Ocean Data Assimilation Research at GFDL

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1. Abstract

Estimating the state of the Earth System is critical for monitoring our planet's climate and for predicting changes to it on time scales from months to decades. Toward these ends, the vast number of atmospheric observations and the growing number of ocean observations must be combined with model estimates of the state of the Earth System by means of data assimilation systems. This project explores the development of new data assimilation techniques using state-of-the-art coupled climate models and applies these techniques to detecting climate change, improving forecasts on seasonal to interannual time scales while providing estimates of their uncertainty, and improving our understanding of predictability at decadal time scales in order to provide a foundation for the development of a NOAA capability for decadal forecasts. This capability will provide the Nation's decision and policy makers with the best possible climate information on critical problems such abrupt climate change, changes in hurricane activity, drought, and sea-level rise.

2. Project Summary

The feasibility of seasonal to decadal predictions largely stems from the role the ocean plays in the predictability of slowly evolving modes of variability. The challenge then is to have the capability to represent this low frequency climate variability within our climate models so that initializing them would offer the potential to predict internal variability in addition to externally-forced climate change. Initialization has three main components: the observing system, the assimilation method, and the model. These three components are combined to produce initial conditions for the climate model. One needs to keep in mind that the initialization problem is different from the state estimation problem.

Historically the sub-surface ocean has been very sparsely observed, and some of the data appear to be significantly biased, making the development and testing of ocean initialization schemes difficult. Studies of historical periods are important in order to assess the likely skill of forecasts over a range of different climate states. However, recent and planned improvements to the observational network promise significant improvements in future forecast skill. Perhaps, most important among these is the recent (2003) deployment of a global array of profiling floats by the ARGO program. These provide for the first time contemporaneous measurements of both temperature and salinity over the upper 2km of the world's oceans, potentially offering a step change in our ability to initialize ocean heat and density anomalies. For example, in the coming decades, can we make useful predictions in the Atlantic Meridional Overturning Circulation? The non-stationary nature of the ocean observing system, particularly due to the paucity of salinity data as well as XBT data only going to 500m, can give rise to spurious decadal variability making it difficult in the assessment of forecasts.

3. Scientific Accomplishments

1. Monthly update of oceanic observation datasets for the ECDA system of GFDL

Global data management systems (data mirroring and quality control (QC) systems) have been continuously maintained and updated for the ensemble coupled data assimilation (ECDA) system (Figure 1). The QC system considers not only the conventional QC process, but also any systematic instrument errors such as XBT fall-rate equation problem, and salinity offsets and pressure sensor errors discovered in some fraction of Argo floats. GFDL's coupled model including reanalysis outputs of ECDA will be consistently compared against these databases, and more detail assessments will be addressed around ocean basins where model biases are conspicuous.

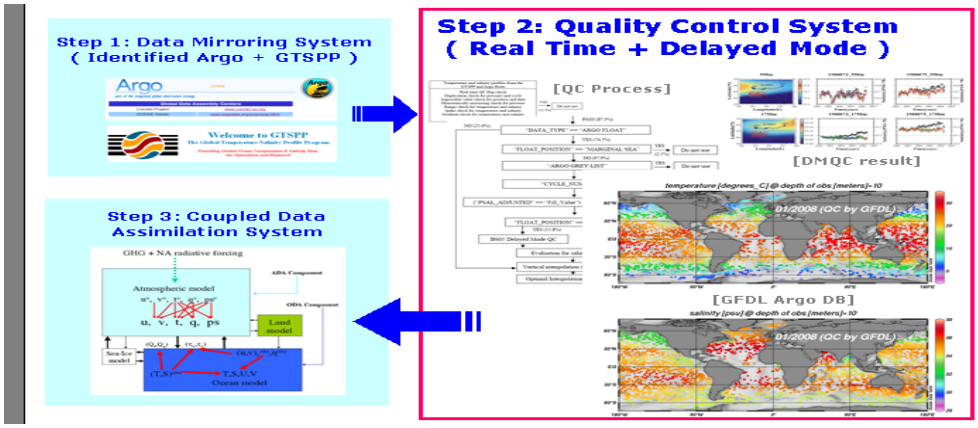

Figure 1. Data process for the GFDL ensemble coupled data assimilation system.

2. Application of sea level data – Investigation of the basin patterns of global sea level changes

Based on independent observations (Argo, AVISO, and GRACE data), we estimate the sea level budget and linear trends for individual ocean basins and the world ocean during 2004-2007. Even though it is confirmed that the seasonal variation of global sea level is balanced by the different sea level components (total sea level changes equals to the sum of the steric height contribution obtained by Argo profiles and any variability in ocean mass observed from GRACE), basin-scale sea level budgets show very different characteristics. Sea level budgets over the South Pacific and Antarctic Ocean maintain a good balance both on seasonal to interannual time scales. Meanwhile, only the satellite altimeter data exhibits a large 4-year trend over the South Indian Ocean (Figure 2). This basin significantly impacts the magnitude of the disagreement for the global sea level budget. Large differences among the 3 different gravity fields related to the hydrologic signals in the Atlantic and Indian Ocean could be one of the major causes of the imbalance in the global sea level budget.

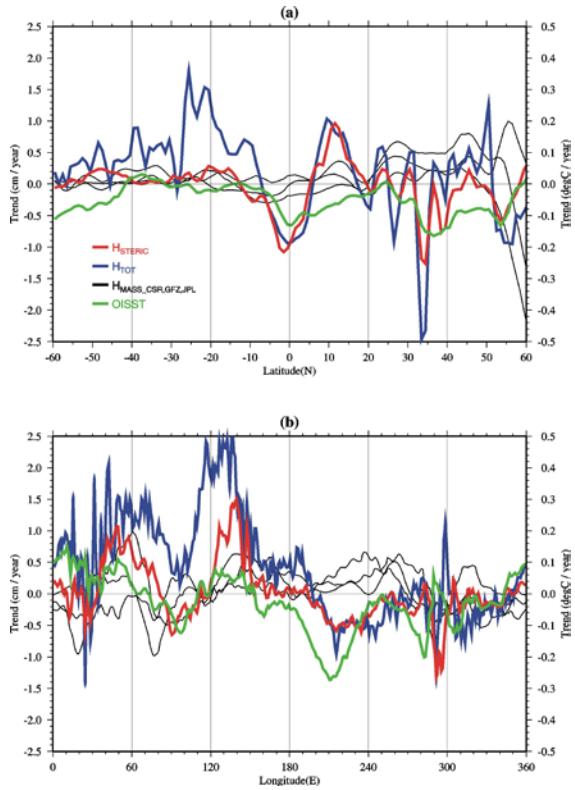

Figure 2. (a) 4-year linear trends of zonally averaged sea level from steric heights (H_{STERIC} in red), altimetric heights (H_{TOT} in blue), 3 different gravity fields (H_{MASS_CSR}, H_{MASS_GFZ}, H_{MASS_JPL} in black), and OISST (green). (b) Lower panel indicates the meridionally averaged results.

3. A construction of pseudo salinity profiles for the improvement of ECDA system in the 20th century

Based on predetermined EOF structure and altimetry data, global salinity profiles are reconstructed and evaluated by using independent observations. Collocated assessment with observed salinity data shows that the pseudo salinity profiles have a general improvement compared to the existing climatology and the reanalysis outputs from the GFDL's coupled data assimilation system. Reanalysis outputs of ECDA show relatively high performance near the surface layer all around the oceans. This indicates a successful coupling effect generating the reliable surface flux change that is not able to be considered in the global pseudo salinity profiles.

Generally, the analysis of salinity field through data assimilation approaches strongly depends on the data coverage of salinity observations. Although international cooperated projects have been recently made to increase the sampling rate of salinity data, sufficient salinity observations remain poor before Argo era. Because the Argo network is very young, important oceanic phenomena on interannual, decadal, or longer time scale are not well reproduced from assimilation models. Therefore, it is worthwhile to consider indirect methods for determining the salinity field before Argo period. Because the proper T-S relationship does not significantly change in time, the predetermined global T-S EOF modes can be easily applied to generate pseudo profiles where only temperature profiles were observed in the 20th century. We expect that the pseudo profiles will significantly affect the reanalysis outputs from ECDA system as shown in Figure 3. Fortunately, there are enough available temperature and altimetry data from 1993, and it has been already proved that the data assimilation's skill is significantly improved when the enough observed salinity included. Our next study will show the direct impact of pseudo salinity profiles on the coupled data assimilation system for the 20th century.

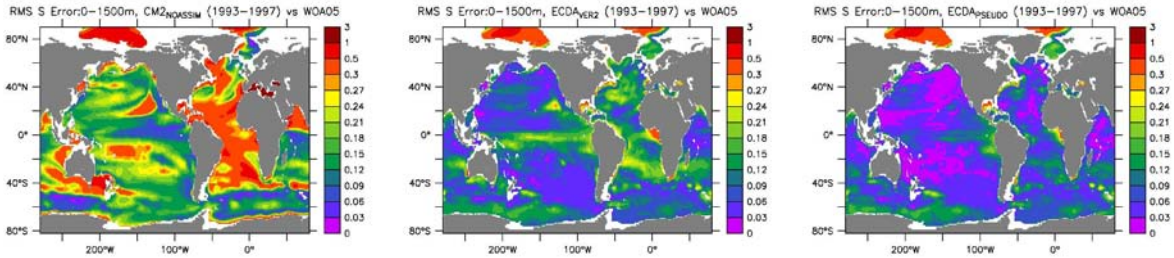

Figure 3. Rms errors over the top 1500 m relative to the World Ocean Atlas 2005. Salinity error in psu for (left) CM2 without assimilation, (center) ECDA_ver.2 using real observation, and (right) ECDA_ver.2 using pseudo salinity profiles for 5 years (1993-1997).

4. The Adequacy of Observing Systems in Monitoring AMOC and North Atlantic Climate

The Atlantic Meridional Overturning Circulation (AMOC) has an important influence on climate, and yet we lack adequate observations of this circulation. Here we assess the adequacy

of past and current widely deployed routine observing systems for monitoring the AMOC and associated North Atlantic climate. To do this we draw on two independent simulations of the 20th century using the GFDL CM2 global ocean-atmosphere model. We treat one simulation as “truth", and then sample from that simulation according to the observing system we are evaluating. We then assimilate these synthetic “observations" into the second simulation. The degree to which this second simulation recovers the first simulation (the “truth”) is an assessment of the adequacy of the observing system being evaluated. For the assimilation we use a fully coupled system that instantaneously exchanges information among all coupled components and produces a nearly balanced and coherent estimate for the North Atlantic climate system. When we use the most complete modern observing system consisting of atmospheric winds and temperature, along with ARGO ocean temperature and salinity down to 2000 meters, a skill estimate of AMOC reconstruction is 90% (out of 100% maximum). Similarly encouraging results hold for other quantities, such as Labrador Sea Water (see Fig. 4). Past observing systems, in which deep ocean temperature and salinity were not available, have a lesser ability to recover the ”true" AMOC. For example, when using the XBT observing system instead of the ARGO system, the normalized skill estimate is reduced to 52%. While these results raise concerns about our ability to properly characterize past variations of the AMOC, they also hold promise for future monitoring of the AMOC and for initializing prediction models.

5. Data Assimilation with Adaptive Parameter Correction for Climate Estimation and Prediction

Parameterized physics play an important role in an atmosphere-ocean coupled model to simulate the evolution of the earth’s climate. The value of a parameter that is used in a model is empirically set according to the knowledge of a modeler about the physical process being parameterized. The uncertainty of model parameters is one of important sources for model bias that causes model climate to drift away from the real world. The uncertainties of model states however include many other sources such as imperfect model dynamical core and physical schemes as well as erroneous initial and boundary conditions interacting with model's nonlinearity. Before the uncertainties of model states being sufficiently reduced by observations, e.g., state estimation not reaching its equilibrium, the error covariance between a parameter and model state is noisy and cannot be applied to instantaneous observations to make an efficient parameter correction. This study has designed a new data assimilation scheme that performs adaptive parameter correction using atmosphere and ocean observed data starting at the equilibrium of state estimation. The observation-updated parameters are applied to improving the next cycle state estimation and the refined covariance of parameter and model state further improves parameter correction. Assimilation experiments based on a simple conceptual coupled model have shown that while providing a systematic way to estimate the whole set of coupled model parameters using observations, the new data assimilation scheme realizes dynamically-adaptive state estimation and parameter correction with a very fast convergence and produces much more accurate observation-estimated states. Forecast experiments initialized from the improved initial conditions and adaptively-corrected parameters exhibit greatly improved forecast skill. Forecast results also show that the new assimilation scheme has some capability to relax the drift of model prediction. Specifically, while dramatically improving “weather" forecasts and extending the predictability of the model climate 4 times longer, the new scheme enhances the anomaly correlation coefficient for long-term climate prediction beyond 50%.

Despite these promises, challenges to implement the new assimilation scheme into a coupled general circulation model still exist. Some practical aspects including potential impacts from the bias of model dynamical core and physical schemes as well as the relative importance of initial conditions and parameters for “weather" forecast and “climate" prediction are tested and based on different configurations of this simple model.

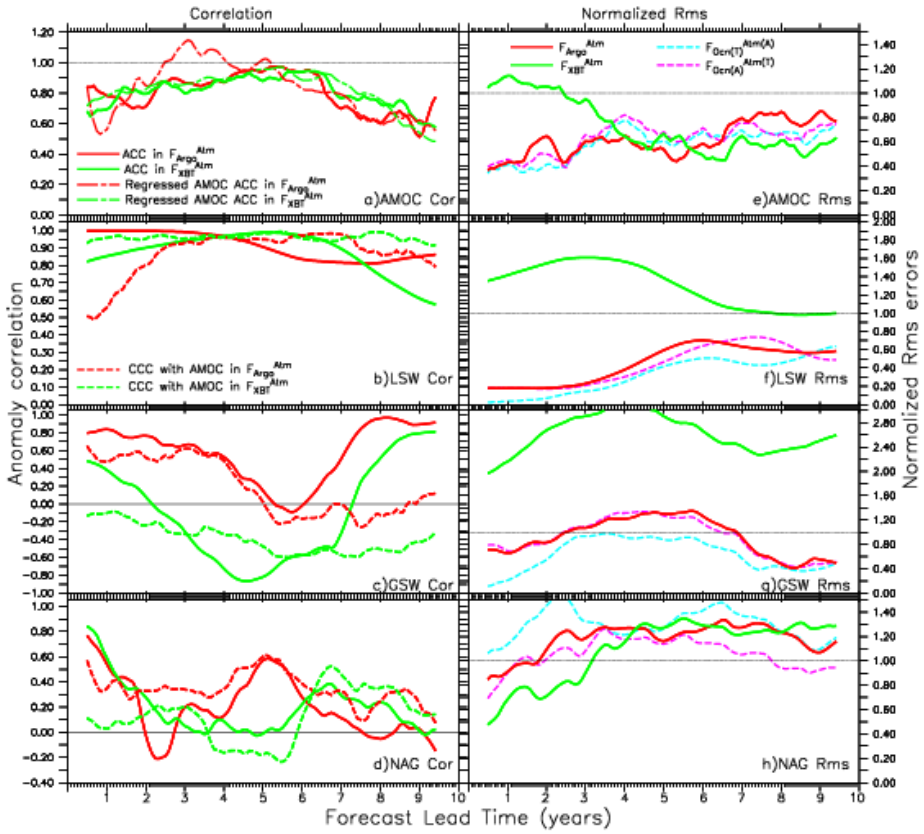

Fig. 4. Forecast skills of the Atlantic meridional overturning circulation (AMOC), Labrador Sea Water (LSW) and Greenland-Iceland-Norwegian Sea Water (GSW) as well as the North Atlantic gyre system (NAG) depending on different observing systems. (Left:**a-d**) Anomaly correlation coefficients (ACCs) and (right:**e-h**) normalized RMSEs of the AMOC (**a**, **e**), LSW (**b**, **f**), GSW (**c**, **g**) and the NAG (**d**, **h**) in $F_{XBT}^{Atm}/F_{ARGO}^{Atm}$ (solid-green/solid-red) that uses the 20th/21st-century climate observing system ($O_{XBT}^{Atm}/O_{ARGO}^{Atm}$) (see **Table** s**1**) to initialize the model. The dashed-green line in **b** is the ACC of the forecast LSW in F_{XBT}. All RMSEs are normalized by a climatological standard deviation[1] computed by the truth. The corresponding ACC of the AMOC estimated by Eq.(2) in F_{XBT}^{Atm} (F_{ARGO}^{Atm}) is plotted by a dashed-dotted-green (-red) line in **a**. The cross-correlation coefficient of the AMOC-LSW, AMOC-GSW and AMOC-NAG in F_{XBT}^{Atm} (F_{ARGO}^{Atm}) is plotted by a dotted-green (-red) line in **b-d**. The RMSE of the idealized forecast experiment using the perfect oceanic initial conditions combined with observation-estimated atmospheric initial conditions, $F_{Ocn(T)}^{Atm(A)}$ [observation-estimated oceanic initial conditions combined with perfect atmospheric initial conditions, $F_{Ocn(A)}^{Atm(T)}$] is plotted in a dotted cyan (pink) line in **e-h**.

4. Education and Outreach

There is an urgent need for information on how the climate system will change over the next several decades. This is a crucial planning horizon for many aspects of societal infrastructure, including water resource planning and ecosystem management. On decadal time scales and regional spatial scales the climate system is strongly influenced by increasing greenhouse gases and changing aerosols. However, the presence of substantial natural decadal scale variability in the climate system complicates the prediction of decadal scale changes.

A major research activity is underway at GFDL focusing on decadal variability and predictability in the climate system. There are fundamental research challenges in understanding the characteristics and mechanisms of decadal variability, and developing the necessary understanding, observing, assimilation and prediction systems that lead to credible decadal predictions.

It is our vision that GFDL will constitute the research underpinning for the assessment of decadal predictability and the development of a decadal predictions system, and will conduct experimental decadal predictions on an ongoing basis. These experimental decadal predictions will be made available to the wider community, including a National Climate Service and IPCC.

5. Publications and Reports

5.1. Publications by Principal Investigators

Chang, Y.-S., A. J. Rosati, S. Zhang, and M. J. Harrison (2009), Objective analysis of monthly temperature and salinity for the world ocean in the 21st century: Comparison with World Ocean Atlas and application to assimilation validation, *J. Geophys. Res., 114, C02014, doi:10.1029/2008JC004970.*

Chang, Y.-S, A. J. Rosati, and G. A. Vecchi (2010), Basin patterns of global sea level changes for 2004-2007. *J. Mar. Syst., 80, 115-124, doi:10.1016/j.jmarsys.2009.11.003.*

Chang, Y.-S, A. J. Rosati, and S. Zhang (2010), A construction of pseudo salinity profiles for the global ocean: Methods and Evaluation, J. Geophys. Res., Submitted

Zhang, S., A. Rosati and M.J. Harrison, 2009: Detection of Multi-Decadal Oceanic Variability by Ocean Data Assimilation System in the Context of a "Perfect" Coupled Model. *J. Geophys. Res., 114, C12018, doi:10.1029/2008JC005261, 2009.*

Zhang, S., A. Rosati, and T. Delworth, 2008: The Adequacy of Observing Systems in Monitoring AMOC and the North Atlantic Climate. Nature, Geoscinces, Submitted

Zhang, S., Z. Liu, A. Rosati, T. Delworth, 2009: Data Assimilation with Adaptive Parameter Correction for Climate Estimation and Prediction, Mon. Wea. Rev., Submitted.

Zhang, S., A. Rosati, 2009: An Adaptively-Inflated Ensemble Filter for Ocean Data Assimilation with a Coupled GCM. Mon. Wea. Rev., Submitted

5.2. Other Relevant Publications

The GFDL ocean reanalysis may be found at (http://www.gfdl.noaa.gov/ocean-data-assimilation).