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

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LONG-TERM GOALS

This consortium project is attempting to use all existing ocean observations, including particularly, 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, including, particularly, global satellite data, as well as in situ

observations of all kinds. The effort includes further demonstration of the practical utility of ocean observing systems through their use in important scientific goals.

OBJECTIVES

The project's central technical goal is to establish, and to continually improve, a complete global ocean state estimate over at least period from 1992 to present, combining all available large-scale data sets with state-of-the-art general circulation models. Two particular interests define the foci: (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 foci involve developing the tools for generating dynamically and kinematically consistent estimates of the changing oceanic state, so as to include as much of the data, and dynamical understanding as is 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.) and will both support and exploit experiments including the Climate Variability and Predictability Program (CLIVAR) and the Global Ocean Data Assimilation Experiment (GODAE).

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 (developed by J. Marshall and colleagues), and which has evolved under ECCO-GODAE use. The 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.   The methods have been developed by the ECCO Consortium. 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.   It is intended that the decadal component will also become an operational system under arrangements still being negotiated.

WORK COMPLETED

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

The JPL-based effort:
The ocean circulation model (MOM4) employed in seasonal-to-interannual climate forecasting at NOAA's National Centers for Environmental Prediction (NCEP) has been ported to NASA Ames's Altix system for comparison and integration with the ongoing near real-time ECCO ocean data assimilation. In simulation mode, the two models have comparable skills in simulating observed sea level variability by satellite altimetry (Jason-1, TOPEX/POSEIDON). The ECCO Kalman filter has been implemented with MOM4 and skills of its assimilation are now being assessed in comparison to the near real-time ECCO analyses. The filter implementation employs FORTRAN90 constructs native

to MOM4 and has been designed to facilitate implementation of additional filters in conjunction with existing ECCO modules. In particular, a new diabatic filter has been designed and tested with the near real-time ECCO system that assimilates satellite sea surface temperature observations. In conjunction with the filter development, the adjoint of MOM4 has been further expanded. The adjoint code for the tracer module has been completed with the addition of input and output routines including those for model forcing. The adjoint for the momentum equation is currently being derived.

The "operational" ECCO filter has also been ported to a next generation eddy-permitting global model to demonstrate estimation at a much higher resolution and with a much larger model than hitherto attempted (now supported primarily through ECCO-2 with NASA funding.) The model employs a cubed-sphere configuration to better simulate mesoscale variability and the global ocean including the Arctic Ocean and sea-ice. The "operational" global coarse resolution is implemented directly to constrain large-scale errors while a regional high-resolution filter is developed over the Agulhas retroflection region to constrain eddy variability.

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 1992-2005. These include satellite and in situ observations are used covering the period from 1993 to at or near 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. More recently, temperatures and salinities observed by elephant seals in the Southern Ocean and off the California coast have been included. All results are made publicly available 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. More generally, a data server (Live Access Server at http://www.ecco-group.org/las/main.pl) provides public access to all results. A next generation eddy-permitting global model has been configured employing a unique cubed-sphere configuration to better simulate meso-scale variability and the global ocean including the Arctic Ocean and sea-ice.

The nature of the solutions obtained for the ocean circulation depends directly upon having realistic estimates of data and model error. Consequently, a great deal of attention has been directed toward more fully quantifying the errors in the ECCO-GODAE data sets, and documented in three papers now in press. Specific attention has been given to altimetry, hydrography, the hydrographic climatologies, the ARGO profiles and the gravity fields.

To obtain higher spatial resolution than is possible with the global model and existing computer resources, a $1/6^{\circ}$ 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, which is a new partner in this ECCO-GODAE effort.

RESULTS
JPL:
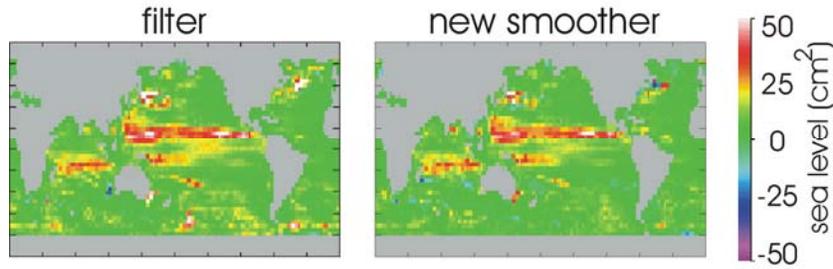
Figure 1: Reduction (positive values) of model-data difference (sea level) by ECCO near real-time Kalman filter (left) and smoother (right) from 1993 to 2006. Note smoother improvements are comparable to those of the filter.

The MITgcm based near real-time ECCO ocean data assimilation has continuously been extended to present by assimilating sea level (satellite altimetry) and temperature profiles (e.g., Argo). Accuracy of the near real-time smoother estimate has been improved by correcting newly identified deficiencies in prior data error specification, particularly those of in situ measurements (Figure 1). A new consistent set of filter and smoother estimates have been implemented and are made available to the larger oceanographic community at the JPL ECCO web site (http://ecco.jpl.nasa.gov/external). Results have been employed in a series of applications that include analyses of tropical heat budgets (Kim et al., 2006, 2007), identifying sources of the Indonesian Throughflow (Figure 2), mechanisms of interannual variations in North Atlantic meridional overturning circulation (Cabanes et al., 2007), and studies of basin-wide sea level fluctuations of semi-enclosed marginal seas (Figure 3).
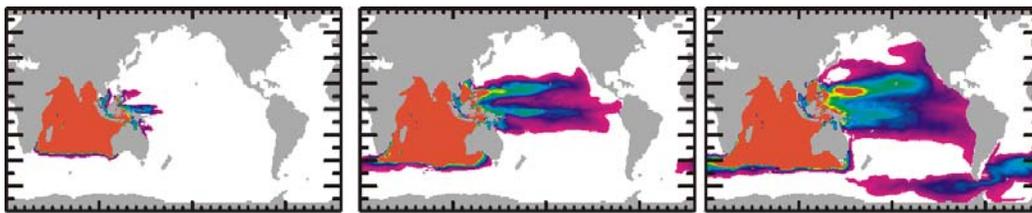
Figure 2: Depth-integrated adjoint tracer evolution at 1-year (left), 6-year (middle), and 12-year (right) prior to reaching the Indian Ocean. Colored regions indicate locations and amount of water that originate from the different regions. Note water pathways of the Indonesian Throughflow and of Southern Ocean origin.
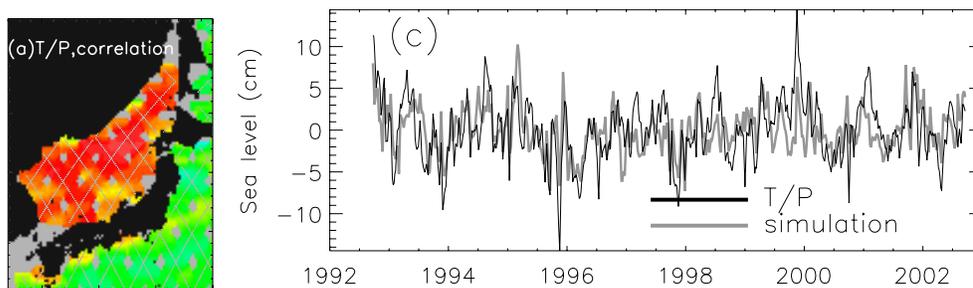
Figure 3: Correlation between sea level and basin-mean Japan-East Sea (JES) sea level (left) and time-series of basin-mean JES sea level for T/P and model (right). Note near uniform nature of the oscillation (left) and the agreement between model and data (right).

In conjunction with the filter development, the adjoint of MOM4 has been further expanded. The adjoint code for the tracer module has been completed with the addition of input and output routines including those for model forcing. In particular, the control space has been expanded to include the adjoint tracer by treating time-varying surface forcing as control variables (allowing for the correction of forcing on a time-varying basis during the estimation). The adjoint for the momentum equation is now being derived. The adjoint for the barotropic part of the momentum equation has been derived and it passes a gradient check over short time periods. Work is now being directed towards long time integrations of the adjoint model, and the derivation of the baroclinic part of the momentum equations. Some of the work involved in adjointing the MOM4 model involves working with the developers of the TAF software (an automatic differentiation software used for deriving the adjoint code) so that it works with the MOM4 code and related interface. To this end, TAF can now (1) parse and modify the FMS (Flexible Modeling System) infrastructure codes used in the MOM4 model as well as other community codes and, (2) handle the overloaded interface subroutines correctly.

MIT/AER

The MIT/AER group has extended the estimates through 2005, and 2006 will be added as soon as Jason altimetry and NCEP/NCAR reanalyses are available. A number of optimizations has been carried out and we now label the solutions as n.xxx, where n denotes a version number, and xxx the number of iterations minimizing the cost function. Primary scientific attention has been paid to version 2 (version 1 was that used in the earlier SIO calculations). Version 3 has a much more realistic ice model (Hibler type), and surface boundary conditions based on atmospheric state variables rather than surface fluxes. Some elements of this are reported in Heimbach et al. (2006). 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.

Version 2 solutions exploring trends (or lack thereof) in the North Atlantic circulation have been published (Wunsch and Heimbach, 2006), In a separate study, Wunsch et al. (2007) use the system to study the behavior of sea level globally over the last 12 years.

ace pres anom yearly trend (m/year) min: -0.046028 max: 0.027868 awm: 9.0885e-09 rmv

-0.015-0.012-0.009-0.006-0.003 0 0.003 0.006 0.009 0.012 0.015

surf_pres_anom_216_trend.fig   2007/1/2 - 10:38:54
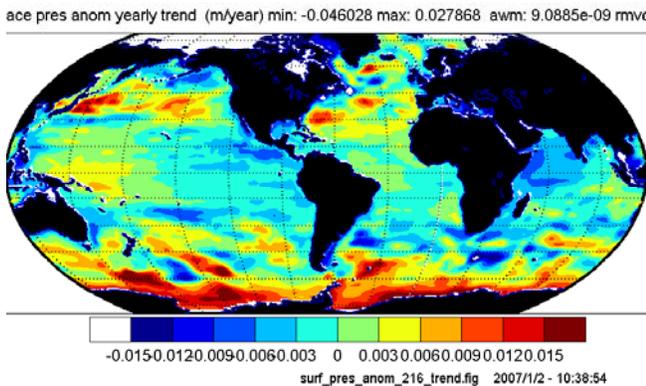
Fig. 4. ECCO-GODAE v2.216 estimate in mm/y of sea level change 1993-2004 from the complete data set and the GCM.
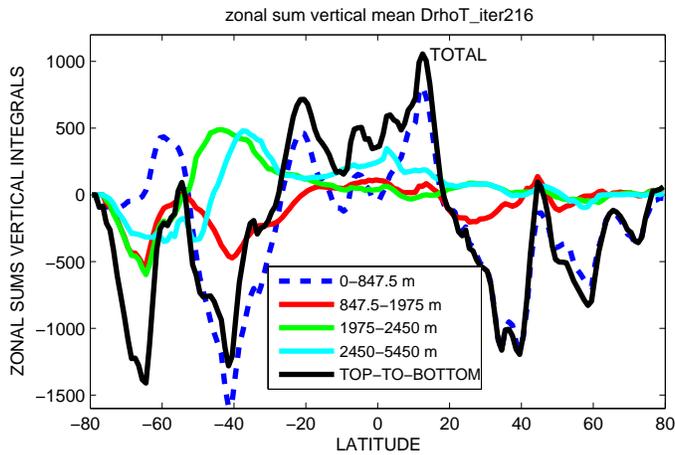
zrat_DrhoT.fig   2006/12/19 – 9:18:56

Fig. 5 Zonal sums of thermal contributions to the sea level trends over different depth ranges. Where the solid black and dashed blue lines are coincident, the sum is dominated by the upper 850m. Where deviations occur, the deeper ocean is contributing significantly.

The next-generation of estimates, referred to as version 4, is a new, truly global grid. A new grid generation algorithm has been developed by Hill et al (2006) which is topologically equivalent to a cubed-sphere grid, but different in its local grid properties: it is characterized by a nominally 1 degree longitude-latitude grid between 82S and about 65N, isotropic scaling with latitude and a telescopic increase to 1/4 degree in resolution near the equator. Beyond 65N the grid is matched to a regular polar cap grid of 90x90 grid cells with an equivalent resolution of about 1/4 degree. The model has 50 vertical levels and uses partial cells. First tuning tests have been conducted.

In a first step towards high-resolution adjoint-based OSE, graduate student M. Mazloff has set up a 1/6 degree Southern Ocean OSE system, and successfully conducted 1-year optimization experiments, using observations for the year 2005. 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.
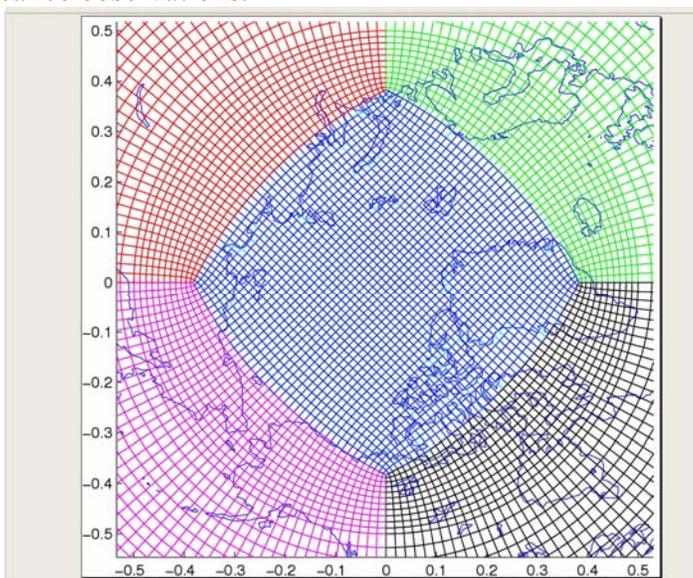
Figure 3. **Polar view looking "down" on mesh lines for coarse form of the new mesh family.**
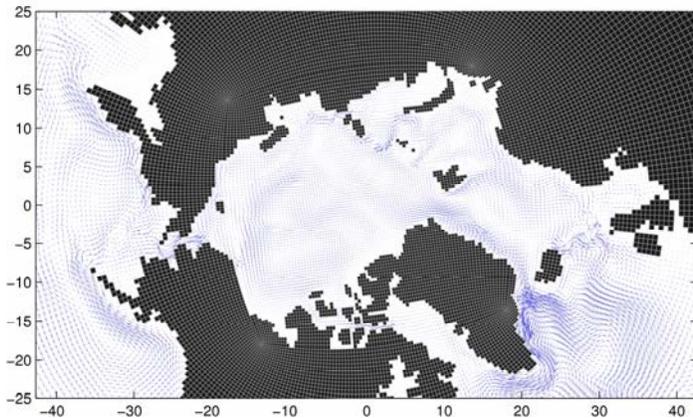
Figure 4. Upper ocean currents on the new mesh in a forward computation.

Several further papers are in advanced states of preparation exploring the annual cycle in the circulation, and various applications to biogeochemical cycles. A NOPP partner program, Coastal Ocean Data Assimilation Experiment of Central California (CODAE), employs ECCO-GODAE results to provide open ocean boundary conditions for their shallow water estimates. A new collaboration with P. Huybers (Harvard University) and funded directly by the NSF has begun applying the ECCO-GODAE machinery to estimates of the ocean circulation during the Last Glacial Maximum.

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 postdoctoral associates (G.Forget, Peng Yu, J. Baehr) are presently working on the project. Four others that worked as post-docs during the last year (O. Wang, J. Willis, S. Ricci, S. Kim) are extending their studies in their respective new positions. 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
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.)

Primarily JPL (2006+):

Cabanes, C., T. Lee, L.-L. Fu, 2007: Mechanism of interannual variation of meridional overturning circulation of the North Atlantic Ocean, *J. Phys. Oceanogr.,* submitted.

Kim, S.-B., I. Fukumori, T. Lee, 2006: The closure of the ocean mixed layer temperature budget using level-coordinate model fields. *J. Ocean. Atmos. Tech.*, **23**, 840-853.

Kim, S.-B., T. Lee, I. Fukumori, 2007: Mechanisms controlling the interannual variation of mixed layer temperature averaged over the NINO3 region. *J. Climate*, in press.

Fukumori, I., D. Menemenlis, T. Lee, 2007: A near-uniform basin-wide sea level fluctuation of the Mediterranean Sea. *J. Phys. Oceanogr.*, in press.

Menemenlis, D., I. Fukumori, T. Lee, 2007: Atlantic to Mediterranean sea level difference driven by winds near Gilbraltar Strait. *J. Phys. Oceanogr.*, in press.

Primarily MIT/AER (2006+):

Ayoub, N., 2006: Estimation of boundary values in a North Atlantic circulation model using an adjoint model. *Ocean Model.*, 12, 319-334.

Forget, G. and C. Wunsch, 2006: Estimated global hydrographic variability. *J. Phys. Oc.,* in press.

Gebbie, G., P. Heimbach and C. Wunsch, 2006: Strategies for nested and eddy-resolving state estimation. *J. Geophys. Res.,* C10073, doi:10.1029/2005JC003094.

Heimbach, P., R. M. Ponte, C. Evangelinos, G. Forget, M. Mazloff, D. Menemenlis, S. Vinogradov and C. Wunsch, 2006: Combining altimetric and all other data with a general circulation model. in: *Proc. 15 Years Prog. in Radar Alt. Venice, 13-18, March 2006*, ESA Special Pub. SP-614, ESTEC, 2200 AG Noordwijk, Netherlands.

Losch, M. and P. Heimbach, 2005: Adjoint sensitivity of an ocean general circulation model to bottom topography. *J. Phys. Oc.,* in press.

Ponte, R. M., C. Wunsch and D. Stammer, 2006: Spatial mapping of time-variable errors in TOPEX/POSEIDON and Jason-1 seasurface height measurements. *J. Atm. Oc. Tech,* in press.

Ponte, R. M. , 2006: Oceanic response to surface loading effects neglected in volume-conserving models. *J. Phys. Oc.* 36, 426-434.

Stammer, D., A. Kőhl, C. Wunsch, 2005: Test of geoid height skill through estimates of the ocean circulation. *J. Atm. Oc. Tech.*, in press.

Wunsch, C. and P. Heimbach, 2006: Practical global oceanic state estimation. *Physica D,* in press.

Wunsch, C., and P. Heimbach, 2006: Decadal changes in the North Atlantic meridional overturning and heat flux. *J. Phys. Oc.*, 36, 2012-2024.

Wunsch, C., R. Ponte and C. Wunsch, 2006: Decadal trends in sea level patterns, submitted for publication.