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Southern Ocean Eddy Compensation Examined with a High-Resolution Ocean Model

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The eastward winds that overlie the Southern Ocean are able to provide the necessary means that allows water at depth to resurface and ensure closure for the meridional overturning circulation. Contemporary studies that employ high-resolution simplified or regional ocean models have however shown that ocean eddies, oceanic storms that origin from the instability of the mean circulation, are able to compensate this wind-driven upwelling. We here present results from a suite of Southern Ocean wind stress perturbation experiments performed with a global ocean model. Simulations with the model are performed at two different horizontal grid resolutions, one where eddies are parameterised and one where they are explicitly resolved. It is shown that the eddy-driven circulation is more surface intensified in the high resolution model, and therefore leads to a different total overturning circulation with present day wind stress magnitude. The wind stress change experiments both indicate that the parameterised eddy circulation underestimates the response to a wind stress change, and that the conceptual view of eddy compensation as a competition solely between a wind-driven and an eddy-induced circulation response might not hold in a more complex model.

1 Introduction

An important property of the large-scale ocean circulation is its ability to transport heat towards the poles, from tropical regions, where Earth receives more energy from the sun than it radiates back to space, to higher latitudes, where the radiation balance is of opposite sign[1]. This heat transport lessens the meridional (i.e. north-south directed) temperature gradient and provides a more mild climate at higher latitudes, as for example in Europe. Obtaining a better understanding of what sets the strength of this so-called meridional overturning circulation thus increase the ability to predict the state of a future climate and interpret output from comprehensive Earth system models.

It is well established that deep- and bottom water masses form at polar latitudes, and that this deep water formation plays a vital part in the overturning circulation (see blue arrows in Fig. 1). However, any complete theory must also explain how these water masses of polar origin return to the surface. In the majority of the latter half of the 20th century, the idea which prevailed was that the deep and abyssal water masses upwelled exclusively and uniformly throughout the world's ocean as a consequence of turbulent mixing in the ocean[2] (yellow arrows, Fig. 1). Modelled by a diffusive-advective balance in the vertical[3], this theory was conceptually able to explain the ocean density stratification but struggled to agree with in situ observations of mixing strengths. More recently it has been recognised that wind-driven adiabatic upwelling in the Southern Ocean also is able to account for a substantial part of the water that has to resurface to close the circulation[4] (green arrows,

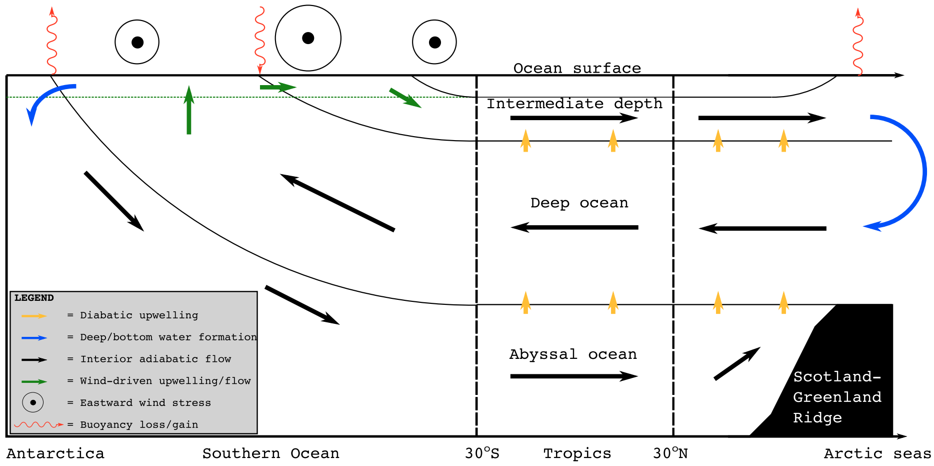

Figure 1. Simplified two-dimensional view of the meridional overturning circulation in the Atlantic Ocean, looking towards west. Arrows and other symbols are explained in the legend. Thin solid black lines represent surfaces of constant density.

Fig. 1), hence alleviating the missing-mixing paradox that surrounds the theory of uniform upwelling.

The Southern Ocean is subject to intense atmospheric eastward winds, which transfer momentum to the underlying ocean (see $\odot$ symbols in Fig. 1). Due to the influence of the Coriolis force, the atmospheric wind stress on the Southern Ocean establishes a northward surface ocean circulation. Divergence in this northward transport, which arise due to meridional variation in the eastward wind strength, facilitate vertical motion in the water column below due to the continuity of mass. As a consequence, isolines of density (isopycnals) are lifted and hence tilts in the meridional direction in the Southern Ocean, along which water is able to return adiabatically from the deep ocean to the surface. Highlighting this physical mechanism, the model study by Toggweiler and Samuels (1995) indeed suggests that the eastward wind stress in the Southern Ocean is able to set the strength of the meridional overturning circulation[5].

The continuing increase in computer power, however, allows ocean models of finer horizontal resolution to be run. Simulations from simplified or regional ocean models that explicitly resolve ocean eddies, the direct analog to high and low pressure systems in the atmosphere, have demonstrated that the eddy field of the Southern Ocean is able to compensate wind-driven changes in the strength of the meridional overturning circulation[6]. This implies that the sensitivity of the overturning circulation to the Southern Ocean wind stress is reduced if the eddy field itself intensifies for stronger wind stress.

In this study we attempt to quantify the strength of eddy compensation in the Southern Ocean by examining the output from wind stress perturbation experiments conducted with an eddy-resolving ocean model. Different to previous studies of eddy compensation, this model solves for the entire global ocean circulation with realistic land boundaries and bottom bathymetry. A comparison to identical experiments conducted with the same model, but of coarser grid resolution where the effect of ocean eddies is parameterised instead of being resolved, is also performed.

2 Model Setup and HPC Details

We use the Community Earth System Model (CESM) with an active ocean and sea-ice model, and with prescribed meteorological boundary conditions. The solution of the governing equations is sought using two different horizontal grid resolutions; a nominal $0.1°$ and $1°$ grid, the former resolution here referred to as eddy-resolving (see right panel of Fig. 2 for a realisation of the surface speed from the Southern Ocean). The vertical axis that belongs to the two horizontal grids differs weakly, but both consist of about 60 vertical levels which distance of separation increases monotonically with depth. The dynamical core of the ocean model is the same for both grid resolutions[7], except for the treatment of motion on the mesoscale which is parameterised on the $1°$ grid by the Gent-McWilliams parameterisation[8]. 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[9], compiled from atmospheric reanalysis and observations, and the fields have a temporal resolution of six hours and repeat themselves exactly after one model year.

The eddy-resolving ocean model[10] requires the calculation of temperature, salinity, density, pressure and three velocity components on more than 100 million grid points for each model time step, a computationally demanding task that requires substantial computer power. Assigned to 4096 cores on the Jülich BlueGene supercomputer JUQUEEN, the model completes about one model year in ten days. The output from the model (gridded state variables, various diagnostics and forcing fields) is stored as three-day mean files which each occupy 86 Gb disc space, and these files are stored on the University of Copenhagen Electronic Research Data Archive (ERDA) on which post-processing is performed.

A 16 model year long spin-up integration of the eddy-resolving model was adopted from colleagues at the National Center for Atmospheric Research (NCAR). This integration was started from present day observations of the state variables but with the ocean

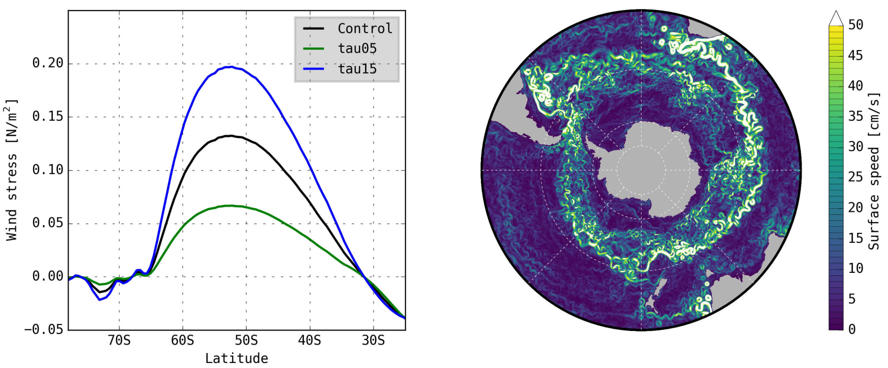

Figure 2. Left) Zonally-averaged zonal wind stress profiles for the different experiments. Right) Three-day mean surface speed from the Southern Ocean.

circulation at rest. A ten model year long control integration was performed on JUQUEEN from the final state of the spin-up. At the end of the control integration, three branch simulations were initiated; a 50% Southern Ocean wind stress increase experiment (blue line, left panel of Fig. 2) of 16 model years, a 50% Southern Ocean wind stress decrease experiment (green line, left panel of Fig. 2) of similar duration, and a further continuation of the control integration (black line, left panel of Fig. 2). The latter simulation is currently in the process and this article focuses on the two wind stress change experiments. Similar experiments were performed with the 1° model, which is computationally cheaper to integrate and is run in-house.

3 Results

We first examine the meridional overturning circulation in the Southern Ocean from the control integrations at the two different grid resolutions. The overturning circulation ψ_I is here realised by computing the meridional volume transport in the ocean at a given latitude below a specific isopycnal, i.e.

$$\psi_I(\theta, \sigma, t) = \oint_0^{2\pi} \int_{\eta_B(\phi,\theta)}^{\eta(\phi,\theta,t)} v(\phi, \theta, z, t)\, \mathrm{d}z\, R\cos(\theta)\, \mathrm{d}\phi. \tag{1}$$

Here v is the meridional velocity field, σ is density, η is the physical height of the σ surface, η_B is the height of the ocean bottom, z is physical depth and R is Earth's radius. Since density increases monotonically with depth, density can be thought of as a pseudo-depth. Circulation in the interior ocean is primarily along lines of constant density why density as a vertical coordinate instead of physical depth is more convenient.

The upper left and right panel of Fig. 3 display the ten-year mean of ψ_I for the Southern Ocean for the 1° and 0.1° resolution model, respectively, before the application of the perturbation. The transport is directed along the isolines of the streamfunction; the blue cell in the heavier water masses denotes a counter-clockwise circulation, and the red cell in the lighter water masses denotes a clockwise circulation. The thick black line is the zonally-averaged (i.e. east-west directed) surface density and helps the reader to identify the surface ocean. Units are in Sverdrups, denoted by Sv (1 Sv $= 10^6\,\mathrm{m}^3/\mathrm{s}$).

Regardless of resolution, both panels display a two-cell meridional overturning circulation of the Southern Ocean. Ocean water of density about $1036.8\,\mathrm{kg/m}^3$ enters the Southern Ocean from the basins to the north, flows poleward at approximately constant density (adiabatic flow) and upwells at the surface ocean around 60°S. At the surface, the water transforms to different density classes and separates into two cells; a lower cell (blue) that represents the northward flow of the dense water that is produced at high southern latitudes close to Antarctica, and an upper cell (red) that represents the northward wind-driven surface flow of lighter water that was mentioned previously in the introduction.

Comparing the modelled circulation between the two grid resolutions, we see that the overturning is overall stronger in the high resolution model. In the high resolution model, both cells are of about 15 Sv strength whereas the upper and lower cell in the coarse resolution model is 7 Sv and 5 Sv only, respectively. To obtain further insight, a decomposition of the streamfunction is appropriate. By considering temporal deviations from the time-mean circulation, it is possible to separate the time-mean of ψ_I into two streamfunctions such

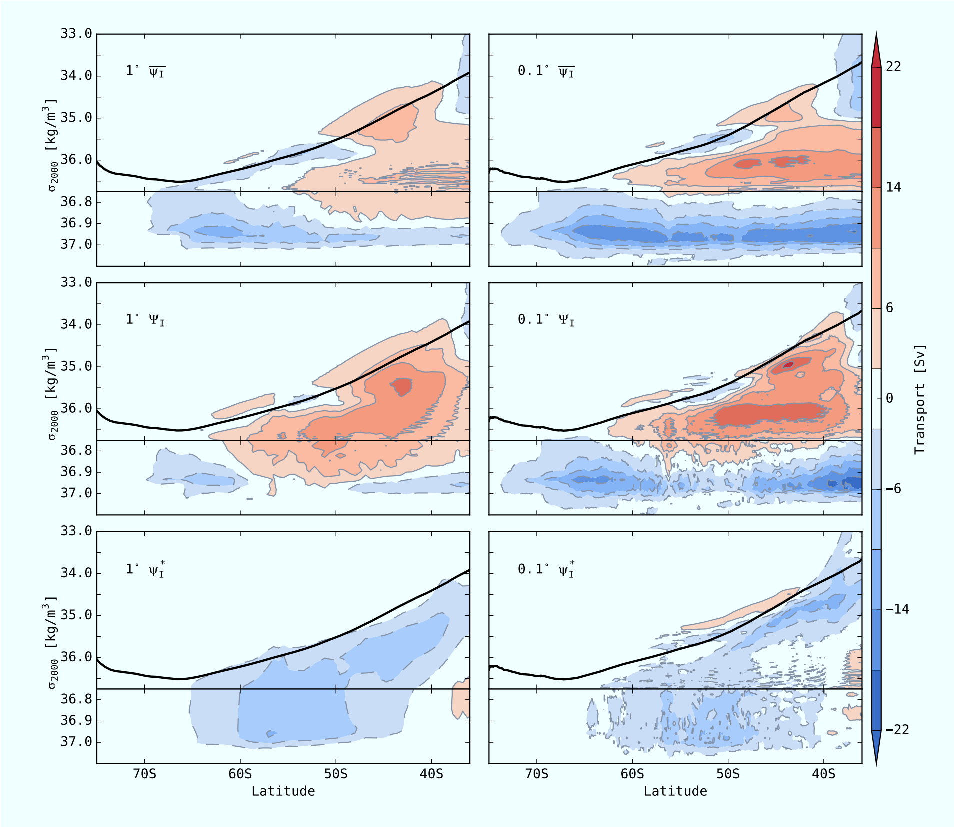

Figure 3. The figure displays the time-mean meridional overturning circulation (upper panels) and its wind-driven (middle panels) and eddy-induced (lower panels) contributions for the $1°$ model (left column) and the $0.1°$ model (right column). The tick labels on the density axis is here written more compactly as the actual density minus $1000\,\mathrm{kg/m^3}$. The black solid line is the zonally-averaged surface density and approximately indicates the surface ocean.

that $\overline{\psi_I} = \Psi_I + \psi_I^*$. Here Ψ_I represent the wind-driven overturning circulation and ψ_I^* represents the circulation driven by the eddies.

The middle panels of Fig. 3 display the wind-driven part of the total circulation Ψ_I. It is seen that the strength of the upper overturning cell is more comparable between the two models, and that the lower cell weakens in both models, especially between 60°S and 50°S. The lower panels of Fig. 3, which show the eddy-induced circulation ψ_I^*, reveals that the overall shape of the eddy circulation is captured by the eddy parameterisation. However, the high resolution model has a more surface-intensified eddy circulation between 50°S and 40°S, which contributes substantially to the difference seen in the upper cell of ψ_I (upper panels).

We now turn the focus towards the response of the meridional overturning circulation in the Southern Ocean wind stress change experiments to quantify the amount of eddy compensation in the model at different grid resolution. Fig. 4 shows the difference in

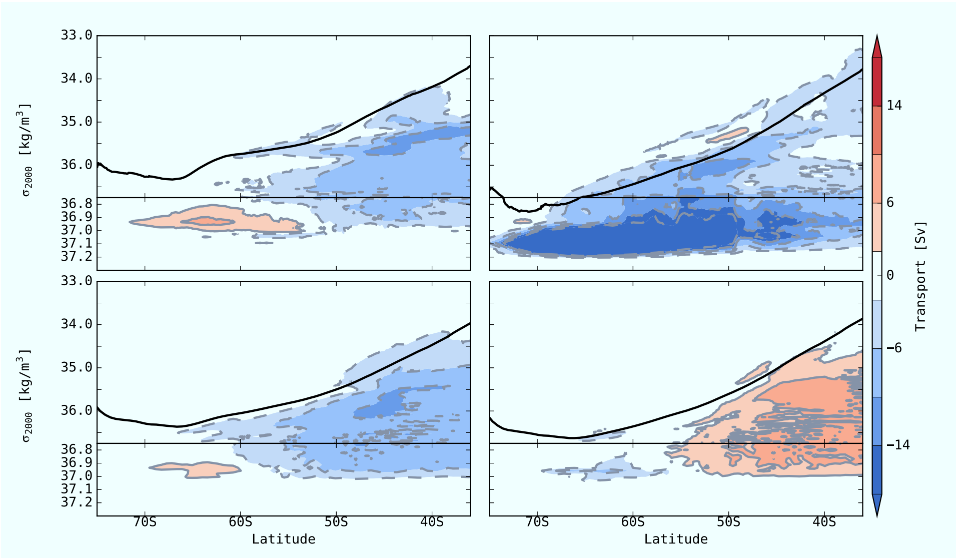

Figure 4. Difference in the meridional overturning circulation as function of model resolution and wind stress magnitude. The upper panels show the difference for the 0.1° model, and the lower panels for the 1° model. The left and right column of panels is associated with the 50% wind stress decrease and increase experiment, respectively.

streamfunction between the mean of the last ten years of the wind stress change experiments and the ten year mean of the control simulation displayed in the upper panels of Fig. 3. The upper and lower panels show the response for the 0.1° and 1° model, respectively. The left column of panels is for the wind stress decrease experiment and the right column is for the wind stress increase experiment.

First examining the wind stress decrease experiment, the two models show similar transient responses in terms of structure and absolute magnitude. Both show a weakening of similar magnitude of the upper overturning cell, and a smaller weakening of the lower overturning cell confined to the high southern latitudes. The weakening of the lower cell corresponds to a northward retreat, which takes place in both models. The maximum of the upper overturning cell in the 0.1° model decreases from $15\,\mathrm{Sv}$ to $6\,\mathrm{Sv}$, a 60% reduction, whereas the upper cell of the 1° model literally collapses and finds a decrease of the upper cell maximum by $9\,\mathrm{Sv}$, which corresponds to 130% relative decrease. Thus, on decadal time scale, the coarse resolution model is more sensitive to a wind stress reduction than the 0.1° model.

It is immediately seen that the two models are subject to a different transient model response when the wind stress is increased. The 1° model finds a general increase of the upper cell and an increase, and displacement, of the maximum from $7\,\mathrm{Sv}$ to $14\,\mathrm{Sv}$. Relatively small changes are also seen in the lower cell between 70°S and 60°S. Surprisingly the 0.1° model shows a weakening of the upper cell opposite to the response seen in the coarse resolution model. The maximum of the upper cell decreases by about $3\,\mathrm{Sv}$, but the lower cell increases in strength by several times the control value. The latter model response opposes the prevailing theory, which states that the upper cell should increase in magnitude to some degree. The unexpected model behaviour is related to a wind-triggered onset of deep convection and an associated sea ice reduction in the Weddell Sea, which conspire to increase the production of bottom water and hence the strength of the lower cell.

4 Discussion and Concluding Remarks

This study examines the transient response of the Southern Ocean meridional overturning circulation to local wind stress changes. An ocean general circulation model, at an eddy-parameterising 1° and an eddy-resolving 0.1° horizontal grid resolution, is employed to investigate whether the parameterised sensitivity to the wind stress matches that of the high resolution model with explicit eddies.

The control integrations with present day wind stress magnitude reveal that the overall overturning is stronger in the high resolution model. It is possible that the weaker lower cell in the 1° model is a result of a poor representation of bottom water formation at coarse resolution, but it is not clear that higher horizontal resolution should mitigate the problem[11]. The difference in the upper overturning cell is possible to explain by a more surface intensified eddy circulation in the 0.1° model, which cancel the wind-driven overturning differently compared to the 1° model.

The parameterised sensitivity to a wind stress decrease is higher on decadal time scale. Both models find a decrease of the upper overturning circulation cell of similar magnitude, but the relative decrease in the 1° model is greater since the background overturning is weaker. The modelled overturning response to a wind stress increase is radically different between the two models. The coarse resolution model behaves in accord with prevailing ideas, whereas the weakening of the upper overturning cell in the high resolution model is opposite to expectations. Moreover, this latter result contrasts the finding of a recent study that examines the same model, but in its fully coupled configuration[12]. According to the present study, deep convection is also able to compensate wind-driven changes in the upper cell.

These findings suggest that the parameterisation underestimates the eddy response on decadal time scale. In addition, the surprising result from the high resolution model shows that the simple view of eddy compensation as a competition solely between the wind-driven and eddy-induced circulation responses might not be applicable to complex ocean models.

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