AOSN-II in Monterey Bay:
Real-Time Error Predictions, Data Assimilation, Adaptive Sampling and Dynamics

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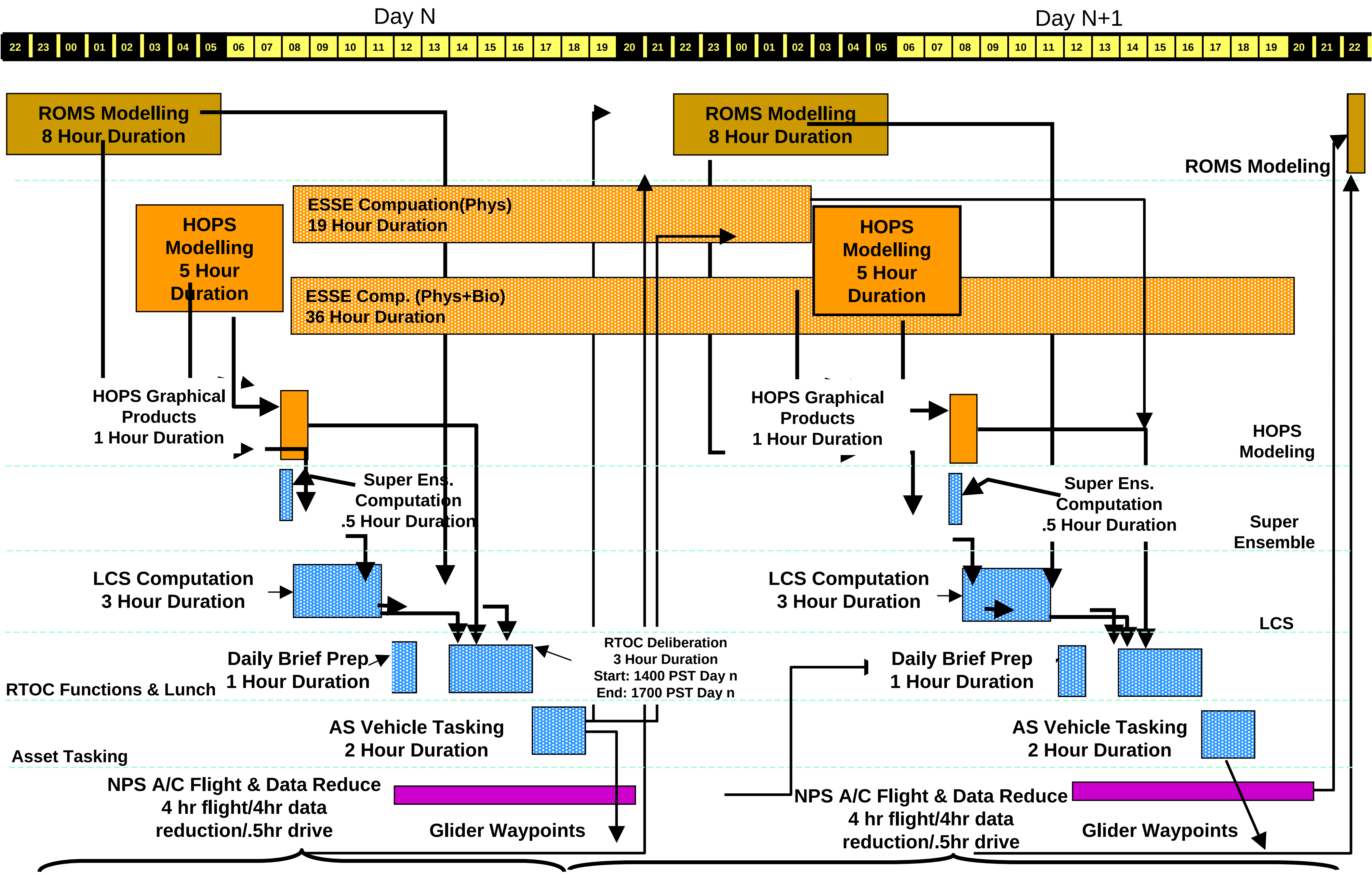
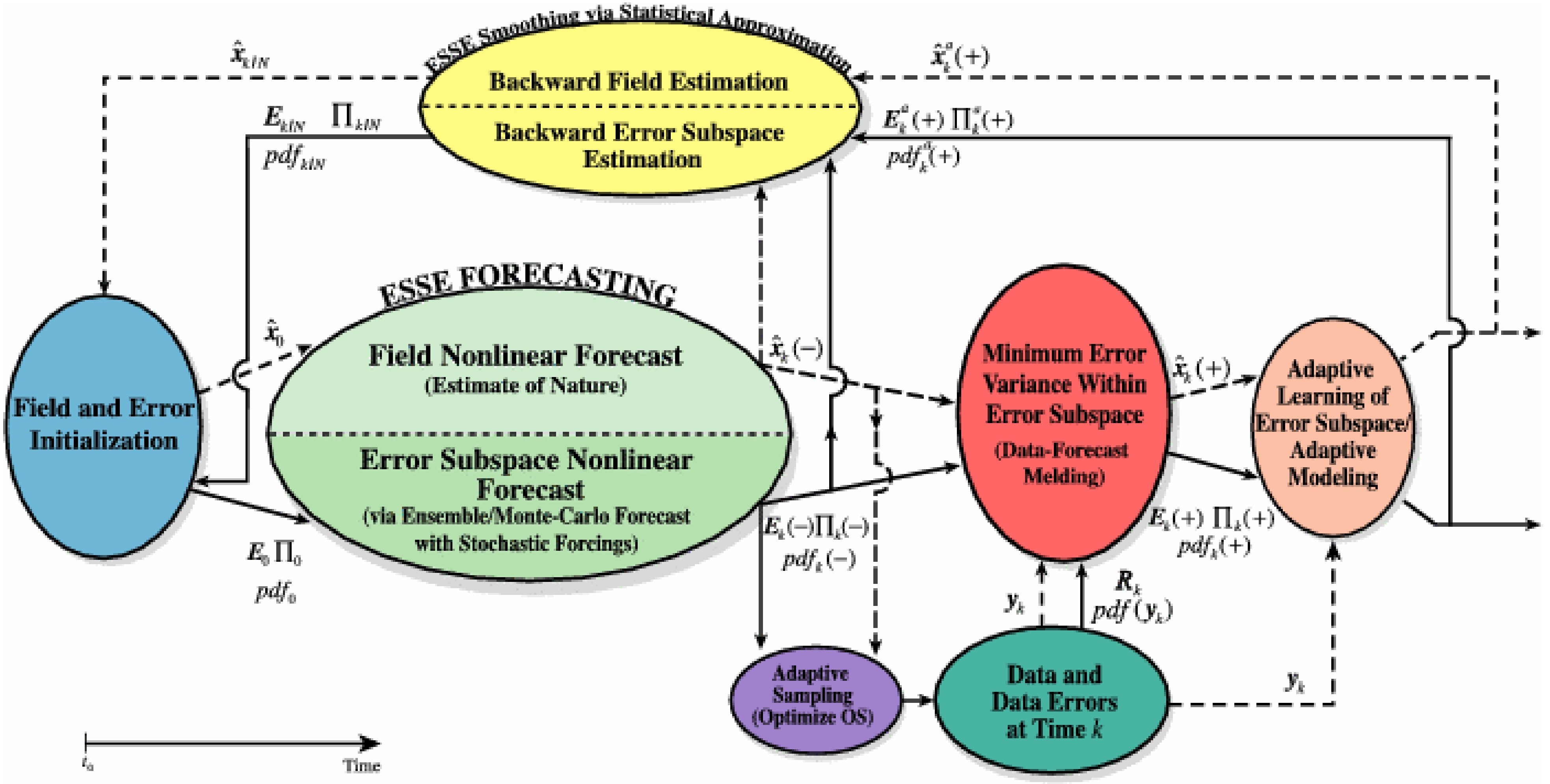


Two-scale Adaptive Sampling:

- Daily identification of features and errors from model forecasts
- Two-hourly data feedback for glider coordination

Error Subspace Statistical Estimation (ESSE)



- Uncertainty forecasts (dynamic error subspace and adaptive error learning)
- Ensemble-based (with nonlinear and stochastic model)
- Multivariate, non-homogeneous and non-isotropic DA
- Consistent DA and adaptive sampling schemes
- Software: not tied to any model, but specifics currently tailored to HOPS

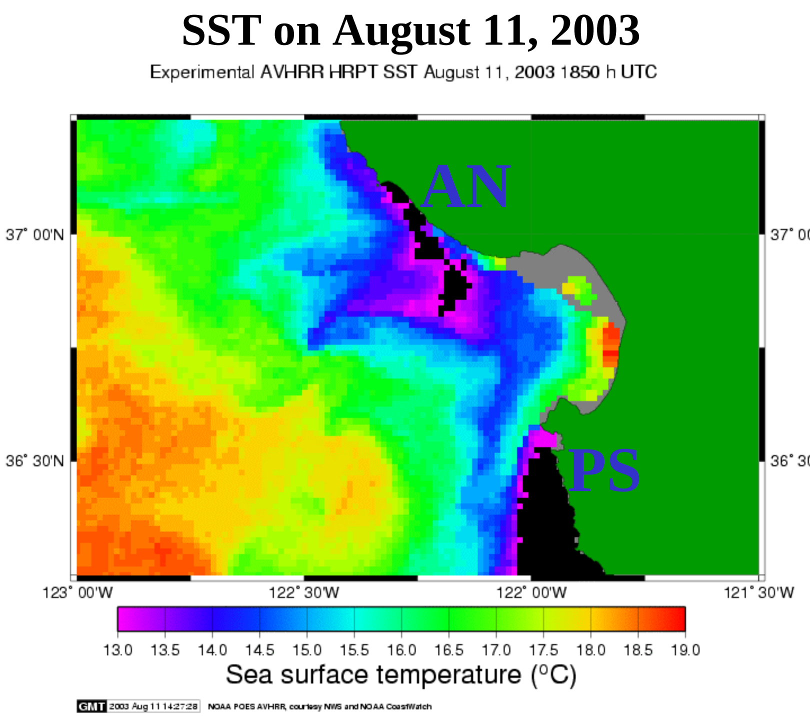
Ocean Regions and Experiments/Operations for which ESSE has been utilized in real-time

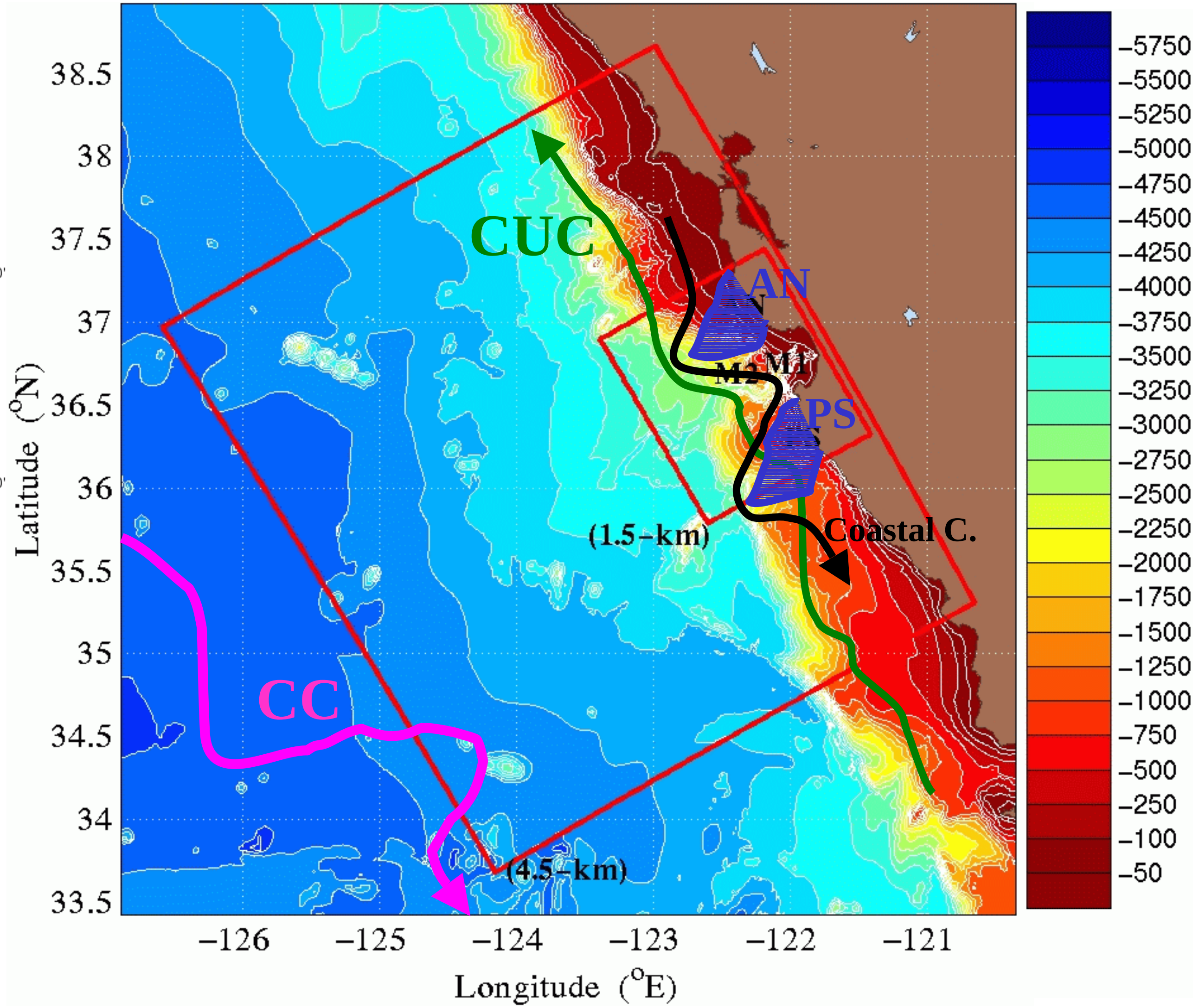
- Strait of Sicily (AIS96-RR96), Summer 1996
- Ionian Sea (RR97), Fall 1997
- Gulf of Cadiz (RR98), Spring 1998
- Massachusetts Bay (LOOPS), Fall 1998
- Georges Bank (AFMIS), Spring 2000
- Massachusetts Bay (ASCOT-01), Spring 2001
- Monterey Bay (AOSN-2), Summer 2003

Real-time ESSE : AOSN-II Accomplishments

- 10 sets of ESSE nowcasts and forecasts of temperature, salinity and velocity, and their uncertainties, issued from 4 Aug. to 3 Sep.
  - Total of 4323 ensemble members: 270 – 500 members per day ($7\ 10^5$ state var.)
  - ESSE fields included: central forecasts, ensemble means, *a priori* (forecast) errors, *a posteriori* errors, dominant singular vectors and covariance fields
  - 10^4 data points quality controlled and assimilated per day: ship (Pt. Sur, Martin, Pt. Lobos), glider (WHOI and Scripps) and aircraft SST data
- Ensemble of stochastic PE model predictions (HOPS)
  - Deterministic atmospheric forcing: 3km and hourly COAMPS flux predictions
  - Stochastic oceanic/atmos. forcings: for sub-mesoscale eddies, BCs and atmos. fluxes
- ESSE fields formed the basis for daily adaptive sampling recommendations
- Adaptive ocean modeling: BCs and model parameters for transfer of atmos. fluxes calibrated and modified in real-time to adapt to evolving conditions
- ESSE dynamical results described and posted on the Web daily
- Real-time research: stochastic error models, coupled physics-biology, tides

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

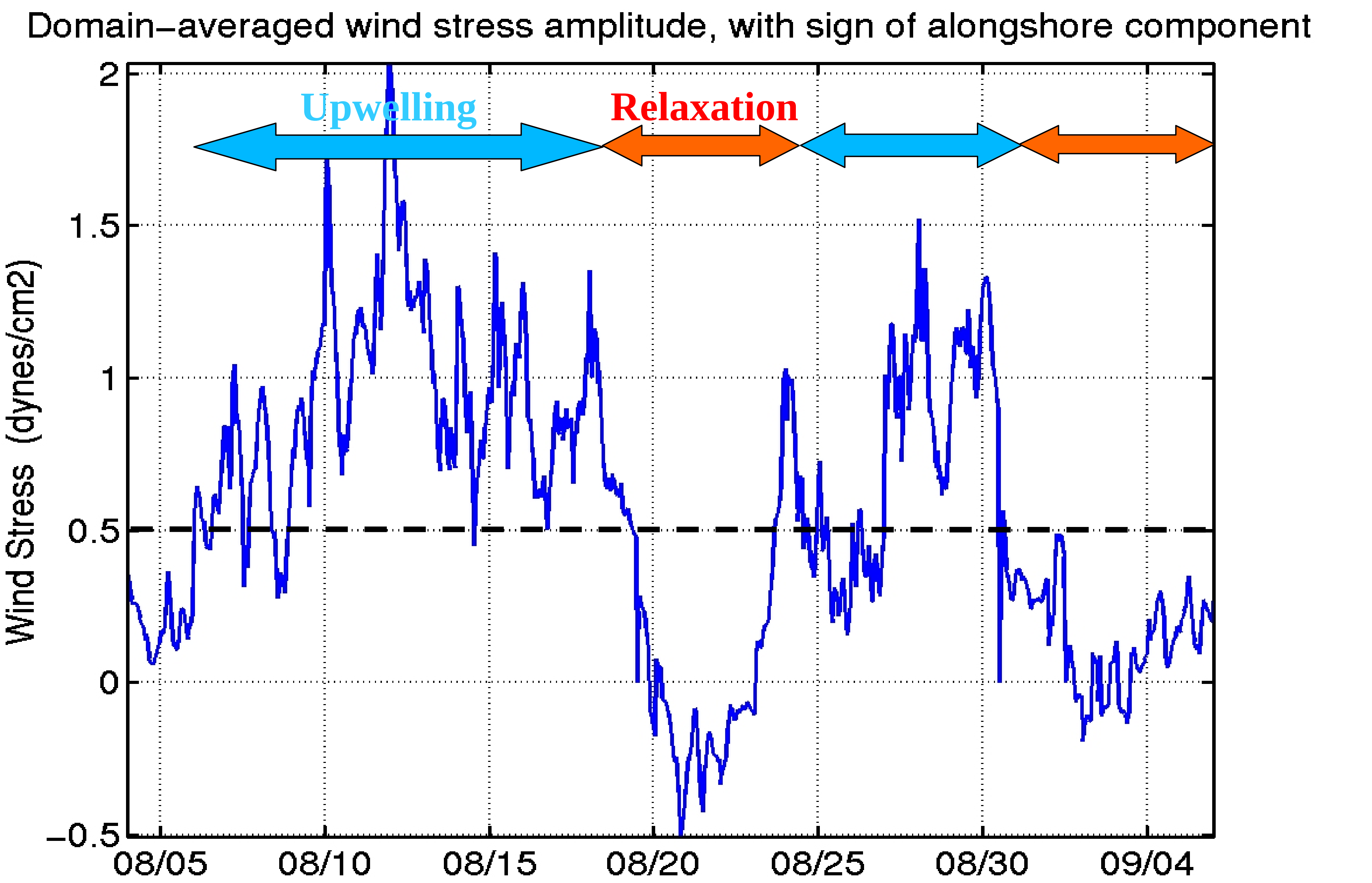




REGIONAL FEATURES

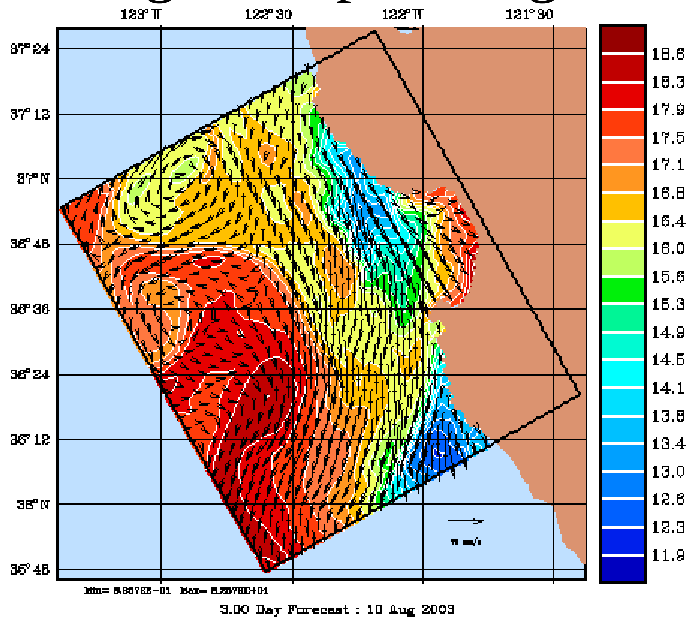
- **Upwelling centers at Pt AN/ Pt Sur:**…………Upwelled water advected equatorward and seaward
- **Coastal current, eddies, squirts, filam., etc:**….Upwelling-induced jets and high (sub)-mesoscale var. in CTZ
- **California Undercurrent (CUC):**……………..Poleward flow/jet, 10-100km offshore, 50-300m depth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

Oceanic responses and atmospheric forcings during August 2003

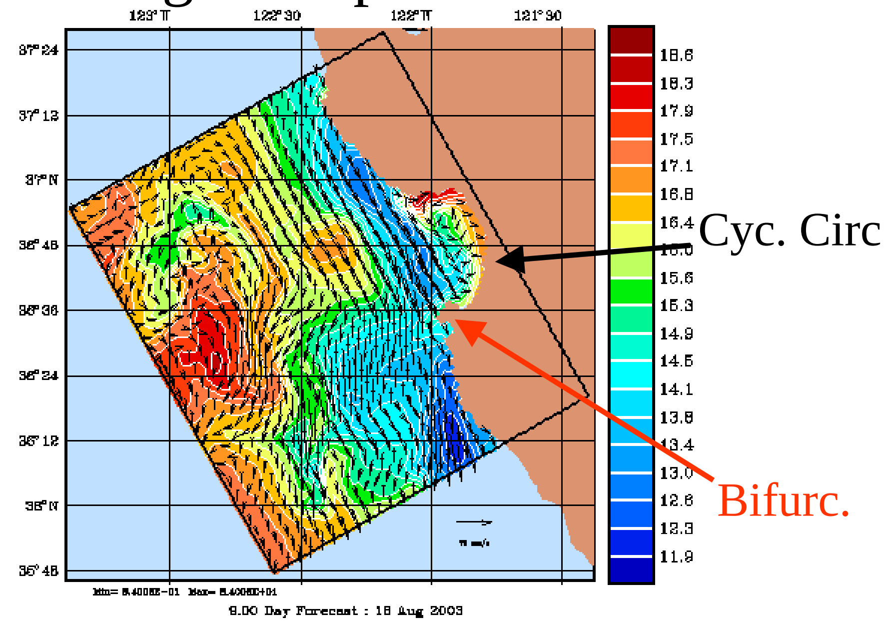


Oceanic responses and atmospheric forcings during August 2003

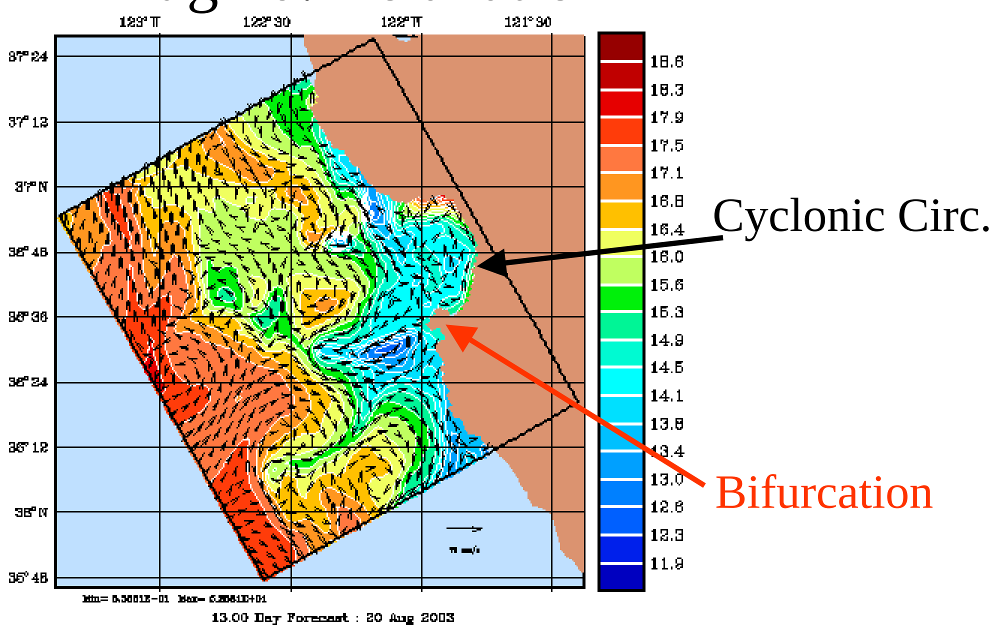
Aug 10: Upwelling



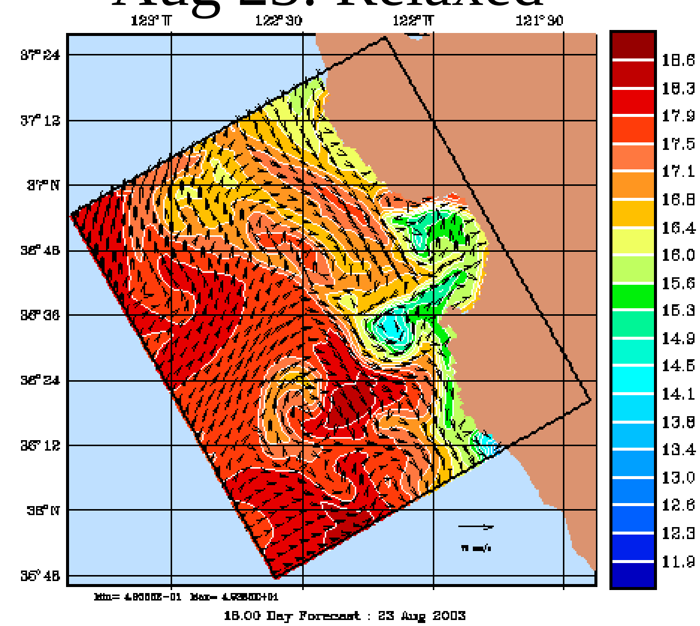
Aug 16: Upwelled



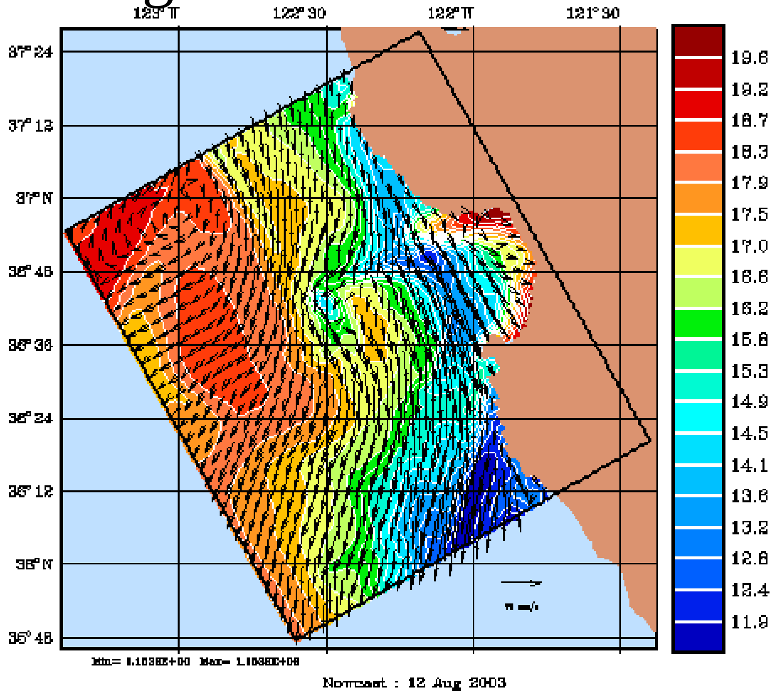
Aug 20: Relaxation



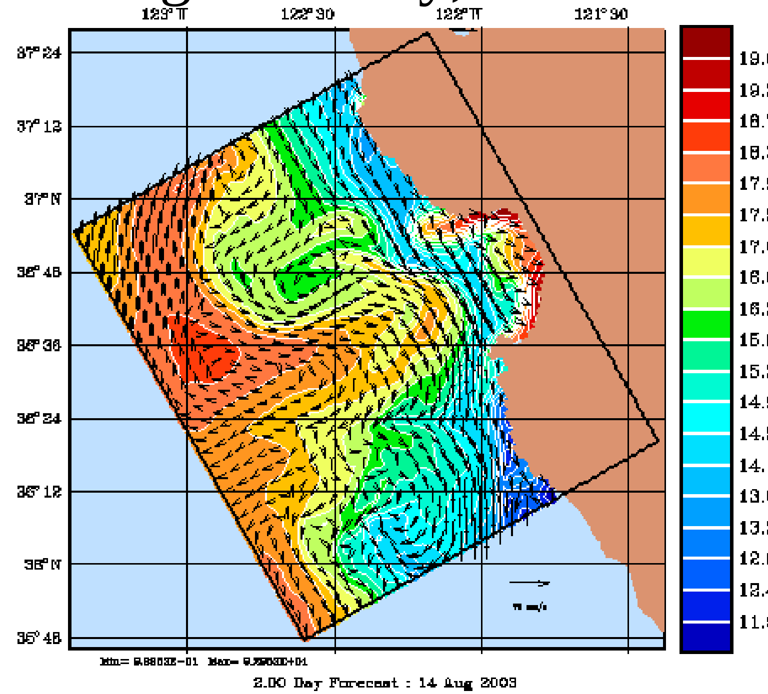
Aug 23: Relaxed



Aug 12: Initial Conditions

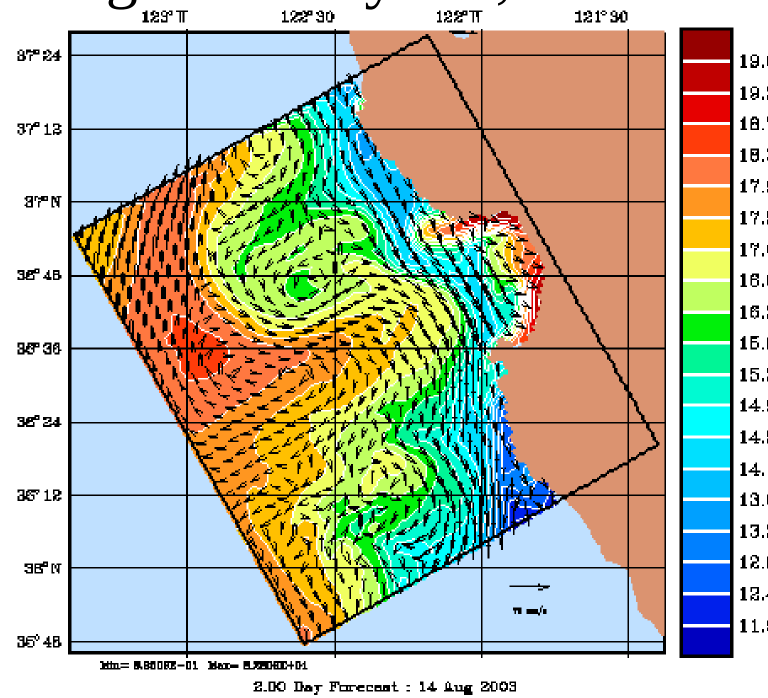


Aug 14: 2-day, central fct.



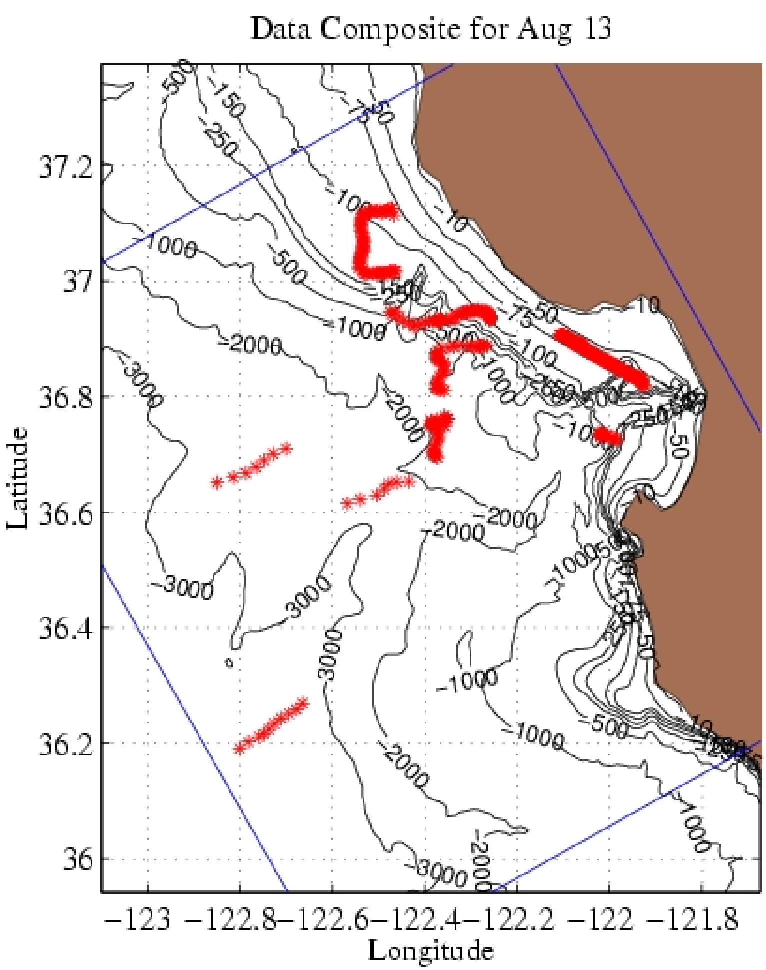
Sample real-time ESSE Products: Ensemble Mean and Central Forecast Issued in real-time

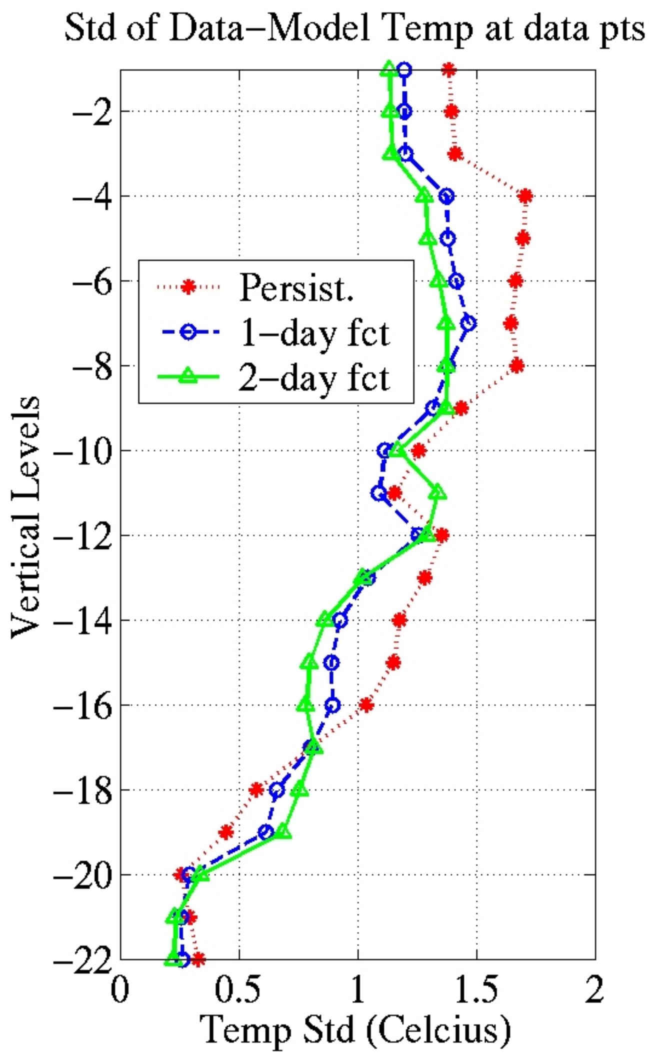
Aug 14: 2-day fct., ens mean

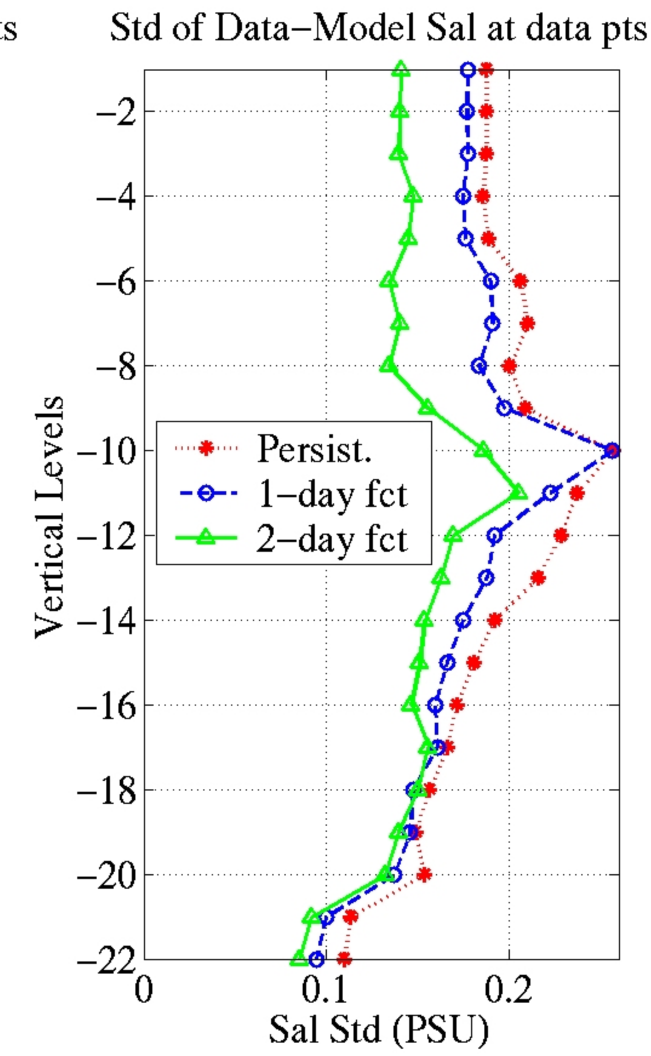


RMSE Estimate

Standard deviations of horizontally-averaged data-model differences





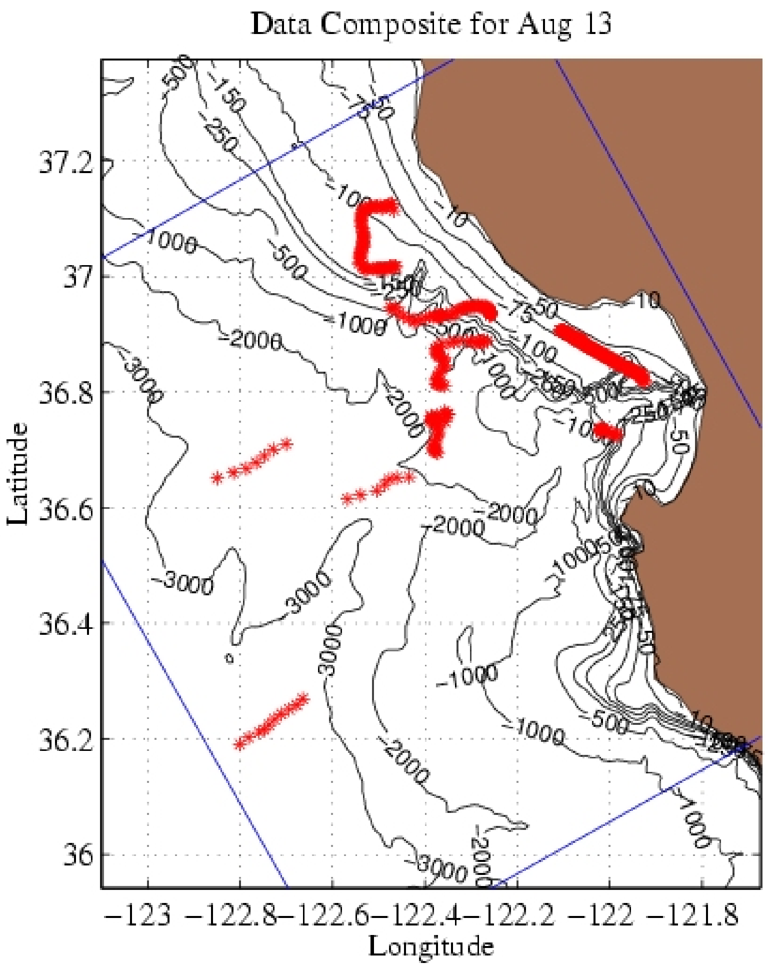


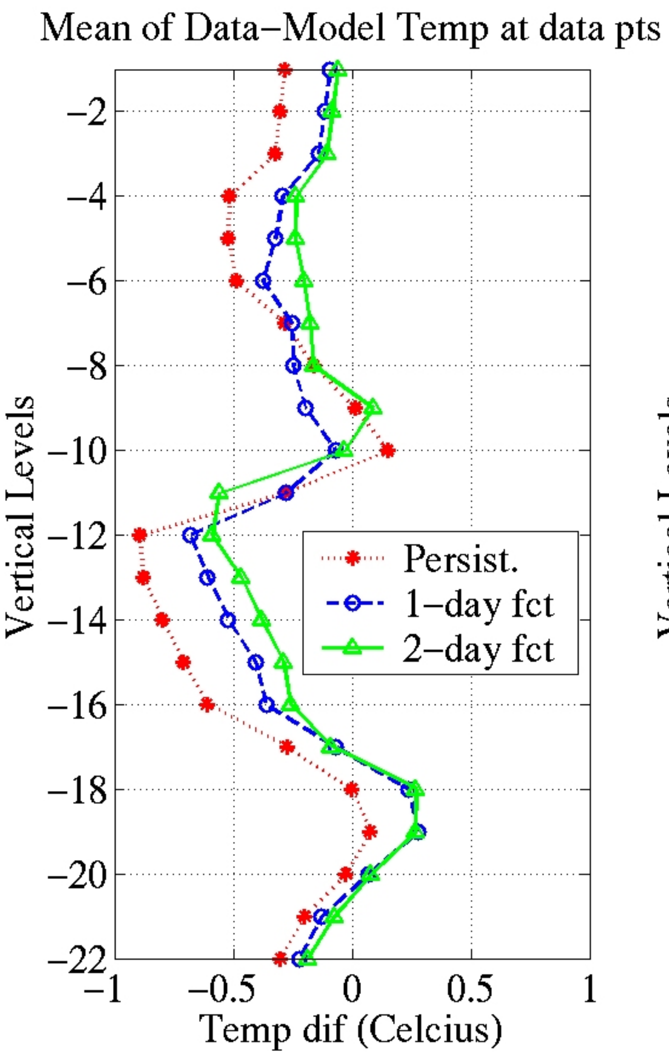
Verification data time: Aug 13
All forecasts are compared to this Aug 13 data

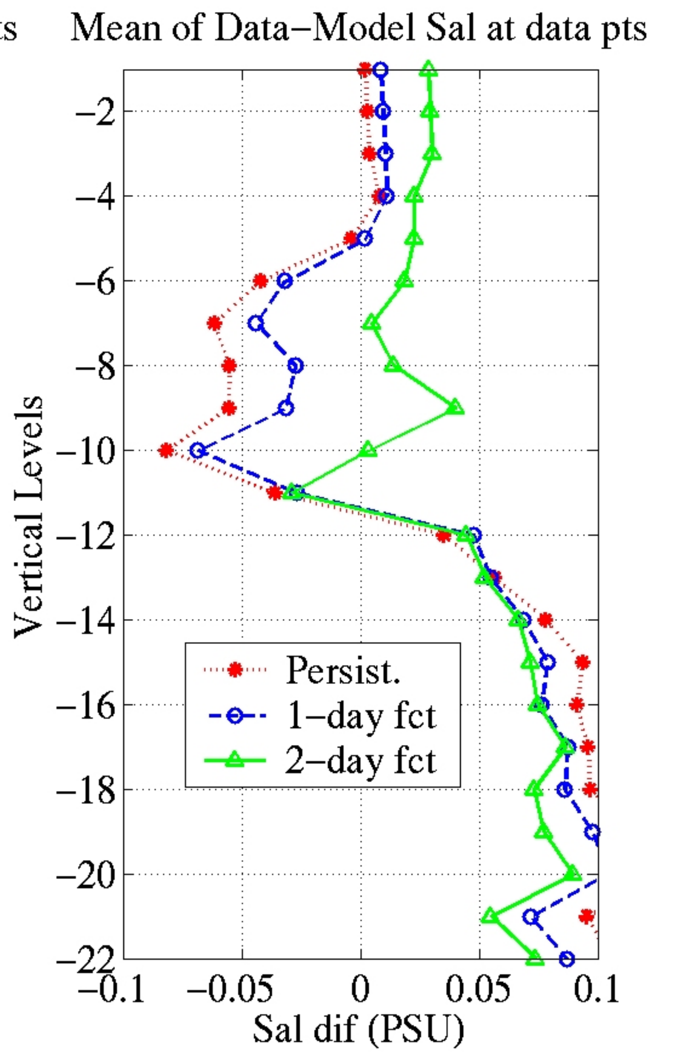
- **Nowcast: Aug 11 (persistence forecast, red)**
- **2-day forecast for Aug 13 (green)**
- **1-day forecast for Aug 12 (blue, to check phase error)**

Bias Estimate

Horizontally-averaged data-model differences







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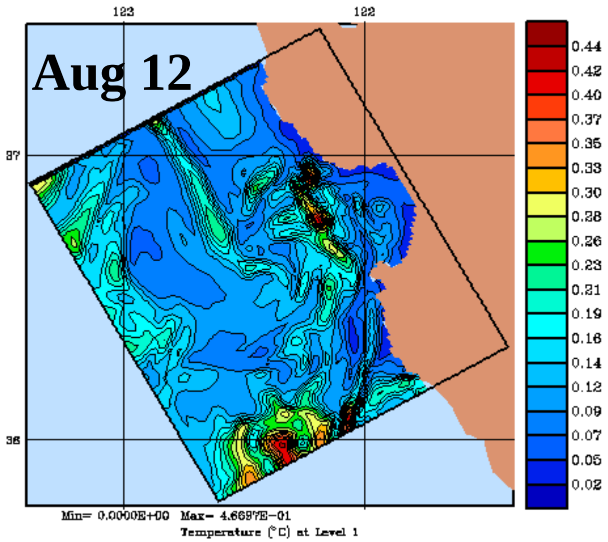
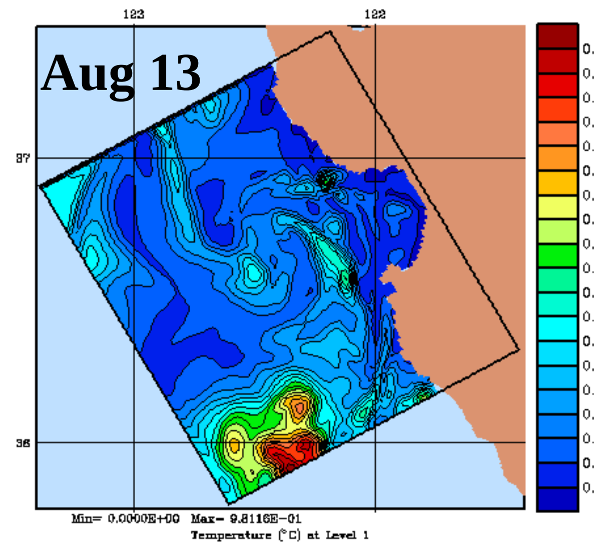
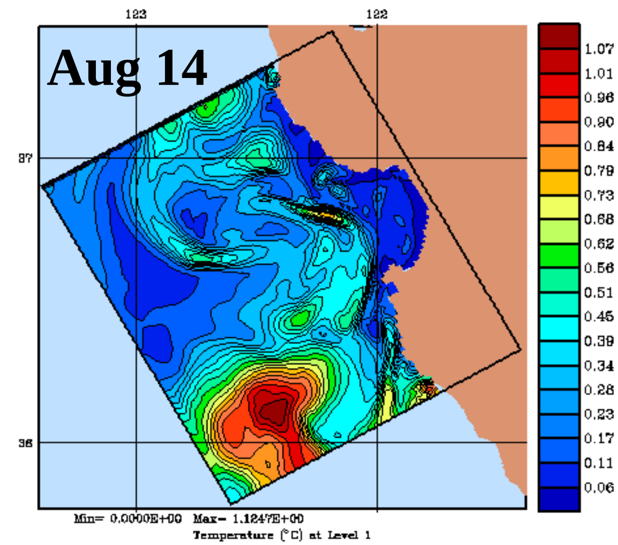
ESSE Surface Temperature Error Standard Deviation Forecasts

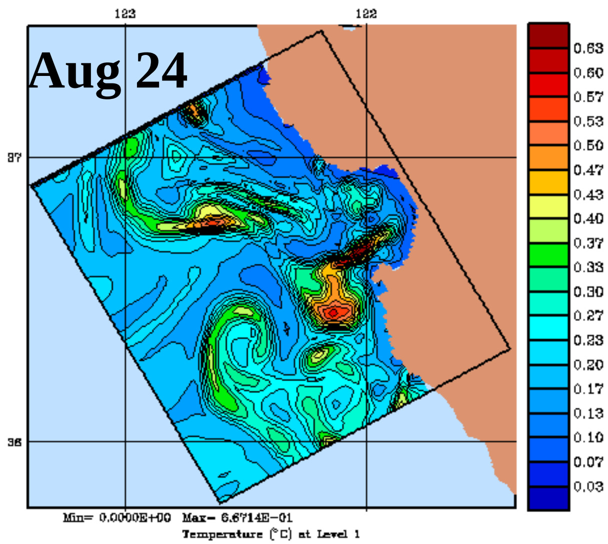


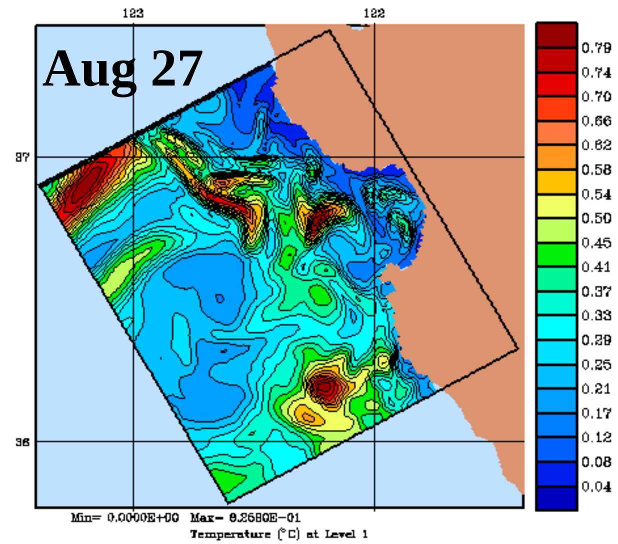


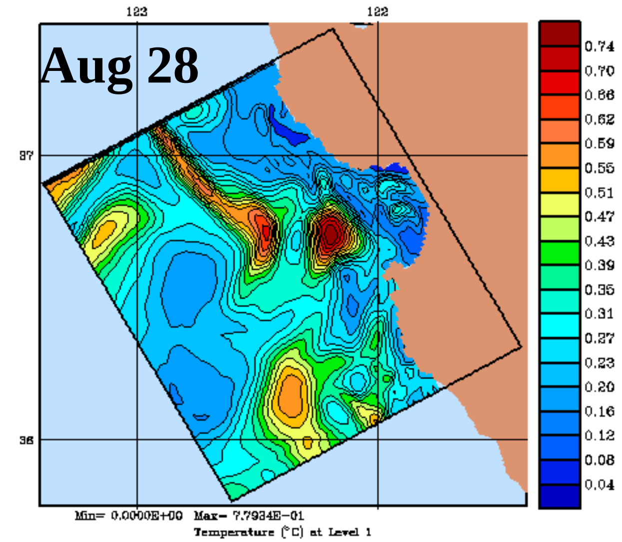


Start of Upwelling

First Upwelling period



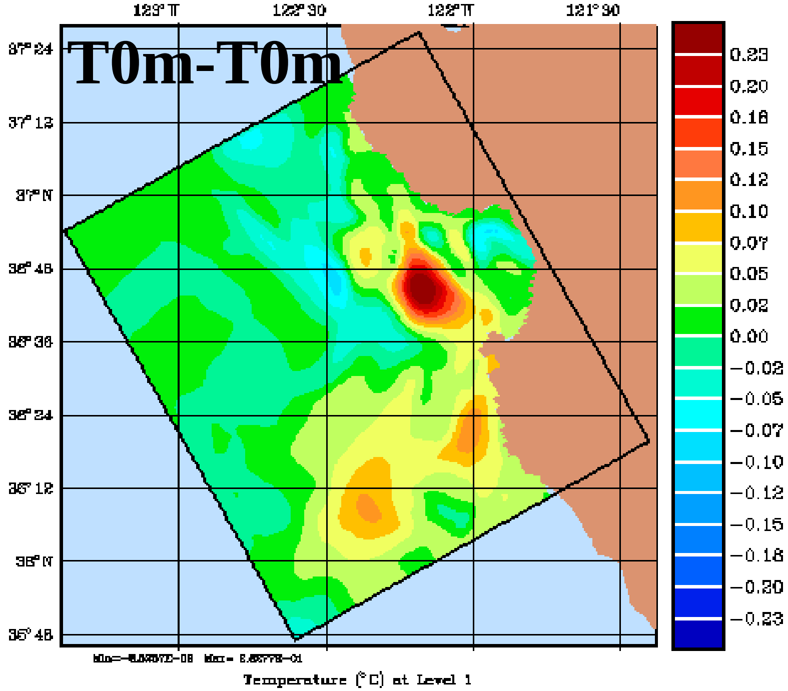


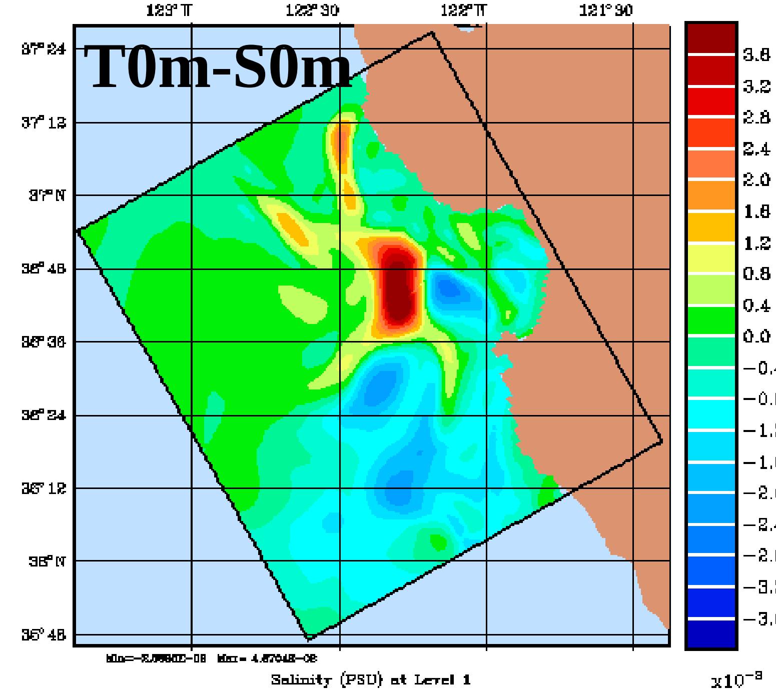


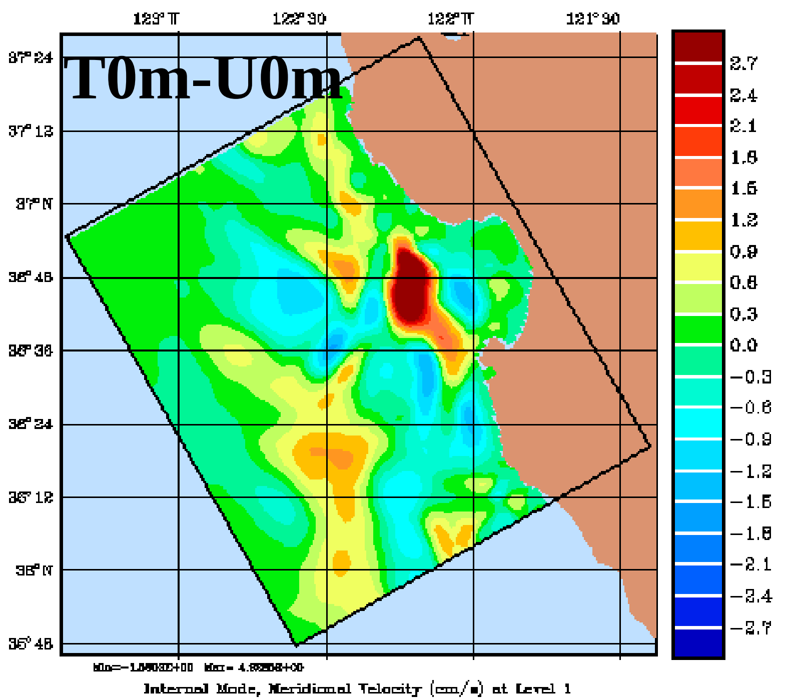
End of Relaxation

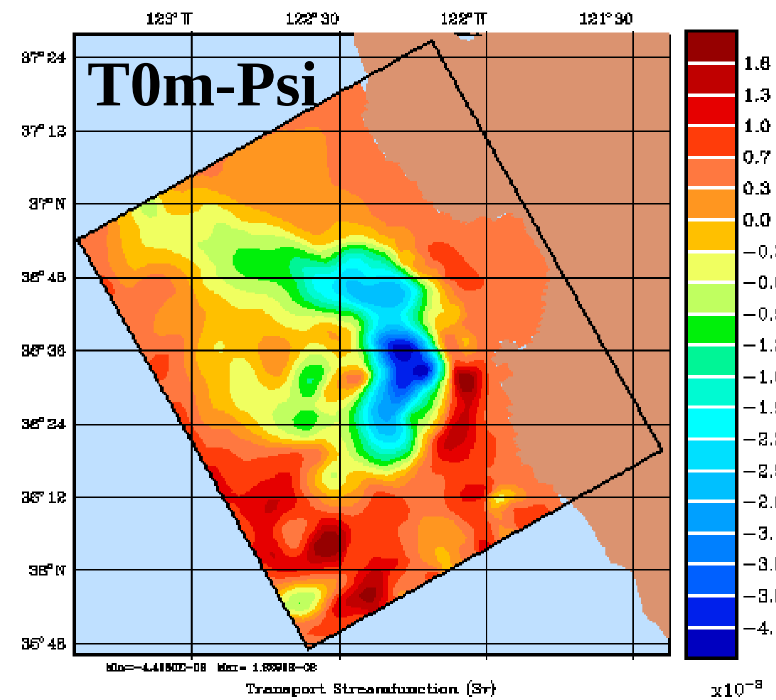
Second Upwelling period

ESSE DA properties: Error covariance function predicted for 28 August









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.:

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

Adaptive Sampling Metric or Cost function:

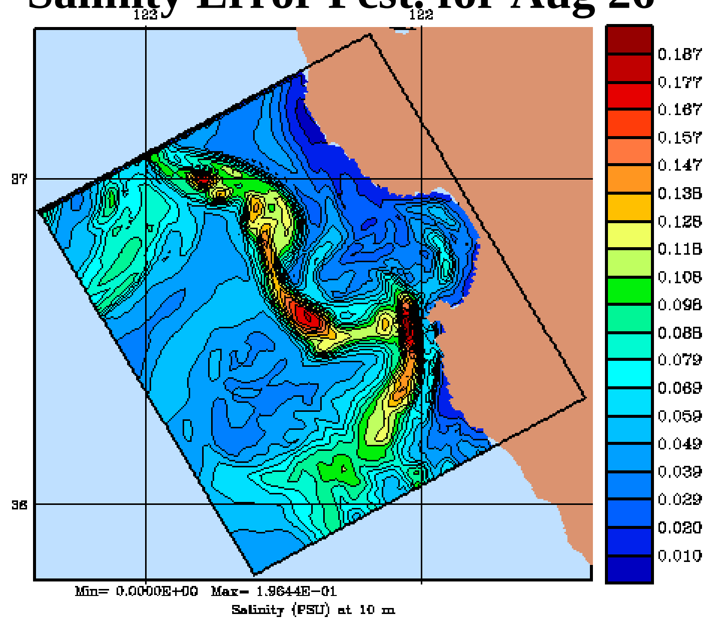
e.g. Find H_i and R_i such that

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

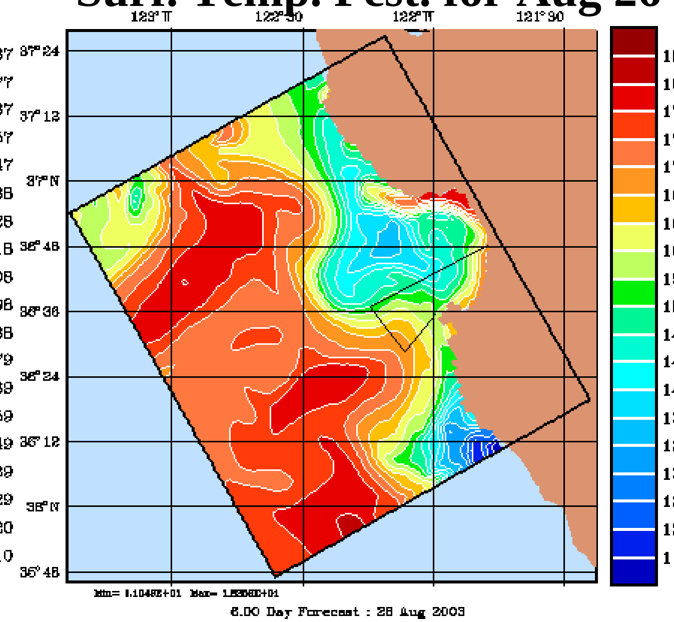
Real-time Adaptive Sampling – R/V Pt. Lobos

- 25 Aug forecast: Large uncertainty for 26 Aug. related to predicted meander of the coastal current which advects warm and fresh waters towards Monterey Bay Peninsula.
- Position and strength of meander were very uncertain (e.g. T and S error St. Dev., based on 450 2-day fcsts.).
- Different ensemble members showed that the meander could be very weak (almost not present) or further north than in the central forecast
- Sampling plan designed to investigate position and strength of meander and region of high forecast uncertainty.

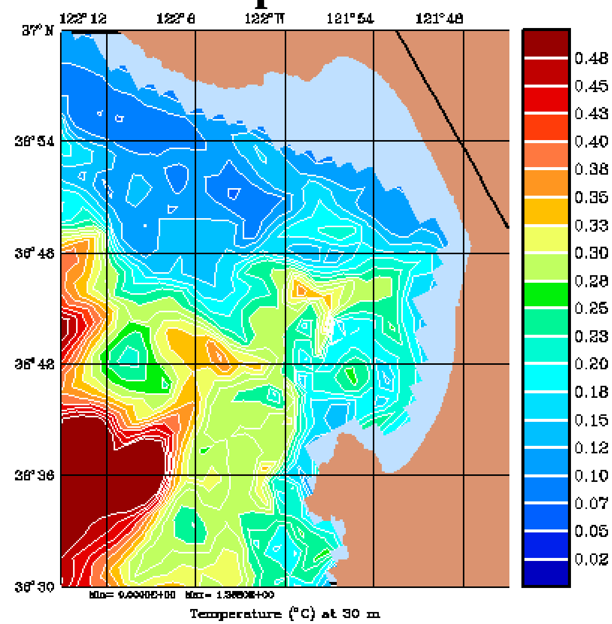
Salinity Error Fcst. for Aug 26



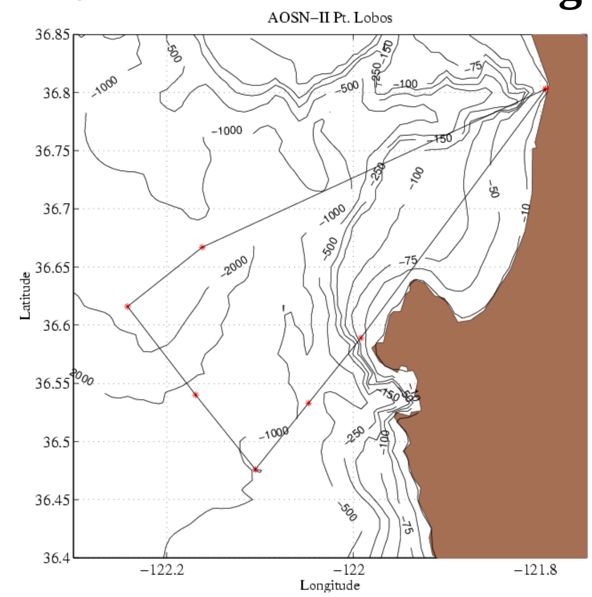
Surf. Temp. Fcst. for Aug 26



MB Temp. Error Fcst.



R/V Pt Lobos track for Aug 26



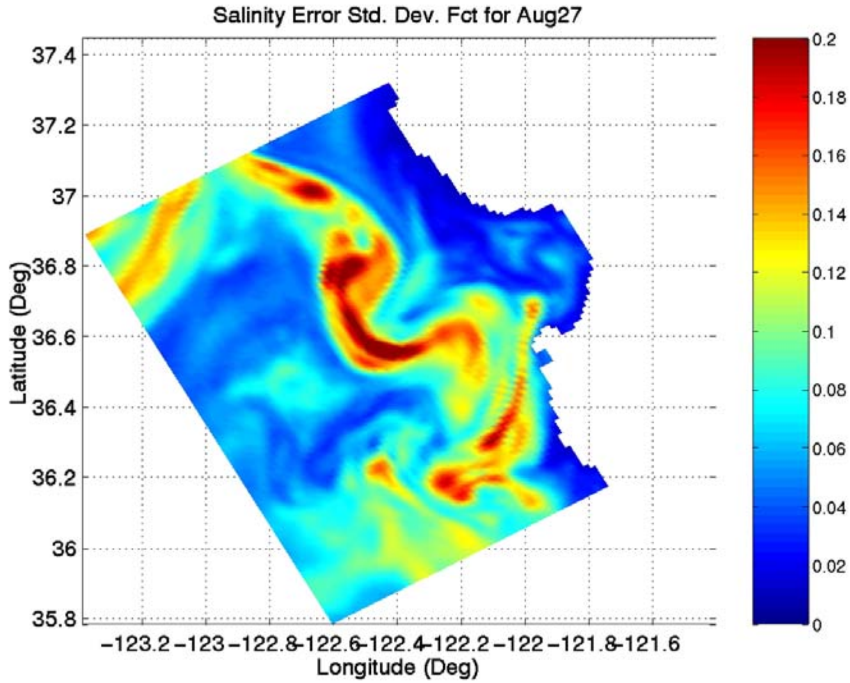
Quantitative Adaptive Sampling via ESSE

- Use exact nonlinear error covariance evolution
- For every choice of adaptive strategy, an ensemble is computed

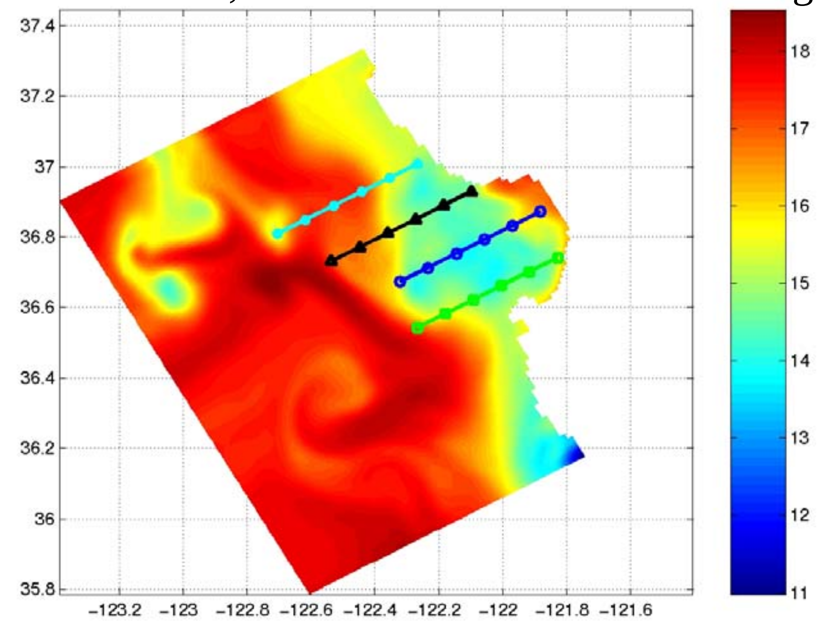
1. Select sets of candidate sampling paths/regions and variables that satisfy operational constraints
2. Forecast reduction of errors for each set based on a tree structure of small ensembles and data assimilation
3. Optimization of sampling plan: select sequence of paths/regions and sensor variables which maximize the predicted nonlinear error reduction in the spatial domain of interest, either at t_f (trace of ``information matrix'' at final time) or over $[t_0 \, , t_f]$

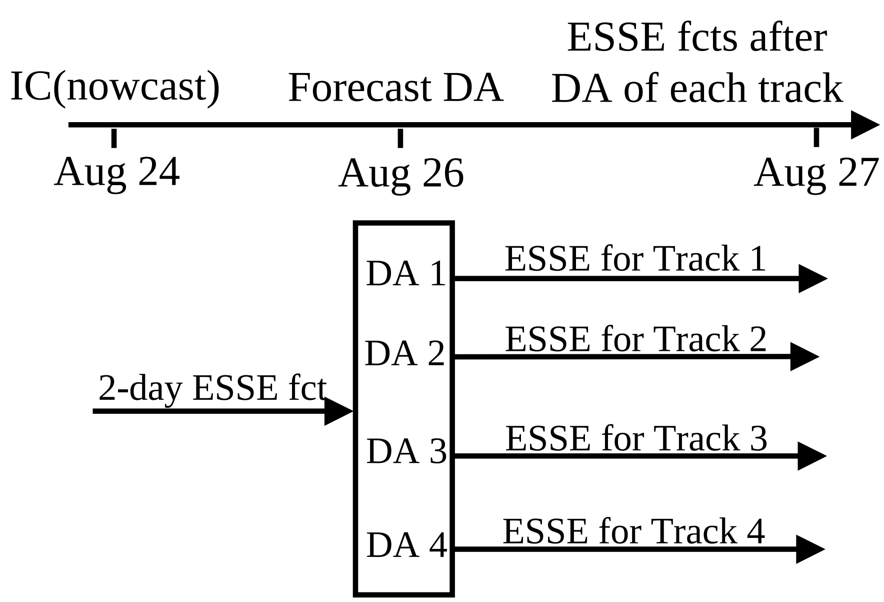
- Outputs:
  - Maps of predicted error reduction for each sampling paths/regions
  - Information (summary) maps: assigns to the location of each sampling region/path the average error reduction over domain of interest
  - Ideal sequence of paths/regions and variables to sample

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



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



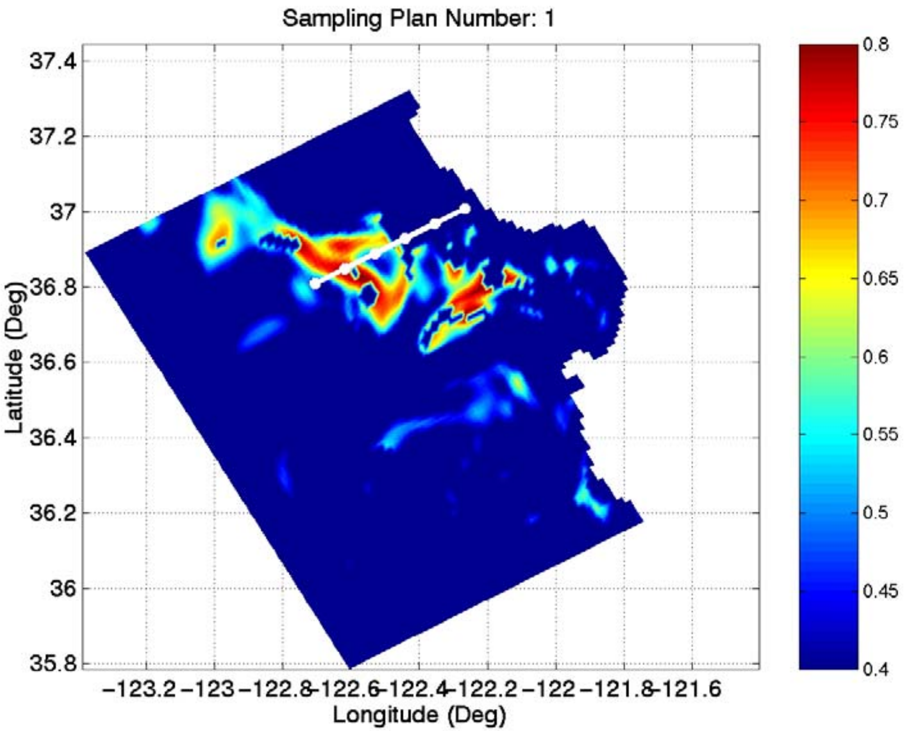


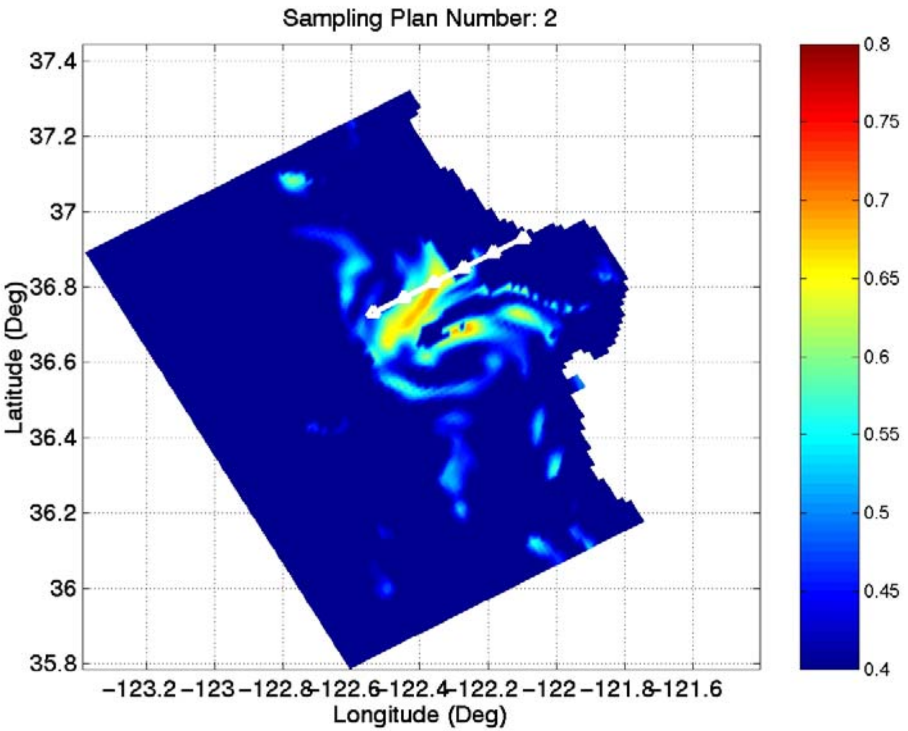
Which sampling on Aug 26 optimally reduces uncertainties on Aug 27?

1. Define relative error reduction as: $(\sigma_{27} - \sigma_{27}^{\text{track } i}) / \sigma_{27}$ ….for $\sigma_{27} > \sigma_{noise}$

   0……………….for $\sigma_{27} \leq \sigma_{noise}$

2. Create relative error reduction maps for each sampling tracks, e.g.:

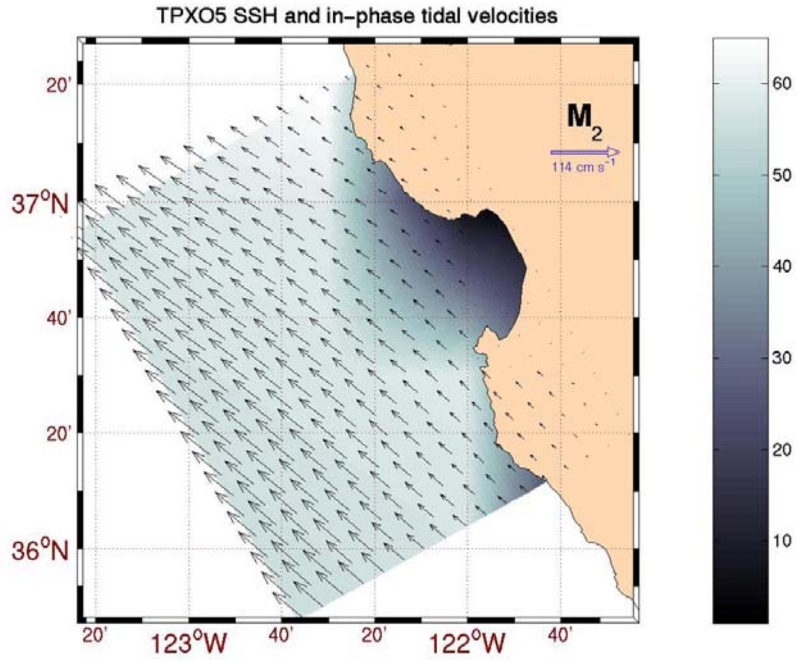


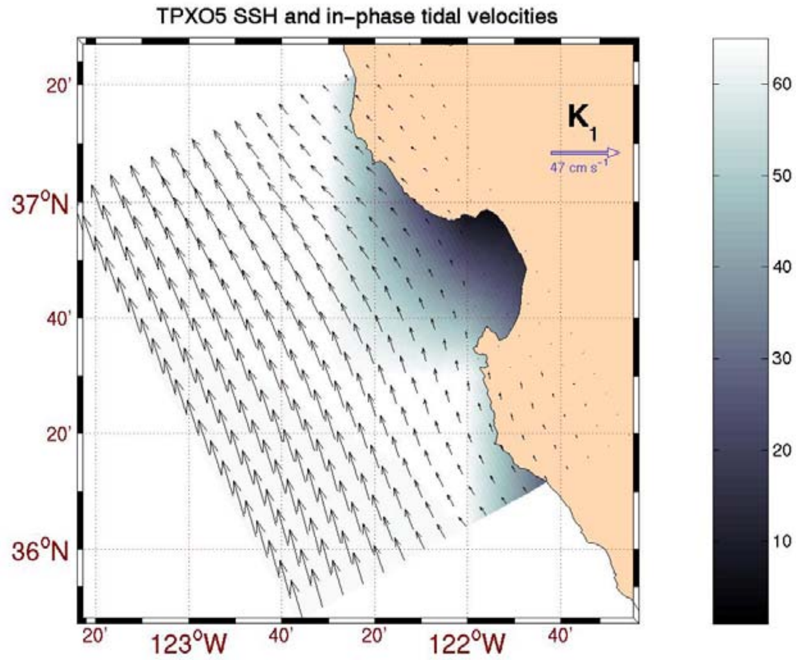


3. Compute average over domain of interest for each variable, e.g. for full domain: Best to worst error reduction: Track 1 (18%), Pt Lobos (17%), …., Track 3 (6%)
4. Create "Aug 26 information map": indicates where to sample on Aug 26 for optimal error reduction on Aug 27

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





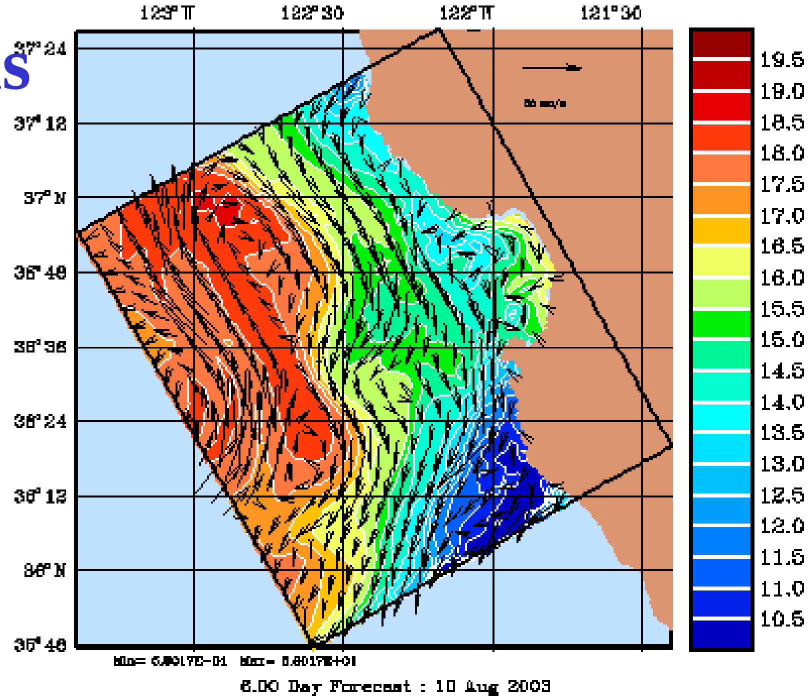
- Used to estimate hierarchy of tidal parameterizations :

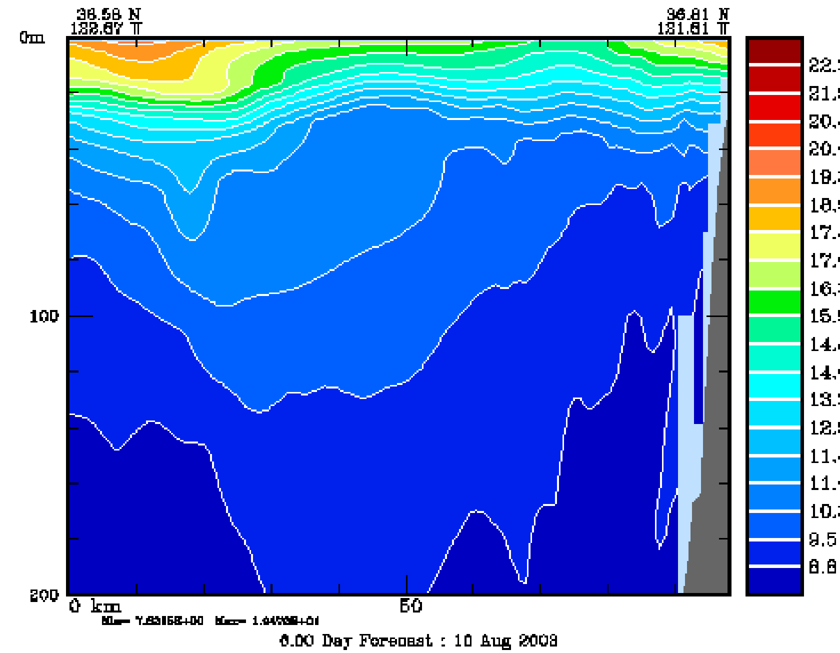
i. Vertical tidal Reynolds stresses (diff., visc.)	$K_T = \alpha \,\|\|\boldsymbol{u}_T\|\|^2$ and $K=max(K_S, K_T)$
ii. Modification of bottom stress	$\tau = C_D \,\|\|\boldsymbol{u}_{S+}\, \boldsymbol{u}_T\|\|\, \boldsymbol{u}_S$
iii. Horiz. momentum tidal Reyn. stresses	Σ_ω (Reyn. stresses averaged 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**

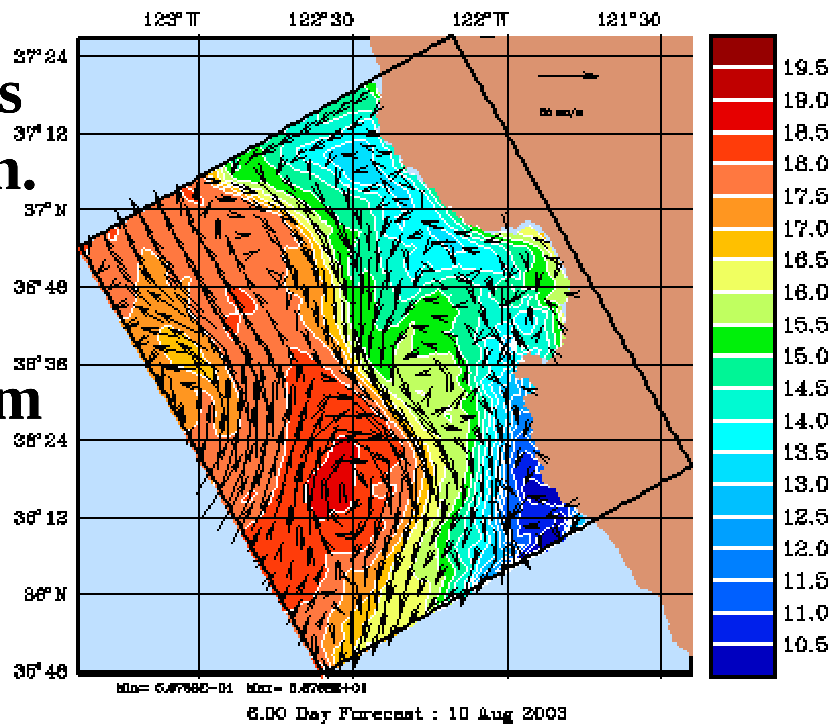
No-tides

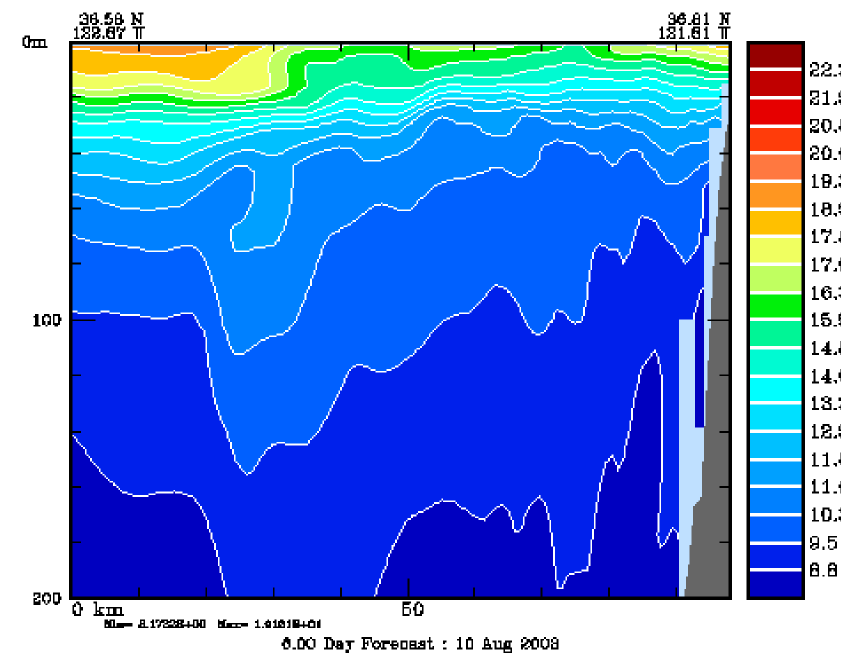




Tidal effects

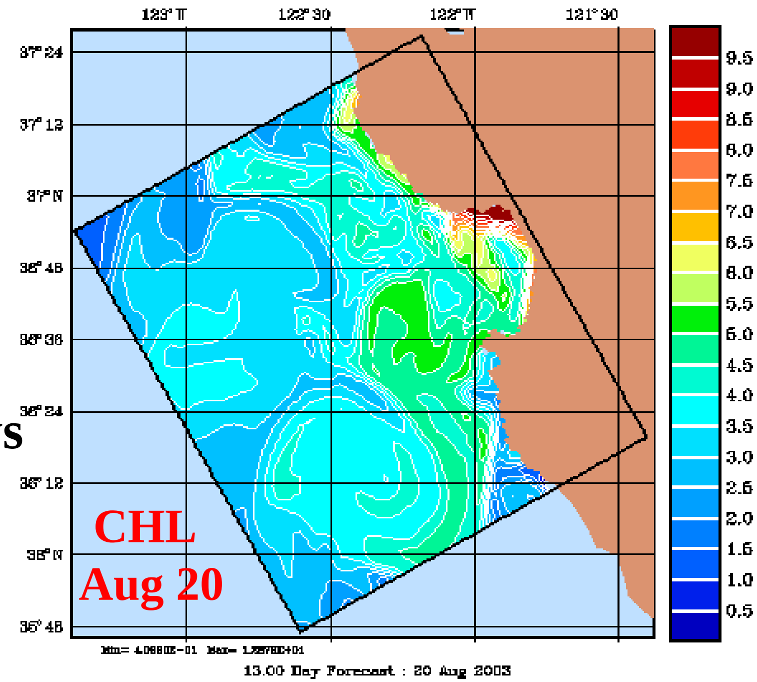
- **Vert. Reyn. Stress**
- **Horiz. Momentum Stress**

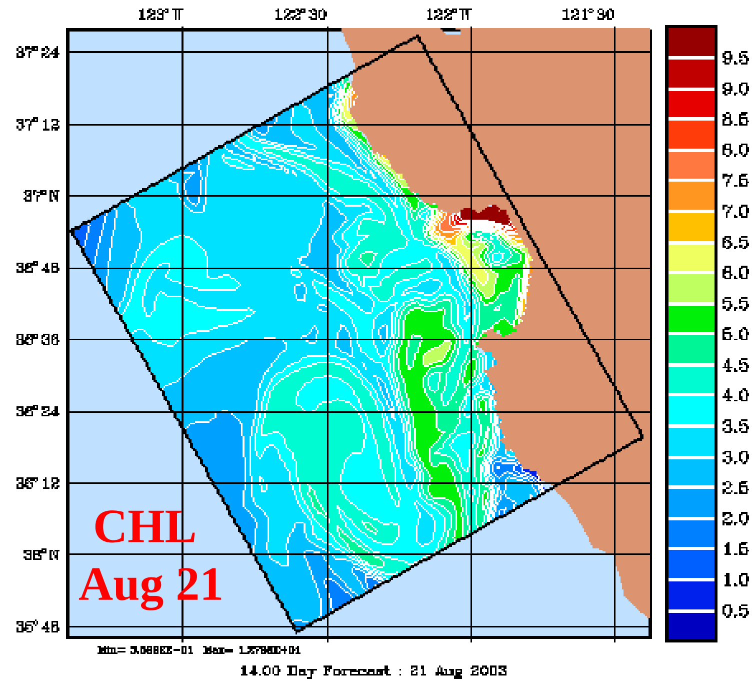


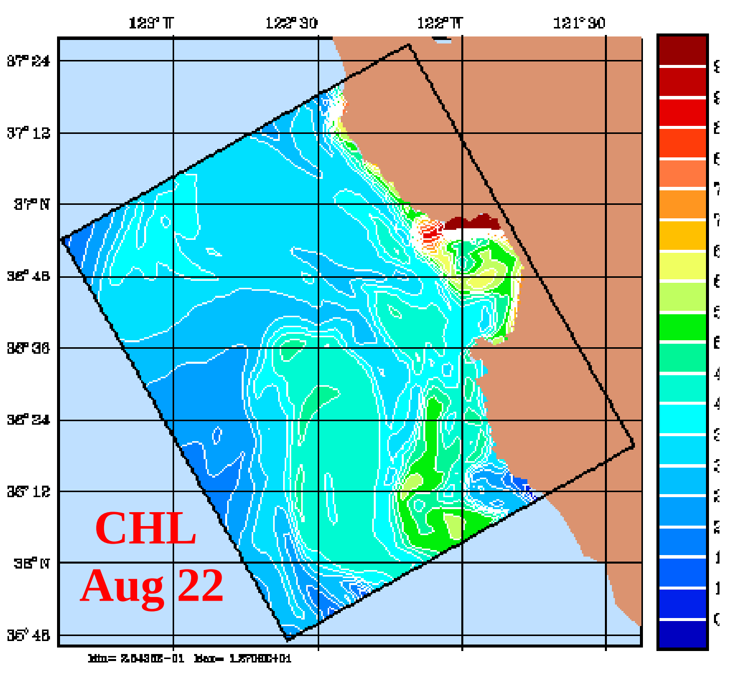


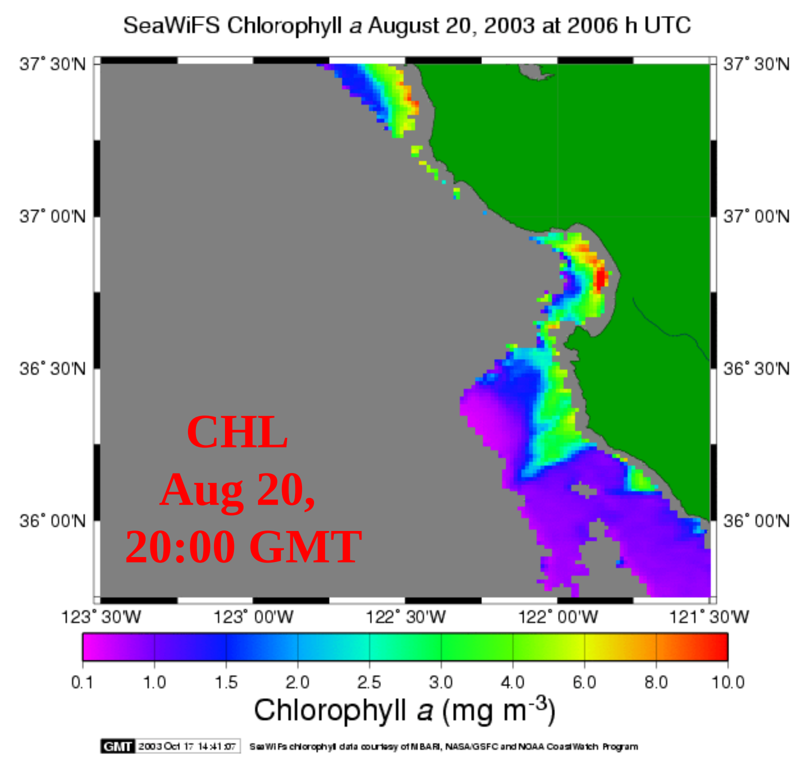
Post-Cruise Surface CHL forecast (Hindcast)

- Starts from zeroth-order dynamically balanced IC on Aug 4
- Then, 13 days of physical DA
- Forecast of 3-5 days afterwards





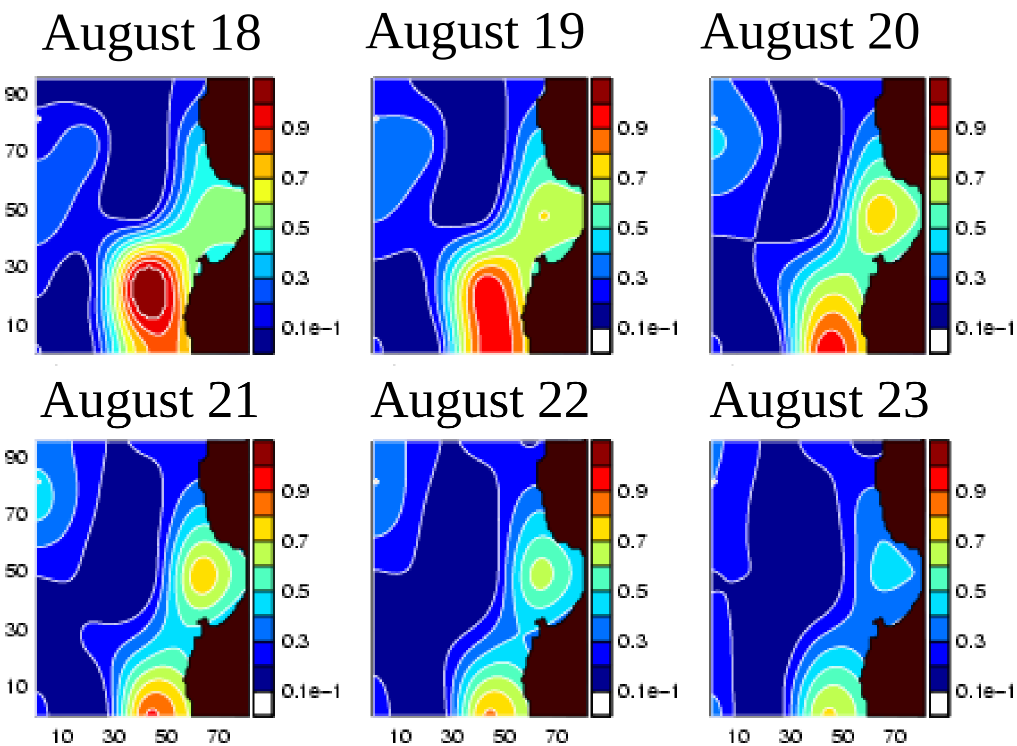




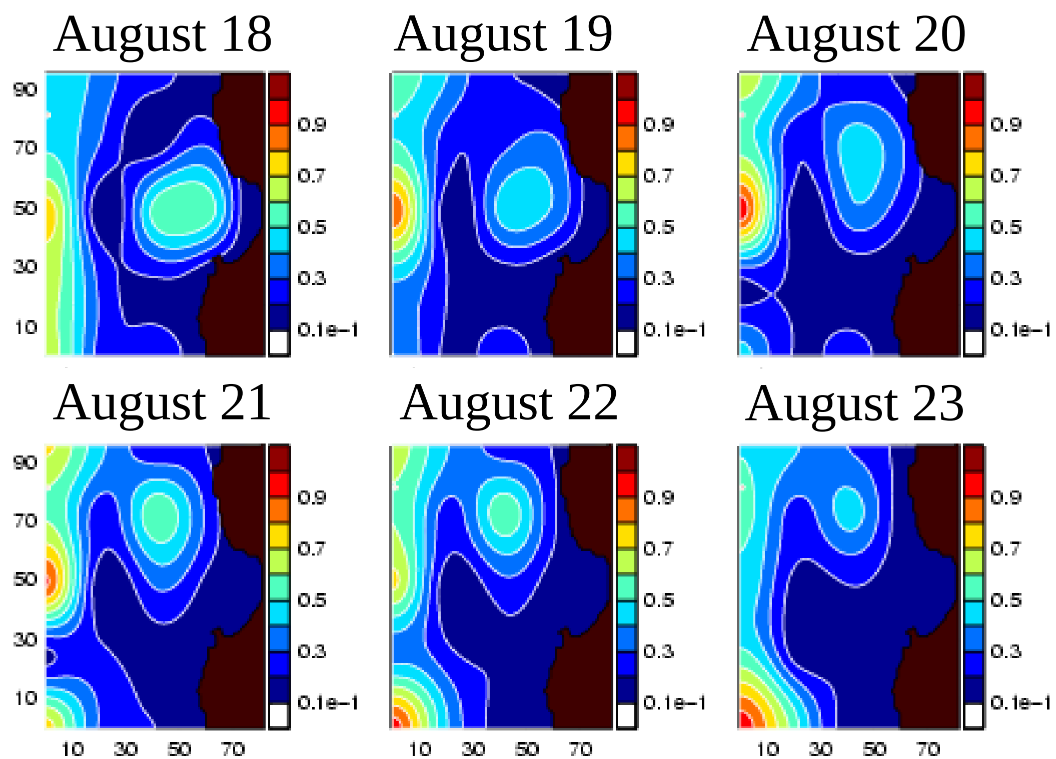
Multi-Scale Energy and Vorticity Analysis

- Multiscale window decomposition in space and time (wavelet-based) of energy/vorticity eqns.
- For example, consider Energetics During Relaxation Period:

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 takes place to account for the decrease in energy (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

Approaches to Multi-Model Adaptive Forecasting

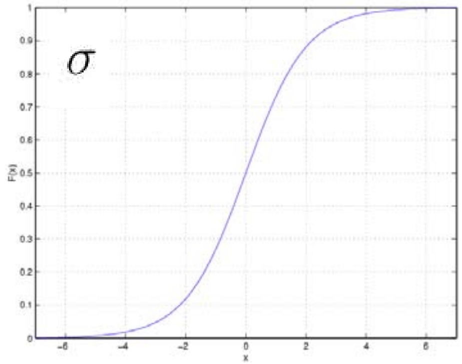
Combine ROMS/HOPS re-analysis temperatures
to fit the M2-buoy temperature at 10 m

By combining the models x_1 and x_2 we attempt to:
1. eliminate and learn systematic errors
2. reduce random errors

- Approach utilized here: neural networks
- A neural network is a non-linear operator which can be adapted (trained) to approximate a target arbitrary non-linear function measuring model-data misfits:

$$I(\mathbf{w}) = \frac{1}{2T}\int_0^T \left(\mathcal{F}\{\mathbf{x}(t)\} - d(t)\right)^2 \, dt$$

Sigmoidal Transfer Function

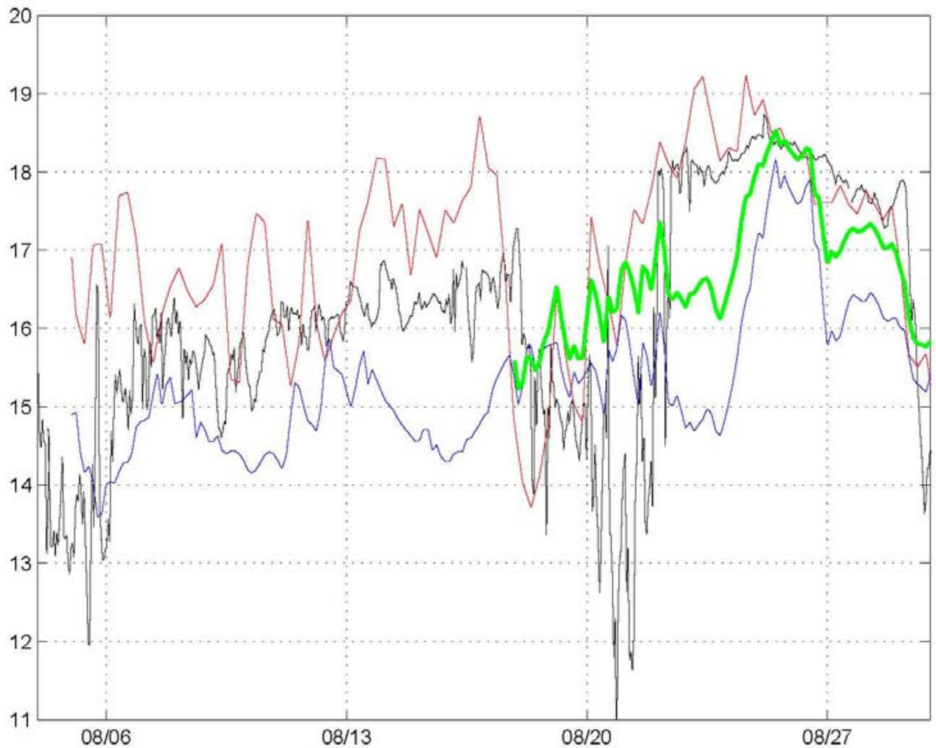


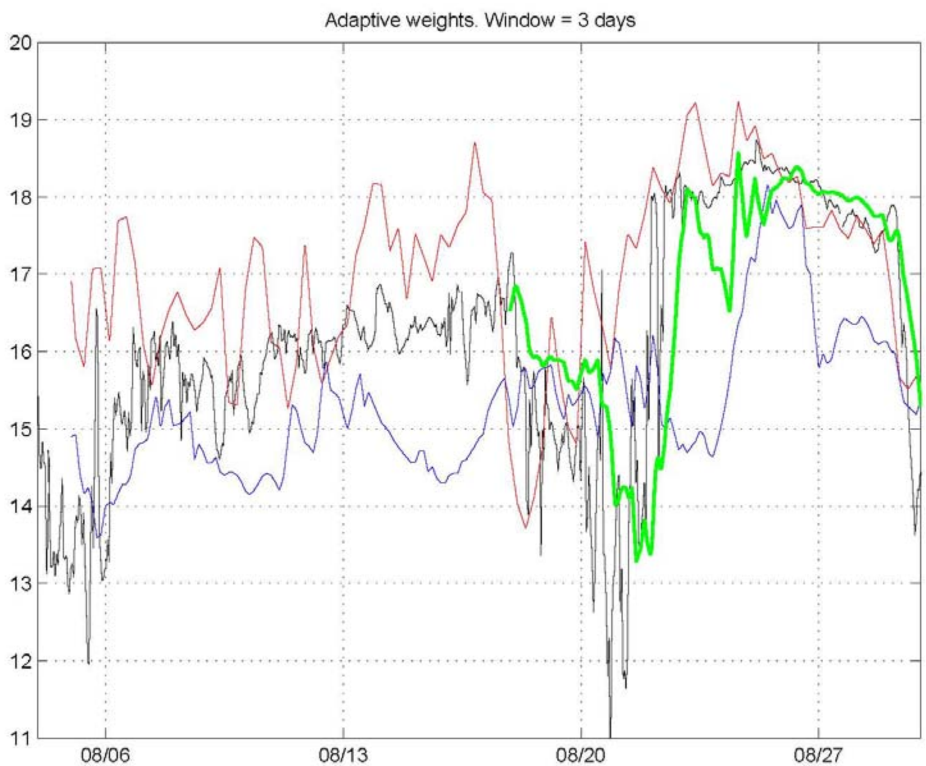
Linear least-squares fit: $\mathcal{F}\{\mathbf{x}(t)\} = \mathcal{L}\{\mathbf{x}(t)\} = w_0 + \sum_{k=1}^{2} w_k x_k(x, y, t)$

Single Sigmoidal layer:

$$\mathcal{F}\{\mathbf{x}(t)\} = \mathcal{L}_2 \Sigma_1 \mathcal{L}_1\{\mathbf{x}\} = w_{20} + w_{21}\ \sigma\left(w_{10} + w_{11} x_1(t) + w_{12} x_2(t)\right)$$

Oleg Logoutov





- Observed (black) temp at the M2mooring
- Modeled temp at the M2mooring:

ROMS re-analysis, HOPS re-analysis

Top: Green – HOPS/ROMS reanalysis combined via neural network trained on the first subset of data (before Aug 17).

Bottom: Green – HOPS/ROMS reanalysis combined via **adaptive** neural network also trained on the first subset of data (before Aug 17), but over moving-window of 3 days decorrelation

Neural Network Least Squares Fit

Training data	w_{20}	w_{21}	w_{10}	w_H	w_R	rms_{1st}	rms_{2nd}
First half	9.472	11.015	−6.175	0.301	0.121	0.72	1.34
Second half	13.197	10.862	−10.764	0.222	0.372	0.80	1.27

Linear Least Squares Fit

Training data	w_0	w_H	w_R	rms_{1st}	rms_{2nd}
First half	−3.118	0.965	0.277	0.733	1.576
Second half	−2.842	0.478	0.690	0.85	1.35

Equal Weights

	w_1	w_2	rms_1	rms_2
	0.5	0.5	0.79	1.39

Individual Models

Model	rms_{1st}	rms_{2nd}
HOPS	1.28	1.82
ROMS	1.45	1.54

AOSN-II Conclusions

- **Monterey-California Current System August 2003 Real-time**:
  - **Fully nonlinear ESSE carried-out consistent: ensemble forecast of fields and errors of 2-3 days duration, Data assimilation, Adaptive sampling and Dynamical analyses**
  - **Onset and sustained upwelling and relaxation phenomena were successfully captured, together with their dynamic mesoscale variabilities and their impacts on uncertainties**
  - **Preliminary evaluations of real-time forecasts indicate generally good RMS/Bias values that beat persistence**
- **Quantitative adaptive sampling through forecasts optimal error reduction**
- **Field and error evolutions, and multi-scale dynamical analyses indicate that during relaxation, energies are transferred from large-scale to mesocales**
- **Combined HOPS-ROMS model estimates trained via neural networks yields an estimate with less error than each**
- **Tidal effects introduce smaller scales and alter mesoscale features**
- **Ongoing research includes:**
  - **Re-analysis fields, descriptive dynamics, methods for skill determination and error models, Coupled physical-biological estimation, Predictability studies**