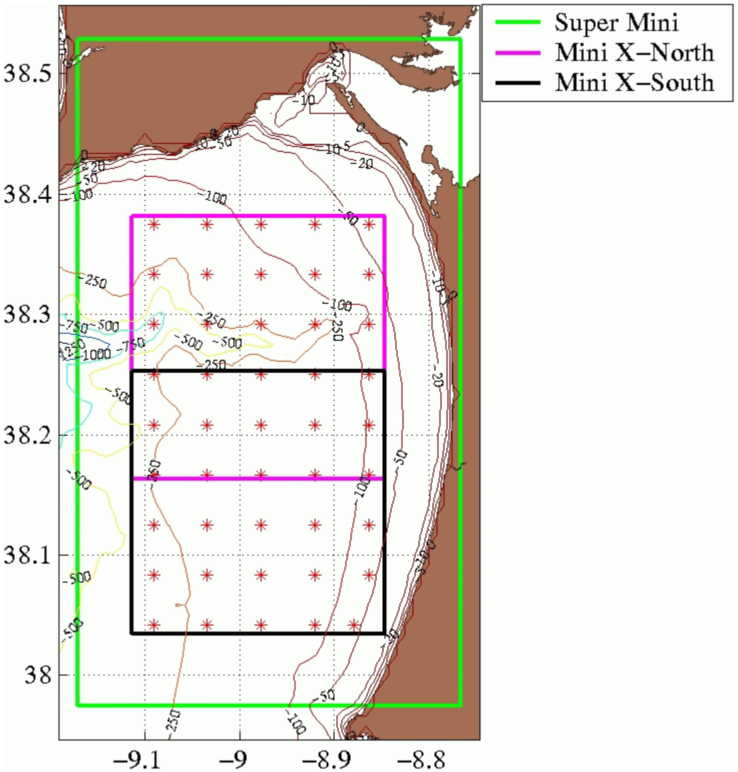
- Near-surface mismatch of model to profiles ⇒ 2004 re-analysis in regional domain
- Assimilation/boundary mismatch

Mini-HOPS

MREA04

- "OSSE" – Reduced number of Mini domains to avoid canyon along the boundary
- No real-time Mini-HOPS simulations





Implementation of Free Surface in HOPS

Dukowicz and Smith algorithm

explicitly maintain surface pressure

$$p(x,y,z,t) = p_s(x,y,t) + \int_z^0 g\rho(x,y,\zeta,t)\,d\zeta \qquad p_s = g\rho_0\eta$$

implicit in time for greater stability

$$\frac{1}{\rho_0 g}\frac{p_s^{n+1}-p_s^n}{\Delta t} + \nabla\cdot\left(H\vec{U}^{n+1}\right) = 0$$

split-time algorithm to enable use of efficient conjugate gradient solvers

$$\begin{aligned}
\hat{\vec{U}} + \hat{k}\times 2\alpha\Delta t\hat{\vec{U}} &= 2\Delta t\vec{F} + O\left(\Delta t^3\right)\\
\nabla\cdot(H\nabla\delta p_s) - \frac{2}{g\alpha(2\Delta t)^2}\delta p_s &= \frac{\rho_0}{2\alpha\Delta t}\nabla\cdot\left[H\left(\hat{\vec{U}}+\vec{U}^n\right)\right]\\
\vec{U}^{n+1} &= \hat{\vec{U}} - \frac{2\alpha\Delta t}{\rho_0}\nabla\delta p_s\\
p_s^{n+1} &= p_s^{n-1} + \delta p_s
\end{aligned}$$

Implementation of Free Surface in HOPS

Adapting for compatibility in HOPS

- **synoptic initialization**
- **open boundary conditions**
  - **including barotropic tidal forcing (testing)**
- **OI assimilation**
  - **tracers, baroclinic velocity assimilations now compatible**
  - **assimilation of elevation and barotropic velocity to be researched**
- **two-way nesting**
  - **upon completion of stand-alone testing**

Validated for MREA-03 and AOSN-II

Real-time Regional Applications

<u>2005</u>

- FAF05: July, Isola Pianosa (near Elba)
- DART05: August/September, Adriatic
- ASAP: November (?), Virtual experiment, Monterey Bay

<u>2006</u>

- ASAP: June (?), Monterey Bay
- MREA06: Time not yet determined, location not yet determined