OCEAN MODELLING ON THE CYBER 205 AT GFDL

MICHAEL D. COX

GFDL/NOAA
PRINCETON UNIVERSITY

PRINCETON, NEW JERSEY

Ocean modelling on the CYBER 205 at GFDL
Michael D. Cox

1. Introduction

At the Geophysical Fluid Dynamics Laboratory, research is carried out for the purpose of understanding various aspects of climate, such as its variability, predictability, stability and sensitivity. The atmosphere and oceans are modelled mathematically and their phenomenology studied by computer simulation methods. The present paper will discuss the present state-of-the-art in the computer simulation of large scale oceans on the CYBER 205. While atmospheric modelling differs in some aspects, the basic approach used is similar.

The equations of the ocean model will be presented in the following section along with a short description of the numerical techniques used to find their solution. Section 3 will deal with computational considerations and a typical solution will be presented in section 4.

2. Equations of the model

The model presented here is the multilevel numerical model described in Bryan (1969). The continuous equations will be given. A detailed description of the finite difference formulation may be found in the above work. The equations of motion are the Navier-Stokes equations written in spherical coordinates and modified by the Boussinesq approximation. Let $m=\sec\phi$, $n=\sin\phi$, $u=a\dot{\lambda}m^{-1}$ and $v=a\dot{\phi}$, where a is the radius of the earth, ϕ the latitude and λ the longitude. It is convenient to define the advection operator

$$\Gamma(\gamma)=ma^{-1}[(u\gamma)_{\lambda}+(v\gamma m^{-1})_{\phi}]+(w\gamma)_{z}. \tag{1}$$

The equations of motion on a sphere are

$$u_t+\Gamma(u)-2\Omega nv=-ma^{-1}(P/\rho_o)_{\lambda}+F^{\lambda}, \tag{2}$$

$$v_t+\Gamma(v)+2\Omega nu= -a^{-1}(P/\rho_o)_\phi+F^\phi, \tag{3}$$

$$\Gamma(1)=0, \tag{4}$$

$$g\rho=-P_z, \tag{5}$$

where ρ_o is unity in cgs units. The conservation equations for the temperature and salinity are

$$T_t+\Gamma(T)=F^T \tag{6}$$

$$S_t+\Gamma(S)=F^S \tag{7}$$

The terms in F contain effects of mixing as well as external driving forces. The equation of state

$$\rho=\rho(T,S,z) \tag{8}$$

is an empirically derived formula relating the local density of seawater to temperature, salinity and depth.

The set of equations (1-8) are cast into finite difference form. The prognostic equations (2,3,6,7) are solved as an initial value problem, placing all terms except the local time derivative on the right hand side and carrying out timesteps to predict new values of velocity, temperature and salinity on a prescribed mesh covering the model ocean domain. Given a certain configuration of steady wind driving and differential surface heating (both entering through the F terms), a statistical steady state is approached asymptotically in time. Time scale analysis of Eqs.(6,7) reveals that O(1000) years of integration is needed to bring the sluggish abyssal layers of the ocean model into a steady state.

3. Computational considerations

Let us consider a rectangular ocean basin model comparable in size to the N. Atlantic Ocean. It extends 60° in longitude, 65° in latitude and 4000 meters in depth. It is desirable to cover this domain with a mesh fine enough to resolve mesoscale (O(100 km)) eddies which play an important role in transporting various properties through the ocean. The minimum resolution needed for this purpose is roughly 1/3rd degree in latitude and somewhat larger, say .4 degree in longitude due to the convergence of meridians on the globe. This results in a horizontal grid space of 150x195 points. Vertically, 18 levels are needed to resolve the scales of interest. This brings the total to just over 1/2 million grid points for which Eqs.(1-8) must be evaluated each timestep.

The longest timestep which can be used without incurring numerical instability is given by the Courant-Friedrichs-Lewy condition

$$c\Delta t/\Delta x<1 \qquad (9)$$

where c is the phase velocity of the fastest moving wave in the ocean. Since high speed external gravity waves have been filtered from this model by the condition w=0 at the surface, the fastest wave is that associated with the internal density gradients (internal gravity wave) which has a speed of roughly 3m/sec. The smallest Δx occurs at the northern wall of the model due to convergence of meridians, and is about 20 km. The resultant Δt is such that roughly 5000 timesteps are necessary to integrate one year. Therefore, 5 million timesteps, or 2.5×10^{12} grid point evaluations of Eqs.(1-8), are required to integrate this model to a steady state. Even the fastest modern day computers cannot accomplish this task in a reasonable time, although steady progress is being made. The former computer at GFDL, the Texas Instruments ASC, took 15 seconds to compute one time step on the above model. At this speed, 2.4 years of computing would be needed to reach a steady state solution. Clearly, compromises must be made in designing experiments which are achievable in a reasonable amount of computer time. This may involve reducing the domain size, or integrating for a shorter period, or both. (Interesting results may be obtained from an integration of O(10) years, particularly for the upper ocean where time scales of adjustment are relatively short.) The greater the computational speed which can be attained, the less severe the compromises must be.

In converting the ASC ocean model to the CYBER 205, the most fundamental alteration of the code had to do with the treatment of land masses. Previously, the computation was carried out only over ocean points by making the DO loop limits functions of the placement of land. The contiguity requirement of the 205 for vectorization allows only the innermost of the three dimensional loops to vectorize in this case. An alternative method of handling land is to compute <u>all</u> points as if they were ocean and, at the end of the timestep, restore the land to its specified value using a masking array. Contiguity is then satisfied and vectorization is enabled through two dimensions. (The third dimension cannot be vectorized because it is cycled through memory from disc.) By using the latter technique, the typical vector length in the computation is increased from 150 in the example above (east-west dimension) to 2700 (east-west times depth dimension) resulting in a considerable decrease in the relative time spent in vector startup.

An additional time saving has been accomplished in an area of the code which is used heavily, but is inherently unvectorizable due to a recursive property. Using Q8 calls to insert machine language directly into the FORTRAN, CDC personnel have "unrolled" this loop, greatly improving on the code generated by the compiler for the equivalent FORTRAN loop.

The use of half-precision on all floating point variables has resulted in a gain of only about 15% in overall running speed, although sections of the code which are 100% vectorized increase in speed by roughly 40%. Additional work is needed to determine why the overall gain is so small considering the high degree of vectorization of the code.

Since the model above is too large to fit into core memory entirely, data is cycled through memory from disc as it is needed each timestep. If this disc transfer cannot be buffered sufficiently well, computation ceases while waiting for the I/O to finish. The result is that the computer may not be used efficiently, particularly if the other jobs running concurrently have the same difficulty. Until recently, this was a severe problem on the 205. The above model, when in the 205 alone, ran only about 15% of the wall clock time. Improved I/O schemes have been developed by CDC personnel at GFDL and currently the same model runs about 80% of the wall clock time when alone. This compares favorably with I/O efficiencies on the ASC.

The CYBER 205 version of the model described above currently takes 4 seconds to compute one timestep, almost a factor of 4 faster than the ASC. While this speed still does not make the experiment proposed at the beginning of this section feasible, the compromises which are necessary to produce an attainable solution are much less severe than before. One such experiment will be described in the following section.

4. An ocean simulation experiment

If one wishes to study the effects of topography on the dynamics of the Gulf Stream, an argument can be made that it is not necessary to consider a domain as large as the one proposed earlier, and that several decades of integration is sufficient. Therefore, let us reduce the domain from 65 to 27 degrees in latitude and from 60 to 32 degrees in longitude. Also, for this purpose, the vertical resolution may be decreased from 18 layers to 5 layers. This produces a model which takes approximately one hour of 205 time to integrate one year of ocean time. Applying surface wind stress and differential heating similar to that of the N. Atlantic, this model has been integrated from rest a total of 20 years. The resulting temperature pattern at the second layer, centered at 212 meters depth, is shown in Fig. 1. The land mass in the northwest corner simulates the gross features of the U.S. east coast. A continental shelf and slope is also included in this solution. The simulated Gulf Stream is revealed by the tightly packed isotherms along the coast and bending out to sea at the point representing Cape Hatteras. In agreement with observations, there exist both cold and warm core "rings" which have broken from the Stream and are drifting westward. An example of the former is centered at about 70°W, 30°N and of the latter at 68°W, 37°N.

Three other experiments have been carried out in this series, altering the topography along the western boundary to study its effect on the path and behavior of the Gulf Stream.

References

Bryan, K., 1969 A numerical method for the study of the circulation of the World Ocean. J. Comput. Phys., 4, 347-376.

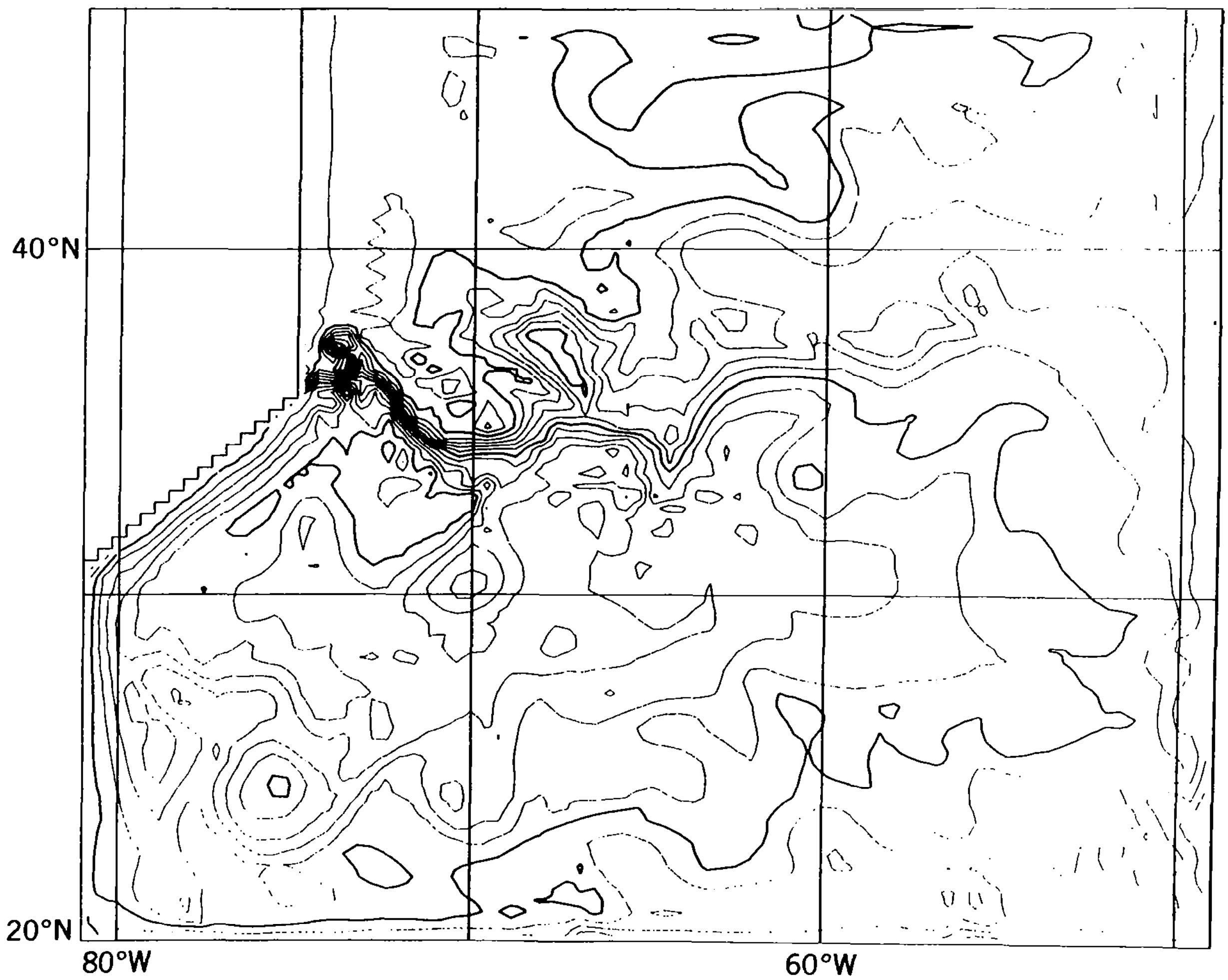

Fig. 1 Temperature at 212 meters depth. The contour interval is 1°C.