Application of the ESSE System to Real-Time Error Forecasting, Data Assimilation and Adaptive Sampling off the Central California Coast during AOSN-II:

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www.deas.harvard.edu/~pierrel
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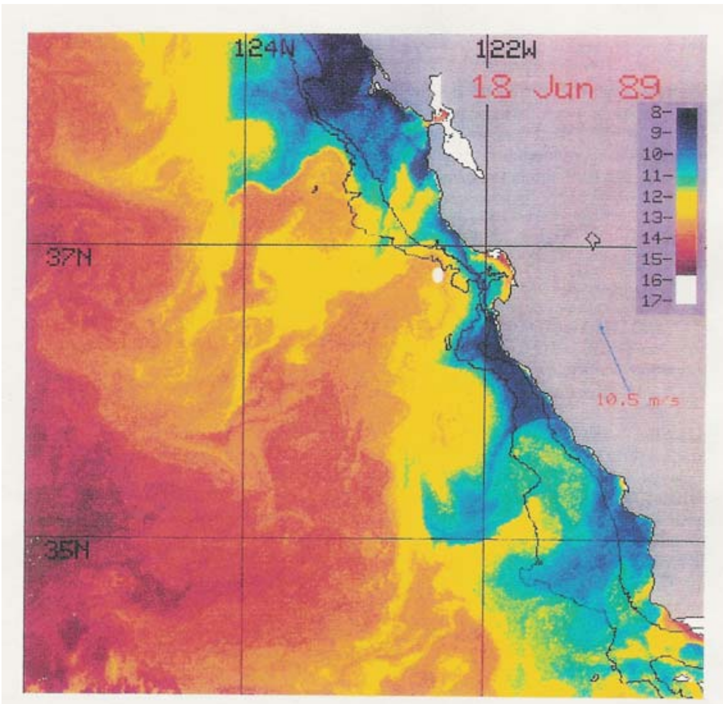
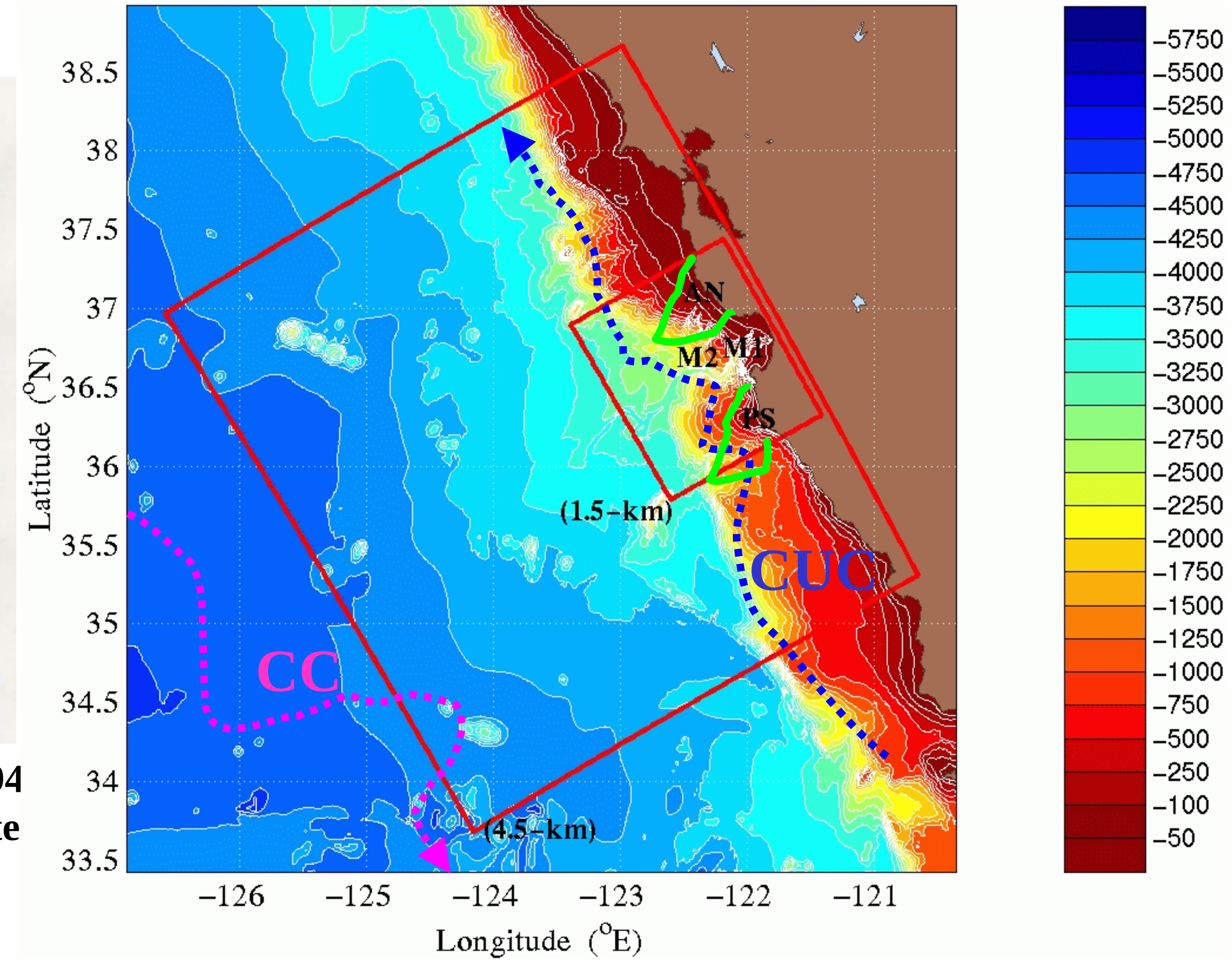
1. **AOSN-II: Ocean physics and August 2003 experiment background**
2. **ERROR SUBSPACE STATISTICAL ESTIMATION (ESSE)**
3. **Field/error predictions, Assimilation, Adaptive sampling, Dynamical investigations**
4. **Conclusions**

AONS-II Team: Cal-Tech, Princeton**,** MBARI, JPL (ROMS), NRL, NPS, WHOI, SIO, etc

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



Conceptual model: Rosenfeld *et al*., 1994
Bifurcated flow from an upwelling cente



Calif. Current System (CCS)

- **Upwelling/Relaxation at Pt AN/ Pt Sur:** Upwelled water advected equatorward and seaward
- **Coastal eddies, jets, squirts, filaments, etc. :** High submesoscale and mesoscale variability in the 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

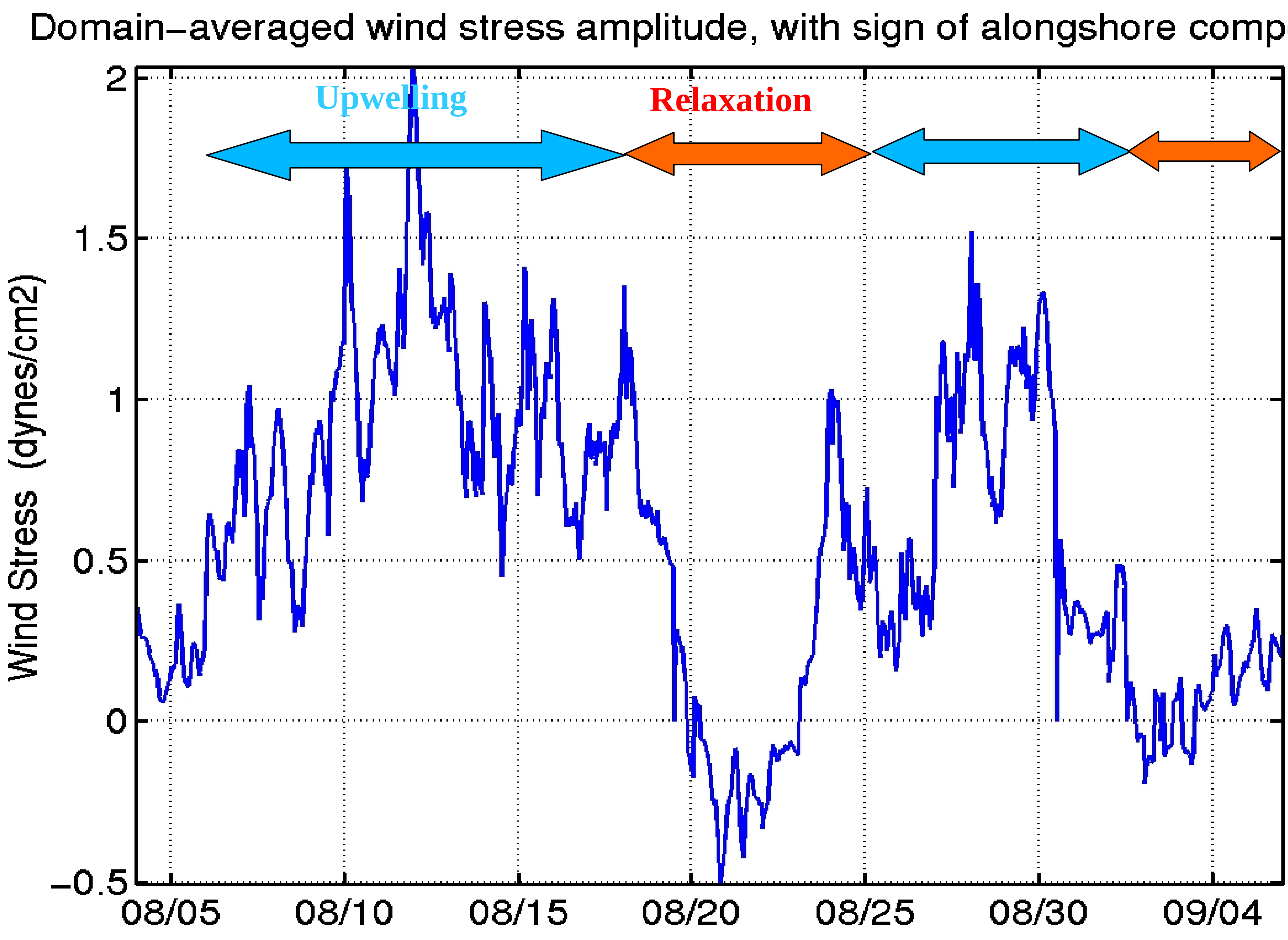
Real-time ESSE : AOSN-II Accomplishments

- 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
- Ensemble of stochastic ocean model predictions
  - PE of Harvard Ocean Prediction System (HOPS)
  - Forced by deterministic 3km and hourly COAMPS flux predictions
  - Oceanic stochastic forcings for sub-mesoscale eddies, BCs and atmos. fluxes
- ESSE results described and posted on the Web daily
  - Discussion of predicted errors, fields/features and their dynamics
  - Outline of uncertainty initialization and forecast procedures
  - Web: http://www.deas.harvard.edu/~leslie/AOSNII/index.html

Real-time ESSE : AOSN-II Accomplishments (Cont.)

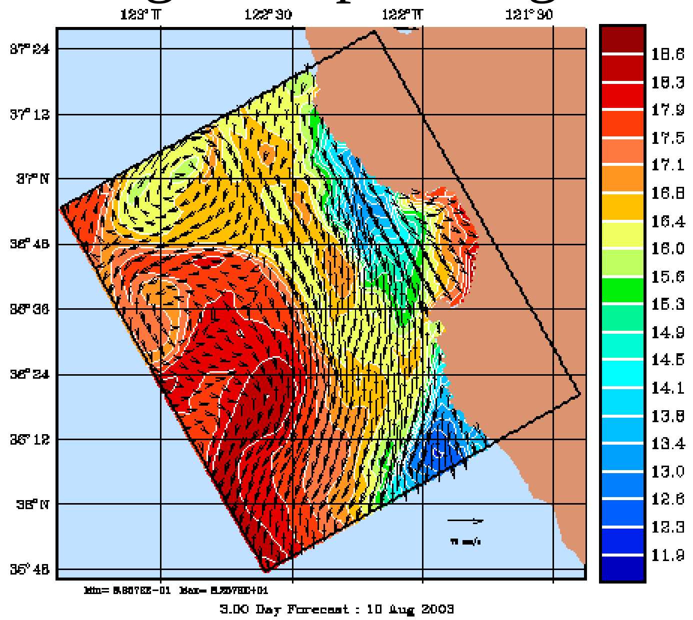
- ESSE data assimilation
  - 10^4 data points per day: ship (Pt. Sur, Martin, Pt. Lobos), glider (WHOI and Scripps) and aircraft SST data, within 24 hours of appearance on data server
  - Data analyzed and quality controlled daily for real-time forecasts
- ESSE fields formed the basis for daily adaptive sampling recommendations
- Adaptive modeling: Oceanic boundary conditions and model parameters for transfer of atmospheric fluxes calibrated and modified in real-time to adapt to evolving conditions
- 23 sets of real-time OI nowcasts and forecasts (Robinson *et al*., Session 1, New Forecast Systems, 4:30pm today)
- Real-time research work on: coupled physics-biology, tides, free-surface PE model

Oceanic responses and atmospheric forcings during August 2003

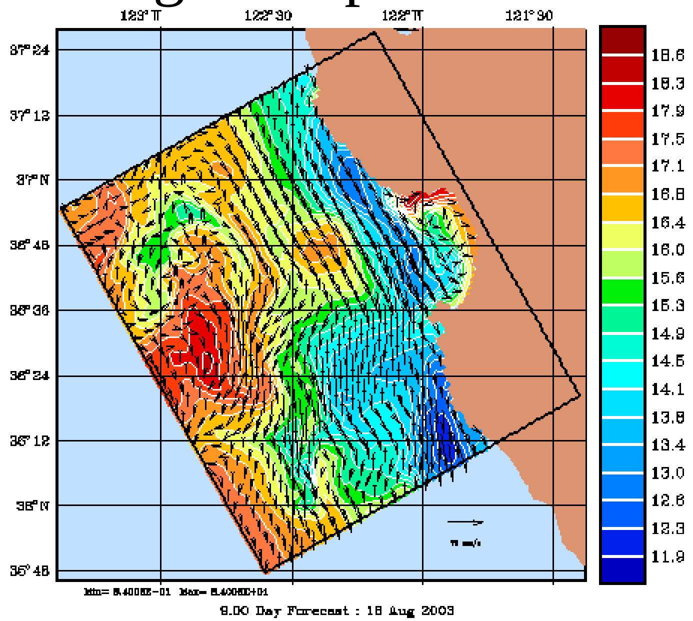


Oceanic responses and atmospheric forcings during August 2003

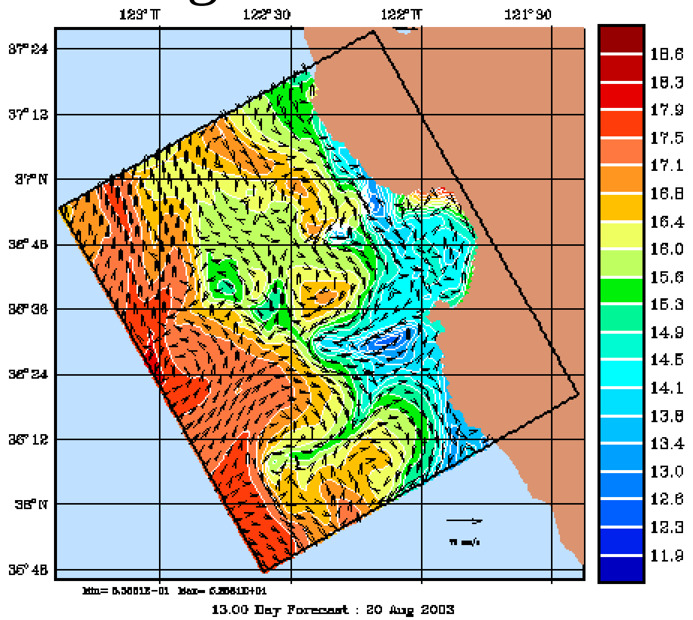
Aug 10: Upwelling



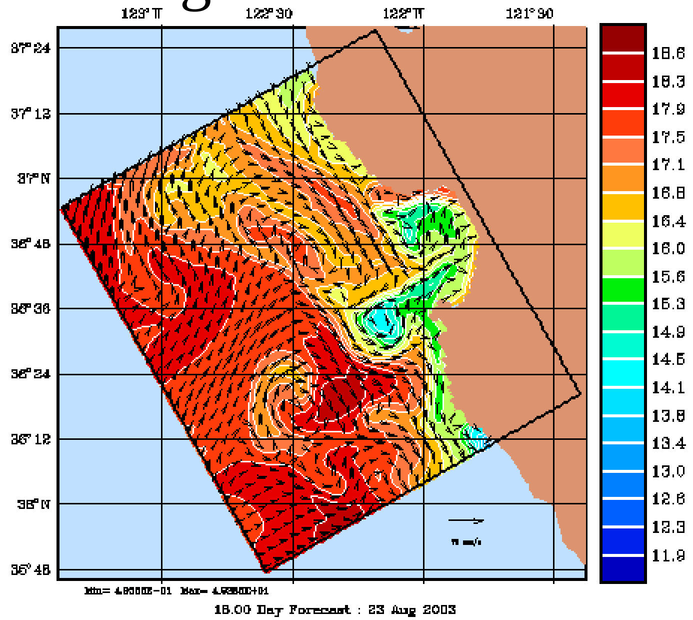
Aug 16: Upwelled



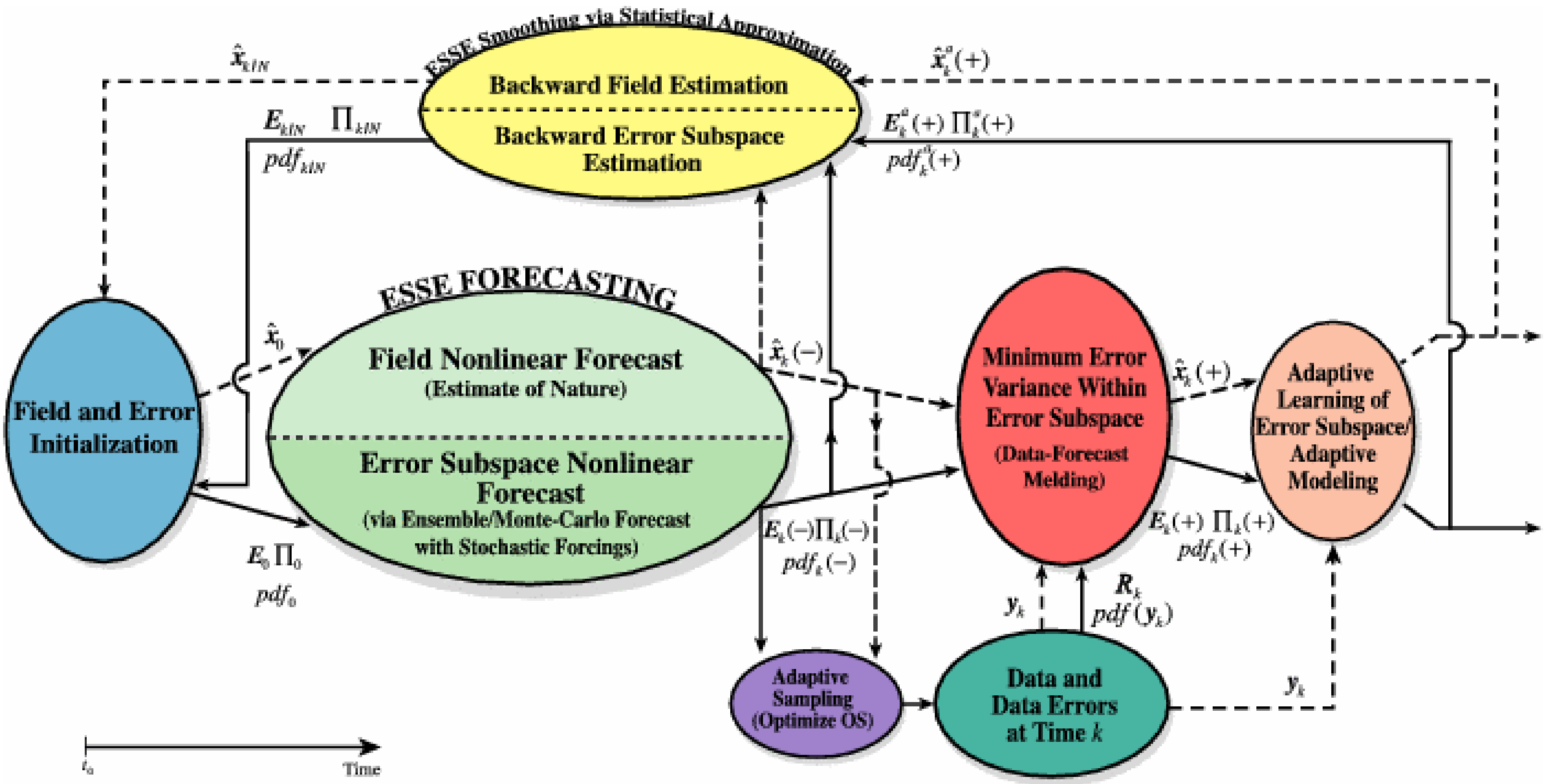
Aug 20: Relaxation



Aug 23: Relaxed



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

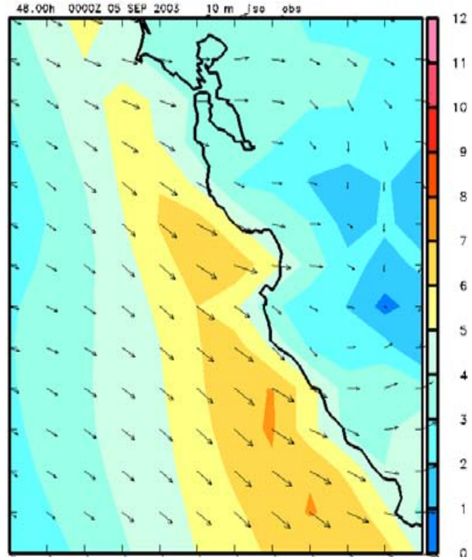
- Strait of Sicily (AIS96-RR96), Summer 1996
- Ionian Sea (RR97), Fall 1997
- Gulf of Cadiz (RR98), Spring 1998
- Massachusetts Bay (LOOPS), Fall 1998
- Georges Bank (AFMIS), Spring 2000
- Massachusetts Bay (ASCOT-01), Spring 2001
- Monterey Bay (AOSN-2), Summer 2003

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

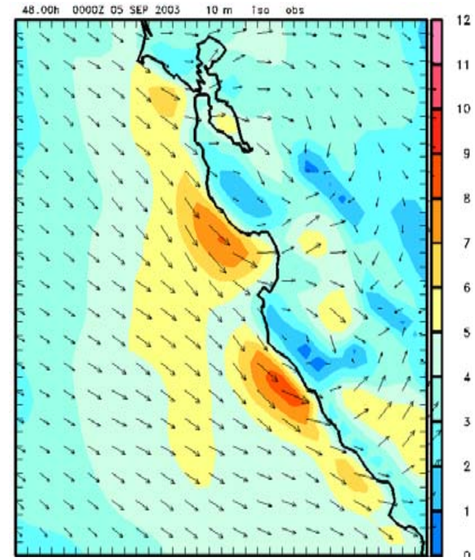
Sensitivity to horizontal resolution

3km improves
Representation of
Coastal Jets
& Coastal Shear Zone

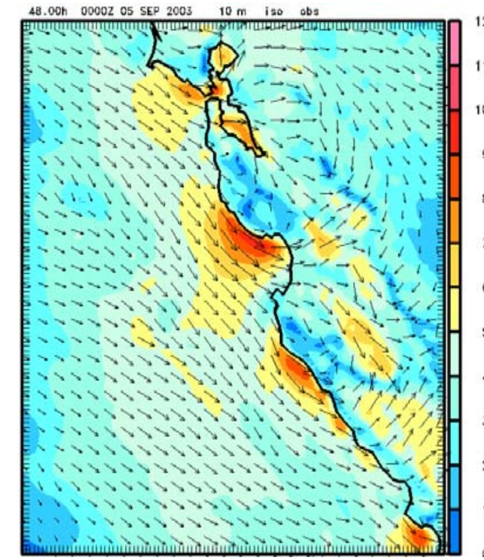
27 km



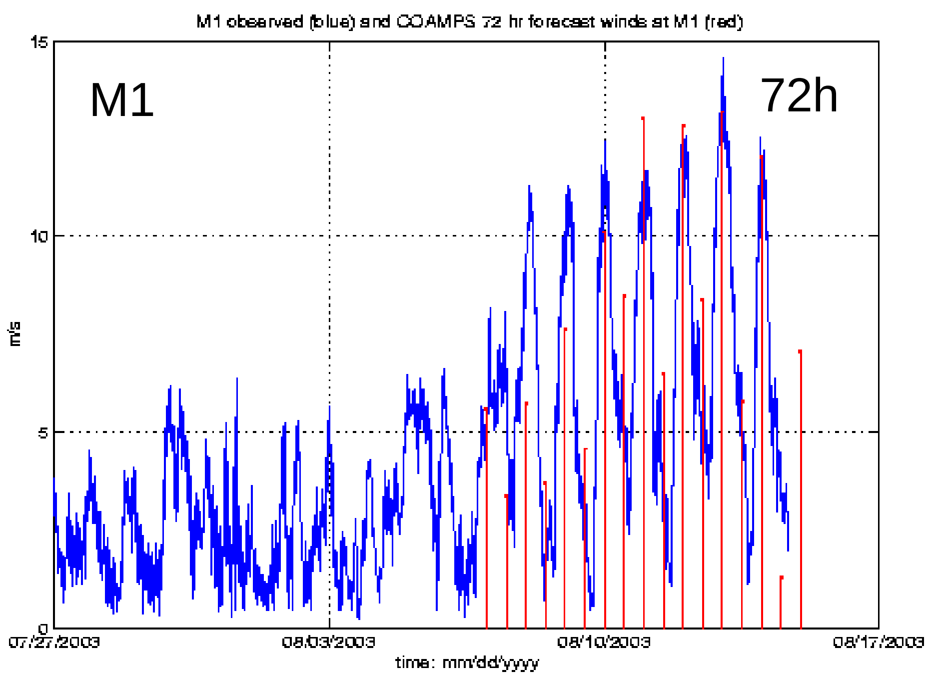
9 km

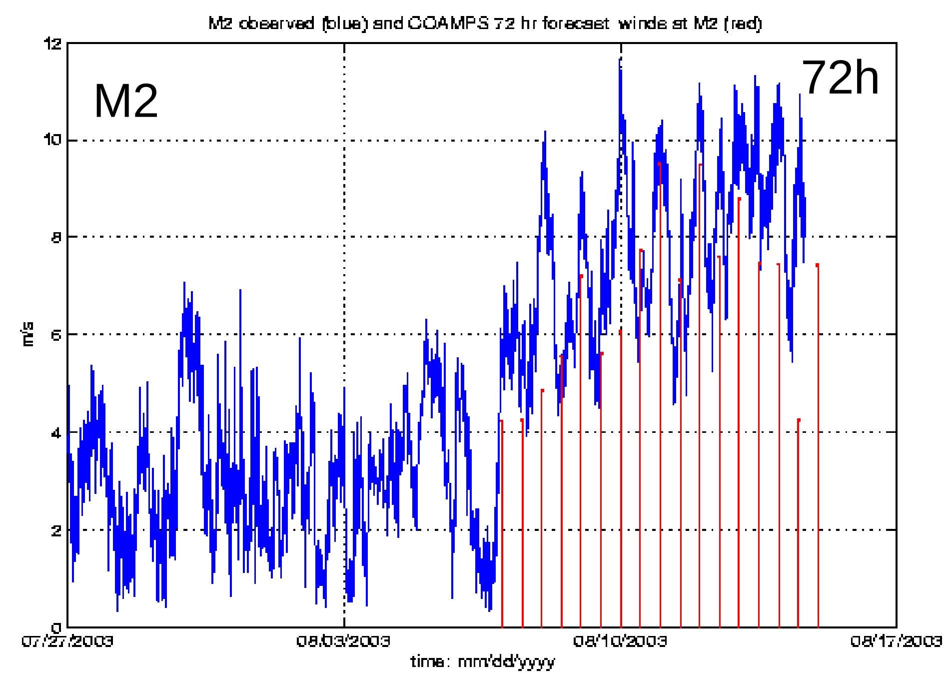


3 km



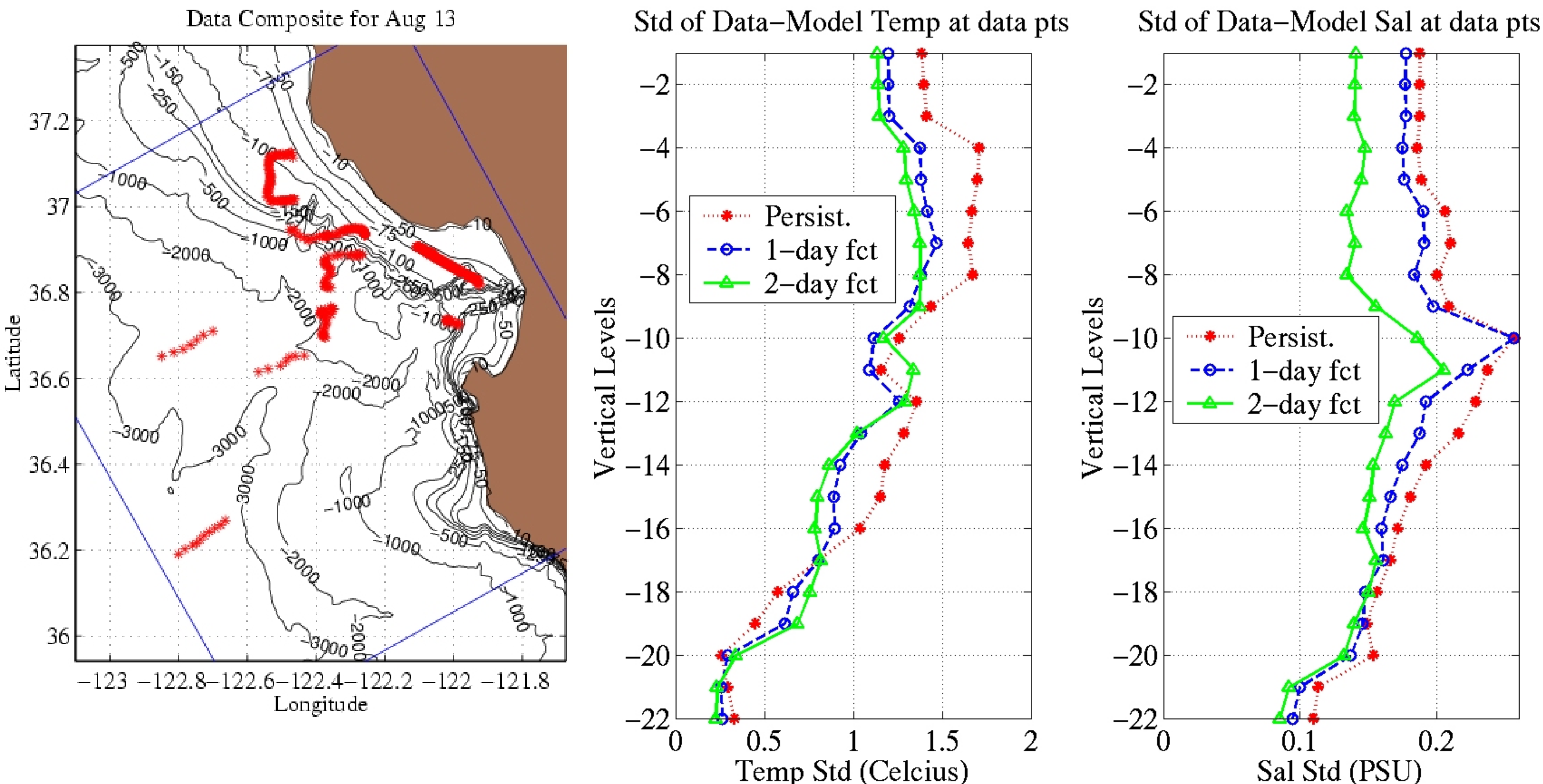
Our evaluations: e.g. Buoy winds (blue) vs COAMPS 72h forecasts (red dots)





RMSE Estimate

Standard deviations of horizontally-averaged data-model differences

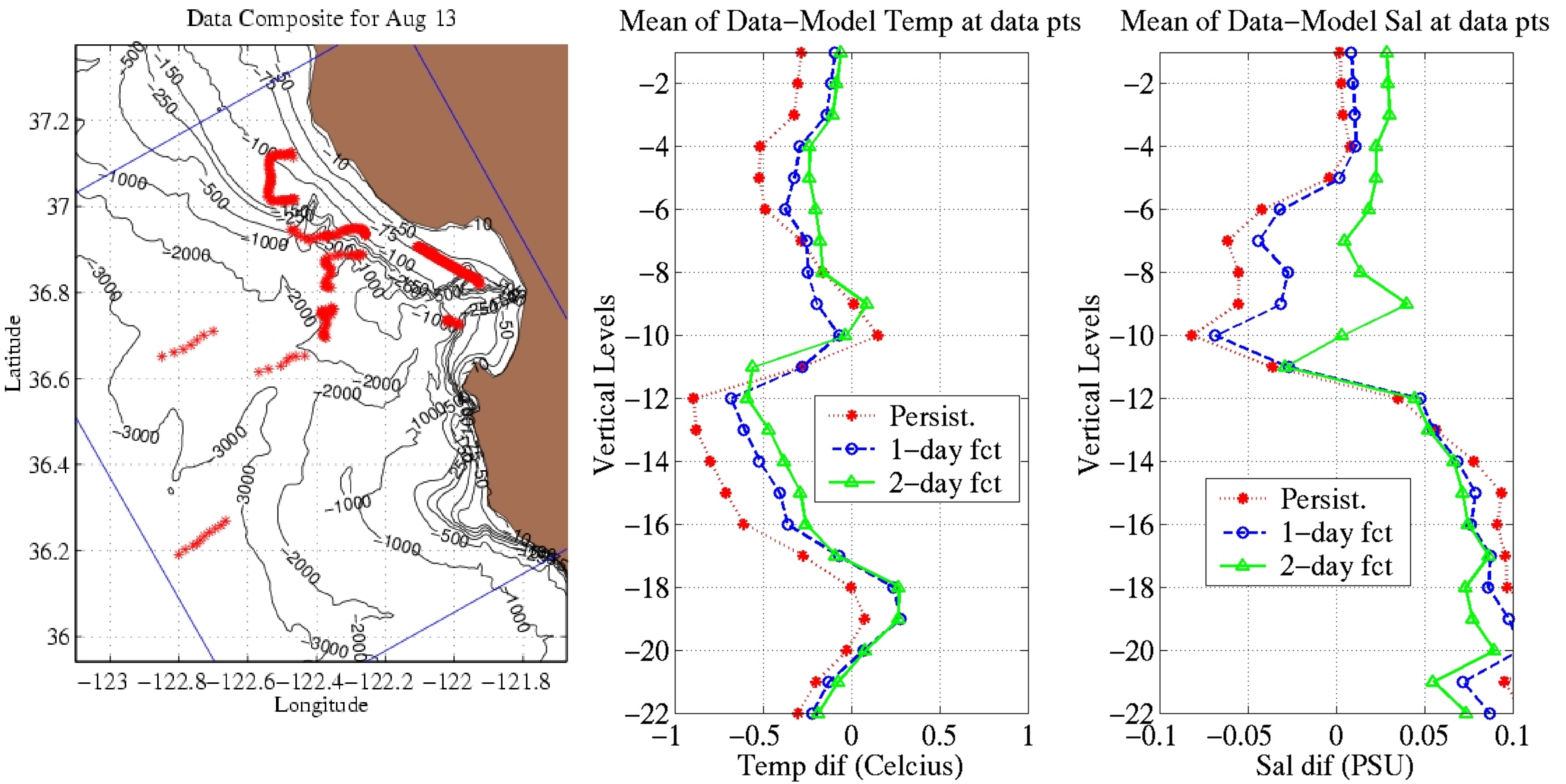


Verification data time: Aug 13

Nowcast (Persistence forecast): Aug 11 **1-day/2-day forecasts: Aug 12/Aug 13**

Bias Estimate

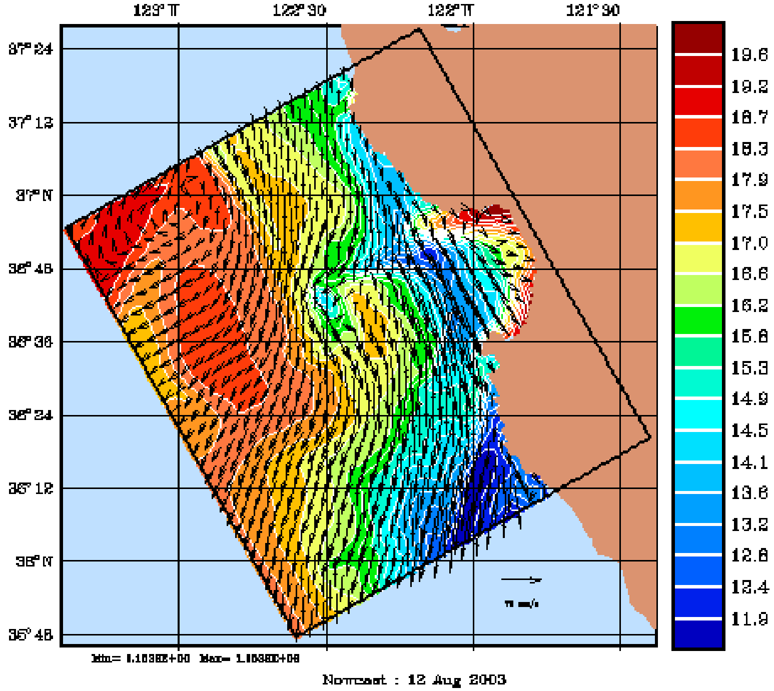
Horizontally-averaged data-model differences



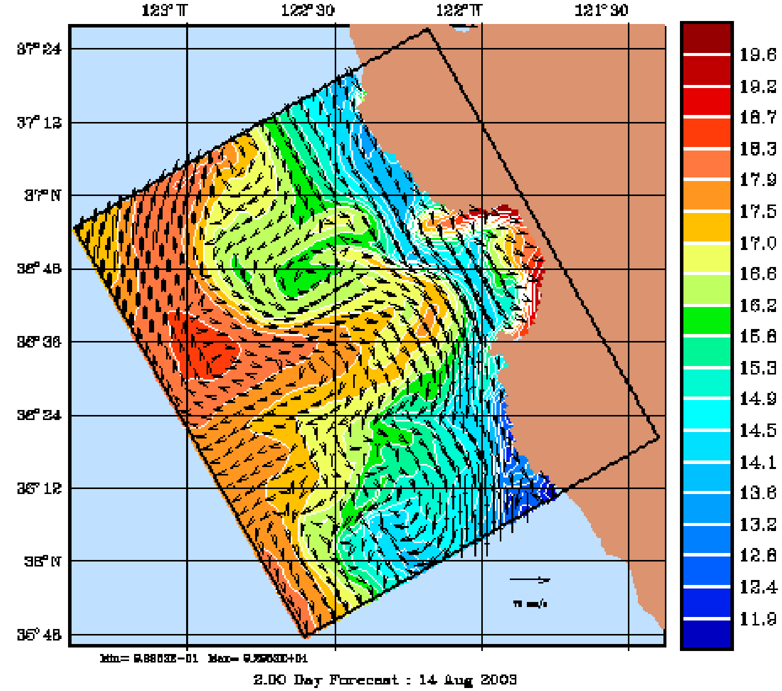
Verification data time: Aug 13

Nowcast (Persistence forecast): Aug 11 **1-day/2-day forecasts: Aug 12/Aug 13**

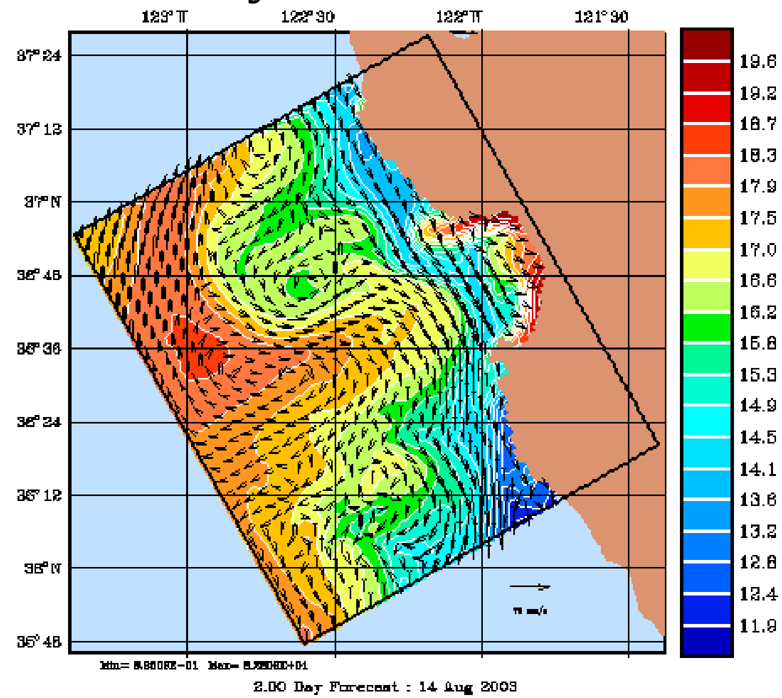
IC, Aug 12



2-day, central fct

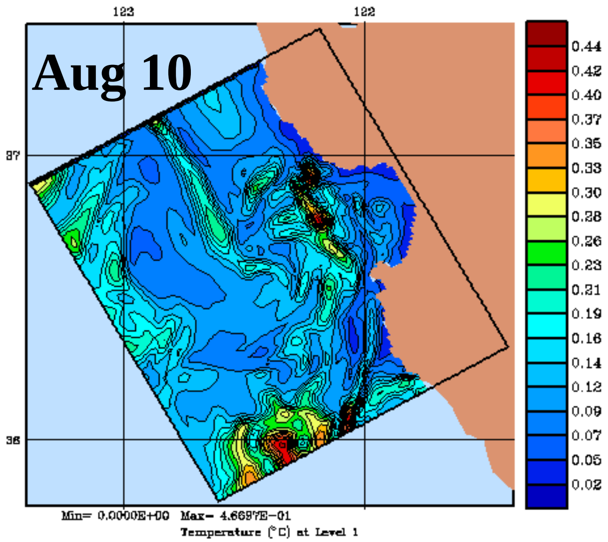


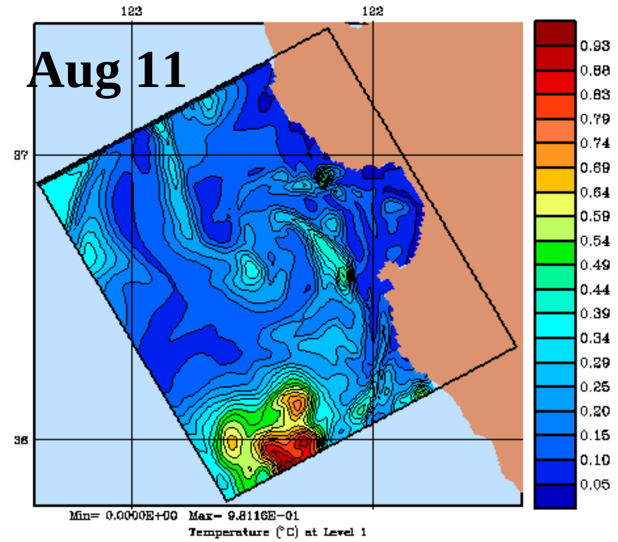
2-day fct, ens mean

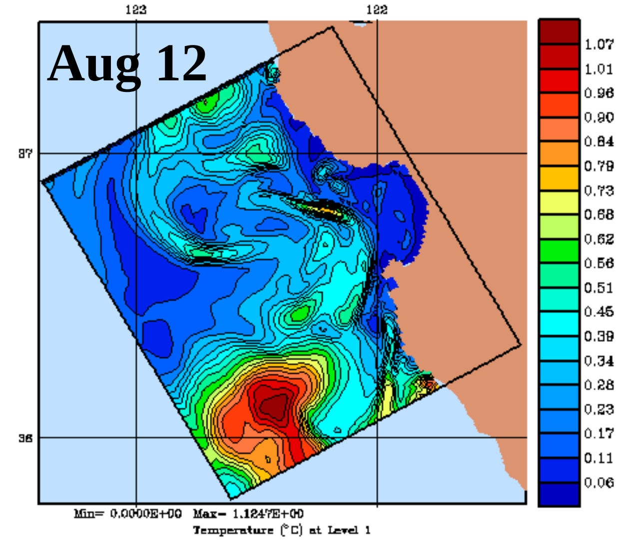


Ensemble Mean and Central Forecast
Issued in real-time

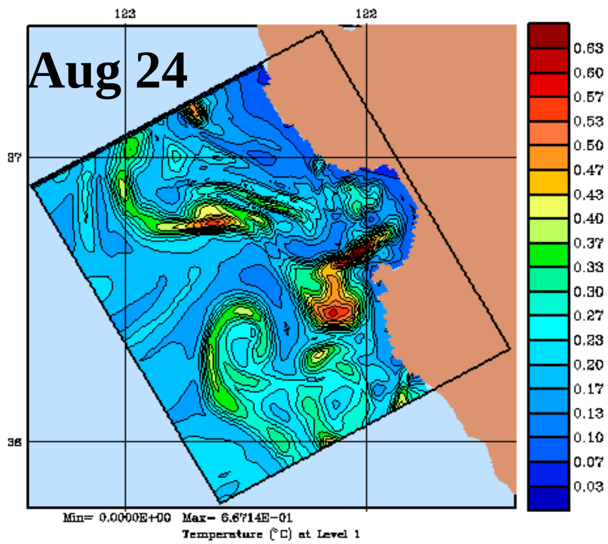
ESSE Surface Temperature Error Standard Deviation Forecasts

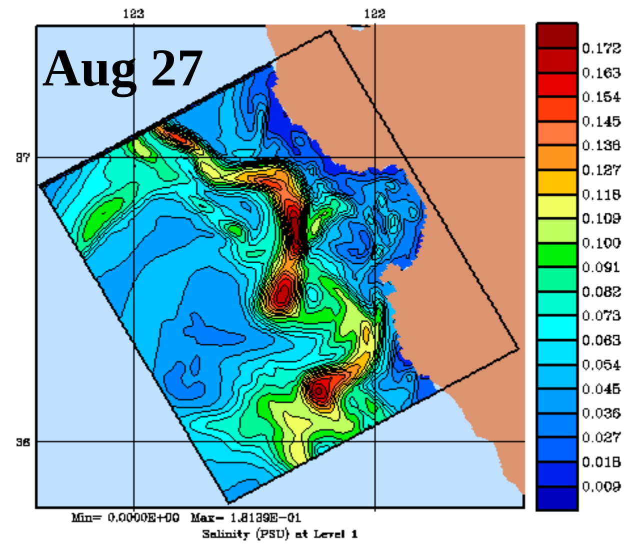


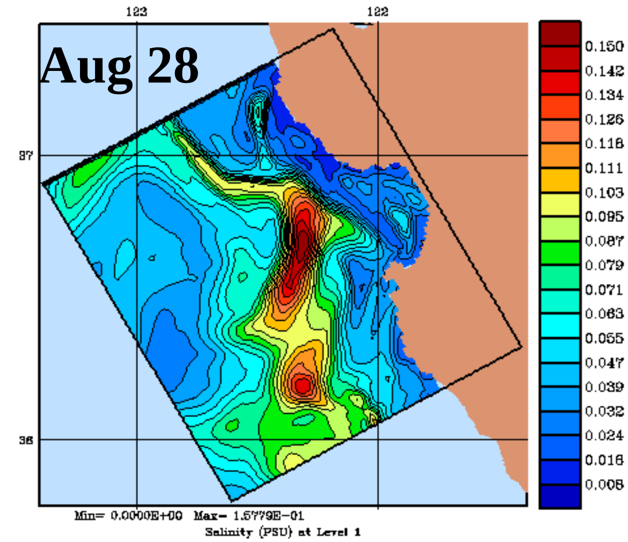




Aug 9 –12: start of Upwelling



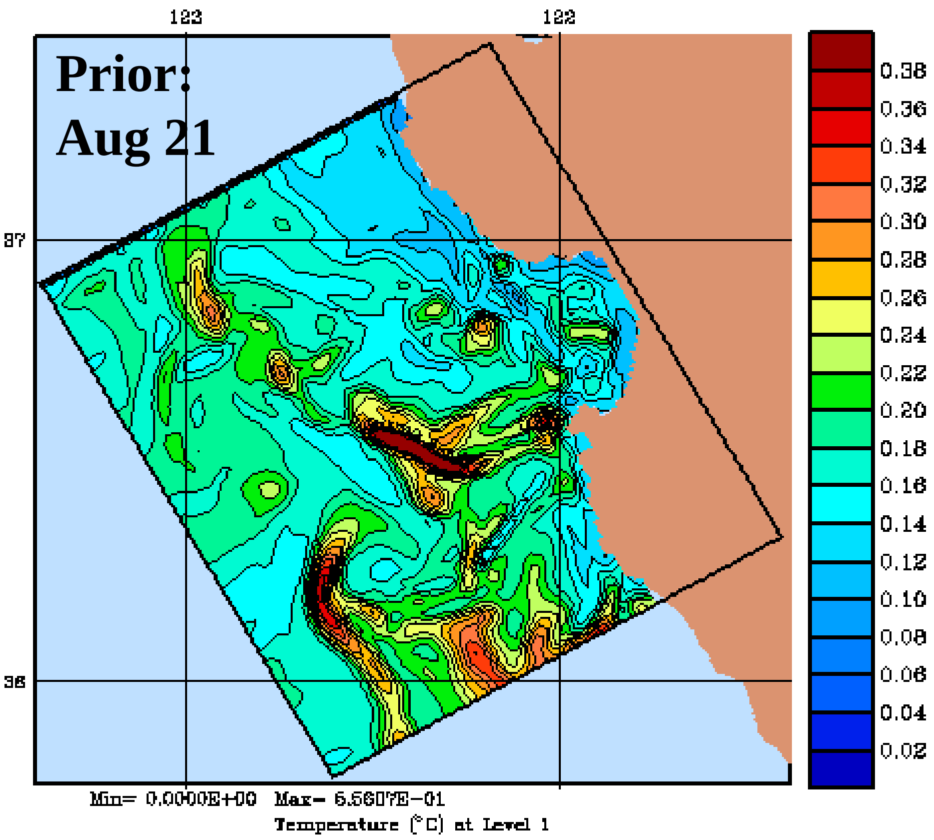


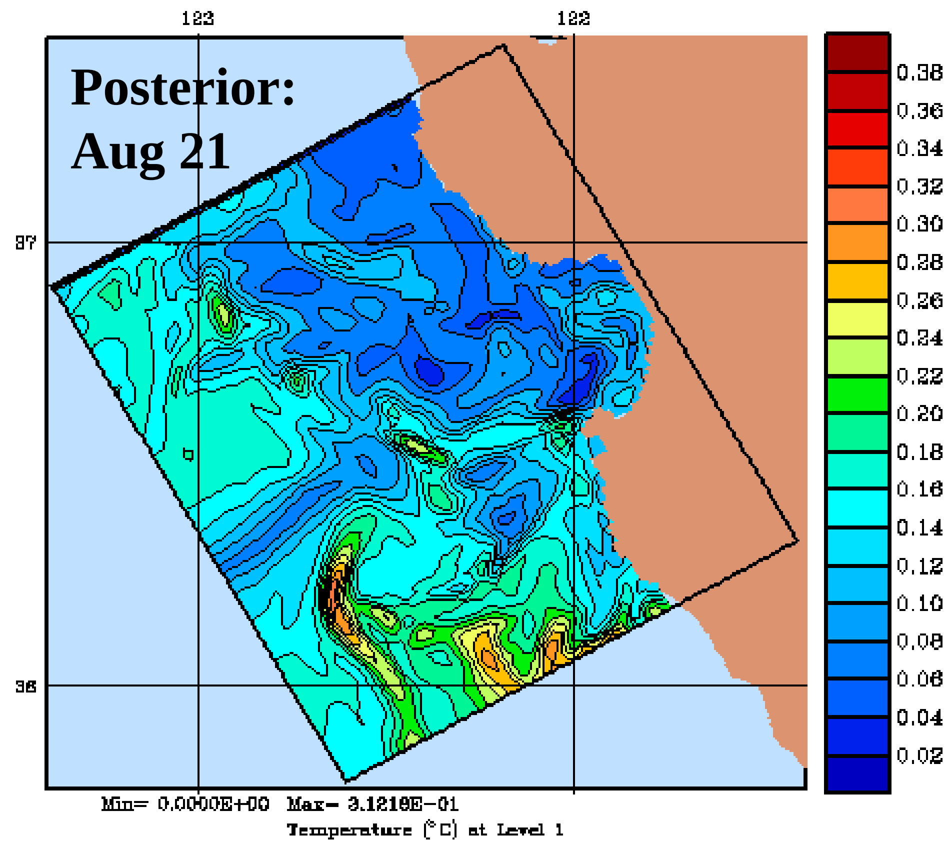


End of Relaxation

Upwelling period

ESSE Surface Temperature Error Standard Deviations: Before and After ESSE data assimilation





ESSE/ETKF schemes for adaptive sampling

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

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

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

Non-lin. Error Cov.: $dP/dt = \langle (x-\hat{x})(M(x)-M(\hat{x}))^T \rangle + \langle (M(x)-M(\hat{x}))(x-\hat{x})^T \rangle + Q$

Linearized Error Cov. : $dP/dt = AP + PA^T + Q$

Metric or Cost function: e.g. $\underset{H_i,R_i}{Min}\, tr(P(t_f)) \quad or \quad \underset{H_i,R_i}{Min} \int_{t_0}^{t_f} tr(P(t))\,dt$

Find H_i and R_i

ETKF: Use linearized error cov. eq.

Replace effect of transfer matrix A by a single priori ensemble

ESSE: Use exact nonlinear err. cov.

For every choice of adaptive strategy, an ensemble is computed

Quantitative Adaptive Sampling via ESSE

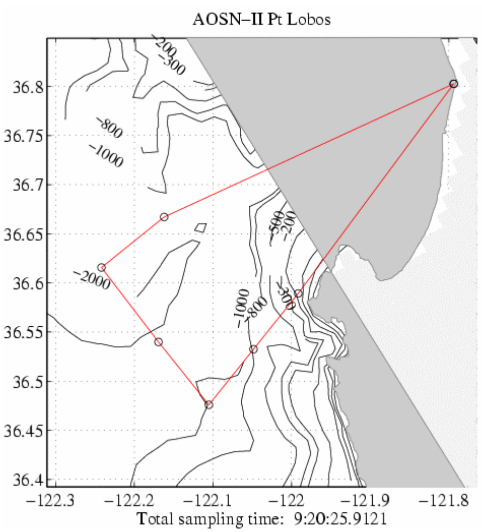
- Select sets of candidate sampling regions and variables that satisfy operational constraints

- Forecast reduction of errors for each set based on a tree structure of ensembles and data assimilation

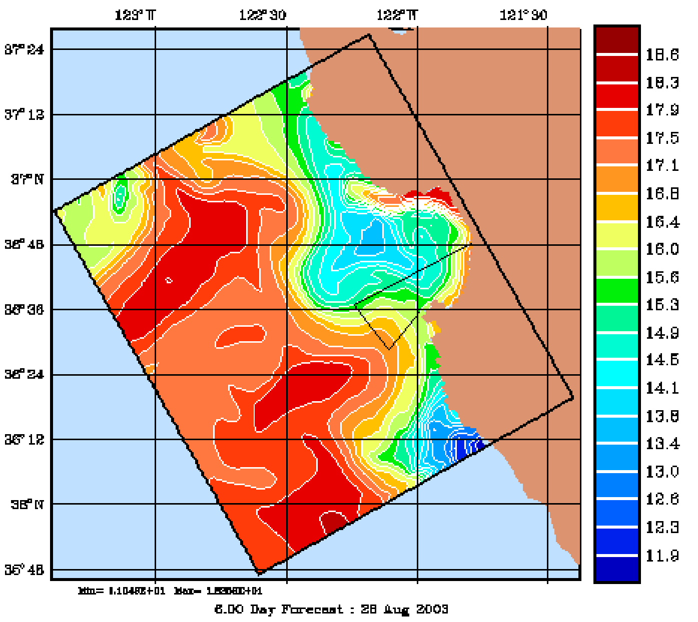
- Sampling path optimization: select sequence of sub-regions/variables which maximize the nonlinear error reduction at t_f (trace of ``information matrix'' at final time) or over $[t_0\ , t_f]$

Real-time Adaptive Sampling – Pt. Lobos

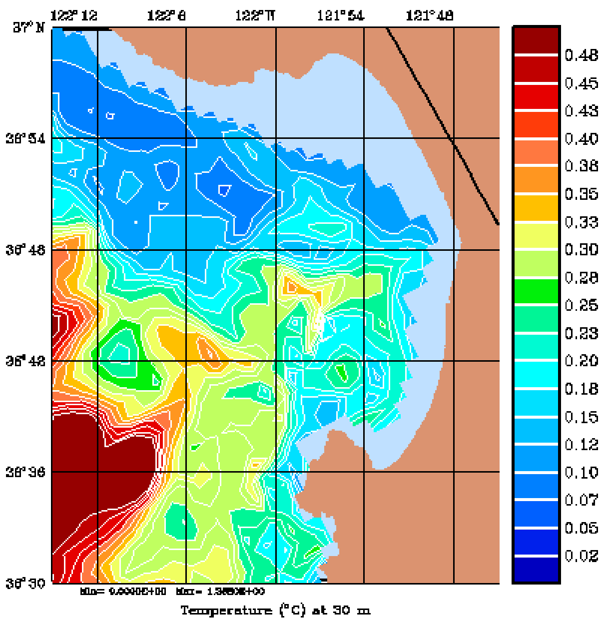
- Large uncertainty forecast on 26 Aug. related to predicted meander of the coastal current which advected warm and fresh waters towards Monterey Bay Peninsula.
- Position and strength of meander were very uncertain (e.g. T and S error St. Dev., based on 450 2-day fcsts).
- Different ensemble members 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.



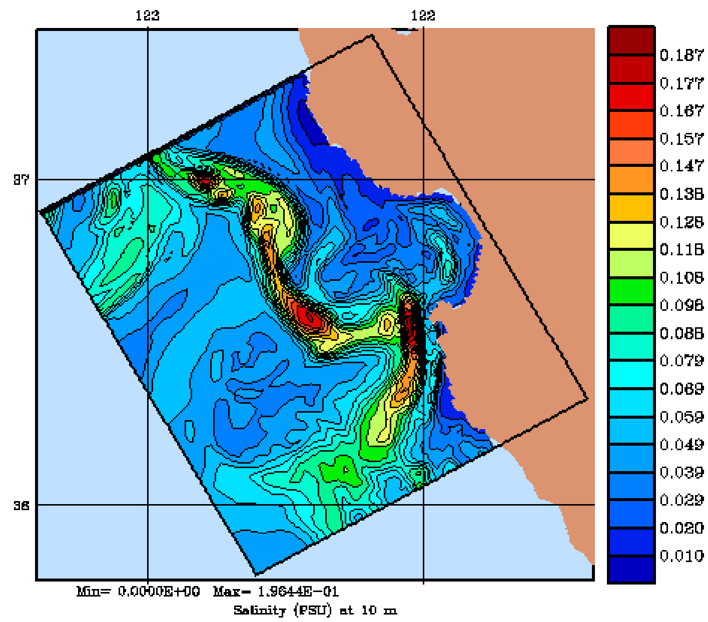
Surf. Temperature Fcst.



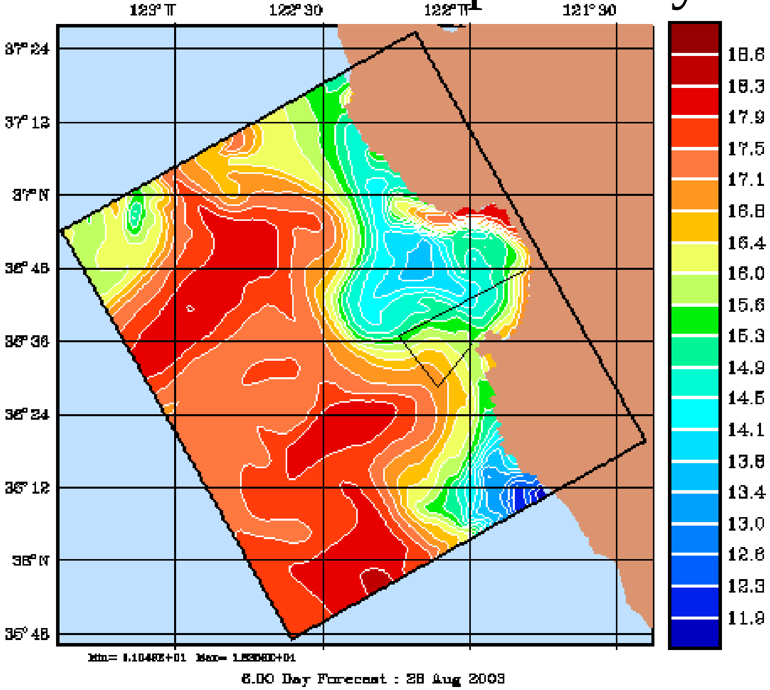
Temperature Error Fcst.



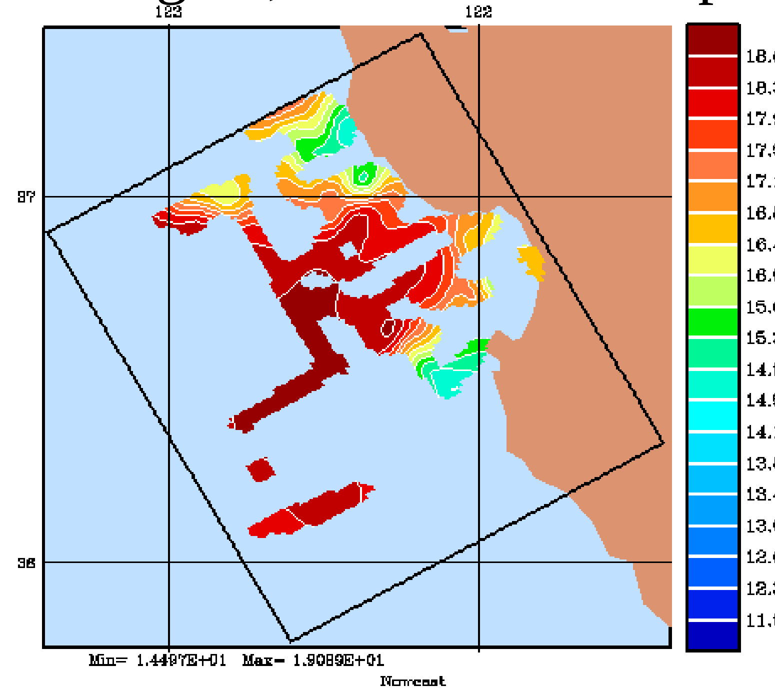
Salinity Error Fcst.



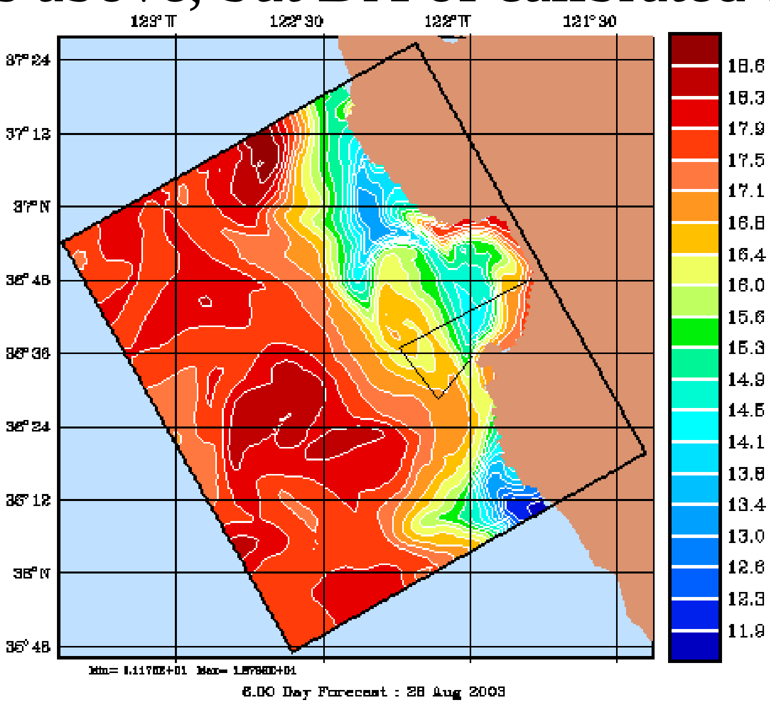
Real-time Temp 2.5 day Forecast



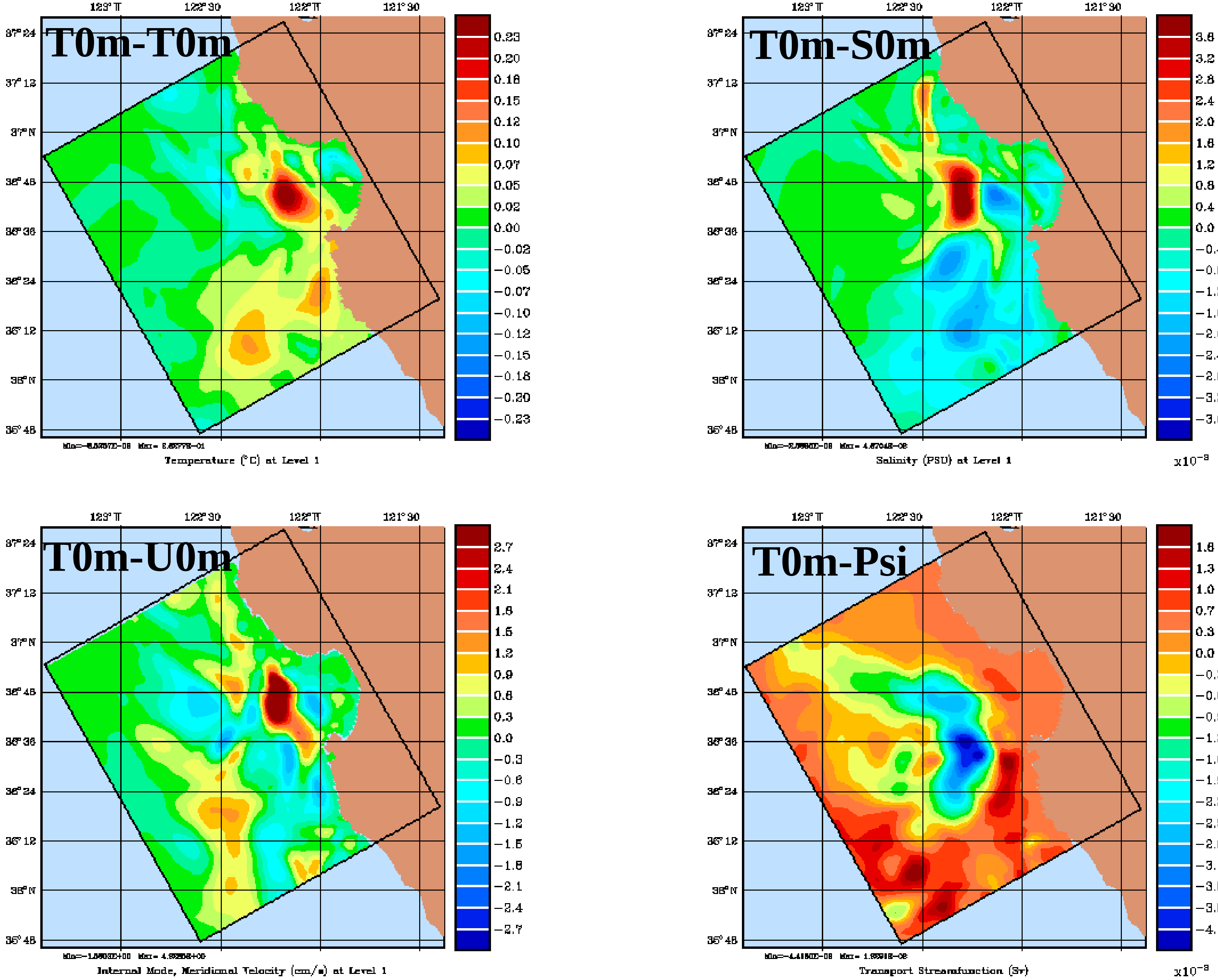
Aug 26, Calibrated Temp



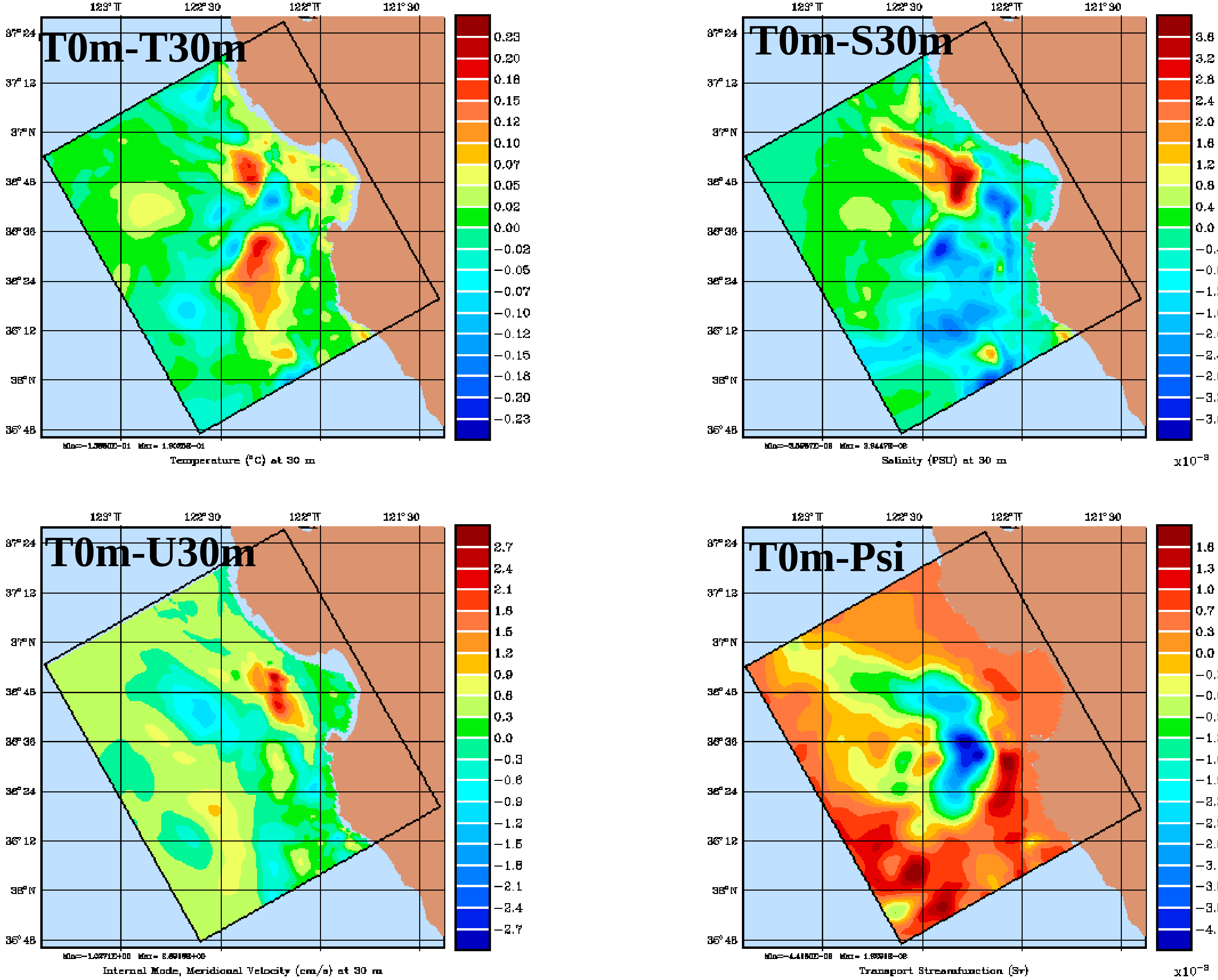
As above, but DA of calibrated data during Aug 20-23



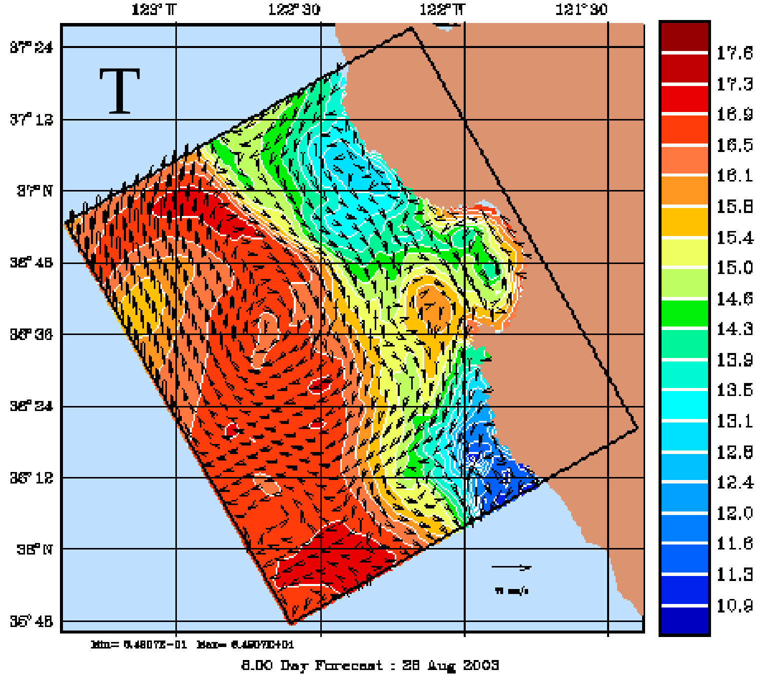
ESSE DA properties: Error covariance function predicted for 28 August

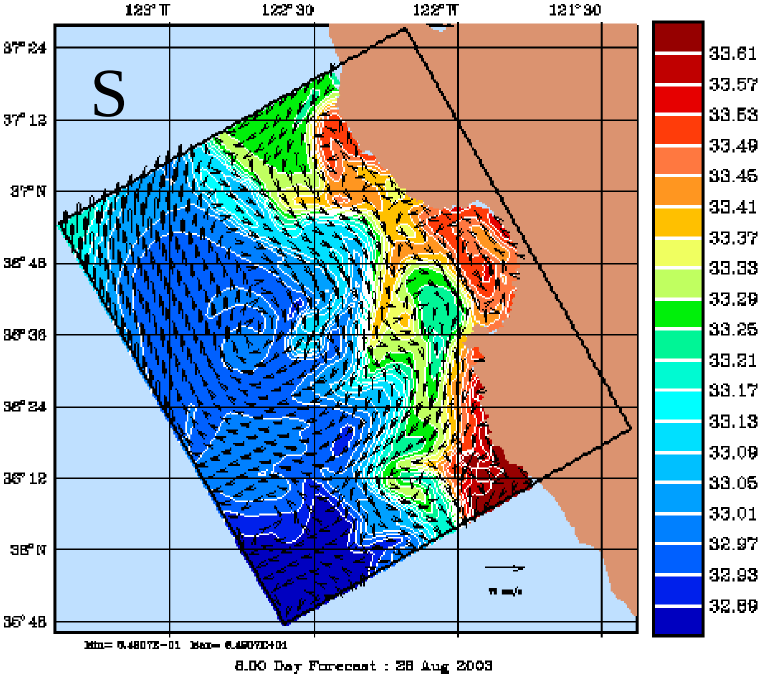


ESSE DA properties: Error covariance function predicted for 28 August

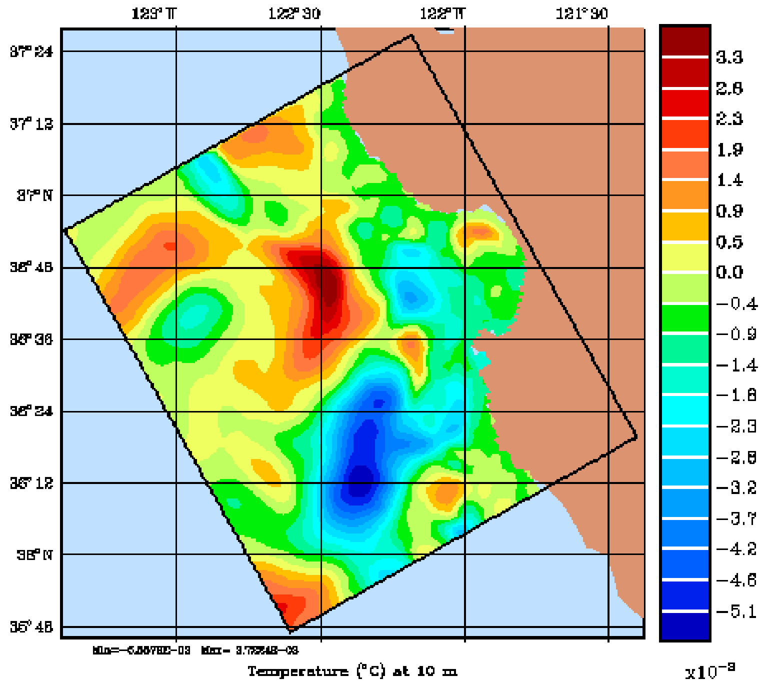


ESSE Field and Error Modes Forecast for August 28 (all at 10m)

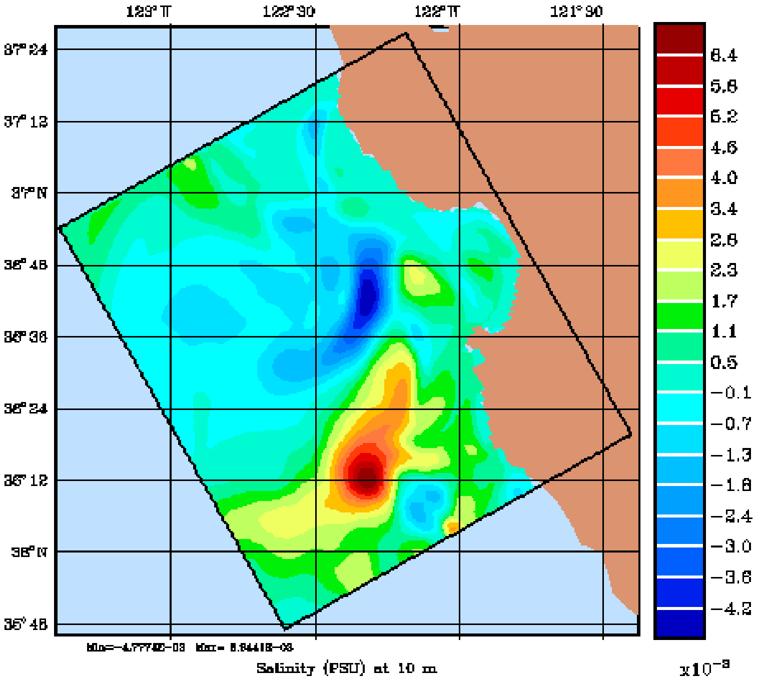




ESSE T error-Sv



ESSE S error-Sv



CONCLUSIONS: ESSE in Monterey Bay-CCS in August 2003

- Consistent fully nonlinear ensemble-based
  - Daily real-time predictions of field and errors
  - Data assimilation
  - Adaptive sampling
  - Dynamical analyses
- Two successions of upwelling and relaxed states (Pt AN << Pt Sur, in phase): these processes strongly impact uncertainties
  - Uncertainty scales generally smaller during relaxation than during upwelling period
- Future work:
  - Finalize evaluation of error forecasts, Re-analysis ESSE fields and error
  - Tidal effects matter: regional-scale offshore, (sub)-mesoscale in the Bay