Transport driven by eddy momentum fluxes in the Gulf Stream Extension region

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[1] The importance of the Gulf Stream Extension region in climate and seasonal prediction research is being increasingly recognised. Here we use satellite-derived eddy momentum fluxes to drive a shallow water model for the North Atlantic Ocean that includes the realistic ocean bottom topography. The results show that the eddy momentum fluxes can drive significant transport, sufficient to explain the observed increase in transport of the Gulf Stream following its separation from the coast at Cape Hatteras, as well as the observed recirculation gyres. The model also captures recirculating gyres seen in the mean sea surface height field within the North Atlantic Current system east of the Grand Banks of Newfoundland, including a representation of the Mann Eddy. Citation: Greatbatch, R. J., X. Zhai, M. Claus, L. Czeschel, and W. Rath (2010), Transport driven by eddy momentum fluxes in the Gulf Stream Extension region, Geophys. Res. Lett., 37, L24401, doi:10.1029/2010GL045473.

1. Introduction

[2] The importance of correctly representing the Gulf Stream and Kuroshio Extension regions in both climate and seasonal forecast models is increasingly being recognised [Rodwell and Folland, 2002; Minobe et al., 2008], yet our understanding of the dynamics of these regions is still far from complete. A common feature of both the Gulf Stream and Kuroshio Extensions is the presence of recirculation gyres north and south of the main current [Hogg et al., 1986; Jayne et al., 2009]. These recirculation gyres are thought to be driven by eddies. Indeed, recirculation gyres are a characteristic feature of quasigeostrophic eddying ocean models that use a flat bottom [e.g., Holland, 1978; Holland et al., 1984]. The similarity between the recirculation gyres in these models and Fofonoff gyres [Fofonoff, 1954] led to extensions of the Fofonoff gyre concept to stratified oceans and their application to explain the observed recirculation regions [e.g., Marshall and Nurser, 1986; Greatbatch, 1987]. A particular feature of the model of Greatbatch [1987] is a region of deep recirculation, extending throughout the depth of the ocean not dissimilar to the observed Gulf Stream recirculation gyres [e.g., Worthington, 1976; Schmitz, 1980; Richardson, 1985]. The transport in Fofonoff-type models of the recirculation regions can exceed by many times the flat-bottomed Sverdrup transport, given by integrating the wind stress curl westwards from the eastern boundary, a feature consistent with observations [Gill, 1971]. The reason for the increase in transport is the shielding of the recirculation to the east by a region in which the advection of mean relative vorticity by the mean flow is important, breaking the traditional linear Sverdrup constraint. In the present paper, we take the alternative point of view and ask how much transport can be driven by linear Sverdrup balance when the forcing is provided by the eddy momentum fluxes, here computed from satellite altimeter data. Our model calculations show that significant transport can be driven by the eddy momentum fluxes and that this transport is comparable to observed transport in the Gulf Stream Extension region.

2. Model

[3] The importance of the eddy momentum fluxes in the dynamics of the atmospheric jet stream is well known [e.g., Marshall and Plumb, 2008]. The role of the eddy momentum fluxes in the ocean is much less clear; in some regions the eddies appear to accelerate jets and in other regions to decelerate jets [Hughes and Ash, 2001]. The reason for the different behaviour in the ocean seems to be the rough and steep bottom topography seen by eddies [Ducet and Le Traon, 2001; Hughes and Ash, 2001; Greatbatch et al., 2010]. The atmospheric storm tracks, on the other hand, are typically found over the oceans [Hoskins and Valdes, 1990] where eddies see an effectively flat bottom. Greatbatch et al. [2010] have used the 13 years of available satellite data to compute eddy momentum fluxes for the Gulf Stream and Kuroshio regions. Greatbatch et al. [2010] argue that while locally it is hard to see evidence that eddies systematically flux momentum into jets, after suitable averaging, a clearer picture emerges. Since the eddies themselves extend to the bottom of the ocean, these authors also emphasise the importance of the variable bottom topography for understanding the ocean response to the eddy momentum fluxes, the idea we take as our starting point here.
respectively, and \( w \) is the vertical component), \( p \) is the pressure, \( (F^v, F^l) \) represents the forcing associated with three-dimensional turbulence (including the wind forcing), the overbar denotes a long time average at fixed height and prime deviations from that average. The terms \( \frac{\partial u^v}{\partial \theta}, \frac{\partial w^v}{\partial \beta} \) play no role in the vertically integrated momentum budget and will not be discussed further. The horizontal eddy fluxes \( u^v, u^w \) and \( v^v, v^w \) are the subject of this paper and have been calculated at the surface using geostrophic velocity anomalies for the period January 1995 to December 2008 computed from the global sea surface height anomaly dataset compiled by the CLS Space Oceanographic Division of Toulouse, France [see Le Traon et al., 1998]. The mean over the whole time series was removed from the zonal and meridional velocity anomalies before computing the fluxes. However, no attempt was made to remove the seasonal cycle (the seasonal cycle of the mean flow is, in fact, weak compared to the eddy variability and can be safely neglected). \( u^v \) is plotted by Greatbatch et al. [2010, Figure 2] [see also Ducet and Le Traon, 2001, Plate 8]. The seemingly chaotic nature of the plotted field can be attributed to the underlying variable and rough bottom topography.

In order to estimate the transport driven by the eddy momentum fluxes, we exploit the fact that the eddy momentum fluxes act over the full depth of the ocean and use a linear barotropic model for an ocean of uniform density but including the realistic bottom topography and coastlines, i.e.,

\[
\begin{align*}
\frac{du}{dt} = & - \frac{g}{c_\theta \cos \theta} \frac{\partial \eta}{\partial \lambda} + Z + \frac{\tau^v_h}{\rho_0 H} \\
\frac{dv}{dt} = & - \frac{g}{c_\theta \cos \theta} \frac{\partial \eta}{\partial \theta} + M - \frac{\tau^w_v}{\rho_0 H} \\
\frac{\partial \eta}{\partial t} + & \frac{1}{a \cos \theta} \left( \frac{\partial (H u)}{\partial \lambda} + \frac{\partial (\cos \theta H v)}{\partial \theta} \right) = 0.
\end{align*}
\]

Here \( \theta \) is latitude, \( \lambda \) is longitude, \( a \) is the radius of the Earth, \( H \) is the ocean depth, \((\tau^v_h, \tau^w_v)\) represents the bottom stress, and \( Z \) and \( M \) are the vertical average of the forcing for the zonal and meridional momentum equations, respectively, that arises from the eddy momentum fluxes (note that direct wind forcing is not included). The particular form we use for \( Z \) and \( M \) is given by

\[
Z = - \frac{1}{2Ha \cos \theta} \left( \frac{\partial}{\partial \lambda} (H u^v)_{|z=0} + \frac{\partial}{\partial \theta} (\cos \theta H v^v)_{|z=0} \right)
\]

and

\[
M = - \frac{1}{2Ha \cos \theta} \left( \frac{\partial}{\partial \lambda} (H u^w)_{|z=0} + \frac{\partial}{\partial \theta} (\cos \theta H v^w)_{|z=0} \right)
\]

where \( u^v, v^v, u^w, v^w \) are the surface fluxes derived from the satellite data and to write (6) and (7) it has been assumed that each of the fluxes, \( u^v, v^w, u^w, v^v \) varies linearly from the computed value at the surface to zero at the bottom. This choice for the vertical structure is based on the observation that eddies in the ocean generally have an equivalent barotropic vertical structure, as noted by Wunsch [1997]. It should be noted that use of a different vertical structure for the momentum fluxes will change only the amplitude of the forcing term, as long as the vertical structure is everywhere self-similar (i.e., a function only of \( z/H \)). For example, assuming the fluxes are everywhere vertically uniform removes the factor of 2 from (6) and (7), doubling the forcing amplitude. Schmitz [1982] provides evidence from 55°W that near the Gulf Stream, \( u^v \) is, in fact, remarkably uniform in the vertical. Indeed the values shown in his Figure 2 for 4000 m depth are similar in magnitude to the surface values used for our model forcing. We also note that in writing (3) and (4), we have neglected any possible feedback on the barotropic mode from the projection of the forcing on to the internal baroclinic modes. To investigate this issue would require the use of a much more complex model than we are using here. For the bottom friction we use a quadratic formulation (the only source of non-linearity in the model)

\[
(\tau^v_h, \tau^w_v)_{|z=0} = k(u^2 + v^2)^{1/2} (u, v)
\]

where \( k = 5 \times 10^{-2} \). The model domain covers the North Atlantic between 100°W to 0° and from 15°N to 55°N and uses realistic bottom topography taken from theETOPO1 data set. The horizontal resolution is 1/6° in latitude and longitude. It should be noted that extending the model further north has no effect on the model results. The results shown in the next section are obtained by running the model to steady state.

3. Results

Figure 1 shows the transport streamfunction computed from the model together with the mean sea surface height contours taken from Niler et al. [2003] to indicate the mean flow by geostrophy. We focus only on the Gulf Stream Extension region since this is where the significant model response is found. A striking feature is the tendency for positive/negative streamfunction values on the south/north side of the Gulf Stream axis, similar to the schematic drawn by Hogg [1992, Figure 10]. The corresponding recirculation gyres carry 50 Sv or more in transport, enough to account for the observed transport in the Gulf Stream Extension region [Gill, 1971; Hogg, 1992; Johns et al., 1995], although it should be noted that the magnitude of the computed transport depends on the vertical structure that has been assumed for the eddy momentum fluxes (confining the fluxes nearer the surface leads to lower transport). Between 50°W and 60°W, the recirculating gyres resemble the observed recirculation gyres [e.g., Schmitz, 1980; Hogg et al., 1986]. In particular, there is a cyclonic gyre circulation bounded by the Grand Banks to the east and the continental slope to the north corresponding to the northern recirculation gyre [Hogg et al., 1986]. The pattern of recirculating gyres straddling the Gulf Stream is also similar in character to that given by Zhai et al. [2004, Figure 2]. Zhai et al. [2004, Figure 2] shows the transport that is driven directly by the eddies in their model. Zhai et al. [2004] attribute the eddy-driven transport to forcing from the Reynolds stress terms although they do not demonstrate this explicitly. It is also striking how the transport streamfunction shown in Figure 1 resembles the total streamfunction found in the 1/10th degree eddy-permitting model of Smith et al. [2000], reproduced here as Figure 2 using the version by Bryan et al. [2007, Figure 4c]. Indeed,
while not exact, there is an interesting correspondence between some of the maxima and minima in Figures 1 and 2, e.g., the “gap” in the streamfunction pattern extending southeastwards from the Grand Banks of Newfoundland at the location of the Southeast Newfoundland Rise, as well as the locations of maxima and minima further to the north and to the west. The similarity between the two streamfunctions almost certainly reflects the influence of the variable bottom topography and supports our assumption that the forcing from the eddy momentum fluxes projects strongly on to the barotropic mode. Looking at Figure 1 in the region immediately to the east of the Grand Banks, we see that the model reproduces a gyre circulation corresponding to the Mann Eddy at 43°N, 42°W [Mann, 1967], be it that the model gyre is displaced slightly northeastwards from the surface signature of the Mann Eddy in Niiler et al.’s [2003] product. The model also indicates several eddy-driven gyres embedded in the North Atlantic Current, east of Newfoundland, with corresponding gyre circulation indicated in Niiler et al.’s [2003] data set, including in the northwest corner [Lazier, 1994] where the North Atlantic Current takes a sharp turn eastwards to pass through the Charlie-Gibbs Fracture zone.

We have run the model using forcing from each of the four terms separately that make up the divergence of the

Figure 1. Model-computed transport streamfunction (colour shading in units of Sverdrups) in the Gulf Stream Extension region. The contours show the mean sea surface height from Niiler et al. [2003] with an interval of 0.1 m.

Figure 2. As Figure 1, but for the barotropic streamfunction in the Gulf Stream region from the model of Smith et al. [2000]. Courtesy of Frank Bryan.
momentum flux in equations (6) and (7). It should be noted that despite our use of quadratic bottom friction, the sum of the four individual streamfunctions adds up to give a field almost the same as that shown in Figure 1. It is clear from Figure 3 that the model response to the $u_0$ and $v_0$ terms show a large cancellation. Nevertheless, the model response to the sum of these terms, also shown in Figure 3, is significant and comparable in magnitude to the model response forced by the $\bar{u}'\bar{u}'|_s$ and $\bar{v}'\bar{v}'|_s$ terms in the zonal momentum equation. The corresponding term in the meridional momentum equation can play a role locally but is more noisy than the model response to the other terms. It should be noted that the model response is not particularly sensitive to the specified friction (as long as this is not too large). This is

Figure 3. As Figure 1 but for the model-computed transport streamfunction (Sv, colour coding) when the model is forced separately by each of terms that appear in equations (6) and (7). Also shown is the sum of the model response to the $\bar{u}'\bar{u}'|_s$ and $\bar{v}'\bar{v}'|_s$ terms and each of the $u_0 v_0$ terms. The contour interval for the mean sea surface height is here 0.2 m.
because the model response is dominated by the integral of the topographic Sverdrup balance

$$J(\Psi, f/H) = \frac{\partial M}{\partial x} - \frac{\partial (\cos \theta Z)}{\partial \theta}$$  \hspace{1cm} (9)$$

along the $f/H$ contours from the equator at the eastern boundary where $\Psi = 0$. An interesting implication of (9) is that the model response is not local but rather depends on the “upstream” forcing along the $f/H$ contours in the direction of the eastern boundary.

4. Summary and Discussion

We have used a simple, barotropic shallow water model to show that the eddy-momentum fluxes can drive significant circulation and transport in the Gulf Stream Extension region analogous to the observed recirculation gyres [Hogg et al., 1986; Schmitz, 1980]. The model also captures several gyre circulations in the North Atlantic Current east of the Grand Banks of Newfoundland that have a surface signature in the mean sea surface height derived by Niiler et al. [2003], including the Mann Eddy [Mann, 1967] (be it displaced slightly north-eastwards in the model). The computed transport streamfunction in the Gulf Stream Extension/North Atlantic Current region is also quite similar to the barotropic streamfunction found in the 1/10th degree eddy-permitting model of Smith et al. [2000]. One reason for the success of the calculation appears to be the influence on the underlying variable bottom topography on both the structure of the eddy fluxes themselves [Ducet and Le Traon, 2001; Greatbatch et al., 2010] and on the model-computed streamfunction. As we have noted, the model response is dominated by the topographic Sverdrup response integrated along the $f/H$ contours, indicating a strong non-local aspect to the model solution. We noted that early theories of the recirculation gyres emphasised the role of advection of mean vorticity for shielding the recirculation gyres from the east and allowing the transport to increase above that given by the flat-bottomed Sverdrup prediction. Here, the model solution is dominated by the topographic Sverdrup response to the forcing imposed by the eddy momentum fluxes, with no need to invoke the mean flow, a possible reason being the variable bottom topography not included in the earlier work. A third approach to explain the increase in transport is to appeal to bottom pressure torque, as by Mellor et al. [1982] or Zhang and Vallis [2007], a factor that may play a role in reality and requires further exploration. It is difficult to assess the impact of the spatial and temporal smoothing inherent in the satellite data used to compute the eddy momentum fluxes that force our model but the general agreement between Figures 1 and 2 suggests that the essence of the forcing is being captured. Only a future study using a much higher resolution satellite data set will be able to answer this question, although studies using the new generation of high resolution models might also help. Finally, we note that there is growing interest in the possible impact of the Gulf Stream Extension region on the atmosphere [e.g., Rodwell and Folland, 2002; Minobe et al., 2008] and there are clear implications from our results for attempts to represent the recirculation gyres in climate or seasonal forecast models. In particular, there is the need to parameterise the eddy momentum fluxes, a potentially daunting task that requires including the impact of the underlying variable bottom topography on these fluxes. It may be that a simpler and more effective alternative is the use of bias-correction techniques, such as the so-called semi-prognostic method reviewed by Greatbatch et al. [2004].

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References


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