NASA Supercomputer Improves Prospects for Ocean Climate Research

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Estimates of ocean circulation constrained by in situ and remotely sensed observations have become routinely available during the past five years, and they are being applied to myriad scientific and operational problems [*Stammer et al.*, 2002]. Under the Global Ocean Data Assimilation Experiment (GODAE), several regional and global estimates have evolved for applications in climate research, seasonal forecasting, naval operations, marine safety, fisheries, the offshore oil industry, coastal management, and other areas.

This article reports on recent progress by one effort, the consortium for Estimating the Circulation and Climate of the Ocean (ECCO), toward a next-generation synthesis of ocean and sea-ice data that is global, that covers the full ocean depth, and that permits eddies.

ECCO is funded by the U.S. National Oceanographic Partnership Program (NOPP) and is a collaboration between the Massachusetts Institute of Technology (MIT), the Jet Propulsion Laboratory (JPL), and the Scripps Institution of Oceanography (SIO). A distinguishing feature of ECCO estimates is their physical consistency. Estimates are obtained by least squares fit (or regression) of the MIT general circulation model (MITgcm [*Marshall et al.*, 1997]) to the available observations; they satisfy the model's time-evolution equations; property budgets are closed and there are no discontinuities when new data are inserted; and the error covariance is propagated through the same physical model as the state vector (the model's prognostic variables: salinity, temperature, velocity, and sea-surface height on a predefined grid), hence more fully utilizing the available data.

Although this represents a huge technical challenge, physically consistent, coarse-resolution estimates are already in production and freely available (http://www.ecco-group.org/). These estimates have proved useful for a large number of oceanographic and interdisciplinary studies on topics such as ocean circulation [*Fukumori et al.*, 2004], biogeochemical cycles [*McKinley et al.*, 2004], air-sea fluxes [*Stammer et al.*, 2004], and geodetic studies [*Dickey et al.*, 2002].

Existing estimates, though, lack the ability to resolve certain processes that are important for accurately representing key climate system dynamics, including mesoscale eddies, flow over narrow sills, boundary currents, regions of deep convection, sea ice, and the Arctic Ocean.

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Here are described three recent advances that bring physically consistent, eddy-permitting, decadal-timescale estimates of the global-ocean and sea-ice circulation within reach: (1) the configuration of an efficient eddying model that achieves a throughput approaching 10 years of model integration per day of computation, (2) the demonstration that initial conditions and surface forcing fields estimated at coarse resolution improve the solution of an eddying model, and (3) the development and deployment of a hierarchy of methods for assimilating observations in a mathematically rigorous way.

Cubed-Sphere Model Configuration on a Parallel Supercomputer

The computational demands of rigorous ocean state estimation are enormous. Depending on the method and on the approximations used, the computational cost of state estimation is several dozen to several thousand times more expensive than integrating a model without state estimation. This has limited the resolution of existing ECCO solutions to horizontal grid spacings of order 100 km. Existing solutions also exclude the Arctic Ocean and lack an interactive sea-ice model, which restricts the utilization of satellite data over polar regions. Therefore, a necessary condition for a next-generation synthesis is an efficient, truly global model and significant computational resources.

For this work, a novel cubed-sphere grid projection is employed (Figure 1). This grid permits relatively even grid spacing throughout the domain, preserves local orthogonality for efficient and accurate time stepping, and avoids polar singularities [*Adcroft et al.*, 2004]. The ocean model is coupled to a sea-ice model that computes ice thickness, ice concentration, and snow cover as per *Zhang et al.* [1998], and that simulates a viscous-plastic rheology using an efficient parallel implementation of the *Zhang and Hibler* [1997] algorithm. Inclusion of sea ice provides for more realistic surface boundary conditions in polar regions, and allows the system to be constrained by polar satellite observations. The sea-ice model also permits estimation of the time-evolving sea-ice thickness distribution.

The results of Figure 1 were obtained on a 512-processor, shared-memory SGI Altix computer operated by the NASA Advanced Supercomputing group at the Ames Research Center (NAS/ARC). The Columbia Supercomputer comprises twenty 512-processor systems, for a combined peak capacity of 61 teraflops, which

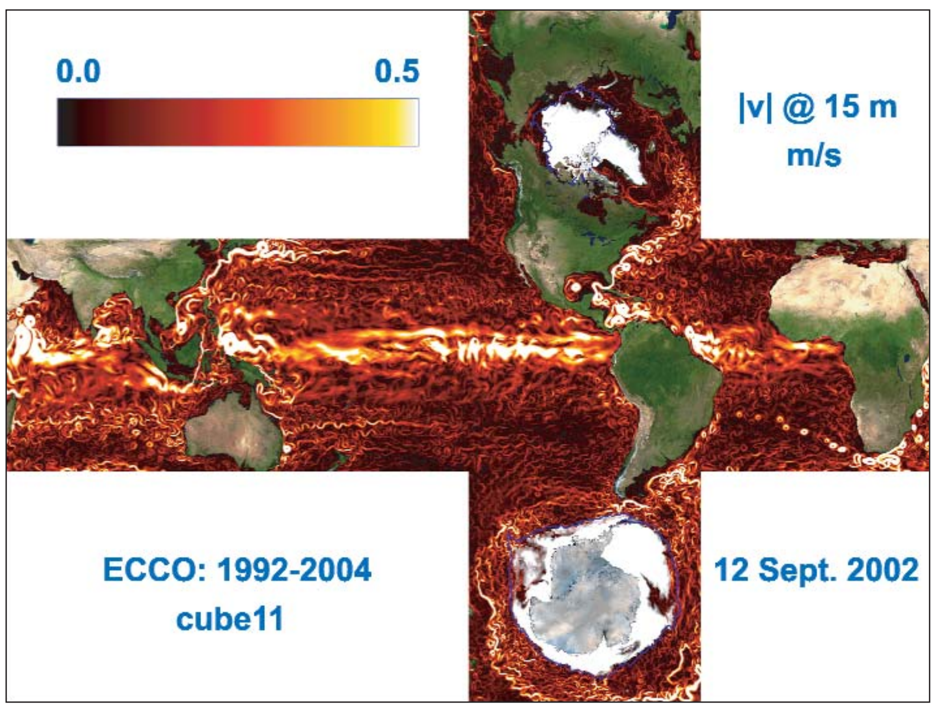

Fig. 1. Cubed-sphere ocean model configuration. The figure shows simulated near-surface (15-m) ocean-current speed and sea-ice cover from a preliminary eddy-permitting integration. Units are m/s. Simulated sea ice is shown as an opaque, white cover. The thin blue line is passive radiometer observations of sea-ice extent (15% concentration). Landmasses and ice shelves are overlain with NASA satellite imagery. Each face of the cube comprises 510 by 510 grid cells with mean horizontal spacing of 18 km. This model configuration can be integrated with a throughput approaching 10 years of simulation per day of computation on a 512-processor partition of the Columbia Supercomputer. This fast throughput makes eddy-permitting estimates possible. Details and animations are available at http://ecco.jpl.nasa.gov/cube_sphere/.

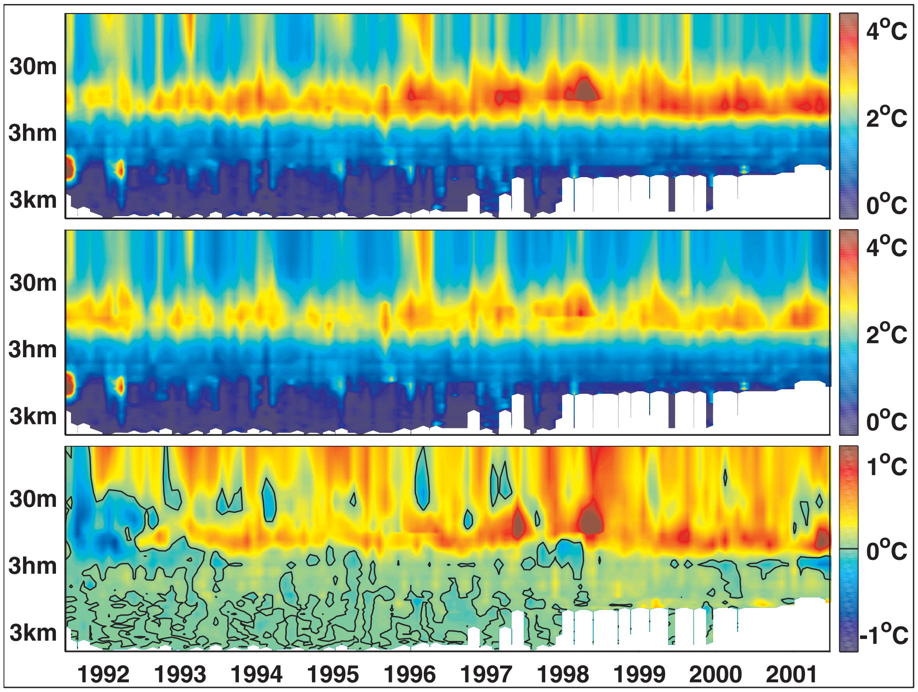

Fig. 2. Globally averaged root-mean-square (rms) difference between simulated and observed temperature during 1992–2001. The top panel shows rms difference between observations and a 1/4-degree integration forced by NCEP-reanalysis surface fluxes. The middle panel shows rms difference between observations and an integration forced by ECCO fluxes. The bottom panel shows the difference between the top two panels. The preponderance of positive values in the bottom panel indicates that the ECCO-forced simulation is closer to observations than the NCEP-forced simulation. Existing coarse-resolution estimates can, therefore, be used to initialize the eddy-permitting estimation effort.

is 50% more capacity than that of Japan's Earth Simulator.

The shared memory architecture of the SGI Altix, the supportive computational resource culture at NAS/ARC, and the advanced numerics and parallelization capabilities of the MITgcm allow the eddying cubed-sphere configuration to be integrated with a throughput approaching 10 years of simulation per day of computation. At this throughput, a next-generation global-ocean and sea-ice synthesis that admits eddies becomes feasible. Early progress toward this objective is discussed below.

Coarse-Resolution Surface Flux Estimates

A first question that has been addressed is whether the existing, coarse-resolution estimates of initial and surface boundary conditions can be used to initialize the eddy-permitting estimation effort. For this purpose, two 1992–2001 integrations were conducted using a near-global configuration with 1/4-degree horizontal grid spacing. The first integration is initialized from the World Ocean Atlas [*Conkright et al.*, 2002] and forced by surface fluxes (wind stress, heat, and freshwater) from the National Centers for Environmental Prediction (NCEP) meteorological reanalysis [*Kistler et al.*, 2001]. Initial conditions and surface fluxes for the second integration are from the ECCO 1-degree, adjoint-method optimization [*Stammer et al.*, 2004]. In addition to the specified surface fluxes, both integrations include surface relaxation terms to observed sea surface temperature and salinity.

The NCEP and the ECCO 1/4-degree simulations were compared with a comprehensive suite of observations [*Menemenlis et al.*, 2005a]. The ECCO boundary conditions generally improve the time-mean and the variability of upper ocean temperature (Figure 2) and salinity. ECCO forcing also improves the strength of the Equatorial Undercurrent and the paths of the Gulf Stream and of the Kuroshio Current near Japan.

In spite of differences in the representation of mesoscale eddies and of other physical processes, the above results indicate that boundary conditions estimated at coarse resolution can improve eddying simulations. Existing solutions can therefore be used to initialize the eddy-permitting estimation effort.

Toward Eddy-Permitting Estimates

Coarse-resolution ECCO solutions were obtained using three rigorous estimation approaches: an adjoint-model method [*Stammer et al.*, 2003], an approximate smoother [*Fukumori*, 2002], and an approach based on the computation of model Green functions (or perturbation experiments) [*Menemenlis et al.*, 2005b]. There is some limited experience in applying adjoint methods to regional eddy-permitting models [*Gebbie*, 2004], and work is under way to extend adjoint methods to global coarse-resolution and to regional high-resolution models that include sea ice. Work is also under way to develop an approximate smoother for an eddy-permitting configuration.

While development of adjoint methods and approximate smoothers continues, preliminary estimates are being obtained using a Green function approach. The fast throughput of the cubed-sphere configuration allows numerous model perturbation experiments to be computed for different initial conditions, surface forcing fields, and empirical model parameters. For example, Figure 3 shows the impact of increased ice albedo on Arctic sea-ice extent.

Formally combining these perturbations in order to minimize a cost function generates state estimates that are consistent with both the underlying model physics and the available observations. Progress toward a first, physically consistent, eddy-permitting estimate of the global-ocean and sea-ice circulation is documented at http://ecco.jpl. nasa.gov/cube_sphere/.

Improved Prospects for Ocean Climate Research

The focus of ocean state estimation during the past five years has been to demonstrate the feasibility and utility of physically consistent, global, sustained estimates, with considerable success for upper ocean and equatorial processes. However, 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 ocean climate therefore requires developing state estimation systems, of the sort described in this article, which can fully capitalize on continuing advances in computational and observational technologies.

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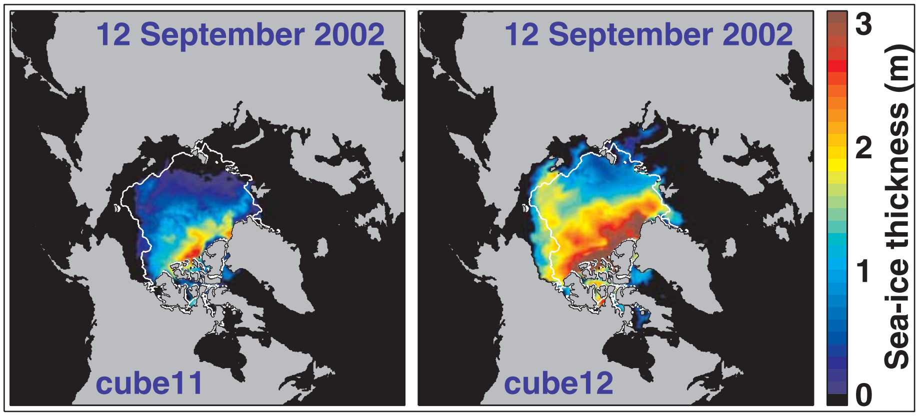

*Fig. 3. Effective sea-ice thickness (thickness times concentration) of (left) a baseline integration is compared with ice thickness from (right) an integration with increased ice albedo. The thin white line is passive radiometer observations of sea-ice extent. The fast throughput of the cubed-sphere configuration on the Columbia Supercomputer allows numerous such perturbation experiments to be computed for different initial conditions, surface forcing fields, and empirical model parameters. Formally combining the different perturbations in order to minimize the overall difference between model and observations generates state estimates that are consistent with both the underlying model physics and the available observations [*Menemenlis et al., *2005b].*

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