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Parameterized and resolved Southern Ocean eddy compensation

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ABSTRACT

The ability to parameterize Southern Ocean eddy effects in a forced coarse resolution ocean general circulation model is assessed. The transient model response to a suite of different Southern Ocean wind stress forcing perturbations is presented and compared to identical experiments performed with the same model in 0.1° eddy-resolving resolution. With forcing of present-day wind stress magnitude and a thickness diffusivity formulated in terms of the local stratification, it is shown that the Southern Ocean residual meridional overturning circulation in the two models is different in structure and magnitude. It is found that the difference in the upper overturning cell is primarily explained by an overly strong subsurface flow in the parameterized eddy-induced circulation while the difference in the lower cell is mainly ascribed to the mean-flow overturning. With a zonally constant decrease of the zonal wind stress by 50% we show that the absolute decrease in the overturning circulation is insensitive to model resolution, and that the meridional isopycnal slope is relaxed in both models. The agreement between the models is not reproduced by a 50% wind stress increase, where the high resolution overturning decreases by 20%, but increases by 100% in the coarse resolution model. It is demonstrated that this difference is explained by changes in surface buoyancy forcing due to a reduced Antarctic sea ice cover, which strongly modulate the overturning response and ocean stratification. We conclude that the parameterized eddies are able to mimic the transient response to altered wind stress in the high resolution model, but partly misrepresent the unperturbed Southern Ocean meridional overturning circulation and associated heat transports.

1. Introduction

The outcropping isopycnals of the Southern Ocean provide an important adiabatic pathway for the meridional overturning circulation and hence aid the ventilation of the deep ocean (Marshall and Speer, 2012). Together with the zonally unblocked Antarctic Circumpolar Current, the Southern Ocean thus plays a central role in the modern view of the ocean general circulation (Gnanadesikan, 1999; Thompson et al., 2016), the global carbon cycle (Sigman and Boyle, 2000; Le Quéré et al., 2007; Bronselaer et al., 2016), ocean heat uptake (Marshall and Zanna, 2014) and the exchange of tracers between the major ocean basins (Thompson, 2008). The southern hemisphere westerlies are a key driving force of the circulation (e.g. Toggweiler and Samuels, 1995; Tansley and Marshall, 2001) and these have been subject to an intensification and poleward shift throughout the last several decades as a result of ozone depletion and anthropogenic emission of carbon dioxide (Thompson and Solomon, 2002; Marshall, 2003). A fundamental question is what implication the wind stress changes have on the global circulation and climate, and whether the relevant physics is faithfully represented in state-of-the-art climate models to allow for meaningful predictions of the response.

In this respect, the mesoscale eddy field in the Southern Ocean (e.g. Frenger et al., 2015) has proven to have a leading order influence on the local dynamics. Ocean models of varying complexity and basin geometry, but with an explicitly resolved eddy field, have demonstrated that a limit exists in which the time-mean transport of a circumpolar current becomes independent of the strength of the overlying zonal wind stress (Hogg and Blundell, 2006; Nadeau and Straub, 2009; Munday et al., 2013; Marshall et al., 2017). Beyond this limit additional momentum input to the surface ocean by the winds mainly fuel a stronger eddy field through baroclinic instability, which facilitates a vertical momentum transfer to the ocean floor and dissipation by form drag (Munk and Palmén, 1951; Johnson and Bryden, 1989), instead of accelerating the current. Recent observations from the Southern Ocean have shown that the isopycnal slope, and hence the baroclinic transport of the Antarctic Circumpolar Current, has indeed been insensitive to the wind stress changes (Böning et al., 2008) while the surface kinetic energy has increased (Hogg et al., 2015), supporting the model results and the notion that the Southern Ocean is in the so-called state of eddy saturation.

Contemporary residual-mean theory also emphasizes the role of mesoscale eddies in setting the strength of the upper cell of the

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meridional overturning in the Southern Ocean. Here they compensate the effect of a wind-driven northward Ekman flow anomaly through an oppositely directed flow akin to a Stokes drift (referred to as eddy compensation, see e.g. Marshall and Radko (2003)). The results from models with explicit eddies show that this is indeed the case (Hallberg and Gnanadesikan, 2006), but also that the sensitivity of the overturning circulation remains non-zero to a wind stress strength that is several times greater than the present day magnitude, unlike the behavior of the zonal transport (Munday et al., 2013). Using an idealized primitive equation model at various eddying resolutions, Morrison and Hogg (2013) likewise demonstrate the sensitivity difference between the zonal and meridional circulation to the zonal wind stress. They argue that the sensitivity difference arises because eddy compensation is a depth-dependent metric, whereas eddy saturation is depth-integrated and thus camouflages potentially higher local sensitivities in the vertical shear of the horizontal velocity field.

In a recent high-resolution coupled model experiment run for two model decades, Bishop et al. (2016) shows that the upper cell of the residual overturning increases in magnitude by 39% to a zonally constant 50% increase of the Southern Ocean zonal wind stress, and that the mean Drake Passage transport changes by 6% only. The degree of compensation and saturation that should be expected on a longer time scale is however still unclear as computational cost limits sufficiently long integrations of comprehensive high resolution ocean models. Moreover, the non-local response of the Atlantic meridional overturning circulation to a Southern Ocean wind stress change is continuously debated. For example, it has been suggested that models with idealized basin geometry do not capture the changes in diapycnal upwelling in the Pacific Ocean. Since this diabatic pathway is also able to provide the necessary closure for the meridional overturning circulation, these models potentially overestimate the role of the Southern Ocean winds (Jochum and Eden, 2015).

The results from eddy-resolving ocean models, despite their simplifications and shortcomings, have questioned the ability of coarse resolution ocean models to represent the eddy effect on the large-scale flow in a wind stress change scenario. Most climate models use the Gent–McWilliams parameterization (Gent and McWilliams, 1990; Gent et al., 1995) to model baroclinic instability and along-isopycnal eddy mixing in the interior ocean, and rely on the assumption that the strength of baroclinic instability is proportional to the isopycnal slope. Comparison studies have shown that when the proportionality parameter in the eddy down-gradient closure, the thickness diffusivity, is a constant, the zonal transport cannot possibly eddy saturate and the meridional circulation is too sensitive to wind stress changes (Hallberg and Gnanadesikan, 2006; Munday et al., 2013). When the eddy diffusivity is allowed to vary in space and time as function of the stratification (Ferreira et al., 2005; Danabasoglu and Marshall, 2007), the transport through Drake Passage shows a less sensitive relationship to the zonal wind stress (Gent and Danabasoglu, 2011). However, the change in the residual overturning still varies considerably among models subject to the same wind stress increase (Farneti et al., 2015), which complicates an assessment of the parameterized eddy effect.

Both Bitz and Polvani (2012) and Bryan et al. (2014) compare climate change experiments between a fully coupled coarse resolution model, using above parameterization, and an identical eddy-resolving model. The model solutions in the study by Bryan et al. (2014) show that the poleward eddy heat transport between 60°S and 50°S increases following an increase in the zonal wind stress in their low resolution model setup, whereas the high resolution model finds a response of opposite sign. Bitz and Polvani (2012) report similar model responses, where the resolved eddies contribute substantially less to the change in poleward heat transport compared to the parameterized eddies. While these results suggest that the parameterized eddies respond oppositely or overly strong to a wind stress change, ambiguity on the performance of the eddy parameterization still remains, because the modelled wind stress changes are dependent on the background climate. This is not necessarily the same at different model resolution, exemplified by Bryan et al. (2014), where differences in Antarctic sea ice thickness influence the modelled climate response. In addition, an increasing body of literature has shown that the strength of the Antarctic Circumpolar Current and the position of its fronts is sensitive to the spatial structure and strength of the wind stress field (Sallée et al., 2008; Morrow et al., 2010; Mazloff, 2012; Dufour et al., 2012; Zika et al., 2013; Langlais et al., 2015). The compilation of these results suggest a return to simpler general circulation model experimental setups with a complete control on the applied wind stress to elucidate the nature of the response.

In the present study we present simulations from the second version of the Parallel Ocean Program (POP) model configured at a horizontal resolution of 1° and 0.1°, the former employing a state-of-the-art eddy parameterization, forced with different prescribed Southern Ocean wind stress scenarios in an attempt to evaluate the performance of parameterized eddies. The results presented here indicate that the parameterized eddy-induced meridional circulation cancel the wind-driven overturning differently than the eddy-resolving model when forced with present day winds. Despite differences in the background ocean state we demonstrate that the two models respond similarly to wind stress perturbations, but note that the model comparison is not straightforward as changes in buoyancy forcing and sea ice cover are able to drive a complex model response. The latter point raises the question to what extent the current concept of eddy compensation is applicable to complex models.

2. Model description, experimental setup and spin-up assessment

We use the Community Earth System Model (CESM) with an active ocean and sea ice model on a global domain with realistic bottom topography with prescribed meteorological boundary conditions. The ocean and sea ice models share the same grid, and the solution of the governing equations is sought using two different horizontal grid resolutions; a tri-polar 0.1° grid, with the meridional grid spacing proportional to the cosine of latitude, and a dipole 1° grid that also has a meridional grid discretization that varies with latitude, with a latitudinal grid spacing of $\sim 0.5°$ in the Southern Ocean. The vertical axis that belongs to the first grid is resolved by 62 z-coordinate levels, with the distance of separation increasing monotonically with depth, and has a partial bottom cell representation in accord with the ETOPO2v2 bathymetry product. The coarse resolution grid holds 60 levels in the vertical and with no partial bottom cells. The dynamical core of the ocean model is the same for both grid resolutions and is documented in Smith et al. (2010), except for the treatment of motion on the mesoscale, which is outlined in the next paragraph. For further information on the grid layouts and aspects of the control integration of the fully coupled models, the reader is referred to Gent et al. (2011) and Small et al. (2014) with respect to the coarse and the fine resolution model, respectively. The prescribed atmosphere used in this study is given by the normal year forcing fields from the second version of the Coordinated Ocean Research Experiment (CORE.v2.NYF, Large and Yeager, 2008), compiled from atmospheric reanalysis and observations, and the fields have a temporal resolution of six hours and repeat themselves after one model year exactly.

Ideally the model solution that evolves on the 0.1° grid should be subject to motion on a characteristic length scale on the order of the first baroclinic Rossby radius (Chelton et al., 1998) and no mesoscale eddy parameterization is therefore enabled. The isopycnal tracer diffusion is likewise disabled, but a biharmonic operator is implemented to represent lateral mixing by subgrid-scale processes that remain unresolved (Bryan and Bachman, 2015). Ocean mesoscale eddies are not explicitly resolved on the 1° grid and are parameterized in the interior ocean using the Gent and McWilliams (1990) isopycnal mixing formulation with the spatiotemporal thickness diffusivity proposed by Ferreira et al. (2005). This choice of the eddy transfer coefficient