Real-time Forecasting of Fields and Uncertainties, Data Assimilation, Adaptive Sampling and Multi-Scale Ocean Dynamics for DART-05

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Generic Goals for Harvard University group

- Continuing HOPS interest in Adriatic
- Ongoing collaboration with NURC
  - JRP: Deterministic and stochastic regional forecasting including sub-mesoscale and near-inertial motions
  - Further MREA-03 studies: Simulations (carry out re-analysis), Data-analysis (characterize observed near-inertial dynamics) and Process studies (idealized/theoretical dynamics and modeling)
- Collaborate with NRL, including focus on transition possibilities
- Build upon HOPS participation in MREA-03 (Ligurian sea) and MREA-04 (Portuguese coastal waters)
  - Nested sub-mesoscale ocean predictions and Mini-HOPS
  - Model training and multi-model ensembles
  - Estimation of model errors and stochastic error models
- Link to PLUSNet and our other ONR/NSF supports and objectives
  - Acquire data for future multi-scale and non-hydrostatic modeling
  - Evaluation of parameterizations (upper-layers, sub-mesoscales), adaptive modeling

Background on recent HU research relevant to DART-05

a. Mini-HOPS -- MREA03-04

- Smaller scale faster processes forecast by deterministic and stochastic approach
- Subjective/Quantitative adaptive response on these scales as data is acquired
- Relocatable nested high-resolution domains

b. HOPS and ESSE -- AOSN-II

- Improved distribution of ensemble runs (by factor 2)
- New sub-optimal adaptive sampling: forecast best sampling tracks via ESSE or nowcast tracks via modified integer programming optimization
- Parameter estimation and evaluation of parameterizations (sub-mesoscales, upper-layers)
- Adaptive ocean modeling

c. Error Analyses and Optimal (Multi) Model Estimates -- MREA03, AOSN-II

- Model training: Engineering fix in real-time for significant forecast improvements
- Efficient combination of models of same and/or overlapping dynamical types

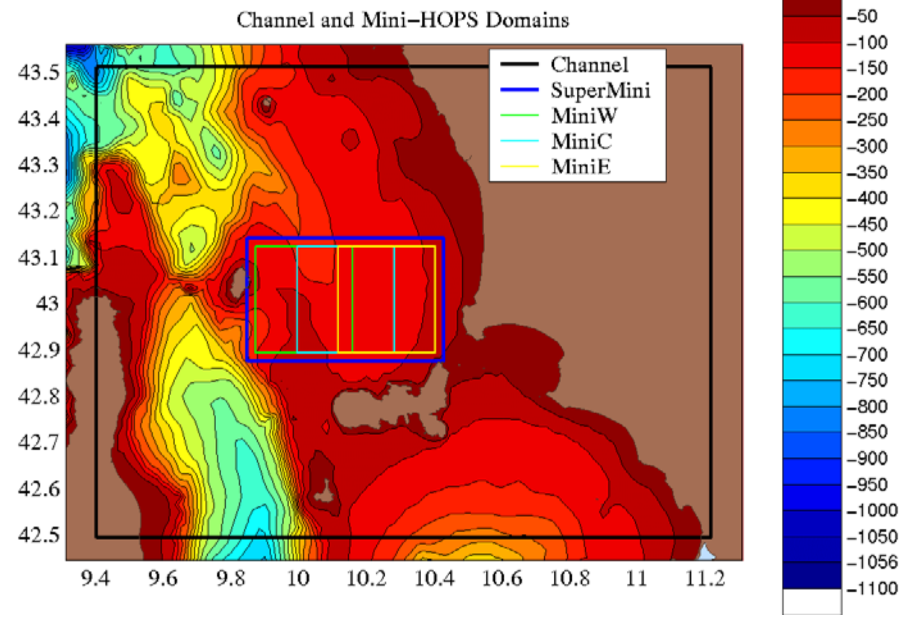
d. Multi-Scale Energy and Vorticity Analyses (MS-EVA) -- AOSN-II

- Multi-scale dynamical processes govern forecasts
- Placement of sensors in hot spots increases impact of data and fidelity of forecasts

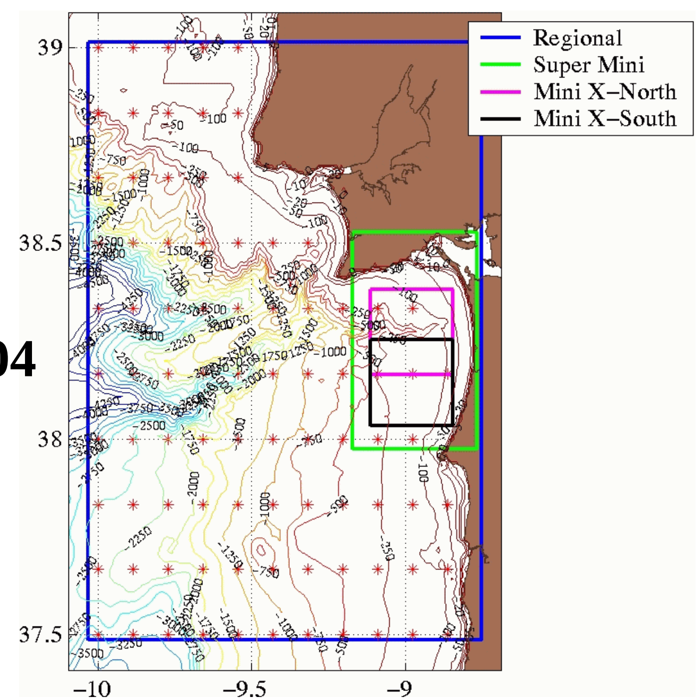
II.a. Mini-HOPS *(E. Coelho and A.R. Robinson)*

- Designed to locally solve the problem of accurate representation of sub-mesoscale synopticity
- Involves rapid real-time collection and assimilation of high-resolution data in high-resolution model nested in a regional model
- Improves impact of local data and produces more accurate local field estimates and short-term forecasts
- For MREA03/04, follow the concept of “Around-the-Ship” modeling (relocatable model)
- Dynamically interpolated and extrapolated high-resolution fields are assimilated through 2-way nesting into large domain models

MREA03 Domains: 11-17 June 03



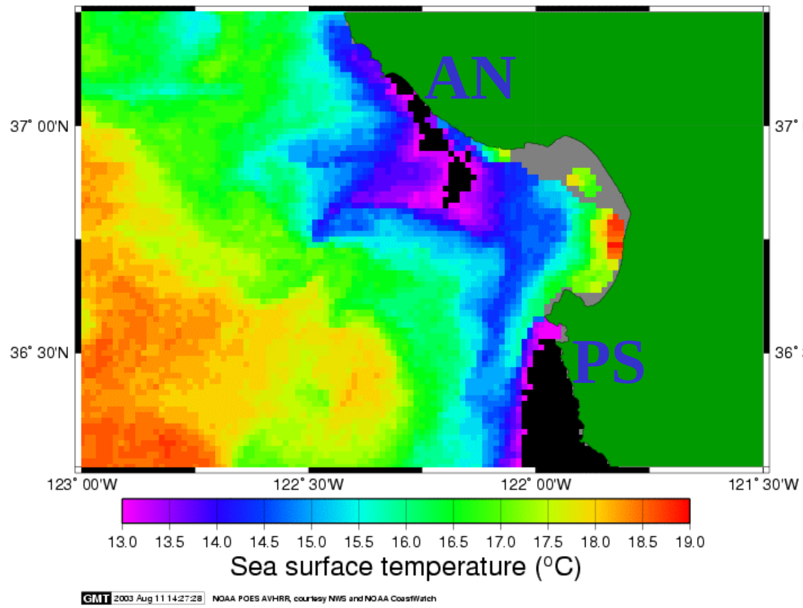
MREA04 Domains 6-10 April 04

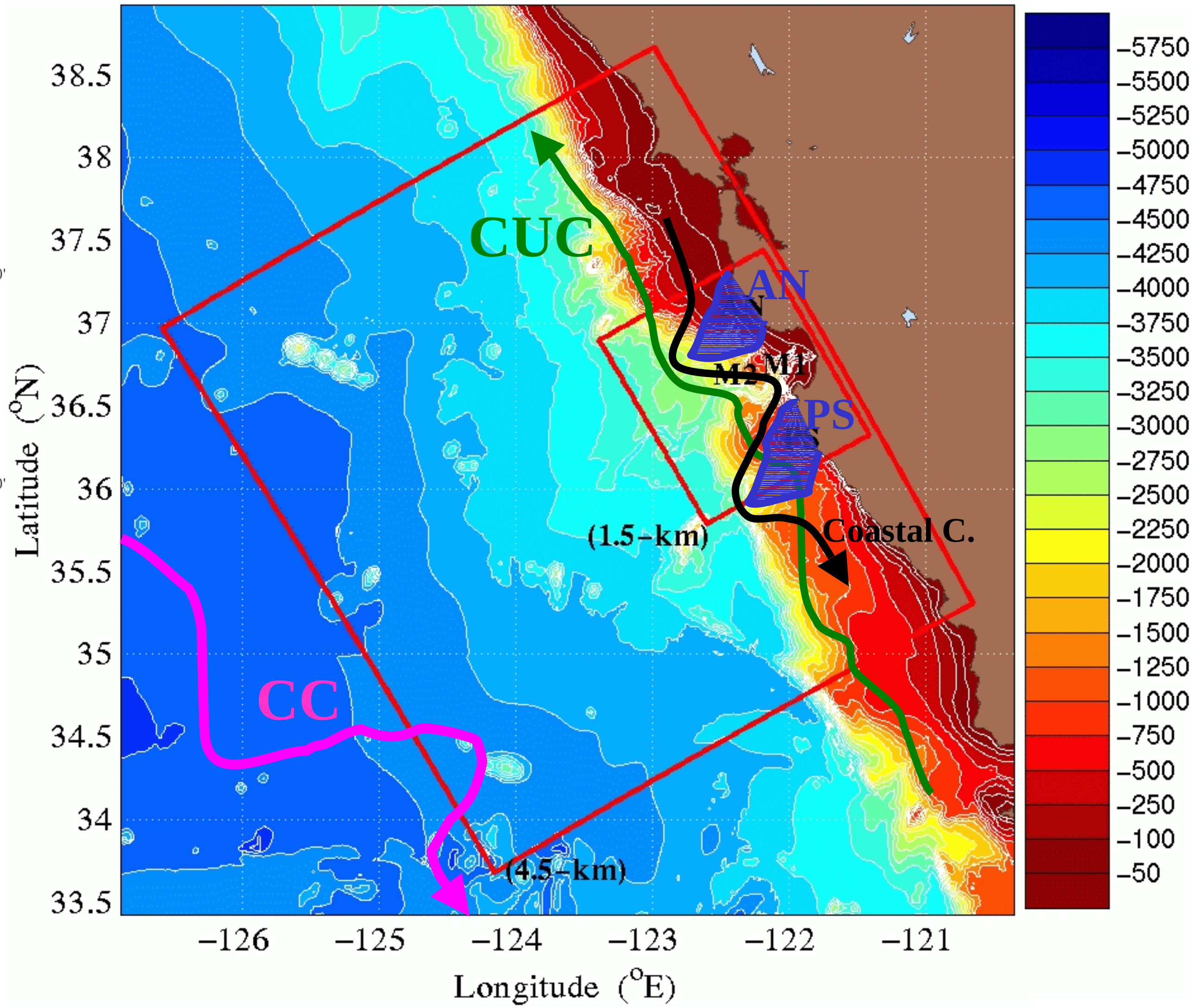


REGIONAL FEATURES of Monterey Bay and California Current System and Real-time Modeling Domains (AOSN-II, 4 Aug. – 3 Sep., 2003)

SST on August 11, 2003

Experimental AVHRR HRPT SST August 11, 2003 1850 h UTC



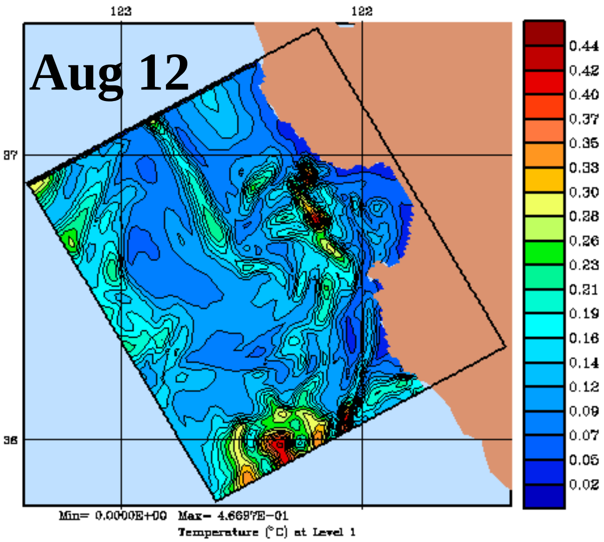


REGIONAL FEATURES

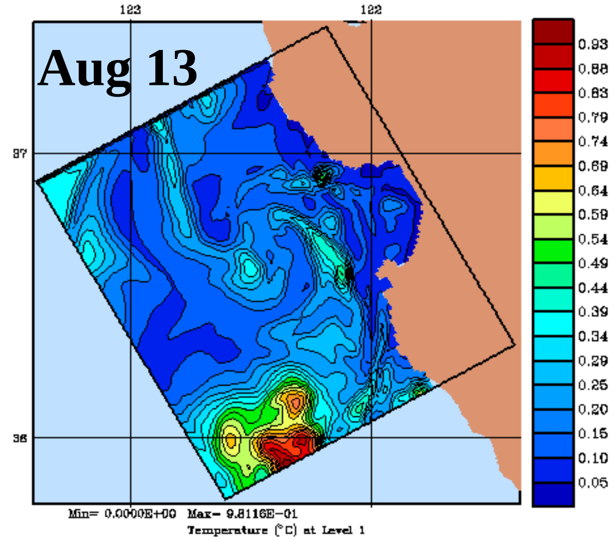
- **Upwelling centers at Pt AN/ Pt Sur:**…………Upwelled water advected equatorward and seaward
- **Coastal current, eddies, squirts, filam., etc:**….Upwelling-induced jets and high (sub)-mesoscale var. in CTZ
- **California Undercurrent (CUC):**……………..Poleward flow/jet, 10-100km offshore, 50-300m depth
- **California Current (CC):**…………………….Broad southward flow, 100-1350km offshore, 0-500m depth

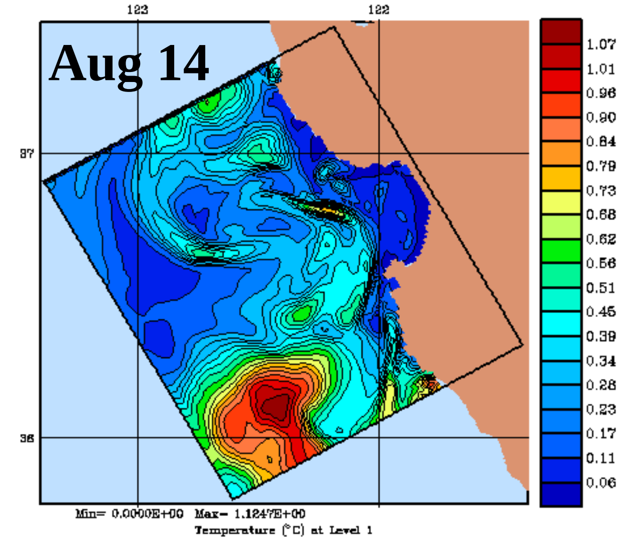
II.b. HOPS and Error Subspace Statistical Estimation (ESSE)

ESSE Surface Temperature Error Standard Deviation Forecasts

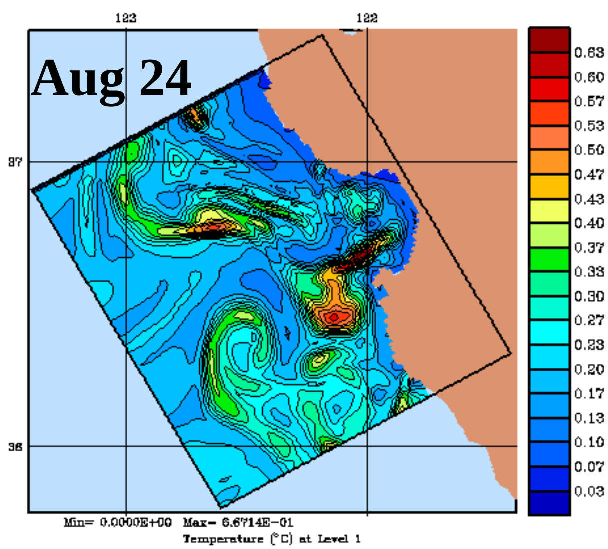


Start of Upwelling

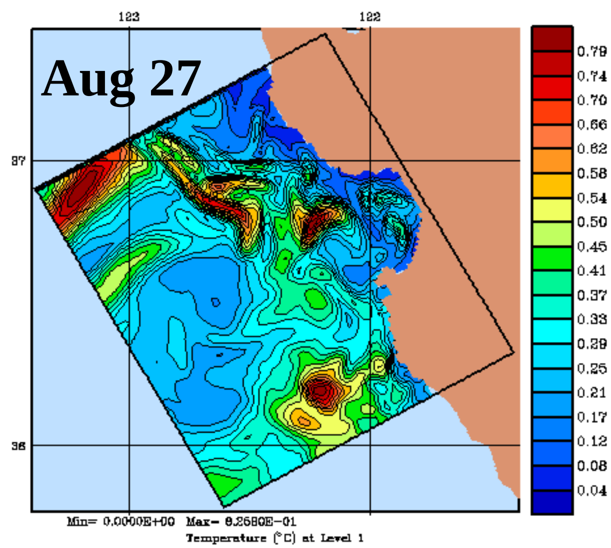


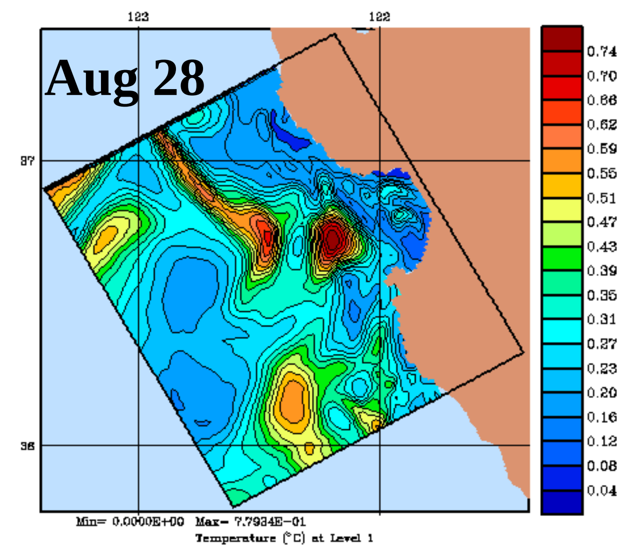


First Upwelling period



End of Relaxation





Second Upwelling period

Adaptive sampling schemes via ESSE

Adaptive Sampling: Use forecasts and their uncertainties to predict the most useful observation system in space (locations/paths) and time (frequencies)

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

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

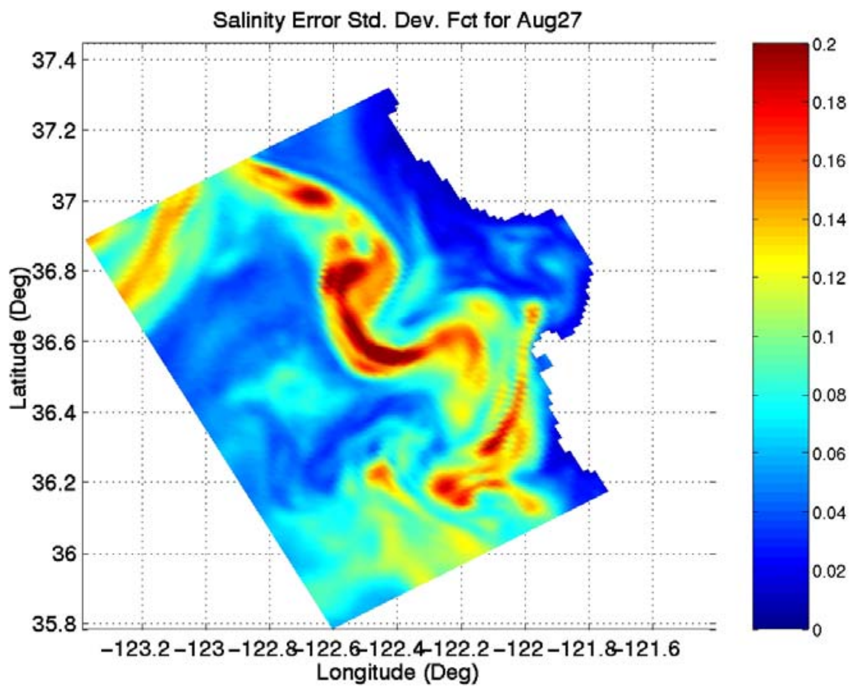
Non-lin. Err. Cov.:

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

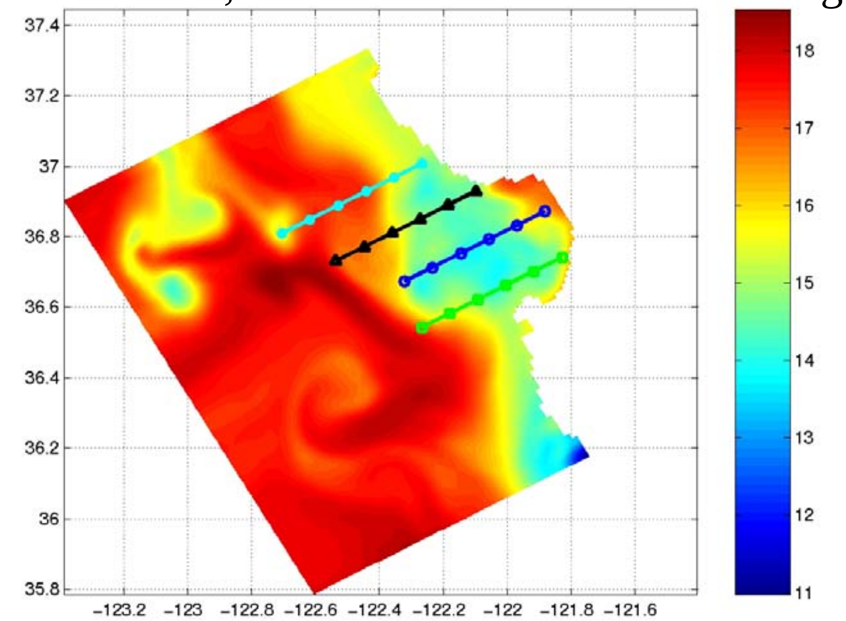
Metric or Cost function: e.g. Find H_i and R_i such that

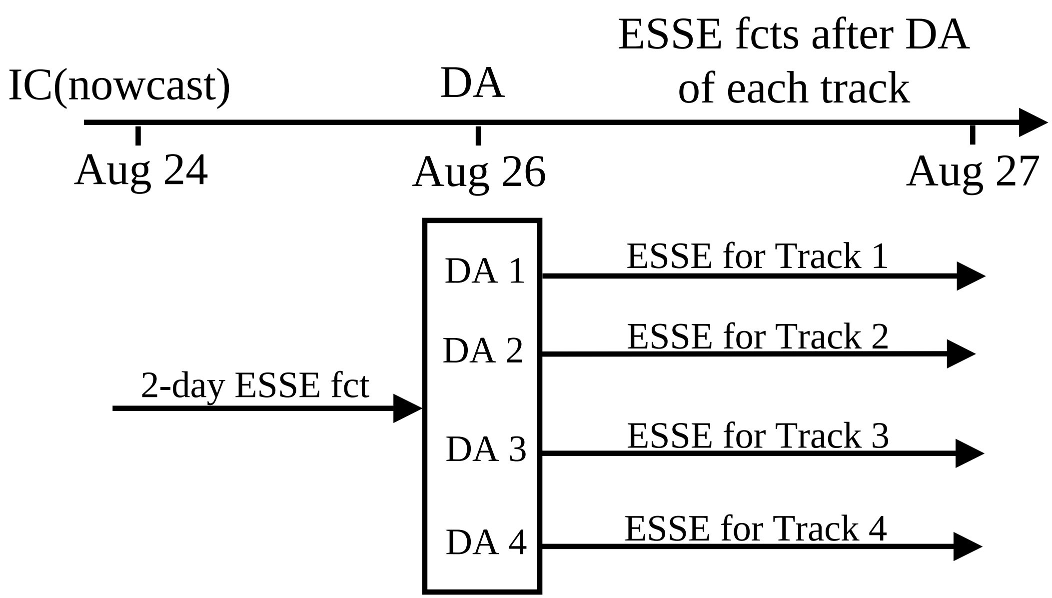
$$\underset{Hi,Ri}{Min} \quad tr(P(t_f)) \qquad or \qquad \underset{Hi,Ri}{Min} \int_{t_0}^{t_f} tr(P(t))\ dt$$

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

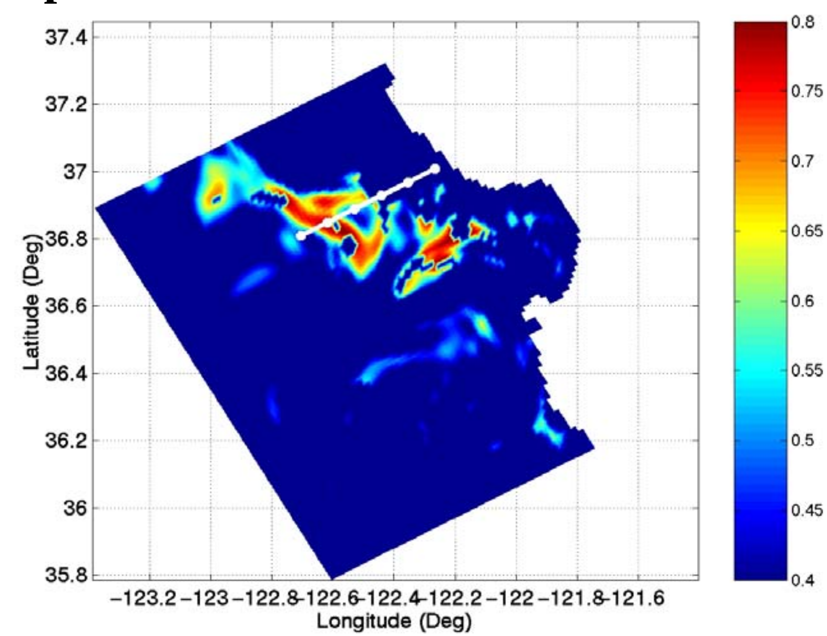


4 candidate tracks, overlaid on surface T fct for Aug 26

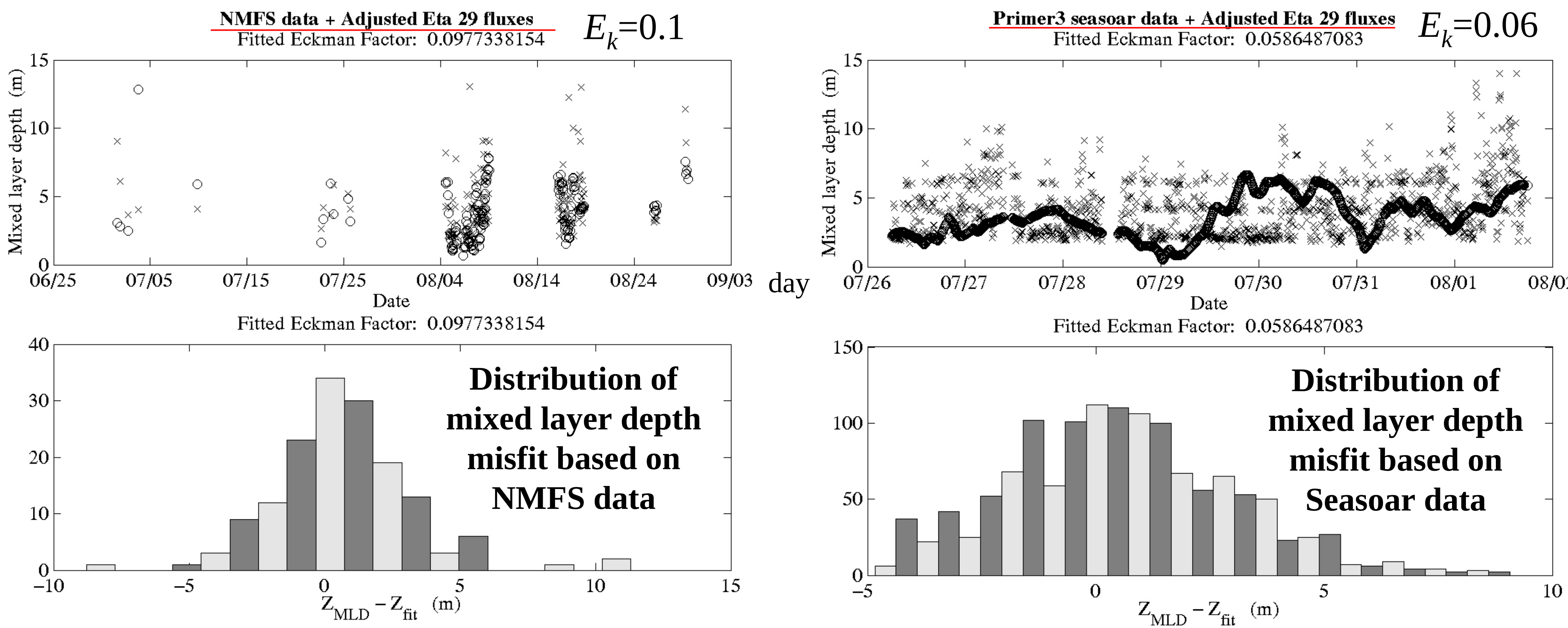




Best predicted relative error reduction: track 1



Multiple Uncertainty Sources. Example of Model Parameters: Mixing layer depth (Ekman factor E_k)



- Similar uncertainties and fit for a few other parameters
- Need for *adaptive modeling* (e.g. parameter values or parameterization structures that evolve as a function of data misfits)
- One reason: (sub)-mesocale coastal variability and atmosphere-ocean interactions are not often stationary at scales of days to a month

II.c. Error Analyses and Optimal (Multi) Model Estimates

- Model Selection: Given several competing options within a model/forecasting system, how to select or switch among options?
- Model Fusion: Given several forecasting models and some past validating data, how do we best combine the models?

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

1. Select appropriate/convenient forecast error parameterization
   - Approximate forecast error covariances and biases models as efficient parametric family:

   $$\mathbf{B} \approx \tilde{\mathbf{B}}(\boldsymbol{\alpha}); \qquad \boldsymbol{\mu} \approx \tilde{\boldsymbol{\mu}}(\boldsymbol{\beta});$$

   - Limit number of free parameters α and β *(for now: error length scale and variance)*

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

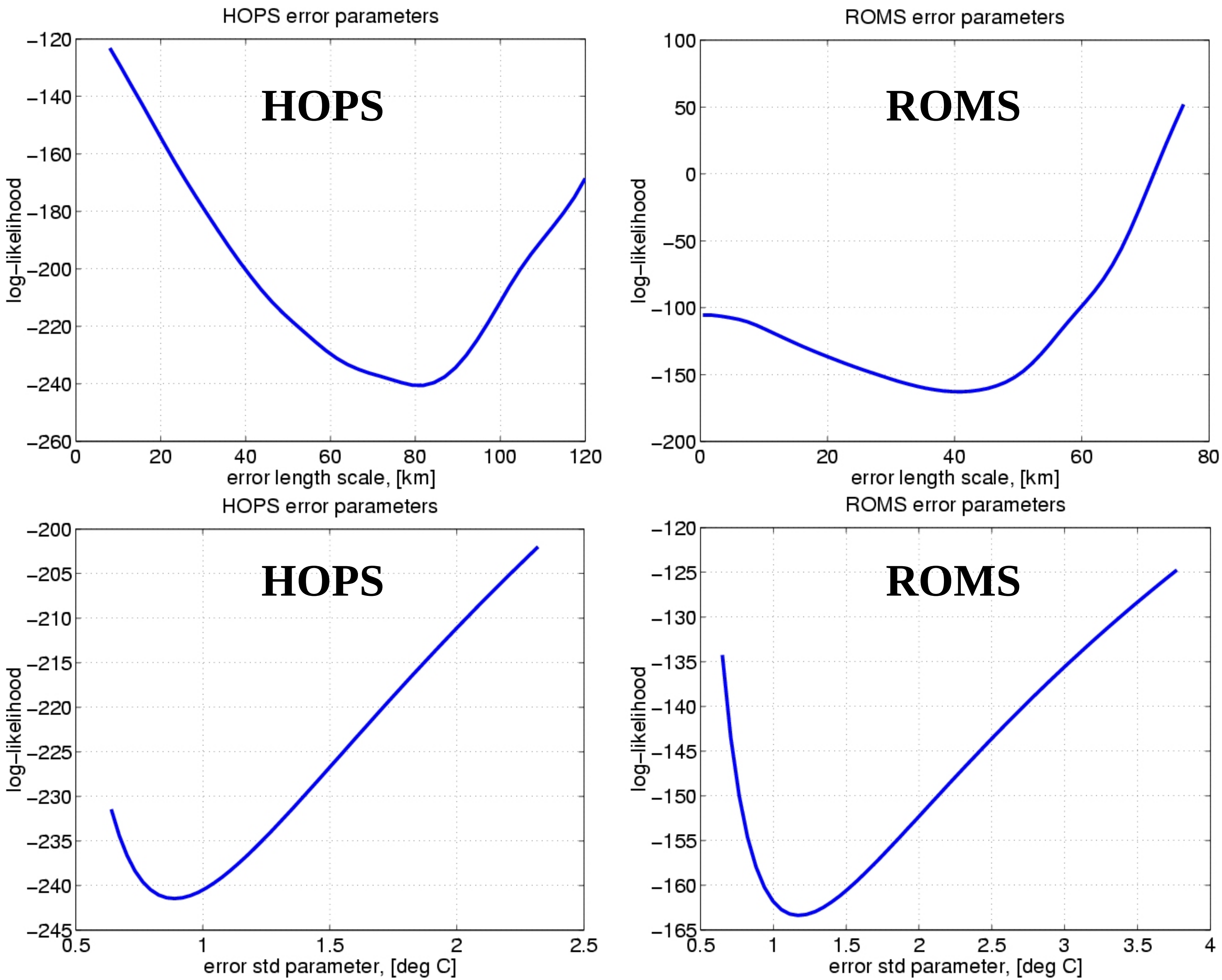
   $$\Theta^* = \arg\max_{\Theta} p(\mathcal{Y}|\Theta)$$ ***y*** is the data, Θ the vector of α's and β's of each model

3. Combine (by Min. Err. Var) or select (most probable) models via Maximum-Likelihood based on the current estimates of error parameters

O. Logoutov

Error Analyses and Optimal (Multi) Model Estimates

Log-Likelihood functions for error parameters

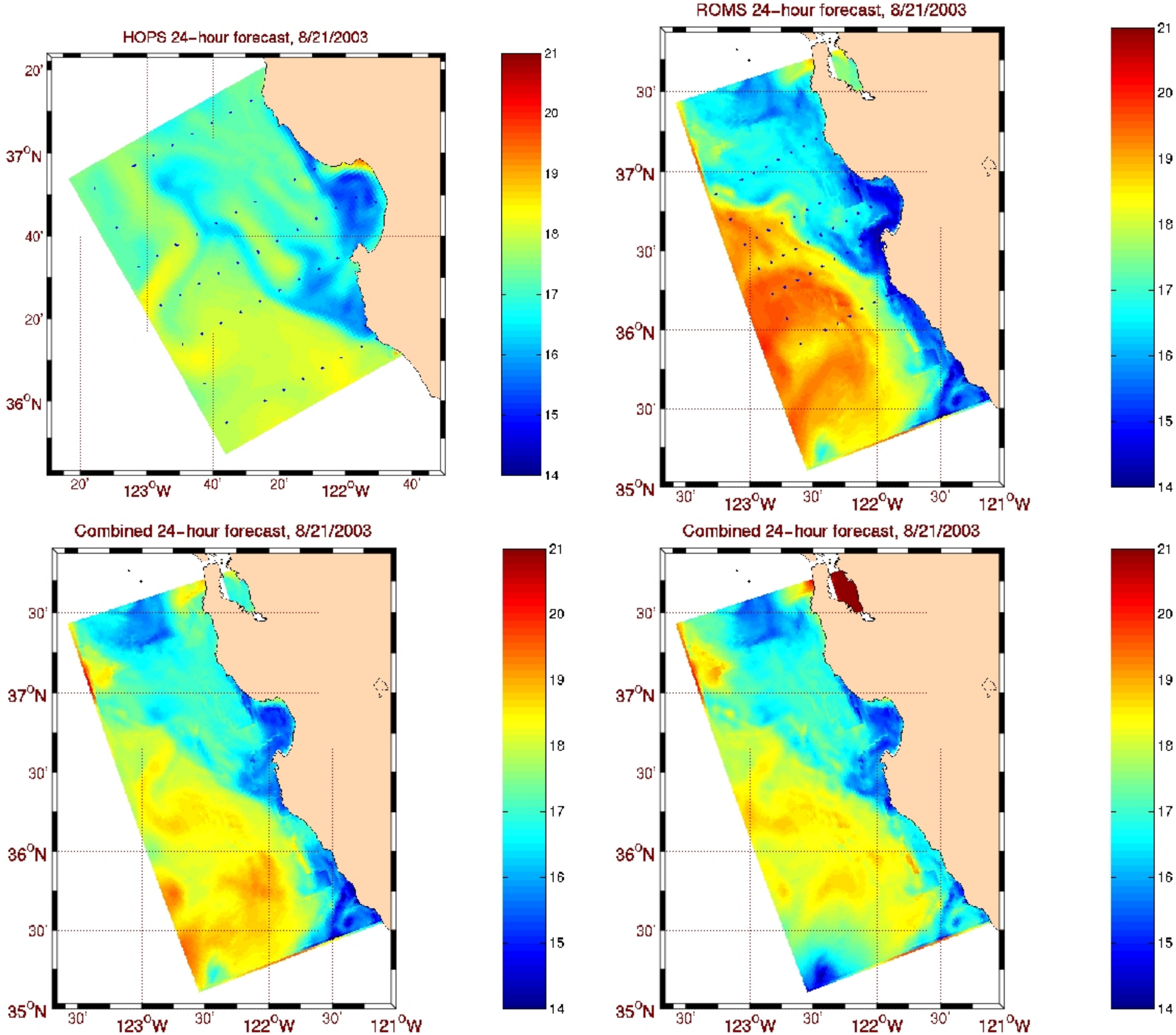


Length Scale

Variance

Error Analyses and Optimal (Multi) Model Estimates

Two-Model Forecasting Example



HOPS and ROMS SST forecast

Left – HOPS (real-time)

Right – ROMS (re-analysis)

Combined SST forecast

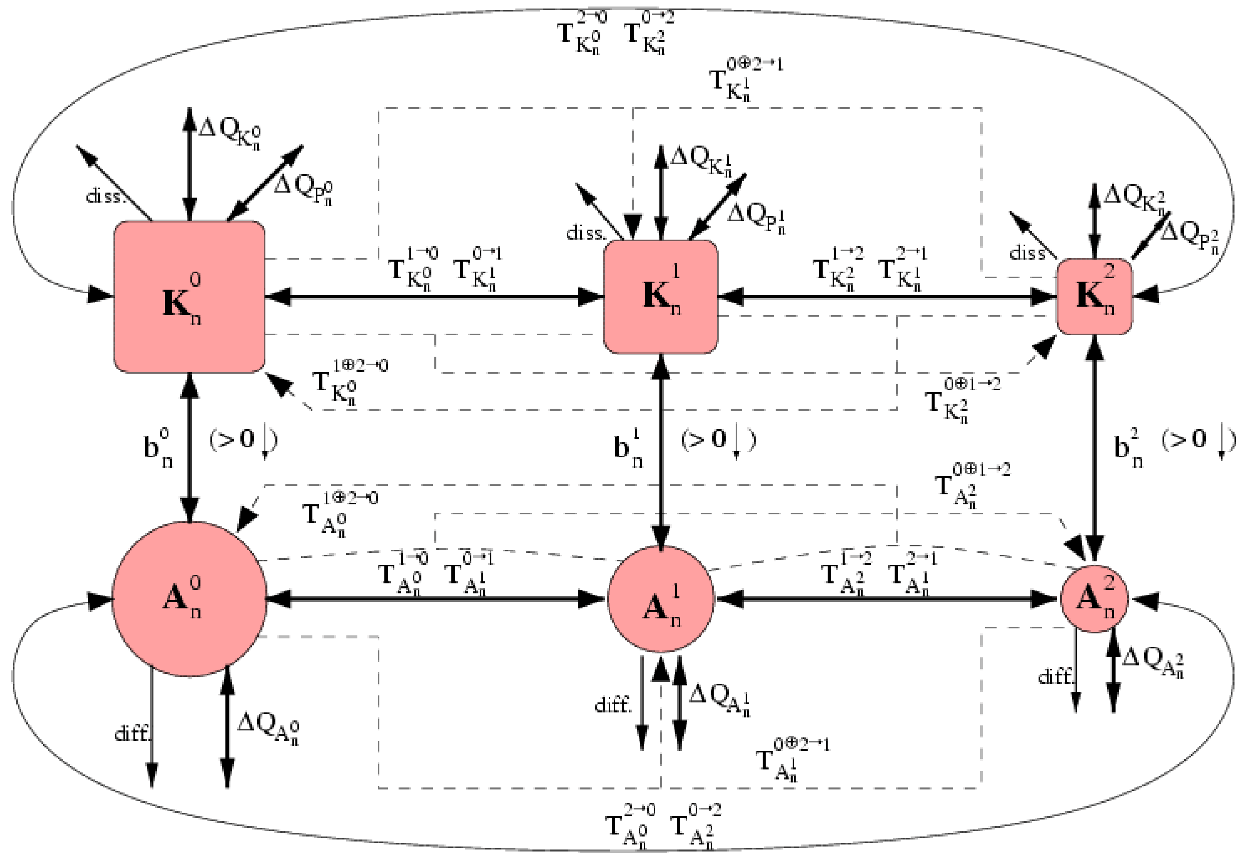
Left – with *a priori* error parameters

Right – with Maximum-Likelihood error parameters

II.d. 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:

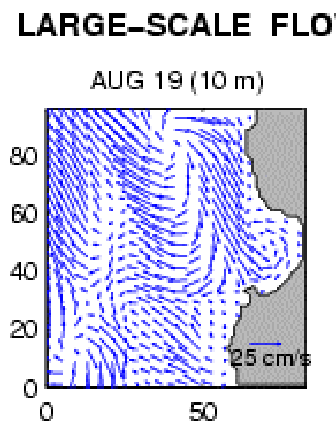
- pattern generation and
- energy and enstrophy
    - transfers
    - transports, and
    - conversions

MS-EVA helps unravel the intricate relationships between events on different scales and locations in phase and physical space.

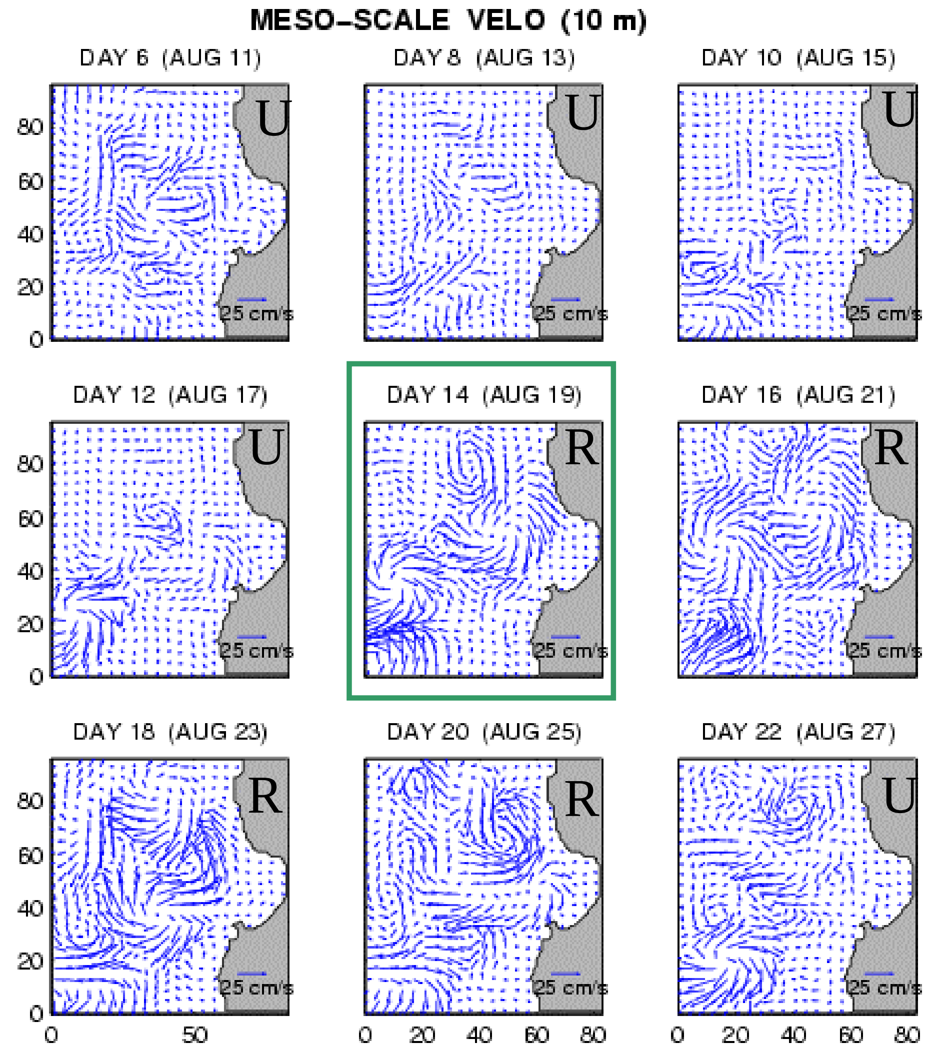
Dr. X. San Liang

Multi-Scale Energy and Vorticity Analysis

Multi-Scale Window Decomposition in AOSN-II Reanalysis



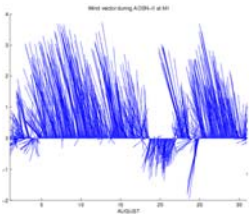
The reconstructed large-scale and meso-scale fields are filtered in the horizontal with features < 5km removed.



Time windows
Large scale: > 8 days, >30km
Meso-scale: 0.5-8 days
Sub-mesoscale: < 0.5 day

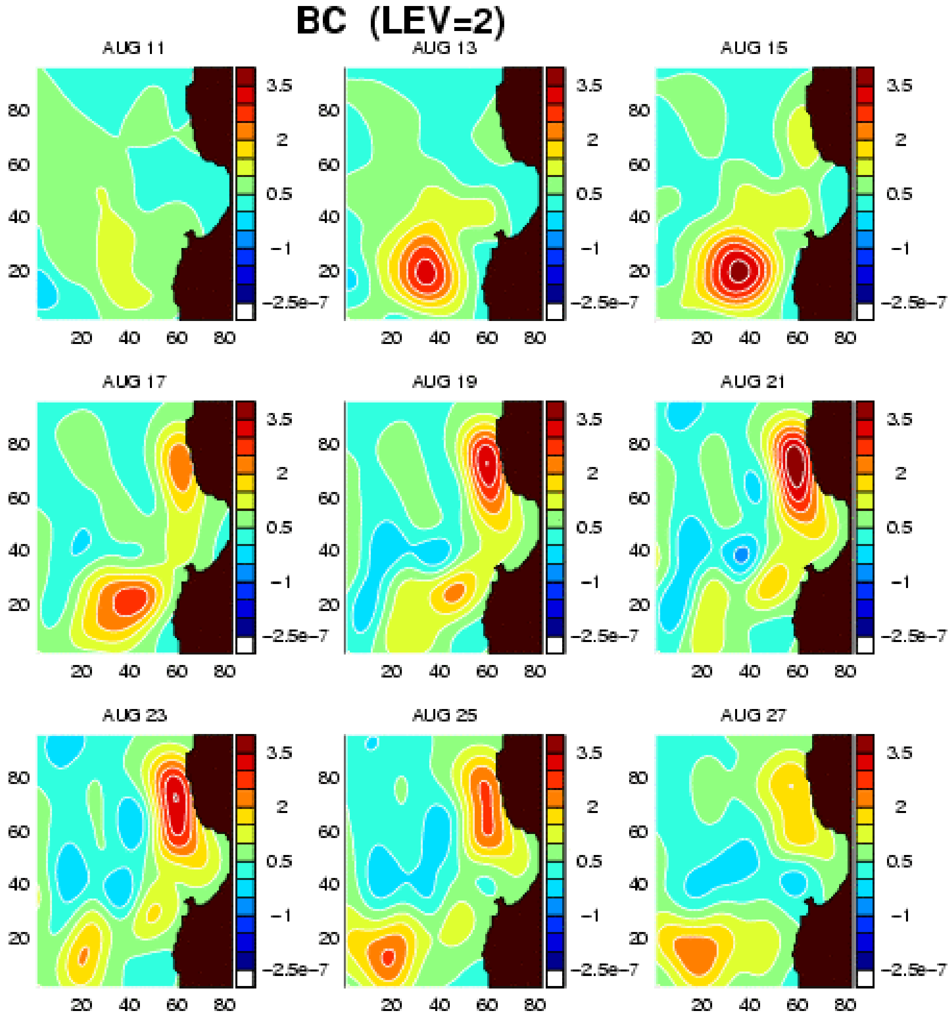
Question: How does the large-scale flow lose stability to generate the meso-scale structures?

Multi-Scale Energy and Vorticity Analysis

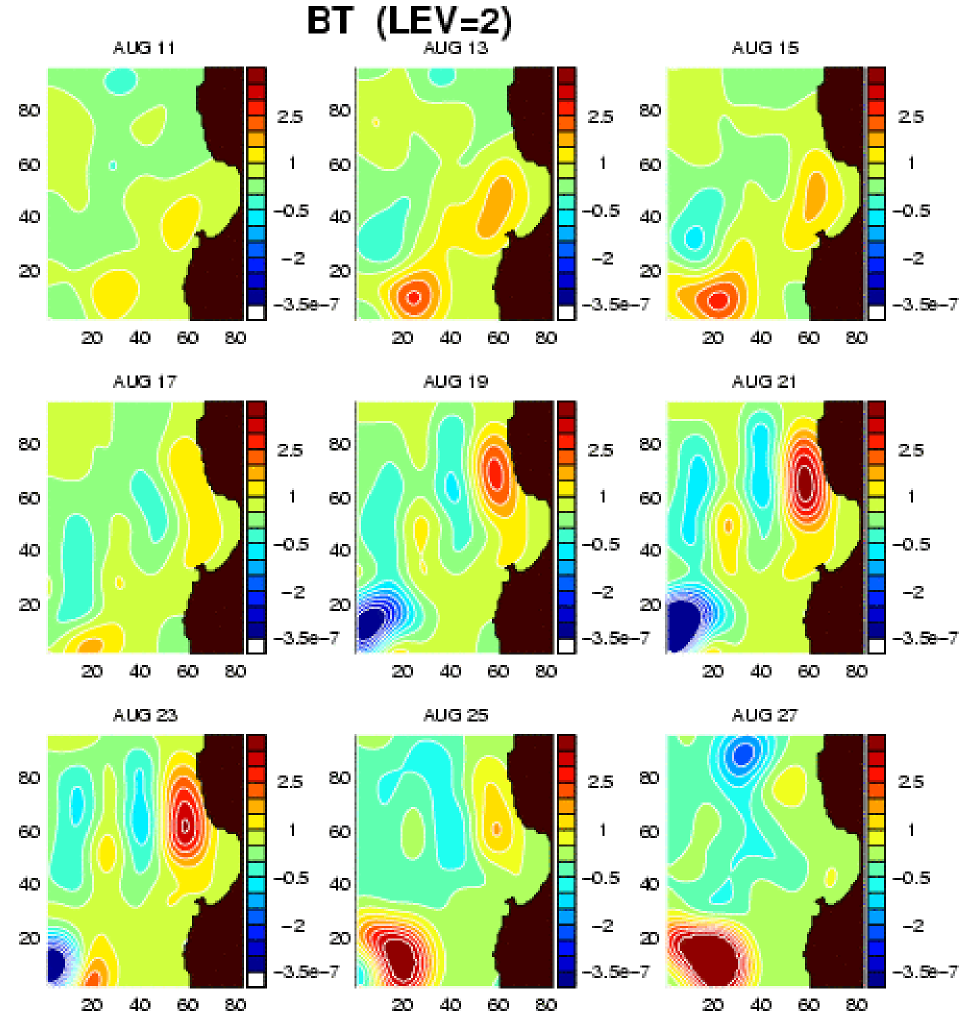


MS-EVA Analysis: 11-27 August 2003

Transfer of APE from large-scale to meso-scale



Transfer of KE from large-scale to meso-scale



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

Specific HU objectives for DART-05

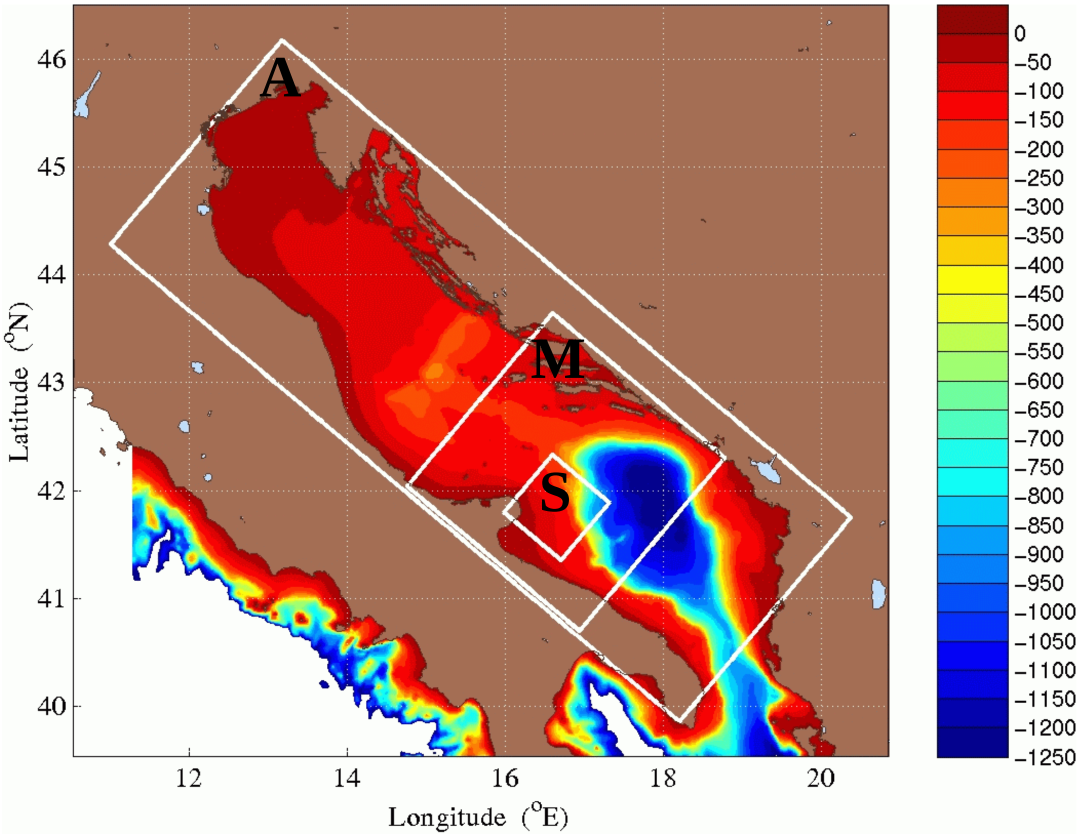
- Physical ocean science
  - Understanding and modeling of sub-mesoscale and small-scale instabilities
  - (Sub)-mesoscale eddy formation and mixing off ``Testa del Gargano" (effects of buoyancy flows, atmospheric forcing and topography)
  - Upper-layers processes: e.g. Drifter predictions (by collaboration, e.g. GNOME, others), Surface boundary layer (SBL) and transfer of atmospheric fluxes (SBL model learning), air-sea interactions (ocean SST feedback)
- Dynamical system identification and Multiple-model estimation
  - Model training and learning (e.g. automated model skill/error evaluation and correction)
  - Adaptive modeling (e.g. SBL)
  - Multi-model and super-ensemble formation and forecasting (NURC, NRL, HU)
- Nested sub-mesoscale, mesoscale and Adriatic real-time forecasting
  - Support efforts of, and collaborate with, Aniello Russo and Paolo Oddo
  - Error predictions, Data assimilation and Adaptive sampling
  - Nested (mini-hops) modeling, including research on high-resolution domains for inertial scales and possibly internal waves

HOPS real-time plans and preparation for DART-05 operations

- Coordinate model preparation and calibration: A. Russo, P. Oddo and HU
  - Evaluate and determine common domains
  - Model calibration via sensitivity simulation studies (numerical and dynamical parameters)
  - Collaborative scientific objectives
- Set-up nested sub-mesoscale, mesoscale and Adriatic HOPS
  - Nested high-resolution (mini-hops) modeling
  - Multi-model and super-ensemble formation and forecasting
  - Error predictions, Data assimilation and Adaptive sampling
- DART-05 multiple groups allow for more real-time scientific interpretation
  - Interest?
    - Real-time descriptive oceanography (data-based, model-based, comparisons)
    - Secondary variables studies, balances of terms
- Investigate possibility of setting-up LAS or other model data access server
  - Enables collaborative real-time science

Potential HOPS Modeling Domains

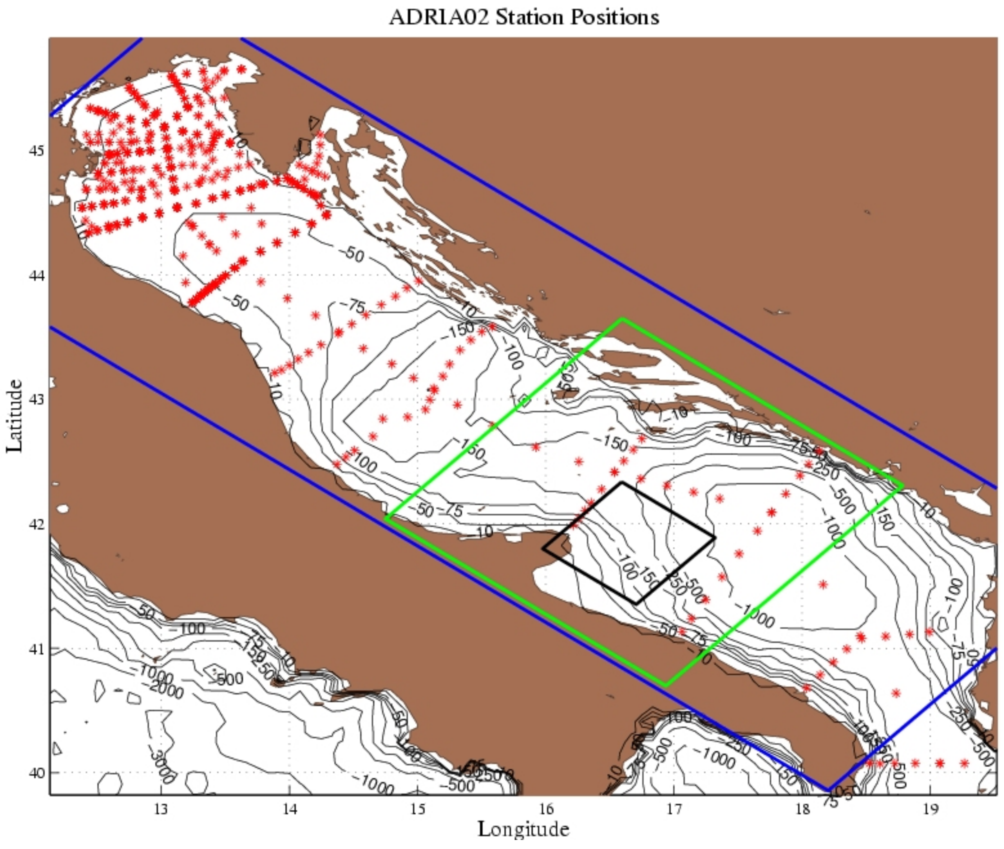
(To be updated based on this meeting)



	Adriatic (A)	Mesoscale (M)	Sub-Mesoscale (S)
Resolution	4.05km	1.35km	0.45km
Size (nx,ny,nz)	190x69x21 (~765x275km)	173x174x21 (~232x234km)	173x174x21 (~77x78km)
Speed (300s dt)	19 minutes/(model day)	44 minutes/(model day)	44 minutes/(model day)
Resolution	9.639km	3.213km	1.071km
Size (nx,ny,nz)	81x32x21 (~771x299km)	77x78x21 (~244x247km)	77x78x21 (~81x82km)
Speed (300s dt)	3.8 minutes/(model day)	8.7 minutes/(model day)	8.7 minutes/(model day)

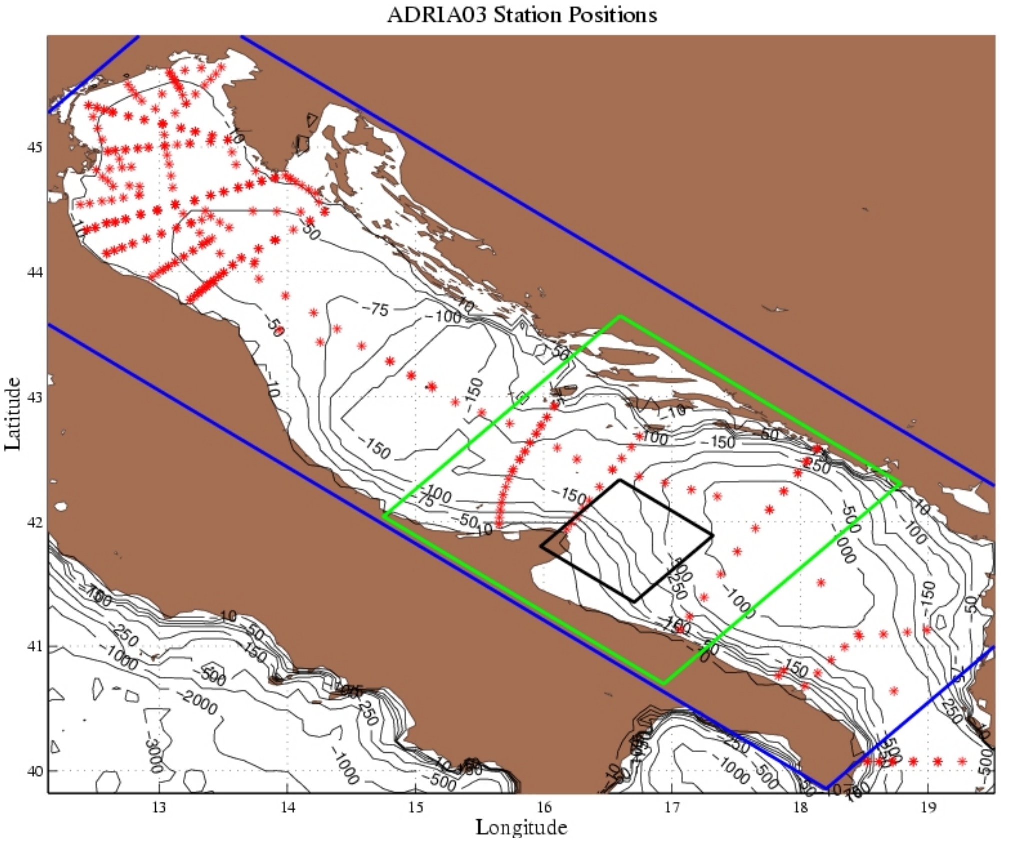
Needed preparation material and resources

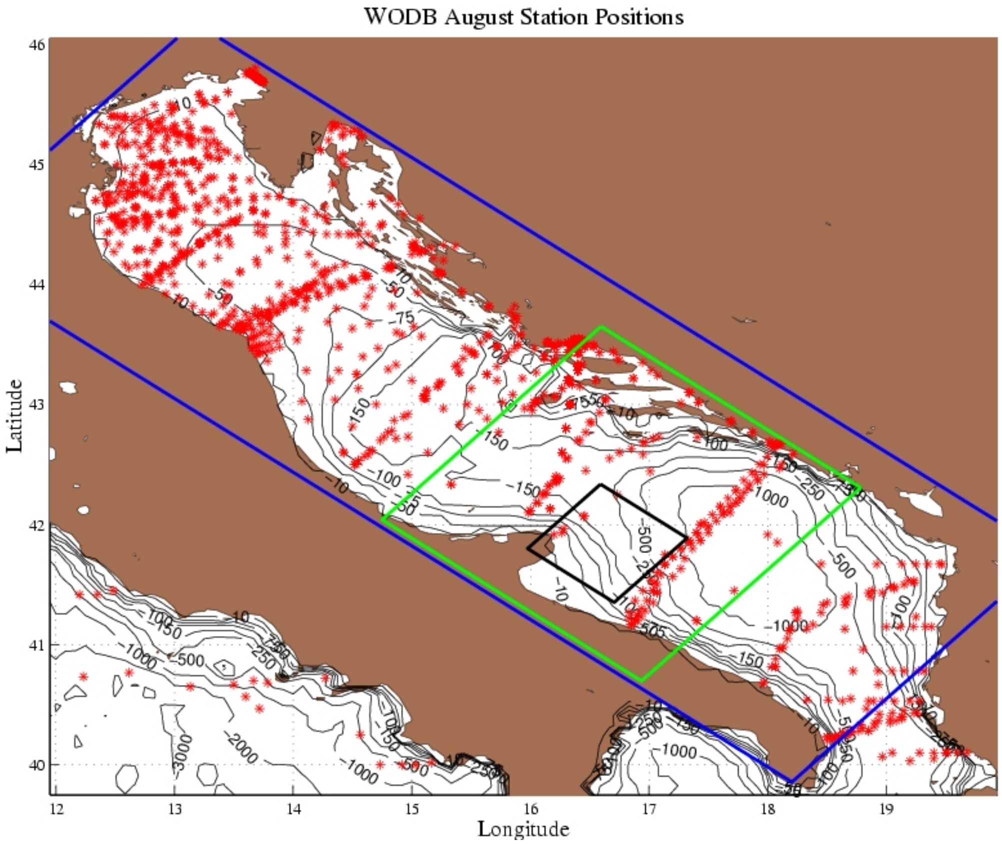
- Bibliography of Adriatic literature (focus on DART-05 goals)
- Who are the local experts on dynamics off "Testa del Gargano"?
  - What are the dominant processes, scales, etc? (internal waves?, over-turning?, tides?)
  - Local historical data sets available?
- Historical and climatological data bases
  - In situ, Satellite and other remote sensing (codar, etc) , Atmospheric Forcing
  - Bathymetries, river inflows, tidal fields
- List of existing model set-ups
  - Web-page and some info on model code, region, resolution, data used, assimilation, etc
- Need real-time access to other modeling outputs (GEOS, LAS?, ftp?)
  - Model training and Multi-model estimation by Oleg Logoutov at HU
- List of existing or planned data collections in Adriatic (other than DART05)
  - Data of opportunity, planned experiments, availability, etc
- DART-05 web-page where all of the above is maintained.



ADRIA02
18 Sep – 22 Oct 2002
542 Profiles

ADRIA03
25 Apr – 10 May 2003
336 Profiles

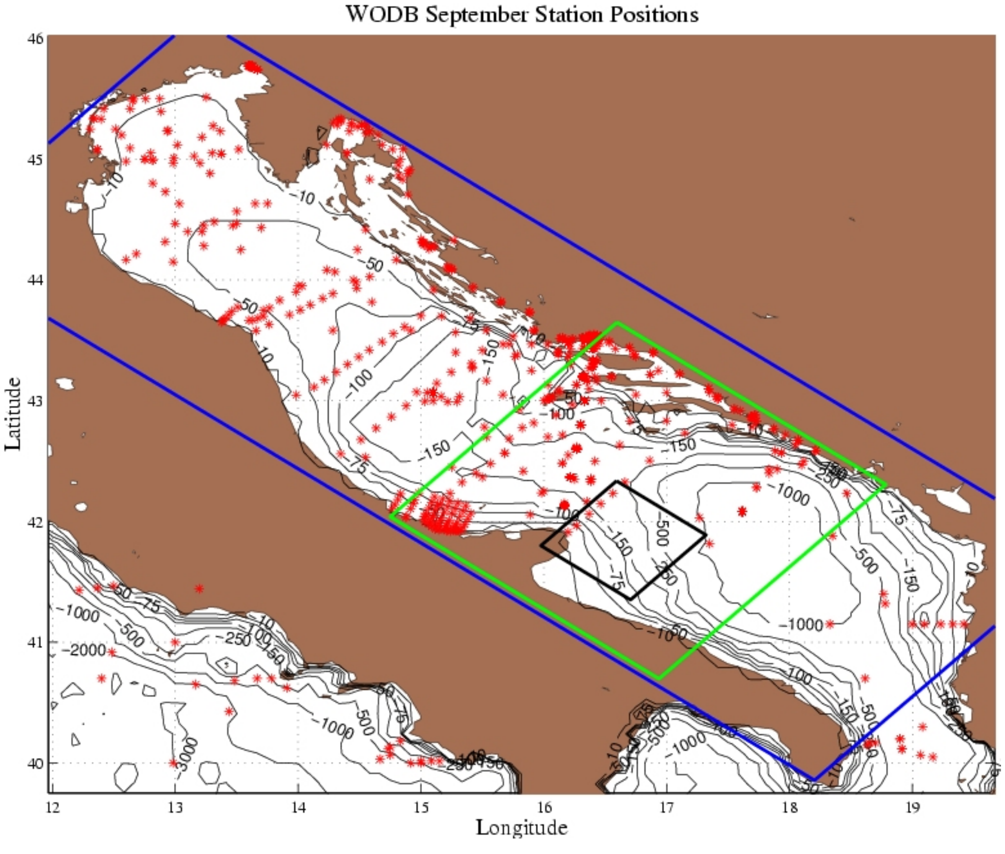




World Ocean Data Base (WODB)

<u>August</u>
1905 – 1987
1474 Profiles

<u>September</u>
1911 – 1983
910 Profiles



Experimental plans to be discussed

- List of real-time sensors and platforms available
  - Spatial and temporal sampling capabilities and constraints
  - Routine or adaptive
- Ocean sampling needs
  - Initialization survey: optimize ship use and deployment of fixed assets
  - Updating surveys: Adaptive and routine
  - Verification surveys: Field forecast evaluation and Model parameterization evaluation
- Repetitive data calibration stations for multi-sensors/platforms
  - Protocols, frequency
- Atmospheric data
- Other data bases: bathymetries, rivers inflows, tides
- Real-time modeling inputs/outputs wishes and needs
  - LAS or not?, GEOS?
- Operations and real-time modeling logistics (who, where, how, which?)

Model calibrations to be discussed

- Bibliography of modeling literature in the Adriatic
- Numerical and scientific tuning
  - Single model (NRL, ROMS, POM, HOPS, etc)
    - e.g. A. Russo, P. Oddo and HU for HOPS
  - Multi-models tuning
- Useful model calibrations via OSSEs
  - OSSEs for initial surveys
    - e.g. which among 2-3 scenarios for initial R/V Alliance survey is best for each of the expected 2-3 dynamical scenario (based on historical wind conditions, remotely-sensed oceanic circulation/features).
  - OSSE for routine data needs
    - e.g. what are optimal routine tracks for the R/V Alliance?
- Multi-model estimations
  - Plans for sharing fields, parameters, etc

CONCLUSIONS

- Joint NURC and NRL DART-05 experiment in Adriatic has potential for substantial scientific and operational contributions to new research topics
- HU will aim to provide as much support as possible
  - Collaboration with A. Russo and P. Oddo for HOPS
  - Collaboration with all modeling groups for multi-model comparison and combination
  - HU techniques: HOPS, Mini-HOPS, ESSE, MsEVA, Model training and multi-models, Adaptive modeling
  - Build on MREA-03, MREA-04 and AOSN-II experiments
  - Link to other HU research necessary for funding
- Important topics to be discussed
  - Preparation material and resources (expertise, data and models)
  - Experimental plans (especially surveys)
  - Modeling plans (especially calibration)
  - Collaborative research topics
  - Overall coordination