The Role of Mesoscale Eddies in the Remote Oceanic Response to Altered Southern Hemisphere Winds

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ABSTRACT

It has been suggested that a strengthening of the Southern Hemisphere winds would induce a more vigorous overturning through an increased northward Ekman flux, bringing more light waters into the oceanic basins and enhancing the upwelling of North Atlantic Deep Water in the Southern Ocean, thereby increasing ocean ventilation. Simulations from a coarse- and a fine-resolution version of a coupled model, subject to idealized wind stress changes in the Southern Ocean, are presented. In the fine-resolution eddy-permitting model, changes in poleward eddy fluxes largely compensate for the enhanced equatorward Ekman transport in the Southern Ocean. As a consequence, northward transport of light waters, pycnocline depth, Northern Hemisphere overturning, and Southern Ocean upwelling anomalies are much reduced compared with simulations in the coarse-resolution model with parameterized eddies. These results suggest a relatively weak sensitivity of present-day global ocean overturning circulation to the projected strengthening of the Southern Hemisphere winds.

1. Introduction

The steady-state meridional overturning circulation (MOC) is driven by both diapycnal mixing and mechanical energy input at the surface (Kuhlbrodt et al. 2007). Wind-driven upwelling in the Southern Ocean (SO) is believed to be the main source of dense-to-light water transformation. Southern Hemispheric winds, through their associated northward Ekman flux, exert a major role in determining the shape and strength of the present day interhemispheric Atlantic MOC (AMOC; Toggweiler and Samuels 1998; Gnanadesikan 1999). Besides the steady circulation, understanding the mechanisms of variability and change of the MOC is of fundamental importance in climate dynamics and in the prediction of the oceanic response to future climate projections under global warming scenarios. Recent modeling studies have shown that Southern Hemisphere subpolar westerly winds will shift poleward and intensify because of changes in radiative forcing (e.g., Fyfe and Saenko 2006), and it has been suggested that an increase in wind energy input will have implications for the large-scale oceanic circulation (Saenko 2007; Delworth and Zeng 2008; Klinger and Cruz 2009). Gnanadesikan (1999) describes the fundamental balance relating the SO winds, eddies, thermocline depth, and interior mixing to North Atlantic Deep Water (NADW) formation in a conceptual framework. Building on the pioneering ideas of Toggweiler and Samuels (1998), the theory presented in Gnanadesikan (1999) demonstrates the role of the SO as a driving mechanism for the MOC and in setting the pycnocline stratification. At steady state, the rate of light-to-dense water conversion in the Northern Hemisphere is balanced both by upwelling through the thermocline and in the SO. The conversion of dense-to-light water in the SO depends upon a balance between wind-induced northward Ekman flux and an eddy-induced southward flux. Further, Gnanadesikan (1999) suggested that, if Southern Hemisphere winds were to strengthen,
the MOC and northward heat transport would also intensify as a consequence of enhanced northward flow of light waters—changes in pycnocline depth and SO upwelling would follow consistently. The above prediction has been validated by recent studies (Gnanadesikan et al. 2007; Delworth and Zeng 2008; Klinger and Cruz 2009).

Here, we revisit the notion that an intensification of the wind stress over the Southern Hemisphere could result in significant remote responses of the ocean circulation with the use of a fine-resolution global coupled climate model. In a recent paper, Farneti et al. (2010) analyze in detail the SO response to anomalous surface forcings with the Geophysical Fluid Dynamics Laboratory Climate Model, versions 2.1 and 2.4 (GFDL CM2.1 and CM2.4). Compared to the case in which eddies are parameterized, and consistent with recent observational (Böning et al. 2008) and idealized modeling studies (Hallberg and Gnanadesikan 2006; Meredith and Hogg 2006), the eddy-permitting integrations show that eddies act as a buffer to atmospheric changes, and the magnitude of the SO response is greatly reduced, leading to weak modifications in residual overturning circulation, isopycnal slopes, and Antarctic Circumpolar Current (ACC) transport. The energized mesoscale eddy field is responsible for an enhanced eddy-induced circulation ($\Psi^*$), which counterbalances changes in the Ekman-induced mean circulation ($\Psi$), thus controlling the residual circulation ($\Psi_{res}$) response to anomalous forcings. In the limit of perfect compensation (i.e., $\Psi' = \Psi^*$, where primes denote an anomaly over the control due to wind stress variations) $\Psi_{res}$ remains constant. We focus in this paper on the remote implications of the degree of such local balance for the global overturning, with an emphasis on the Atlantic Ocean.

2. Model and experimental design

We use two GFDL global coupled climate models. The first one is CM2.1 (Delworth et al. 2006), with an ocean model resolution of $1^\circ$, a progressively finer meridional resolution equatorward of $30^\circ$ reaching $1/3^\circ$ at the equator, and 50 unevenly spaced vertical levels. The model employs a parameterization for eddy-induced advection and along isopycnal diffusion of tracers (Gent and McWilliams 1990; Gent et al. 1995). The atmospheric model uses the finite-volume dynamical core, has a horizontal resolution of $2.5^\circ \times 2^\circ$, and 24 vertical levels. The second model, CM2.4, is a finer spatial resolution version of CM2.1. The ocean model has a resolution of $1/4^\circ$ with an approximately constant aspect ratio, translating into gridbox sizes of approximately 27 km at the equator, reducing to as small as 9 km at high latitudes. In addition to finer resolution, the ocean climate model does not use a parameterization of mesoscale eddy mixing, has more accurate numerics, and substantially smaller viscosity (Farneti et al. 2010). Consistent with the move toward finer oceanic resolution, the atmospheric horizontal resolution was refined to $1^\circ \times 1^\circ$.

For both models, we present results from two different simulations. The first is a control run (CTL), where greenhouse gas concentrations are held fixed at 1990 concentrations, which provides us with baseline climatic conditions in the coupled models. In a zonally averaged sense, the meridional density gradient across the ACC is very similar in both models and observations (Farneti et al. 2010; Böning et al. 2008). Care should be taken when comparing the control runs to observations, because the control run experiences 1990 radiative forcing every year, whereas in nature the radiative forcing (and associated climatic response) has evolved over time as the atmospheric composition has changed. From this multicentury control simulation, three time periods are chosen to provide initial conditions for a three-member ensemble of Southern Hemisphere momentum flux perturbation experiments. In these experiments, an anomalous wind stress pattern is added to the wind stress felt by the ocean between latitudes 20° and 75°S. The wind stress anomaly is derived as the difference in the late twenty-first century between a CM2.1 simulation with Special Report on Emissions Scenario (SRES) A1B radiative forcing scenario and a control simulation. To elicit a clear response signal, the pattern is multiplied by a factor of 3 before being used (experiment POS3). The resulting time mean zonal mean zonal wind stress felt by the ocean in the two simulations is shown in Fig. 1a. Delworth and Zeng (2008) analyzed POS3 simulations with CM2.1. We extend here their work by studying the response of a finer-resolution coupled model to the same anomalous wind stress patterns. Because of computational cost, POS3 experiments are 200 years long for CM2.1 but only 40 years long for CM2.4. We will thus focus our analysis on the first 40 years of both integrations and show anomalies in the ocean circulation response computed as time means between model years 31–40 of the ensemble mean of the POS3 runs minus the corresponding CTL solution.

3. Results

In Fig. 1a, we show the zonal mean zonal wind stress in the CTL and POS3 experiments. The time mean wind stress felt by the ocean in the two models is nearly identical. However, the AMOC response is very different. Figures 1b and 1c show the time series of the anomalies in maximum value of the AMOC, computed at 20°N in the CTL and POS3 experiments for CM2.1 and CM2.4, respectively. The coarse-resolution model shows a
strengthening of the AMOC of about 3 Sv (1 Sv = $10^6$ m$^3$ s$^{-1}$) after 40 years, and it will continue to strengthen for the following century, as shown in Fig. 3 of Delworth and Zeng (2008). The model with explicit eddies exhibits a much weaker intensification of northward volume flux, of around 1 Sv, suggesting a reduced anomalous northward Ekman transport in the SO feeding the upper limb of the AMOC.

Global and Atlantic MOC anomalies are shown in Fig. 2. Consistent with most coarse-resolution climate models (Sen Gupta et al. 2009), strengthening of the SO wind stress drives a local circulation anomaly that penetrates into the deep ocean, as the anomalous northward Ekman flow is balanced by a return southward flow at depth, resulting in a significant intensification of the Deacon Cell in CM2.1 (Fig. 2a). However, the response in the eddy-permitting CM2.4 model (Fig. 2b) is less than 30% of that found with CM2.1 because, it is argued, the energized mesoscale eddies induce an overturning circulation anomaly opposing the increased Eulerian circulation (Farneti et al. 2010). The remote implications are readily seen in Figs. 2c and 2d, where we focus on the Atlantic basin response. Considering the time mean for years 31–40, the AMOC in CM2.1 has attained an anomaly of around 3 Sv at 20$^\circ$N, whereas it is roughly only a third of that in CM2.4 (1 Sv; see also Figs. 1b,c). Further, focusing on the latitude at which the upper limb of the MOC—driven by SO processes—enters the Atlantic basin ($\sim$30$^\circ$S), a streamfunction anomaly of 7 Sv is present for CM2.1 while only 1 Sv has penetrated into the Atlantic in CM2.4. This result suggests that the two solutions will most likely continue to diverge, and differences between the two models will grow with longer integrations. Similar discrepancies between models are found in the Indo-Pacific basin (not shown).

The deep MOC is responsible for a large fraction of the meridional energy transport in the ocean and in the total climate system (Vallis and Farneti 2009). Changes in MOC strength are thus expected to lead to a significant response in ocean heat transport (OHT) in the different basins. Farneti et al. (2010) show how, in the SO, wind-induced changes in meridional eddy heat transport are partially compensating for the anomalous heat transport accomplished by the mean flow. Figure 3 examines the Global, Southern Ocean, and Atlantic Ocean OHT anomalies in the two models under POS3 forcing. Globally, as expected, OHT anomalies are weaker in the model with explicit eddies. Locally, the SO stands out as being buffered from the anomalous zonal momentum input from surface winds because of the energized mesoscale eddy field (Fig. 3b). The reduced anomalous flow of water in the upper layers from the SO in to the oceanic basins induces a weaker OHT response in the Atlantic (again,

![Fig. 1](http://journals.ametsoc.org/jpo/article-pdf/40/10/2348/4505975/2010jpo4480_1.pdf)

(01/01/00) CLIMATE AND OCEAN CIRCULATION

(a) Zonal mean zonal wind stress (Pa) felt by the ocean for the CTL and POS3 experiment. Response of the AMOC to POS3 changes in wind stress over the Southern Ocean for (b) CM2.1 and (c) CM2.4. The quantity plotted is the anomaly in Sv (with respect to the climatological-averaged value of CTL) of the maximum value of the overturning streamfunction at 20$^\circ$N in the Atlantic. All values plotted are three-member ensemble means. Thin lines are for annual mean data, while thick lines denote 11-yr running means.
roughly 30% than with parameterized eddies), with broad implications for Northern Hemisphere climate (Fig. 3c).

We now turn our attention to the evolution of the oceanic pycnocline and associated light and dense water fluxes. Simple scalings relate the pycnocline depth to the strength of the overturning, so that the two have been predicted to increase with stronger Southern Hemisphere winds (Toggweiler and Samuels 1998; Gnanadesikan 1999). The pycnocline depth is given by (Gnanadesikan et al. 2007)

\[ D_s = \int_0^H \left[ \sigma_s(z) - \sigma_s(z = -H) \right] dz \]

where \( \sigma_s \) is the potential density referenced to 2000 m, and a depth \( H = 2500 \) m is chosen to avoid any topographical interference (results are not sensitive to the choice of reference pressure or depth). The zonally averaged pycnocline depth anomalies for the two models subject to POS3 anomalous forcings are shown in Fig. 4. Indeed, \( D_s \) increases with enhanced wind stress in both models but striking differences exist. In particular, the local response in the SO is greatly attenuated in CM2.4 (Fig. 4a), and the Atlantic pycnocline shows a much reduced deep penetration of light surface water (Fig. 4b).

Changes in thermocline depth can be thought as a proxy for changes in meridional transport of light and dense waters. Following Gnanadesikan et al. (2003), we partition the two waters with a value of \( \sigma_0 = 27.5 \), which in
the model separates Antarctic Intermediate Waters from North Atlantic and North Pacific Deep Waters, and plot the anomalous northward transport of light water in Fig. 5. In CM2.1, dense-to-light water transformation in the SO increases with stronger winds, leading to a greater conversion of light-to-dense waters, mainly in the North Atlantic. The same is not true for CM2.4, which shows only modest differences in meridional fluxes.

4. Discussion and conclusions

In a recent study (Farneti et al. 2010), we presented solutions to idealized Southern Hemisphere winds perturbation experiments in two different global climate coupled models: one with parameterized eddies and one with permitted eddies. Results from the fine-resolution global coupled climate model showed that wind-induced modifications in northward Ekman transport are largely...

FIG. 3. OHT anomalies (POS3–CTL, units of PW) in CM2.1 (solid lines) and CM2.4 (dashed lines) for (a) the global ocean, (b) the Southern Ocean, and (c) the Atlantic Ocean.

FIG. 4. Zonally averaged (a) global and (b) Atlantic anomalies in pycnocline depth (m) for CM2.1 (solid lines) and CM2.4 (dashed lines).
balanced by enhanced eddy-induced fluxes in the SO. Here, we have shown that, compared with simulations with parameterized eddies, the net change in northward transport of light water, pycnocline depth, Northern Hemisphere overturning, and Southern Ocean upwelling is significantly reduced in the eddy-permitting model.

Based on fine-resolution coupled model studies (Farneti et al. 2010) and observational estimates (Böning et al. 2008), the ACC seems to be in an “eddy-saturated” parameter regime, where increasing wind forcing does not alter the circumpolar transport. However, this does not necessarily mean that the ACC has always been in a saturated state, as buoyancy forcing and a meridional shift of the westerlies could alter the dynamics of the ACC in past and future climates. There is no buoyancy forcing in the eddy saturation theory of Straub (1993), which argues that ACC transport is controlled by stratification and not wind stress. Local and remote buoyancy forcings play a major role in setting the stratification and transport of the ACC (Gnanadesikan and Hallberg 2000), and the relative importance of buoyancy and eddy fluxes is not well constrained. Hence, diabatic forcings may well move the model away from an eddy-saturated state into a regime in which momentum flux does modify the properties of the flow in the ACC region, with little eddy generation (a buoyancy-dominated regime; Hallberg and Gnanadesikan 2001). Moreover, although the ACC horizontal flow might be in an eddy-saturated state, this does not necessarily imply a total compensation between mean and eddy components of the meridional overturning circulation [as shown in Farneti et al. (2010) and the present study], thereby allowing for some anomalous SO upwelling and ventilation of deep water. How different

the stratification was and will be in the ACC, what sets the critical slope whereby the ACC is moved into an eddy-saturated parameter space, and how effective the mesoscale eddies can be in counteracting the wind-driven overturning are outstanding problems that remain to be elucidated. Moreover, water mass transformations in the SO have implications that go beyond the physical properties of the flow. For instance, the SO provides a major sink for anthropogenic CO₂ (Gruber et al. 2009). Weaker ocean ventilation sensitivity, as shown by Fig. 5, might also have implications for estimates of future trends in air–sea fluxes of carbon.

A caveat should be placed on the results from the GFDL CM2.1 coarse-resolution model because they pertain to one particular model and implementation of eddy-mixing scheme. An improved numerical implementation or a different choice of parameter values could have resulted in a response more in agreement with the eddy-permitting model. Our intention here is to understand what the sensitivity is of the present-day global ocean overturning circulation to the projected strengthening of the Southern Hemisphere winds. Based on modeling results presented here, the global oceanic circulation sensitivity to changes in Southern Hemisphere winds is much weaker than suggested in previous modeling studies (e.g., Delworth and Zeng 2008; Klinger and Cruz 2009). We could anticipate that fully eddy‐resolving models may achieve a higher degree of compensation between eddy and mean flow transports. In view of the above, further studies with fine-resolution coupled climate models, improved representations of mesoscale eddy-induced transport, and simple conceptual models are still needed for a better understanding of past and future changes in the global ocean overturning circulation.

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