Viscosity parameterization and the Gulf Stream separation

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Abstract. Recent advances in computer architecture allow for numerical integration of state-of-the-art ocean models at basin scale with a grid resolution of 1/10° or higher. At that resolution, the Gulf Stream's separation at Cape Hatteras is well simulated, but substantial differences from observations are still observed in its path, strength, and variability. Several high resolution (1/12°) North Atlantic simulations performed with the Miami Isopycnic Coordinate Ocean Model (MICOM) are discussed and the results suggest that, even with such a fine grid spacing, the modeled large scale circulation is still quite sensitive to choices in forcing and viscosity parameterization.

1. Introduction

Until recently, most ocean general circulation models (OGCMs) had great difficulties in reproducing the basic pattern of the Gulf Stream. The modeled Gulf Stream had in general the tendency to separate far north of Cape Hatteras and to form a large stationary anticyclonic eddy at the separation latitude [see Dengg *et al.* (1996) for a review]. Simulations with grid resolution of 1/10° or higher are now able to realistically represent the Gulf Stream separation (Paiva *et al.*, 1999; Smith *et al.*, 2000; Hurlburt and Hogan, 2000). These results support the view that a good representation of the inertial boundary layer is an important factor in the separation process (Özgökmen *et al.*, 1997). The fine mesh size also resolves the first Rossby radius of deformation everywhere in the subtropical gyre (marginally in the subpolar gyre), therefore providing a good representation of baroclinic instability processes (Paiva *et al.*, 1999; Smith *et al.*, 2000).

However, despite the more realistic behavior, the representation of the Gulf Stream separation differs from one simulation to the next, sometimes significantly. This paper discusses some of the factors influencing the modeled circulation in the Miami Isopycnic Coordinate Ocean Model (MICOM). It will be shown that even with such a fine grid spacing, the viscosity parameterization remains of importance for the modeled large scale ocean circulation.

2. Mean sea surface height fields

Figures 1 and 2 display the mean sea surface height (SSH) from two MICOM simulations with an horizontal resolution of $\Delta\phi = 1/12°$. The horizontal grid is defined on a Mercator projection with the resolution given by $\Delta\phi \times \Delta\phi\cos(\phi)$, where ϕ is the latitude. The first simulation (Fig. 1), configured from 28°S to 65°N, was integrated with MICOM for 20 years using monthly climatological COADS-based forcing (including freshwater flux) plus a weak restoration to monthly climatological surface salinity (Paiva *et al.*, 1999, Garraffo *et al.*, 2001a,b). The second simulation (Fig. 2), configured from 28°S to 70°N, including the Mediterannean Sea, was first spun-up for 6 years with MICOM using monthly climatological ECMWF atmospheric fields (including freshwater flux) plus a weak restoration to monthly climatological surface salinity, and is presently further integrated using 6-hourly ECMWF forcing from 1979 to 2000.

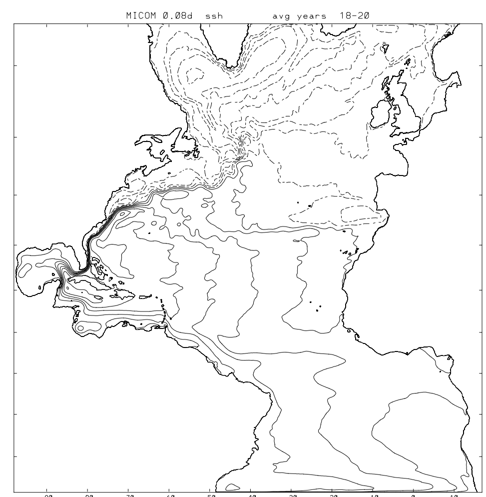

Figure 1. 3-year-mean model SSH field for the 1/12° COADS-forced MICOM. The viscosity operator is a combination of biharmonic ($A_4 = V_D \Delta x^3$, with $V_D = 1$ cm/s) and Laplacian ($A_2 = \max$ [.1 $\Delta x^2 \times$ deformation tensor, $V_D \Delta x$], with $V_D = .5$ cm/s).

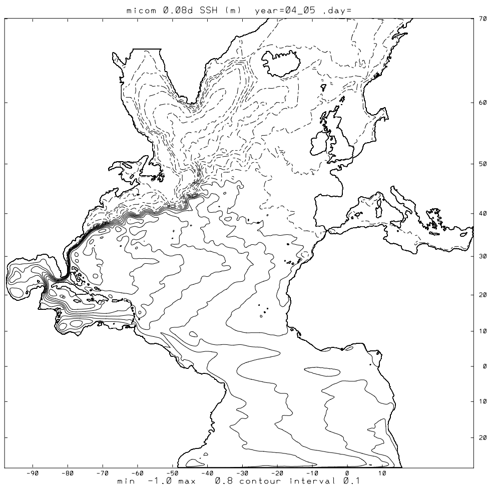

Figure 2. 2-year-mean model SSH field for the 1/12° ECMWF-forced MICOM. The viscosity operator is the same as for the COADS-forced run (see caption of Fig. 1).

In both simulations, the simulated Gulf Stream path agrees well with observations until the location of the New England Seamounts chain. Eastward of the chain, the ECMWF-forced run (Fig. 2) exhibits a path that agree well with observations everywhere. In the COADS-forced run (Fig. 1), the path east of the New England Seamounts chain is displaced northward by about 1° to 2°. This northward shift in the COADS-forced run is associated with a larger than observed seasonal migration of the path [observed annual signal of up to 100 km, north of the mean from August to November and south of the mean from March to June (A. Mariano, 1999, personal communication)]. This higher than observed seasonal shift results primarily from the fact that the MICOM bulk Kraus-Turner mixed layer is on the average deeper in the COADS-forced run than in the ECMWF-forced run (not illustrated). The deepening of the mixed layer in winter induces a decrease in the magnitude of the upper layer velocities because MICOM's mixed layer does not allow vertical shear (Kraus and Turner, 1967). A deeper mixed layer in the COADS-forced run therefore implies a Gulf Stream that is less inertial than in the ECMWF-forced run. The end result is that in the latter run, the modeled Gulf Stream path agrees well with observations and does not exhibit a higher than observed seasonal shift in latitude eastward of the New England seamounts chain.

The impact of the seamounts on the Gulf Stream path and variability was further investigated in a 3-year sensitivity experiment with COADS forcing in which the bottom topography was modified by removing the New England seamounts. The impact of removing the seamounts on the Gulf Stream path was found to be negligible (not illustrated).

3. Importance of the viscosity parameterization

When the grid spacing reaches a certain threshold, the energy cascade from the small to the large scales should be properly represented by the model physics. Dissipation should then be prescribed for numerical reasons only in order to remove the inevitable accumulation of enstrophy on the grid scale. This is the reason why higher order operators such as the biharmonic form of friction have traditionally been favored in eddy-resolving or eddy-permitting numerical simulations (Holland, 1978; Bryan and Holland, 1989; Smith *et al.*, 2000). Higher order operators remove numerical noise on the grid scale and leave the larger scales mostly untouched by allowing dynamics at the resolved scales of motion to dominate the subgrid-scale parameterization (Griffies and Hallberg, 2000).

In addition to numerical closure, the viscosity operator can also be a parameterization of smaller scales. One of the most difficult tasks in defining the parameterization is the specification of the Reynolds stresses in terms of only the resolved scales' velocities [see Pedlosky (1979) for a review] and the common practice has been to assume that the turbulent motion acts on the large scale flow in a similar manner as molecular viscosity. However, the resulting Laplacian form of dissipation removes both kinetic energy and enstrophy over a broad range of spatial scales, and its use in numerical models in general implies less energetic flow fields than in cases with more highly scale-selective dissipation operators. In order to assess the impact of the dissipation operator on the Gulf Stream system, several sensitivity experiments were performed with MICOM using Laplacian and biharmonic operators for the viscosity in the momentum equations.

The mean SSH of two simulations performed with two different magnitudes of the biharmonic viscosity coefficient are displayed in Figs. 3 and 4, respectively (COADS-forced run). When a relatively small value of the biharmonic viscosity coefficient is used (see caption of Fig. 3 for details), the western boundary current is seen to separate from the coast early at the Charleston bump before Cape Hatteras (Fig. 3). A similar result was observed with the 1/10° Los Alamos Parallel Ocean Model (POP) during the spin-up phase in which both the viscosity and diffusion had to be increased by a factor of 3 in order to eliminate this feature (Smith *et al.*, 2000). An increase in the magnitude of the biharmonic viscosity operator in MICOM did indeed also eliminate the early detachment seen in Fig. 3, but it also

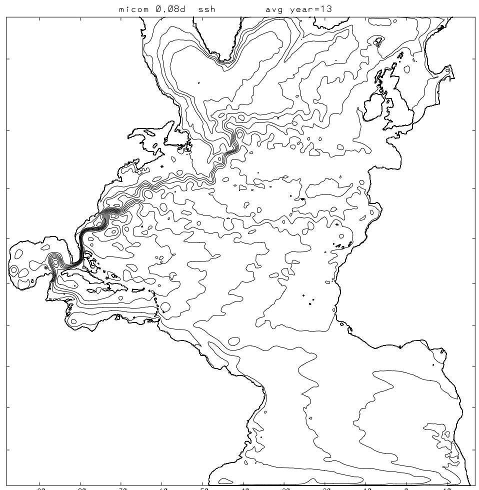

Figure 3. 1-year-mean model SSH field with a biharmonic viscosity operator; $A_4 = \max\,[.1\ \Delta x^4 \times$ deformation tensor, $V_D \Delta x^3]$, with $V_D = 1$ cm/s.

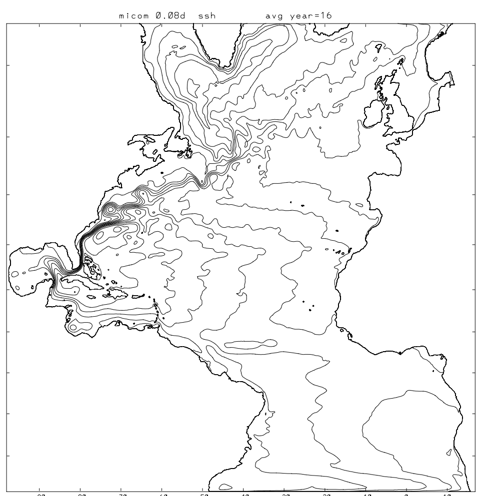

Figure 4. 1-year-mean model SSH field with a biharmonic viscosity operator; $A_4 = \max\,[\Delta x^4 \times$ deformation tensor, $V_D \Delta x^3]$, with $V_D = 2$ cm/s.

led to the establishment of a permanent eddy north of Cape Hatteras (Fig. 4). This eddy results from a series of warm core (anticyclonic) rings that propagate westward, collide with the western boundary, and are only weakly dissipated by the biharmonic viscosity operator. This behavior is reminiscent of other simulations performed with biharmonic dissipation (Smith *et al.*, 2000). The fact that this permanent eddy only appears with biharmonic operators seems to indicate an incorrect representation of the eddy/mean flow and/or of the eddy/topography interactions, possibly because of the scale selectiveness of the higher order operator that allows features that are marginally resolved by the grid spacing. In all simulations, the grid spacing is such that both the inertial and the viscous boundary layers are resolved (very well for the inertial and minimally for the viscous).

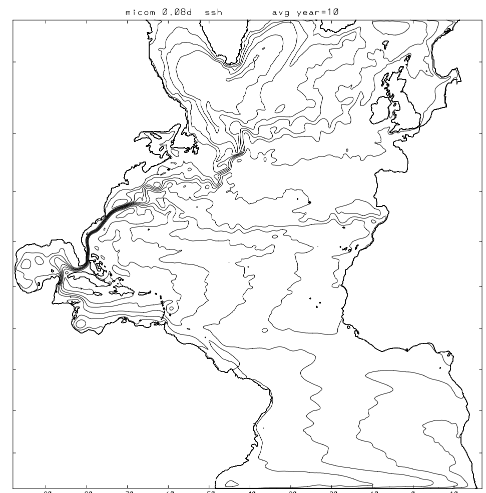

Figure 5. 1-year-mean model SSH field with a Laplacian viscosity operator; $A_2 = \max\,[.1\ \Delta x^2 \times$ deformation tensor, $V_D \Delta x]$, with $V_D = 1$ cm/s.

The mean SSH of the simulation performed with the Laplacian viscosity operator is displayed in Fig. 5 (COADS-forced run). The magnitude of the Laplacian viscosity coefficient is the minimum value needed for numerical stability. In that simulation (Fig. 5), the Gulf Stream separates well from the coast, but does not penetrate further than the New England Seamounts.

Overall, neither the Laplacian nor the biharmonic viscosity operator alone provide satisfactory results regarding the Gulf Stream system behavior. With the biharmonic operator, eddies are found to retain their structure for longer periods of time than with a Laplacian operator, but with undesirable effects on several features of the large scale circulation. With the Laplacian operator, the western boundary current and its separation are well represented, but with a weak penetration of the Gulf Stream.

With a Laplacian (harmonic) dissipation operator, the evolution of a wave $c(t)e^{ikx}$ is damped exponentially with a spin-down time $\tau_2 = A_2^{-1}\left(\frac{2}{\Delta x}\sin\left(\frac{k\Delta x}{2}\right)\right)^{-2}$. In the case of a biharmonic operator, the spin-down time is $\tau_4 = A_4^{-1}\left(\frac{2}{\Delta x}\sin\left(\frac{k\Delta x}{2}\right)\right)^{-4}$. For comparison purposes, constant harmonic and biharmonic viscosity coefficients can be expressed as a function of a diffusive velocity V_D and the grid spacing Δx as $A_2 = V_D \Delta x$ and $A_4 = V_D \Delta x^3$, respectively. Examples of spin-down times for both operators are given in Fig. 6 for the average grid

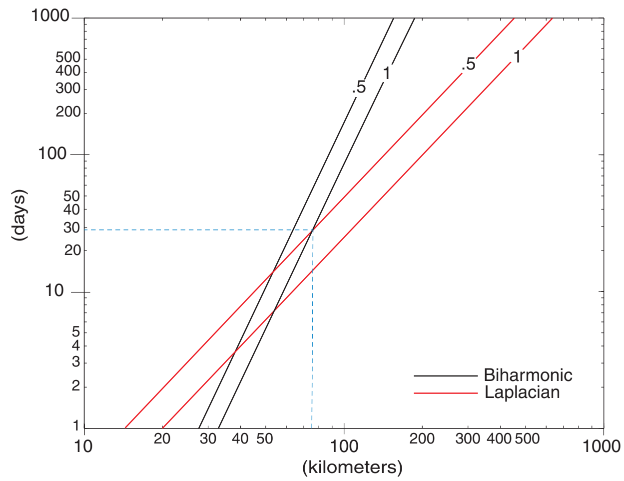

Figure 6. Laplacian and biharmonic decay time scale as a function of the wavelength k for values of the diffusive velocity $V_D = .5$ and 1 cm/s, respectively.

spacing of the MICOM simulations (6 km). For the same diffusive velocity, the biharmonic operator more strongly selects the small scales to dissipate and leaves the large scales relatively untouched.

The Laplacian experiment of Fig. 5, when contrasted to the biharmonic experiments of Figs. 3 and 4, suggests that some damping of the larger scales is necessary for a reasonable western boundary current behavior. The best separation/penetration results were obtained in the COADS-forced and the ECMWF-forced runs shown in Figs. 1 and 2 in which the viscosity operator was prescribed as a combination of the biharmonic and Laplacian operators. The main motivation for combining the two operators (see caption of Fig. 1 for details) was to be able to retain the scale selectiveness of the biharmonic operator and to provide some damping at the larger scales [performed in this case by the Laplacian operator for k greater than 80 km (Fig. 6)]. This allowed us to reduce the magnitude of the Laplacian coefficent A_2 by 50% and, at the same time, ensure numerical stability with an effective damping of the smaller scales via the biharmonic operator (Fig. 6). When combined, the individual diffusive velocity V_D specified for each operator is smaller than the mimimum value that is needed for numerical stability when only one of the operators is specified.

4. Summary and discussion

These results appear to suggest that, in a realistic setting, even with such a fine grid spacing, the modeled large scale ocean circulation is strongly dependent upon the choices made for the viscosity operators. Furthermore, it appears that the cascade of energy from the small scales to the larger scales may not take place as anticipated and that some large scale information is needed for a proper representation of the western boundary current. In the experiments described in this paper, the latter is taking place via the Laplacian viscosity operator. Hyperviscosity (∇^{2n} operator with $n \geq 2$) is often used in numerical simulations of turbulent flows to extend the range of the inviscid inertial cascade. It has, however, been argued that it may also contribute non-trivial spurious dynamics (Jiménez, 1994). While it can be firmly stated that a resolution of 1/10° is sufficient for the Gulf Stream to separate from the coast at Cape Hatteras (Paiva *et al.*, 1999; Hurlburt and Hogan, 2000; Smith *et al.*, 2000), it is not yet clear what is the optimal resolution for a correct Gulf Stream penetration and variability. A four-fold increase in resolution from 1/16° to 1/64° with the Laplacian operator in the hydrodynamic (i.e. no thermal forcing) Navy Layered Ocean Model (NLOM - Hurlburt and Hogan, 2000) brought the SSH variability to observed levels without altering the pattern of the large scale circulation. While numerical simulations at the above-noted resolutions are becoming more common, they still demand the latest in computing facilities. A four-fold increase in resolution for the thermodynamically forced models cannot be realistically implemented with the present computer resources. Thus, further evaluation of the impact of various dissipation operators on the large scale circulation should be pursued.

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