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GLOBAL OCEAN MODELING ON THE CONNECTION MACHINE

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We have developed a version of the Bryan-Cox-Semtner ocean model (Bryan, 1969; Semtner, 1976; Cox, 1984) for massively parallel computers. Such models are three-dimensional, Eulerian models that use latitude and longitude as the horizontal spherical coordinates and fixed depth levels as the vertical coordinate. The incompressible Navier-Stokes equations, with a turbulent eddy viscosity, and mass continuity equation are solved, subject to the hydrostatic and Boussinesq approximations. The traditional model formulation uses a rigid-lid approximation (vertical velocity = 0 at the ocean surface) to eliminate fast surface waves. These waves would otherwise require that a very short time step be used in numerical simulations, which would greatly increase the computational cost. To solve the equations with the rigid-lid assumption, the equations of motion are split into two parts: a set of two-dimensional "barotropic" equations describing the vertically-averaged flow, and a set of three-dimensional "baroclinic" equations describing temperature, salinity and deviations of the horizontal velocities from the vertically-averaged flow.

The baroclinic equations are solved explicitly with a simple forward time-stepping scheme, which is well suited to parallel machines and presents no difficulty on the Connection Machine (CM). The barotropic equations, on the other hand, are two-dimensional elliptic equations linking nearest-neighbor grid points that are solved at each time step using iterative techniques. For historical reasons dating back to Bryan (1969), the barotropic equations in the original model were formulated in terms of a streamfunction. This required solving an additional equation for each island that linked all points around the island. These extra equations created vectorization difficulties in the Cray version and communications difficulties on the CM because a separate summation around each island is required on every iteration in the

elliptic solver. This limited the number of islands that could be treated in high-resolution simulations (Semtner and Chervin, 1988).

These considerations led us to focus on the barotropic equations and look for new methods and algorithms to speed up this part of the code. We have developed and implemented two new numerical formulations of the barotropic equations that involve the surface-pressure field rather than the streamfunction. These methods have several advantages over the streamfunction method and are more efficient for both parallel and vector computers [Smith et al (1992) and Dukowicz et al. (1992)].

The first method maintains the rigid-lid approximation but reformulates the barotropic equations to solve for the unknown surface-pressure field rather than the streamfunction. In this approximation, the surface pressure represents the pressure that would have to be applied to the top of the ocean to keep it flat (as if capped by a rigid lid). There is still an elliptic equation to be solved by iteration, but the boundary conditions are simpler and much easier to implement. Unlike the streamfunction formulation, there are no additional equations for the islands and no summation is needed around each island; therefore, any number of islands can be included in the computational grid at no extra computational cost.

Furthermore, and perhaps more importantly, this method can easily handle steep gradients in the bottom topography. The matrix operator in the surface-pressure formulation is proportional to the depth field H , whereas in the streamfunction formulation it is proportional to $1/H$. As a result, the streamfunction method is much more sensitive to rapid variations in depth, especially in shallow areas such as the edges of continental shelves or high underwater mountain ranges. Because it is difficult to converge to a solution with such a rapidly varying operator, it is necessary in the streamfunction method to remove steep gradients by smoothing the depth field. The surface-pressure method, on the

other hand, converges in all cases without smoothing. Smoothing of the depth field could significantly affect the physical accuracy of the numerical simulation, especially if it involves strong currents interacting with the bottom topography.

The rigid lid approximation has the inherent disadvantage that, for transient flow, the surface height cannot be accurately computed from the surface pressure. Furthermore, the elliptic operators in both streamfunction and surface-pressure rigid-lid formulations are relatively poorly conditioned, particularly when realistic bottom topography is used, making convergence slow in an iterative solver.

These considerations led us to develop a second method that is also a surface-pressure formulation, but which removes the rigid-lid approximation and allows for a free surface (Dukowicz and Smith, 1993). The barotropic equations are solved using an implicit time-stepping scheme which is designed to accurately represent Rossby waves and long-wavelength gravity waves, while selectively damping computational modes and high-frequency or short-wavelength gravity waves. The benefits of this method are increased physical realism and fidelity of the model, and much improved convergence speed of the barotropic solver compared to the rigid-lid formulations. The free surface adds an additional diagonal term to the elliptic operator making it much better conditioned. As a result, the barotropic part of the code is now roughly an order of magnitude faster than the original streamfunction version (the exact improvement depends on the number of islands in the computational grid). In the free-surface formulation, the surface pressure is proportional to the mass of water above a reference level near the surface, and it is also proportional to the sea surface height. Thus the surface height is now a prognostic variable that may be compared to global satellite observations of surface elevation to validate the model, and satellite data may be more easily assimilated into the model.

The barotropic equations, in both the rigid-lid surface pressure and the implicit free-surface formulations, involve solving a large matrix equation using iterative methods. We chose to use conjugate gradient methods for this purpose because they are both effective and

parallelizable. Conjugate gradient methods are most effective when the matrix is symmetric. Unfortunately, the presence of the Coriolis terms in the barotropic equations make the matrix non-symmetric. We use an approximate factorization method (Dukowicz and Dvinsky, 1992) to split off the Coriolis terms, which retains the accuracy of the time discretization of these equations and leaves a symmetric matrix to which a standard conjugate gradient method may be applied. We also developed a new parallelizable preconditioning method which is very effective in accelerating the convergence of the conjugate gradient solution (Smith et al., 1992). This method exploits the idea of a local approximate inverse to find a symmetric preconditioning matrix. While it is relatively expensive to calculate this preconditioner, it need be done only once for a given computational grid.

Simulations of the ocean circulation capable of resolving features whose size is determined by the Rossby radius of deformation, such as mesoscale eddies and narrow western boundary currents, have been pursued aggressively as computing power has increased during the past decade. Much progress has been made with regional models (Bryan and Holland, 1989; FRAM Group, 1991) and global-scale models (Semtner and Chervin, 1988, 1992). In their earlier work, Semtner and Chervin (1988, 1992) carried out integrations for multiple decades at 0.5° resolution in latitude and longitude. They are presently engaged in a higher resolution simulation (Semtner, personal communication) with 900 longitude points (0.4°), 500 non-uniformly spaced latitude points (average spacing 0.25°) from 75°S to 65°N .

Even finer-resolutions global-scale simulations are now feasible with our revised model running on the massively parallel CM5 computer. A simulation is now underway with 1280 longitude points (0.28°), 896 non-uniformly spaced latitude points extending from 77°S to 77°N , and 20 depth levels. As in the latest simulation by Semtner and Chervin, the latitude spacing is chosen so that the grid cells are approximately square at all latitudes (a Mercator grid). With 896 points, the average latitudinal spacing is 0.17° , and the resolution ranges from 31 km at the equator to 7 km at 77° . For comparison, the Rossby radius of

deformation ranges from roughly 25 km at mid-latitudes to about 10 km near the poles.

The simulation was initialized with three-dimensional temperature and salinity fields provided by collaborator A. Semtner; values on the 1280x896 grid were interpolated from output of the ongoing 900x500 simulation by Semtner and Chervin. The model was then run for 300 days with constant surface forcing to smooth out any transients due to the interpolation. The model is now being integrated using seasonally varying surface winds, obtained from ECMWF analyses for the 1985-93 period, and restoring boundary conditions for temperature and salinity in the top layer, using Levitus (1982) climatology. The surface forcing datasets were also provided by Semtner. The improved numerical methods in the model allow it to be integrated with a 30-minute time step even at this fine spatial resolution. Running on 256 nodes of the 1024-node CM5 at Los Alamos, we are able to simulate one year in 28 hours. Results from the simulation will be presented.

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