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Southern Ocean circulation's impact on atmospheric CO_2 concentration

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In the context of past and present climate change, the Southern Ocean (SO) has been identified as a crucial region modulating the concentration of atmospheric CO_2. The sustained upwelling of carbon-rich deep waters and inefficient nutrient utilization at the surface of the SO leads to an outgassing of natural CO_2, while anthropogenic CO_2 is entrained to depth during the formation of Antarctic Bottom water (AABW), Antarctic intermediate water (AAIW) and sub-Antarctic mode water (SAMW). Changes to the SO circulation resulting from both dynamic and buoyancy forcing can alter the rate of upwelling as well as formation and subsequent transport of AABW, AAIW and SAMW, thus impacting the air-sea CO_2 exchange in the SO. Models of all complexity robustly show that stronger southern hemispheric (SH) westerlies enhance SO upwelling, thus leading to stronger natural CO_2 outgassing, with a sensitivity of 0.13 GtC/yr for a 10% increase in SH westerly windstress. While the impact of changes in the position of the SH westerly winds was previously unclear, recent simulations with high-resolution ocean/sea-ice/carbon cycle models show that a poleward shift of the SH westerlies also enhances natural CO_2 outgassing with a sensitivity of 0.08GtC/yr for a 5° poleward shift. While enhanced AABW transport reduces deep ocean natural DIC concentration and increases surface natural DIC concentration, it acts on a multi-decadal timescale. Future work should better constrain both the natural and anthropogenic carbon cycle response to changes in AABW and the compound impacts of dynamic and buoyancy changes on the SO marine carbon cycle.

1 Introduction

Despite covering only about 25% of the world's ocean surface, the Southern Ocean (SO, south of 35°S) is one of today's largest sink of both anthropogenic carbon and excess heat, accounting for ~40% of the oceanic anthropogenic carbon uptake and ~72% of the excess heat uptake (Sabine et al., 2004; Mikaloff-Fletcher et al., 2006; Shi et al., 2018). This oversized role is due to the unique overturning circulation of the SO that brings deep water up to the surface and leads to the formation of deep and intermediate water masses. A key driver of this overturning are the strong westerly winds that peak in strength around 55°S and are bounded by easterly winds on their Antarctic and subtropical flanks. These winds create a divergent surface flow and steeply tilted isopycnals that outcrop south of the maximum westerly wind stress to allow old, nutrient rich Circumpolar Deep Water (CDW) to upwell from mid-depths to the surface (Figure 1A). Due to Ekman transport within the westerly wind belt, Antarctic surface waters move equatorwards, freshen and warm. As a result, there is an outgassing of natural CO_2 south of the sub-Antarctic front and particularly south of the polar front. As CDW equilibrates with the atmosphere, its dissolved inorganic carbon (DIC) is consumed by phytoplankton, thus decreasing the surface water pCO_2, leading to an oceanic uptake of atmospheric CO_2, a process referred to as the biological pump (Talley, 2013).

The CDW that rises to the SO surface is replaced by downward flows of surface waters in other regions. In the current context of elevated atmospheric CO_2 concentration, these downward flows entrain carbon, and particularly anthropogenic carbon, as well as heat in the SO interior (Frölicher et al., 2015; Gruber et al., 2019), primarily within Antarctic Intermediate Water (AAIW), but also within Antarctic Bottom Water (AABW) and sub-Antarctic Mode Water (SAMW) (Figure 1B). AAIW subducts along isopycnals into the SO interior equatorward of the sub-Antarctic front where wind driven surface flows converge. Winter deepening of the mixed layer north of the Antarctic Circumpolar Current (ACC) leads to the

formation of SAMW, which overlays AAIW (Morrison et al., 2022). Closer to Antarctica, dense shelf waters, the precursor of AABW are formed on the Antarctic continental shelf in the Ross Sea, Weddell Sea, Prydz Bay, and Adelie Land (Purkey et al., 2018), through brine rejection and ocean/ice-shelf interactions.

Observational products suggest that the SO total (sum of anthropogenic and natural) CO_2 fluxes exhibit large decadal-scale variability (LeQuéré et al., 2007; Matear and Lenton, 2008; Landschützer et al., 2015; Bushinsky et al., 2019; Gruber et al., 2019; Keppler and Landschützer, 2019; Gruber et al., 2023), with a lower than expected total CO_2 uptake in the 1990s and early 2000s (LeQuéré et al., 2007; Landschützer et al., 2015; Gruber et al., 2019) and probably during the mid-2010s (Bushinsky et al., 2019; Gruber et al., 2019; Keppler and Landschützer, 2019; Landschützer et al., 2020). The main hypothesis to explain the stagnation in the CO_2 uptake observed in the 1990s and early 2000s is the concurrent positive SAM trend (LeQuéré et al., 2007; Lovenduski et al., 2008; Resplandy et al., 2015; Gruber et al., 2023), which corresponds to a strengthening and poleward shift of the SH westerlies. As the CO_2 uptake re-invigorated, particularly between 2002 and 2012, other hypotheses to explain the variability emerged such as regional wind variability associated with the zonal wave number 3 pattern (Keppler and Landschützer, 2019), solubility effects (Landschützer et al. 2015) and changes in atmospheric CO_2 growth rate (McKinley et al., 2020). While hindcast experiments support a dominant role of the SAM in modulating the SO CO_2 fluxes (Gruber et al., 2019; Hauck et al., 2020; Menviel et al., 2023), they underestimate the observed SO CO_2 flux variability. This could be due to an under-estimation of Southern Ocean stratification (de Lavergne et al., 2014), potentially linked to enhanced Antarctic basal melt rates (Adusumilli et al., 2020), which would weaken AABW formation and transport (Li, 2023). The individual and compound roles of changes in SH westerly wind strength and position, and AABW formation and transport on the marine carbon cycle need to be fully understood to constrain changes in SO CO_2 fluxes.
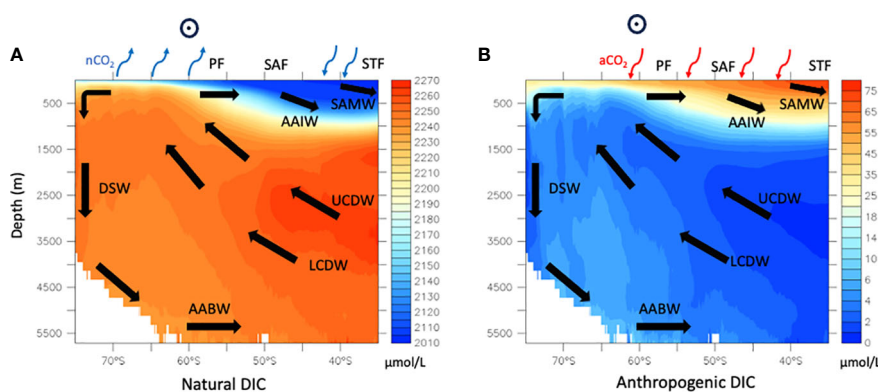

FIGURE 1
Schematic showing zonally averaged Southern Ocean **(A)** natural DIC and **(B)** anthropogenic DIC concentration (μmol/L) averaged over years 2017-2021 in the ACCESS-OM2-01 simulation. Blue and red arrows at the ocean's surface represent the natural and anthropogenic CO_2 fluxes, respectively, and the westerly wind is represented by a circle above. PF, SAF and STF are the positions of the Polar Front, Subantarctic Front and Subtropical Front, respectively. Thick black arrows in the ocean interior represent the circulation of water masses: Dense Shelf Water (DSW), Antarctic Bottom Water (AABW), Lower Circumpolar Deep Water (LCDW), Upper Circumpolar Deep Water (UCDW), Antarctic Intermediate Water (AAIW), and Subantarctic Mode Water (SAMW).

While overall the SO has mitigated the rise in atmospheric CO_2 since at least the 1980s, SO CO_2 outgassing has been suggested to induce an increase in atmospheric CO_2 during deglaciations as well as past abrupt climate change events (Anderson et al., 2009; Skinner et al., 2010; Watson et al., 2015; Rae et al., 2018; Shuttleworth et al., 2021; Gray et al., 2023). SO stratification during glacial periods, potentially arising from a large sea-ice cover, weaker and/or equatorward shifted SH westerlies would allow a carbon accumulation in the deep ocean (Toggweiler et al., 2006; Menviel et al., 2017). The breakdown of this stratification during deglaciations and Antarctic warm events, i.e. millennial-scale warm periods over Antarctica and the Southern Ocean (Buizert and Members, 2015), would lead to a SO CO_2 outgassing and an increase in atmospheric CO_2 of up to 20 ppm (Ahn and Brook, 2008; Marcott et al., 2014; Menviel et al., 2018; Bauska et al., 2021). An improved understanding of the interplay between SO circulation and marine carbon cycle is however needed to refine our understanding of these past climate change events.

Here we provide a perspective on past, present and future relationship between changes in atmospheric CO_2 and SO circulation arising from both changes in surface wind and buoyancy. We also present recent advances and future work.

2 Southern hemispheric westerly winds

There is a general consensus that stronger SH westerly winds enhance SO natural CO_2 outgassing by increasing the upward transport of DIC-rich CDW, thus leading to an increase in atmospheric CO_2 (Gottschalk et al., 2020). This DIC increase mostly arises from the advective upwelling of CDW along isopycnals into the mixed layer, although increased vertical diffusion at the base of the mixed layer could also significantly contribute to the higher surface DIC (Dufour et al., 2013). Enhanced upwelling of CDW can also enhance primary production, which acts to increase the export of organic carbon to depth, thus lowering atmospheric CO_2 (Menviel, 2008; Hauck et al., 2013). However, most studies found this negative feedback to only have a small impact on the CO_2 fluxes (Dufour et al., 2013) and to mostly impact carbon uptake north of the sub-Antarctic front (Menviel et al., 2023).

Depending on the pCO_2 of the upwelled water, the magnitude of the negative biological feedback as well as the resolution of the ocean model used, which can impact the outcrop area of deep water and SO circulation response, a 10% strengthening of the SH westerly wind stress has been found to lead to a 2.7 ppm +/- 0.5 ppm CO_2 increase (Menviel et al., 2008; Menviel et al., 2015; Huiskamp et al., 2016; Lauderdale et al., 2017; Menviel et al., 2018; Gottschalk et al., 2019). While Toggweiler et al. (2006) hypothesized that a poleward shift of the SH westerly should enhance the SO CO_2 outgassing, simulations performed with coarse resolution models led to mixed results, with a poleward SH westerly shift leading to both an increase and a decrease in atmospheric CO_2 depending on the model used (Gottschalk et al., 2019).

Most modelling studies that assessed the impact of SH westerly changes on the marine carbon cycle were performed with models that could not resolve mesoscale eddies (Lenton and Matear, 2007; Lovenduski et al., 2007; Lovenduski et al., 2008; Menviel, 2008; Tschumi et al., 2011; Dufour et al., 2013; Hauck et al., 2013; Völker and Köhler, 2013; Huiskamp et al., 2016; Lauderdale et al., 2017). Mesoscale eddies are prevalent in the SO, particularly downstream of topographic features that intercept the path of the Antarctic Circumpolar Current (ACC) (Sokolov and Rintoul, 2009; Frenger et al., 2015). In the SO, eddy induced transports oppose the Ekman-driven overturning transport via eddy compensation. Eddy-permitting and eddy-rich models have thus highlighted the role of eddy compensation in mitigating the Southern Ocean overturning change due to increased wind stress (Meredith et al., 2012; Morrison and Hogg, 2013). It has further been suggested that climate models that did not use a variable eddy parametrization coefficient most likely overestimated the wind-driven response (Gent, 2016).

A recent study (Menviel et al., 2023) assessed the impact of changes in the strength and position of the SH westerlies on SO CO_2 fluxes, associated with a positive trend of the SAM over the last 42 years in a global eddy-rich model (ACCESS-OM2-01, 0.1° resolution, 75 vertical levels) forced by the 55-year Japanese Reanalysis for driving oceans (JRA55-do) (Tsujino et al., 2018). This simulation shows that positive phases of the SAM (stronger and poleward shifted SH westerlies) lead to enhanced SO CO_2 outgassing south of the polar front, and reduced CO_2 uptake north of the sub-Antarctic front. The CO_2 outgassing is maximum over topography features such as over the eastern part of the Southeast Indian Ridge, east of the Drake Passage and over the Southwest Indian Ridge, which could be due to enhanced eddy mixing over topography linked to the merging of multiple jets.

Here, we synthesize these results and merge them with other experiments performed with the suite of ACCESS-OM2 models. This includes the ACCESS-OM2 (1° and 50 vertical levels) and ACCESS-OM2-01 (0.1° and 75 vertical levels) forced by the JRA55-do reanalysis over the period 1958 to 2021 (Tsujino et al., 2018; Kiss et al., 2020) as well as four idealized perturbation experiments performed with the ACCESS-OM2-025 (0.25° and 50 vertical levels), in which the SH near surface wind speeds are abruptly modified (Hogg et al., 2017). The zonally uniform and temporally steady perturbations are applied to the CORE-NYF 6-hourly wind field between 27°S and 70°S with smoothing within 5° latitude of the perturbation boundaries. The perturbations include i) a 20% increase in SH westerly windstress between 32°S and 65°S, ii) a 20% increase with a 4° poleward shift, iii) a ~16% decrease, and iv) a ~4° equatorward shift of the SH westerly windstress. The first three idealized experiments are integrated for 42 years, while the last one is run for 125 years (Gray et al., 2023).

In all the simulations performed with the suite of ACCESS-OM2 models, stronger and poleward shifted SH westerlies lead to enhanced CO_2 outgassing south of the polar front (Figure 1). A robust linear relationship is obtained between the natural SO CO_2 flux and mean SO windstress (Figure 2A). The SO CO_2 outgassing increases by 13 ± 3 GtC/yr per N/m² (therefore ~0.13 GtC/yr per 10% windstress increase). These results show that an eddy-rich

model displays a similar sensitivity to changes in SO upwelling than a coarse-resolution model with a varying isopycnal thickness diffusivity (Kiss et al., 2020).

While the relationship between the position of the maximum SO windstress and SO CO_2 fluxes is weak, there is still a significant relationship, with enhanced SO CO_2 outgassing as the SH westerlies shift poleward, with a sensitivity of 0.016 ± 0.04 GtC/° latitude (Figure 2B). As the SH westerlies move poleward, so does the divergence, which leads to a steepening of heavier isopycnals, thus increasing the upwelling pathway of carbon-rich deep-waters (Toggweiler et al., 2006; Gray et al., 2023).

While many modelling studies assessed the impact of SH westerly changes on natural CO_2 fluxes, the impact on anthropogenic CO_2 fluxes has been less studied. Nevertheless, the results suggest that stronger SH westerlies also enhance the uptake of anthropogenic CO_2 in the SO, but the amplitude of this enhanced SO anthropogenic CO_2 uptake is only one third of the associated enhanced natural CO_2 outgassing (Lovenduski et al., 2008; Menviel et al., 2023). As such stronger SH westerlies reduce the total SO CO_2 uptake.

3 Antarctic bottom water transport

AABW is the densest large-scale water mass in the global ocean and it fills roughly 35% of the global ocean volume. As AABW moves northward in the abyss, it upwells through diapycnal mixing in the sub-tropics and tropics into deep waters (Talley, 2013). These deep waters, i.e. North Atlantic Deep Water (NADW), Indian Deep Water (IDW) and Pacific Deep Water (PDW) are then often upwelled at the surface of the Southern Ocean as CDW. Changes in AABW formation and transport, can arise from changes in SH westerlies, but also changes in sea-ice cover and polynya opening. For example, a poleward strengthening of the SH westerlies in the ACCESS-OM2-025 enhances the northward transport of sea-ice, thus leading to enhanced AABW formation and transport (Hogg

et al., 2017; Menviel et al., 2018). On the contrary, stronger polar easterlies increase the build-up of sea ice over the continental shelf, which reduces AABW formation (Jeong et al., 2022; Schmidt et al., 2023). Changes in buoyancy forcing resulting from changes in sea-ice formation can also affect AABW formation and transport. Polynya openings in the Antarctic coastal zone trigger large deep-ocean convection events, which strengthen the lower overturning cell (Hogg et al., 2017; Jeong et al., 2022). On the other hand, reduced sea-ice formation and associated warmer conditions can decrease the density of surface waters, thus increasing stratification and decreasing the formation of AABW (Choudhury et al., 2022; Zhou et al., 2023).

In turn, changes in AABW formation and transport affect the oceanic DIC concentration and atmospheric CO_2. Figure 3 shows zonally averaged DIC anomalies in two experiments which feature stronger AABW transport, but one is generated by surface SO salinification in an Earth system model of intermediate complexity, LOVECLIM (Menviel et al., 2015) ($\triangle$AABW=+14 Sv, Figures 3A, B) and the other by a poleward strengthening of the SH westerlies in the ACCESS-OM2-025 ($\triangle$AABW=+11 Sv, Figures 3C–F). In both cases, enhanced AABW transport leads to a natural DIC decrease in the deep ocean (Figures 3A, C). This arises i) from a decrease in remineralized DIC (Figures 3B, D), i.e. a decrease in the amount of carbon that can accumulate in the deep ocean resulting from a lower residence time of AABW; and ii) from a larger proportion of southern sourced waters with lower DIC concentration being advected to the deep North Pacific. The deep North Pacific indeed host the oldest watermass with the highest DIC concentration. As this enhanced lower overturning cell reduces deep ocean DIC concentration, it leads to an increase in DIC concentration above 1500m depth north of 40°S and in the mixed layer of the Southern Ocean (Figures 3A, C), thus resulting in a weaker vertical DIC gradient.

The differences in simulated DIC anomalies between the SO salinification and SH westerly poleward strengthening experiments could be attributed i) to the different length of the experiments (100 years vs 50 years): the DIC anomaly needs more than 50 years to
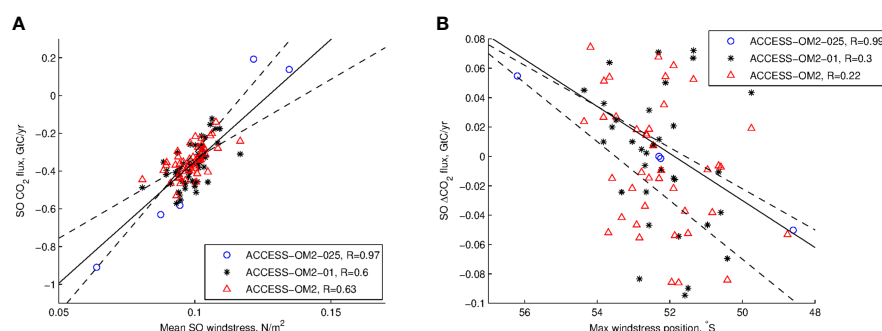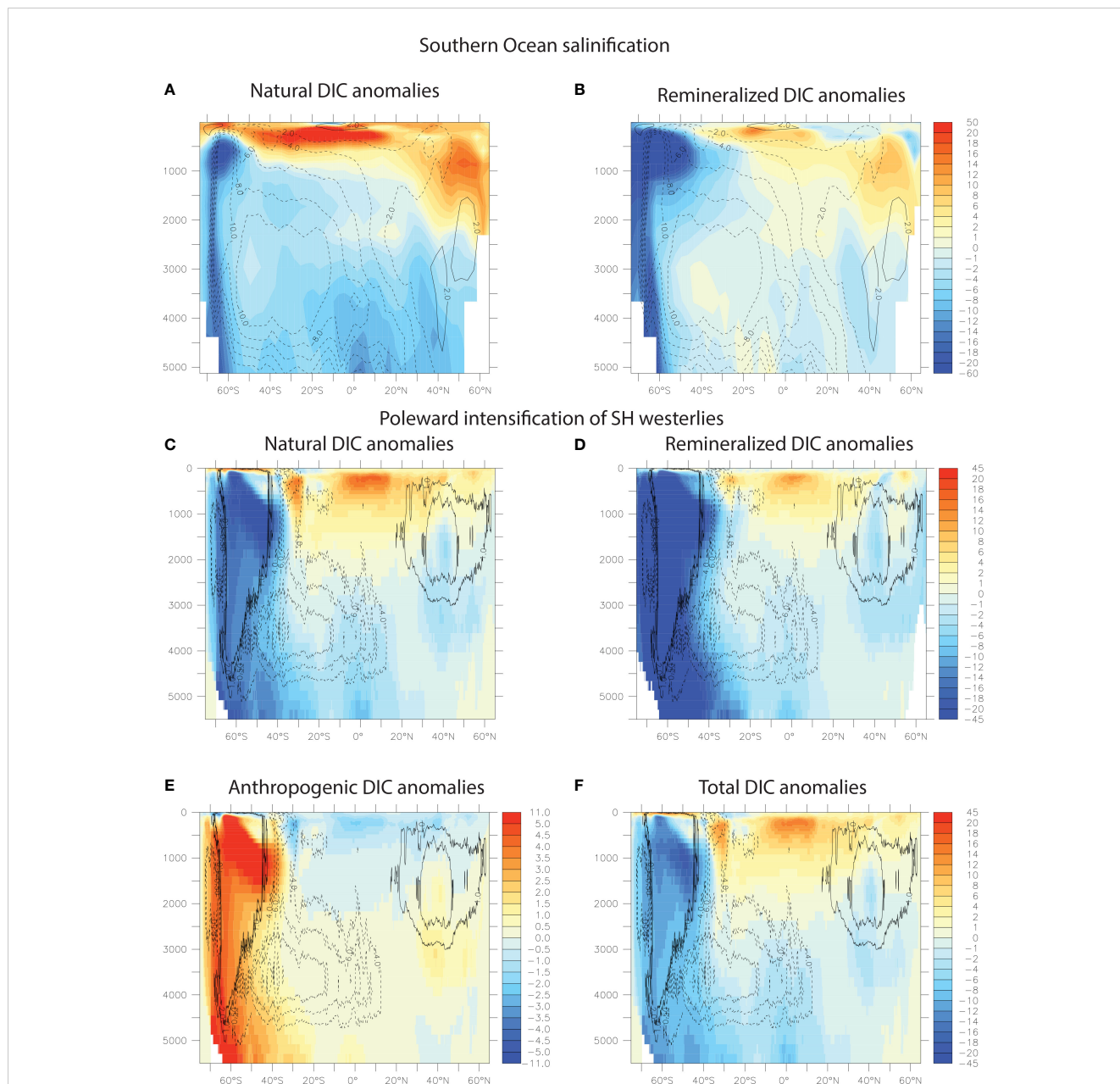
FIGURE 3
Zonally-averaged **(A)** natural DIC and **(B)** remineralized DIC anomalies (mmol/m^3) after 100 years for the SO salinification experiment performed with the Earth system model of intermediate complexity LOVECLIM (Menviel et al., 2015). Zonally-averaged **(C)** natural DIC, **(D)** remineralized DIC, **(E)** anthropogenic DIC and **(F)** total DIC anomalies (mmol/m^3) after 50 years for the poleward intensified SH westerlies (+20% and 4° poleward shift) experiment performed with the ACCESS-OM2-025 (Menviel et al., 2018). Overlaid are the global overturning streamfunction anomalies (Sv).

reach the deep North Pacific; ii) the poleward strengthening of the winds enhance the upper overturning cell (Hogg et al., 2017) (Figure 3C); and iii) the poleward strengthening of the SH westerlies leads to the opening of a polynya, which triggers a large deep-ocean convection event in SO.

Even though the preformed carbon entrained in the downwelling branch of AABW can increase, thus also leading to a significant increase in anthropogenic DIC concentration in the Southern Ocean (Figure 3E), this cannot compensate for the loss of natural DIC (Figure 3C) thus leading to negative total DIC anomalies (Figure 3F).

4 Discussion

Both dynamical and buoyancy changes can impact SO circulation and thus the SO CO_2 air-sea gas exchange, as well as the oceanic DIC distribution. As changes in the strength and position of the SH westerlies modulate the upwelling of carbon-rich deep-waters to the surface of the SO, it has long been suggested that changes in the SH westerlies could modulate the atmospheric CO_2 concentration (Russell et al., 2006; Toggweiler et al., 2006). While coarse resolution models consistently showed that stronger SH westerlies enhance the SO natural CO_2 outgassing (Gottschalk et al., 2019), the

lack of representation of mesoscale eddies within these modelling framework cast doubts on this result. In addition, due to the misrepresentation of AABW formation and the coarse resolution of the models used, the impact of changes in the position of SH westerlies on SO CO_2 flux was debated (Gottschalk et al., 2019). New results obtained with an eddy-rich model, which correctly forms dense-shelf water, show that mesoscale eddies do not significantly diminish the carbon cycle response to the wind-driven circulation and that poleward shifted SH westerlies enhance the SO natural CO_2 outgassing (Menviel et al., 2023).

In line with this, present-day hindcast simulations have suggested that changes in SH westerlies associated with the SAM were the dominant factor modulating the SO air-sea CO_2 exchange (Lenton and Matear, 2007; Lovenduski et al., 2007; Lovenduski et al., 2008). However, these simulations have not been able to reproduce the observational-based estimates contemporary CO_2 fluxes in SO (Lequere et al., 2018; Gruber et al., 2019; Hauck et al., 2020), even with eddy-rich ocean models (Menviel et al., 2023) forced with atmospheric reanalyses. Gloege et al. (2021) found that the decadal-scale variability in SO contemporary CO_2 flux could be overestimated by 30% due to undersampling. On the other hand, hindcast simulations could also underestimate the variability due to an overestimation of negative feedbacks (e.g. biological). The impact of changes in the strength and position of the SH westerlies should be further studied in eddy-permitting or eddy-resolving models that include complex ecosystem models.

The underestimation of the decadal-scale CO_2 variability could also be due to a poor representation of changes in buoyancy forcing, for example arising from enhanced Antarctic basal melt rates (Adusumilli et al., 2020), that could weaken AABW (Li, 2023). Buoyancy gain on the Antarctic shelf through either increased meltwater or warming will weaken the formation of AABW, and its subsequent transport (Menviel et al., 2010; Bintanja et al., 2013; Li, 2023). As a water mass ages, it accumulates remineralized nutrients. Weaker AABW transport increases the remineralized nutrient content in the deep ocean, which has been shown to increase the vertical DIC gradient and reduce SO natural CO_2 outgassing (Ito and Follows, 2005; Menviel et al., 2015). Future hindcast simulations should thus also include changes in Antarctic basal melt rates, with the caveat that the present-day carbon cycle could still be responding to changes that occurred decades ago.

In addition, as most models used to study the impact of changes in the oceanic circulation form AABW through deep-ocean convection, the impact of changes in dense-shelf water formation on the marine carbon cycle needs to be studied. In particular, the transport pathway of carbon from the abyss into deep waters and back to the surface as a function of bottom and deep water masses transport and volume should be better constrained. While both changes in SO upwelling strength and AABW formation can impact atmospheric CO_2, the marine carbon cycle response timescales are different: the SH westerlies impact the SO CO_2 outgassing within just a few months (Lenton and Matear, 2007; Menviel et al., 2023), while changes in AABW formation and transport only significantly impact air-sea CO_2 fluxes on a multi-decadal timescale (Menviel et al., 2018).

Finally, buoyancy and dynamic SO forcing can oppose each other, thus leading to a complex time-evolving oceanic circulation and thus marine carbon cycle response. In the context of past, present and future climate change, the individual and compound effects of changes in SH westerly, sea-ice formation and melt, formation of SO watermasses and the marine carbon cycle need to be better constrained to understand the resultant changes in atmospheric CO_2.

Data availability statement

The datasets presented in this study can be found in the Dryad repository https://datadryad.org/stash/share/E21b0EPD0x4ZXYb5JUt41sM42fEqhdA40hl8bnC1-2Y.

Author contributions

LM: Conceptualization, Formal Analysis, Investigation, Methodology, Writing – original draft. PS: Conceptualization, Methodology, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Adusumilli, S., Fricker, H., Medley, B., Padman, L., and Siegfried, M. (2020). Interannual variations in meltwater input to the Southern Ocean from Antarctic ice shelves. *Nat. Geosciences* 13, 616–620. doi: 10.1038/s41561-020-0616-z

Ahn, J., and Brook, E. (2008). Atmospheric CO_2 and climate on millennial time scales during the last glacial period. *Science* 322, doi:10.1126/science.1160832.

Anderson, R. F., Ali, S., Bradtmiller, L., Nielsen, S., Fleisher, M., Anderson, B., et al. (2009). Wind-driven upwelling in the Southern Ocean and the deglacial rise in Atmospheric CO_2. *Science* 323, 1443–1448.

Bauska, T., Brook, E., and Marcott, S. (2021). Abrupt changes in the global carbon cycle during the last glacial period. *Nat. Geosci.* 14, 91–96. doi: 10.1038/s41561-020-00680-2

Bintanja, R., van Oldenborgh, G., and Drijfhout, S. (2013). Important role for ocean warming and increased ice-shelf melt in antarctic sea-ice expansion. *Nat. Geosci.* 6, 376–379.

Buizert, C., and Members, W. D. P. (2015). Precise interpolar phasing of abrupt climate change during the last ice age. *Nature* 520, 661–665. doi: 10.1038/nature14401

Bushinsky, S. M., Landschützer, P., Rödenbeck, C., Gray, A. R., Baker, D., Mazloff, M. R., et al. (2019). Reassessing southern ocean air-sea CO2 flux estimates with the addition of biogeochemical float observations. *Global Biogeochemical Cycles* 33, 1370–1388. doi: 10.1029/2019GB006176

Choudhury, D., Menviel, L., Meissner, K. J., Yeung, N. K. H., Chamberlain, M., and Ziehn, T. (2022). Marine carbon cycle response to a warmer southern ocean: the case of the last interglacial. *Climate Past* 18, 507–523. doi: 10.5194/cp-18-507-2022

de Lavergne, C., Palter, J., Galbraith, E., Bernardello, R., and Marinov, I. (2014). Cessation of deep convection in the open Southern Ocean under anthropogenic climate change. *Nat. Climate Change* 4, 278–282. doi: 10.1038/NCLIMATE2132

Dufour, C. O., Sommer, J. L., Gehlen, M., Orr, J. C., Molines, J.-M., Simeon, J., et al. (2013). Eddy compensation and controls of the enhanced sea-to-air CO2 flux during positive phases of the Southern Annular Mode. *Global Biogeochemical Cycles* 27, 950–961. doi: 10.1002/gbc.20090

Frenger, I., Münnich, M., Gruber, N., and Knutti, R. (2015). Southern Ocean eddy phenomenology. *J. Geophysical Research: Oceans* 120, 7413–7449. doi: 10.1002/2015JC011047

Frölicher, T. L., Sarmiento, J. L., Paynter, D. J., Dunne, J. P., Krasting, J. P. , and Winton, M. (2015). Dominance of the southern ocean in anthropogenic carbon and heat uptake in CMIP5 models. *J. Climate* 28, 862–886. doi: 10.1175/JCLI-D-14-00117.1

Gent, P. R. (2016). Effects of southern hemisphere wind changes on the meridional overturning circulation in ocean models. *Annu. Rev. Mar. Sci.* 8, 79–94. doi: 10.1146/annurev-marine-122414-033929

Gloege, L., McKinley, G. A., Landschützer, P., Fay, A. R., Frölicher, T. L., Fyfe, J. C., et al. (2021). Quantifying errors in observationally based estimates of ocean carbon sink variability. *Global Biogeochemical Cycles* 35, e2020GB006788. doi: 10.1029/2020GB006788

Gottschalk, J., Battaglia, G., Fischer, H., Frölicher, T. L., Jaccard, S. L., Jeltsch-Thömmes, A., et al. (2019). Mechanisms of millennial-scale atmospheric co2 change in numerical model simulations. *Quaternary Sci. Rev.* 220, 30–74. doi: 10.1016/j.quascirev.2019.05.013

Gottschalk, J., Skinner, L. C., Jaccard, S. L., Menviel, L., Nehrbass-Ahles, C., and Waelbroeck, C. (2020). Southern Ocean link between changes in atmospheric CO2 levels and northern-hemisphere climate anomalies during the last two glacial periods. *Quaternary Sci. Rev.* 230, 106067. doi: 10.1016/j.quascirev.2019.106067

Gray, W. R., de Lavergne, C., Jnglin Wills, R. C., Menviel, L., Spence, P., Holzer, M., et al. (2023). Poleward shift in the southern hemisphere westerly winds synchronous with the deglacial rise in co2. *Paleoceanography Paleoclimatology* 38, e2023PA004666. doi: 10.1029/2023PA004666

Gruber, N., Bakker, D., DeVries, T., Gregor, L., Hauck, J., Landschützer, P., et al. (2023). Trends and variability in the ocean carbon sink. *Nat.Rev Earth Environ.* 4, 119–134. doi: 10.1038/s43017-022-00381-x

Gruber, N., Landschützer, P., and Lovenduski, N. (2019). The variable Southern Ocean carbon sink. *Annu. Rev. Mar. Sci.* 11, 159–186.

Hauck, J., Völker, C., Wang, T., Hoppema, M., Losch, M., and Wolf-Gladrow, D. A. (2013). Seasonally different carbon flux changes in the southern ocean inresponse to the southern annular mode. *Global Biogeochemical Cycles* 27, 1236–1245. doi: 10.1002/2013GB004600

Hauck, J., Zeising, M., Le Quéré, C., Gruber, N., Bakker, D. C. E., Bopp, L., et al. (2020). Consistency and challenges in the ocean carbon sink estimate for the global carbon budget. *Front. Mar. Sci.* 7. doi: 10.3389/fmars.2020.571720

Hogg, A., Spence, P., Saenko, O., and Downes, S. (2017). The energetics of southern ocean upwelling. *J. Phys. Oceanogr.* 47, 135–153.

Huiskamp, W. N., Meissner, K. J., and d'Orgeville, M. (2016). Competition between ocean carbon pumps in simulations with varying Southern Hemisphere westerly wind forcing. *Climate Dynamics* 46, 3463–3480. doi: 10.1007/s00382-015-2781-0

Ito, T., and Follows, M. (2005). Preformed phosphate, soft tissue pump and atmospheric CO_2. *J. Mar. Res.* 63, 813–839.

Jeong, H., Turner, A. K., Roberts, A. F., Veneziani, M., Price, S. P., Asay-Davis, X. S., et al. (2022). Southern ocean polynyas and dense water formation in a high-resolution, coupled earth system model. *Cryosphere Discussions* 2022, 1–32. doi: 10.5194/tc-2022-133

Keppler, L., and Landschützer, P. (2019). Regional wind variability modulates the southern ocean carbon sink. *Sci. Rep.* 9, 7384. doi: 10.1038/s41598-019-43826-y

Kiss, A. E., Hogg, A. M., Hannah, N., Boeira Dias, F., Brassington, G. B., Chamberlain, M. A., et al. (2020). ACCESS-OM2 v1.0: a global ocean–sea ice model at three resolutions. *Geoscientific Model. Dev.* 13, 401–442. doi: 10.5194/gmd-13-401-2020

Landschützer, P., Gruber, N., and Bakker, D. (2020). *An observation-based global monthly gridded sea surface pCO2 product from 1982 onward and its monthly climatology (NCEI Accession 0160558)*. (NOAA: NOAA National Centers for Environmental Information). doi: 10.7289/V5Z899N6

Landschützer, P., Gruber, N., Haumann, F. A., Rödenbeck, C., Bakker, D. C. E., van Heuven, S., et al. (2015). The reinvigoration of the Southern Ocean carbon sink. *Science* 349, 1221–1224. doi: 10.1126/science.aab2620

Lauderdale, J. M., Williams, R. G., Munday, D. R., and Marshall, D. P. (2017). The impact of Southern Ocean residual upwelling on atmospheric CO2 on centennial and millennial timescales. *Climate Dynamics* 48, 1611–1631. doi: 10.1007/s00382-016-3163-y

Lenton, A., and Matear, R. (2007). Role of the southern annular mode (SAM) in southern ocean CO_2 uptake. *Global Biogeochemical Cycles* 21. doi: 10.1029/2006GB002714

Lequere, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., et al. (2018). Global carbon budget 2018. *Earth System Sci. Data* 10, 2141–2194. doi: 10.5194/essd-10-2141-2018

LeQuéré, C., Rödenbeck, C., Buitenhuis, E., Conway, T., Langenfelds, R., Gomez, A., et al. (2007). Saturation of the Southern Ocean CO_2 sink due to recent climate change. *Science* 316, 1735–1738.

Li, E. M. H. A. S. R. A. M. (2023). Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater. *Nature* 615, 841–847. doi: 10.1038/s41586-023-05762-w

Lovenduski, N., Gruber, N., and Doney, S. (2008). Toward a mechanistic understanding of the decadal trends in the Southern Ocean carbon sink. *Global Biogeochemical Cycles* 22GB3016. doi: 10.1029/2007GB003139

Lovenduski, N., Gruber, N., Doney, S., and Lima, I. (2007). Enhanced CO_2 outgassing in the Southern Ocean from a positive phase of the Southern Annular Mode. *Global Biogeochemical Cycles* 21. doi: 10.1029/2006GB002900

Marcott, S., Bauska, T., Buizert, C., Steig, E., Rosen, J., Cuffey, K., et al. (2014). Centennial-scale changes in the global carbon cycle during the last deglaciation. *Nature* 514, 616–619. doi: 10.1038/nature13799

Matear, R., and Lenton, A. (2008). Impact of historical climate change on the southern ocean carbon cycle. *J. Climate* 21, 5820–5834. doi: 10.1175/2008JCLI2194.1

McKinley, G. A., Fay, A. R., Eddebbar, Y. A., Gloege, L., and Lovenduski, N. S. (2020). External forcing explains recent decadal variability of the ocean carbon sink. *AGU Adv.* 1, e2019AV000149. doi: 10.1029/2019AV000149

Menviel, L. (2008). Climate-carbon cycle interactions on millennial to glacial timescales as simulated by a model of intermediate complexity, LOVECLIM. Ph.D. thesis (University of Hawai'i).

Menviel, L., Mouchet, A., Meissner, K., Joos, F., and England, M. (2015). Impact of oceanic circulation changes on atmospheric $\delta^{13}CO_2$. *Global Biogeochemical Cycles* 29, 1944–1961. doi: 10.1002/2015GB005207

Menviel, L. C., Spence, P., Kiss, A. E., Chamberlain, M. A., Hayashida, H., England, M. H., et al. (2023). Enhanced Southern Ocean CO_2 outgassing as a result of stronger and poleward shifted southern hemispheric westerlies. *EGUsphere* 2023, 1–27. doi: 10.5194/egusphere-2023-390

Menviel, L., Spence, P., Yu, J., Chamberlain, M., Matear, R., Meissner, K., et al. (2018). Southern Hemisphere westerlies as a driver of the early deglacial atmospheric CO_2 rise. *Nat. Commun.* 92503. doi: 10.1038/s41467-018-04876-4

Menviel, L., Timmermann, A., Mouchet, A., and Timm, O. (2008). Climate and marine carbon cycle response to changes in the strength of the southern hemispheric westerlies. *Paleoceanography* 23. doi: 10.1029/2008PA001604

Menviel, L., Timmermann, A., Mouchet, A., and Timm, O. (2010). Climate and biogeochemical response to a rapid melting of the West-Antarctic Ice Sheet during interglacials and implications for future climate. *Paleoceanography* 25, doi:10.1029/2009PA001892.

Menviel, L., Yu, J., Joos, F., Mouchet, A., Meissner, K., and England, M. (2017). Poorly ventilated deep ocean at the Last Glacial Maximum inferred from carbon isotopes: a data-model comparison study. *Paleoceanography* 32, 2–17. doi: 10.1002/2016PA003024

Meredith, M. P., Garabato, A. C. N., Hogg, A. M. , and Farneti, R. (2012). Sensitivity of the overturning circulation in the southern ocean to decadal changes in wind forcing. *J. Climate* 25, 99–110. doi: 10.1175/2011JCLI4204.1

Mikaloff-Fletcher, S., Gruber, N., Jacobson, A., Doney, S., Dutkiewicz, S., Gerber, M., et al. (2006). Inverse estimates of anthropogenic CO_2 uptake, tranport, and storage by the ocean. *Global Biogeochemical Cycles* 20, GB2002. doi: 10.1029/2005GB002530

Morrison, A., and Hogg, A. (2013). On the relationship between southern ocean overturning and ACC transport. *J. Phys. Oceanogr.* 43, 140–148. doi: 10.1175/JPO-D-12-057.1

Morrison, A. K., Waugh, D. W., Hogg, A. M., Jones, D. C., and Abernathey, R. P. (2022). Ventilation of the southern ocean pycnocline. *Annu. Rev. Mar. Sci.* 14, 405–430. doi: 10.1146/annurev-marine-010419-011012

Purkey, S. G., Smethie, W. M., Gebbie, G., Gordon, A. L., Sonnerup, R. E., Warner, M. J., et al. (2018). A synoptic view of the ventilation and circulation of antarctic bottom water from chlorofluorocarbons and natural tracers. *Annu. Rev. Mar. Sci.* 10, 503–527. doi: 10.1146/annurev-marine-121916-063414

Rae, J., Burke, A., Robinson, L., Adkins, J., Chen, T., Cole, C., et al. (2018). CO_2 storage and release in the deep Southern Ocean on millennial to centennial timescales. *Nature* 562, 569–573. doi: 10.1038/s41586-018-0614-0

Resplandy, L., Séférian, R., and Bopp, L. (2015). Natural variability of CO2 and O2 fluxes: What can we learn from centuries-long climate models simulations? *J. Geophysical Research: Oceans* 120, 384–404. doi: 10.1002/2014JC010463

Russell, J. L., Dixon, K. W., Gnanadesikan, A., Stouffer, R. J., and Toggweiler, J. R. (2006). The southern hemisphere westerlies in a warming world: Propping open the door to the deep ocean. *J. Climate* 19, 6382–6390. doi: 10.1175/JCLI3984.1

Sabine, C., Feely, R., Gruber, N., Key, R., Lee, K., Bullister, J., et al. (2004). The oceanic sink of anthropogenic CO_2. *Science* 305, 367–371.

Schmidt, C., Morrison, A. K., and England, M. H. (2023). Wind- and sea-ice-driven interannual variability of antarctic bottom water formation. *J. Geophysical Research: Oceans* 128, e2023JC019774. doi: 10.1029/2023JC019774

Shi, J.-R., Xie, S.-P., and Talley, L. D. (2018). Evolving relative importance of the southern ocean and north atlantic in anthropogenic ocean heat uptake. *J. Climate* 31, 7459–7479. doi: 10.1175/JCLI-D-18-0170.1

Shuttleworth, R., Bostock, H., Chalk, T., Calvo, E., Jaccard, S., Pelejero, C., et al. (2021). Early deglacial co2 release from the sub-antarctic atlantic and pacific oceans. *Earth Planetary Sci. Lett.* 554, 116649. doi: 10.1016/j.epsl.2020.116649

Skinner, L., Fallon, S., Waelbroeck, C., Michel, E., and Barker, S. (2010). Ventilation of the deep Southern Ocean and deglacial CO_2 rise. *Science* 328, 1147–1151.

Sokolov, S., and Rintoul, S. R. (2009). Circumpolar structure and distribution of the antarctic circumpolar current fronts: 1. mean circumpolar paths. *J. Geophysical Research: Oceans* 114. doi: 10.1029/2008JC005108

Talley, L. D. (2013). Closure of the global overturning circulation through the Indian, pacific, and southern oceans: Schematics and transports. *Oceanography* 26, 80–97.

Toggweiler, J., Russell, J., and Carson, S. (2006). Midlatitude westerlies, atmospheric CO_2, and climate change during ice ages. *Paleoceanography* 21, PA2005. doi: 10.1029/2005PA001154

Tschumi, T., Joos, F., Gehlen, M., and Heinze, C. (2011). Deep ocean ventilation, carbon isotopes, marine sedimentation and the deglacial CO_2 rise. *Climate Past* 7, 771–800. doi: 10.5194/cp-7-771-2011

Tsujino, H., Urakawa, S., Nakano, H., Small, R. J., Kim, W. M., Yeager, S. G., et al. (2018). JRA-55 based surface dataset for driving ocean–sea-ice models (JRA55-do). *Ocean Model.* 130, 79–139. doi: 10.1016/j.ocemod.2018.07.002

Völker, C., and Köhler, P. (2013). Responses of ocean circulation and carbon cycle to changes in the position of the Southern Hemisphere westerlies at Last Glacial Maximum. *Paleoceanography* 28, 726–739. doi: 10.1002/2013PA002556

Watson, A., Vallis, G., and Nikurashin, M. (2015). Southern Ocean buoyancy forcing of ocean ventilation and glacial atmospheric CO_2. *Nat. Geosci.* 8, 861–864. doi: 10.1038/ngeo2538

Zhou, S., Meijers, A., Meredith, M., Abrahamsen, E. P., Holland, P. R., Silvano, A., et al. (2023). Slowdown of Antarctic Bottom Water export driven by climatic wind and sea-ice changes. *Nat. Clim. Change* 13, 701–709. doi: 10.1038/s41558-023-01695-4