Reviewer 2:

Menviel et al. analysed the Southern Ocean CO_2 sink using an eddy-rich global ocean biogeochemical model. Based on the results of their model, they argued that variations in the Southern Ocean CO_2 sink are mainly driven by changes in the outgassing of natural CO_2 and are related to the Southern Annular Mode (SAM). This variability in CO_2 flux could be explained by variations in surface dissolved inorganic carbon (DIC).

Such a modelling study, using a high-resolution ocean model, is essential as most of the currently used global ocean biogeochemical models cannot resolve eddies. The results presented in this study could help to improve our understanding of the Southern Ocean CO_2 sink. However, I have some questions about some of the results presented in this study (major comment). Therefore, the paper will probably be a significant scientific contribution with some revisions.

We thank the Reviewer for their helpful comments on our manuscript. We have made significant changes to the manuscript, including i) an improved and clearer comparison with observations, ii) an improved presentation of both full and detrended results, and iii) the inclusion of a similar simulation performed with the 1 degree version of the model.

We provide a point-by-point answer below in blue, with excerpts from the revised manuscript in green.

Major comments:

1) Authors mentioned that they model can reproduce some decadal variabilities of the Southern Ocean CO2 sink suggested by an observation-based product (i.e., SOM-FFN), and suggested an influence of the SAM, line 5: "*The simulated total CO2 flux exhibits decadal scale variability […] in phase with observations and with variability in the Southern Annular Mode (SAM). Notably, a stagnation of the total CO2 uptake is simulated between 1982 and 2000, while a re-invigoration is simulated between 2000 and 2012.*"

These statements seem to be supported by the lines:

- Line 173: "*nCO2 fluxes are strongly correlated with the SAM index calculated from the JRA-55do dataset (R=0.62 for annual mean data and R=0.82 with a 5-year smoothing, Figs. 2b and S3)*"
- Line 192: "*The simulated and observational estimates of tCO2 flux are well correlated (R=0.55) and both display minimum tCO2 uptake in 2000-2001, and maximum in the early 1990s and early 2010s.*"
- Line 197: "*The nCO2 flux variability dominates the changes in tCO2 uptake with a strengthening of the winds and a poleward shift both reducing the tCO2 uptake (Figs. 2c,g and S3).*"

Did the authors remove the trends from the time series of nCO2, tCO2 (from their model and from SOM-FFN) and SAM before calculating the correlation coefficients? If not, the correlation coefficients between nCO2 and SAM, or between simulated and observed tCO2 estimates, are mainly influenced by the linear trend and do not provide information on the phasing between observed and simulated signals.

1) Regarding the nCO_2 fluxes. In the first version of the manuscript, we were only presenting non-detrended nCO_2 fluxes and SAM index. The reason behind this is that we are also interested in the multi-decadal-scale relation between the two. We however understand that the multi-decadal-scale increase in SAM could dominate the increase in SO nCO_2 outgassing. Therefore, to better highlight the short-term impact of the SAM, we are now showing the relationship between detrended nCO_2 fluxes and detrended SAM in the new Figure 3 (Figure R1) as well as scatter plots in Figure S4 (Figure R2).

   Following some of the other comments from Reviewer 2 and as detailed below, we are also now focusing our analysis on the period 1980 to 2021.

   The correlation between the detrended nCO_2 fluxes and SAM index is still significant at R=0.46, with increased nCO_2 outgassing during positive phases of the SAM. We also note that not only does the SAM index of the year impact nCO_2, but there is a "memory effect", with the SAM index of the previous year also modulating nCO_2. As such, if we plot the SO nCO_2 fluxes as a function of the detrended SAM index averaged over the current and previous year (as shown in Fig. R2, now Fig. S3), the correlation between the two is 0.8.

   We have amended the text to accurately reflect the detrended and non-detrended relationships.

   "Since the SAM index displays a trend towards the positive phase between 1980 and 2021, the correlation mentioned above includes both interannual variability as well as decadal-scale changes. To also assess whether changes in the SAM significantly impact nCO_2 fluxes on an interannual timescale, we calculate the correlation between the detrended SAM index and detrended nCO_2 flux. The correlation is significant ($p<0.05$) and equals 0.46. We however note that if the detrended SAM index is averaged over two years (mean of the current and previous year), then the correlation equals 0.8 (Fig. S4a), indicating that the atmospheric forcing during the previous year also impacts surface natural pCO_2."

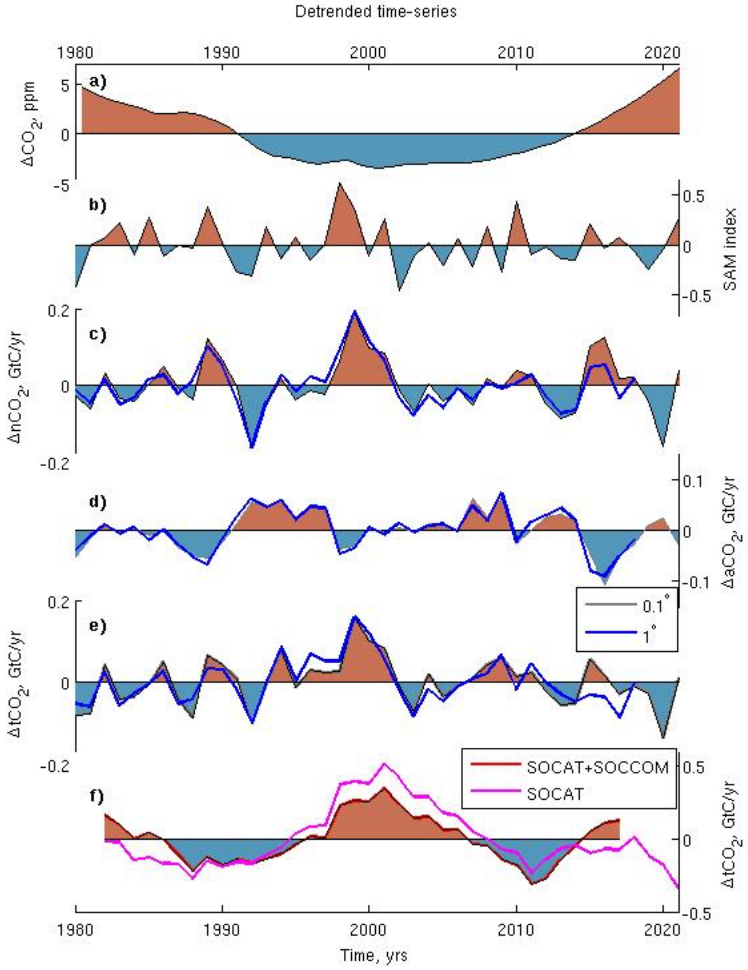

Figure R1: Detrended time-series of a) annual mean atmospheric CO_2 (ppm) used as forcing; b) SAM index calculated from the JRA55-do dataset (Stewart et al., 2020); Simulated integrated ocean to atmosphere CO_2 fluxes in the 0.1° (black) and 1° (blue) simulations: c) nCO_2, d) aCO_2, e) tCO_2. f) Detrended SO tCO_2 flux as derived from the SOM-FFN including both the SOCAT and SOCCOM data (red) (Bushinsky et al., 2019), and including the SOCAT data only (magenta) (Landschutzer et al., 2020). All the CO_2 fluxes are integrated over the SO (35°S-80°S) and are in GtC/yr. The correlation coefficients between the detrended SAM index and detrended nCO_2, aCO_2 and tCO_2 are 0.8, -0.42 and 0.69.

2) Regarding the tCO_2 fluxes, we are now showing and displaying correlation coefficients for both the detrended and non-detrended data.

The non-detrended SO tCO_2 fluxes have a correlation coefficient with the tCO_2 flux estimates of Bushinski et al., (2019) of 0.55, while the correlation coefficient with the estimates of Landschutzer et al., (2020) is 0.79.

We have added the following text to the manuscript:

“The simulated tCO_2 uptake increases by only 0.003 GtC/yr^2 between 1980 and 1998 (Fig. 2e), in agreement with both observational estimates (Fig. 2f). While the simulated tCO_2 uptake decreases in between 1998 and 2001 as in the observations, the magnitude of this simulated change is smaller than in the observational estimates.

Similarly, while both simulation and observational estimates display an increase in tCO$_2$ uptake in the early 2000s, the reinvigoration only lasts until 2003 in the simulation, while it lasts until 2010 in both observational datasets. Finally, similar to the SOCAT only product, the simulation suggests a stagnation of the tCO$_2$ uptake between 2011 and 2018, while the SOCAT+SOCCOM product suggests a decrease in tCO$_2$ uptake.

While the simulated tCO$_2$ changes are within the uncertainty range of the observational estimates (+/-0.15 GtC/yr) (Bushinsky et al., 2019) for most of the simulated period, the simulated variations are lower and outside of the uncertainty range between 1998 and 2005."

The detrended data are less well correlated, at 0.35 for Bushinski et al (2019) and 0.37 for Landschutzer et al., (2020). We have added the following text:

"The correlation between detrended simulated and observationally estimated tCO$_2$ fluxes are 0.35 for SOCAT + SOCCOM (Bushinsky et al., 2019) and 0.37 for SOCAT only (Landschutzer et al., 2020). The two main disagreements between simulation and observations are in the mid 1990s and the late 2000s/early 2010s, when the ACCESS-OM2-01 simulates relatively low tCO$_2$ uptake (Fig.3e) while the observational estimates suggest high tCO$_2$ uptake (Fig. 3f). During these two periods the detrended nCO$_2$ fluxes are small, whereas the detrended aCO$_2$ fluxes are positive. These periods of low tCO$_2$ uptake in the model are thus due to reduced aCO$_2$ uptake, probably resulting from the atmospheric CO$_2$ forcing. "

The scatter plots of detrended aCO$_2$ and tCO$_2$ fluxes versus detrended SAM index are also shown in figure R2. The relationship between aCO$_2$ and SAM, with enhanced aCO$_2$ uptake during positive phases of the SAM is now significant at R=0.42. nCO$_2$ still dominates the tCO$_2$ relationship with the SAM, with a correlation coefficient of 0.69.

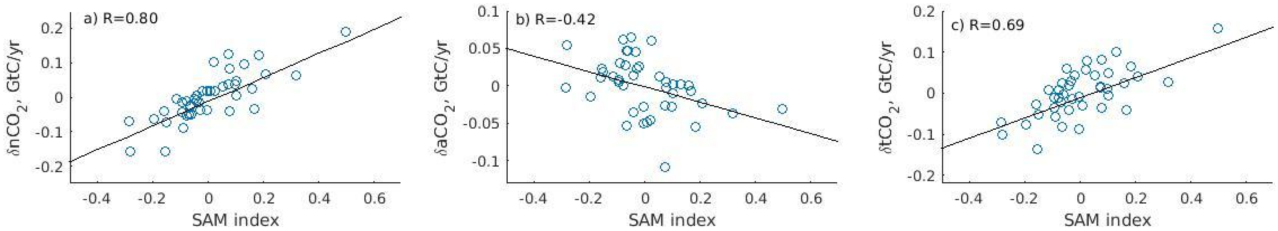

Figure R2: (from left to right) Detrended nCO$_2$, aCO$_2$ and tCO$_2$ fluxes versus detrended SAM index.

Furthermore, according to Figure 2, the stagnation in tCO2 uptake suggested by SOM-FFN is limited to the 1990s and not between 1982 and 2000 as the model simulated. In SOM-FFN, a reinvigoration occurred between 2000 and 2012, while the model simulated a reinvigoration only in the early 2000s (as the authors also mention in line 335: "*In agreement with observations, a re-invigoration of tCO2 uptake is simulated in the early 2000s.*"). Therefore, the statement "in phase with observations" in the abstract is misleading and does not seem to be supported by the authors' results. The relationships presented in this manuscript are specific to their model and cannot be fully used to explain the variations in the Southern Ocean CO2 sink suggested by the observation-based method.

We have re-written that part of the Results as follow:

“The simulated tCO_2 uptake increases by only 0.003 GtC/yr^2 between 1980 and 1998 (Fig. 2e), in agreement with both observational estimates (Fig. 2f). While the simulated tCO_2 uptake decreases in between 1998 and 2001 as in the observations, the magnitude of this simulated change is smaller than in the observational estimates.

Similarly, while both simulation and observational estimates display an increase in tCO_2 uptake in the early 2000s, the reinvigoration only lasts until 2003 in the simulation, while it lasts until 2010 in both observational datasets. Finally, similar to the SOCAT only product, the simulation suggests a stagnation of the tCO_2 uptake between 2011 and 2018, while the SOCAT+SOCCOM product suggests a decrease in tCO_2 uptake.

While the simulated tCO_2 changes are within the uncertainty range of the observational estimates (+/-0.15 GtC/yr) (Bushinsky et al., 2019) for most of the simulated period, the simulated variations are lower and outside of the uncertainty range between 1998 and 2005.”

If possible, and to better assess the added value of using a high-resolution ocean model, a comparison between tCO2 in the Southern Ocean simulated by the eddy-rich model presented here and by a global ocean biogeochemical model with lower spatial resolution should be added to Figure 2 (and in the manuscript).

Following from the Reviewer’s suggestion, we are now including in Figures 2 (Figure R1) and the new Figure 3 (Figure R3) the results of a similar simulation performed with the 1 degree resolution version of the ACCESS-OM2. The 1 degree and 0.1 degree experiments are forced by the same JRA55-do forcing.

The time-evolution of the Southern Ocean CO_2 fluxes displays similar variability in both resolutions. While the 0.1 degree resolution provides a much better representation of small-scale processes and interaction with bathymetry thus providing a better representation of regional changes (Figs. 1 and 7), the 1 degree simulation captures well the large-scale processes (Figs. S4 and S8).

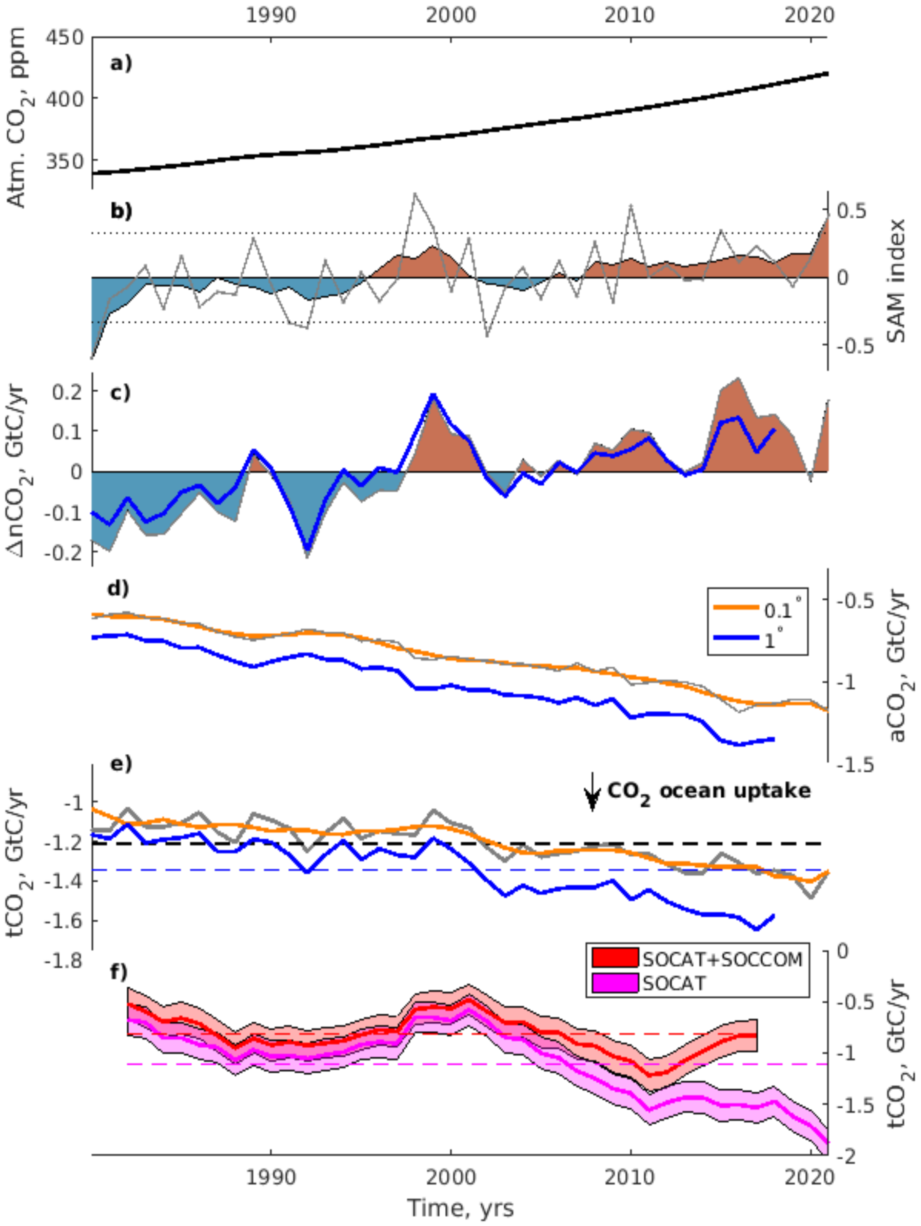

Figure R3: Non-detrended time series. Time series of a) annual mean atmospheric CO$_2$ concentration used as forcing, b) SAM index calculated from the JRA55-do dataset (Stewart et al., 2020). The horizontal dotted lines represent the thresholds used to define positive and negative SAM in the composites. Simulated integrated ocean to atmosphere CO$_2$ fluxes in the (annual mean in grey and 5-yr running mean in orange) 0.1∘ and (blue) 1∘ simulations: c) nCO2, d) aCO2, and e) tCO2. f) SO tCO2 flux as derived from the SOM-FFN (red) including both the SOCAT and SOCCOM data (Bushinsky et al., 2019), and (magenta) only including the SOCAT data (Landschutzer et al., 2020). The shading represents an uncertainty of 0.15 GtC/yr. All the CO2 fluxes are integrated over the SO (35∘S-80∘S) and are in GtC/yr. Dashed horizontal lines represent the 1980-2021 mean.

2) An important result from this modelling study is that "*The total SO CO2 uptake capability thus reduced since 1970 in response to a shift towards positive phases of the SAM.*" (line 13).

As mentioned by the authors in the introduction, Line 66: "*More recently, by analysing changes in SO tCO2 fluxes between 1980 and 2016, Keppler and Landschützer (2019) suggested that the net effect of the SAM on tCO2 uptake was nil and that instead the variability was arising from regional shifts in surface pressure linked to zonal wavenumber 3.*"

The authors need to discuss the discrepancy between their results and the results from Keppler and Landschützer (2019). Is a trend toward more positive SAM the only reason to explain a reduced CO2 uptake capability by the Southern Ocean since 1970? What about the other factors that could induce a long-term increase in the vertical stratification of the Southern Ocean and reduce its ability to absorb anthropogenic CO2 (e.g., Bourgeois T, Goris N, Schwinger J, Tjiputra JF. Stratification constrains future heat and carbon uptake in the Southern Ocean between 30°S and 55°S. Nat Commun. 2022, 13(1))? Although the SAM index could have an influence, it seems that other mechanisms can also influence the long-term changes in the Southern Ocean CO2 sink and need to be evaluated and discussed.

We agree with the Reviewer that changes in vertical stratification could impact tCO_2 uptake. We were already discussing this on L. 319-322, but we are now expanding the discussion by adding reference to Bourgeois et al., (2022) and more directly discussing the discrepancy with Keppler and Landschützer (2019).

"In addition, the underestimation of the simulated tCO_2 uptake in the late 2000s/early 2010s could be due a mis-representation of Southern Ocean stratification. It has indeed been suggested that the overturning rate of the lower cell was weaker during that time period (de Vries et al., 2017) due to enhanced stratification in the Southern Ocean (de Lavergne et al., 2014), linked to enhanced Antarctic basal melt rates (Adusumili et al., 2020). Enhanced stratification in the Southern Ocean would weaken the aCO_2 uptake (Bourgeois et al., 2022), but would reduce the nCO_2 outgassing (Menviel et al., 2015), thus potentially enhancing tCO_2 uptake."

and L. 370:

"This is in contrast to the conclusion of Keppler & Landschutzer, (2019) that the SAM had a net zero effect on SO tCO_2 uptake. Both our study and the one of Keppler & Landschutzer (2019) highlighted enhanced tCO_2 outgassing south of 50S during positive phases of the SAM as well as zonal asymmetries with a region of enhanced tCO_2 uptake in the Pacific sector of the SO. While Keppler & Landschutzer (2019) suggest this is linked to the zonal wave number 3 pattern, we attribute these asymmetries to the bathymetry and different poleward trends of the westerlies in the different sectors of the SO."

Minor comments:

3) Several references could be added in the introduction section and help the discussion. For example, studies that are partly based on observations and that have also demonstrated the influence of the SH westerlies on the air-sea CO2 flux:

- Gregor L, Kok S, Monteiro PMS. Interannual drivers of the seasonal cycle of CO2 in the Southern Ocean. Biogeosciences. 2018, 15(8), 2361–78.
- Nevison CD, Munro DR, Lovenduski NS, Keeling RF, Manizza M, Morgan EJ, et al. Southern Annular Mode Influence on Wintertime Ventilation of the Southern Ocean Detected in Atmospheric O2 and CO2 Measurements. Geophys Res Lett. 2020, 47(4), e2019GL085667.

An important modelling study that focuses on natural carbon variability:

- Resplandy L, Séférian R, Bopp L. Natural variability of CO2 and O2 fluxes: What can we learn from centuries-long climate models simulations? J Geophys Res Oceans. 2015, 120(1), 384–404.

The most recent review about the ocean CO2 sink variability:

- Gruber N, Bakker DCE, DeVries T, Gregor L, Hauck J, Landschützer P, et al. Trends and variability in the ocean carbon sink. Nat Rev Earth Environ. 2023, 4(2), 119–34.

We thank the referee for pointing us to these studies. We have now added some sentences in the Introduction to refer to the work of Gregor et al., (2018), Nevison et al., (2019), Resplandy et al., (2015) and Gruber et al., (2023).

4) Line 120: “Biogeochemical fields other than oxygen were initialised at the start of cycle 4 (1958). A uniform 0.01 mmol m−3 initial value was used for phytoplankton, zooplankton, detritus and CaCO3. […] Here, we skip the first twelve years of the fourth cycle (i.e. 1958-1970) from our analysis to allow the simulation to recover from the reset at the end of the previous cycle”

Twelve years is a relatively short period for the model to reach a steady state or recover from the reset. Could you provide in supplementary figures evidence that the biogeochemical fields have reach a steady state?

Could this influence the conclusion that (line 345) “we find that biological processes do not significantly impact air-sea CO2 fluxes on decadal-time scales, and that the changes in surface nDIC arise from changes in oceanic circulation”?

In the revised manuscript, we skip the first 22 years of the fourth cycle (i.e. 1958-1980) to allow the model to recover from the reset. This procedure follows the general protocol outlined by the phase II of the Coordinated Ocean-ice Reference Experiments.

We are also now including as figure S2 (Figure R4 here) the time evolution of nDIC, PO4 and O2 in the Southern Ocean and at different depth over the course of the experiment for both the 0.1 degree and 1 degree versions of the model.

The concentrations of the different tracers are not constant through the simulations since the atmospheric forcing varies (among other reasons). However, apart from surface PO4, the trends are much lower than 1%. The nDIC trends at the surface and in the deep are 0.02%, and 0.1% at intermediate depth. While the surface PO4 trend is 1.3% (which could also be due to the trend towards a positive SAM), the trends at intermediate depth and at depth are of 0.1%. The O2 trend at the surface is 0.08%, while below 500m it is 0.8%.

As also seen in Figure R5, there is no significant trend in the Southern Ocean detritus concentration averaged between 40 and 100m depth (i.e. the location of the maximum detritus concentration).

As such, we think our models are equilibrated enough to assess the impact of recent changes in atmospheric forcing on Southern Ocean CO_2 fluxes.

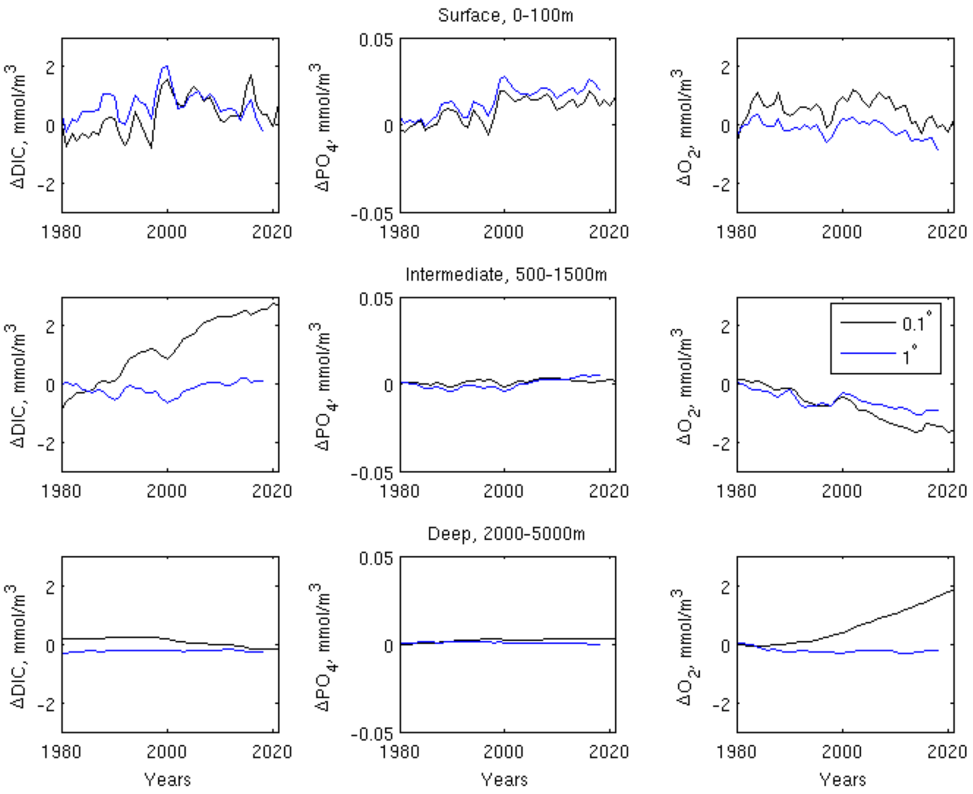

Figure R4: Biogeochemical tracers time-series averaged over the Southern Ocean (35S-75S) in the ACCESS-OM2-01 (black) and ACCESS-OM2 (blue). (From left to right) nDIC, PO4 and O2 averaged over (top) the top 100m, (middle) between 500 and 1500m depth and (bottom) below 2000m depth.

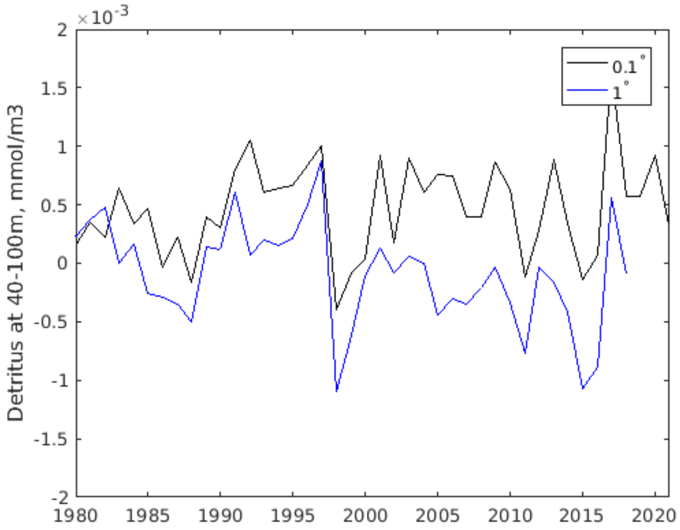

Figure R5: Time-series of detritus concentration (mmol/m3) averaged over the Southern Ocean (35S-75S) and over 40-100m depth in the ACCESS-OM2-01 (black) and ACCESS-OM2 (blue).

5) Line 155: "…from autonomous biogeochemical floats (Gray et al., 2018; Prend et al., 2022)." In figure 1 caption, it says Bushinsky et al. (2019). Which one is used?

We are now being clearer and adding more information on the observational estimates that are used to compare with the model outputs. In Figure 1, we are now using version 2022 of Landschutzer et al., (2016 & 2020). In Figures 2 and 3, we are showing both Landschutzer et al., (2020) and Bushinsky et al., (2019).

6) Line 161: "…highlighting an uptake of aCO2 everywhere south of 35°S (Fig. 1d), with a maximum south of the PF (~56.3°S, Fig. S2d)." This is quite surprising. Normally, most of the aCO2 uptake should occur more north between the Polar Front and the Subpolar Front. For example, in:

- Gruber et al. (2019 – Annu. Rev. Mar. Sci.): "In contrast to natural CO2, the entire Southern Ocean south of 35°S is a sink for anthropogenic CO2 […] The majority of this uptake occurs between the Antarctic Polar Front and the Subpolar Front, leading to a distinct ring of high-uptake fluxes at the latitudes between 45°S and 55°S."
- See also figure 4 in Gruber et al. (2023 – Nat. Rev. Earth Environ.).

Could you explain the reason for this misrepresentation of the aCO2 uptake, and how is this impacting the conclusion (line 305) "the strengthening and poleward shift of the SH westerlies only had a small impact on aCO2 uptake "?

Gruber et al., (2023) indeed show an increase in aCO_2 uptake everywhere in the Southern Ocean since 1990, with a maximum at about 50S. This is in line with the simulation, even if in the simulation, there are two zonally-averaged maximum aCO_2 uptake at 42S and at 55S (old Fig. S2). It should be noted that the simulated and estimated changes in tCO_2 both suggest a maximum increase in tCO_2 uptake at about 40S. In the simulation, the aCO_2 changes are obtained by subtracting the nCO_2 from the tCO_2. Similarly for observational products, assumptions have to be made to estimate the aCO_2 from the tCO_2.

The simulation suggests an increase in nCO2 outgassing south of 50S over the course of the simulation, with little changes in tCO_2. That indicates that there might also be an increase in aCO_2 uptake in that region. The increase in nCO_2 outgassing is linked to the enhanced upwelling, driven by the strengthening and poleward shift of the westerlies.

By comparing the detrended aCO_2 fluxes with the detrended SAM, we are now suggesting that positive phases of the SAM lead to enhanced aCO_2 uptake, even though the magnitude of that effect is still small (~25% of the nCO_2 change).

The text is modified to reflect this.

7) Line 176: "…similar correlation…" The correlation value needs to be provided in the text.

We removed that part of the text and instead mention in the methods that the SAM index calculated from the JRA-55do dataset captures well the SAM index based on observations (Marshall et al., 2003, Stewart et al., 2020).

8) Line 178: "The nCO2 outgassing occurs in…" and line 185: "The increase in aCO2 uptake occurs everywhere…" These sentences can be removed as the information was provided in the previous section 3.1.

These sentences were removed.

9) Line 183: "A weak correlation…" is the correlation statistically significant or not?

This was amended to:

"A weak but significant ($p < 0.05$) relationship…"

10) Figure 3 and Line 202: "As the outgassing of nCO2 occurs south of the SAF, we focus our analysis on that region. The natural pCO2 increase south of 50°S…". A clear definition and location of the front is provided (e.g., Figure 1). Instead of using the 50°S limit, the values should be averaged exactly is the area south of the front.

This figure as well as this section of the manuscript were significantly modified. The results are now shown as maps and not timeseries.

11) Section 3.4. "Changes in oceanic DIC". This section presents results which are not used in the following discussion. Furthermore, the figure 7 is the same as figure S8. These results need to be compared and discussed with published studies, otherwise this section should be removed.

The anthropogenic and total DIC shown in Figures 7 and S8 were different, as the mean trend was taken out from Fig. 7 whereas Fig. S8 was showing the full results. Nevertheless, the anthropogenic and total DIC are not shown anymore. Therefore Fig. S8 was removed and Fig. S7 was combined with Fig. 7. The results of this section are now moved earlier in the Results section.