Diagnosing the Role of Eddies in Driving the Circulation of the Northwest Atlantic Ocean

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Abstract.
In this letter we present a variation of the recently proposed "semi-prognostic method" for use with ocean models. The new version has the advantage that model drift is effectively prevented, while at the same time the meso-scale eddy field is free to evolve. We use the method to probe the importance of the eddy-driven circulation in the northwest Atlantic Ocean. For the particular model we use here, it is shown that the eddies strongly reinforce the eastward Gulf Stream jet and the northern recirculation in the slope region, with over 50% of the total transport of this recirculation being directly eddy-driven. The eddies also play a role in setting the temperature and salinity properties of the "northwest corner" southeast of Newfoundland.

1. Introduction

Ocean models contain systematic errors because of both physical and numerical inaccuracies, e.g. in the parameterization of unresolved physical processes and numerical truncation error. Therefore ocean models almost inevitably show a tendency to drift away from climatology in multi-year simulations. For example, the Gulf Stream tends to separate too far to the north, and the recirculation in the slope region between the Gulf Stream and the eastern Canadian Shelf tends to disappear after several years of simulation (see, for example, *Willebrand et al.* [2001]). In addition, the model temperature can be in error by as much as 10^oC in the "northwest corner" region southeast of Newfoundland (*Lazier* [1994]; see *Greatbatch et al.* [2004]). One way to correct for model drift is to follow *Sarmiento and Bryan* [1982] and add Newtonian relaxation terms to the tracer equations so as to "nudge" the model temperature and salinity towards climatology. This is equivalent to adding internal buoyancy sources and sinks to the model tracer equations, and is not consistent with the observation that the diapycnal mixing is weak in the ocean interior (e.g., *Gregg* [1989]; *Ledwell et al.* [1998]). As an alternative, *Sheng et al.* [2001] proposed the "semi-prognostic" method, which has the advantage of adjusting the model momentum equations and leaving the tracer equations unchanged. *Eden et al.* [2004] modified the original semi-prognostic method and reduced some of the drawbacks of the original method (see *Greatbatch et al.* [2004] for an overview). However, the semi-prognostic method does not prevent model drift completely; instead, it just slows it down (as can be seen from Fig. 14 in *Sheng et al.* [2001]).

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In this note, we explore a new technique based on the semi-prognostic method in which model drift is effectively prevented, while at the same time meso-scale eddies are allowed to evolve as freely as possible. We use the new method as a diagnostic tool to show the importance of eddies for driving the circulation in the northwest Atlantic Ocean. There is also a counterpart to this new method, which we point out but do not explore here.

2. Ocean model and methods

The model is the northwest Atlantic Ocean model developed by *Sheng et al.* [2001]. The model domain spans the area between 30^oW and 76^oW and 35^oN and 66^oN with a horizontal resolution of about $1/3^o$ in longitude. There are 31 unevenly spaced z levels. The model is initialized with January mean temperature and salinity fields and forced by monthly mean COADS (Comprehensive Ocean-Atmosphere Data Set) surface heat flux and 12-hourly NCEP (National Center for Environmental Prediction) wind stress starting at the beginning of January 1990. The model sea surface salinity is restored to the monthly mean climatology on a time scale of 15 days. Along the model's open boundaries, temperature and salinity are restored to climatology and the transport is specified as described in *Sheng et al.* [2001].

2.1. The semi-prognostic method

The semi-prognostic method was introduced originally by *Sheng et al.* [2001] for the purpose of adjusting a model to correct for systematic error. The adjustment is accomplished by replacing the density variable ρ in the model's hydrostatic equation by a linear combination of the model-computed density ρ_m and an input density ρ_c (in our case, climatological density):

$$\rho = \alpha\rho_m + (1-\alpha)\rho_c \equiv \rho_m + (1-\alpha)(\rho_c - \rho_m) \qquad (1)$$

where $\rho_m = \rho(T, S, p_{ref})$ is the density calculated from the model potential temperature T and salinity S, p_{ref} is the reference pressure at the center of each z level, and α is the linear combination coefficient with a value between 0 and 1 (Sheng et al. chose 0.5). Using (1), the model's hydrostatic equation can be written as:

$$\frac{\partial p}{\partial z} = -g\rho_m - g(1-\alpha)(\rho_c - \rho_m), \qquad (2)$$

where the second term on the right hand side of (2) appears as a correction term and g is the acceleration due to gravity. As noted by *Sheng et al.* [2001], the above procedure is equivalent to adding a forcing term to the horizontal momentum equations. (It is important to note that the semi-prognostic method is adiabatic, leaving the temperature and salinity equations unconstrained). The presence of $\rho_m g$ in the correction term on the right hand side of (2) leads to damping of the meso-scale eddy field in the model. *Eden et al.* [2004] smoothed the second term to avoid this damping. However, the smoothing does not prevent the slow drift of the mean circulation.

2.2. The new (semi-diagnostic) method

We start from a diagnostic model, where the density variable in the hydrostatic equation is specified from climatology ρ_c, i.e.,

$$\frac{\partial p}{\partial z} = -g\rho_c \tag{3}$$

We now rewrite (3) as

$$\frac{\partial p}{\partial z} = -g\rho_m - g(\rho_c - \rho_m) \tag{4}$$

(the same as (2) with $\alpha = 0$). The new method, which we call the "semi-diagnostic" method, uses equation (4) in the model, but with the correction term $g(\rho_c - \rho_m)$ spatially filtered so that

$$\frac{\partial p}{\partial z} = -g\rho_m - \overline{(\rho_c - \rho_m)}g. \tag{5}$$

Since $\overline{-g\rho_m - \overline{(\rho_c - \rho_m)g}} = -\overline{\rho_c}g$, it follows that the large-scale flow field of the model is strongly constrained by the large-scale climatology, $\overline{\rho_c}$. Meanwhile, the eddy field, which depends on the first term $-g\rho_m$, is free to develop. Furthermore, there is no coefficient α involved in equation (5), as in the semi-prognostic method, avoiding the difficulty of choosing its value. In the semi-prognostic method, the mean flow field of the model is not as strongly constrained as in the new method. This is because in Sheng et al.'s case, $\overline{-g\rho_m - 0.5(\rho_c - \rho_m)g} = -\overline{(0.5\rho_c + 0.5\rho_m)}g$, which means that only 50% of the mean flow field of the model is constrained by the climatology, and this is true for both the original semi-prognostic (*Sheng et al.* [2001]) and the smoothed semi-prognostic (*Eden et al.* [2004]) methods. It is for this reason that the semi-prognostic method cannot completely prevent model drift.

We have applied the semi-diagnostic method to the northwest Atlantic Ocean model using spatial filtering on a scale of roughly 300 km (sufficient to release the eddy field) for the overbar in (5). The input density, ρ_c, is taken from the high resolution climatology of *Geshelin et al.* [1999]. Use of the semi-diagnostic method maintains the northern recirculation, between the Gulf Stream and the eastern Canadian shelf (Fig. 1a), whereas in the semi-prognostic case ($\alpha = 0.5$, Fig. 1b) the recirculation gradually disappears. (It is important to note that the semi-prognostic model nevertheless shows much less drift than a prognostic model with the same model parameters (*Sheng et al.* [2001])). Furthermore, the semi-diagnostic case has been run for 10 years with no evidence of model drift. The transport carried by the recirculation is about 15-20 Sverdrups (Sv) in the semi-diagnostic model, and is comparable to estimates from observations (e.g., *Hogg et al.* [1986]). The semi-diagnostic method also generates a sharper front at the Gulf Stream than the semi-prognostic case (Figs. 1a,b).

It is not hard to imagine the counterpart to the semi-diagnostic method. This time we start with the hydrostatic equation seen by a prognostic model, i.e.,

$$\frac{\partial p}{\partial z} = -g\rho_m \equiv -g\rho_c - (\rho_m - \rho_c)g \tag{6}$$

rather than (3). By spatially filtering the second term, we get

$$\frac{\partial p}{\partial z} = -g\rho_c - \overline{(\rho_m - \rho_c)}g. \tag{7}$$

Since $\overline{-g\rho_c - \overline{(\rho_m - \rho_c)g}} = -\overline{\rho_m}g$, the large-scale flow field of the model is free to evolve in this case. Here we do not envisage the input density ρ_c as being the climatological density field, but rather high-frequency density fluctuations derived from altimetric data (e.g., *Cooper and Haines* [1996]) or from a higher resolution model (as in a nested modelling system; *Zhai et al.* [2004]). We leave exploration of the counterpart method to a later paper.

3. The eddy-driven circulation in the northwest Atlantic Ocean

It has long been known that eddies are an essential element in understanding the general circulation both in the atmosphere (e.g., *Philips* [1956]) and the ocean (e.g., *Gill et al.* [1974]; *Holland and Lin* [1975]). For example, the northern recirculation gyre of the Gulf Stream is thought to be mostly driven by eddies (e.g., *Holland and Rhines* [1980]; *Hogg* [1983]). However, since the flow is highly geostrophic, momentum balances are not a useful way for determining the importance of the eddies; the Reynolds stresses are usually one or two orders of magnitude smaller than the Coriolis and pressure gradient terms (*Holland and Lin* [1975]). As we now show, the semi-diagnostic method provides a simple way to determine the importance of eddies for driving the mean circulation.

At discussed in Section 2, use of the semi-diagnostic method can maintain the large-scale circulation, while at the same time leaving the mesoscale eddies free to develop. If the first term in (5) is filtered spatially in the same way as the second term, we get

$$\frac{\partial p}{\partial z} = -\overline{\rho_m}g - \overline{(\rho_c - \rho_m)}g = -\overline{\rho_c}g. \tag{8}$$

To understand the role of the eddies, an additional diagnostic model run is conducted using (8) in place of the model hydrostatic equation. In this calculation, there are no eddies (because the model is diagnostic) and temperature and salinity are treated as passive tracers. It follows that the difference between the annual mean fields in the semi-diagnostic and diagnostic cases is due entirely to the presence of mesoscale eddies in the semi-diagnostic case and their absense in the diagnostic case. In comparison with Fig. 1a, the annual mean transport streamfunction in the diagnostic case (Fig. 1c) shows a weaker front marking the Gulf Stream, and a weaker northern recirculation; only about 5-10 Sv annual transport (Fig. 1b) compared to 15-20 Sv in the semi-diagnostic case. The difference between Fig. 1a and Fig. 1c represents the eddy-driven circulation (Fig. 2). The eddies strengthen the Gulf Stream jet and the North Atlantic Current in the northwest corner (by 10-15 Sv) and strongly reinforce the northern recirculation gyre of the Gulf Stream by over 50%, and, correspondingly the outflow along the slope of the subpolar gyre (by 5-10 Sv) (Fig. 2). The eddies alter the mean flow by fluxing momentum up the gradient in the Gulf Stream and adjacent northwest corner region (*Holland and Lin* [1975], *Wardle and Marshall* [2000]). Our results also support the theoretical study by *Greatbatch* [1987].

The annual mean temperature field at 45 m depth in the semi-diagnostic and diagnostic model runs is shown in Fig. 3. It is important to note that the temperature field is not directly constrained in the model and has the same evolution equation as in an uncorrected model. In both cases, the model temperature field compares well with climatology. However, in the semi-diagnostic case, the northwest corner region is more strongly developed and penetrates more strongly into the Labrador Sea. The difference between these two model versions can be explained entirely by the presence of the eddies in the semi-diagnostic model, but not in the diagnostic model. It follows that the eddies play a role in shaping the hydrographic structure of the northwest corner region in the semi-diagnostic case.

4. Summary and Discussion

Many studies (e.g. transient tracers or the carbon cycle) require ocean models to be run for many decades. Model drift can be a serious problem in such situations calling into questioning the fidelity of the model results (see *Zhao et al.* [2004]). Nudging in the tracer equations is not desirable, since unrealistic diapycnal mixing is introduced into the model. The semi-diagnostic method introduced here adjusts the model momentum equations, as in the semi-prognostic method, leaving the model tracer equations unchanged. Different from the semi-prognostic method, which can only slow model drift, the semi-diagnostic method strongly inhibits model drift. Meanwhile, meso-scale eddies are allowed to develop freely, enabling the method to be used as a diagnostic tool to probe the importance of eddies for driving the circulation. In a model of the northwest Atlantic Ocean, we found that the eddies strongly reinforce the Gulf Stream jet and the North Atlantic Current. Over half of the transport of the northern recirculation gyre of the Gulf Stream is driven by eddies. The eddies also play a role in shaping the hydrographic structure of the northwest corner region. We note, however, that while these results are broadly consistent with the role we expect eddies to play in this region, the particular diagnosis we have carried out depends on both the model used, the quality of the input climatology, ρ_c, and the precise form of the averaging operator in (5).

The counterpart of the semi-diagnostic method was also introduced. In this case, the high frequency, small scale structures in the model are constrained, but the large-scale circulation is completely free to evolve. We suggest that this method could be used as a means of assimilating high-frequency data (e.g., the altimetric data) or as a technique for nesting models (*Zhai et al.* [2004] describe the use of the semi-prognostic method as a nesting technique). The semi-diagnostic model can be used to constrain the large-scale structure of the inner (higher-resolution) model, and its counterpart to transfer information about small scales back to the outer model. We plan to explore these issues in a later paper.

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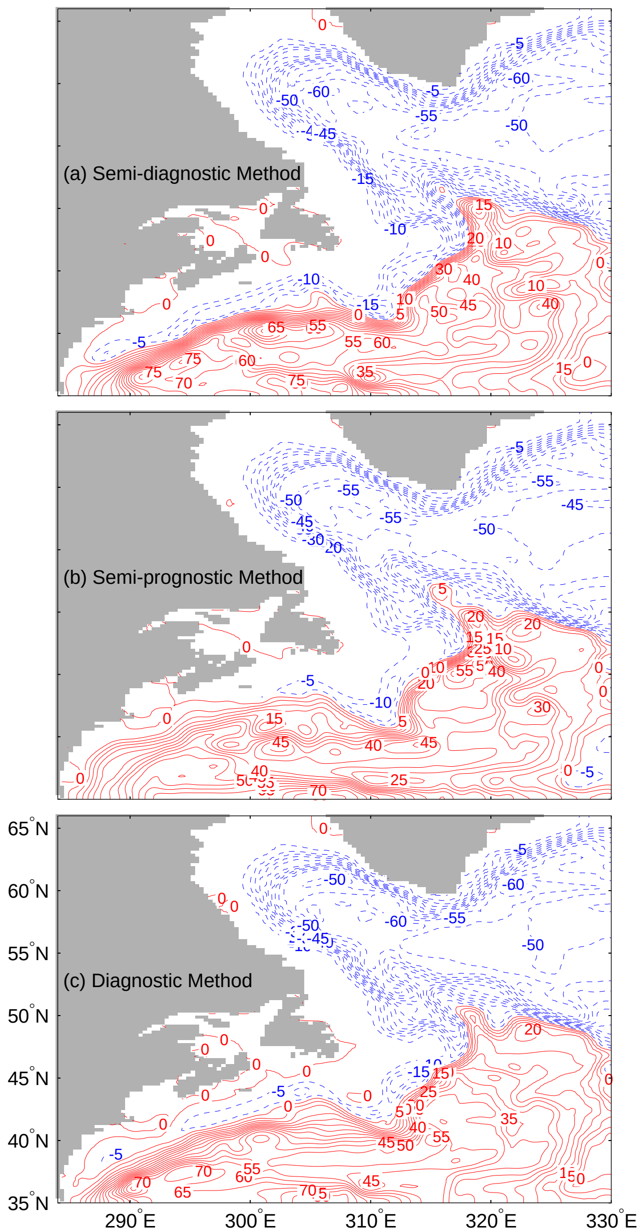

Figure 1. Model-calculated annual mean horizontal transport streamfunctions in year 3 using the (a) semi-diagnostic, (b) semi-prognostic and (c) diagnostic methods. The red contours represent anticyclonic transport and blue contours cyclonic transport. The contour interval is 5 Sv.

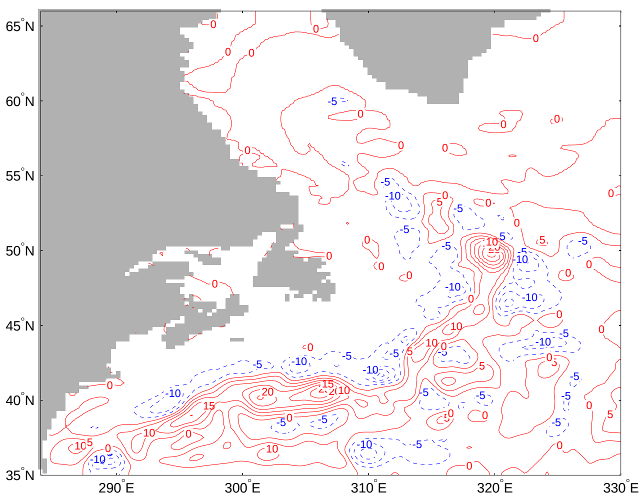

Figure 2. The eddy-driven annual mean transport (in Sv) computed by the model.

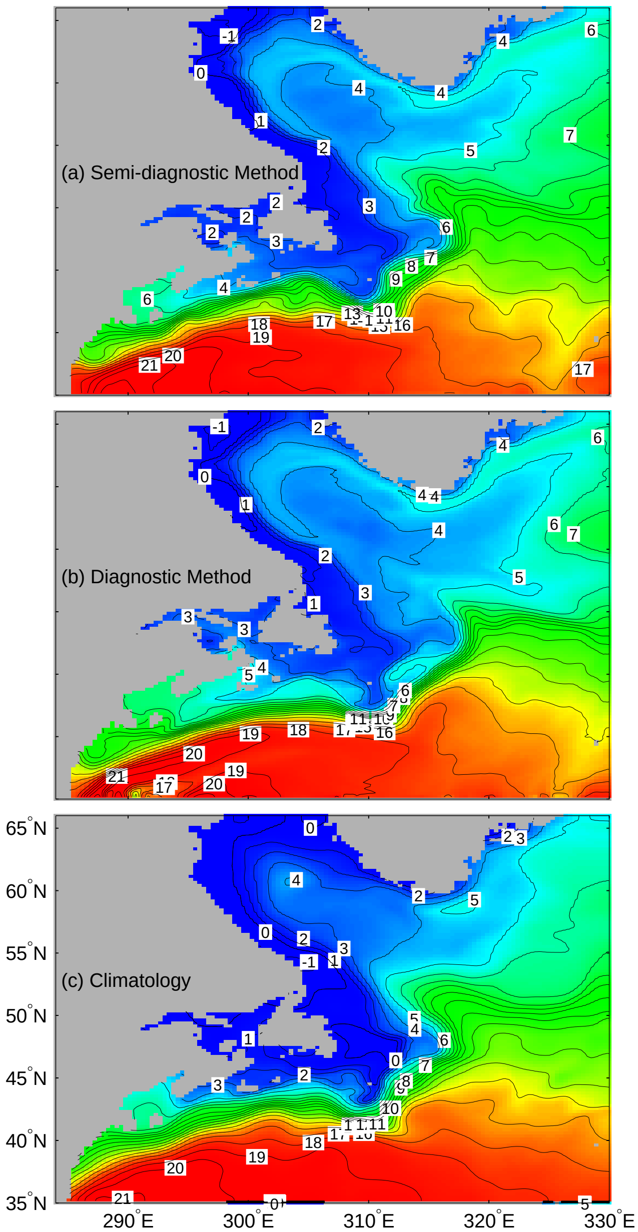

Figure 3. Model-calculated annual mean temperature at 45 m depth in year 3 using the (a) semi-diagnostic and (b) diagnostic methods. (c) Climatological temperature at the same depth. The contour interval is 2^{o}C.