GLOBAL OCEAN AND SEA ICE STATE ESTIMATION IN THE PRESENCE OF EDDIES

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ABSTRACT

We aim to demonstrate the feasibility and utility of global, eddying ocean and sea ice state estimation. A first synthesis for the period 1992-2002 has been obtained using a Green's functions approach. Data constraints include hydrography, altimetry, gravity, drifter, and observations of sea-ice. Although the control space is small (~80 parameters), this first global-ocean and sea ice data synthesis substantially reduces large-scale biases and drifts of the model relative to observations and to the baseline integration. A second synthesis is being obtained during the ARGO-rich period using the adjoint method, which permits a much larger number of control parameters to be estimated.

1. INTRODUCTION

The Estimating the Circulation and Climate of the Ocean (ECCO) project was established in 1998 as part of the World Ocean Circulation Experiment (WOCE) with the goal of combining a General Circulation Model with diverse observations in order to produce a quantitative depiction of the time-evolving global ocean state. Such combinations, also known as data assimilation, are important because available remotely sensed and in situ observations are sparse and incomplete compared to the scales and properties of ocean circulation. These combinations also provide rigorous consistency tests for both models and data. In contrast to numerical weather prediction, which also combines models and data, ECCO estimates are physically consistent; in particular, ECCO estimates do not contain discontinuities when and where data are ingested. First generation ECCO solutions are available and widely used for numerous science applications [1] but the coarse horizontal grid spacing coupled with the lack of sea ice limits their ability to describe the real ocean. To address these shortcomings, the ECCO, Phase II (ECCO2) project aims to demonstrate the feasibility and utility of ocean state estimation in the presence of eddies and ice.

2. MODEL DESCRIPTION

ECCO2 data syntheses are obtained by least squares fit of a global full-depth-ocean and sea-ice configuration of the Massachusetts Institute of Technology general circulation model (MITgcm) [2] to the available satellite and in-situ data. A first, global ECCO2 solution was obtained on a cube-sphere grid projection with mean horizontal grid spacing of 18 km coupled to a dynamic/thermodynamic sea ice model [3]. Recently this ECCO2 model configuration has been extended to include an explicit representation of ice shelf cavities [4]. Fig. 1 shows some early ice shelf cavity results.

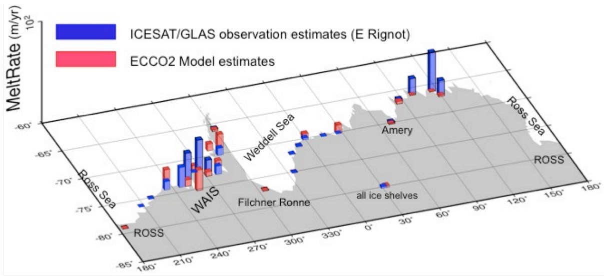

Figure 1. ECCO2 estimates of melt rate under Antarctic ice shelves are compared to ICESAT/GLAS estimates from E. Rignot (pers. comm. 2009).

3. GREEN'S FUNCTION OPTIMIZATION

The first high-resolution global-ocean and sea-ice data synthesis was obtained for the period 1992-2002 by calibrating a small number (~80) of control variables using Green's functions [5]. Control parameters include initial temperature and salinity, atmospheric surface boundary conditions, background vertical diffusivity, critical Richardson numbers, air-ocean, ice-ocean, air-ice drag coefficients, ice, ocean, and snow albedos, bottom drag, and vertical viscosity. Data constraints include sea level anomaly, time-mean sea level, sea surface temperature, vertical temperature and salinity profiles, and sea ice concentration, motion, and thickness. This first global-ocean and sea ice data synthesis substantially reduces large-scale biases and drifts of the model relative to observations and to the baseline integration, including removal of a global warm bias of up to 3° C in the top 750 m, more realistic Arctic and Antarctic sea ice extent, thickness, and velocity, improved vertical stratification relative to observations, and more realistic transports, for example, through the Drake Passage and the Indonesian Throughflow [6].

4. ADJOINT-METHOD OPTIMIZATION

The technical centerpiece of the ECCO2 project is an adjoint-method optimization of the global, eddying configuration of the MITgcm. The objective is to bring the model into consistency with the available data in a least squares sense using the method of Lagrange multipliers. Briefly, the sensitivity of the cost function (a weighted quadratic function of the model-data misfit) with respect to the control variables is generated via the adjoint model integration. This sensitivity information is used to iteratively adjust the control variables in order to reduce the cost function. The adjoint method permits the adjustment of a much larger number of control variables than was possible using the Green's function approach. At the writing of this short article, the period of optimizations spans January 2004 to April 2005 (a short demonstration period chosen to speed up the computations and because it is the beginning of the ARGO-rich period) and twelve adjoint-forward iterations have been completed for an overall cost function reduction of 30% (Fig. 2). Data constraints currently include the OCean Comprehensive Atlas (OCCA) [7], along-track Jason and Envisat sea surface height, Level-2P AMSR-E sea surface temperature, ARGO and XBT temperature profiles and ARGO salinity profiles. The control variables include initial temperature and salinity conditions, surface atmospheric boundary conditions, and the background vertical diffusivity coefficient.

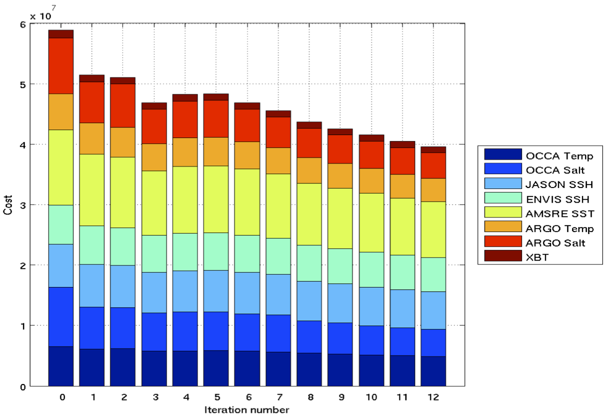

Figure 2. Cost function reduction during the first twelve adjoint-method iterations.

5. EARLY SCIENCE APPLICATIONS

ECCO2 modeling and estimation tools and results are freely available to the science community. Model configurations and parameterizations are available at http://mitgcm.org. Automatic differentiation tools are available at http://www-unix.mcs.anl.gov/OpenAD. Finally, modeling and estimation results are available at http://ecco2.org. Preliminary ECCO2 solutions have been used to estimate errors for coarse-resolution optimizations [8,9], to improve eddy parameterizations [10], to study the impact of mesoscale eddies on the large-scale circulation [11,12,13], to study the polar oceans [14,15,16], and to drive biogeochemical [17], acoustic [18], and electromagnetic [19] models. These published applications (and others in progress) illustrate the scientific usefulness of physically consistent, eddying ocean and sea ice state estimation.

6. CONCLUDING REMARKS

The focus of ocean state estimation during the past ten years has been to demonstrate the feasibility and utility of physically-consistent, global, sustained estimates, with considerable success for upper ocean and for equatorial processes. But many pressing scientific questions, for example, quantifying and monitoring ocean sources and sinks in the global carbon cycle, understanding the recent evolution and variability of the Polar Oceans, and quantifying the time-evolving term balances within and between different components of the Earth System, require much improved accuracy in the estimation of water mass formation and transformation rates, eddy-mixed layer interactions, and high-latitude processes. The accurate monitoring of these processes in turn requires developing state estimation systems, of the sort we have described here, that can fully capitalize on continuing advances in computational and observational technologies.

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