

## On the Relationship between Southern Ocean Overturning and ACC Transport

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### ABSTRACT

The eddy field in the Southern Ocean offsets the impact of strengthening winds on the meridional overturning circulation and Antarctic Circumpolar Current (ACC) transport. There is widespread belief that the sensitivities of the overturning and ACC transport are dynamically linked, with limitation of the ACC transport response implying limitation of the overturning response. Here, an idealized numerical model is employed to investigate the response of the large-scale circulation in the Southern Ocean to wind stress perturbations at eddy-permitting to eddy-resolving scales. Significant differences are observed between the sensitivities and the resolution dependence of the overturning and ACC transport, indicating that they are controlled by distinct dynamical mechanisms. The modeled overturning is significantly more sensitive to change than the ACC transport, with the possible implication that the Southern Ocean overturning may increase in response to future wind stress changes without measurable changes in the ACC transport. It is hypothesized that the dynamical distinction between the zonal and meridional transport sensitivities is derived from the depth dependence of the extent of cancellation between the Ekman and eddy-induced transports.

### 1. Introduction

The overturning of deep, carbon rich water masses in the Southern Ocean is closely linked to the outgassing rate of natural CO<sub>2</sub>, and hence future changes in upwelling may significantly impact the present-day global oceanic sink of atmospheric CO<sub>2</sub>. The strong link between outgassing and overturning (Toggweiler et al. 2006) has led to the suggestion that the Southern Ocean sink has weakened in response to increased westerly winds, owing to an inferred enhancement of the overturning circulation (Le Quéré et al. 2007; Lovenduski et al. 2008). However, a number of recent eddy-permitting and eddy-resolving numerical studies (e.g., Meredith and Hogg 2006; Hallberg and Gnanadesikan 2006; Farneti et al. 2010) have shown that the sensitivity of the large-scale circulations in the Southern Ocean may be reduced by eddy effects. This has led to the suggestion that the overturning circulation may be less sensitive to changes in wind stress than previously

thought. Despite the heightened focus on these questions, there remains significant uncertainty regarding the degree of sensitivity of the Southern Ocean circulation to wind stress and the potential interplay between the dynamical responses of the overturning and Antarctic Circumpolar Current (ACC) transport.

Numerical models and observations reveal the dominant role of the mesoscale eddy field in controlling the response of the ACC transport to changes in wind stress. Eddy-permitting and eddy-resolving models (Meredith and Hogg 2006; Hallberg and Gnanadesikan 2006; Farneti et al. 2010; Jones et al. 2011) show a decreased sensitivity of the zonal ACC transport relative to coarse-resolution models that use a temporally invariant Gent and McWilliams (1990) eddy parameterization. Limited response of the Southern Ocean isopycnal slopes over decadal time scales has also been observed, despite significant intensification of the westerlies (Böning et al. 2008). The limited sensitivity of the ACC transport is thought to be a result of the near-linear response of the eddy kinetic energy to increasing wind stress; increased momentum input by surface wind stress is transferred to the bottom via enhanced interfacial form stress, rather than providing an acceleration of the zonal transport (Meredith and Hogg 2006). This phenomenon is termed

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*eddy saturation*. Most eddy-permitting models show a weak, nonzero ACC transport sensitivity ( $\sim 10\%$ – $20\%$  ACC increase for doubled wind stress).

A similar phenomenon, termed *eddy compensation*, has been observed in eddy-permitting and eddy-resolving numerical models of the upper meridional overturning circulation (Hallberg and Gnanadesikan 2006; Viebahn and Eden 2010; Farneti et al. 2010; Abernathey et al. 2011). Increased wind stress over the Southern Ocean results in a one-to-one increase in the northward surface Ekman transport ( $\bar{\psi} = \bar{v}h = \tau/\rho f$ ), which is at least partially compensated by an opposing increase in the southward eddy-induced transport ( $\psi^* = \bar{v}'h'$ ) (detailed in the theory of Marshall and Radko 2003). Thus the residual overturning, which is the sum of the Ekman and eddy-induced transports ( $\psi_{\text{res}} = \bar{\psi} + \psi^*$ ), increases substantially less than the Ekman transport. Perfect eddy compensation, whereby increases in the Ekman transport are exactly balanced by increases in the eddy-induced transport, has been hypothesized to occur at sufficiently high resolution and wind stress (Hallberg and Gnanadesikan 2006; Farneti et al. 2010). However, two eddy-resolving numerical experiments (Viebahn and Eden 2010; Abernathey et al. 2011), albeit with flat-bottom bathymetry, still show moderate increases in the residual overturning with wind stress.

The eddy compensation and saturation seen in these numerical studies has led to the development of a simplified conceptual framework portraying the response of the Southern Ocean to wind stress perturbations (e.g., Böning et al. 2008; Farneti et al. 2010; Hofmann and Morales Maqueda 2011). As the westerlies increase in strength, increased northward Ekman transport is cancelled to some degree by increased southward eddy-induced transport. In the conceptual framework, this has the effect of limiting the increase in the net residual overturning, as well as limiting the increase in the tilt of the isopycnals (and therefore the ACC transport, through the thermal wind relation). Theories of the overturning circulation (e.g., Marshall and Radko 2003), are based on this conceptual framework of a balance between the mean and eddy components of the overturning.

This simple conceptual picture of the Southern Ocean implies that if the ACC is eddy saturated, the overturning is therefore also eddy compensated (e.g., Böning et al. 2008; Farneti et al. 2010; Gent and Danabasoglu 2011; Hofmann and Morales Maqueda 2011). The assumption that there is a one-to-one relation between eddy saturation and compensation has perhaps been reinforced by the use of idealized numerical models suitable for investigating one, but not both, of the overturning or ACC transport. Eddy saturation at eddy-resolving scales has

primarily been studied in quasigeostrophic channel models, with closed northern boundaries and by definition no diabatic transport or overturning (Meredith and Hogg 2006), while eddy compensation at eddy-resolving scales has only been examined in flat-bottom models (Viebahn and Eden 2010; Abernathey et al. 2011), in which the momentum input by surface wind stress is balanced by bottom friction rather than topographic form stress, thereby resulting in unrealistic ACC transports roughly 10 times the observed value (Munk and Palmen 1951).

However, there is growing evidence that eddy saturation and compensation are not as tightly linked as this simple conceptual framework might imply. The recent scaling theory of Meredith et al. (2012) demonstrated that under the assumption of complete eddy saturation, the expected response of the eddy-induced overturning spans a range resulting in moderate increases in overturning, rather than perfect eddy compensation. In addition, Downes et al. (2011) have analyzed the effect of a single wind stress perturbation in a coupled eddy-permitting model and observed significant changes in the magnitude and spatial distribution of subduction rates, despite minimal increase in ACC transport.

In this paper we use an idealized numerical model to investigate the responses of both the ACC transport and residual overturning circulation under a wide range of wind stress perturbations and resolutions, from eddy-permitting to eddy-resolving scales.

## 2. Numerical model and experiments

We use Generalized Ocean Layer Dynamics (GOLD), a primitive equation, isopycnal layered ocean model (Hallberg and Gnanadesikan 2006; Adcroft et al. 2008; Hallberg and Adcroft 2009), with an experimental setup similar to that described in Morrison et al. (2011). The idealized domain is a zonally reentrant,  $40^\circ$  wide sector of the Southern Ocean with a simple Drake Passage–like sill, providing an unblocked circumpolar passage down to 2500 m below the surface, with a maximum ocean depth of 4000 m (Fig. 1a). The latitudinal extent is  $70^\circ\text{S}$  to the equator at the northern boundary. The northern boundary is relaxed to a density stratification derived from observational data, using a sponge of width of  $2^\circ$  in latitude, with a decay time scale of 1 day. The sponge provides an effective parameterization of North Atlantic Deep Water formation, without constraining incoming velocities. While the sponge places a nonideal constraint on the model, reducing the freedom of the isopycnals to adjust over long time scales, it reduces the spinup time scale from  $O(1000 \text{ yr})$  to  $O(100 \text{ yr})$ , thereby allowing the exploration

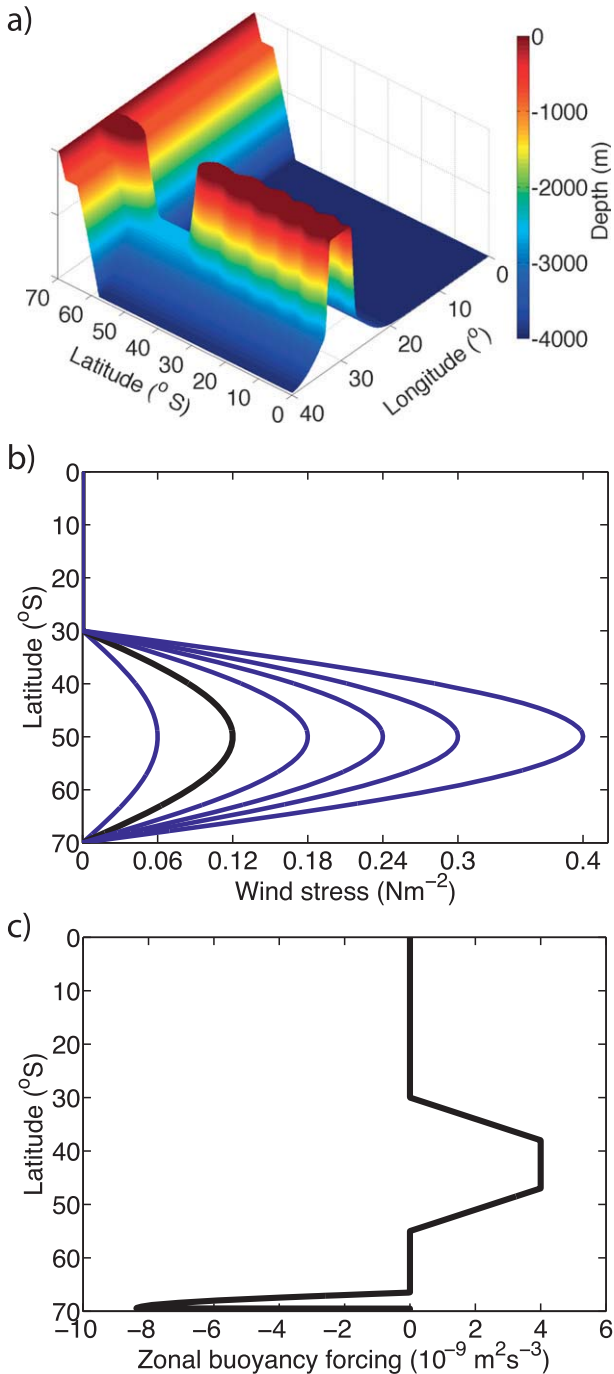


FIG. 1. Model bathymetry and forcing. (a) Bathymetry, (b) zonally averaged wind stress (control in black, perturbations in blue), and (c) zonally averaged buoyancy forcing are shown.

of a large parameter space at eddy-resolving scales. The caveat is that the results are applicable to relatively fast (decadal) responses of the Southern Ocean, rather than the millennial time-scale adjustment of the deep stratification (Jones et al. 2011).

A Mercator grid, with grid size decreasing toward the southern boundary, is employed at four horizontal resolutions ( $1/4^\circ$ ,  $1/8^\circ$ ,  $1/12^\circ$ , and  $1/16^\circ$ ), resulting in square grid cells of size 13.9, 7.0, 4.6, and 3.5 km at  $60^\circ\text{S}$ , respectively, compared with a Rossby radius  $\sim 13$  km at  $60^\circ\text{S}$ . Eddy parameterizations are not used in any of the simulations. A three-layer bulk mixed layer is used, in addition to nine interior constant density layers. Biharmonic viscosity with an additional Smagorinsky component provides numerical closure, with biharmonic coefficients set to  $2 \times 10^{11} \text{ m}^4 \text{ s}^{-1}$  ( $1/4^\circ$ ),  $2 \times 10^{10} \text{ m}^4 \text{ s}^{-1}$  ( $1/8^\circ$ ),  $8 \times 10^9 \text{ m}^4 \text{ s}^{-1}$  ( $1/12^\circ$ ), and  $5 \times 10^9 \text{ m}^4 \text{ s}^{-1}$  ( $1/16^\circ$ ). A weak diapycnal diffusivity of  $10^{-6} \text{ m}^2 \text{ s}^{-1}$  in the interior ensures a largely adiabatic circulation.

The model is forced by idealized, temporally invariant wind stress and surface buoyancy forcing (Figs. 1b,c). The wind stress is sinusoidal and zonally uniform, while the buoyancy forcing is fixed and noninteractive, with a positive (i.e., acting to decrease the density of surface waters), zonally uniform forcing in the midlatitudes and a region of spatially localized, negative buoyancy forcing near the southern boundary. The control cases have a maximum wind stress of  $0.12 \text{ N m}^{-2}$  and a spinup period of  $\sim 120$  years. Wind stress perturbations applied at the end of the control spinup are allowed to reach equilibrium ( $\sim 30$  years) and 25-yr averages after these spinup times are used in the analysis.

### 3. Results

#### a. Mean state and eddy kinetic energy

The surface forcing generates a Southern Ocean-like state with isopycnals tilted toward the surface in the south, an energetic eddy field with associated fronts and jets, and an upper and lower meridional overturning cell. The spinup time series, mean stratification, surface density snapshot, and mean overturning for the  $1/8^\circ$  control simulation are illustrated in Fig. 2 of Morrison et al. (2011). The ACC transport in the control runs ranges from 85 to 110 Sv ( $1 \text{ Sv} \equiv 10^6 \text{ m}^3 \text{ s}^{-1}$ ), decreasing in magnitude with increasing resolution. The lower overturning cell (analogous to Antarctic Bottom Water) is driven principally by the negative buoyancy forcing near the southern boundary. The upper meridional overturning cell simulates the upwelling of North Atlantic Deep Water in the latitudes unblocked by bathymetry. Scaled up to the full width of the Southern Ocean, the transports of the upper and lower cells in the  $1/8^\circ$  control run are 23 and 9 Sv, respectively. The meridional overturning in the model is largely adiabatic in the interior, with diapycnal transport occurring predominantly in the mixed layers, as allowed by the

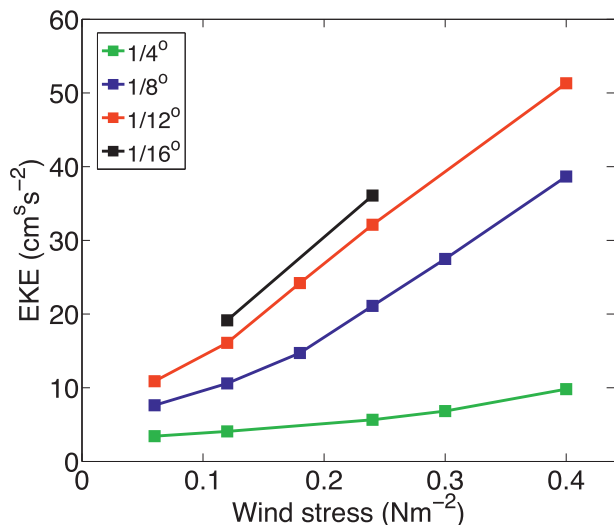


FIG. 2. Variation of eddy kinetic energy with wind stress and resolution, averaged over 40°–65°S and full depth.

surface buoyancy forcing and lateral diabatic eddy buoyancy fluxes.

We first illustrate the sensitivity of the eddy kinetic energy [EKE =  $(u'^2 + v'^2)/2$ ] in the model to changes in resolution and wind stress (Fig. 2), as the response of the eddy field is expected to have a significant impact on the dynamics of both the overturning and ACC transport. Consistent with previous observational (Meredith and Hogg 2006) and eddy-permitting numerical (Hallberg

and Gnanadesikan 2006; Abernathey et al. 2011; Meredith et al. 2012) studies we find an approximately linear relationship between wind stress and EKE. The eddy field in the “eddy-permitting” 1/4° simulation is both weaker and less sensitive to change than that in the higher-resolution simulations. The magnitude of the EKE continues to increase with resolution from 1/8° → 1/12° → 1/16°. However, the response of the EKE to wind stress (as indicated by the gradient of the lines in Fig. 2) is similar between these resolutions, particularly at high values of wind stress. We therefore may expect to see some convergence in the response of the Southern Ocean circulation at large values of wind stress and high resolution.

*b. Overturning response*

The modeled residual overturning in the upper cell is partially eddy compensated, as shown by the divergence of the Ekman and residual overturning in Fig. 3a. We define the residual overturning as the maximum of the zonally averaged overturning streamfunction at 30°S. Because of the adiabatic nature of the overturning, the results are largely unaffected by the choice of latitude used in the analysis. The mean component of the overturning (dashed black line in Fig. 3a) is taken as the maximum of the theoretically calculated Ekman transport ( $\bar{\psi} = \tau/\rho f$ ). The 1/8° residual overturning increases moderately with wind stress, though the sensitivity is substantially reduced in comparison with the changes in

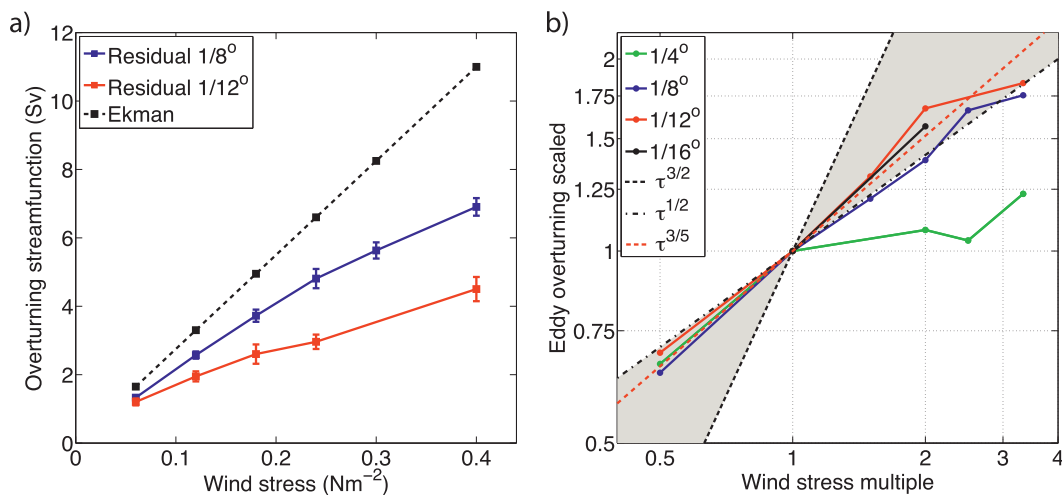


FIG. 3. Partial eddy compensation. (a) The maximum of the residual overturning streamfunction,  $\psi_{res}$ , at 30°S in the 1/8° simulation (solid blue) and 1/12° simulation (solid red), compared with the theoretically calculated maximum Ekman transport (dashed black). The error bars show the standard deviation of 1-yr overturning averages from the 25-yr mean. (b) Sensitivity of the zonally averaged, eddy-induced overturning streamfunction  $\psi^*$  on isopycnal layer 1027.5, averaged between 40° and 60°S (solid lines), compared with the scaling arguments of Meredith et al. (2012):  $\psi^* \sim \tau^{3/2}$  (black dashed) and  $\psi^* \sim \tau^{1/2}$  (black dot dashed). The red dashed line shows the diffusivity scaling ( $\psi^* \sim \tau^{3/5}$ ) used for the ACC transport prediction in Fig. 5.

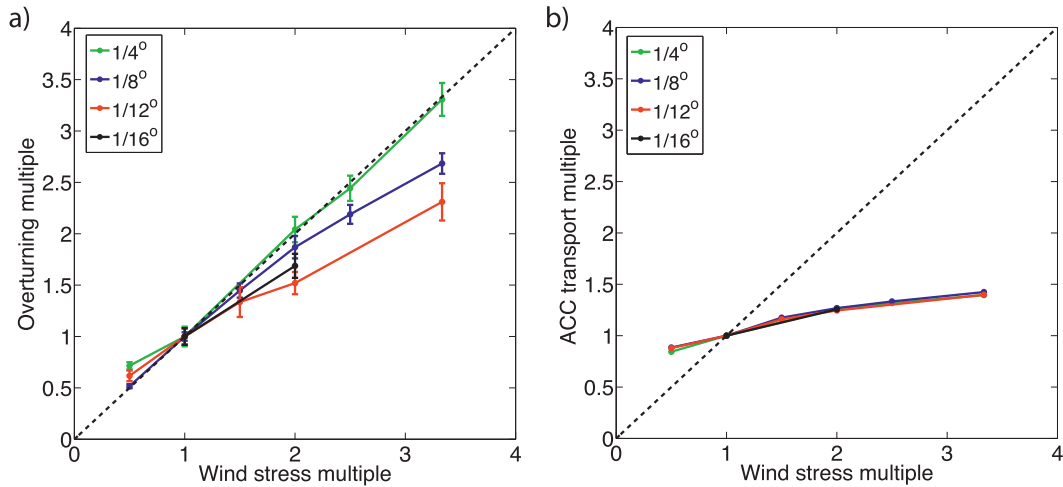


FIG. 4. (a) Maximum residual overturning streamfunction at 30°S, scaled relative to the magnitude of the overturning in the control wind stress case ( $\tau = 0.12 \text{ N m}^{-2}$ ). The dashed black line corresponds to a one-to-one increase in overturning with wind stress (but not necessarily zero eddy compensation). Perfect eddy compensation would be represented by a horizontal line. The error bars show the standard deviation of 1-yr overturning averages from the 25-yr mean. (b) ACC transport sensitivity. The dashed black line corresponds to a one-to-one increase in transport with wind stress. Perfect eddy saturation would be represented by a horizontal line. Error bars as for Fig. 4a have been excluded because of the minimal variability of ACC transport.

Ekman transport. There is a significant increase in the amount of compensation between  $1/8^\circ$  resolution and  $1/12^\circ$ , both nominally “eddy-resolving” models.

The zonally averaged, eddy-induced overturning  $\psi^*$  in the higher-resolution simulations scales in accordance with the high EKE limit of Meredith et al. (2012) (Fig. 3b). The scaling theory predicts that the isopycnal eddy diffusivity response should lie between  $K \sim \tau^{1/2}$  (high EKE) and  $K \sim \tau^{3/2}$  (low EKE). To extend the scaling to a prediction for the eddy-induced overturning (i.e.,  $\psi^* = K\bar{s} \sim K \sim \tau^{1/2}$ ), it is necessary to make the assumption that the dependence of the isopycnal slope  $\bar{s}$  on wind stress is negligible (i.e., the ACC transport is close to eddy saturation). Evidence for this is provided by previous numerical studies (Viebahn and Eden 2010; Abernathey et al. 2011) as well as the simulations under discussion (e.g., Figures 4b, 5b, and 7a). The  $1/4^\circ$  eddy-induced overturning has a much weaker sensitivity to wind stress in comparison with the higher-resolution simulations, reflecting the weak magnitude and limited response of the EKE at this resolution.

As may be expected from the variation of EKE and eddy-induced overturning with resolution, the extent of eddy compensation in the residual overturning circulation is also resolution dependent (Fig. 4a). To compare the different resolutions, we have scaled the overturning relative to the magnitude of the overturning in the control case for each resolution. The dotted line in Fig. 4a represents a one-to-one increase

in the residual overturning with wind stress. However, if the magnitude of the residual overturning transport is less than the Ekman transport (i.e.,  $\psi^* \neq 0$ ), this dotted line does not necessarily imply zero eddy compensation; a linearly increasing eddy overturning could produce a residual overturning scaling of one-to-one or

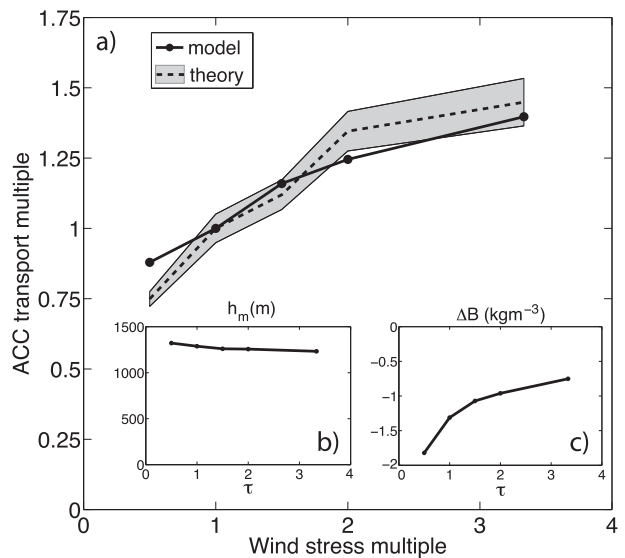


FIG. 5. (a) Comparison of the  $1/12^\circ$  modeled ACC transport sensitivity (solid) with the theoretical prediction of Olbers and Visbeck (2005) (dashed). The shaded region accounts for the variability in the residual overturning (using the uncertainty values shown in Fig. 4a). (b) Representative mean isopycnal depth. (c) Surface density difference between 40° and 60°S.

even greater. Weak eddy compensation is seen in the  $\frac{1}{4}^\circ$  simulation, corresponding to the weak sensitivity of the EKE at lower resolution. Enhanced eddy compensation is seen in the higher-resolution runs, yet all of the simulations show at least a moderate increase of the overturning with wind stress. We note that the sensitivities of the  $\frac{1}{12}^\circ$  and  $\frac{1}{16}^\circ$  simulations are similar to previous high-resolution idealized model studies (Viebahn and Eden 2010; Abernathey et al. 2011). The overturning response appears to converge at  $\frac{1}{12}^\circ$ , as was also the case for the EKE anomalies. The implication of this convergence is that, even at resolutions above  $\frac{1}{16}^\circ$ , perfect eddy compensation would not occur in this model.

*c. ACC response*

In contrast to the overturning circulation response, the modeled ACC transport sensitivity shows a surprising independence of resolution (Fig. 4b). Partial eddy saturation is observed at all resolutions, from eddy-permitting to eddy-resolving. A doubling of wind stress results in a weak increase in ACC transport of  $\sim 25\%$ . The weak, but nonzero response of the ACC transport is similar to other primitive equation, eddy-permitting studies of the ACC (Hallberg and Gnanadesikan 2006; Farneti et al. 2010; Jones et al. 2011).

Theories predicting the response of the ACC transport to changing wind stress vary from complete eddy saturation (Straub 1993) to a linear dependence on applied wind stress (Gnanadesikan and Hallberg 2000; Marshall and Radko 2003). We compare the modeled ACC sensitivity to the scaling theory of Olbers and Visbeck (2005), which is a modification of Marshall and Radko (2003), updated to include the effect of a nonzero residual overturning circulation on the prediction of ACC transport. Assuming an adiabatic interior and a vertically constant eddy diffusivity  $K$ , Olbers and Visbeck (2005) write the transport as

$$T_{\text{ACC}} \sim \frac{-g\Delta B h_m}{Kf^2} (\tau + \psi_{\text{res}}), \quad (1)$$

where  $\Delta B$  is the meridional density difference across the ACC, and  $h_m$  is a representative mean isopycnal depth. Consistent with the limited sensitivity of the ACC transport, we find that  $h_m$  responds only weakly to wind stress perturbations (Fig. 5b) and for the purposes of reducing the complexity of the scaling, we assume  $h_m$  is constant. The meridional density difference  $\Delta B$  depends strongly on wind stress (Fig. 5c) and therefore cannot be ignored. Incorporating a power-law scaling for the eddy diffusivity  $K \sim \tau^n$  (to be determined from the model data in Fig. 3b) reduces the ACC transport scaling to

$$T_{\text{ACC}} \sim -\Delta B(\tau^{(1-n)} + \psi_{\text{res}}\tau^{-n}). \quad (2)$$

For the  $\frac{1}{12}^\circ$  simulation, we find that a diffusivity scaling of  $K \sim \tau^{3/5}$  (as shown by the dashed red line in Fig. 3b) provides a surprisingly good fit between the theory and modeled ACC transport (Fig. 5a). The slope of the theoretical prediction is very sensitive to the choice of diffusivity scaling. We also find a good fit for the  $\frac{1}{8}^\circ$  simulation using  $K \sim \tau^{1/2}$ .

**4. Discussion and conclusions**

Comparison of Figs. 4a and 4b reveals that the model is substantially closer to the eddy saturation limit than it is to the eddy compensation limit, consistent with the scaling predictions of Meredith et al. (2012). At the highest resolution ( $\frac{1}{16}^\circ$ ), a doubling of wind stress results in a 70% increase in the overturning, but only a 25% increase in the ACC transport. This difference in sensitivities holds significance for observational studies attempting to measure changes in the Southern Ocean overturning by indirect methods, such as via stratification changes. For example, Böning et al. (2008) concluded that the overturning has not responded to recent changes in wind stress because there has been no discernible variation in the zonally averaged isopycnal slopes. However, our results indicate that it is possible to have a Southern Ocean-like state where large changes in the overturning may occur, despite minimal changes in the isopycnal slopes and ACC transport. We would expect the sensitivities of the overturning and ACC transport to diverge even further with the use of a surface buoyancy relaxation condition, instead of the fixed flux condition we have presented here. Surface relaxation allows for the buoyancy flux to also increase with wind stress, thereby resulting in larger increases in the overturning when compared with fixed flux experiments (Abernathey et al. 2011).

The discrepancy between the obvious resolution dependence of the EKE and overturning sensitivity and the resolution independence of the ACC transport sensitivity conflicts with the simple conceptual picture of the Southern Ocean presented in section 1. In the simple model, increased wind stress acts to increase the surface southward eddy-induced transport, which partially opposes the increase in the northward Ekman transport. The net result of the changes in the Ekman and eddy-induced transports is often considered to have the effect of limiting both the increase in residual overturning (eddy compensation) and the increase in isopycnal slopes (eddy saturation). However, our numerical model results conflict with this simple conceptual

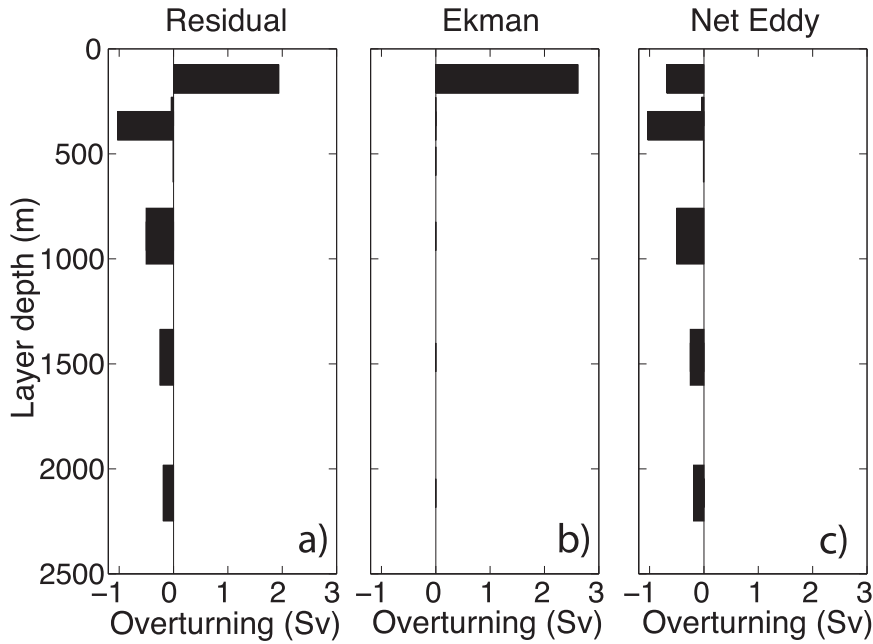


FIG. 6. Depth structure of the changes in meridional transport at 53°S in the  $1/12^\circ$  simulation as a result of wind stress doubling from  $\tau = 0.12 \rightarrow 0.24 \text{ N m}^{-2}$ . Only the portion of the overturning above the depth of topography is shown. The top bar in each figure shows transport in the bulk mixed layer, while lower bars show transport in interior isopycnal layers. Positive values reflect northward transport. (a) The zonally averaged, residual meridional transport ( $\overline{v\bar{h}}$ ). (b) Theoretically calculated Ekman transport at 53°S ( $\tau/\rho f$ ). (c) Net eddy-induced overturning ( $\overline{v\bar{h}} - \tau/\rho f$ ).

model. As the resolution in the numerical model is increased from eddy-permitting to eddy-resolving, we observe an enhanced response of the southward eddy-induced transport, which increases the extent of eddy compensation. Yet as the eddy field increases with resolution, we observe no change in the degree of eddy saturation. Given that the numerical model contains the essential dynamics of the Southern Ocean, it is likely that eddy saturation and eddy compensation in the real ocean are controlled by different factors, and that the simple conceptual framework is deficient.

One plausible explanation for the increase in eddy compensation with resolution, but constant eddy saturation, is the different depth profiles of the changing Ekman and eddy-induced transports, as also hypothesized by Meredith et al. (2012). The depth structure of the different components of the overturning in the mean state has been investigated in several previous studies (e.g., Speer et al. 2000a,b; Olbers et al. 2004). However, here we focus on the vertical structure of the meridional transport anomalies, in response to changing wind stress. The increase in the northward Ekman transport is surface intensified and confined to the mixed layer (Fig. 6b), while the increase in the southward eddy-induced transport is spread across all layers

(Fig. 6c). Therefore the degree of cancellation between the two components will vary with depth.

Figure 7 shows the variation of zonal and meridional transports for different density layers in the  $1/12^\circ$  model. Over the full depth of the water column, the meridional transports consistently increase in such a way as to enhance the overturning. However, the changes in zonal transport are more spatially variable (both in depth and latitude) and regions exist where the isopycnals flatten and the zonal transport decreases, despite increasing wind stress. Careful consideration of the stratification changes in Fig. 7d of Farneti et al. (2010) reveals a similar response of the isopycnal slopes in a coupled eddy-permitting model, with a flattening of isopycnals in the northern part of the ACC region and steepening limited to the south.

In summary, we have shown that there is not a one-to-one relationship between the responses of the Southern Ocean overturning and ACC transport to increasing wind stress. The modeled overturning is significantly more sensitive to change than the ACC transport, even at  $1/16^\circ$  resolution. The implication of these results is that future increases in overturning may occur without noticeable changes in stratification or ACC transport. As the model resolution is refined from eddy-permitting to

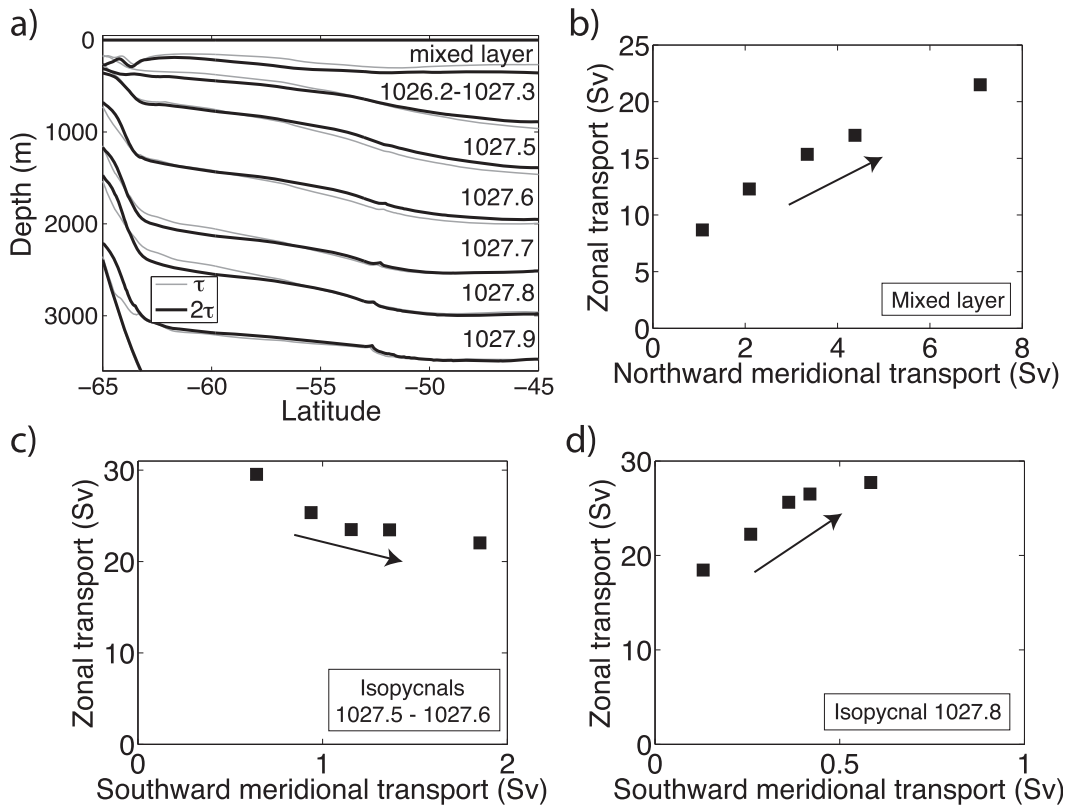


FIG. 7. (a) Zonally averaged isopycnals in the  $1/12^\circ$  simulation for the control (thin gray) and doubled (thick black) wind stress runs. The meridional vs zonal transport summed across (b) the mixed layers, (c) isopycnal layers 1027.5–1027.6, as labeled in (a), and (d) isopycnal layer 1027.8. The arrows indicate the direction of wind stress increase.

eddy-resolving, the eddy kinetic energy and the degree of eddy compensation increase. However, the eddy saturation is surprisingly resolution independent. We hypothesize that the lack of a dynamical link between eddy compensation and eddy saturation is a result of the depth dependence of the cancellation between the Ekman and eddy-induced transports. The overturning response is particularly sensitive to the balance between Ekman and eddy-induced transports near the surface, while the ACC transport is a depth-integrated measure and will depend on stratification changes throughout the water column. However, it remains unclear as to what sets the degree of eddy saturation in different models and why, above eddy-permitting scales, this should not be affected by resolution and the associated large changes in eddy kinetic energy.

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