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

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LONG-TERM GOALS

This consortium project aims to advance 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 enormous range of energetic spatial scales. This project, building upon earlier experience, is establishing the means by which a quantitative description of the global ocean 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 estimation over the 21-plus-year period from 1985 to present, combining all available large-scale data sets with state-of-the-art general circulation models. Two particular interests define the initial 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 (Marshall et al., 1997). The state estimation (called "data assimilation" in meteorology) 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 (Marotzke et al., 1999; Stammer et al., 2002; 2003; Fukumori, 2003). The system will also be 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 in an arrangement still being negotiated.

WORK COMPLETED

The decadal-scale state estimation system, previously operating at Scripps Institution of Oceanography under ECCO-1, has been successfully transferred to MIT/GFDL, and the period of state estimates extended through 2003. At JPL, a hierarchical assimilation system has been established for producing routine analysis of ocean circulation. In both the seasonal-interannual and decadal efforts, satellite and in situ observations are used covering the period from 1993 to at or near present, including satellite altimetry, in situ hydrography (both climatological and synoptic) and NCEP/NCAR produced surface meteorology. Many other data are employed in the decadal calculations. Near real-time analyses are updated approximately every ten days. A data server (Live Access Server at http://www.ecco-group.org/las/main.pl) provides public access to all completed. 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 (Figure 1).

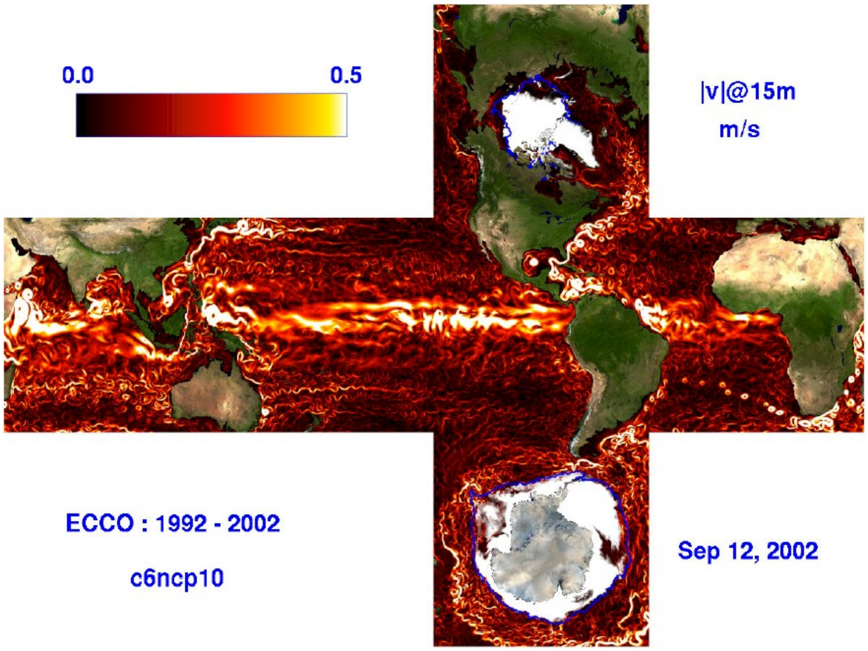

Figure 1: *Cubed-sphere ocean model configuration. The figure shows simulated near-surface (15-m) ocean-current speed and sea-ice cover from a preliminary eddy-permitting integration. Units are m/s. Each face of the cube comprises 510 by 510 grid cells for a mean horizontal grid spacing of 18 km. Simulated sea-ice is shown as an opaque, white cover. Animation of this figure (1992-2002) and more information about this integration are available at http://ecco.jpl.nasa.gov/cube_sphere/. It represents the expected next generation of ECCO model.*

Physical processes represented in the model have direct impact on the state estimates. Consequently in a number of publications, specific elements of the model have been scrutinized. Similarly, tests are underway of various applications of the estimation techniques, and their modification. New data are being added, e.g., the ARGO float profiles at the positions displayed in Fig. 2. Error estimates for the data being used are central to the results as well, and are now the focus of specific scrutiny. (See publication list.)

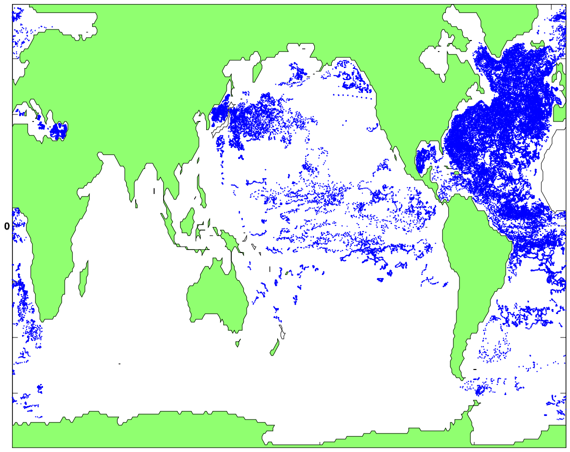

Figure 2 Positions of ARGO float profiles now used in the state estimates.

Because this project is the extension to semi-operational form of the preceding ECCO-1 program, there are a large number of scientific results now available, and which for completeness, are listed in the publications and on-line, but not further discussed here.

RESULTS

Analysis of satellite measurements of wind stress from ERS scatterometers during the 1992-2000 period suggests a substantial weakening of the southeasterly trade wind over the South Indian Ocean (Figure 3). The resultant decrease in the southward transport of warm surface water out of the tropical Indian Ocean is nearly $7x10^6$ m^3/s, which is nearly 70% of its time-mean value. Sea level data from the TOPEX/Poseidon satellite altimeter indicates a coincident decrease of the northward transport of colder subsurface water (not shown). Together, these two types of data suggest a near-decadal slowdown of the shallow overturning cell in the South Indian Ocean by as much as 70%. These changes have important implications to upper-ocean heat budget, decadal climate variability, and biochemistry of the Indian-Ocean region (Lee, 2004).

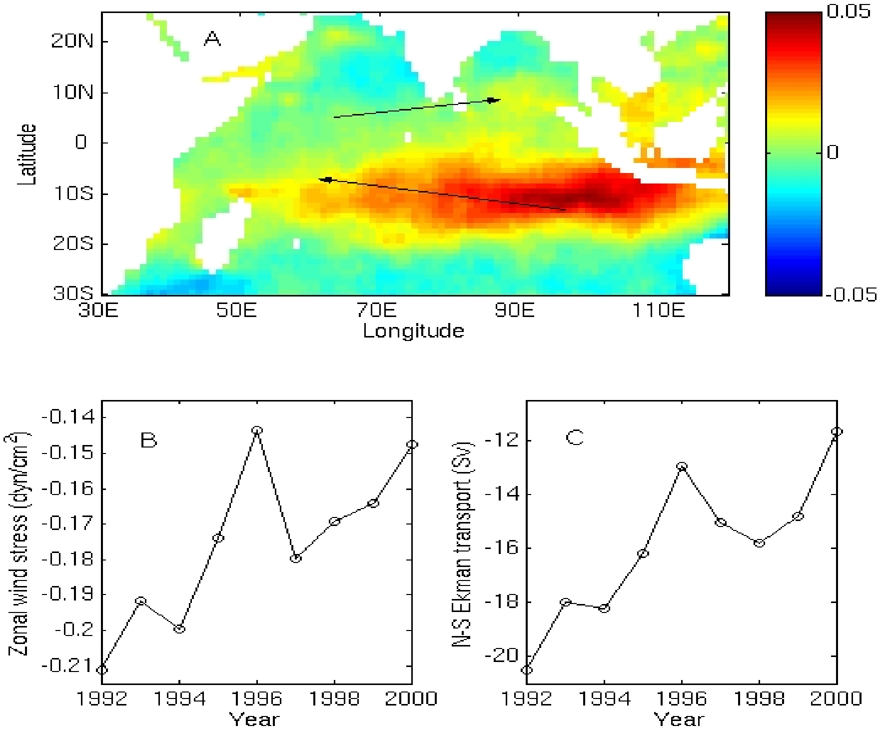

***Figure 3**: (A) 1992-2000 linear trend of zonal wind stress in dyn/cm^2/year (positive values indicate weaker easterly wind) estimated from ERS scatterometer. The arrows schematically show the directions of the annual-mean wind. (B) Time series of zonal wind stress averaged over 20º-0ºS. (C) Time series of meridional Ekman transport at 10ºS.*

A significant interannual change in the temperature-salinity relationship has been found in the eastern Equatorial Pacific Ocean (Wang *et al.*, 2004a); water is found to be warmer (0.5ºC to 1ºC) and saltier (0.1 to 0.2) during El Niño years than otherwise in the pycnocline ($24.5 \le \sigma_0 \le 26$ kg m^{-3}) (Figure 4). Model analyses using an adjoint simulated passive tracer indicates that changes during El Niño years can be attributed to a larger convergence of saltier water from the Southern Hemisphere and a smaller convergence of fresher water from the Northern Hemisphere (Figure 5) (Wang *et al.*, 2004b). Results indicate that studies of data assimilation that employ statistical relationships between temperature and salinity should be altered accordingly. The results also provide new insight into the mechanism of El Niño. Whereas traditional studies have focused on the zonal (east-west) "sloshing" of the water masses, the findings here identify a significant meridional (north-south) convergence associated with El Niño.

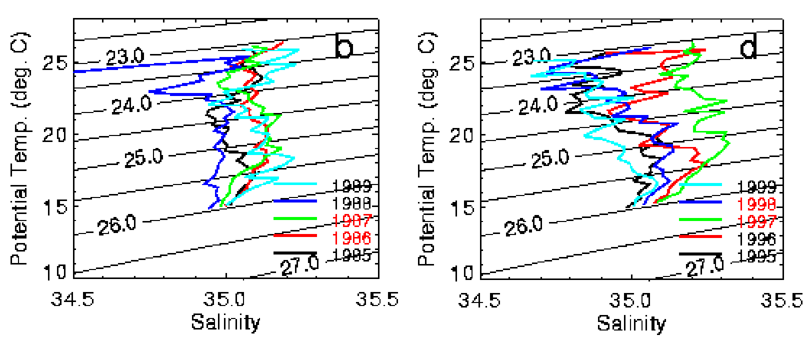

***Figure 4**: Annual mean temperature-salinity relationships from TAO hydrographic observation; (Left) 1985-1989, (Right) 1995-1999. El Niño years are 1986, 1987, 1997, 1998.*

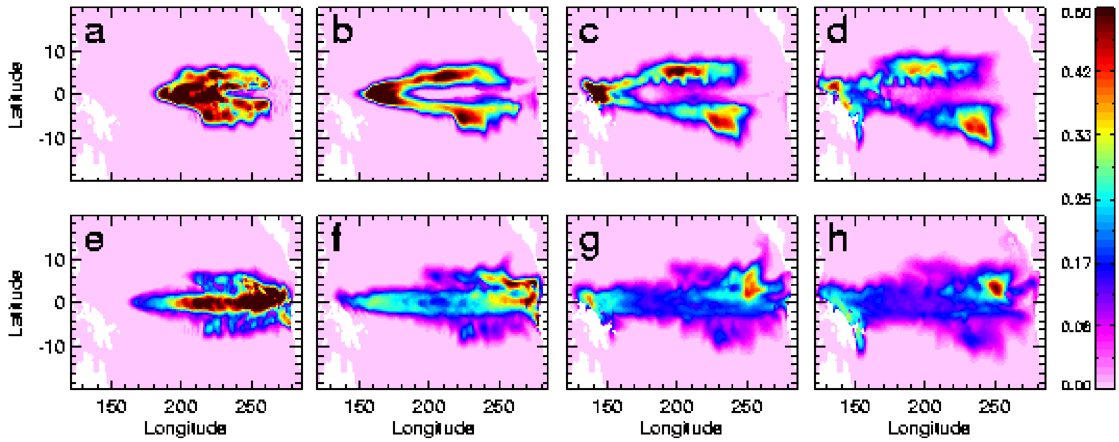

***Figure 5**: Temporal evolution of vertically integrated adjoint tracer distribution (arbitrary tracer unit) released in the pycnocline ($24.5 \leq \sigma_\theta \leq 26$ kg m^{-3}) of the eastern equatorial Pacific (5ºS~5ºN, 150ºW~90ºW) at the end of 1997 (a, b, c, d) and the end of 1996 (e, f, g, h). The former is an El Niño year and the latter is a non-El Niño year. The panels are, from left to right, -3 (a, e), -6, (b, f), -9 (c, g), and -12 (d, h) months from the end of the respective years.*

The sensitivity of carbon uptake in the ocean model as an example of the use of the Lagrange multipliers (adjoint solution) was studied by Hill et al. (2004). Wunsch (2005a,b) has examined the relative roles of mixing and stress in governing model heat budgets. The spherical-cube model and its extension to the atmosphere are described by Adcroft et al. (2004) and Marshall et al. (2004). See the list of publications for further results.

IMPACT AND APPLICATIONS

Economic Development. The investigation will lead to improved 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.

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.

Science Education and Communication: A number of graduate students (S. Yuan, M. Mazloff) and postdoctoral associates (G. Forget, O.Wang, S.Kim) are working on the project. Additional students and post-docs have been supported also both at MIT and SIO on the predecessor project. Our collaborator, Prof. D. Stammer, previously at SIO, and now located at the University of Hamburg, is continuing to work with us, bringing to bear resources and people on the project without direct costs to NOPP.

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