Combining Ensemble and Variational Data Assimilation

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LONG-TERM GOALS

The long-term goal of this project is to develop and apply practical methods for data assimilation to improve the short-range prediction of mesoscale ocean variability.

OBJECTIVES

The primary objective of this work is to develop an ocean data assimilation system that exploits the strengths of both the ensemble-based (e.g., Evensen 2003; Houtekamer and Mitchell 1998; Tippett et al. 2003) and variational (e.g., Bennett 2002) approaches to data assimilation. The first step in this project is to perform a comprehensive inter-comparison of an ensemble-based data assimilation system with a 4d-var system for a suite of coastal model configurations. The second step is to identify the strengths and weaknesses of each system and to improve both systems by *borrowing* components from the other system. Ultimately, a single ensemble-var system will be developed. We will investigate the extent to which the ensemble-var system can outperform both the ensemble-based and variational approaches, both in terms of forecast skill (accuracy) and computational efficiency (throughput).

APPROACH

An ensemble-based data assimilation system, based on an Ensemble Optimal Interpolation (EnOI) scheme (Oke et al. 2002; Evensen 2003), has been developed and tested for a range of applications by Dr. Oke (Oke et al. 2005; 2008; 2009; 2010), and a four-dimensional variational (4d-var) system, based on the representer method (Chua and Bennett, 2001, Bennett, 2002), has been tested for coastal ocean applications by Dr. Kurapov (Kurapov et al., 2007, 2009, 2010). Conceptually, both the ensemble and variational approaches perform analogous tasks. Both methods implicitly generate estimates of the system's background error covariance, both interpolate and extrapolate background innovations (model-observation differences) onto the full model state (including all variables at all model grid points), and both seek to minimize some norm of the model-observation misfits. The ensemble-approach has an advantage that it uses the non-linear model operator to generate and evolve

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the system’s error covariance, but has the disadvantage that it is rank deficient (i.e., usually uses too few ensemble members to completely span the error sub-space of the system). The variational representer-based approach, by contrast, is full rank, but it uses linear operators to derive the system's error covariance, or representers. The ensemble-approach is typically implemented as a three-dimensional interpolation (e.g., Oke et al. 2005; 2008) and the representer approach is fundamentally four-dimensional (Kurapov et al. 2007, 2009). There are pros and cons of both approaches. Under this project, we will exploit the strengths of both approaches, with the goal of developing a superior ensemble-var data assimilation system.

A first step in this project is to apply the EnOI and 4d-var assimilation systems to the same application. The performance of both systems will be assessed when they assimilate the same observations to constrain the same model. Work has begun to achieve this inter-comparison.

Dr. Alexander Kurapov is the PI on this project and leads coastal ocean data assimilation activities at Oregon State University (OSU). Under this project, he is working closely with Dr. Peter Oke from CSIRO Marine and Atmospheric Research (Australia). To help accomplish challenging modeling and assimilation tasks off Australian coasts, Dr. Sangil Kim will join the OSU team as a post-doctoral research associate, beginning 1 January 2011. He will add to the group his expertise in ensemble-based data assimilation, predictability, and modeling coastal ocean processes (Kim et al., 2008, 2009a, 2009b).

WORK COMPLETED

In collaboration with our Australian colleagues we have begun implementation of our AVRORA-ROMS assimilation system to an area along the southern Australian coast (Bonney coast). It is chosen as a site for the initial comparisons since dynamics there are similar to upwelling off Oregon coast, where our variational system showed promising results (Kurapov et al., 2010).

To develop initial understanding of advantages of the variational system vs. OI, we have run comparative analyses with the Oregon model. Cases in a series of longer (6-day) and shorter (1-day) assimilation windows were analyzed. The case with shorter assimilation windows must be closer to OI. To further illustrate the value of the 4D dynamics in data assimilation, we have done preliminary analysis of the non-local features in representer functions (proxies for model time- and space- variable error covariances, computed using AVRORA tangent linear and adjoint codes).

We have also continued to advance our numerical assimilation codes to improve parallelism of computations and enable higher resolution assimilative computations than is presently possible.

RESULTS

Assimilation of in a series of very short windows is potentially close to the OI case. We have assimilated altimetry in a series of 1-day time windows and 6-day time windows. Area-averaged RMS model-data differences for SST forecasts (unassimilated, used for verification) are consistently better in a case with 6-day assimilation windows (Figure 1, top), favoring the 4DVAR approach. The SST model-data correlations are similar in both cases, providing substantial improvement over the model run without assimilation (Figure 1, bottom). The increased correlation with observed (but unassimilated) SST, compared to the free-run model, indicates that SSH assimilation improves geometry of the upwelling front (Figure 2).

In representer computations, the output of the adjoint model at the initial time shows the model error covariance of the observed variable and all initial fields, assuming that the errors at initial time are not correlated. Evidence of dynamical features associated with time-variable dynamics would show potential value of the variational approach (since such features are generally not present in 3DVAR or OI). Adjoint solutions are obtained by running the AVRORA adjoint model backward in time. Estimated for the alongtrack SSH slope near coast (Figure 3), such a solution reveals covariability of the observed value at t=3 d, with the ocean state at the earlier, initial, time south of the observational location, explained as an effect of coastal trapped waves (CTW). In practice of variational data assimilation, to compute the initial correction, the result of the adjoint solution is convolved with the initial model error covariance, specified a priori. Implementation of the multivariate geostrophically balanced initial error covariance, standard in our system, filters out the (CTW) feature from the initial correction. This theoretical analysis shows that our adjoint model provides opportunity to correct initial and boundary conditions in accordance with the fundamental 4-dimensional coastal ocean dynamics. Research on appropriate prior initial error covariances, that retain all important dynamical features in the initial correction, must be continued. The present project will show whether combined variational/ensemble approach helps in this regard.

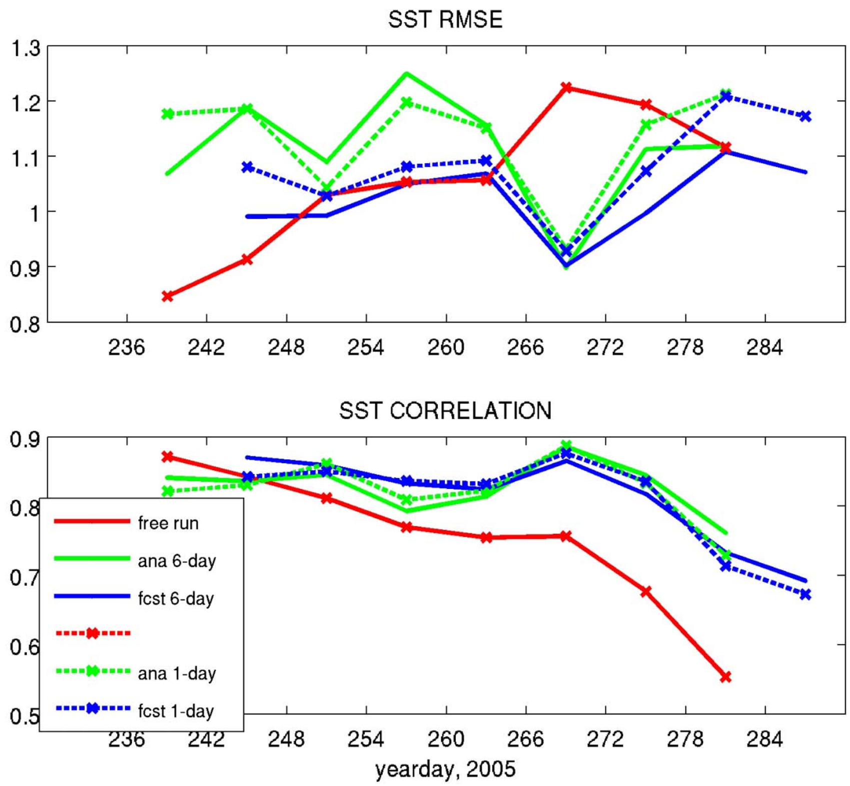

Figure 1. Results of assimilation of alongtrack altimetry are verified against unassimilated satellite SST: (top) SST model-data RMS error and (bottom) SST model-data correlation averaged over 6-day periods and the area of the Oregon coastal ocean model, free run model (red), analyses (green), and 6-day forecasts (blue). Computations performed in a series of 6-day time windows (solid) are generally similar to those in shorter, 1-day windows (dashed). The forecast RMS error is better when using longer windows. In both cases, data assimilation improves SST model-data correlation, as geometry of the SST front is corrected (see Figure 2).

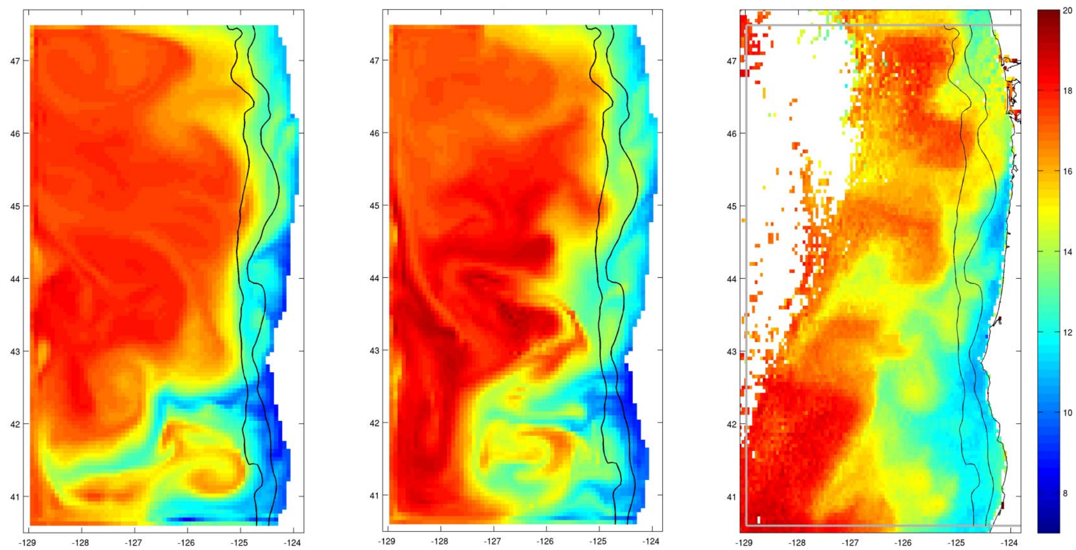

Figure 2. Assimilation of satellite alongtrack SSH data in the coastal transition zone off Oregon qualitatively improves the geometry of the SST front: (left) prior, free run 6-km resolution model, (center) model constrained by assimilation of SSH altimetry beginning June 2005, (right) verification GOES SST daily composite (all images are for 25 September 2005).

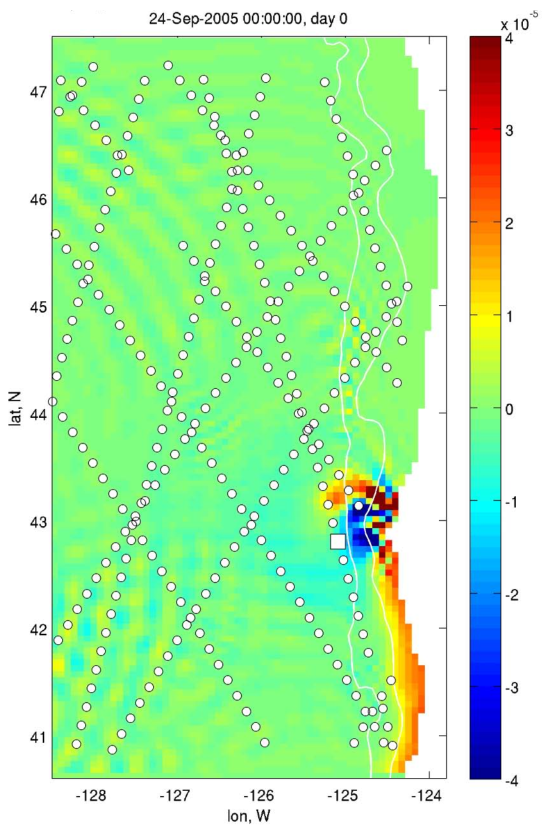

Figure 3. The SSH component of the adjoint solution for the observation of the alongtrack SSH slope at the location shown as square, showing that the error in the observed model variable at later time (t=3 d) co-varies with the initial error in the SSH south of the observational location, as an effect of coastally trapped waves.

IMPACT/APPLICATIONS

Implementation of the variational data assimilation system off Australian coast will provide a new testbed and critical feedback to the system developers. Attention to the details of the model error formulation will facilitate assimilation system improvements to better utilize dynamical information and optimize use of sparse and diverse data sets.

RELATED PROJECTS

NSF, "Modeling, assimilation, and analysis of the shelf – open ocean exchange off Oregon." The data assimilation system utilized and advanced in this project will be used to study effect of surface assimilation on subsurface fields and ultimately effects of climate variability on coastal ocean circulation.

NOAA-IOOS, "Enhancing the Pacific Northwest Regional Coastal Observing System (RCOOS) of Northwestern American Network of Ocean Observing Systems (NANOOS)". Data assimilation system improvements will be incorporated in the pilot real-time ocean forecast system run operationally off Oregon with assimilation of satellite alongtrack SSH, GOES SST, and HF radar surface currents.

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