A Consortium For Ocean Circulation And Climate Estimation

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LONG-TERM GOALS

The project aims to advance ocean data assimilation into a quasi-operational tool for studying ocean circulation. Observing the complete state of the ocean is difficult owing to its turbulent nature and to the sparseness and limitation of extant measurements. This project will establish a routine description of the global ocean by optimally combining available observations using a general circulation model, to monitor, to assess, and to understand ocean circulation. The effort further aims to demonstrate the practical utility of ocean observing systems by developing applications of such syntheses.

OBJECTIVES

The project's central technical goal is to establish a complete global ocean state estimation over the 16-plus year period from 1985 to present at 1/4º resolution with complete error descriptions, combining all available large-scale data sets with a state-of-the-art general circulation model. Tools necessary for such synthesis will be advanced, including improvements in models and assimilation techniques, with an emphasis on devising practical solutions in marshaling diverse data sets and large numerical models on a routine basis. The effort will exploit existing and ongoing oceanographic experiments (e.g., WOCE) and satellite missions (e.g., Jason-1) and will support planned experiments including the Climate Variability and Predictability Program (CLIVAR) and the Global Ocean Data Assimilation Experiment (GODAE).

APPROACH AND WORK PLAN

Advanced data assimilation schemes and state-of-the-art numerical ocean general circulation models are employed to analyze global oceanographic observations. The model is based on a parallel version of the MIT ocean general circulation model (Marshall et al., 1997) that exploits massively parallel supercomputers. The present model extends from 80°S to 80°N and employs advanced mixing schemes to best simulate diabatic processes. A hierarchical assimilation system is devised for computational efficiency that consists of a Kalman filter and smoother (KFS), and the adjoint method. The approach is characterized by the physical consistency of its solution's temporal evolution (Stammer et al., 2002; Fukumori, 2003a).

The ECCO activities are performed in three groups located at MIT (J. Marshall and C. Wunsch), JPL (I. Fukumori, L.-L. Fu, T. Lee, D. Menemenlis, and V. Zlotnicki) and SIO (D. Stammer (PI), R. Davis, P. Niiler and Bruce Cornuelle). Each institution has its own task within the entire approach, covering model development, estimation activities, data preparation and scientific analyses. The ongoing ocean state estimations are based on the MIT GCM (Marshall, et al., 1997) and two parallel optimization efforts: MIT and SIO use the adjoint method (Lagrange multipliers or constrained optimization method), exploiting the Tangent-linear and Adjoint Compiler (TAMC) of Giering and Kaminski, (1997) as described in Marotzke et al. (1999), while JPL's focus is primarily on a reduced state Kalman filter, e.g., Fukumori et al., (1999). Those data assimilation activities can be summarized as finding a rigorous solution of the time-varying model state over time that minimizes in a least-squares sense a sum of model-data misfits and deviations from model equations while taking into account the errors in both.

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).

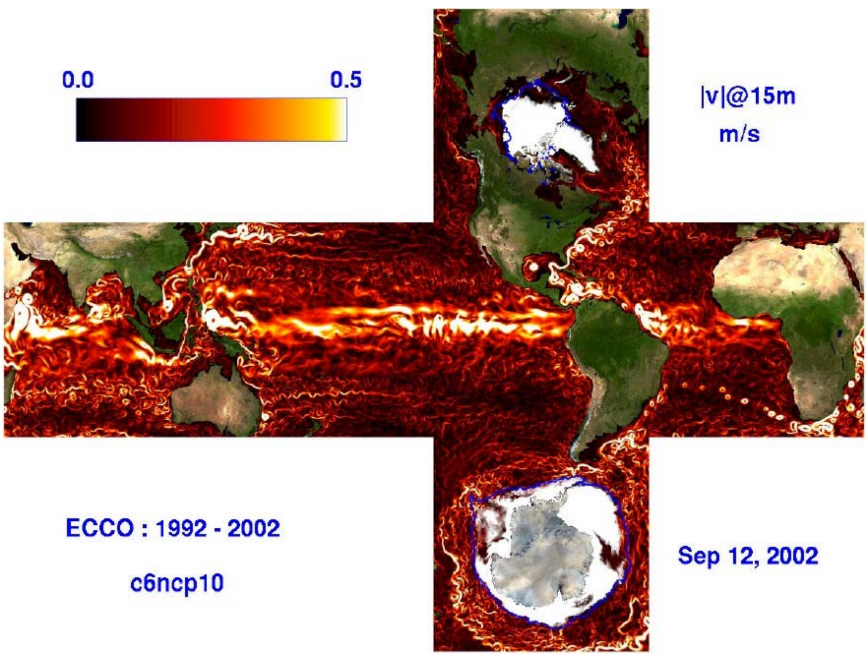

Figure 1: *Cubed-sphere ocean model configuration. The figure shows simulated near-surface (15-m) ocean-current speed and sea-ice cover from a preliminary eddy-permitting integration. Units are m/s. Each face of the cube comprises 510 by 510 grid cells for a mean horizontal grid spacing of 18 km. Simulated 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. 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.)

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 7×10^6 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).

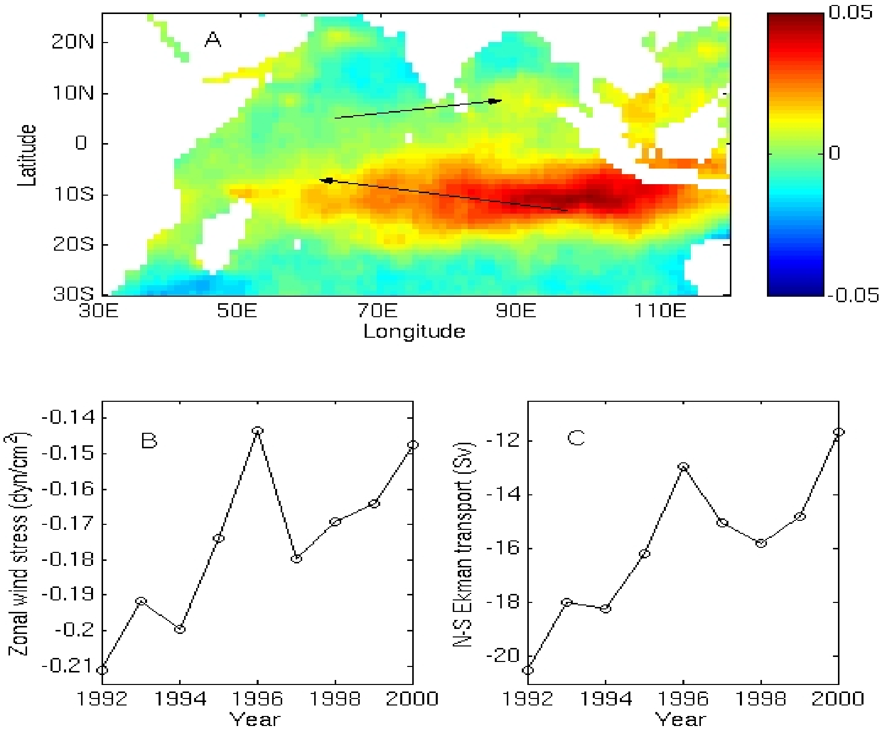

Figure 3*: (A) 1992-2000 linear trend of zonal wind stress in dyn/cm^2/year (positive values indicate weaker easterly wind) estimated from ERS scatterometer. The arrows schematically show the directions of the annual-mean wind. (B) Time series of zonal wind stress averaged over 20º-0ºS. (C) Time series 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 ($24.5 \le \sigma_\theta \le 26$ kg m^{-3}). 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(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.

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.

At SIO, activities by D. Stammer and his group were centered around performing a global ocean data synthesis estimate on a 1 degree spatial grid over the 50-year period 1952 through 2002 using the MIT adjoint model. This run is still ongoing. In parallel new GRACE geoid models were used to test the sensitivity of the estimate to details of the geoid.

IMPACT AND APPLICATIONSIMPACT AND APPLICATIONS

Data assimilation's regular and complete description of the ocean facilitates a wide range of studies in ocean circulation and its applications. This is because it is difficult to make inferences about the ocean continuum from individual measurements without knowledge of the surroundings. Processes controlling the state of the ocean and its evolution can be diagnosed and monitored to help detect and anticipate climate variability. Descriptions of ocean circulation also help understand and quantify the carbon cycle and other biogeochemical processes of the ocean that are affected by advection and mixing (see "TRANSITIONS" below.) Data assimilation contributes to practical applications of oceanography that require complete descriptions of the time evolving flow field and thermal structure such as fishing, shipping, search and rescue, industrial and naval operations, and weather forecasting. Model-data syntheses also help identify sources of model inaccuracies, providing an objective basis for ocean model improvement. Additionally, data assimilation helps in the design of optimal observing systems by quantifying impacts of different observing strategies on the accuracy of the syntheses.

Finally, the assimilation system itself (adjoint and Kalman filter and smoother) provides a versatile tool for other applications. The assimilation system can be employed to assimilate other data types and/or applied to other configurations including regional and biogeochemical studies. The MIT general circulation model can also be converted to an atmosphere model, and thus provide a system for atmospheric and/or coupled ocean-atmosphere data assimilations. Application of the model adjoint to sensitivity studies is an emerging area of investigation that provides new insight into the workings of complex systems.

The impact of the ECCO project is potentially huge because it is pioneering a new way of doing oceanography. We are demonstrating that global ocean models can be meaningfully constrained by global observations to yield an estimate of the state that is better then either model or observations alone. We believe that the methods being explored in ECCO will become widely used in oceanography and change the way we observe and model the ocean.

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

The now available synthesis will be presented at the final WOCE conference, end of 2002 as a major mile stone within the evolution of oceanography. Furthermore it is anticipated that, in two to three years, the project will be able to address the US CLIVAR and GODAE related objective of depicting the time-evolving ocean state with spatial resolution up to ¼ degree globally and in parallel 50-year long reanalysis effort. In addition we will provide regional approaches with substantially higher resolution which are required for quantitative studies of the ocean circulation.

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.)