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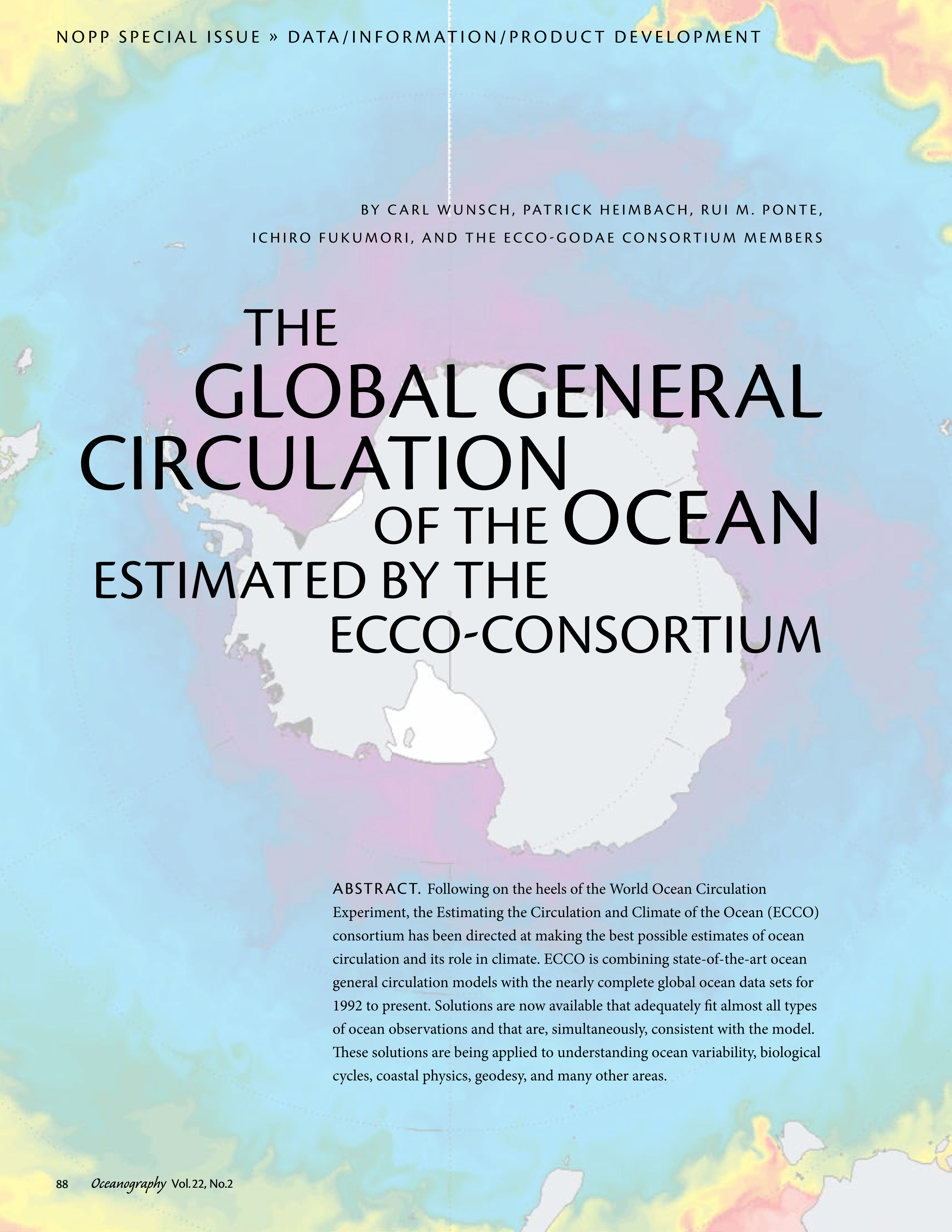
Oceanography



BY CARL WUNSCH, PATRICK HEIMBACH, RUI M. PONTE,
ICHIRO FUKUMORI, AND THE ECCO-GODAE CONSORTIUM MEMBERS

THE GLOBAL GENERAL CIRCULATION OF THE OCEAN ESTIMATED BY THE ECCO-CONSORTIUM

ABSTRACT. Following on the heels of the World Ocean Circulation Experiment, the Estimating the Circulation and Climate of the Ocean (ECCO) consortium has been directed at making the best possible estimates of ocean circulation and its role in climate. ECCO is combining state-of-the-art ocean general circulation models with the nearly complete global ocean data sets for 1992 to present. Solutions are now available that adequately fit almost all types of ocean observations and that are, simultaneously, consistent with the model. These solutions are being applied to understanding ocean variability, biological cycles, coastal physics, geodesy, and many other areas.

INTRODUCTION

The consortium that came to be called Estimating the Circulation and Climate of the Ocean (ECCO), and its various subcomponents, supported by the National Oceanographic Partnership Program (NOPP), had its origins in the World Ocean Circulation Experiment (WOCE). That experiment, conceived around 1980, was intended to depict the ocean as a major element of the global climate system with high fidelity. Some of the roots of WOCE are described in Siedler et al. (2001) and Wunsch (2006a).

By 1980, it was clear that growing concerns about climate change, in particular the ongoing rise in atmospheric CO_2, meant that it was necessary to greatly improve understanding of the ocean's behavior worldwide. Developments in a large number of technologies (e.g., satellites, floats, drifters, chemical tracers) made it conceivable that oceanographers would be able to determine with useful accuracy the entire three-dimensional ocean circulation and its variability over a period of five to 10 years, and that this ability would lay the foundation for understanding the behavior of the entire ocean over decades to come. It was also believed that oceanic general circulation models (GCMs) inevitably would become more capable and realistic, and that without a greatly enhanced observational capability, they would become essentially untestable.

Because the observational technologies were so disparate, and because the coverage by any one type of sensor was likely to be very spatially and temporally inhomogeneous, a true global picture of the ocean would be possible only by combining the diverse data sets into a unified whole through the use of a GCM. The meteorological methodology called "data assimilation" appeared to be applicable to the oceanographic problem, suggesting in a rough way the technical feasibility of what could be done. But, as described below, the analogy is significantly misleading.

By the time the major WOCE field components had concluded operations in the mid to late 1990s (see Figure 1), planning had begun for a program that would synthesize WOCE data; that program ultimately became ECCO. It was clear then that adequate computer power was going to be a major issue, but computers and ancillary equipment (e.g., storage devices) were still roughly following Moore's Law, and a reasonable expectation was that calculations that were very difficult in 1998 would likely be relatively easy in 2008. That expectation has generally been fulfilled, at least for calculations approaching eddy-permitting horizontal resolutions.

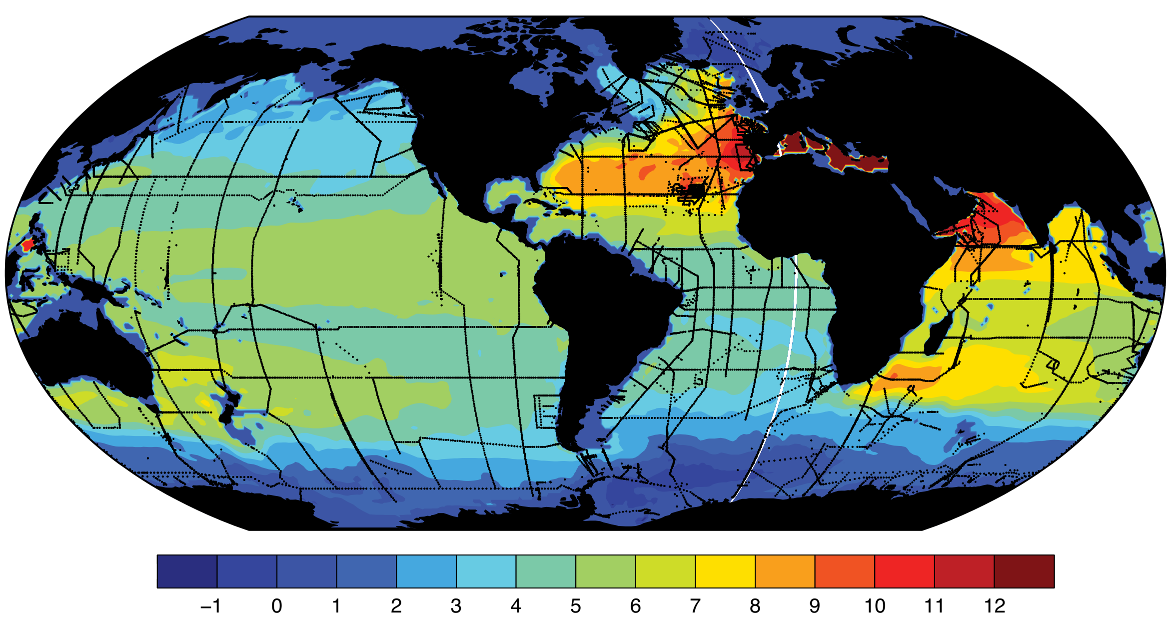


Figure 1. The distribution of conductivity-temperature-depth (CTD) data used in the ECCO-GODAE estimates, superimposed upon the time-averaged 800-m temperature as estimated through the optimization procedure described in the text. Table 1 lists the WOCE-era and later data used by the project.

AN OUTLINE OF ECCO

Oceanographers have, generally speaking, two knowledge reservoirs: (1) theory (the fluid is described by the Navier-Stokes equations plus a few supplementary statements such as the equation of state), and (2) observations. The ECCO challenge is to combine these two knowledge reservoirs, taking advantage of their complementarity, in such a way that ocean circulation could be consistently described and understood. The ECCO problem is one of interpolation: fit a model to a data set during a finite time interval, $0 \le t \le T$, over the entire three-dimensional volume of the ocean. The word "fit" requires definition. Let y_i be any data point at time t_i at location in latitude and longitude φ_i, λ_i and depth d_i, and let $\tilde{y}_i$ be the value at that time and place that the model calculates (commonly, the model, which in our case is on a grid, is interpolated to the data's nearest time and geographical location). Almost universally, $\tilde{y}_i \neq y_i$—that is, the model does not agree with the data. But data are *always* imperfect (noisy) and models are also imperfect (the reason why they are called models rather than reality). So, how far apart should one permit the difference $\tilde{y}_i - y_i$ to be before proclaiming that the model needs modifying to render it consistent with the data?

An infinite number of ways exist to measure misfit. The ECCO choice is the most nearly conventional one and is $\delta_i^2 = (\tilde{y}_i - y_i)^2 / \sigma_i^2$ where σ_i^2 is the *expected* misfit and is the sum of estimated variance of the noise in y_i and the estimated square of the model error. In an ideal situation, all δ_i would have values not far from one—meaning that the model and data agreed within one or two standard deviations of the expected errors in data and models. Typically, $\delta_i^2 >> 1$, and one then seeks to minimize the "cost" or "misfit" or "objective" function summed over all data types and times and locations:

$$J = \sum_i (\tilde{y}_i - y_i)^2 / \sigma_i^2 = \sum_i \delta_i^2 \qquad (1)$$

How does one adjust a model so that J is made sufficiently small that, on average, the misfits are acceptable? The answer leads to the question of which elements of a model are regarded as subject to possible adjustment. Although modelers make very long lists of approximations and guesses in their models, most would probably agree that in modeling the ocean today, any list of likely error sources would include the initial conditions (the starting temperatures, salinities, and velocities), the boundary conditions (forcing by the atmosphere through exchanges of momentum [the wind stress] and buoyancy [freshwater, heat]), and internal parameters such as eddy-mixing coefficients. It is these fields that one wishes to adjust so that the model trajectory in space and time passes within about one standard deviation of all of the observations. Collectively, the fields one is willing to adjust are called the "controls" as they are analogous to the problem of making a robotic arm, for example, pass through a set of predetermined configurations and positions within acceptable errors.[1] (Methods such as "robust control" exist for optimizing among different model structures, but they have not apparently ever been attempted in the present context.)

Writing the problem as one of driving the value of J down to an acceptable level leads to a conventional least squares problem, closely analogous to the familiar process of fitting a straight line to a set of noisy data points. The major differences from that elementary problem are mainly technical rather than conceptual: (1) the number of terms in Equation 1 in some of our calculations is several billion; (2) practitioners of least squares will recognize that knowledge of the σ_i (the "weights") is essential, largely determines the solution, and requires a deep understanding of each data point and model output type; (3) when the model is adjusted, whatever solution is subsequently obtained must actually satisfy the model equations, which for an ocean GCM are highly nonlinear. These problems, particularly (1), render the ECCO problem computationally challenging, albeit conceptually simple.

There are many ways to solve least-squares problems, either exactly or approximately. At the beginning of the ECCO project, and given the size of the problem, two candidate methods, at least, appeared to be potentially practical: (A) so-called sequential methods, based upon using an approximate form of the Kalman filter followed by a time-reversed operation called an RTS smoother, again in an approximate form, and (B) the ancient mathematical method of Lagrange multipliers, which has come to be known in the ocean context as the adjoint method and in meteorology as 4DVAR.

Basic summaries of these methods

[1] A more complete statement of J has cross terms proportional to $(\tilde{y}_i - y_i)(\tilde{y}_j - y_j)$, $i \neq j$, permitting the use of space-time covariances of the noise.

can be found in Wunsch (2006b), and we will not attempt to describe them further here. It is, however, worth pausing to explain one of the major contrasts with the already-mentioned meteorological practice. Numerical weather prediction is obviously directed at *forecasting* and commonly uses an approach related to the first part of method (A). An atmospheric GCM is run forward to an analysis time, t_2 and the equivalent of the δ_i computed above. Where the model and data differ significantly (however defined), adjustments of varying sophistication are made to the model to bring it into agreement with the data at that moment, and the forward computation is resumed, thus producing the forecast (see Figure 2).

From the ECCO—climate—point of view, there are two issues. Data arriving at the analysis time t_2 and later may carry important information about what the state of the atmosphere had to have been hours or days earlier. This information is not normally used because the weather forecaster is concerned primarily with the future, not with improving estimates of the past. Second, the adjustment at t_2 usually introduces either jumps or unphysical terms (e.g., adjusting the temperature at 500 mb implies a heat source or sink there) into the model equations and the resulting trajectory no longer satisfies the model equations, rendering physical understanding difficult at best. The purpose of the smoothing step used in ECCO method (A) is to carry the information at t_2 backward into the past so as to both fully exploit its information content about the state in the past, and to force the solution to exactly satisfy the model equations. A solution that satisfies known equations over years and decades is essential for computing physically meaningful budgets of heat, freshwater, carbon, and a whole suite of biogeochemical characteristics. Method (B) achieves the same end by using a different numerical procedure.

Among the earliest results from ECCO were inferences that both methods are practical and produce similar solutions (the numerical approximations are somewhat different in nonlinear systems), and that a choice between them is not a matter of principle, but primarily one of convenience and problem-dependent efficiency. We do not further discuss their pros and cons here. Specific experience with the filter/smoother and Lagrange multiplier methodologies is described by Fukumori et al. (1999) and Wunsch and Heimbach (2007), respectively, as well as by many of the other references.

The original effort to carry out these calculations was funded by the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF) as part of WOCE synthesis activities, and then formally as ECCO under NOPP starting in 1999. Following the demonstration of the basic system, ECCO-GODAE was

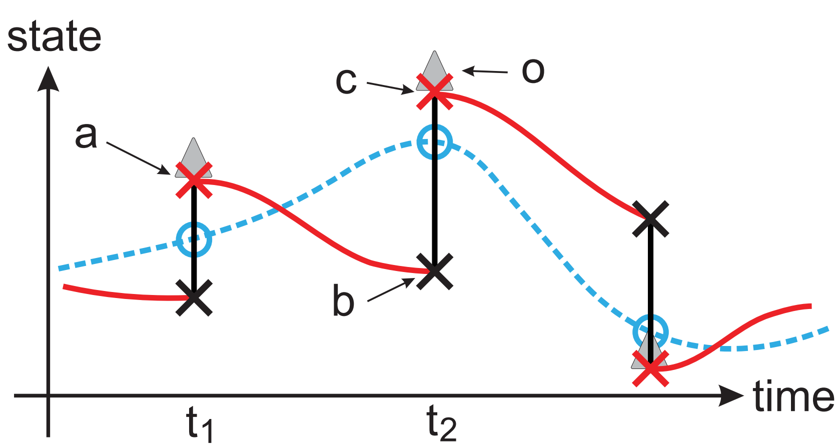


Figure 2. Schematic of the time evolution of one component of a model state vector when using pure filtering methods. At time t_1, the model is integrated from the starting condition shown by the red "x" labeled "a" until time t_2, where the estimated state is the black "x" denoted "b." At time t_2 (the analysis time), a high-quality observation with small relative error is available (the triangle denoted "o"). Because the observation is of high quality, the analysis step forces the model to jump from state value "b" to new estimated state value "c." The computation continues forward in time from this new starting condition. The changes from "b" to "c" at analysis times do not satisfy the model equations, an issue of no concern in forecasting, but central to understanding climate evolution. A smoothing step, such as employed in the RTS algorithm, produces the dashed blue curve by using data at all times following t_1, t_2, and which then satisfies the underlying model equations.

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formulated in 2004 under continued NOPP funding to address the goals of the Global Ocean Data Assimilation Experiment (GODAE). A separate project called ECCO2, described very briefly at the end of this article, was subsequently established to explore eddy-resolving state estimation problems; there is also a German partner project, called GECCO, that emphasizes extending the estimation period back to about 1950. We refer generically to ECCO, often without specifying precisely which member of the growing family is meant.

THE ECCO DATA SETS

ECCO goals have been primarily about decadal and longer *climate change*, and required the production of dynamically and kinematically consistent estimates of ocean circulation over approximately a decade and longer, exploiting *all* of the data and data types that became available within WOCE. One never actually acquires all observations nor are the errors sufficiently understood in all of them to make it possible to introduce them into Equation 1. Nonetheless, Table 1 lists the data currently in use in one of the ECCO-GODAE configurations (that from the Massachusetts Institute of Technology-Atmospheric and Environmental Research Inc. partnership). A full discussion of these data, how they were quality controlled and edited, and in particular, how they are weighted, would require a very lengthy paper. But, because the data are so important to the solutions, some comments about the most important or interesting ones are useful. An important, but often overlooked, ECCO-GODAE byproduct is the continuing quality control, formatting, and public posting of all of the data sets listed in Table 1. Detailed understanding of the global data sets, including at least some approximation to an error estimate on all scales, is an unglamorous but essential activity.

Altimetry

Altimeter data now dominate oceanographic observation numbers. ECCO-GODAE uses the data from *all* of the altimetric satellites that have flown since 1992 (TOPEX/POSEIDON, ERS-1 and 2, GEOSAT Follow-On, Envisat, Jason-1). Each satellite has biases and differing random error components (see Fu and Cazenave, 2001, for a general discussion.) In present use, the local errors are dominated by eddy variability (Ponte et al., 2007b), but there are regional exceptions, and differing global mean trends are a problem. Approximately 3.5×10^7 values for the period 1992 to 2006 are employed separately as a time mean and as daily anomalies. Determining appropriate error estimates is difficult, and, following comparisons of the simultaneous measurements by TOPEX and Jason-1, error estimates were generally increased. The nature of large-scale errors in altimetry, with their consequences for sea level rise and net heating and freshening of the ocean, remains largely enigmatic (see the discussion in Wunsch et al., 2007).

Hydrography

By "hydrography" we mean temperature and salinity data however they are observed. As used in ECCO, data are gathered primarily with conductivity-temperature-depth (CTD) sensors, expendable bathythermographs (XBTs), and Argo profilers, as well as the elephant seal described separately below. Figure 1 shows the distribution of CTD data used in the interval 1992–2007. Compilations of the historical data into climatologies are now familiar. ECCO-GODAE uses the so-called WOCE climatology of Gouretski and Koltermann (2004): 15-year averages of model temperatures and salinities are permitted to deviate, in J, from the climatology by amounts varying with three-dimensional position. In the presence of interannual phenomena such as El Niño, and the greatly varying space-time sampling making up such climatologies, determining sensible, spatially variable, weights, σ_i, becomes a major effort all by itself (e.g., Forget and Wunsch, 2006). Recent widely publicized calibration and other errors in profiling floats (Willis et al., 2007) and in XBT measurements (Gouretski and Koltermann, 2007), among other problems, have a direct influence on J and must be accommodated.

Elephant Seal Data

These exciting data are temperature and salinity measurements obtained from diving elephant seals, primarily in the Southern Ocean, as part of the international Southern Elephant seals as Oceanographic Samplers (SEaOS) program (Biuw et al., 2007; Charrassin et al., 2008; also http://biology.st-andrews.ac.uk/seaos). They are singled out here because they are almost our only data sets from under the Antarctic sea ice, and they perhaps represent the future, in which ever more species are used to obtain a truly global observation system.[2] Figure 3 shows the available coverage.

[2] Perhaps, one day, animals can be bred to grow their own temperature, salinity, and pressure sensors, and GPS transmitters! Whether the existing system is damaging to the animals, and the more general ethical questions concerning animal use, must be discussed elsewhere.

Table 1. Data used in MIT-AER ECCO-GODAE estimates as of April 2006

Data Type	Source	Spatial Extent	Variable(s)	Duration	Number of Values
Altimetry: TOPEX/POSEIDON	PO.DAAC	Global, equatorward of 65°	height anomaly, temporal average	1993–2002	(4500/day) 2.5×10^{7}
Altimetry: Jason	PO.DAAC	Global, equatorward of 65°	height anomaly, temporal average	2002–2006	included above
Altimetry: Geosat Follow-On (GFO)	US Navy, NOAA	Global, equatorward of 65°	height anomaly	2001–2006	(4300/day) 2.4×10^{7}
Altimetry: ERS-1/2, Envisat	AVISO	Global, equatorward of 81.5°	height anomaly	1992–2006	(3800/day) 2.1×10^{7}
Hydrographic climatology	Gouretski and Koltermann (2004)	global, 300 m to seafloor	temperature, salinity	1950–2002 inhomogeneous average	(monthly) 1.7×10^{7}
Hydrographic climatology	World Ocean Atlas (2001), Conkright et al. (2001)	global to 300 m	temperature, salinity	multidecadal average seasonal cycle	included above
CTD synoptic section data	Various, including WOCE Hydrographic Program	global, all seasons, to 3000 m	temperature, salinity	1992–2005	(17,000 profiles) 2×10^{6}
Expendable bathythermo-graphs (XBTs)	D. Behringer (NCEP)	global, but little Southern Ocean	temperature	1992–2006	(470,000 profiles) 1.2×10^{7}
Argo and pre-Argo float profiles	Ifremer	global, above 2500 m	temperature, salinity	1992–2006	(280,000 profiles) 2.2×10^{7}
Sea surface temperature	Reynolds and Smith (1995)	global	temperature	1992–2006	(monthly) 7.3×10^{6}
Sea surface salinity	Études Climatiques de l'Ocean Pacifique (ECOP)	tropical Pacific	salinity	1992–1999	(monthly) 5.5×10^{6}
TRMM Microwave Imager (TMI)	NASA/NOAA	global	temperature	1998–2006	(monthly) 7.3×10^{6}
Geoid (GRACE mission)	GRACE SM004-GRACE3 CLS/GFZ (M.-H. Rio)	global	mean dynamic topography	NA	(1 deg) 5.8×10^{4}
Bottom topography	Smith and Sandwell (1997) + ETOPO5	Smith/Sandwell to 72.006, ETOPO5 to 79.5	water depth	NA	(1 deg) 5.8×10^{4}
TOGA-TAO, Pirata array	PMEL, NOAA	tropical Pacific	temperature, salinity	1992–2006	(daily) 2.2×10^{6}
SEaOS	Sea Mammal Research U. St. Andrews, Scotland	Southern Ocean	temperature, salinity	2004–2005	(17,346 profiles) 5.5×10^{5}
Florida Current transport	NOAA/AOML	Florida Straits	mass flux	2002–2006	5.5×10^{3}
FORCING:					
Wind stress-scatterometer	PODAAC	global	stress	1992–2006	9.4×10^{6}
Wind stress	NCEP/NCAR reanalysis Kalnay et al. (1996)	global	stress	1992–2006	(192 x 94–6hr) 4×10^{8}
Heat flux	NCEP/NCAR reanalysis	global	lw + sensible + latent heat	1992–2006	(192 x 94–6hr) 2×10^{8}
Freshwater flux	NCEP/NCAR reanalysis	global	evap-precip	1992–2006	(192 x 94–6hr) 2×10^{8}
Short/long wave radiation (experimental)	NCEP/NCAR reanalysis	global	Sw	1992–2006	(192 x 94–6hr) 2×10^{8}
					Total Variables = 1.14×10^{9}
WITHHELD (as of October 2008)					
Tide gauges		global, sparse	sea level		
TOGA-TAO array		equatorial oceans	velocity		
Tomographic integrals		North Pacific	heat content		
Float and drifter velocities		global	velocity		

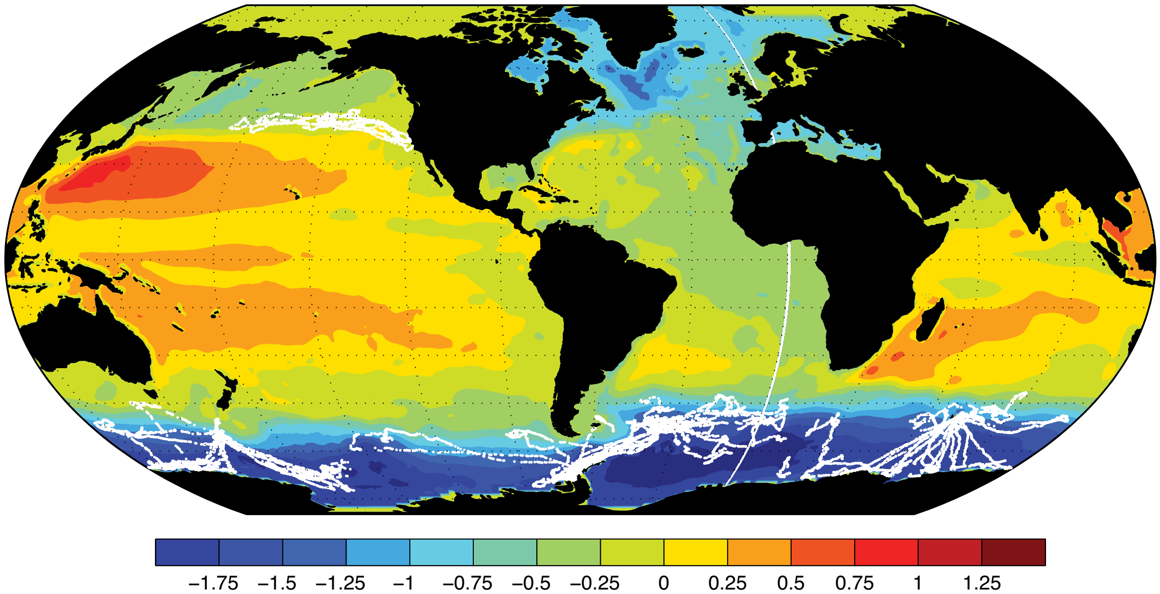

Figure 3. Positions of the available elephant seal data from the Southern Elephant seals as Oceanographic Samplers (SEaOS) program (e.g., Biuw et al., 2007) are shown in white, superimposed upon the ECCO-GODAE estimated time-mean sea surface topography (meters) relative to the geoid. North Pacific profiles are all from 2008 and, thus, have not yet been included in the calculations.

Meteorological Fields

Meteorological data are used indirectly via the estimates made through the so-called NCEP-NCAR reanalysis. Reanalysis fields consist of atmospheric variables such as air temperature, specific humidity, and 10-m winds, or derived air-sea momentum, buoyancy, and radiative fluxes, calculated using a weather forecast model, thus providing gridded data every six hours at roughly 1.8° spatial resolution. These fields provide initial estimates of the surface boundary forcing functions, and they can be applied in two distinct ways (e.g., as the stress produced by the meteorological model, or via bulk formulae employing instead the 10-m wind estimate). A major and still unresolved problem is the establishment of useful error bars on these estimates, as they translate directly into the weights, σ_i. Stammer et al. (2002) discuss the somewhat ad hoc nature of the weights being used. Failure of the existing reanalyses to conserve energy and water render them problematic for climate computations such as those in ECCO-GODAE. Over the period 1992 to 2004, imbalances in global net freshwater fluxes are on the order of several centimeters per year, and those of enthalpy fluxes in excess of 2 W m^{-2}. Water and heat budgets computed from simulations forced with such fluxes are not easy to interpret. Regional partition of such imbalances is even harder to assess in the absence of knowledge of what consistent lateral fluxes ought to be. This issue is touched upon briefly later, as it represents a major community challenge.

THE ECCO MODELS

The main, but not the only, GCM used in ECCO-GODAE has been an evolving version of the MIT model described by Marshall et al. (1997) and Adcroft et al. (2002). This model was developed at MIT simultaneously with the formulation of ECCO and ECCO-GODAE[3] and has been structured in ways to ease its use in our estimation procedures. Because the misfits of the model, before adjustment, are known for every one of the terms in J, one can argue that the MITgcm is the most comprehensively tested model that exists today. Its evolution since the original formulation has been dictated, in significant measure, by knowledge of its relationship to the ECCO data sets.

Practitioners of least squares will know that minimization of J is conventionally carried out by taking its derivatives with respect to the adjustable parameters (the controls) and setting them to zero. In the present case, both J and the model, which also has to be differentiated, exist not as algebraic expressions but as computer codes. A

[3] Development of the MITgcm was initially funded under the Acoustic Tomography of the Ocean Circulation program (see ATOC Consortium, 1998) with support from DARPA (SERDP) and NSF.

major development that rendered the Lagrange multiplier method (LMM) practical was the development by Ralf Giering (Giering and Kaminski, 1998; see also Marotzke et al., 1999; Heimbach et al., 2005) of an automatic or algorithmic differentiation (AD) tool that, rather remarkably, takes the derivatives of a Fortran code and produces the result in the form of another useful Fortran code (Griewank and Walther, 2008). In the LMM, the multipliers evolve in time and are commonly called the "adjoint model."[4] The MITgcm is thus accompanied by this dual model—one that has the profound interpretation as the sensitivity of the model to any adjustable parameter (see Marotzke et al., 1999; Bugnion et al., 2006). ECCO-GODAE, with NSF support, helped sponsor development of the open-source AD tool OpenAD (see Utke et al., 2008), which is publicly available for download (http://www.mcs.anl.gov/OpenAD/). The tool is currently being improved to enable the first comprehensive treatment of parallel Message Passing Interface (MPI) operations (Utke et al., in press); its use is strongly encouraged. Note that the derivatives are used implicitly in the form of matrix times vector products—the explicit set of normal equations is never directly employed. A summary of current adjoint-based applications of the MITgcm is given in Heimbach, 2008.

Although the MITgcm has been the main focus in ECCO, significant attention has also been directed toward similar use of the Modular Ocean Model (MOM4) of the Geophysical Fluid Dynamics Laboratory (GFDL) in conjunction with both GFDL and the National Centers for Environmental Prediction (NCEP). Adjoint and smoother codes are under development for that model and will be described elsewhere.

ECCO RESULTS

The Global Solutions

The ECCO and ECCO-GODAE results will be seen to represent what a statistician would call "best estimates." These solutions are not "correct" in any simple sense: as computer power grew, model resolution became better; as new data have been obtained, and as the data came to be better understood, the weights in J have been changed and the number of terms greatly increased. Because of the size and nonlinearity of the problem, J is minimized iteratively. The result is a whole suite of solutions that necessarily depend upon the evolving understanding and growth of computing power. In addition, many special experimental calculations have been done, for example, treating bottom topography as a control parameter (Losch and Heimbach, 2007), adjusting eddy stress coefficients (Ferreira et al., 2005) and mixing parameters (Stammer, 2005), and testing the consequences of assuming near-perfect data types. The reader is referred to the Web site http://www.ecco-group.org/ for a comprehensive list of papers and reports. The model, the quality-controlled data, the solutions, and most of the software are publicly available. (See the Appendix for an explanation on how to obtain any of these products.)

The first ECCO results were the near-global[5] adjoint solutions described by Stammer et al. (2002) and run over the interval 1992–1997 on a 2° x 2° horizontal grid, and a near-global analysis of shorter duration (1997–2000) with enhanced tropical resolution (0.3°) run by Lee and Fukumori (2003). A series of Kalman filters and RTS smoothers have also been devised for this higher-resolution model following Fukumori (2002), producing near-real-time analyses of the global ocean (http://ecco.jpl.nasa.gov/external). In recent years, the near-global adjoint calculations have been run at 1° horizontal resolution over the interval 1992–2007, with more data types (e.g., the Argo float data became available after about 2002) and much longer data durations. Almost all of the weights, σ_i, have been modified significantly from their initial estimates.

Global GCMs represent a very long list of approximations, and it would be both unreasonable and wrong to claim globally uniform accuracy. Use of models, whether constrained to observations as here, or run in conventional forward mode, require considerable skill and judgment, particularly in deducing whether the inevitable errors are acceptable in the context of the particular application. Although no sweeping generalities are possible, the ECCO-GODAE results have proven useful in a wide spectrum of applications, some from within the group, many from outside. Because of the breadth of uses, we can only give the flavor of some of them here.

[4] Technically, the adjoint represents the so-called reverse mode partial derivatives.
[5] Solutions are called "near-global" because only recently has it been technically possible to include the Arctic.

Sea Level Change

Figures 4 and 5 display the estimate of the complex patterns of global sea level change inferred from the *combined* altimetry, in situ data, and GCM, and show the ability in such a synthesis to make inferences about the entire water column—something that is normally omitted in studies using only a single data type (updated from Wunsch et al., 2007).

Biological Applications

Understanding of the sustenance and evolution of biological communities depends directly upon having accurate physical flow and mixing fields. Stephenie Dutkiewicz of MIT and

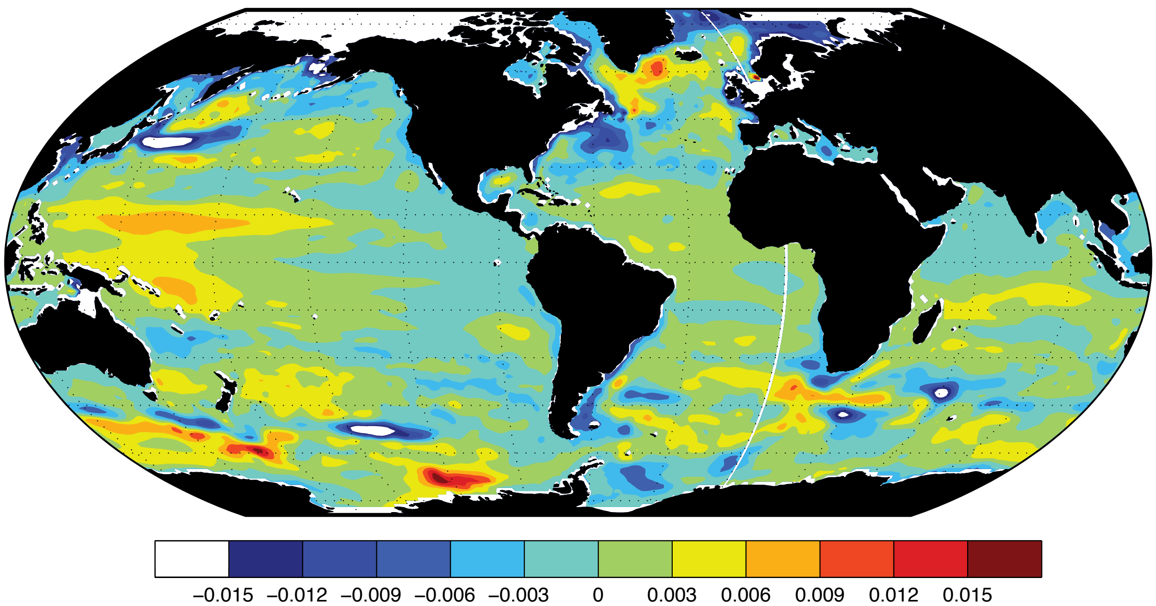

Figure 4. Estimated trends in sea level in meters per year over the interval 1993–2004 from an ECCO-GODAE solution. This chart is an updated version of that published by Wunsch et al. (2007) and differs primarily in the Southern Ocean where the addition of a full sea-ice model makes a qualitative difference.

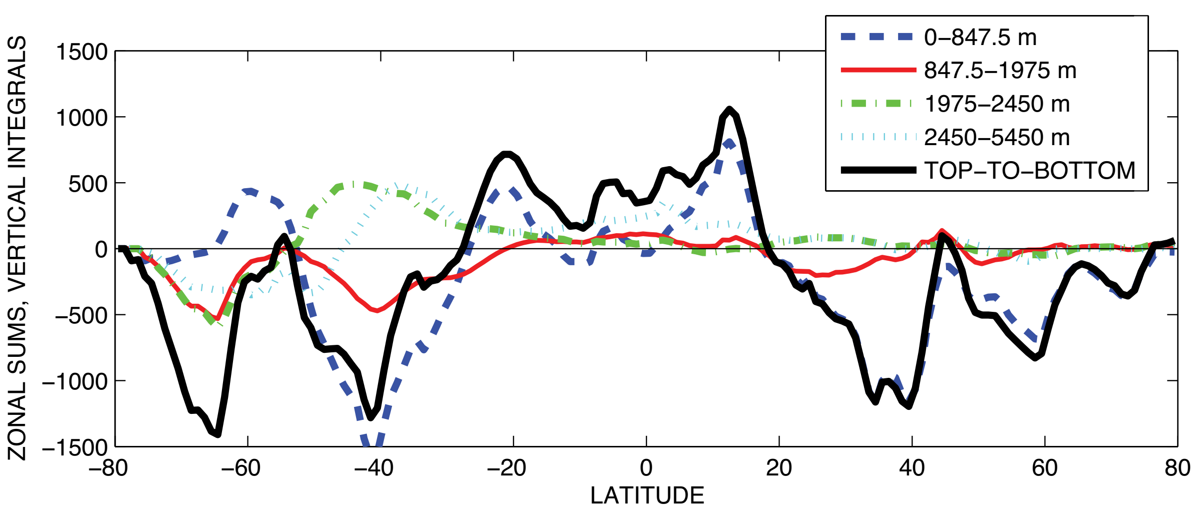

Figure 5. Employment of a global state estimate makes it possible to estimate contributions to oceanic change that are only indirectly observed. Here, the contribution to sea level trends from thermal effects over the entire water column is calculated from one of the ECCO-GODAE solutions (Wunsch et al., 2007). Where the black and dashed blue lines coincide, changes are dominated by the upper 800 m, but where they differ, as in the Southern Ocean and in mid latitudes, the much deeper layers of the ocean contribute significantly and must be accounted for.

colleagues have used the ECCO-GODAE global estimates to study the structure and time evolution of interacting and competing ecosystems, for example, as depicted in Figure 6. (See preprint of submitted article [Dutkiewicz, Follows, and Bragg: Modelling the Coupling of Ocean Ecology and Biogeochemistry] at http://ocean.mit.edu/~stephd.)

Coastal Physics

The coastal ocean responds measurably to forcing by the offshore, deep-water ocean. Veniziani et al. (2008) describe the use of the global ECCO estimates as the offshore boundary conditions in a California coastal model. Figure 7 shows their regional mean surface topography estimate.

Earth Rotation and Geodesy

Estimates of oceanic mass and velocity fields produced by ECCO have been used to interpret geodetic measurements of Earth's orientation in space and its variable gravity field, and to highlight the major role of ocean angular momentum variability in explaining observed polar motion (e.g., Gross et al., 2005; Ponte et al., 2001, 2007a). Comparisons with the geodetic data provide entirely independent tests of the ECCO results.

Climate Trends

Global warming has led to widely distributed pronouncements about potential major shifts in or, sometimes, collapse of ocean circulation. Some of these assertions are based upon extremely limited data sets or time scales, as discussed by Wunsch and Heimbach (2006) for the case of decadal variations in the North Atlantic mass and enthalpy transports, and by Wunsch and Heimbach (2009) for the global meridional overturning circulation (MOC). The ECCO-GODAE synthesis permits quantitative use of all available data globally to distinguish possible trends in any quantity calculatable from the model state vector. Figures 8 and 9 show two representative results.

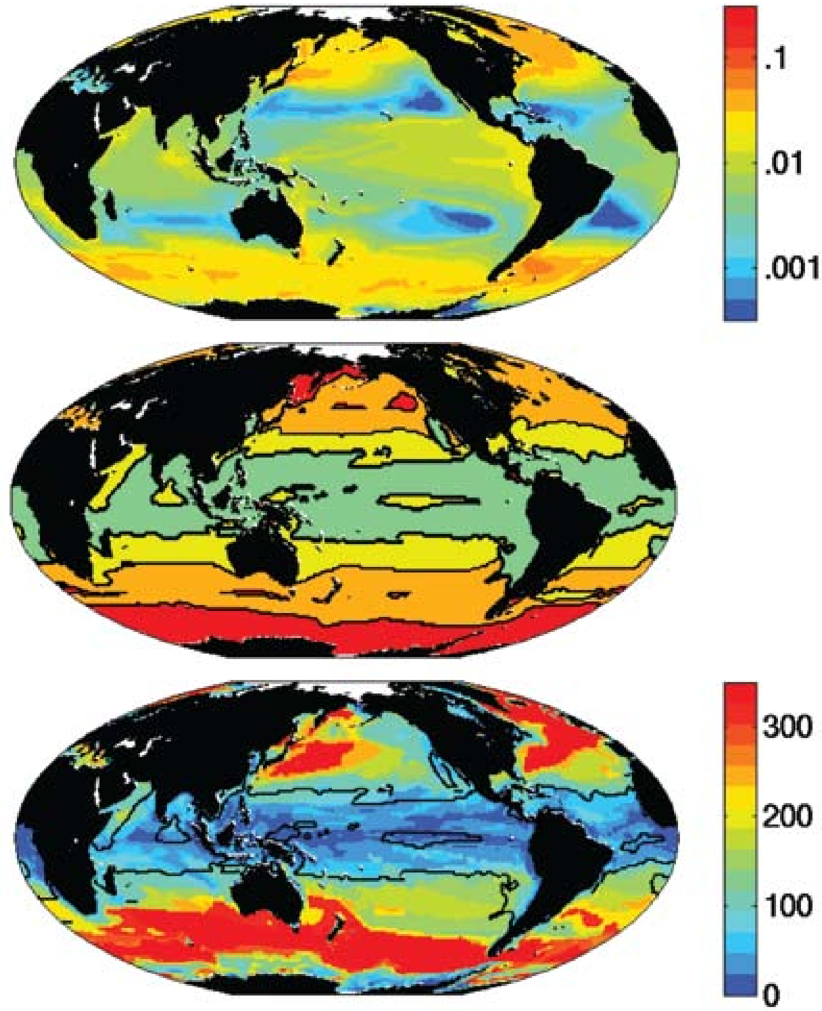

Figure 6. Results from a self-assembling ecosystem model embedded in the ECCO-GODAE state estimate fields. (Top) Total annual mean biomass of phytoplankton (µM P) averaged over the top 50 m. (Middle) Emergent biogeography of four major functional groups, mapped as four regimes according to the relative contributions of four major functional groups. The functional groups are determined by summing biomass contributions from four broad classes of initialized phytoplankton types: (1) diatom analogs (red), (2) other large phytoplankton (orange), (3) other small phytoplankton (yellow), and (4) *Prochlorococcus* analogs (green). (Bottom) Relative regional stability shown by annual range of mixed-layer depth (m). Mixed-layer depths are from ECCO-GODAE state estimates (Wunsch and Heimbach, 2007). Solid lines enclose the regions where the *Prochlorococcus* analogs, which have the lowest nutrient requirements but also cannot assimilate nitrate, dominate. (Preprint of article on this work available at: http://ocean.mit.edu/~stephd.)

Sensitivity Analysis

In addition to their use in optimization problems, model adjoints are

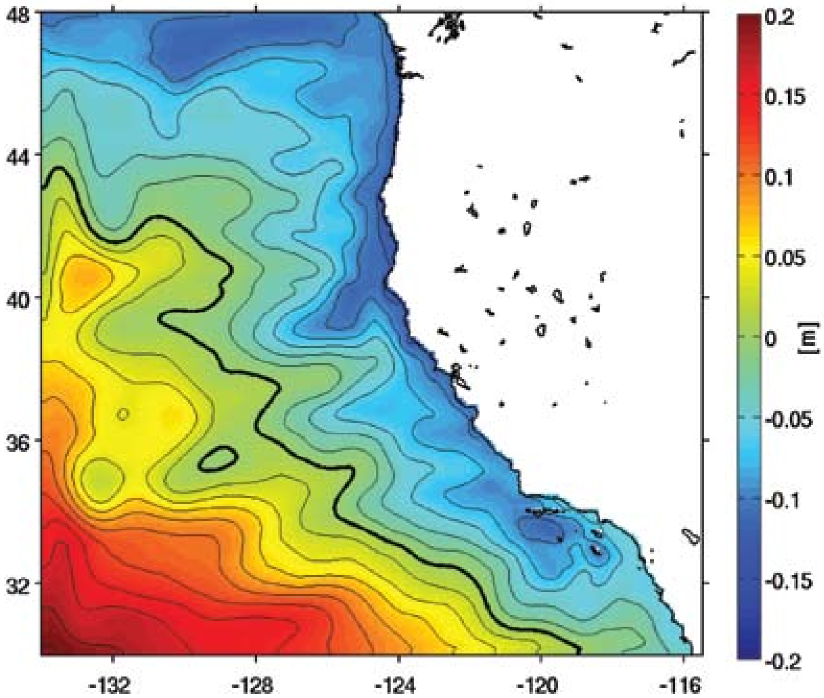

Figure 7. Five-year mean sea surface height from a regional ocean model simulation using ECCO-GODAE open ocean boundary conditions. The coastal model is ROMS (Regional Ocean Modeling System) and the atmospheric forcing is COAMPS (Coupled Ocean Atmosphere Mesoscale Prediction System). Contour interval is 2 cm. *Courtesy C. Edwards. See Veneziani et al., 2008*

useful in analyzing the sensitivity and workings of the modeled circulation. Among numerous examples, some already mentioned, the MITgcm adjoint has been employed in identifying causal factors in oceanic variability (e.g., Fukumori et al., 2007), studying pathways of circulation (Fukumori et al., 2004), and exploring observing system design (Köhl and Stammer, 2004).

Climate Forecasting

The combined model-data estimates have been used to initialize coupled ocean-atmosphere models for seasonal-to-interannual climate forecasting (e.g., Cazes-Boezio et al., 2008; Yulaeva et al., 2008).

Budgets

One of the unique characteristics in many of the ECCO estimates is their physically consistent closure of modeled property budgets. Kim et al. (2004, 2007) exploited this quality in studying near surface temperature budgets in regions of the Pacific Ocean, and Wang et al. (2004) examined changes in water mass characteristics associated with the 1997–1998 El Niño.

Paleoclimate

Understanding how the ocean adjusts to major injection of tracers at the sea surface is one of the major goals of paleoceanographic studies. One of the ECCO-GODAE solutions was used by Wunsch and Heimbach (2008) to demonstrate the very long times required for the ocean to come to equilibrium. Khatiwala (2007) implemented a transport matrix representation of the MITgcm, enabling tracer calculations with efficiencies greatly exceeding those in normal off-line calculations, and demonstrated it with a millennial scale SF_6 tracer calculation.

Non-normal Growth and Uncertainty Quantification

In a novel application, a combined tangent linear and adjoint model of the MITgcm (both derived via AD) was used in a Harvard University PhD thesis by Laure Zanna to investigate non-normal growth of climate-relevant metrics, such as tropical sea-surface temperature (SST) anomalies and the MOC, by calculating singular vectors of the system (results available at http://www.earth.ox.ac.uk/~laurez/Zannaetal2008.pdf). This application holds promise for uncertainty quantification, the determination of interannual to interdecadal time scales of natural climate variability, and the efficient generation of ensembles for Monte Carlo estimation methods.

Regional Estimates

Among the major approximations used in ocean models are parameterizations of subgrid-scale processes such as eddies, internal waves, and others thought to mix and modify properties. None of these parameterizations is believed rigorously correct, and some subgrid-scale processes, such as intense boundary currents, are not parameterized at all. For many short-time-scale modeling purposes, such as mesoscale forecasting, modest errors in models do not have time to sum to troublesome

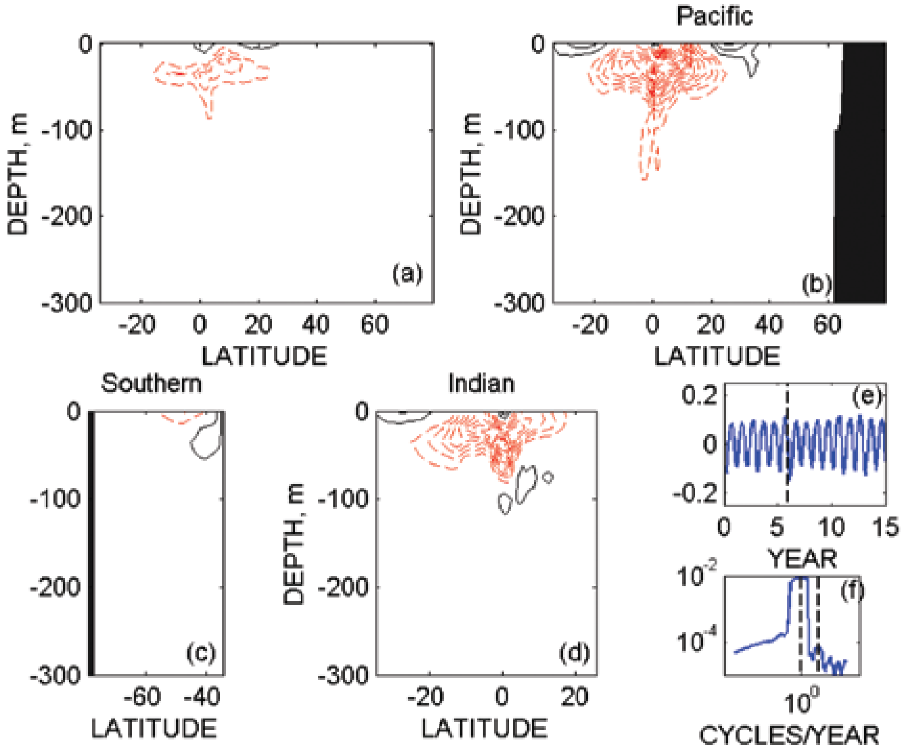

Figure 8. First empirical orthogonal function (annual mean data) of the zonally integrated meridional enthalpy transport (Wunsch and Heimbach, 2008). In (e), the time coefficient is indicated by vertical lines indicating the 1997–1998 El Niño. No obvious trend exists.

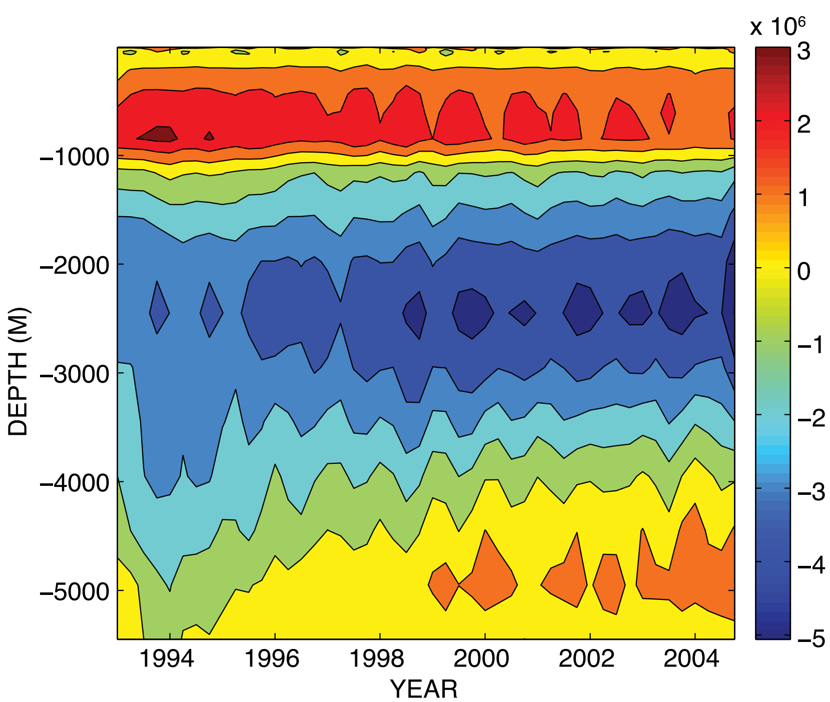

Figure 9. Seasonal averages (three months) of volume transport contours ($m^3 s^{-1}$) through time as a function of depth at 27°N in the North Atlantic Ocean. There are shifts on the longest observed time scales, but no simple trends. *From Wunsch and Heimbach, 2006*

size. But, when a system is integrated over years and decades, even comparatively slight errors can accumulate and eventually swamp the best model. The goal of using much higher resolution pervades oceanography, and in ECCO-GODAE, estimates with much finer scales than are present in the central estimates are sought.

Ayoub (2006) produced one of the first regional models within the ECCO framework, for a non-eddy-resolving version of the Atlantic. Gebbie et al. (2006) showed how to embed an open-ocean subregion at high resolution within a coarser-resolution global model. Similar studies were conducted for the tropical Pacific by Hoteit et al. (2006, and as described in a submitted manuscript). In the most ambitious such calculation to date, Mazloff (2008) and recent work of author Wunsch and colleagues used a 1/6° eddy-permitting model of the entire Southern Ocean with an open boundary at 24.7°S as shown in Figure 10. Because of the computational burden (an adjoint model requiring on the order of 600 processors), the solution shown was restricted to the two years 2005 and 2006, but is nonetheless fully constrained in the same way as the global model. Among other inferences, we have concluded that the presence of eddies in a model does not necessarily prevent use of the optimization procedures that ECCO-GODAE has been employing.[6]

[6] It is possible that much more intense eddy motions than seen in the Southern Ocean State Estimate could render ineffective the line-search algorithm used in ECCO-GODAE. Although we have not yet seen such behavior, its possibility remains. Alternative optimization methods, not dependent upon the local derivatives of the Lagrange multiplier method, can then be used.

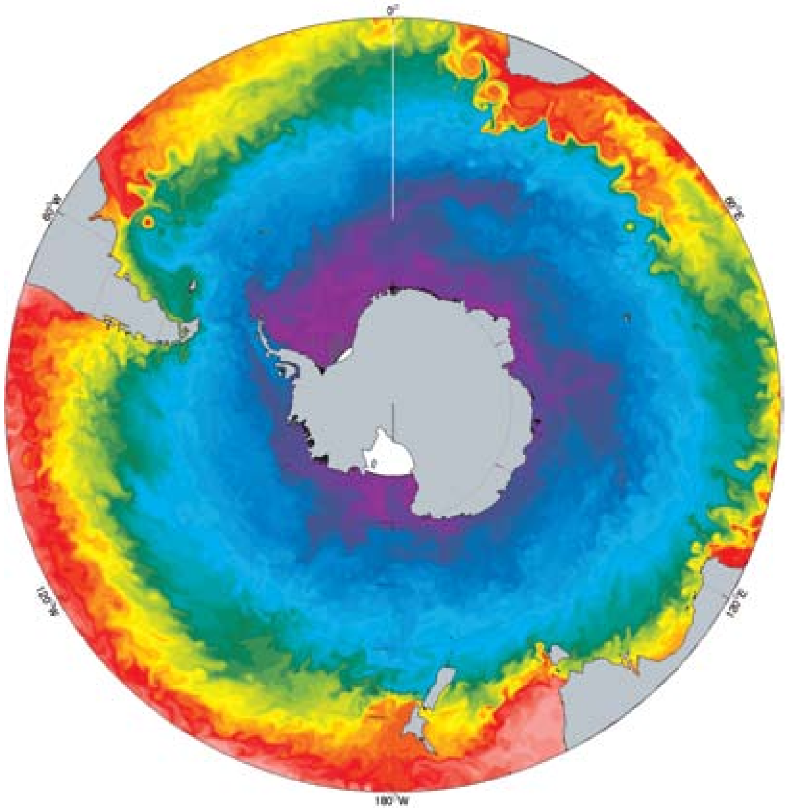

Figure 10. Dye injected at the surface shows the ECCO-GODAE Southern Ocean State Estimate by Mazloff (2008). An artificial tracer with zonally uniform but monotonically increasing concentration to the north was introduced into the 1/6° near-optimized model surface flow field. The dye vividly renders the small-scale structures present in Southern Ocean circulation. (An animation is available from the authors.) *Data provided by Matthew Mazloff, Scripps Institution of Oceanography, and Ryan Abernathey, MIT, and colleagues. A manuscript discussing the results of this project has been submitted for publication.*

Sea Ice

High-latitude processes play a crucial role in climate variability and call for accurate description of the underlying state and its decadal variations. Since the beginning of continuous satellite remote sensing of Arctic and Antarctic sea-ice concentration and extent in 1978, both hemispheres have exhibited distinct behavior in terms of trends. Whereas Arctic sea-ice extent seems to be in decline, Antarctic concentration has increased slightly (the significance of both trends remains unclear). Complex processes are at work, involving the coupled ocean/atmosphere/sea-ice system, and no simple explanations are currently available. As a consequence, substantial resources have been invested in improving polar observations as part of the International Polar Year (March 2007–March 2009). An obvious requirement is that these data be synthesized in much the same way as was anticipated in WOCE. To meet this challenge, and to extend the current ECCO state estimates, which are limited meridionally to 80°N, to truly global products, ECCO and the MITgcm developers have embarked on a coupled estimation system that should enable users to fully exploit both sea ice and oceanographic observations to constrain the combined ocean/sea-ice system. To achieve this result within the adjoint modeling framework, a new sea-ice model has recently been developed and coupled to the MITgcm (Campin et al. 2008, and recent work of author Heimbach, Martin Losch of the Alfred Wegner Institute for Polar and Marine Research, An T. Nguyen and Dimitris Menemenlis of JPL, and their collaborators). Although its numerical approaches in terms of its thermodynamics (Parkinson-Washington-type zero layer) and dynamics (Hibler-type rheology) are conventional, it distinguishes itself from existing sea-ice models by the ability to yield efficient, stable adjoint code using automatic differentiation tools.

For his MIT PhD thesis, Ian Fenty is currently employing and extending the coupled adjoint system to produce an ocean/sea-ice state estimate of the Labrador Sea. Over the coming year we anticipate this system to be deployed in a truly global configuration, similar to that in ECCO2, but at initially coarser resolution for decadal production purposes.

THE FUTURE

ECCO-GODAE has had some success in showing the feasibility of dynamically and kinematically consistent global and regional solutions that employ the great majority of the existing data sets available from 1992 to the present. Existing solutions are now being used for many studies ranging from localized dynamics to global heat and biogeochemical budgets. There is, however, always room for improvements of many types, and efforts are underway to implement many of them.

Among the improvements expected, we have already mentioned higher resolution, both vertical and horizontal. The so-called ECCO2 project, funded primarily by NASA, is directed at achieving the goal of global-scale, eddy-resolving state estimation (Menemenlis et al., 2005). Figure 11 shows an example of the type of solution that is becoming possible. This particular solution is only partly adjusted to fit the observations and it has been run only over a limited time duration. As computer power and numerical methods improve, it will eventually become the central product.

In the near term (a year or so), the existing lower-resolution system is expected to be improved in a large number of ways, including better tropical and high-latitude resolution. Surface boundary conditions are being changed to be more fully consistent with known dynamics and kinematics (particularly important for sea level change studies). The full thermodynamic and dynamic sea-ice model described above is being coupled to the ocean model. The remaining data not now fully exploited, such as surface drifter trajectories and the GRACE time-dependent gravity field, are being included—as rapidly as useful error estimates for them become available. The time duration of the estimates is being extended as data accumulate into the future. Many other changes are being made, including the extension of the control vector to include all of the empirical parameters of the model.

The ECCO models and systems are now being applied well outside the original focus. Among other applications, a major effort is underway (Follows et al., 2007) to incorporate full biogeochemical cycles. In another application, for her MIT PhD thesis, Holly Dail is determining ocean circulation during the last glacial maximum, and an effort is ongoing to generate an ECCO-like system for continental ice sheets (Heimbach and Bugnion, in press).

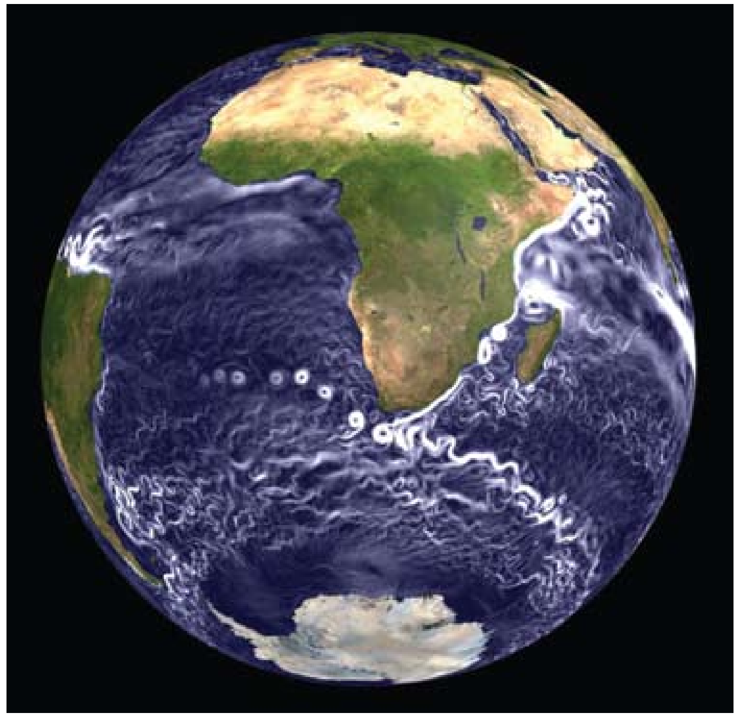

Figure 11. Surface speed in one of the partially constrained ECCO2 solutions at much higher resolution than is now possible with the fully constrained ECCO-GODAE estimates. *Courtesy of D. Menemenlis*

Questions about how the ocean is behaving under a changing climate, and how it is likely to change in the future, require continued observations and interpretation using the best available theoretical tools. The NOPP-funded ECCO-GODAE has shown the utility of model-data combinations directed at decadal and longer time scales. It seems unlikely that full understanding of the ocean is possible without such combinations. The existence of NOPP has provided a capability for the wider community that is essential for understanding as the ocean and climate and biospheres change.

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during ECCO, as have many others too numerous to mention here. The OpenAD development owes a great deal to Eric Itsweire (NSF).

APPENDIX: OBTAINING THE ECCO-GODAE PRODUCTS

The model almost exclusively used by the ECCO-GODAE consortium is based on the MITgcm, and has been frequently updated to remain consistent both with ECCO-GODAE needs and with its general improvements. Complete documentation and the model itself, along with various test and tutorial configurations (including the ECCO-GODAE production configuration), are available at http://mitgcm.org.

The automatic differentiation (AD) tool, TAF, is licensed from FastOpt (Hamburg, Germany) and thus we cannot make it publicly available. Note, however, that the adjoint model produced by it in the ECCO-GODAE production configuration *is* available. Holders of TAF licenses can readily generate it themselves. As the MITgcm code is always evolving, compatibility with the AD tool is tested automatically on a nightly basis. We have also developed, with NSF support, an open-source AD tool (called openAD) with colleagues at Argonne National Laboratory and Rice University. Its use is strongly encouraged. Documentation and codes are available at http://www.mcs.anl.gov/OpenAD/. The MITgcm model repository contains test configurations for the use of OpenAD.

Various state estimates (each consisting of a full set of variables required to conduct offline calculations and budget analyses, including temperature, salinity, pressure, three components of velocity, mixing coefficients, and all adjusted forcing fields) are accessible online as monthly mean fields, and in some cases as daily means. An overview with specific links to available products is given at http://www.ecco-group.org/products.htm. The fields are disseminated through various server protocols: the Live Access Server (LAS), Distributed Oceanographic Data System (OPeNDAP/DODS), IRI/LDEO Climate Data Library (Ingrid), GrADS Data Server (GDS), and (only at SDSC) Storage Resource Broker (SRB). Most products reside at MIT and are mirrored at the San Diego Supercomputing Center (SDSC), with the exception of the ECCO-JPL and the ECCO2 solutions, which reside at NASA/JPL. A list of servers with links is available at http://www.ecco-group.org/servers.htm. The data sets and estimates are intermittently updated as new data become available and as an estimate is regarded as significantly changed from a previous one.

Also available online, and part of the list of products, are the quality-controlled data sets used in the estimates, along with prior error estimates.

Advice is available from the group (email any of the authors) about which solutions might be most suited to a particular application. We are also able to extract subsets of the model output if that is more convenient for users and, in general, we want to assist in the use of these products.

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