U. S. GODAE: Sustained Global Ocean State Estimation for Scientific and Practical Application

Carl Wunsch-PI
Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology
Room 54-1524, Cambridge MA 02139
Phone: (617) 253-5937 Fax: (617) 253-4464 E-mail: cwunsch@mit.edu

Ichiro Fukumori
Jet Propulsion Laboratory, M/S 300-323, Pasadena, CA 91109
Phone: (818) 354-6965 FAX: (818) 393-6720 E-mail: fukumori@jpl.nasa.gov

Tong Lee
Jet Propulsion Laboratory, M/S 300-323, Pasadena, CA 91109
Phone: (818) 354-1401 FAX: (818) 393-6720 E-mail: tlee@pacific.jpl.nasa.gov

Dimitris Menemenlis
Jet Propulsion Laboratory, M/S 300-323, Pasadena, CA 91109
Phone: (818) 354-1656 FAX: (818) 393-6720 E-mail: dimitri@pacific.jpl.nasa.gov

David W. Behringer
NOAA, National Weather Service, NCEP, W/NP23, RM 807, 5220 Auth Road,
Camp Springs, MD 20746-4304
Phone: 301-763-8000 x7551 FAX: 301-763-8545 E-mail: david.behringer@noaa.gov

Michele Rienecker
NASA/GSFC Code 913, Greenbelt, MD 20771 Tel: (301) 614-564
FAX: (301) 614-6297 E-mail: michele.rienecker@gsfc.nasa.gov

Rui Ponte
AER, 131 Hartwell Avenue, Lexington, MA 02421-3126
Tel: 781-761-2288, FAX: 781-761-2299, E-mail: ponte@aer.com

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LONG-TERM GOALS

This consortium project is attempting to use all existing ocean observations, including satellite data, for the purpose of understanding and ultimately predicting, the ocean on climate time-scales. To this end it is advancing ocean “state estimation” as a practical, quasi-operational tool, for studying the ocean circulation and its influence on societal problems such as climate change, sea level rise, and biological impacts. Observing the ocean is difficult owing to its turbulent nature and very large range of energetic spatial scales. This project is establishing the means by which a quantitative description of the global ocean is and will be routinely and continuously available. The methodology employs state-of-the-art general circulation models, statistical estimation techniques, and the complete range of available oceanic observations. The effort includes further demonstration of the practical utility of ocean observing systems through their use in important scientific goals.

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OBJECTIVES

The project has been producing and improving complete global ocean state estimates over at least the period from 1992 to present, combining large-scale data sets with state-of-the-art general circulation models. Two of the foci are: (1) Understanding of processes underlying the seasonal-to-interannual changes of ocean circulation and their use with the estimates and models to predict climate variability. (2) Decadal time-scale climate change in the ocean, and its understanding for potential future prediction. Both involve developing the tools for generating dynamically and kinematically consistent estimates of the changing oceanic state, so as to include all existing data, and dynamical understanding now available to the oceanographic community. Data from previous and ongoing large-scale ocean observation programs are being used, including WOCE and Argo, and satellite missions (e.g., TOPEX/POSEIDON, Jason-1, QuikScat, etc.). The efforts are all directed in some measure at CLIVAR goals.

APPROACH

Advanced state estimation schemes and state-of-the-art numerical ocean general circulation models are employed to analyze and understand global oceanographic observations, and render general circulation models consistent with the data within estimated errors of model and data. One central model is based on a parallel version of the MIT ocean general circulation model, (J. Marshall and colleagues), and which has evolved under ECCO-GODAE use. State estimation (related to, but distinct from, "data assimilation" in weather forecasting) methods are based upon exploitation of techniques developed in both sequential methods (Kalman filter and subsequent smoothers) and in Lagrange multiplier methods (adjoints) as well as a simplified method based on Green functions. Additional development has taken place toward open-source software, with NSF support. The system is also being implemented with ocean components of seasonal-to-interannual climate forecasting systems of NOAA's National Centers for Environmental Prediction (NCEP) and NASA's Goddard Space Flight Center (GSFC), with the goal of further optimizing these operational analysis and forecasting systems.

WORK COMPLETED

It is convenient to divide this report into two overlapping efforts---one based at JPL/GMAO/NCEP, the other at MIT/AER.

JPL/GMAO/NCEP:

This effort is primarily focused on seasonal-to-interannual variabilities of the ocean. The MITgcm-based near real-time ECCO estimates have been extended to the present by using sea level (satellite altimetry) and temperature profiles (e.g., Argo). Results are public at (http://ecco.jpl.nasa.gov/external) and are now used in various applications by outside groups.

A new ocean analysis system is being established using MOM4, employed in seasonal-to-interannual climate forecasting at NOAA's National Centers for Environmental Prediction (NCEP). A Kalman filter has been implemented for it. A robust spatial interpolation algorithm has been devised to interpolate variabilities around coastal geometry. Filter implementation also uses adjoints for computational efficiency (transpose of linear operations). Skills of this MOM4-based analysis are comparable to that of the on-going MITgcm-based estimates (Figure 1).

MOM4 has been implemented in the GEOS-5 model suite under ESMF, and associated with the GMAO ocean data assimilation system version 2 (ODAS-2), and implemented the ESMF gridded component (GMAOodas_GridComp.F90) which interfaces the ocean analysis system with the GEOS-5 system. Test simulations of the model configuration undertaken with NCEP revealed issues with the subsurface salinity structure in the western equatorial Pacific. The use of daily forcing rectified the problem somewhat. Topographic configuration problems arose – Torres Strait had to be closed to ensure numerical stability and a realistic transport stream function.

The adjoint of the MOM4 momentum equations has been developed. Together with the tracer module adjoint, the entire MOM4 adjoint is near completion. Communication routines are being implemented for parallelization. Extended integration (in time) will be performed to test the accuracy and efficiency of the code.

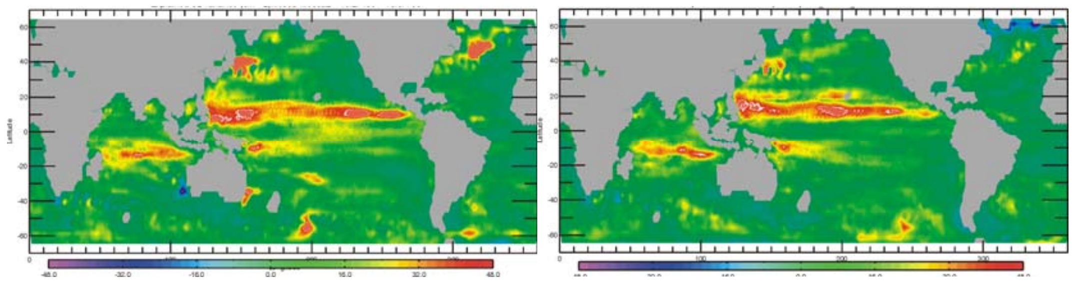

Figure 1: Reduction (positive values) of model-data difference (sea level) by ECCO Kalman filter; MITgcm (left) and MOM4 (right) from 1993 to 2006. (Color range from -48 cm^2 to +48 cm^2.)

MIT/AER:
This effort is focused on decadal-scale state estimation. Time-evolving oceanic state estimates are based upon a state-of-the-art oceanic model, and a very large fraction of the global ocean observations in the period 1992-2006. These include nearly all in situ observations 1992 to present, including altimetry, in situ hydrography (both climatological and synoptic) and NCEP/NCAR produced surface meteorology and almost all of the available Argo temperature and salinity profile data and many others. More recently, temperatures and salinities observed by elephant seals in the Southern Ocean have been included. The results are fully consistent with the GCM physics and are thus dynamically self-consistent over the approximately 15 years of estimation. All results are public within a few weeks of the estimates and are now being used by a variety of outside groups (including e.g., the NOPP program on Assessing the Impact of GODAE Boundary Conditions on coastal California. Data servers (including the Live Access Server at http://www.ecco-group.org/las/main.pl) provides public access to all results. Model extensions and improvements are made continuously.

Much attention has been directed toward more fully quantifying the errors in the ECCO-GODAE data sets, and documented in three published papers. To obtain higher spatial resolution than is possible with the global model and existing computer resources, a 1/6^{o} horizontal resolution model with an open northern boundary has been constructed for the Southern Ocean. The control vector has been extended to include the northern inflows whose initial estimates are taken from the global results. This model is running at the San Diego Supercomputer Center.

RESULTS

JPL/GMAO/NCEP:
Using 20-year forcing from ECMWF, NCEP Reanalysis 2, and the GMAO's GEOS-4 products, ensembles of fields representing uncertainty in the ocean state estimates were used to estimate global multi-variate forecast error covariances. Salinity covariance scales in the equatorial Pacific are zonally exaggerated compared with those estimated from the Poseidon ocean model using similar techniques and also using an Ensemble Kalman Filter (Keppenne et al., 2008), perhaps indicating a model bias. Covariance localization is needed to ameliorate the impact of small ensembles on covariances at large lags.

The MOM4 ODAS-2 has now undergone preliminary testing, including the test of an on-line bias correction scheme following Dee and da Silva (QJRMS, 1998). The results along the equatorial oceans of a one-year cycling of the analysis with on-line bias estimation are shown in Figure 2.

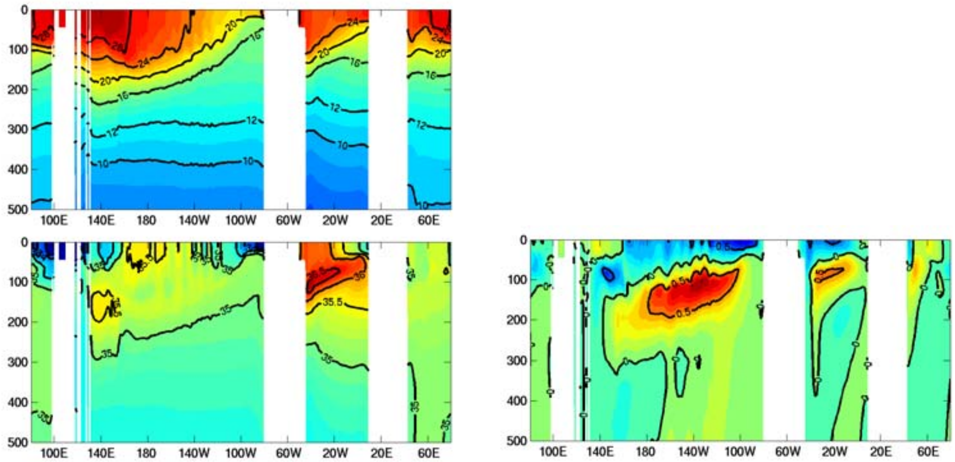

Figure 2: Temperature (top left), salinity (bottom left), and zonal current (bottom right) along the equatorial ocean after one year of assimilation for on-line bias correction of MOM4 under the GEOS-5 model system.

A novel spatial interpolation algorithm has been devised using distances along shortest pathways over the ocean. The distances are based on rates of diffusion. The method minimizes spurious extrapolation over land (Figure 3) and is utilized in the new MOM4 assimilation system.

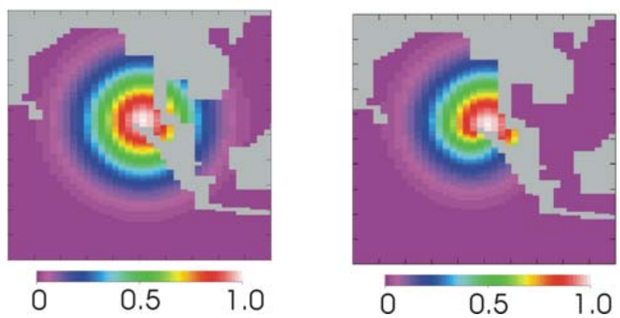

Figure 3. Normalized distance (d) from a point in the Andaman Sea shown as $exp(-d^2)$; spherical distance (left), distance over the ocean (right). Note absence of spurious values across the Malay Peninsula in the right panel.

Altimetric sea surface height (SSH) measurements reveal decadal variability in the Indo-Pacific region that is characterized by a reversal of a trend before and after the turn of the 20th century. From these measurements, Lee and McPhaden (2007) inferred decadal changes in the subtropical and subpolar gyres and in the Subtropical Cells (STCs), i.e., the shallow meridional overturning circulations that connect the upper tropical and subtropical oceans. large-scale changes of SSH associated with subtropical and subpolar gyres are similar to the observations, as well as SSH changes at the coasts of the western Pacific and eastern Indian Oceans. The latter skills are significant because SSH at these locations are important to determining the lower branches of the STCs.

MIT/AER

The MIT/AER group has extended the estimates through 2006. Many major improvements have been made in the model and we are about to move to so-called version 3, which has a full ice sub-model, uses atmospheric state variables and other improvements. Version 4, which will include the Arctic is nearly ready for use (see Heimbach et al., 2006; Wunsch and Heimbach, 2007). We exploit the computer resources at the Geophysical Fluid Dynamics Laboratory (GFDL, NOAA) our partner in this work., but also those at NCAR, the San Diego Supercomputer Center and NASA Ames.

Major scientific results have been reported by Wunsch and Heimbach (2006---on the temporal stability of the North Atlantic overturning circulation), the time required for the ocean to reach tracer equilibrium (Wunsch and Heimbach, 2007; see Fig. 4), Wunsch et al. (2007---global sea level patterns. See Fig. 5.),. Many other results are in preparation, including the PhD thesis of M. Mazloff (2008---describing a high resolution estimate for the Southern Ocean). Other results include analysis of the GRACE satellite time-varying bottom pressure estimates (Ponte et al., 2007) , the seasonal cycle in sea level (Vinogradov, 2007), and several others for which there is insufficient space here to describe properly.

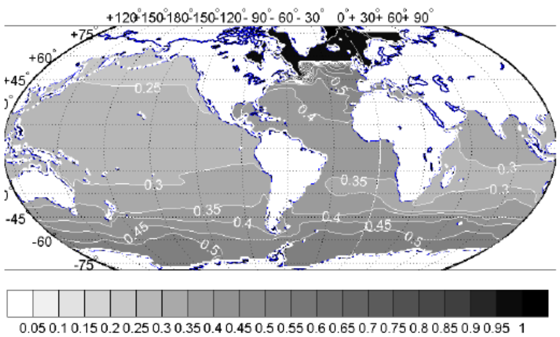

Fig. 4. Estimate of the tracer concentration at 2000m from a dye distribution introduced at the surface of the northern North Atlantic Ocean afte 2000 years as computed from the MIT/AER ECCO/GODAE estimates of the ocean circulation. Such results are important for understanding the time it takes for the ocean to reach physical equilibrium, and in the interpretation of paleoclimate data.

The next-generation of estimates, version 4, uses a new, global, grid. In a first step towards high-resolution adjoint-based OSE, graduate student M. Mazloff is running a 1/6 degree Southern Ocean model with data, and successfully constructed a 2-year optimization experiment. He is also now analyzing, using the adjoint solution, the sensitivity of the mass transport in the Southern Ocean to model and boundary parameters. Another regional model, for the Labrador Sea, is being used by another PhD student, Ian Fenty, to more specifically study the problems of constraining models with sea ice observations and successful estimates now exist. This work will comprise another PhD thesis.

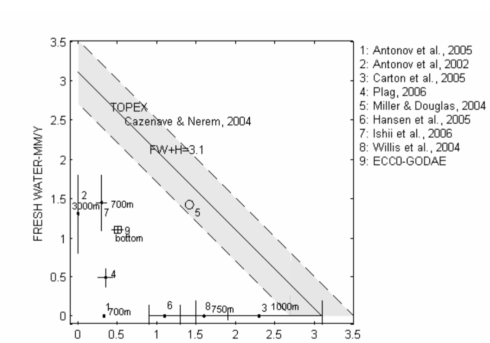

Figure 5. Attribution of sea level trends from altimetry (line with error band) between thermal and freshwater effects. The ECCO-GODAE solution uses all in situ data as well as the altimetry, suitably weighted, and thus does not confirm the high altimetric estimate. Resolving this discrepancy remains as a problem.

Several further papers are in advanced states of preparation exploring the annual cycle in the circulation, and various applications to biogeochemical cycles.

IMPACT AND APPLICATIONS

Economic Development. The investigations are improving descriptions of the ocean (e.g., temperature structure) and its circulation that are useful for fisheries, shipping, search and rescue, industrial and naval operations, and weather forecasting. Model results will also provide a means to design optimal observing systems that will help maximize the value of available resources for ocean monitoring, research, and applications.

Quality of Life. The study should provide a better means for assessing climate change and its mechanisms, including global warming and global sea level rise, which have wide societal impacts. These elements can be defined as related to national security in the wide sense.

Science Education and Communication. The study provides an opportunity for graduate students and postdoctoral scientists to learn the tools that are necessary to optimally utilize ocean circulation models and observations, and to employ the results in scientific applications and investigations of their own. A number of postodoctoral associates (G.Forget, P. Yu, D. Halkides, Z. Ye, J. Baehr) are presently working on the project. In addition a number of post-graduate students (I. Fenty, M. Mazloff, H. Dail) are working in ECCO-GODAE for PhD degrees, and one undergraduate (E. Olson) completed a master's degree.

TRANSITIONS

National Security. To the extent that climate change, including especially global and regional sea level rise are regarded as security problems, this project is directed at understanding what is going on now, and ultimately what could occur in the futre.

Economic Development: The assimilation system is being integrated into an operational seasonal-to-interannual prediction system of NOAA's National Centers of Environmental Prediction to assess the assimilation's impact and fidelity in climate forecasting.

PUBLICATIONS

(Note that many more publications arising from the prior NOPP ECCO Consortium, and from earlier years of the present grant also exist, and can be located at http://www.ecco-group.org/publications.html as well as the linked site to ECCO reports.)

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