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Effects of Southern Hemisphere Wind Changes on the Meridional Overturning Circulation in Ocean Models

Peter R. Gent

National Center for Atmospheric Research, Boulder, Colorado 80307-3000; email: gent@ucar.edu

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Southern Ocean, eddy compensation, Atlantic Ocean

Abstract

Observations show that the Southern Hemisphere zonal wind stress maximum has increased significantly over the past 30 years. Eddy-resolving ocean models show that the resulting increase in the Southern Ocean mean flow meridional overturning circulation (MOC) is partially compensated by an increase in the eddy MOC. This effect can be reproduced in the non-eddy-resolving ocean component of a climate model, providing the eddy parameterization coefficient is variable and not a constant. If the coefficient is a constant, then the Southern Ocean mean MOC change is balanced by an unrealistically large change in the Atlantic Ocean MOC. Southern Ocean eddy compensation means that Southern Hemisphere winds cannot be the dominant mechanism driving midlatitude North Atlantic MOC variability.

1. INTRODUCTION

The strongest surface zonal winds in the Southern Hemisphere occur in a jet whose maximum is located at a latitude between 50°S and 55°S. Direct satellite observations and atmospheric reanalyses show that the maximum zonal wind stress forcing the ocean increased by at least 20% during the period 1980–2010 (Swart & Fyfe 2012, Bracegirdle et al. 2013, Farneti et al. 2015). Model studies that use a high-top atmosphere that includes the stratosphere indicate that this increase is due both to the deepening of the ozone hole in the stratosphere and to the increasing levels of carbon dioxide in the atmosphere over those 30 years. Therefore, a very important question for Earth's climate system is, what changes to the Southern Hemisphere ocean circulation have been caused by this substantial increase in zonal wind stress? **Figure 1** shows a schematic of the Southern Ocean meridional overturning circulation (MOC), the locations of the different ocean fronts and water masses, and the atmospheric forcing and fluxes.

However, there are relatively few ocean observations that can help to answer this question. There are observations showing that the Southern Ocean, defined to be south of 35°S, warmed significantly from 1980 to 2010 (Böning et al. 2008, Gille 2008) and became less saline over this period (Böning et al. 2008, Durack & Wijffels 2010). In addition, Böning et al. (2008) showed that there has been little change to the meridional isopycnal slopes in the upper 2 km across the polar and subantarctic fronts, suggesting that there has also been little change to the transport of the Antarctic Circumpolar Current (ACC) over these 30 years. This is very difficult to confirm from observations because ACC transport estimates have error estimates of at least several sverdrups (Sv).

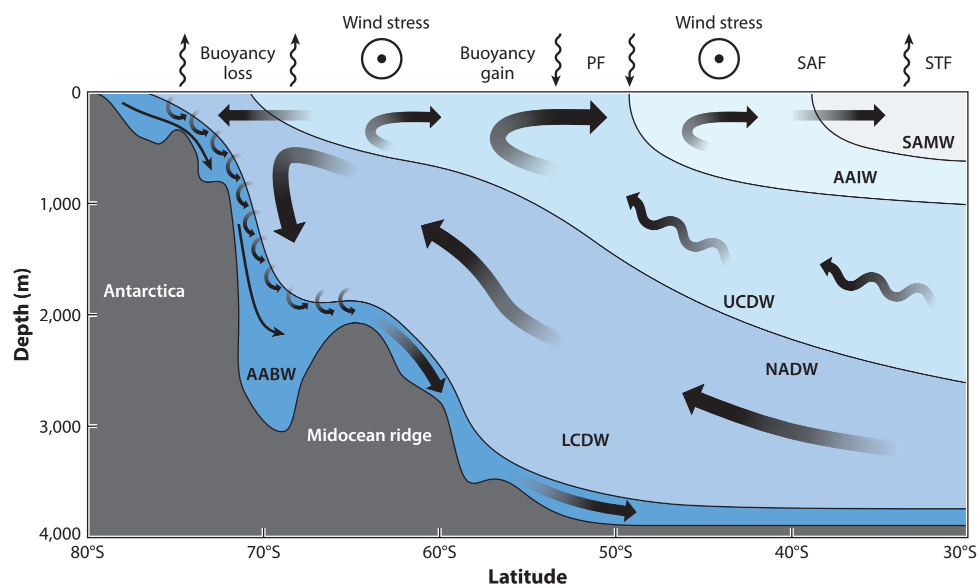

Figure 1

Schematic of the Southern Ocean meridional overturning circulation, the locations of ocean fronts and water masses, and atmospheric forcing and fluxes. Abbreviations: AABW, Antarctic Bottom Water; AAIW, Antarctic Intermediate Water; LCDW, Lower Circumpolar Deep Water; NADW, North Atlantic Deep Water; PF, polar front; SAF, subantarctic front; SAMW, Subantarctic Mode Water; STF, subtropical front; UCDW, Upper Circumpolar Deep Water. Adapted from figure 8 of Speer et al. (2000).

Because there are no direct measurements of the MOC in the Southern Ocean, addressing how increased zonal wind stress has affected the MOC requires the use of numerical models. However, it is worthwhile to remember what the statistician George Box (1979) wrote: "Essentially all models are wrong, but some are useful." Answering the question of how the MOC has changed is important because the MOC affects the large Southern Ocean uptake of heat, carbon dioxide, and other passive tracers. The answer will also help to address whether these uptakes will decrease, remain the same, or increase in the future.

The outline of this review is as follows: Section 2 summarizes results from ocean models that have horizontal resolution of $\leq$0.1° (called eddy-resolving models) and $\leq$0.25° (called eddy-permitting models). Section 3 outlines results from non-eddy-resolving models that have a resolution of approximately 0.5° or coarser. Section 4 contains results from non-eddy-resolving models in which the eddy parameterization coefficient is allowed to vary in space and time. A general discussion is given in Section 5.

2. EDDY-RESOLVING AND EDDY-PERMITTING OCEAN MODELS

2.1. Quasi-Geostrophic Channel Models

Meredith & Hogg (2006), Hogg et al. (2008), and Meredith et al. (2012) used a three-level quasi-geostrophic model with eddy-resolving horizontal resolution of 0.1° and a 3,000-km-wide periodic channel. The results showed that the eddy kinetic energy (EKE) level takes 2–3 years to respond to an increase in the magnitude of the zonal wind stress, but that, once this adjustment is completed, EKE is linearly proportional to the zonal wind stress magnitude. The increase in eddy activity results in an increase of eddy heat transport to the south, which counteracts a small increase in the northward heat transport resulting from an enhanced surface Ekman flow. Quasi-geostrophic models are unable to generate diapycnal flow and so are not suitable for direct investigation of the Southern Ocean MOC, which has to be studied in primitive equation models. However, the results of increasing EKE and southward eddy heat transport with stronger zonal wind stress remain true in all models.

2.2. Ocean Models with Simple Geometry

Henning & Vallis (2005), Viebahn & Eden (2010), and Wolfe & Cessi (2010) used domains where the northern part is an enclosed ocean and the southern part is a periodic channel. Abernathey et al. (2011) used a periodic channel, but near the northern boundary the temperature is relaxed to a prescribed vertical profile. Henning & Vallis (2005) used eddy-permitting horizontal resolution of 0.25°, and the three other studies all used a 5-km grid, which is well into the eddy-resolving regime. Henning & Vallis (2005) found that, with very strong wind stress, the depth scale of ocean stratification increases until the eddy MOC can entirely balance the mean flow MOC, so that their sum (called the residual flow MOC) is zero. Small wind stress changes about this large mean value result in the eddy MOC change completely balancing the mean MOC change, which has come to be called complete eddy compensation of the mean flow. Henning & Vallis (2005) concluded, "We have seen that eddies have a pronounced effect on the circulation in a circumpolar current, although in a case with realistic winds and buoyancy forcing, the eddies do not wholly balance the mean circulation" (p. 894). The degree to which the eddy MOC change compensates the mean MOC change caused by increased Southern Hemisphere zonal wind stress is the key question that needs to be answered by eddy-resolving ocean models.

Abernathey et al. (2011) stated, "We find that increased eddy circulation does generally compensate for increased Ekman circulation under stronger winds. However, the degree of compensation depends on the surface boundary conditions" (p. 2262). Note that the Ekman circulation is the near-surface component of the mean MOC. If a fixed flux boundary condition is used, then the eddy compensation is nearly complete; however, as noted by Abernathey et al. (2011), Wolfe & Cessi (2010) "used a relaxation boundary condition and found much greater sensitivity: in certain locations, they found an increase in the residual MOC transport almost equal to the increase in Ekman transport" (p. 2275). This suggests that eddy compensation is weak in certain locations, although Wolfe & Cessi (2010) did say that all their experiments had small residual circulations in the channel part of their domain. Wolfe & Cessi (2010) showed that the changes in the mean and eddy MOCs occur at different depths and different densities in the Southern Ocean, so that eddy compensation cannot be absolutely complete.

Munday et al. (2013) used an idealized domain that is only 20° wide, including the periodic area at the south, and eddy-permitting horizontal resolution of 0.17°. However, the small domain allowed the integrations to be run to near equilibrium and use of a wide range of Southern Hemisphere zonal wind stress maxima from 0 to 1 N m^{-2}. Their figure 9*b* shows that the maximum MOC in the periodic area increases somewhat with maximum zonal wind stress in the realistic range near 0.2 N m^{-2} but is almost independent of the wind stress in the range near 1 N m^{-2}. This indicates that eddy compensation is occurring at all zonal wind stress strengths but is almost complete at the very large value of 1 N m^{-2}.

2.3. Ocean Models with Realistic Geometry

Hallberg & Gnanadesikan (2006) used an isopycnal coordinate model with eddy-permitting resolution of 0.17°. They examined two perturbation runs where the zonal wind stress is increased and decreased by 20% compared with the control run, which is forced by a realistic annually averaged wind stress distribution. In their abstract, they wrote, "The overturning response to changes in the winds is also sensitive to the presence of eddies. In noneddying simulations, changing the Ekman transport produces comparable changes in the overturning, much of it involving transformation of deep waters and resembling the mean circulation. In the eddy-permitting simulations, a significant fraction of the Ekman transport changes are compensated by eddy-induced transport drawing from lighter waters than does the mean overturning" (p. 2232). This paper is significant in that it was one of the first to address Southern Ocean MOC changes.

Screen et al. (2009) analyzed results from the Ocean Circulation and Climate Advanced Model run at eddy-resolving resolution of 0.08°. They did not specifically address changes to the mean and eddy MOCs, but they did find that EKE takes 2–3 years to adjust to an increase in the Southern Hemisphere zonal wind stress. After this time, the eddies transport more heat southward across the ACC latitudes, which implies a stronger eddy MOC that would compensate to some degree the increase in the mean flow MOC.

Dufour et al. (2012) used the Nucleus for European Modeling of the Ocean model at 0.25° resolution to study the response of the MOC to changes in the southern annular mode. They wrote, "The mean Eulerian overturning. . .shows the same general structure as the total overturning, but it is partially compensated by the transient-eddy overturning" (p. 6967). They also pointed out that the standing eddy component of the MOC plays a large role in the response to changes in wind forcing.

2.4. Coupled Climate Models

Spence et al. (2009, 2010) analyzed results from the University of Victoria climate model, which has a simplified atmosphere component in which the wind stress is specified rather than calculated. The highest-resolution ocean component used was 0.2° × 0.4°, which is in the eddy-permitting regime. They ran climate change experiments out to 2050 with a relatively modest increase in the Southern Hemisphere wind stress. Eddy activity in the Southern Ocean increased, which increased the poleward eddy heat transport, but changes in the eddy MOC were not presented.

Much more extensive analysis had been done on experiments when a large Southern Hemisphere zonal wind stress increase is imposed in the Geophysical Fluid Dynamics Laboratory (GFDL) climate model CM2.4. This model has atmospheric resolution of 1° and eddy-permitting ocean resolution of 0.25°. Control and increased stress runs were performed in which the increased stress run nearly doubled the zonal wind stress maximum in the Southern Hemisphere to 0.33 N m^{-2} and the maximum location moved approximately 3° to the south to 56°S. Results from these runs were published by Farneti et al. (2010), Farneti & Delworth (2010), Downes et al. (2011), and Meredith et al. (2012). **Figure 2** shows the residual, mean, and eddy MOCs plotted against potential density referenced to 2 km (sigma-2) south of 35°S for the control run and from years 31 to 40 of the increased wind stress run. Even though the zonal wind stress has nearly doubled, there is only a modest increase in the residual MOC maximum of approximately 3.5 Sv. **Figure 2** shows that the mean MOC maximum increases by approximately 8.5 Sv, which is compensated by an eddy MOC maximum increase of approximately 5 Sv. This indicates that the eddy MOC compensates approximately 60% of the mean MOC increase. Note that the MOC cell maximum at 60°S and sigma-2 > 37 kg m^{-3}, which forms the Antarctic Bottom Water in the model, increases sharply in the increased wind stress run. This is due to an increase in the mean MOC, which is not compensated by an eddy MOC increase.

Farneti & Delworth (2010) concentrated on the remote effects of the large increase in Southern Hemisphere zonal wind stress. **Figure 3*a*** shows the residual MOC change after years 31–40 in the Atlantic north of 35°S. The increase in the main Atlantic overturning cell between 600 m and 3 km is less than 2 Sv everywhere, compared with the control run MOC, which has a maximum of just over 20 Sv at 36°N between 800 m and 1 km depth. This indicates that, if the CM2.4 zonal wind stress increase were more in line with the observed increase from 1980 to 2010 of just over 20%, then the increase in the Atlantic Ocean MOC would be very small—almost certainly less than 0.5 Sv everywhere.

3. NON-EDDY-RESOLVING MODELS WITH NO EDDY COMPENSATION

3.1. Models with no Eddy Advection

Toggweiler & Samuels (1993, 1995) were the first to suggest that the Southern Hemisphere zonal winds are very important in setting the strength of the Atlantic MOC. They used the ocean component of the early GFDL climate model, which had very coarse resolution of 4.5° × 3.75° × 12 vertical levels. The temperature and salinity equations used mean flow advection, Laplacian horizontal diffusion, and 30-day restoring boundary conditions. Toggweiler & Samuels (1995) stated, "Oceanographers usually think of the formation of the North Atlantic Deep Water as the quintessential example of an overturning circulation driven by thermohaline processes. This paper entertains the idea that the magnitude of NADW outflows from the Atlantic basin may be dictated by the wind stress in the latitude band of Drake Passage. The feasibility of such a linkage

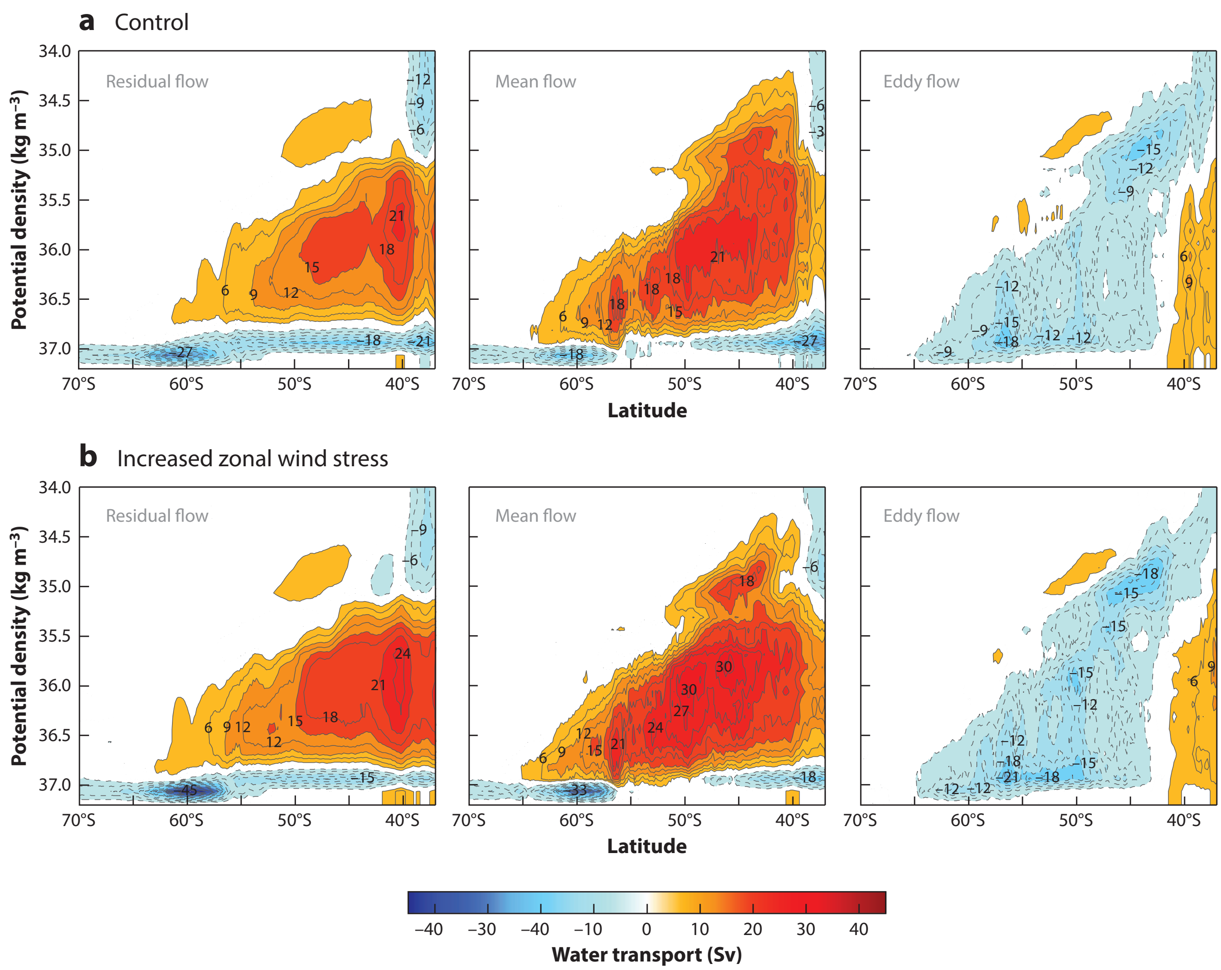

Figure 2

Residual, mean, and eddy meridional overturning circulations plotted against potential density referenced to 2 km (sigma-2) from the Geophysical Fluid Dynamics Laboratory climate model CM2.4. The top row (panel *a*) shows the control run; the bottom row (panel *b*) shows the run with strongly increased Southern Hemisphere zonal wind stress. Adapted from figure 10 of Farneti et al. (2010).

will be demonstrated using a low-resolution ocean general circulation model" (pp. 478–79). They called this the "Drake Passage effect," and these papers are widely referenced in support of the hypothesis that the Southern Hemisphere westerlies are very important in setting the strength of the North Atlantic MOC.

Rahmstorf & England (1997) used the same ocean model as Toggweiler & Samuels (1993, 1995) coupled to a very simple flux-adjusted diffusive atmosphere. This atmospheric feedback enables thermohaline forcing to generate approximately 75% of the model's North Atlantic Deep Water. In addition, the enhanced mean MOC resulting from increased Southern Hemisphere winds is mostly balanced just north of Drake Passage and is balanced only to a lesser degree by an increased North Atlantic MOC. They concluded that "the influence of Southern Ocean winds on NADW flow is only moderate and not as strong as previously suggested" (p. 2040).

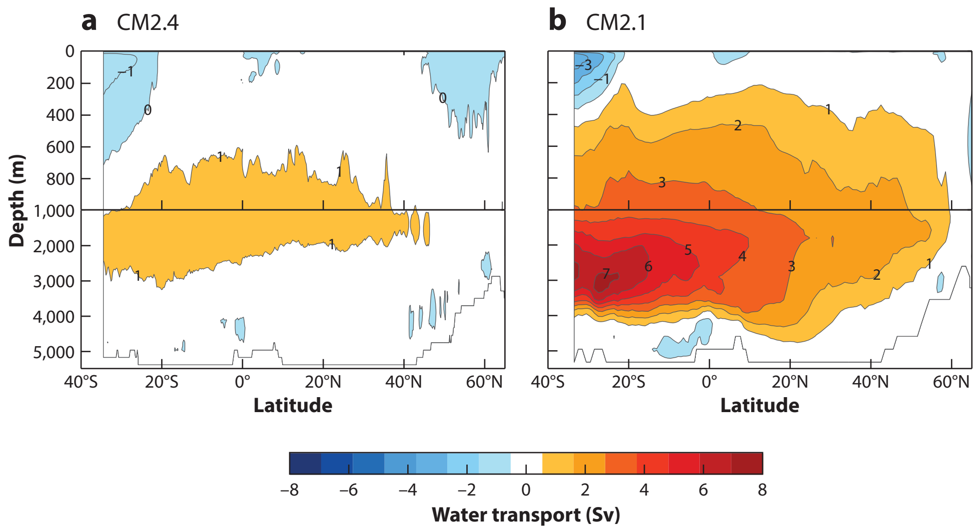

Figure 3

Change in the Atlantic meridional overturning circulation resulting from strongly increased Southern Hemisphere zonal wind stress in two Geophysical Fluid Dynamics Laboratory climate models: (*a*) CM2.4 and (*b*) the standard version of CM2.1. Adapted from figure 2 of Farneti & Delworth (2010).

Gnanadesikan & Hallberg (2000) showed results using the same ocean model as Toggweiler & Samuels (1993, 1995) and concluded, "Increasing the winds in these [Drake Passage] latitudes increases the transformation of dense water to light water within the Southern Ocean, which must be compensated by a stronger Northern Hemisphere overturning" (p. 2032). They also showed results from a much-higher-resolution 0.75° × 0.5° isopycnal model with two layers in a simple geometry domain. Their section 2*c* was one of the first discussions about the possibility of eddy effects compensating the mean flow when the Southern Hemisphere wind forcing is changed.

McDermott (1996) used a similar very-coarse-resolution ocean model but with a simplified geometry domain, and stated in his concluding section, "The Drake Passage effect can be reproduced in an ocean general circulation model with very simplified geometry" (p. 1252). Similar conclusions were also reached in the coarse-resolution model study of Hasumi & Suginohara (1999) and the 1°-resolution model study of Hirabara et al. (2007).

3.2. Models with Eddy Advection

The first ocean model to study the Drake Passage effect with an updated eddy parameterization, but in an idealized domain, was used by Klinger et al. (2003). The updated parameterization used mixing of temperature and salinity along isopycnal surfaces (Redi 1982) and included an eddy advection [Gent & McWilliams 1990 (GM)]. These were implemented in both depth coordinate and isopycnal coordinate models with various resolutions down to horizontal resolution of 1°. Klinger et al. (2003) concluded that, both with the different coordinate models and with the old and updated eddy parameterizations, "for all versions of the experiments, increases in diapycnal mixing or subpolar [Southern Hemisphere] wind stress increase the strength of the model's North Atlantic Deep Water (NADW) meridional overturning cell" (p. 263). The constant GM coefficient means that the eddy advection does not respond when the Southern Hemisphere wind stress is increased, providing the isopycnal layer thicknesses remain the same.

There have been quite a large number of studies, using both depth and isopycnal models with the Redi (1982) and Gent & McWilliams (1990) parameterization, of the MOC sensitivity to an increase in the Southern Hemisphere zonal wind stress. Studies in which the GM coefficient was kept constant have been performed by Hirabara et al. (2007), Klinger & Cruz (2009), Sijp & England (2009), Kamenkovich & Radko (2011), Sévellec & Fedorov (2011), and Wei et al. (2012), among many others. All of these studies showed a Drake Passage effect in which an increased mean Southern Ocean MOC caused by an increased zonal wind stress was balanced by an increase in the North Atlantic MOC.

Munday et al. (2013) also ran experiments at 2° and 0.5° horizontal resolutions in their idealized domain and compared the results with the 0.17°-resolution results described in Section 2.2. They used different, but constant, values of the GM coefficient. Their figure 9*b* shows that the degree of eddy compensation is somewhat worse at 0.5° resolution and considerably worse at 2° resolution, compared with the eddy-permitting 0.17°-resolution degree of eddy compensation.

4. NON-EDDY-RESOLVING MODELS WITH EDDY COMPENSATION

Delworth & Zeng (2008), Farneti & Delworth (2010), and Farneti et al. (2010) showed results from the GFDL climate model CM2.1 when the same large Southern Hemisphere zonal wind stress increase is imposed as in the CM2.4 model (described in Section 2.4). The ocean component of CM2.1 has horizontal resolution of 1° and uses the GM eddy parameterization. The coefficient is variable in the horizontal and in time and is diagnosed by the vertical integral between 100 m and 2 km depth of the potential density horizontal gradient. As a stronger zonal wind stress is applied, the mean MOC increases, which tends to steepen the isopycnal surfaces across the ACC. This results in a larger GM coefficient, which is exactly what is needed to simulate an increased eddy response and eddy MOC. Unfortunately, in the standard version of CM2.1, the GM coefficient is capped at 600 m^2 s^{-1}. This value has been used in 1° models when the GM coefficient is a global constant in order to produce a realistic ACC transport when the wind stress is approximately the observed strength. When the zonal wind stress was nearly doubled, the diagnosed values of the GM coefficient were much larger than 600 m^2 s^{-1} but were pegged back to that value by the imposed cap. This had the effect of making the standard CM2.1 response to the increased wind stress very similar to the response if the GM coefficient were kept constant at 600 m^2 s^{-1}. The response described by Delworth & Zeng (2008), Farneti & Delworth (2010), and Farneti et al. (2010) for the standard CM2.1 is very much like the response described in Section 3.2 for models with a constant GM coefficient. The increased mean MOC in the ACC region is not compensated locally by an increase in the eddy MOC, and so it must be balanced by an increase in the mean MOC in the Atlantic. **Figure 3** shows the standard CM2.1 Atlantic response alongside the CM2.4 response. In standard CM2.1, the Atlantic MOC increases by over 7 Sv near 25°S, and the response is over 4 Sv just north of the equator. This response is much larger than in CM2.4, where the ocean resolution is 0.25° and no eddy parameterization is used.

However, Farneti & Gent (2011) repeated these experiments with a modified version of CM2.1 in which the cap on the GM coefficient was doubled to 1,200 m^2 s^{-1}. A new control run showed that the present-day climate simulation is degraded in some aspects compared with the standard CM2.1 control run. However, in the run where the Southern Hemisphere zonal wind stress was nearly doubled, there was very little capping of the diagnosed GM coefficient. The eddy MOC across the ACC did increase to partially compensate the increased mean MOC. **Figure 4** shows the change in the mean MOC for the nearly doubled wind stress run compared with the control. The Atlantic MOC increase near 20°S is now just over 4 Sv, compared with over 7 Sv in the standard CM2.1. Therefore, eddy compensation does occur in the modified CM2.1, but the degree of eddy

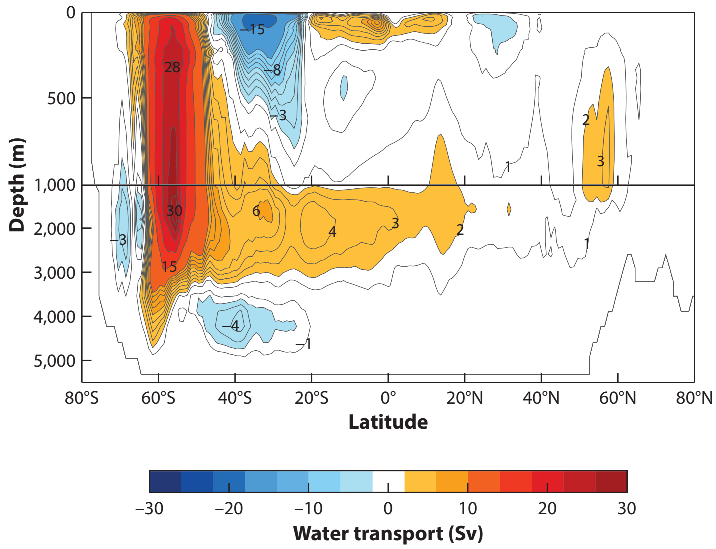

Figure 4

Change in the global ocean meridional overturning circulation resulting from strongly increased Southern Hemisphere zonal wind stress in a modified version of the Geophysical Fluid Dynamics Laboratory climate model CM2.1 in which the cap on the GM (Gent & McWilliams 1990) coefficient was doubled to 1,200 $m^2\ s^{-1}$. Adapted from figure 8 of Farneti & Gent (2011).

compensation is considerably smaller than in CM2.4, which results in a larger mean MOC change in **Figure 4** compared with that shown in **Figure 3*a***.

Hofmann & Morales-Maqueda (2011) used a non-eddy-resolving ocean model rather than a climate model and imposed changes to the Southern Hemisphere zonal wind stress. This model parameterized eddy effects using the GM scheme where the coefficient varies in three dimensions based on the local Richardson number and the Rossby radius of deformation for the length scale. This model also shows a degree of eddy compensation in that the eddy MOC increases to partially balance the increased mean MOC across the ACC.

A third case of partial eddy compensation was described by Gent & Danabasoglu (2011), who used Community Climate System Model version 4 (CCSM4). The ocean component was documented by Danabasoglu et al. (2012), and the GM coefficient varies in the vertical as well as in the horizontal and in time. A control run and a perturbation run, in which the zonal wind stress is multiplied by a factor of 1.5 south of 35°S, were analyzed. **Figure 5** shows the residual, mean, and eddy MOCs south of 35°S in the control and perturbation runs, plotted against sigma-2. The mean flow MOC maximum increased from 16.7 Sv to 20.2 Sv in the perturbation run, whereas the negative eddy MOC maximum increased from 12.8 Sv to 15.5 Sv. This partially compensates the mean MOC increase, so that the residual MOC maximum increases by only 1.4 Sv. **Figure 5** again shows that the mean and eddy MOC maxima occur at different latitudes and densities, so that the eddy MOC cannot possibly completely compensate the mean flow MOC. The degree of eddy compensation in CCSM4 is approximately 60%, which is a similar percentage to that found in the GFDL CM2.4 climate model by Farneti et al. (2010).

Iudicone et al. (2008a,b) ran a coarse-resolution 2° × 2° × 31 levels model in which the GM coefficient depended on the baroclinic instability growth rate, following Treguier et al. (1997).

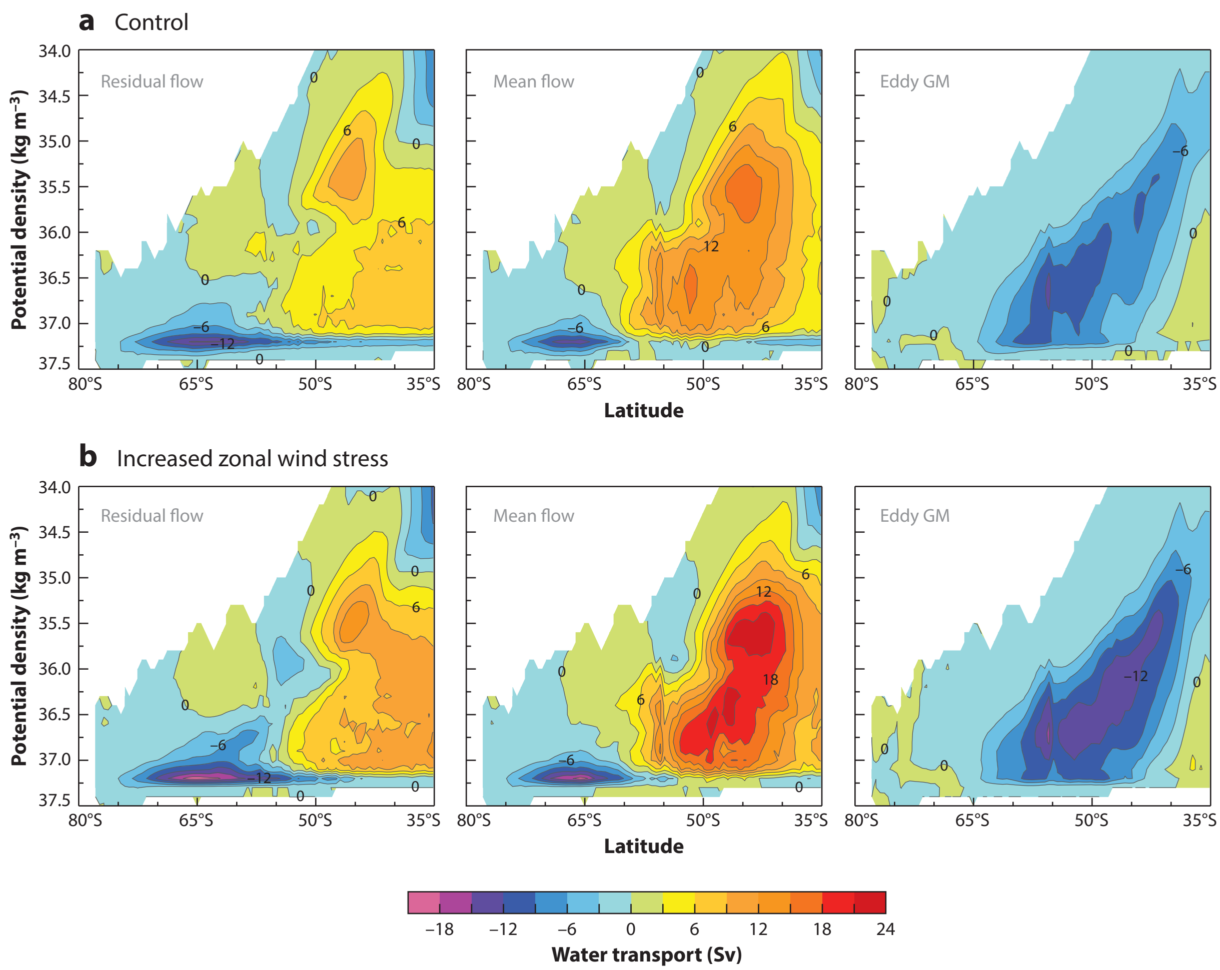

Figure 5

Residual, mean, and eddy meridional overturning circulations plotted against potential density referenced to 2 km (sigma-2) from Community Climate System Model version 4. The top row (panel *a*) shows the control run; the bottom row (panel *b*) shows the run with a 50% increase in Southern Hemisphere zonal wind stress. Abbreviation: GM, Gent & McWilliams (1990). Adapted from figure 3 of Gent & Danabasoglu (2011).

There was only a small Drake Passage effect, and the model did not confirm the findings of Toggweiler & Samuels (1995). Marini et al. (2011) used the same ocean component in a fully coupled climate model and found a correlation between the Southern Antarctic Mode and the North Atlantic MOC after 7 years, which they concluded was due to atmospheric teleconnections and not to ocean MOC changes.

5. DISCUSSION

Eddy-resolving ocean models have consistently found that the level of EKE near the ACC, the strength of the northward Ekman flow, and the mean flow MOC across the ACC are all linearly proportional to the strength of the Southern Hemisphere zonal wind stress maximum. In addition, they have shown that the eddy MOC across the ACC partially compensates the change in the mean MOC, so that the change in the residual MOC is reduced compared with the mean MOC change. However, the degree of eddy compensation varies among different models. It depends on the surface boundary conditions in ocean-only runs, with reduced eddy compensation when a relaxation (rather than fixed flux) boundary condition is used.

Meredith et al. (2012) used a theoretical argument to estimate how the isopycnal eddy diffusivity across the ACC depends on the EKE. For small EKE, the eddy diffusivity is proportional to the 3/2 power, but for large EKE it is proportional to the 1/2 power. They then assumed that the EKE is linearly proportional to the strength of the Southern Hemisphere zonal wind stress, and showed in their figure 6 that the CM2.4 results of Farneti et al. (2010) and the results of Viebahn & Eden (2010) lie between these two limits. Note that the degree of eddy compensation in CM2.4 (**Figure 3*a***) is larger than that in the results of Viebahn & Eden (2010). I conclude that eddy compensation definitely occurs in all eddy-resolving models and that the degree of eddy compensation is approximately 50%.

Another consistent result across all eddy-resolving models is that the ACC transport through Drake Passage does not vary much at all with the strength of the Southern Hemisphere zonal wind stress maximum. In several models, the ACC increases by less than 10 Sv, even when the zonal wind stress is increased by 50%. The independence of the ACC transport from the strength of the wind stress is called eddy saturation, and all eddy-resolving models show that the degree of eddy saturation is much higher than the degree of eddy compensation. Morrison & Hogg (2013) discussed in detail the relationship between eddy saturation and compensation.

The work described in Section 4 shows that a degree of eddy compensation can be achieved in the non-eddy-resolving ocean components of climate models provided that the GM coefficient is allowed to vary. Three different definitions of the coefficient have been used. In CM2.1, the coefficient is constant with depth but varies horizontally with the baroclinicity of the upper ocean. In the study by Hofmann & Morales-Maqueda (2011), the coefficient is three-dimensional because it depends on the local Richardson number and Rossby radius of deformation. In the CCSM4 model used by Gent & Danabasoglu (2011), the coefficient varies proportionally to the square of the buoyancy frequency and so varies in the horizontal and decays with depth, mimicking the decay of EKE with depth. All three specifications give a degree of eddy compensation, and figure 6 of Meredith et al. (2012) shows that the modified CM2.1 used by Farneti & Gent (2011), with the doubled eddy coefficient cap, gives a degree of eddy compensation that lies just within their theoretical bounds, whereas the standard CM2.1 lies well outside their bounds. Note, however, that the degree of eddy compensation in the modified CM2.1 is still considerably smaller than that in the eddy-permitting CM2.4.

There is another reason why using a variable GM coefficient in climate models is very important. In a model with no eddy compensation, the increased Southern Hemisphere zonal wind stress over the past 30 years strengthens the mean MOC across the ACC. This brings more water from the carbon-rich deeper ocean to near the surface south of the ACC, which in turn reduces the amount of carbon dioxide that the ocean can take up from the atmosphere in this region and so reduces the effectiveness of the ocean carbon dioxide sink. Munday et al. (2014) used an idealized domain with 2° and 0.5° resolution and different, but constant, GM coefficients. Their figure 5 shows that the level of atmospheric carbon dioxide monotonically increases with increased Southern Hemisphere zonal wind stress because the ocean takes up less carbon dioxide. In a climate model with eddy compensation, this effect is reduced (Lovenduski et al. 2013, Swart et al. 2014). Swart et al. (2014) showed that in a climate model with a variable GM coefficient, the reduction in ocean carbon dioxide uptake over the past 30 years is only approximately 40% of the reduction when the GM coefficient is a constant. As the stratosphere ozone hole recovers over the next 40–50 years, it is expected that the Southern Hemisphere zonal winds will not increase nearly as rapidly as they have over the past 30 years (Polvani et al. 2011). Therefore, I conclude that it is not at all certain that the effectiveness of the Southern Ocean carbon dioxide sink will decrease over the next 40–50 years.

Section 3 summarizes a large body of work using non-eddy-resolving ocean models that do not have eddy compensation. In these models, the local increase in the mean MOC caused by increased Southern Hemisphere zonal wind stress is balanced by an increase in the mean MOC in the Atlantic. The response would be very similar to that of the standard version of CM2.1, in which the GM coefficient is capped at 600 m^2 s^{-1} (**Figure 3*b***). This body of work has led to the conclusion that changes in the strength of the Southern Hemisphere winds can be a significant driver of variability in the North Atlantic MOC. For example, Kuhlbrodt et al. (2007), in their review "On the Driving Processes of the Atlantic Meridional Overturning Circulation," described an important process in their section 4, entitled "Wind-Driven Upwelling in the Southern Ocean." They stated, "If this mechanism dominates, the strength of the AMOC [Atlantic MOC] is controlled by winds acting on the surface of the Southern Ocean" (p. 14).

Yeager & Danabasoglu (2014) documented a diametrically opposite view of North Atlantic MOC variability. They forced the ocean and sea ice components of CCSM4 over the period 1958–2007 using the best estimate of the atmosphere variables and freshwater forcing, called the CORE-II forcing (Large & Yeager 2009). The same components are in the fully coupled model used by Gent & Danabasoglu (2011), so the GM coefficient is variable, and eddy compensation occurs. Yeager & Danabasoglu (2014) then performed a series of experiments in which they retained interannual variability only in some of the forcing fields. In one experiment, the only forcing field with interannual variability was the wind stress south of 35°S. Their section 6 showed that the small changes in the residual MOC caused by changing Southern Hemisphere winds were mostly balanced by changes in the Atlantic MOC south of the equator. The peak-to-peak change of the midlatitude North Atlantic MOC maximum from 1958 to 2007 caused by Southern Hemisphere winds was 0.7 Sv, which is very small compared with the 6.3-Sv peak-to-peak change caused by the buoyancy-driven variability of deep convection in the Labrador Sea. Yeager & Danabasoglu (2014) concluded, "The M.SO [Southern Hemisphere wind] signal is very weak north of the equator, and is far weaker than buoyancy-driven AMOC signals north of about 20°N" (p. 3239). From this analysis and the very-small-amplitude response in the North Atlantic from the GFDL CM2.4 climate model shown in **Figure 3*a***, I conclude that eddy compensation in the Southern Ocean means that Southern Hemisphere winds drive very little variability in the Atlantic MOC north of the equator, and certainly cannot be the dominant mechanism driving midlatitude North Atlantic MOC variability.

Downes & Hogg (2013) analyzed eddy compensation in the suite of models from phase 5 of the Coupled Model Intercomparison Project, and Farneti et al. (2015) analyzed a suite of non-eddy-resolving ocean models using the CORE-II forcing. Both studies confirmed that Southern Ocean eddy compensation occurs in non-eddy-resolving models only when the GM coefficient is variable, and that this strongly reduces the effect of Southern Hemisphere zonal wind stress changes on the strength of the midlatitude North Atlantic MOC maximum.

Another possible way that changes in Southern Hemisphere winds can affect the Atlantic MOC is through changes in the leakage of Agulhas water from the Indian Ocean into the South Atlantic. Biastoch et al. (2008), Biastoch & Böning (2013), and Durgadoo et al. (2013) studied this mechanism using a 0.1°-resolution regional model of the area south of South Africa that was nested in a 0.5°-resolution global model with no eddy parameterization. They showed that changes in the Southern Hemisphere zonal wind stress can cause changes in Agulhas leakage and, consequently, small changes to the Atlantic MOC, but the changes are confined to south of 20°N.

Therefore, again, the Southern Hemisphere westerlies have very little influence on the variability of the midlatitude North Atlantic MOC maximum.

SUMMARY POINTS

1. High-resolution ocean models with realistic geometry show that the Southern Ocean eddy meridional overturning circulation (MOC) partially compensates changes in the mean MOC caused by a change in the Southern Hemisphere zonal wind stress maximum, with a good estimate being approximately 50% compensation.
2. A degree of eddy compensation can be simulated in the non-eddy-resolving component of a climate model, providing the Gent & McWilliams (1990) (GM) coefficient is a variable function such that it increases across the Antarctic Circumpolar Current when the Southern Hemisphere zonal wind stress increases.
3. Non-eddy-resolving ocean models with either no eddy advection or a constant GM coefficient cannot simulate eddy compensation, and the Southern Ocean mean MOC change resulting from increased wind stress is balanced by unrealistically large changes in the Atlantic Ocean MOC.
4. Southern Ocean eddy compensation means that changes in the Southern Hemisphere zonal wind stress have a very small effect on the maximum value of the North Atlantic MOC and cannot be the dominant mechanism driving midlatitude North Atlantic MOC variability.

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