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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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
Calif. Current System (CCS)

- Upwelling/Relaxation at Pt AN/ Pt Sur:
  - Upwelled water advected equatorward and seaward
- Coastal eddies, jets, squirts, filaments, etc.:
- California Undercurrent (CUC):
  - Poleward flow/jet, 10-100km offshore, 50-300m depth
- California Current (CC):
  - Broad southward flow, 100-1350km offshore, 0-500m depth

Conceptual model: Rosenfeld et al., 1994
Bifurcated flow from an upwelling cente
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 ($7 \times 10^5$ 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 forceings 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

Domain-averaged wind stress amplitude, with sign of alongshore component.
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

Our evaluations: e.g. Buoy winds (blue) vs COAMPS 72h forecasts (red dots)
RMSE Estimate
Standard deviations of horizontally-averaged data-model differences

Data Composite for Aug 13

Std of Data–Model Temp at data pts

Std of Data–Model Sal at data pts

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
Ensemble Mean and Central Forecast
Issued in real-time
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: $dx = M(x)dt + d\eta \quad \eta \sim (0, Q)$
Measurement: $y = H(x) + \varepsilon \quad \varepsilon \sim (0, R)$

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

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

Metric or Cost function: e.g. $\min_{HiRi} \text{tr}(P(t_f))$ or $\min_{HiRi} \int_{t_0}^{t_f} \text{tr}(P(t)) dt$

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.
Aug 26, Calibrated Temp

Real-time Temp 2.5 day Forecast

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)
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