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Interactive comment on “Wind driven changes in the ocean carbon sink” *by* N. C. Swart et al.

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Responses to Reviewer 1

This paper investigates the sensitivity of global ocean carbon uptake to variable and changing wind stress, with an emphasis on the Southern Ocean region. There has been quite a bit of debate in the literature about air-sea carbon fluxes in this region and their sensitivity to wind stress and eddy transport, and as such, this paper represents a nice contribution to the debate. The paper is generally well-written and the conclusions are sound. I recommend its publication in Biogeosciences, provided that the three major comments below are addressed during revision.

We thank the reviewer for their comments, all of which we respond to below.

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Major comments:

1) The paper is strongly focused on the Southern Ocean wind and CO2 flux trends, but not exclusively so. For example, several figures show the global flux response to global wind changes, and yet, there is very little discussion about the wind-driven changes in CO2 flux outside of the Southern Ocean. What might drive these changes? More discussion on this point is needed in the paper. Also, Figure 3 is confusing: the wind trend is for the Southern Ocean, but the CO2 flux trend is for the global ocean (or is it?). Please clarify.

To address this point we have added discussion on wind-driven changes in other parts of the ocean in section 3.2

“It is noteworthy that the outgassing between 45° and 60° S is surrounded by bands of wind-induced ingassing to the north and south. Such compensating changes are also evident in the northern hemisphere between 20° and 60° S, where changes in the Northern Annular Mode and westerly jet (Gillett and Fyfe, 2013) also play a role. In the tropics changes in the trade winds lead to a tripole of fluxes with (relative) ingassing to the south of the equator and outgassing between around 20° to 30° north and south. There are also differences by ocean basin, particularly in the tropics, which are not shown here. The positive globally integrated flux shown in Fig.2b is thus the net result of partial cancellation between regions of large wind induced ingassing and outgassing, which partly reflects opposing changes between the natural and anthropogenic CO_2 *fluxes (Zickfeld et al., 2008).”*

We have also emphasized the importance of regional differences in section 3.3 and in the conclusions. Figure 3 did show Southern Ocean wind trends and global ocean CO2 flux trends. The reviewer is right that is confusing. We have chosen to show Southern Ocean CO_2 **flux trends in Figure 3b to be consistent with the wind trends in Figure 3a. The conclusions remain the same as before because the global flux trends are dominated by the Southern Ocean.**

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2) I have little doubt that introducing the variable GM coefficient into the model simulations caused the mean state of the model to drift from the simulation with constant GM, and yet the different mean states of the model are not discussed. Please quantify the difference in the mean ocean circulation with and without variable GM. How does this difference in mean state affect your interpretation of the overturning or CO2 flux response to changes in wind?

The reviewer is correct that the variable GM scheme changes the mean climate state, but this does not alter our conclusions. We now discuss and quantify these differences for the reader in section 3.4:

"The mean climate state under the two eddy schemes also differs. In the CONTROL simulations with constant pre-industrial wind and radiative forcing, the Southern Ocean residual overturning circulation is 5 Sv or about 25% weaker under the variable GM scheme. There are also differences in the Antarctic Circumpolar Current, the subtropical gyres, sea surface temperatures (up to about 0.5° C on zonal average) and sea-ice. These differences in the climate and circulation of the mean-state can all affect the surface carbon flux and may also influence the response to changing winds. Nonetheless, even if considered purely in percentage terms relative to the baseline state, changes in the residual overturning circulation shown above are much larger with a constant GM scheme. The partial eddy compensation that occurs in our variable GM simulations is also in agreement with recent theoretical predictions (Meredith et al., 2011), eddy resolving model simulations (Morrison and Hogg, 2012), and other coarse-resolution simulations using a similar variable GM scheme (Lovenduski et al., 2013), which gives us confidence in the robustness of our result"

We also note that here we are interested in the wind effect, which we calculate as the difference between a FIXED wind and TRANSIENT wind experiment both for the constant GM case and for the variable GM case. This differencing has the effect of removing the mean climate or baseline state and thus revealing the changes due to winds. As noted above, even in percentage terms relative to the

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baseline state, changes are larger under the constant GM scheme. Thus, our interpretation of the changes remains the same as before.

3) A major finding in the paper is the connection between changes in MOC in constant/variable GM simulations and the changes in air-sea CO2 flux. However the discussion is missing the link between a different MOC response to wind and a different air-sea CO2 flux response to wind in the two sets of simulations. Exactly how does variable GM affect the transport of CO2 by eddies in the Southern Ocean? Please demonstrate that it is the eddy transport of CO2 that changes between these simulations, and not something else (e.g., a variable GM coefficient could cause differences in SST, which affect CO2 solubility, or differences in the depth of the mixed layer, which affect CO2 entrainment).

We now quantify the DIC budget of the surface Southern Ocean to show that the GM coefficient strongly affects the eddy advection of DIC, and therefore the coefficient influences the surface CO2 flux directly, while the contribution of other effects is generally small. We show these results in a new figure (now Figure 6, also attached below) and quantify them in a full discussion in section 3.4.:

“These changes in the overturning circulation can be connected to changes in the surface carbon flux by considering the Dissolved Inorganic Carbon budget of the surface Southern Ocean for the box south of 45° S and between 0 and 100 m, which is given by:

$$\frac{\partial DIC_{100m}}{\partial t} = J_{adv} + J_{iso} + J_{dia} + J_{gas} + J_{bio} \qquad (1)$$

where $J_{adv}, J_{iso}, J_{dia}, J_{gas}, J_{bio}$ represent the fluxes due to Eulerian mean advection, isopyncal mixing arising from parameterized eddies, diapycnal mixing, the sea-air gas exchange and biological processes respectively, as given in Lovenduski et al. (2013). Wind changes increase the surface DIC concentration and lead to the outgassing of

CO_2 in both the constant and variable GM experiment, but the changes are greatest with the constant coefficient (6a, b). There is little difference in the biological or diapycnal mixing induced fluxes between the experiments. Rather, the advective and isopycnal mixing terms are primarily responsible. The isopycnal mixing term associated with the parameterized eddies contains contributions due to along-isopycnal diffusion and due to advection associated with the eddy induced transport velocities Gent et al. (1995). The flux of DIC driven by this eddy advection is given by

$$(Fe_y,\ Fe_z) = (v^* \cdot DIC,\ w^* \cdot DIC) \tag{2}$$

where Fe_y is the horizontal component and Fe_z is the vertical component. There are equivalent terms for the Eulerian mean advection. Wind changes increase vertical advection of DIC into the Southern Ocean surface box by the Eulerian mean circulation (Fig. 6c), representing increased wind-driven upwelling of carbon rich deep waters. These changes in DIC advection by the mean circulation are basically the same regardless of GM coefficient. Fluxes due to eddies act in the opposite sense, moving DIC downward out of the surface Southern Ocean. Wind changes also increase this net eddy flux, but the changes are larger under the variable GM scheme because of the increases in K_{GM} (Fig. 6c). There are also compensating changes in horizontal eddy advection of DIC (Fig. 6d), which tends to bring DIC into the Southern Ocean. When summing the vertical and horizontal components the total effect of eddy induced advection is to remove DIC from the surface Southern Ocean, and this effect is greater under the variable GM scheme (Fig. 6e). These changes in DIC advection by eddies link the differences in surface CO_2 flux seen between the constant and variable GM simulations directly to the differences in the GM coefficient. There are also indirect effects of differences in the GM scheme, such as changes in sea surface temperature, but the role of K_{GM} driven advection dominates, consistent with Lovenduski et al. (2013). ”

Minor comment:

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-Section 3.2, line 4 should read “air to sea” instead of “sea to air”

The convention that we are using is that fluxes are positive out of the ocean, and thus “sea to air“ is in fact the correct terminology to reflect this.

Figures

Figure 6 Wind induced effect on a) surface carbon flux south of 45°S, b) DIC inventory integrated south 45°S and over the upper 100m, c) vertical flux of DIC by Eulerian mean advection (solid lines) and by eddy induced advection (dashed lines) integrated south 45°S, d) the horizontal components of the DIC advective flux at 45°S and integrated over 0 to 100 m and e) the total advective flux of DIC given by the sum of c) and d). The wind-induced effect is given by the TRANSIENT minus FIXED experiments, and results are shown for the constant GM (black) and variable GM (red) coefficients.

Interactive comment on Biogeosciences Discuss., 11, 8023, 2014.

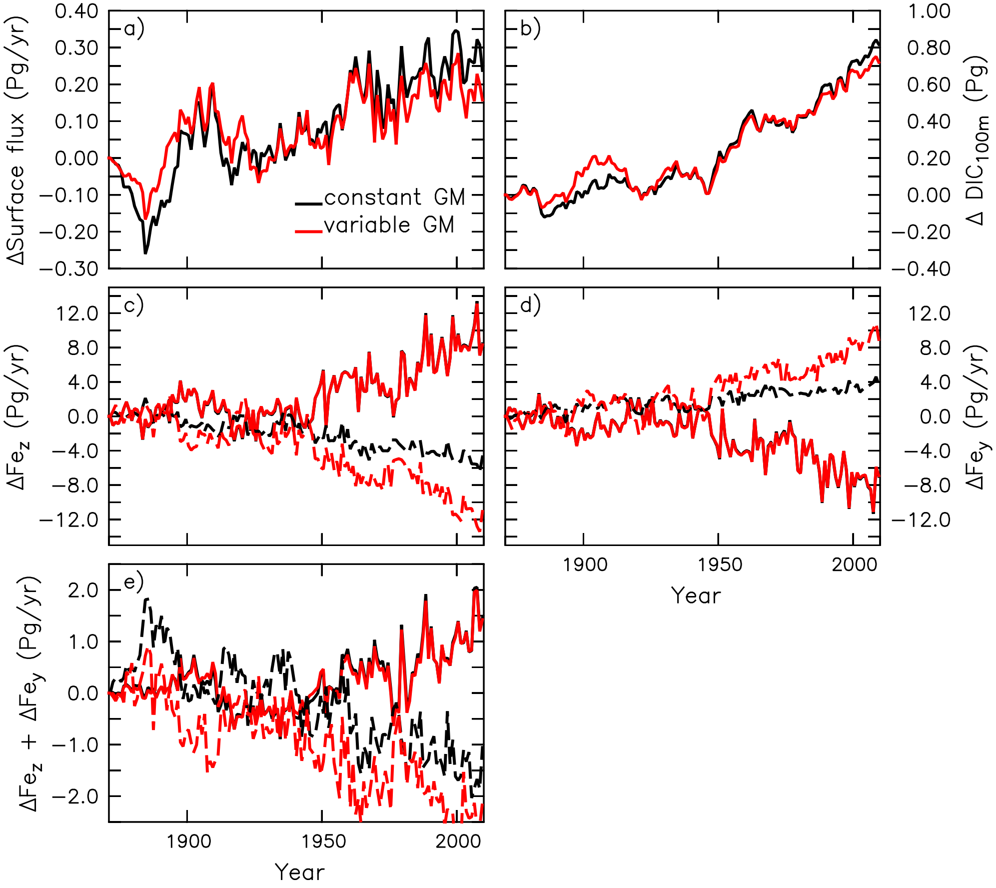

Fig. 1. New Figure 6. See caption above.

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