The Predictability of the Wind-Driven Ocean Circulation Investigated Through Data Assimilation

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LONG-TERM GOALS

To investigate basic predictability issues related to model sensitivities, to uncertainties in the initial and boundary conditions; how these sensitivities are dependent on different model dynamics, different data types and data distribution; how their assessment can lead to the evaluation of model errors as intrinsic component of the data assimilation method used.

OBJECTIVES

1. To develop accurate representations of the ocean systems as it evolves in space and time.
2. To increase the predictability of energetic oceanic regions through data assimilation approaches.

APPROACH AND WORK COMPLETED

The major accomplishments achieved during the last two years of the research can be summarized under three categories.

I. Construction and application of innovative Kalman filters for ocean data assimilation.

The major problem of ocean data assimilation is arguably the high dimension of the state vector, hence innovative methods must be used to obtain efficient, and affordable, data assimilation packages which can be used with fully realistic ocean general circulation models (OGCM's). One such approach is to use an approximation to the extended Kalman filter in which the error covariances and corrections to the forecasts are calculated in a reduced dimension sub-space spanned by a small number of empirical orthogonal functions (EOFs) of the time-evolution of the unconstrained OGCM. The strategy used was to first test the method in an idealized, quasi-geostrophic model of the wind-driven circulation in a double gyre ocean as proof-of-concept (publication 3), and then apply the methodology to a fully realistic OGCM of the Tropical Atlantic Ocean (publication 4). In the first idealized application, the filter was implemented using both temporally evolving and asymptotically stationary error covariances, and also compared with the more traditional approach in which the error covariance is prescribed a simple functional form. The results showed not only that the reduced-rank filter outperforms the assimilation using the prescribed error covariance; but also that the performance of the filter with stationary error covariance is extremely similar to the much more computationally expensive filter with flow-dependent covariance. In the assimilation with the Atlantic OGCM, first synthetic SSHA simulated by the model are assimilated in a twin-experiment approach; second

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assimilations of the real TOPEX altimetry SSHA are carried out. The overall results showed that the TOPEX SSHA assimilation significantly improves the model power spectra and the correlation between the observed SSH and the depth of the model thermocline.

II. Construction of an Ensemble Kalman Filter (EnKF) for ocean data assimilation. To our knowledge, this is the first EnKF constructed and used with a fully realistic OGCM.

Again the filter was first constructed for the idealized wind-driven gyre circulation model, and also compared with the already available reduced-rank filter (publication 5); and then applied to the Tropical Atlantic OGCM with the assimilation of TOPEX altimetry data (publication 6). The EnKF is expensive and computationally intensive and it is unclear if it can used with realistic OGCM. The second study indeed demonstrates this feasibility. To circumvent the problem of high dimensionality, three innovations are introduced: i) the observations are assimilated one-at-a-time; ii) the projection of the forecast error covariance onto the observational space is handled instead than the direct forecast error covariance; iii) the filtering algorithm is parallelized. The identical twin experiment assimilating synthetic SSHA data shows that the EnKF is able to constrain the deep ocean circulation as well as the surface one. The rms error of the assimilation results is less than 50% of the forecast error without assimilation. Assimilation of the TOPEAX altimetry data results in about 23% reduction of the RMS error with the observed SSHA relative to the unconstrained model simulation.

III. Quantitative assessment of the predictability of the wind-driven circulation.

The predictability of the idealized wind-driven circulation in the double gyre ocean was first investigated (publication 2). This circulation is endowed of multiple flow-regimes with a quasi-periodic behavior (high energy with a strong nonlinear jet; low energy with strong localized inertial regions) in the high viscosity case. Evaluation of the singular vectors and associated singular values, shows that in this case the behavior of the dominant singular value may be used to predict a transition of the large scale circulation from one regime to another. The low viscosity case leads to a chaotic regime of the circulation and the predictive capability of the singular value is lost. These results can be rationalized as follows. In the weakly periodic regime, the mesoscale content is relatively low and the predictability of the large-scale circulation is determined by the large –scale structure of the flow. In the strongly chaotic regime, with energetic mesoscale eddies, the predictability of the flow is a much stronger function of the local mesoscale structure, hence the large-scale patterns revealed by the dominant singular vectors do not determine any longer the flow predictability. In the second study, the predictability of the Tropical Atlantic was assessed through the assimilation of TOPEX altimetry data Publication 4).

Such an assimilation is shown to significantly constrain the subsurface thermocline structure and the equatorial system of currents simulated by the OGCM through the comparison with the subsurface thermal structure reconstructed from XBT data. The impact of SSHA altimetry assimilation is also assessed for the zonally integrated meridional transport across different latitudes. This diagnostics demonstrates that the surface and subsurface thermocline structure and its variability are significantly improved but only within the equatorial band confined between 13 N and 13 S of the equator.

No improvement is found in the sub-tropical regions. These results show that the equatorial band is endowed with enhanced predictability as the vertical thermal structure is determined by the constraint imposed by the SSHA assimilation. The extra-equatorial latitudes on the other side remain relatively unaffected and hence need interior constraints.

RELATED PROJECTS

NSF ITR/AP: An Ensemble Approach to Data Assimilation in the Earth Sciences.
Principal Investigator: Dennis B. McLaughlin

In this project, the focus is on very large nonlinear problems that are not amenable to traditional data assimilation techniques but are of crucial interest to researchers in the earth sciences. Ensemble data assimilation methods constitute the major approach.

IMPACT/APPLICATIONS

1. Construction and application of innovative Kalman Filter methods for ocean data assimilation. In particular, we have developed the absolute first Ensemble Kalman Filter for a fully realistic, primitive equation Ocean General Circulation Model of the Tropical Atlantic which is being used for the assimilation of real TOPEX altimetric data.

2. Quantitative assessment of the predictability of the different regions of the Tropical Atlantic as determined by the assimilation of the TOPEX data and comparison of the reconstructed thermal structure with in-situ XBT data. In particular, we have demonstrated that the equatorial band between 10ºS and 10ºN is endowed with enhanced predictability as the entire thermocline structure can be reconstructed by the assimilation, while the extra-tropical latitudes are relatively unaffected and hence need interior constraints.

PUBLICATIONS AND PRESENTATIONS

Publications

S. Jiang and P. Malanotte-Rizzoli, 1999, "On the predictability of regional oceanic jet stream: the impact of model errors at the inflow boundary", *J. Marine Res.*, 57, 641-669. [published, refereed]

A. Mahadevan, J. Lu, P. Malanotte-Rizzoli and S.P. Meacham, 2001, "The predictability of large-scale wind-driven flows", *Nonlinear Processes in Geophys.*, 8, 449-465, [published, refereed]

M. Buehner and P. Malanotte-Rizzoli, 2003, "Reduced-rank Kalman filters applied to an idealized model of the wind-driven circulation", *J. Geophys. Res.*, 108, C6, 3192- 3247; DOI: 10.1029/2001JC000873. [published, refereed]

M. Buehner, P.Malanotte-Rizzoli, A.J. Busalacchi and T. Inui, 2003, "Estimation of the tropical Atlantic circulation from altimetry data using a reduced-rank stationary Kalman filter", to appear in *Interhemispheric Exchanges in the Atlantic Ocean*, Elsevier Oceanography Series, [in press, refereed book]

X. Zang and P.Malanotte-Rizzoli, 2003, "A comparison of assimilation results from the Ensemble Kalman filter and the Reduced-Rank Extended Kalman filter", *Nonlinear Processes in Geophys.*
[in press, refereed]

X. Zang and P. Malanotte Rizzoli, 2003, "Assimilation of Topex altimetry data with and Ensemble Kalman filter developed for a primitive equation OGCM of the tropical Atlantic", in preparation.

Invited presentations

The predictability of regional oceanic jet streams. AGU - San Francisco, December 2000.

The predictability of the large-scale wind-driven circulation, EGS - Nice, March 2001.

Balanced initializations in ocean modeling, EGS- Nice, March 2001.

Recent experience with practical ocean data assimilation, AMS - Orlando, January 2002.

Reduced -rank vs Ensemble Kalman filter assimilations in an idealized model of the wind-driven circulation, EGS, Nice, April 2002.