*The ECCO Report Series* [1]

# The Consortium for Estimating the Circulation and Climate of the Ocean (ECCO)

## — Science Goals and Task Plan —

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# 1 Introduction

In the past two decades, a major world-wide effort has been directed at observing the global ocean. As organized within a number of international programs including the World Ocean Circulation Experiment (WOCE), the Tropical Ocean Global Atmosphere program (TOGA), and the Joint Global Ocean Flux Study (JGOFS) these observations have been intended to make it possible to understand the role of the ocean in climate, in biogeochemical fluxes, the causes of sealevel rise, and a wide variety of other major processes and applications. As a consequence of these, and related programs, we now have continuing global, and near-global observations of the ocean.

Organizers of some of the field programs recognized that a full understanding of the ocean could emerge only by combining these observations with theoretical knowledge of the ocean as represented in large-scale models of the sea. The need is analogous to the capability long-used in meteorology and called "assimilation," where numerical models are joined with data to produce twice-daily or more frequent estimates of the full atmospheric state. The increasingly urgent need for a comparable global-scale oceanographic synthesis is now widely perceived in many areas of oceanography, but particularly acutely in the successor large-scale field programs. These latter include the WOCE synthesis projects, the Climate Variability program (CLIVAR), the Global Ecology Experiment (GLOBEC), the Global Ocean Data Assimilation Experiment (GODAE) and others (Powell, 1998). Producing the capability for such a synthesis, and carrying it out, has proven difficult in part because of technical and scientific challenges, but also because of limited manpower and computational resources.

But with the need to achieve a global oceanographic state estimation capability becoming ever more pressing, a group of scientists at the Massachusetts Institute of Technology, the Jet Propulsion Laboratory, and the Scripps Institution of Oceanography has formed a consortium for "Estimating the Circulation and Climate of the Ocean" (ECCO). This collaboration has been formed under the National Ocean Partnership Program (NOPP) with funding provided from the National Science Foundation, the National Aeronautics and Space Administration, and the Office of Naval Research. The consortium intends to bring ocean state estimation from its current experimental status to that of a practical and quasi-operational tool for studying large-scale ocean dynamics, designing observational strategies, and examining the ocean's role in climate variability. It is the purpose of this document to explain what ECCO is and how it intends to achieve its goals.

# 2 The Underlying Science

Many of the most important of the consequences of the ocean for climate, such as the transports of heat, the uptake of carbon from the atmosphere, and the nature and the varying regions of sealevel rise, are not directly measurable. They are instead inferred from observations of other, related quantities (e.g., velocity) for which instrumentation does exist. Furthermore, the set of observations available of the ocean is extremely diverse, including moored current velocities, temperature and salinity measurements from ships, space-borne observations of sealevel variations, and many other data types. These observations are connectable both to each other, and the desired derived quantities, via the equations of fluid dynamics. For example, the meridional flux of heat in the North Atlantic, an important element of climate, is inferred by combining current meter observations, electrical cable measurements of water transport, satellite altimetric measurements of the seasurface, and meteorological estimates of the windfield, among other data. For understanding the present day climate, the extent to which it is changing, the places in which nutrients are being moved, and a host of other scientific questions, we need systematic syntheses of the observations with our best understanding of the physical principles determing the ocean circulation.

But many of the physical relations governing the fluid are not adequately understood either. One needs methods for testing the existing, very complex numerical models against the observations, in order to determine model accuracy and precision. More generally such testing is required for biogeochemical and other models. Ultimately one needs skilful models to compute scenarios for how the climate will change in the future.

# 3 Methodologies

Over the last decade global ocean circulation models (GCMs) have evolved and improved strikingly in numerous ways (e.g., Semtner and Chervin, 1992; Smith et al., 1992; Marshall et al., 1997a,b). Today, global GCMs have achieved a sufficient degree of realism to render it meaningful to directly compare them to the global observations and to form combinations with those data. Global ocean models exist today with lateral spatial resolutions of $1/10°$, and regional models exist with much higher resolution (limited resolution has always been a major obstacle in ocean models). Over the past 20 years, enough has also been learned about the estimation procedures (see the books by Daley, 1991, Bennett, 1992 and Wunsch, 1996) so that the models and observations can be brought together to give us a description of the ocean that is better than either alone. Combined with the newly available global data base, one has the three elements required for ocean state estimation: models, observations, and algorithms.

The problem of combining dynamical models with observations is a well-known one, and is a highly developed subject under the general rubric of "estimation theory", but is also well known in control theory, and in the special meteorological literature as data "assimilation". Theoretical possibilities for solving the oceanographic problem are quite clear and uncontroversial from a mathematical point of view. The major issues are instead ones of practicality. The equations of fluid dynamics governing the ocean circulation show that the volume of numbers required to accurately depict the ocean at any given moment is immense (larger than $10^6$ or greater). Calculation of the time evolution of the system involves solving the highly non-linear equations of fluid dynamics on a rotating spherical shell of immense geographic complexity in a problem formally too large for the largest existing computers.

Several different methods are known for achieving both a mathematically ideal ("optimum") solution to the problem, and useful approximations to its solution. One method, which initially is intended as our central approach is known as the "adjoint method" in meteorology and oceanography; it is the "Pontryagin Principle" of control theory; more generally, it is the method of Lagrange multipliers. A considerable oceanographic literature has accumulated in the past 10 years (Thacker and Long, 1988; Wunsch, 1988; Tziperman and Thacker, 1989; Marotzke and Wunsch 1993; Malanotte-Rizzoli, 1996; Sirkes and Tziperman, 1997) and there is some experience also, in meteorology (e.g., Errico 1997).

We will only very briefly summarize the elements. Write the GCM in greatly condensed fashion as a time-stepping rule:

$$\mathbf{x}(t+1) = \mathcal{L}(\tilde{\mathbf{x}}(t), \boldsymbol{\tau}, ..., \boldsymbol{\epsilon}) \tag{1}$$

where $\mathbf{x}(t)$ is the model "state vector" (velocity, temperature, salinity, pressure,...) at all model grid points and model time $t$. $\boldsymbol{\tau}$ is the wind field and other boundary conditions, and $\boldsymbol{\epsilon}$ represents model errors of all kinds, unknown internal parameters and errors in boundary condition forcing. $\mathcal{L}$ is the operator which carries the model-state one step forward in time and which in practice is a computer code of many thousands of lines. ECCO employs primarily the MIT GCM of Marshall et al. (1997a,b). The observations can also be written in terms of the state vector, $\mathbf{x}(t)$, generically (assumed linear, however), as

$$\mathbf{y}(t) = \mathbf{E}(t)\,\mathbf{x}(t) + \mathbf{n}(t) \tag{2}$$

where $\mathbf{x}(t)$ now represents the true ocean state, $\mathbf{E}(t)$ is the observation response matrix, and $\mathbf{n}(t)$ is the inevitable observation noise (notation is from Wunsch, 1996).

Most practical assimilation methods are equivalent to finding the least-squares value of a measure of the misfit between observations and the model,

$$J = \sum_t \left[\mathbf{y}(t) - \mathbf{E}(t)\,\tilde{\mathbf{x}}(t)\right]^T \mathbf{W}(t)\left[\mathbf{y}(t) - \mathbf{E}(t)\,\tilde{\mathbf{x}}(t)\right] \tag{3}$$

where $\mathbf{W}$ is a weight matrix, often chosen to be the inverse covariance of $\mathbf{n}(t)$ and $\tilde{\mathbf{x}}$ is the model simulation of the ocean state. In general terms, the assimilation problem is one of optimization: to minimize $J$ subject to Eq. (1) by adjusting model parameters including initial and boundary conditions, mixing coefficients etc., known as "control variables", and lumped into $\boldsymbol{\epsilon}$. Here the adjoint method has proven to be very efficient in providing a way to iteratively solve the above minimization problem. In practice, it is a problem of huge dimension and is intrinsically non-linear. In an ongoing global oceanic estimation experiment (at $1°$ horizontal resolution, 20 vertical levels, and 6 state variables at each grid point), the state vector has about $10^6$ elements at each time step and there are about $10^7$ control variables to be optimally chosen.

The adjoint solution has been made practical through the automatic differentiation compiler of Giering and Kaminski (1999) (see also, Marotzke et al., 1999) which permits generation of the adjoint model code directly from the source code of the GCM (1). Moreover, the coding of the MIT model was designed by C. Hill and A. Adcroft at MIT, so that it would have a tight interface with the Giering and Kaminski (1999) compiler and yet not compromise the ability to efficiently target a wide variety of parallel computers. The resulting forward/adjoint software tool is now very versatile and runs efficiently across a wide range of modern computer architectures.

Alternative methods are also useful. Kalman filters, and related, so-called smoothers, are sequential algorithms for solving the same optimization problem (3) subject to the same model constrained (e.g., Wunsch, 1996, Fukumori and Malanotte-Rizzoli, 1995; Fukumori, et al., 1999). The Kalman filter and smoothers are not iterative, rather they are recursive in time (Wunsch, 1996). Specifically, the filter combines data at each instant (when available) and the state predicted by the model from the previous time step. The result is then integrated in time and the procedure is repeated for the next time-step. Operationally, the Kalman filter is in effect a statistical average of data and model state, weighted according to their respective uncertainties (error covariances). The algorithm guarantees that information of past measurements are all contained within the predicted model state and therefore past data need not be used again. The savings in storage (past data need not be saved) and computation (optimal estimates need not be recomputed from the beginning of the measurements) is an important consideration in real-time estimation and prediction.

The filtered state is optimal with respect to measurements of the past. The smoother additionally uses data that lie formally in the future; because future observations contain information about the past, the smoothed estimates have smaller expected uncertainties than filtered results. In particular, the smoother literally "smooths" the filtered results by employing the future observations.

The computational difficulty of Kalman filtering, and subsequent smoothing, lies in evaluating the error covariances that make up the filter and smoother. The state error evolves in time according to model dynamics and the information gained from the observations. In particular, the dynamical evolution of the error covariance is typically several orders of magnitude more computationally demanding than the forward model.

Because of their great importance, a large literature exists on approximations to the sequential algorithms directed at reducing the computational requirements. These often involve projecting the full state vector onto a reduced sub-set of presumed dominant modes (see Fukumori et al., 1999 and references there).

When correctly formulated, the adjoint method and the filter/smoother algorithms produce identical results for the state vectors and control variables. The adjoint method is computationally more efficient because, as an iterative method, it neither requires nor provides the error covariances of the results. Filter/smoother algorithms, as sequential methods, do demand and thus provide, the error covariances, which are also correct for the adjoint method, up to discrepancies in approximations to one or both of the different methods. In general, however, the two methods are complementary, and both are being pursued within ECCO.

# 4 The Global Effort

The production and evaluation of continuing three-dimensional estimates of the global state of the ocean is our central goal and the foundation of ECCO. The main, and first, task is to bring together a global GCM with existing global data streams — including TOPEX/POSEIDON altimeter observations (see Fu et al., 1994; Wunsch and Stammer, 1998) and *in situ* hydrographic and current measurements (see WOCE ) — to obtain the best possible estimate of the time-evolving ocean circulation and related uncertainties.

Our intermediate technical goal is a complete global-scale ocean state estimate over the 15 year period 1986-2000 at the highest possible resolution along with a complete error description. This encompasses the TOPEX/POSEIDON period (launched in October 1992) and includes most of the WOCE and TOGA data. Although very demanding, this computation is already feasible, in principle, on existing computer resources, but will require the planned NOPP "hub" to realize it.

To develop the technical understanding required to incorporate all available data types, develop associated error covariances, and to continue to improve models in support of the global estimate, we begin with coarser-resolution global and basin-wide models. This approach will also permit us to develop near-real time capabilities in support of community needs.

Preliminary results are described by Stammer, et al. (1997), who carried out a feasibility calculation with data restricted to one year, using the MIT GCM and its adjoint model. We now have under way a global adjoint estimation covering a full 6-year span and using a more complete representation of model physics (see Stammer et al., 1999). Improvements include an increased model resolution to 1°, an extended estimation period to 6 years (1993 through 1997), as well as more accurate representations of straits and sills in the topography. Equally important, a complete mixed layer model (Large et al., 1994) and an eddy parameterization (Gent and McWilliams, 1990) have been incorporated into the forward and adjoint model.

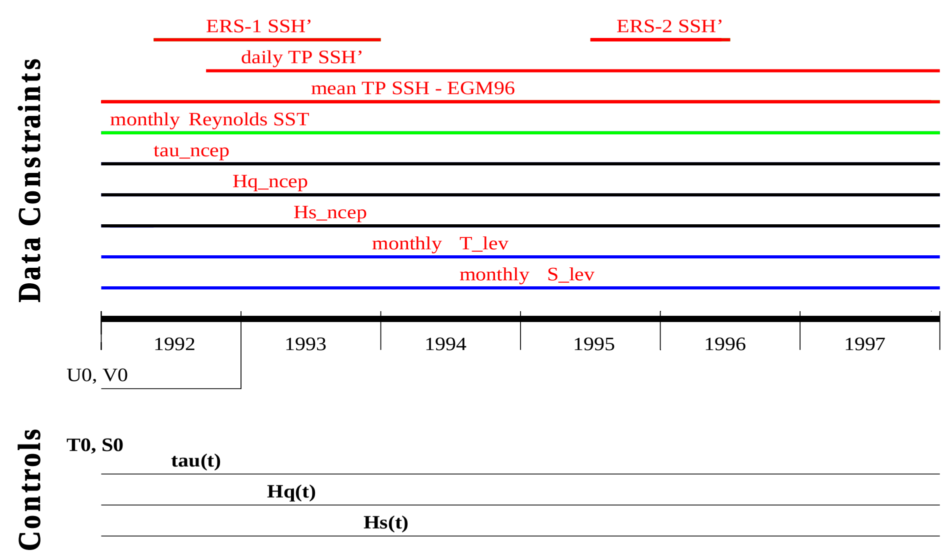



Figure 1: Schematic of the ongoing optimization. The upper part of the figures shows the data constraints and their distribution in time. The lower part shows the "control" parameters (initial $T$ and $S$ fields and the time-varying surface forcing: wind stress, heat and fresh water fluxes) which are adjusted to bring the model into consistency with the data.

The data which are being used to constrain the model (see Fig. 1) include the absolute and time-varying T/P data (relative to the EGM-96 geoid model; see Lemoine et al., 1997) from October 1992 through December 1997, SSH anomalies from the ERS-1 and ERS-2 satellites, monthly mean SST data (Reynolds and Smith, 1994), and the twice-daily time-varying NCEP Re-Analysis fluxes of momentum, heat and freshwater. In addition, monthly means of the model state are required to remain within assigned bounds of the monthly-mean Levitus et al. (1994) climatology, and NSCAT estimates of wind stress errors (D. Chelton, personal communication, 1997) are being employed. At the moment, all error covariance matrices $\mathbf{W}_j$ are diagonal with the important exception of the $\mathbf{W}_{EGM96}$ matrix for the mean sea surface height which is fully non-diagonal and dense and is identical to the EGM96 error covariance matrix to degree and order 70.

Formally this leads to the following cost function:

$$
\begin{aligned}
J \;=\; & \frac{1}{2}[(\overline{\boldsymbol{\eta}} - \overline{\boldsymbol{\eta}}_{tp})^T \mathbf{W}_{geoid}(\overline{\boldsymbol{\eta}} - \overline{\boldsymbol{\eta}}_{tp}) \\
& + (\boldsymbol{\eta}' - \boldsymbol{\eta}'_{tp})^T \mathbf{W}_{\boldsymbol{\eta}}(\boldsymbol{\eta}' - \boldsymbol{\eta}'_{tp}) + (\boldsymbol{\eta}' - \boldsymbol{\eta}'_{ers})^T \mathbf{W}_{\boldsymbol{\eta}}(\boldsymbol{\eta}' - \boldsymbol{\eta}'_{ers}) \\
& + (\boldsymbol{\delta\tau}_x)^T \mathbf{W}_{\boldsymbol{\tau}_x}(\boldsymbol{\delta\tau}_x) + (\boldsymbol{\delta\tau}_y)^T \mathbf{W}_{\boldsymbol{\tau}_y}(\boldsymbol{\delta\tau}_y) + (\delta\mathbf{H}_Q)^T \mathbf{W}_{H_Q}(\delta\mathbf{H}_Q) \\
& + (\delta\mathbf{H}_F)^T \mathbf{W}_{H_F}(\delta\mathbf{H}_F) + (\delta\mathbf{T}_0)^T \mathbf{W}_T(\delta\mathbf{T}_0) + (\delta\mathbf{S}_0)^T \mathbf{W}_S(\delta\mathbf{S}_0) \\
& + \sum_i (\overline{\mathbf{T}_{\mathbf{1}i}} - \overline{\mathbf{T}}_{iSST})^T \mathbf{W}_T(\overline{\mathbf{T}_{\mathbf{1}i}} - \overline{\mathbf{T}_{\mathbf{SST}i}}) \\
& + \sum_i (\overline{\mathbf{T}}_i - \overline{\mathbf{T}_{\mathbf{Lev}i}})^T \mathbf{W}_T(\overline{\mathbf{T}}_i - \overline{\mathbf{T}_{\mathbf{Lev}i}}) \\
& + \sum_i (\overline{\mathbf{S}}_i - \overline{\mathbf{S}_{\mathbf{Lev}i}})^T \mathbf{W}_S(\overline{\mathbf{S}}_i - \overline{\mathbf{S}_{\mathbf{Lev}i}})],
\end{aligned}
\tag{4}
$$

Here $\eta$, $\eta_{tp}$ and $\eta_{ers}$ denote the sea surface height in the model, and as measured by TOPEX/POSEIDON and the ERS satellites, respectively. Primed quantities are deviations from a time mean which is denoted by the overbar. The fields $\delta\tau_x$, $\delta\tau_y$, $\delta H_Q$, $\delta H_f$, $\delta T_0$ and $\delta S_0$ denote changes in the wind stress fields, net heat flux, net fresh water flux and the initial T and S fields, respectively. $T_{1i}$ and $T_{iSST}$ stand for the model temperature in the top layer and SST observations, respectively and the last two sums represent the difference between monthly mean model and Levitus T and S fields.

Reduction of $J$ to a statistically acceptable value and form while maintaining the values as solutions to the GCM is the central computational goal. The global adjoint estimate that emerges will serve as a starting point for ECCO. Results thus far show that the envisioned synthesis can be fully realized. Many of the results from the ongoing computation can be seen on the Website http://puddle.mit.edu/˜detlef/OSE/global.html. To give a feeling for what can be done now, Figs. 2 through 5 show selected results after a considerable reduction in the model-data misfit, but before reaching a fully optimized state (the calculation is still progressing).

In Fig. 2 we show the changes to the time-mean zonal winds tress $\tau_x$ and surface heat flux $H_q$ required to minimize model-data differences over the 6-year long assimilation period, after 40 iterations (and is the same for all following figures). These and similar changes in meridional wind stress and freshwater flux will be used to understand and improve uncertainties in meteorological forcing fields after a fully optimized solution has been obtained.

The mean sea surface height (in cm) of the constrained model is shown in Fig. 3. All major circulation features are visible in the figure, although represented by fairly smooth structures due to the coarse model resolution. Associated with the sea surface height field is a time-varying model circulation that can be applied to various scientific problems. The figure shows in its lower panel float trajectories simulated by those velocity fields of the constrained model over the 6-year period. The floats were released in the model at the location and at the time they have been deployed in the real ocean. Our goal is ultimately to include float data in the estimation procedure, and the first step toward this goal is to compare our simulation with the real trajectories.

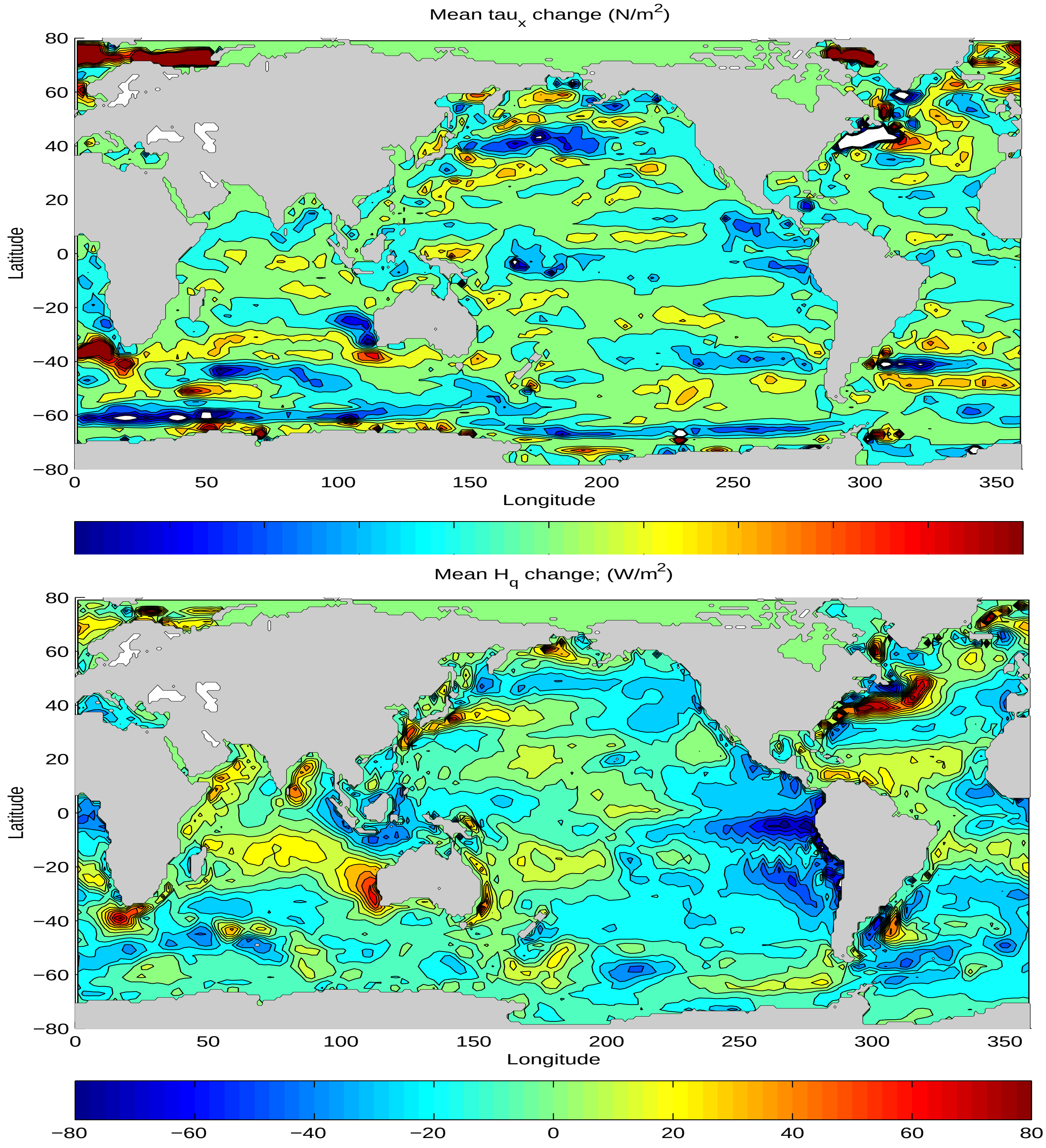
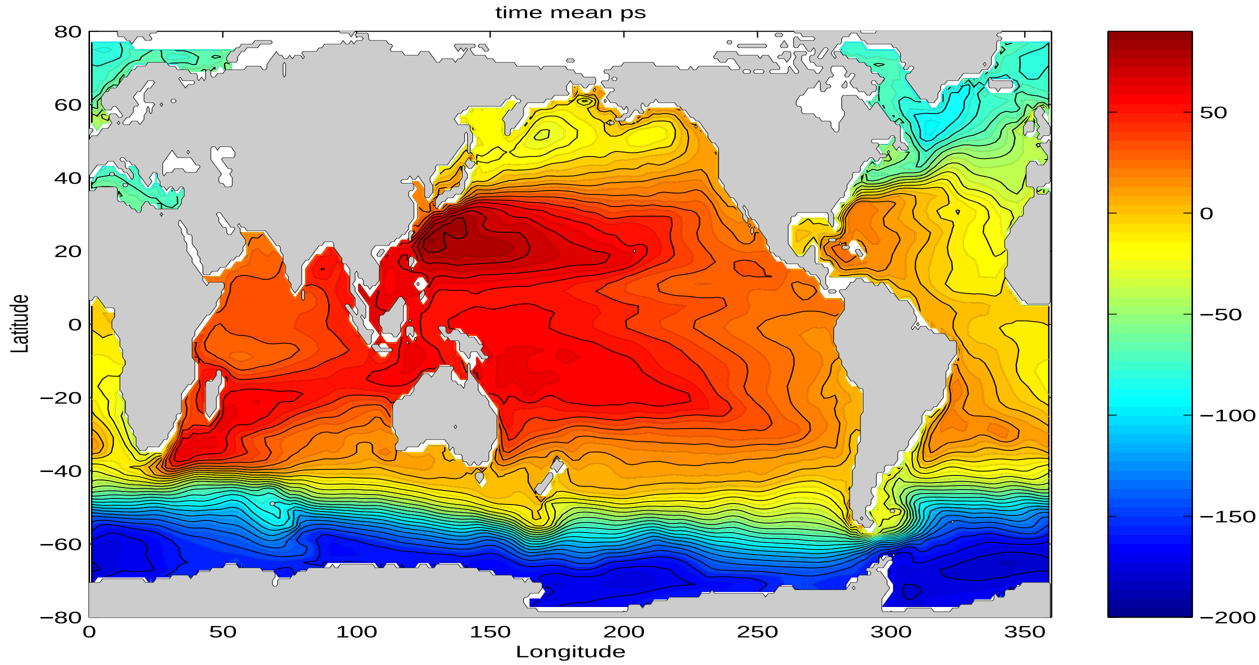



Figure 2: Changes to the time-mean zonal winds tress $\tau_x$ and surface heat flux $H_q$ required to minimize model-data differences over the 6-year long assimilation period, after 40 iterations (the same for all following figures). These and similar changes in meridional wind stress and and freshwater flux will be used to understand and improve uncertainties in meteorological forcing fields after a fully optimized solution has been obtained.



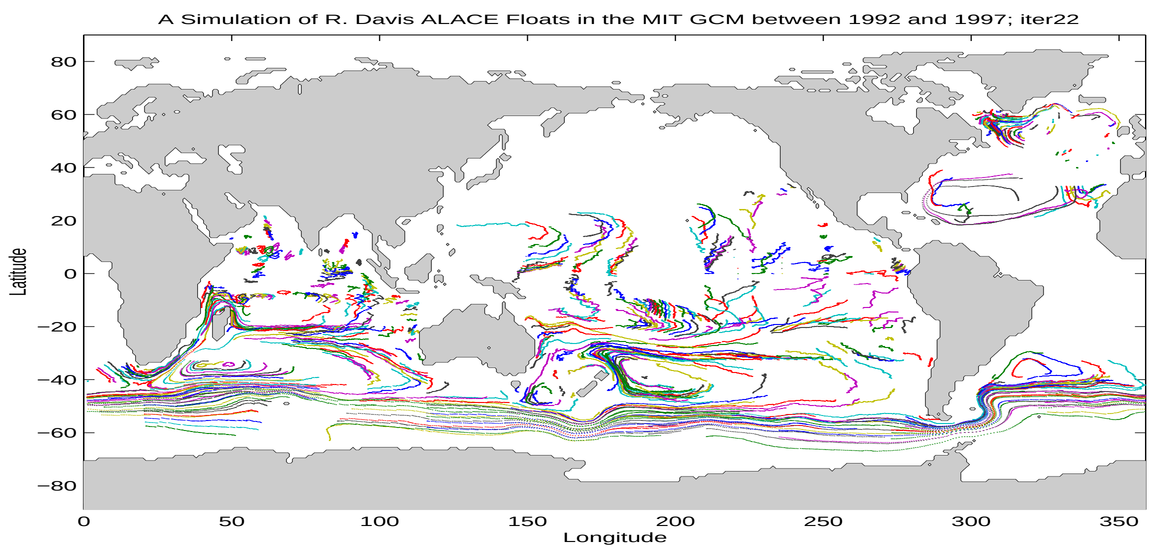




Figure 3: (top) Mean sea surface height (in cm) of the constrained model. (bottom) Float trajectories simulated by the constrained model over the 6-year period. They are now being compared with WOCE PALACE trajectories prior to their use in the state estimation (e.g., Davis, 1998).

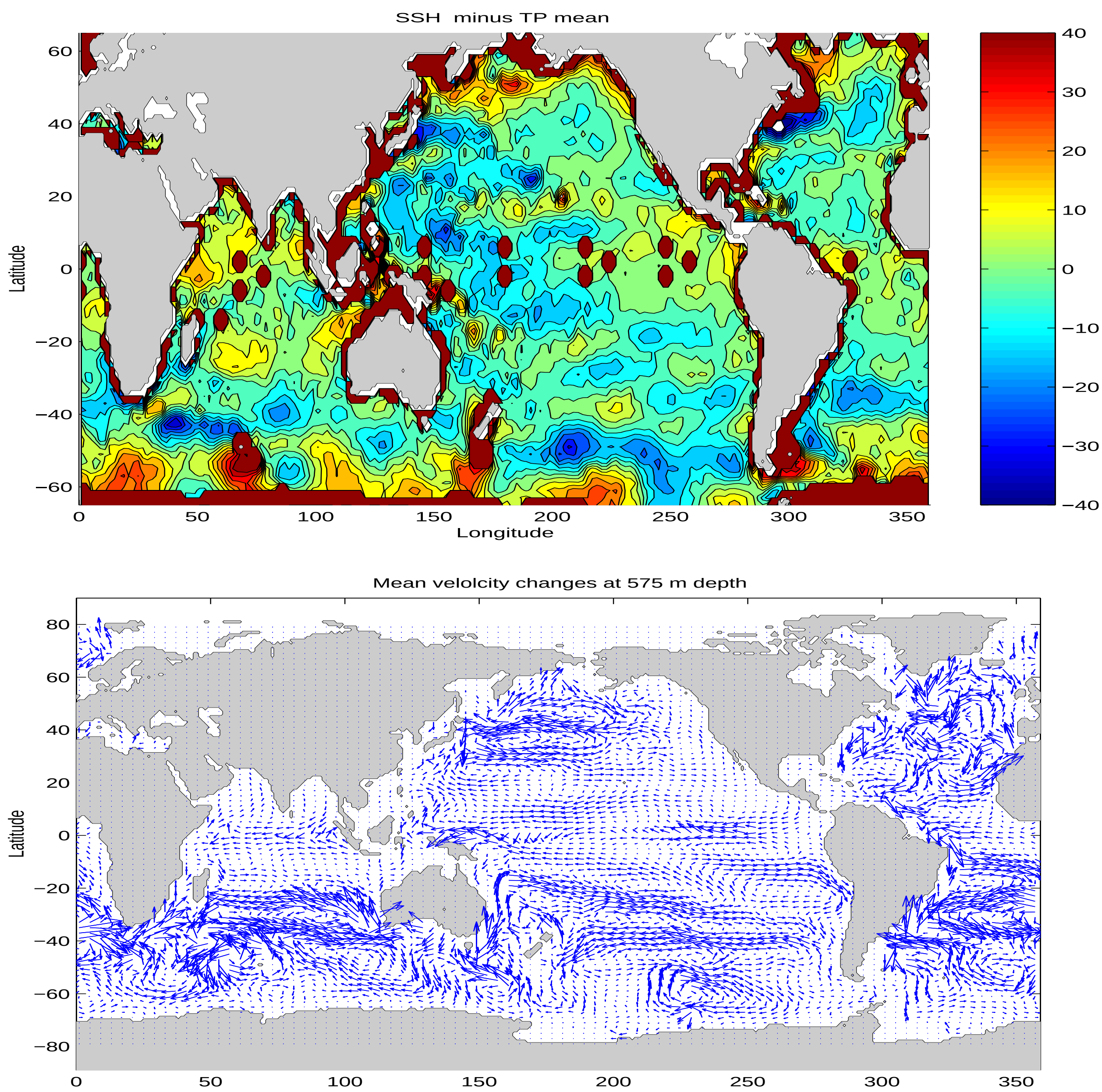



Figure 4: (Top) The model-data misfit of absolute sea surface height (in cm). There is a close correlation of the residuals with independent information about the error of the EGM96 geoid model. (Bottom) The difference between the first-guess mean flow field at 575 m depth and that obtained from the constrained model. Maximum amplitudes are about 1.2 cm/s, or a full 30% of the mean.

In Fig. 4 we display the model-data misfit of absolute sea surface height (in cm). These residuals closely resemble previously-estimated errors of the EGM96 geoid model. One of our goals is to apply the inferred mean sea surface height field to produce an improved marine geoid model.

The difference between the first-guess mean flow field at 575 m depth and that obtained from the constrained model is shown in the lower panel of Fig. 4. Maximum amplitudes are about 1.2 cm/s, or a full 30% of the mean. It can be anticipated that these and similar changes in the stratification will have a substantial impact on the ocean transport properties.

Estimates of zonally integrated heat transport are shown in Fig. 5 from the latitudes 36°N (top) and 25°N (middle pannel). The convergence of zonally integrated heat transport estimates between those latitudes is ishown in the bottom panel. There is a significant amount of high-frequency variations superimposed on the seasonal and inter-annual variability. This variability needs to be analyzed in terms of its relation to (local and remote) air-sea interactions, heat storage and, ultimately, its climate implications.

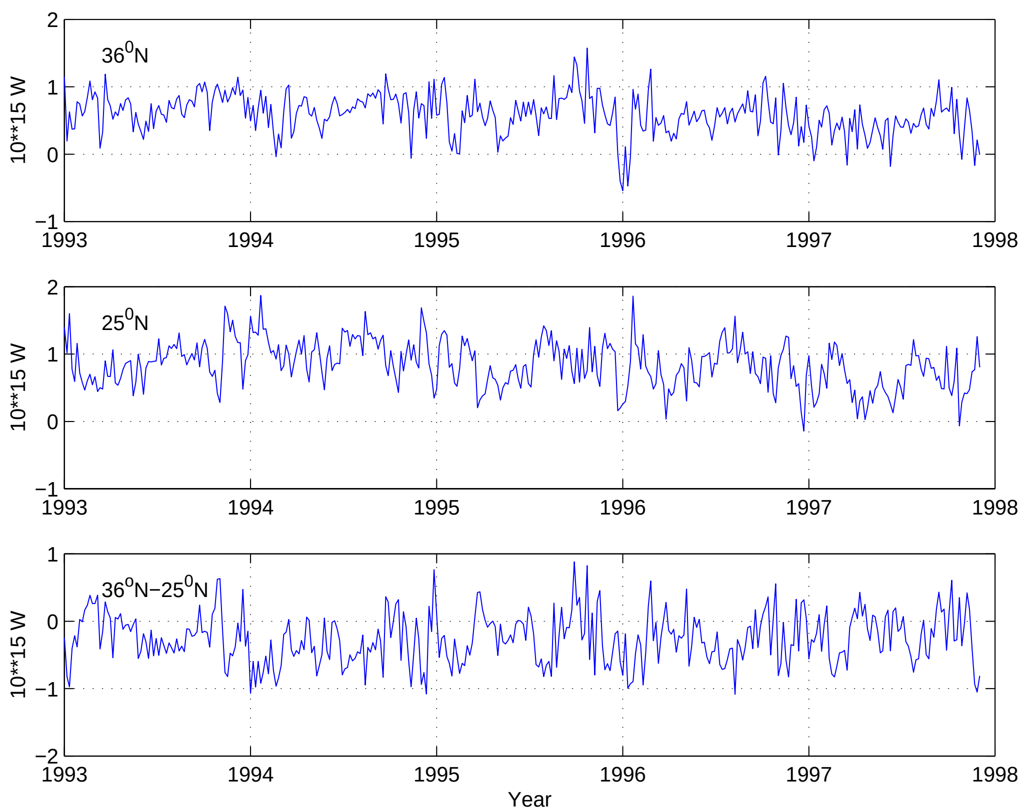



Figure 5: Estimates of zonally integrated heat transport computed for the latitudes 36°N (top) and 25°N (middle pannel). The convergence of zonally integrated heat transport estimates between those latitudes is ishown in the bottom panel.

Many of our global science foci are related to the large-scale ocean variability, and associated

interaction of the ocean with the atmosphere. Accordingly phenomenological studies on basin to global scale will include the calculation of meridional fluxes and flux divergences of heat, fresh water, carbon, and nutrients so as to determine the basic oceanic climate state and its interaction with the atmosphere. Key elements here are:
(1) Heat and freshwater balance in the upper tropical and sub-tropical Pacific and Atlantic Oceans including the relative contributions of upwelling and subduction, horizontal advection, mixing, air-sea exchange, and local storage;
(2) Tropical-subtropical exchange and mid-latitude subduction including temporal variability and north/south asymmetry of the western boundary current, how water is subducted in the subtropical oceans, its subsequent path, and how its properties are changed;
(3) Decadal variability throughout the tropical and higher-latitude oceans, including circulation in the subtropical gyre, Ekman pumping, mixed layer processes, and Ekman transport.

Our estimated state is constrained by ocean observations; this however, does not guarantee that the state estimate will agree or be fully consistent with the observed ocean state. Disagreements may indicate model errors, inappropriate *a priori* assumptions about error covariance matrices or mistaken interpretations of the data. Reconciliation of the estimated state with observational descriptions is therefore an important element in the estimation procedure and requires full community involvement. We will therefore carry out careful comparisons of the state estimates with selected data sets (see below). Comparisons of model and data will be both statistical (i.e., rms misfits of dynamically significant variables, and associated spectra) descriptive, and phenomenological.

The above-mentioned calculations are now possible and are being made routinely and continually improved (as numerical weather analyses have improved over time), and many facets of oceanography - regional and coastal applications, physical-biological and bio-geochemical modeling, air-sea interaction, theory and models of the general circulation of the ocean - and indeed fields outside of oceanography, such as geodesy, are beginning to rely upon the resulting products.

An example of a specifically oceanographic application is the off-line use (M. Follows, personal communication, 1998) in transient tracer and biogeochemical (oxygen, carbon) models. A quite different application, somewhat outside the realm of oceanography, is understanding the changes in earth's rotation and polar motion owing to fluctuations in ocean circulation (Ponte et al., 1998; Ponte and Stammer, 1999). It has already been demonstrated that our present estimate of ocean topography, if used to compute a marine geoid by subtracting it as the ocean component from mean altimetric sea surface height observations, often improves computed satellite orbits relative to those obtained with conventional geoid models (N. Pavlis, personal communication, 1998).

# 5 Regional Foci

Embedded within our overall global effort, there are two major regional foci to support CLIVAR Basin-wide Extended Climate Studies (BECS) in the Atlantic (Atlantic Climate Variability Experiment; ACVE) and in the Pacific (Pacific Basin-wide Extended Climate Study; P-BECS). CLIVAR (CLIVAR, 1998) is concerned with seasonal to decadal phenomena like ENSO, the Pacific Decadal Oscillation, the North Atlantic Oscillation, the tropical Atlantic variability of SST and its associated atmospheric pattern. These are large-scale, recurrent patterns of variability that involve the ocean and influence continental climate. CLIVAR recognized that the emerging ability of ocean state estimation makes it feasible to diagnose processes inside a dynamical model that was constrained by feasible large-scale observations.The community has begun to plan a BECS for the North Atlantic and Pacifc.

ECCO plans to develop the modeling and state estimation capabilities required for the upcoming BECSs to reach their goals. This demands the use of higher spatial resolution than is feasible with a global model. The many scientific and practical commonalities between global and regional assimilation studies, and between the Atlantic and Pacific BECS themselves, make it desirable to approach their more operational and technical aspects together. Commonalities include scientific questions (e.g., tropical-subtropical interaction through shallow overturning circulations, variations in upper ocean mixing and entrainment, variations of boundary current transports and locations), observing networks and data links, model improvements, as well as many questions related to state estimation.

Our strategy for the regional foci is to embed the models of the Atlantic and the Pacific into the global, but coarser-resolution, ocean state estimate, thus using the global solution to provide first-guess boundary conditions that subsequently are further modified as part of the regional optimization. As described below, the resolution in the regional approaches will be increased towards the equator and possibly towards the eastern and western boundaries. At the same time the resolution will also be enhanced in the vertical, e.g., to allow a more appropriate estimate of shallow ocean phenomena involved in the tropical-subtropical interaction in low latitudes. The ultimate goal of the global work is ocean state estimation with at least eddy-permitting resolution. Our experience with eddy-resolving state estimation is rudimentary and we propose to gain insight into this first on a regional scale in the Atlantic and Pacific areas. Experience from those regional approaches will subsequently be built into the global estimation.

*The Atlantic*

Climate Variability (CLIVAR) of the Atlantic sector comprises three primary phenomena: Tropical Atlantic Variability (TAV), The North Atlantic Oscillation (NAO) and Atlantic Meridional Overturning Circulation (MOC). A sustained, Atlantic-wide observing system is being planned - The Atlantic Climate Variability Experiment (ACVE) - to provide the data necessary to test proposed hypotheses and to test models in the framework of CLIVAR (Visbeck, Stammer, Tool, et al., 1998)[2]

The existing and planned programs in the Atlantic basin: the PIRATA (Pilot Research Moored Array in the Tropical Atlantic) program, the PALACE float and XBT arrays, tide gauges, surface drifters (as part of WOCE) and atmospheric soundings provide the context for our state estimation efforts in the Atlantic. A number of consortia of PIs has been deeply involved in the planning of ACVE and the execution of recent major sea-going experiments in the Atlantic - ACCE and the Labrador Sea Deep Convection Experiment (Lab Sea Group, 1998).

The objective of our state estimate will be (1) to arrive at the best possible description of the evolving Atlantic Ocean during the WOCE period, augmented by data from regional process studies such as the Labrador Sea Experiment, (2) to evaluate this description against available surface and subsurface observations, with particular attention to poorly understood phenomena such

[2]See http://www.ldeo.columbia.edu/~visbeck/acve/.

as the development, propagation, and decay of heat content and salinity anomalies, subtropical-tropical interaction, and to basic features such as the distribution of principal water masses, (3) to interpret the analysis in terms of theories of subduction, convection, and thermocline ventilation, (4) and to use it as a vehicle for planning and refining ACVE.

To make a start on the problem, the MIT forward/adjoint model has already been configured in the Atlantic, extending from 35°S to 80°N. This model has a resolution of 1° decreasing to 1/3° in the tropical band. The necessary open ocean boundary conditions at the southern and northeastern boundaries have been implemented as described by Zhang and Marotzke (1999) with the initial estimate of the boundary values taken from the global model estimates and then refined as part of the optimization procedure. This code is prototypical of the regional model in the Pacific that will also be embedded in the global estimates. We plan to push the resolution down to 1/6° as soon as is practical.

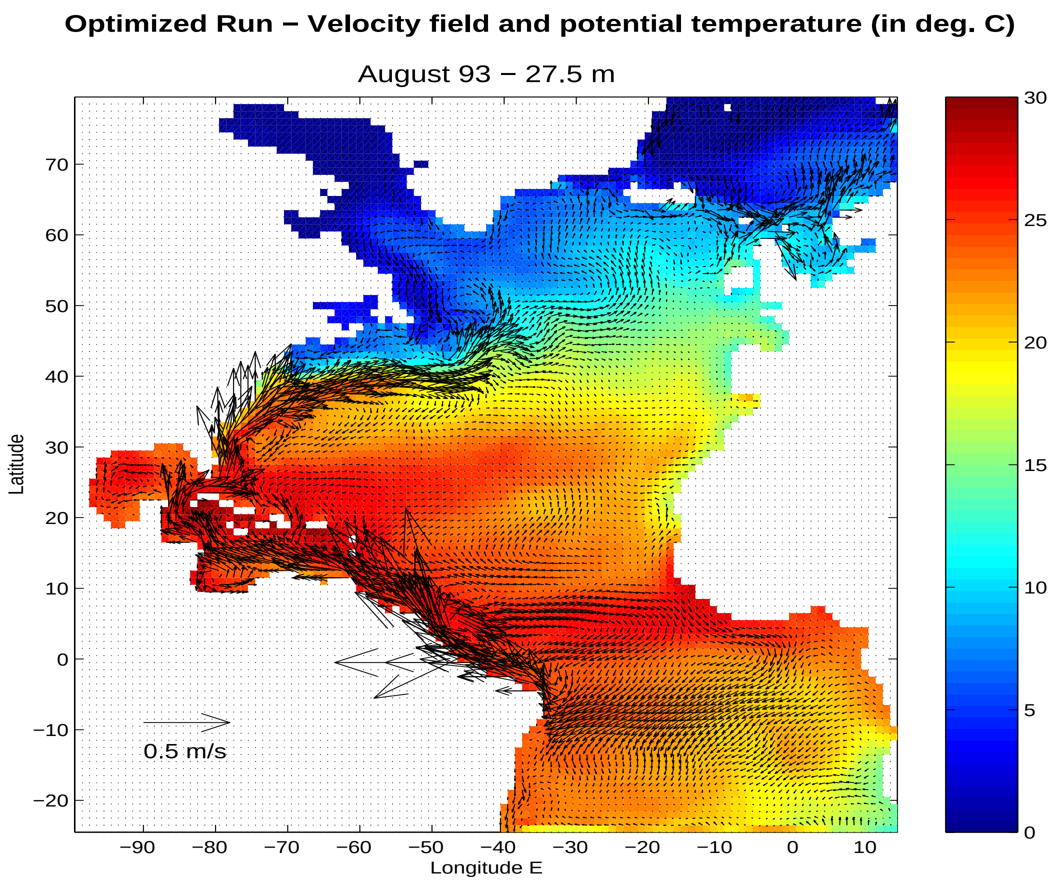



Figure 6: Mean Agust velocity and potential temperature field at 27.5 meter depth in the Atlatic model version. The fields represent a partially optimized model solution (N. Ayoub, pers. communication, 1999) which in addition to the initial T and S fields and the time-varying forcing fields it northeastern and southern boundary conditions as part of the control vector.

*The Pacific:*

The other planned CLIVAR BECS in the Pacific is described in Lukas et al. (1998)[3]. A central focus will be on El Niño/Southern Oscillation (ENSO), its decadal modulation, and decadal variability such as the Pacific Decadal Oscillation (PDO). ENSO is the strongest seasonal-to-interannual variability signal and affects many regions around the globe. ENSO theories which invoke adiabatic oceanic wave propagation along the equatorial wave guide are helpful in understanding the dominant characteristics of ENSO but do not provide a complete picture of how ENSO develops. Even in wave-like models, parameterized diabatic processes are central to the formation of ocean thermal anomalies involved in the ENSO cycle. Diabatic processes involved in the exchange of subtropical and tropical thermocline waters are suspected of modulating, on decadal time scales, the evolution and predictability of ENSO cycle. Diabatic processes appear also to be at the heart of the air-sea coupling associated with the PDO. The several suggested mechanisms of PDO include ocean processes like variation of circulation in the subtropical gyre, trans-basin Rossby waves, wind-driven mixed layer entrainment and the same kinds of subtropical-tropical interactions that may affect ENSO.

The Pacific BECS is intended to add to the Pacific observational network enough data that an ocean model can indeed be constrained and the questions of mechanism in ENSO, decadal modulation of ENSO, and in the PDO can be explored inside the estimated state. There are ongoing efforts to model the Pacific Basin, while working with all of the available data types. As in the Atlantic, adjoint solutions will also be employed in the Pacific to determine the sensitivity of stratification in the equatorial Pacific to both local and remote subtropical forcing. In particular, dynamical and advective pathways can be determined, thus addressing the question of whether the equatorial Pacific stratification is more strongly influenced by the North Pacific or the South Pacific. Interaction with the many other groups studying ENSO and related phenomena is expected here.

*Sensitivity Studies:*

The solution of the adjoint model provides more than just a minimization procedure, for the adjoint variables themselves carry important information about dynamics related, for example, to the adjustment of the ocean to changing atmospheric boundary conditions. The adjoint model can therefore also be used to calculate the sensitivities of key dynamical or climate variables (e.g., meridional overturning strength at certain locations, maximum meridional heat transport, SST, stratification), to the forcing or to quantities that are more readily observable. One example is given by Marotzke et al. (1999) who calculated the sensitivity of the 1993 annual-mean Atlantic heat transport at 29°N to variations in the hydrographic conditions on 1 January 1993 and to variations in wind stress. This computation which is illustrated in Fig. 7 must be considered highly preliminary since it is based on the relatively crude global assimilation solution of Stammer et al. (1997), but it demonstrates the potential of adjoint sensitivity calculations to elucidate dynamical pathways and to determine where and which specific type of observations are mostly needed to constrain climatically important estimates.

[3]See http://www.soest.hawaii.edu/~rlukas/PBECS/pbecs.html.

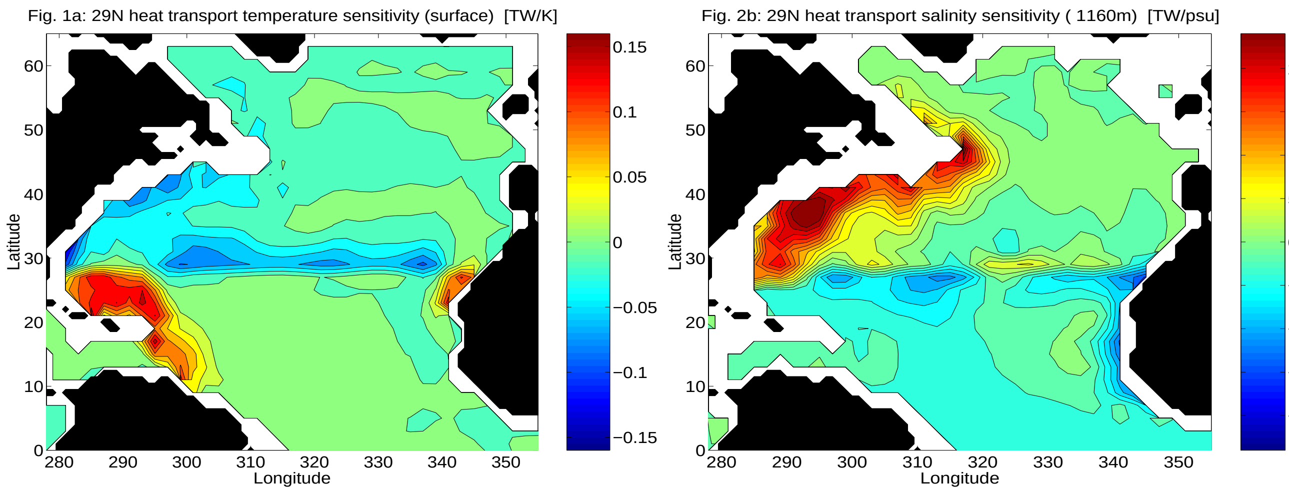



Figure 7: (a) Sensitivity of Atlantic heat transport across 29° N (1993 mean), to surface temperature on 1 January 1993. The contour interval is 0.02 x $10^{12}$ W/K. ( b) Sensitivity of Atlantic heat transport across 29° N (1993 mean), to salinity at 1160m depth, on January 1993. Contour interval is 0.02 x $10^{12}$ W/psu. See Marotzke et al. (1999) for details.

# 6 Consortium Tasks

*Observations:*
Many of the model subcomponents, the inverse error covariance estimates $\mathbf{W}$, and optimization methods are regarded as preliminary and part of the proposed work is to bring all of them to a more operational level. *A posteriori* errors will be used to evaluate and possibly revise *a priori* data and model error covariances used in the estimation procedure.

Although we have experience in the assimilation of a wide variety of data types (see listing above), a goal is to accommodate the entirety of the oceanic observation set including the suite of *in situ* hydrographic and current observations, to the extent that observations are (a) overlapping with our estimation period, and (b) more than purely regional. Bringing in a new data type is a two-step process: first one simply compares the existing state estimates with the new data (this is essentially a comparison of $\mathbf{y}(t)$ in (2) with $\mathbf{E}(t)\,\tilde{\mathbf{x}}(t)$ where $\tilde{\mathbf{x}}(t)$ is the *estimated* (modeled) ocean state (as distinguished from the real one). Given some understanding of the uncertainty of $\tilde{\mathbf{x}}(t)$ (see below), and of the noise in $\mathbf{y}(t)$ (specified by a covariance for the noise, $\mathbf{n}(t)$) one must decide if there is a basic consistency between the model and data already being used, and the new data. Assuming statistical consistency has been found, one can turn to using the new observations to make an improved estimate.

The data to be dealt with next include (not in priority order) autonomous float velocity and profile data (becoming ARGO; see Argo Science Team, 1998); the WOCE hydrographic lines (not as climatologies); current meter data (especially the TAO array); XBTs; satellite sea surface temperature; and the forthcoming GRACE mission time-dependent gravity data (Hughes et al., 1999). Note that tomographic data have already been used (Menemenlis et al., 1996; The ATOC

Consortium, 1998) in regional assimilations. An example of a first comparison is illustrated in Fig. 4b, which shows the computed float trajectories for comparison with the WOCE results (e.g., Davis, 1998).

Some of these new data types should be comparatively straightforward to use, being just variations on data already in-hand (e.g., the GRACE data, the floats if used as Eulerian values, etc.). Others raise potential difficulties (the floats if used in trajectory form; the hydrography because of the very long baroclinic and mixing adjustment times of the ocean). Some thought has been given to these latter problems. For example, for the hydrography, large-scale baroclinic adjustment EOFs or equivalent long range covariances, can be used to "short-circuit" the long adjustment times. To fully understand the hydrographic adjustment problem, we propose to use the fully implicit LSG model (Max-Planck Institut für Meteorologie, Hamburg, MPI) which allows 500 to 1000 year runs by using a one-month time step to understand the long adjustment processes of the ocean interior to varying surface forcing. This work will reside primarily with our MPI partners. Estimated space and time scales of the variations in $T$ and $S$ can be used subsequently as hydrographic weighting factors in the global assimilation.

*Model Development*

GCMs continue to evolve and we will continue to make improvements to ours, particularly insofar as serious model/data combinations always turn up model problems, which become more subtle as time goes on. Responsibility for the model will remain with Marshall's group at MIT.

The MIT model, as a new code, has several features of particular interest to us:

1) The kernel algorithm and code was designed to exploit parallel computing technologies (Hill and Shaw, 1995; Shaw et al.; 1998).

2) It is algorithmically advanced, incorporating innovations from the wider ocean modeling community, such as an implicit free-surface methods (Dukovicz and Smith, 1994) and efficient preconditioners (Dukowicz et al., 1993), a mixed layer formulation KPP (Large et al., 1994) and interior mixing algorithms GM (Gent and McWilliams, 1990). Local innovations include finite-volume and shaved-cell representations of topography (Adcroft et al, 1997); a new treatment of the Coriolis force on the staggered grid (Adcroft et al., 1999); spatially variable eddy-transfer coefficients (Visbeck et al., 1997); parametric representations of convection (Marshall and Schott, 1999); and a non-hydrostatic capability is available.

3) It relaxes some conventional assumptions made in the hydrostatic primitive equations: hydrostatic, quasi-hydrostatic and non-hydrostatic versions are available, allowing it to be applied to coastal and small-scale process studies (Marshall et al., 1998).

Our initial emphasis on improvements will be in accord with the emerging views of the community, as expressed, for example, in Gent (1998) and Stammer et al. (1998):

(a) Allowing background eddy-transfer coefficients to be functions of space to capture stirring by spatially non-uniform geostrophic eddies—simple ideas have been put forward and implemented by our group in (Visbeck et al., 1997). But their performance needs to be evaluated against global data sets in the context of the model-data synthesis.

(b) Evaluation, in the light of the observations, of the KPP upper boundary layer mixing scheme and its interaction with ice models, eddy-parameterization schemes and performance in key regions of deep convection and water-mass transformation.

(c) Improvements of the bottom boundary layer of the code - e.g. Beckman and Döscher (1997)

- exploiting our partial bottom cell scheme Adcroft et al. (1997), to permit conservation of T/S properties of water masses flowing over topography.
(d) Improved resolution, either through spatially-non-uniform gridding methods or increased computational power.
(e) Use of a generalized vertical coordinate to exploit the best properties of height-coordinates (near the surface), isentropic coordinates (in the interior) and sigma coordinates (near the bottom).

*Model Configuration*
Our final goal is a global ocean state estimation with a resolution of about $1/4^\circ$, horizontally. However, the first step is to increase our current resolution, to span a longer time period and to encompass the data types outlined above. For that purpose we propose to carry out the global estimation on a grid with $1^\circ$ nominal spacing between $\pm 22^\circ$ and $\pm 80^\circ$ in latitude, telescoping down to $0.3^\circ$ meridionally near the equator. This set-up is now being used at JPL and includes high-end physical parameterizations of the mixed-layer and subgrid-scale eddy processes. This resolution and model domain are believed to be a minimum required to address many of our scientific objectives. Higher-resolution regional experiments will be carried out to gain experience with eddy-permitting resolution in support of regional studies. Regional approaches are also required with varying spatial resolution for many practical purposes, e.g., to test new data types, *a priori* statistical assumptions or new model components.

*Computational Efficiency and Resources*
Limited computer power is a major obstacle to routine production of (say) daily estimates of the three-dimensional flow field consistent with all of the above observations. An ocean modeling "hub" was called for in Powell (1998) and is envisioned in the NOPP announcement. In the meantime, until an adequate NOPP hub is in place, we will require all of the computational resources available to us at SDSC, JPL, and anywhere else; and we will also help to bring a hub into being. At the present time, the global calculation is running on the NPACI CRAY T90 computer, located at the San Diego Supercomputer Center adjacent to SIO. The same model code is now also being run by our JPL partner on the JPL Origin 2000 computer. It is our intention to run the system at both institutions (i.e., JPL and SIO/SDSC), swapping state estimates and model changes back and forth to take maximum advantage of existing computer resources and manpower at both locations.

The optimization procedure at the heart of the assimilation method consumes most of the computer resources. Improving the efficiency of the algorithms will, therefore, be a major priority. The JPL group will have primary responsibility for continued development of the filter/smoother methodologies, which in the future, might become a practical alternative for near-real time ocean estimates in support of operational applications.

*Becoming Operational*
One of our major practical goals is to bring ocean state estimation from its present experimental stage to quasi-operational applications. The skill of such estimates can be expected to improve over time as general scientific understanding improves, and as the models and methods are refined.

An immediate need for operational estimates of the ocean state is now increasingly recognized and is described in various WMO/GOOS/GCOS/GODAE documents (see also Powell, 1998). In particular, recent studies at both MIT and JPL have shown that the ocean responds very rapidly to large-scale wind bursts on time scales of hours to days and on space scales of hundreds to thousands of kilometers (basin to global scale). These motions represent a signal which is important for coastal and other applications. But there is also an immediate practical issue: they are/will be aliased by the present sampling of the ocean by TOPEX/POSEIDON and successors, and particularly by the proposed GRACE time-varying gravity mission (Hughes et al., 1999). Preliminary studies suggest (e.g., Fu and Smith, 1996) that OGCMs have sufficient skill in simulating the fast barotropic fluctuation of the ocean and that much of this aliasing can be reduced by calculating the high frequency response of the ocean to the time-varying wind (and atmospheric pressure) fields. Subtracting it from the observed signals is likely to significantly improve our observational data base.[4]

We intend to gain experience with operational ocean modeling, by setting up the infrastructure and data links (i.e., links to meteorological centers providing forcing fields), to provide "forecasts" (simulations) of the high-frequency barotropic large-scale variability of the ocean. This work is expected to teach us a great deal about the practical aspects of maintaining a continuing estimation stream for the full global model over all accessible time scales. Here JPL will undertake, using the MIT model in either barotropic or full baroclinic mode, whichever is chosen, operational simulations of the ocean circulation by the time of launch of JASON-1 (2001) and GRACE (2001).

Because GRACE data reduction will run approximately two weeks to one month behind real-time, it should be possible, using the existing optimization formalism, to use altimeter data formally future to the date of observation to increase the skill of the model estimate. Analysis of the results will be shared between JPL and MIT (Wunsch and V. Zlotnicki of JPL are members of the GRACE Science Team.)

# 7 Anticipated Results and Community Interactions

A major ECCO goal is to make all of the estimates widely available to the scientific community. We anticipate a variety of results evolving through this NOPP activity, ranging from maintenance of data and model output for outside users, to operational products of the ocean state, to best possible estimates of climate-related heat and freshwater flux, as well as carbon budgets. Specifically we will provide during the funding period:
- Near real-time estimates of the time-evolution of the full 3-D ocean state.
- Estimates of ocean transports and budgets on an (approximately) weekly basis.
- Improved understanding of data and model errors.
- Improved model components.
- Improved understanding of climate observing system design.
- Improved ocean state estimation methodology with near-eddy resolution.

The consortium will need to rely on wider community interactions in most of its activities. Not

[4] Experiments are continuing on understanding the skill of simpler barotropic models relative to those of the full baroclinic one (a conference on time- dependent mass and gravity variations over the ocean will take place in April in the UK).

only will we depend upon the oceanographic and space observation communities at large for data access, and expertise in its use, but model innovations made elsewhere will be incorporated into our own computations. Results from the consortium's own model development effort and assimilation products should be of use to a very wide community (noted above as including coastal, biological, carbon cycle, tropical forecasts, etc.).

Because the consortium efforts will benefit from user feedback, our goal is to make our collaboration as open as possible. As envisioned, this means redistributing data (where permitted), assimilation products, computational algorithms (model) etc. to anyone who is interested. Various mechanisms exist in the community facilitating such collaborations. These range from "user" meetings, to summer schools (one is expected to take place at NCAR in the summer of 2000), visitor programs, public data bases, etc. As the NOPP process moves to establish other nodes, e.g., in the coastal area, and a hub, these other groupings would provide a natural mechanism for some of the requisite interaction.

To facilitate an easy interaction with the community we will also maintain a data and model output flow both for internal use and to outside users. This work will primarily reside with our JPL partner who will make results available via the Internet and build the required user and outreach Webpage. JPL has already considerable experience in this work from ongoing TOPEX/-POSEIDON and JASON activities.

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