A HIGH RESOLUTION SIMULATION OF THE WIND- AND THERMOHALINE-DRIVEN CIRCULATION IN THE NORTH ATLANTIC OCEAN

Frank O. Bryan and William R. Holland

National Center for Atmospheric Research, P.O. Box 3000, Boulder, Colorado, 80307

ABSTRACT

A simulation of the general circulation of the North Atlantic Ocean has been carried out using a thermodynamic primitive equation numerical model with sufficient horizontal resolution to explicitly include the hydrodynamic instability processes responsible for eddy formation. The model is forced with climatological, seasonally varying, wind stress and surface heat and salt fluxes. The role of eddies in the general circulation, including their interactions with thermodynamic processes such as poleward heat transport and thermocline ventilation are being investigated. While the simulation has some obvious deficiencies, the overall quality of the solution is very good, leading us to believe that the next level of model development should be directed at more accurate representations of diapycnal processes and the incorporation of more realistic surface forcing.

INTRODUCTION

The ubiquity of mesoscale motions and their importance in the general circulation are well established facts in oceanography. The role that ocean eddies play in global climate is still an open question however. The sparsity of current measurements precludes direct estimates of the eddy contribution in basin- to global-scale heat budgets. The dichotomy that has existed in ocean modeling over the last decade has also prevented us from answering this question. On one hand are models with active thermodynamics and moderate to high vertical resolution, but low horizontal resolution. These have been developed in an attempt to represent the large-scale hydrographic structure and climatic properties (water mass formation rates, heat and freshwater transports, sea surface temperature anomalies, etc.) of individual ocean basins or the world ocean. The strong dissipation required to maintain numerical stability in these low resolution models inhibits physically realistic hydrodynamic instabilities as well. Thus, the only source of variability in this type of simulation is time dependence in the imposed atmospheric forcing (or open boundary conditions if they exist). This class of models has been moderately successful in simulating the mean circulation and hydrographic structure of the world ocean, e.g., Bryan (1979), Meehl et al. (1982), and the variability of the upper ocean circulation where the variability is primarily wind forced, e.g., Sarmiento (1986), Philander et al. (1987). On the other hand are models with high horizontal resolution, but low vertical resolution, and generally incomplete treatment of thermodynamic processes. These have been developed in order to investigate the dynamics of time-dependent circulation systems including mesoscale eddies and their interactions with the mean flow. This class of models has shown some success in representing the distributions of eddy variability and the structure of western boundary currents of the subtropical gyre circulations systems, e.g., Holland et al. (1983), Holland (1985, 1986). Studies carried out with these models have provided insights leading to major advances in the theory of the ocean general circulation. The majority of these calculations have been carried out using the quasigeostrophic equation system. This system does not contain the high frequency gravity waves, and is hence much more economical to integrate than the primitive equation system. However, thermohaline processes are difficult to incorporate into these models and they are limited to non-global domains.

The advent of the current generation of supercomputers has facilitated the convergence of these two modeling approaches. Basin- to global-scale simulations which include both a complete representation of the thermodynamic processes responsible for water mass formation and sufficient horizontal resolution to allow the hydrodynamic instabilities responsible for eddy formation have become feasible. In this paper we describe such a calculation for the circulation in the North Atlantic basin. In addition to addressing basic questions about the role of mesoscale motions in the ocean general circulation and climate, this experiment is meant to serve as a benchmark to judge our progress in basin-scale modeling. The results of this experiment and their analysis will help guide future development efforts by indicating which aspects of the models are most in need of improvement and which are most successful and by providing a reference solution against which to compare succesive experiments. These analyses are still underway, so only a preliminary overview of the results will be presented here.

MODEL CONFIGURATION

The basic model used in this experiment is the primitive equation model developed at the NOAA Geophysical Fluid Dynamics Laboratory by Bryan (1969) and Cox (1984). This model has been used extensively for a variety of ocean modeling problems. The equations of motion are formulated using second-order finite-differences on the Arakawa B-grid (Arakawa and Lamb, 1977) and conserve total heat content (or arbitrary scalar tracer content), mass, energy, and tracer variance in the absence of explicit dissipation or forcing. The horizontal resolution is 1/3° in latitude and 2/5° in longitude. This gives equal grid spacing in the north-south and east-west directions of 37 km at 34° latitude. Note that this is approximately equal to the radius of deformation for the first baroclinic mode in mid-latitudes, so that the resolution is just barely adequate to represent many of the eddying processes. There are 30 discrete levels in the vertical, with a spacing of 35 m at the surface and smoothly stretching to 250 m by 1000 m depth. Below 1000 m the vertical grid spacing is a constant 250 m. The computational domain is the North Atlantic basin from 15°S to 65°N latitude, including the Caribbean Sea and Gulf of Mexico, but excluding the Mediterranean Sea (Figure 1). Cuba and Hispañola are treated as true islands, requiring special treatment of the boundary conditions on the barotropic streamfunction. Bottom topography is represented in the model as stacked grid boxes, so that the bottom lies on the interface between two grid levels. The topography is derived from a digital terrain data set with 5′ latitude-longitude resolution using a simple nearest neighbor approach. The only smoothing performed is to remove single grid point holes or spikes.

Since this is the first experiment of its kind, we had little guidance in choosing parameterization schemes. Several criteria were considered when making these choices. First, we wanted this experiment to represent the state-of-the art in general circulation modeling. As this is to be the first experiment in a series and will provide a reference point for comparing future solutions, it was desirable to keep the parameterizations in this initial experiment fairly simple. The horizontal dissipation mechanism is a highly scale-selective, biharmonic operator with a coefficient of -2.5×10^{19} cm^4s^{-1} for both momentum and tracers. The vertical dissipation mechanism is the more traditional second order operator with constant coefficients of 30 cm^2s^{-1} for momentum and 0.3 cm^2s^{-1} for tracers. Additional dissipation of momentum is provided by a quadratic bottom drag. A Kraus-Turner type, surface mixed-layer parameterization is included as a purely vertical process, that is, there is no horizontal communication of mixed-layer depth or turbulence levels between adjacent grid points. A conventional adjustment scheme is used to treat free convective mixing.

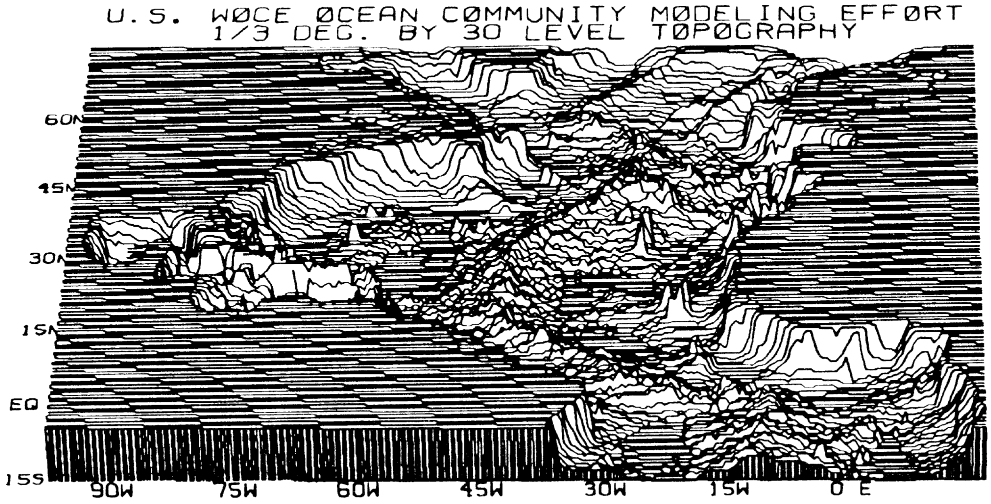

Figure 1. Three-dimensional perspective view of the bottom topography used in the experiment.

The surface boundary conditions are all based on seasonal climatological data sets. The wind stress and wind work values are taken from the Hellerman and Rosenstein (1983) climatology. The surface thermal boundary conditions are specified by a linear bulk formula described by Han (1984). In this scheme the heat flux is a linear function of the difference between the model-predicted, sea surface temperature and a prescribed "effective" atmospheric temperature that includes corrections for effects like direct solar radiation. The proportionality coefficient varies temporally and spatially, and is primarily a function of surface wind speed. Due to the lack of reliable data sets for precipitation over the ocean, the surface boundary condition for fresh water flux is implemented as a linear damping of salinity in the first model level towards the Levitus (1982) seasonal climatology. Linear interpolation between monthly or seasonal means is used to obtain necessary values for all surface forcing fields at each model time step.The restriction of the model domain to a less than global one decreases the computational burden considerably but introduces the complication of open boundaries. In this experiment these are treated by closing the boundaries to inflow or outflow but introducing narrow "buffer zones" adjacent to them. In these buffer zones the temperature and salinity are damped towards their (seasonally varying) climatological values on a time scale of 25 days at the outer edge (approximately 150 km from the walls), linearly decreasing to 5 days adjacent to the wall. The damping terms in these buffer zones must provide the heat and salt sources and, for example, sinks to convert southward flowing North Atlantic Deep Water to northward flowing surfaces waters at the southern boundary.

The experiment was initialized with temperature and salinity for January conditions from the Levitus (1982) climatology. Due to the rather strong smoothing used to construct this data set, a number of frontal features are seriously distorted in the initial condition. For example, the cold slope water north of the Gulf Stream west of 40°W is almost completely missing from the initial condition.

The model contains over two million grid points, and requires approximately 50 Cray XMP CPU hours for each year of integration. The evolving model solution was sampled at three-day intervals during the final five years of the simulation. The resulting archive of 600 samples requires over 50 Gigabytes of mass storage. Regional and temporal subsamples of the archive, as well as various statistics derived from it, are being made available to interested investigators.

RESULTS

The complexity of the solution and the volume of data required to describe it prevent a thorough description of the results in any single paper. Indeed, many investigators are involved in the analysis of this experiment since such a wide variety of phenomena are represented in the solution. In this section we will give an overview of the largest scale features of the circulation and some of the processes relevant to the climate problem.

Mean Circulation, Water Masses and Variability

During the relatively short integration, there is little drift of the basic hydrographic structure away from that described by the initial conditions. The level mean temperatures for depths less than 2000 m warm slightly during the integration, and those below 2000 m cool slightly. The mean, sea surface temperature (SST) for January over the last 15 years of the simulation is shown in Figure 2a, and the difference between the model January mean SST and the Levitus (1982) climatology is shown in Figure 2b. Over most of the basin, the model differs from the climatology by less than 1°C. The largest differences are found in the Gulf Stream region. The model Gulf Stream is displaced to the north of the mean observed position between 50°W and 75°W. This results in large positive differences on the inshore side of the Gulf Stream. The differences between the climatological SST's and the model predictions for other months show similar patterns. A 1° resolution version of the model has a similar pattern as well, with the exception that the region of anomalously warm SST along the western boundary has a larger areal extent. This is an indication that surface temperatures and heat storage away from regions of strong currents are determined primarily by local vertical processes, as suggested by Gill and Niiler (1973), and that the specification of the surface heat flux and mixed layer parameterization in the model are reasonably accurate.

The model is also successful in simulating the formation of both subtropical and subpolar mode waters. Meridional temperature sections in the upper layers of the western basin are shown in Figure 3 for January and July during the final year of the integration. During winter the mixed layer extends to 300 m depth on the south side of

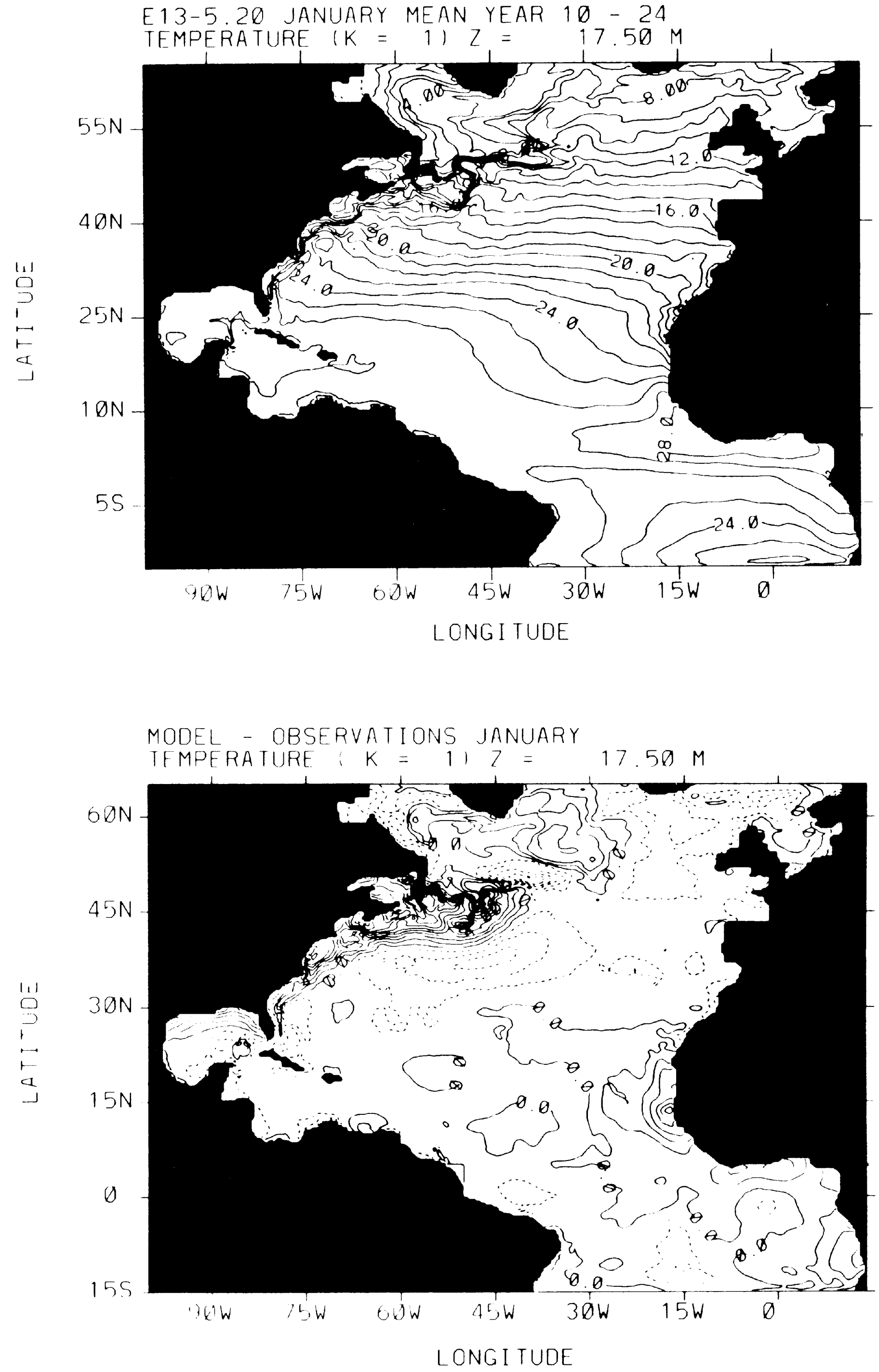

Figure 2. (a) Mean January sea surface temperature from the final 15 years of the experiment. (b) Difference between the model mean January sea surface temperatures and the Levitus (1982) January climatology.