Theory and Practice of Data Assimilation in Ocean Modeling

Robert N. Miller
College of Oceanic and Atmospheric Sciences
Oregon State University
Oceanography Admin. Bldg. 104
Corvallis, OR 97331-5503
voice: (541)737-4555 fax: (541)737-2064 email: miller@oce.orst.edu
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LONG-TERM GOALS

The long range goal of this project is to combine computational models with observational data to form the best picture of the ocean as an evolving system, and use that picture to understand the physical influences which govern the ocean's behavior. Oceanic observations are sparse and models are limited in accuracy, but taken together, one can form a quantitative description of the state of the ocean that is superior to any based on either models or data alone. Along with the goal of analysis and prediction, we seek reliable estimates of the errors in our results. We expect our results to have implications beyond data assimilation. In particular, we hope this research will lead to enhanced understanding of the implications of nonlinearity and randomness for predictability of the ocean and atmosphere. To this end, we include among our long term goals the assessment of sensitivity of models to errors in initial and boundary conditions.

OBJECTIVES

The principal objective of this project is the development, implementation and validation of practical data assimilation methods for synoptic ocean models. By "data assimilation" we mean the construction of a composite estimate of the state of the ocean based on a combination of observed data with computational model output. Since data assimilation methods which give the most and best information are highly resource intensive, and often not practical for use with detailed models, we are particularly interested in the price paid in terms of accuracy and confidence for using economical but suboptimal data assimilation methods.

Optimized methods require accurate knowledge of the statistics of the errors in the model and the data. It is therefore an objective to understand in detail the sensitivity of the data assimilation scheme to the details of the defining error estimates.

APPROACH

The basic assumptions underlying data assimilation methods in use or proposed are known to be false to some degree. We plan to study the consequences of these assumptions by constructing a hierarchy of schemes with decreasing reliance on ad hoc assumptions. It is our guiding philosophy that the best way to learn how to design and implement the most economical methods that meet our needs is to begin by implementing methods which are as close to optimal as possible. From that point, we can quantify the loss of accuracy and the saving of resources associated with each simplification of the model or the

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data assimilation scheme.

Prior estimates of the model and data error statistics determine the relative weighting of the model output and the observations in the final product. Reliable posterior error estimates, i.e., estimates of the error in the final product, are an essential part of any data assimilation system. We plan to use real and simulated data in a few specific cases to study the impact of prior error estimates on the analysis and on the posterior error estimates.

Work is proceeding toward a theoretical basis for the next generation of data assimilation methods in which randomness and nonlinearity must be taken into account. To this end, we are applying tools from stochastic differential equations and from dynamical systems theory. Since our model systems are characterized by high dimensional state spaces, Monte Carlo methods must be used to study the behavior of the stochastic systems. These Monte Carlo methods are highly resource intensive for systems with large state dimension, so the individual cases must be chosen judiciously.

In our study of the sensitivity of models to initial, boundary and forcing errors, we seek to find the most efficient representation of the perturbations to the initial conditions which grow most rapidly, since these modes will govern the evolution of model errors. We are therefore investigating breeding modes similar to those used to generate ensembles for forecast validation at NCEP (Toth and Kalnay, 1993), and singular vectors of the form used to generate ensembles at ECMWF (Molteni et al, 1996).

WORK COMPLETED

We have applied a stochastic nonlinear filter to our quasigeostrophic channel model, and found its performance to be different from, but not necessarily better than the extended Kalman filter and the ensemble Kalman filter. A paper describing this work (Miller et al., 1998; see “publications” below.) has been accepted in Tellus.

We have succeeded in generating breeding modes (see, e.g., Toth and Kalnay, 1993) for our barotropic channel model; see figure.

RESULTS

From the results of our nonlinear filtering experiment, it seems likely that our observation scheme did not contain enough information to constrain even the optimal data assimilation scheme in this case. While we cannot absolutely rule out the possibility that we have not achieved an adequate solution of the nonlinear filtering equations, the evidence strongly suggests that the observations are inadequate to constrain the analysis system, and the analysis resulting from our nonlinear filtering experiment is the best that can be done. Results from our experiments with breeding modes are consistent with this hypothesis.

IMPACT/APPLICATIONS

Major weather centers, including the US National Center for Environmental Prediction (NCEP) and the European Center for Medium-Range Weather Forecasting (ECMWF) now use ensemble methods for operational forecast validation. Our work on Monte Carlo methods should provide enhanced capability for validation of forecasts of the ocean and atmosphere, in addition to application to data assimilation. Our work on breeding modes and planned work on other schemes for ensemble generation should provide guidance in optimizing methods for generation of ensembles.

RELATED PROJECTS

"The Prediction of Wind-Driven Coastal Circulation," a two-year program under the National Oceanographic Partnership Program (NOPP) began last summer. The objective of that two-year project is to produce a practical nowcast system for the ocean off the Oregon coast. This project includes a modeling and a field component. The NOPP team includes Professors Allen and Miller

"Assimilation of Coastal Radar Surface Current Measurements in Shelf Circulation Models." Work is in progress on the investigation of data assimilation systems for use with surface velocity data from coastal radar. This project is in collaboration with Professor John Allen and Richard Scott.

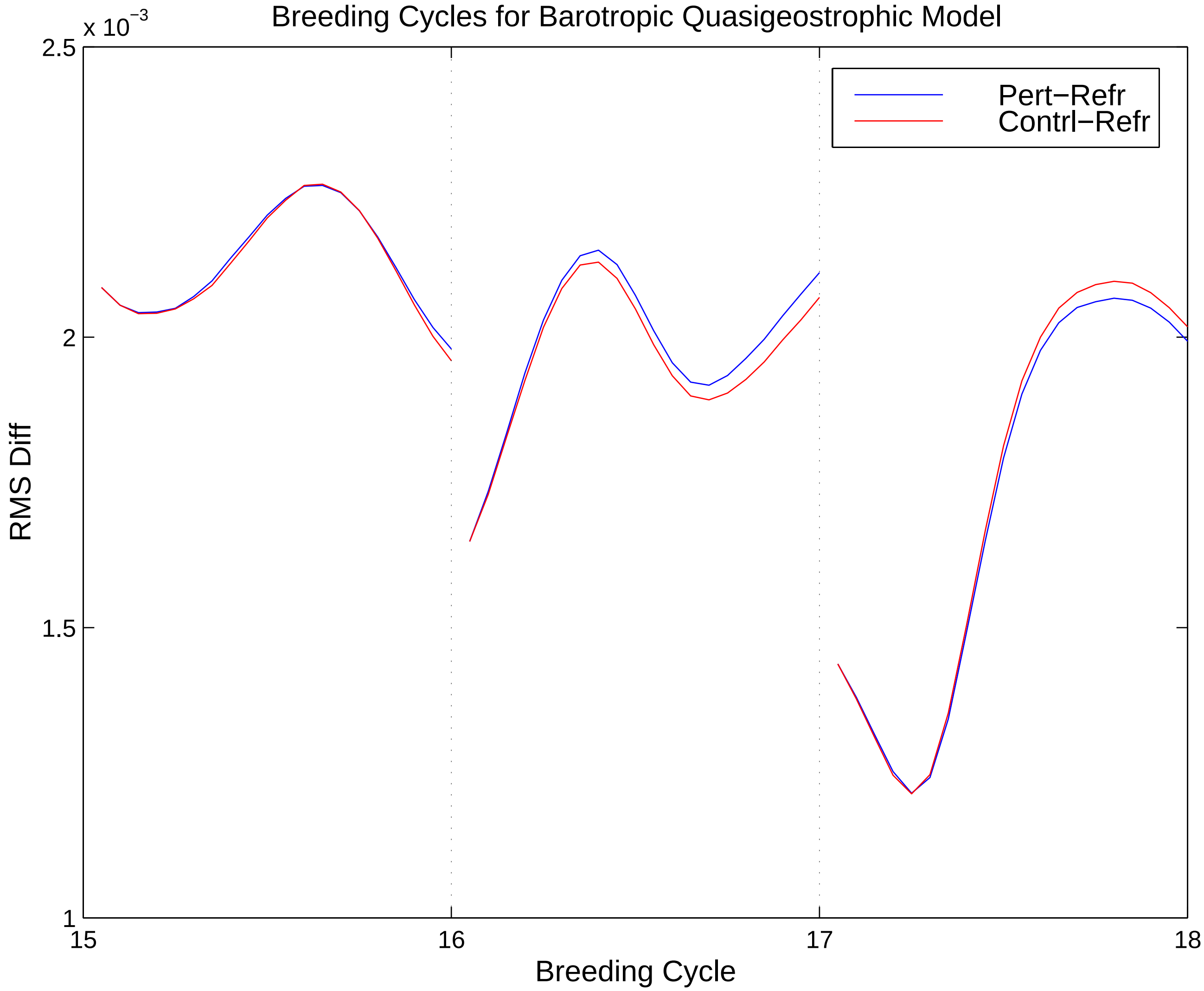
REFERENCES

Toth, Z. and E. Kalnay, 1993: Ensemble forecasting at NMC: the generation of perturbations. Bull. Am. Meteorol. Soc., 74, 2317-2330.

Molteni, F., R. Buizza, T. N. Palmer and T. Petroliagis, 1996: The ECMWF ensemble prediction system: Methodology and validation. Q. J. R. Meteorol. Soc., 122, 73-119.

PUBLICATIONS

Miller, R. N., E. F. Carter and S. T. Blue, 1998: Data assimilation into nonlinear stochastic models. Tellus, in press.



Selected results of a breeding experiment with our spectral model of a barotropic quasigeostrophic channel with sinusoidal topography. In this twin experiment, the control run is initialized with noisy observations from the reference run, and updated with observations every breeding cycle. Successive perturbations to the control run are generated according to the breeding method described by Toth and Kalnay (1993). This plot shows RMS differences between the control and the reference in red and between the perturbed control and reference in blue. The reference run is a stable limit cycle. The breeding cycle is about one-half period. Note that the perturbed trajectory is actually closer to the reference than the control at the end of the last cycle shown.