Chapter 5

Strengthening of Southern Ocean carbon uptake through increasing stratification*

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Abstract

To date, the Southern Ocean constitutes the strongest sink for anthropogenic carbon-dioxide in the global ocean. Concerns have been raised that increased surface ocean density stratification and increased westerly winds due to the anthropogenic perturbation of the climate system could weaken this sink and potentially amplify global warming. Here, we study the sensitivity of the Southern Ocean carbon-dioxide uptake to stratification changes induced by recent changes surface freshwater fluxes from sea ice using a regional ocean circulation model. Contrary to expectations, our simulations reveal a strengthening of the net carbon-dioxide uptake in response to an increasing stratification. This strengthened uptake is mostly a response to an increased surface freshwater input from sea ice into the upwelling region, which inhibits the upwelling of deep, warm, and carbon-rich waters into the surface layer, and outweighs a reduction of the uptake that is associated with the subduction of carbon-dioxide by intermediate and mode waters. Additionally, our simulations reveal no substantial reduction in response to changes in the surface winds that occurred over recent decades. Consequently, our results provide a potential explanation for the recent finding that the Southern Ocean carbon-dioxide sink has not weakened but rather strengthened over recent decades. While the sea-ice freshwater input to the upwelling region increased during this period, global climate models project a future decline of the sea-ice cover, which would imply a reversal of the effect. In contrast, in a cold glacial climate, stronger sea-ice fluxes could considerably enhance the stratification in the upwelling region, resulting in a reduced outgassing of carbon-dioxide, which provides a potential explanation for lower atmospheric carbon-dioxide concentrations during past cold climates.

5.1 Introduction

The increase in the atmospheric carbon-dioxide (CO_2) concentrations through human activity since the pre-industrial era has turned the Southern Ocean from a region of net CO_2 release to a CO_2 sink (Hoppema, 2004; Gruber et al., 2009). Thereby, it has taken up a proportionally much larger amount of anthropogenic CO_2 than any other region of the global ocean (Mikaloff Fletcher et al., 2006; Khatiwala et al., 2009; Frölicher et al., 2015). Simulations with global climate models suggest that an increasing surface density stratification due to future warming and enhanced surface freshwater fluxes could weaken this uptake of anthropogenic CO_2 and therefore amplify global warming (Manabe and Stouffer, 1993; Sarmiento et al., 1998). In contrast, paleoceanographic data indicate that an increasing stratification reduces the outgassing of natural CO_2 by inhibiting the upwelling of deep and carbon-rich waters—a process that was suggested to control atmospheric CO_2 variations over past glacial–interglacial climate states (Francois et al., 1997; Toggweiler, 1999; Sigman et al., 2004; Watson and Naveira Garabato, 2006; Skinner et al., 2010). Combining these two lines of argument, an increasing stratification in the Southern Ocean could either decrease or increase the atmospheric CO_2 concentration, depending on the net effect of changes in upwelling and subduction of CO_2. Model experiments show that this net effect is very sensitive to the background atmospheric CO_2 concentration as well as the type, pattern, magnitude of the surface fluxes (Matear and Lenton, 2008; Lovenduski and Ito, 2009; Bernardello et al., 2014a,b). As a consequence of large uncertainties in the observed surface fluxes (Speer et al., 2012; Bourassa et al., 2013) and global models (Downes et al., 2010; Sallée et al., 2013a; Stössel et al., 2015), the response of the Southern Ocean carbon fluxes to changes in the surface stratification remains largely unconstrained for past, present, and future climates. In this study, we address this issue by using new observation-based constraints on the surface fluxes from the sea ice and their changes over recent decades (Haumann et al., 2016b) to analyze the sensitivity of the carbon fluxes to stratification changes in a present-day climate.

The majority of the global ocean's deep waters surface through upwelling in the Southern Ocean (Talley, 2013). This upwelling occurs due to wind- and buoyancy-driven vertical transport (Speer et al., 2000; Morrison et al., 2011; Marshall and Speer, 2012) and mixing (Watson et al., 2013), which return large amounts of dissolved inorganic carbon (DIC) and nutrients from the deep ocean to the surface (Marinov et al., 2006). While vertical transport is mostly responsible for elevating the DIC-rich waters from the deep ocean to waters below the mixed layer, mixing at the base of the mixed layer is the predominant reason for the penetration of these waters to the surface (Dufour et al., 2013). The resulting over-saturation of the partial pressure of CO_2 (pCO_2) in the surface waters with respect to the atmosphere leads to a natural CO_2 release from the Southern Ocean (Gruber et al., 2009). This release occurs during austral winter in a region between the sea-ice edge and the Subantarctic Front (SAF) where deep mixed layers and a weak density stratification ease the surfacing of the deep waters (Takahashi et al., 2002; Landschützer et al., 2014b). The situation is reversed during austral summer, when wind-driven mixing decreases and surface waters stratify due to warming and sea-ice melting (Haumann et al., 2016b). As these waters are transported northward by surface Ekman transport, intense biological production removes carbon from the surface ocean (Hauck et al., 2013). As a result, the pCO_2 at the surface drops below the atmospheric level leading to a natural uptake of CO_2 by the ocean during summer. However, this uptake is considerably smaller than the outgassing during winter, leading to a net annual loss of natural CO_2 from these waters to the atmosphere before they are subducted as Antarctic Intermediate Water (AAIW; Mikaloff Fletcher et al., 2007; Gruber et al., 2009). Another portion of these southern sourced waters mixes with southward flowing subtropical waters, that were enriched in CO_2, between the SAF and the Subtropical Front (STF). Therefore, the subduction of these waters as Subantarctic Mode Water (SAMW) leads to a natural uptake of CO_2 from the atmosphere (Mikaloff Fletcher et al., 2007).

The uptake of anthropogenic CO_2 is the sum of a reduced outgassing from the upwelling waters and an enhanced uptake, which result from the elevated pCO_2 in the atmosphere relative to the pre-industrial ocean's pCO_2. The net uptake would saturate very rapidly if the CO_2 was not removed from the surface ocean through mixing and transport (Sarmiento et al., 1992). Since most of the global subsurface waters form in the Southern Ocean (DeVries and Primeau, 2011), it is one of the most effective regions to take up anthropogenic CO_2. AAIW and SAMW draw down anthropogenic CO_2 from the surface ocean and store it in deeper layers (Caldeira and Duffy, 2000). However, while AAIW mainly subducts anthropogenic CO_2 through a reduced outgassing, SAMW subducts it through an enhanced uptake (Mikaloff Fletcher et al., 2006; Gruber et al., 2009; Iudicone et al., 2011). Besides this transport mechanism, mixing at the base of the mixed layer is a critical factor for the invasion of anthropogenic CO_2 to the subsurface layers (Dufour et al., 2013; Bopp et al., 2015).

Changes in surface winds and buoyancy forcing could alter both the natural CO_2 release and the uptake of anthropogenic CO_2 by changing the vertical transport and mixing. The increase in westerly winds in response to the anthropogenic forcing (Thompson et al., 2011; Abram et al., 2014) potentially enhances the net overturning circulation and changes its vertical structure despite a compensation by meso-scale eddies (Meredith et al., 2012). At the same time, the increasing winds deepen the surface mixed layer (Sallée et al., 2010b). Both these processes would enhance the natural CO_2 release from the Southern Ocean (Le Quéré et al., 2007; Lovenduski et al., 2007, 2008; Lenton et al., 2009; Dufour et al., 2013). Yet, very recent observational studies show that contrary to expectations, the Southern Ocean carbon sink actually strengthened again over the last decade despite a continued strengthening of the westerly winds (Fay et al., 2014; Landschützer et al., 2015b; Munro et al., 2015). Observation-based estimates of surface CO_2 fluxes over the past 30 years suggest that Southern Ocean CO_2 sink did not saturate but actually strengthened according to what is expected from the increase of atmospheric pCO_2 alone (Landschützer et al., 2015b). This finding raises the questions if other mechanisms are at work in the long-term that counter-act a potential decreasing CO_2 sink due to increasing winds. Matear and Lenton (2008) suggest that a more stable surface ocean due to increasing surface heat and freshwater fluxes could have balanced the effect induced by the increasing winds over recent decades. Salinity observations reveal a wide-spread surface freshening in this region (Durack et al., 2012), which led to an overall increased surface stabilization (chapter 4; Haumann et al., 2017). A major portion of this freshening and stabilization can be attributed to an increased transport of freshwater by sea ice into this region (chapter 2; Haumann et al., 2016b).

Here, we study the sensitivity of the present-day Southern Ocean carbon fluxes to stratification changes by perturbing a regional ocean model that realistically simulates the Southern Ocean surface stratification in the upwelling region. We specifically address the question whether observed changes in surface freshwater fluxes from sea ice could have counter-acted the wind-driven increased upwelling of carbon-rich deep waters over recent decades and thereby maintained an efficient Southern Ocean carbon sink. The recent constraints on the surface freshwater flux balance and its changes enable us to better understand this response of the Southern Ocean CO_2 uptake. Moreover, our findings have direct implications for the understanding on changes in the Southern Ocean CO_2 uptake in response to stratification changes in colder past and warmer future climates as outlined in section 5.4.

5.2 Methods

We used the Regional Ocean Modeling System (ROMS; UCLA-ETH version; Shchepetkin and McWilliams, 2005; Gruber et al., 2011), which was adapted for the use in the Southern Ocean as described in detail by Haumann et al. (2017, chapters 3 and 4). In this study, we run ROMS at a horizontal resolution of 0.5°, which corresponds to a resolution of about 50 km at the northern boundary (24° S) and about 25 km at the Antarctic coast. ROMS does not have any eddy-parameterizations, instead the advection scheme contains a resolution dependent hyperdiffusion to ensure numerical stability (Shchepetkin and McWilliams, 1998). Vertical mixing processes are parameterized using the K-profile parameterization (KPP; Large et al., 1994; Shchepetkin, 2005; McWilliams et al., 2009) with some modifications described in detail in chapter 3. In the vertical, the stretched, terrain-following coordinate system (Song and Haidvogel, 1994; Shchepetkin and McWilliams, 2003, 2005) is divided into 64 layers. ROMS generally reproduces a realistic water mass structure and circulation in the Southern Ocean as described in the evaluation of the physical model by Haumann et al. (chapter 3; 2017).

For this study, we additionally use the coupled Biological Elemental Cycling (BEC) model (Moore et al., 2004; Jin et al., 2008; Yang and Gruber, 2016, see section 3.3 for details). BEC is forced at the surface with the climatological mean atmospheric CO_2 concentration of 370 ppm and surface deposition of iron and dust from Mahowald et al. (2009). At the northern boundary and as initial conditions we use World Ocean Atlas 2013 (Boyer et al., 2013) for nutrients (Garcia et al., 2014b) and oxygen (Garcia et al., 2014a), the Global Data Analysis Project for dissolved inorganic carbon and alkalinity (Key et al., 2004; Lee et al., 2006), the SeaWiFS climatology of chlorophyll-a (SeaWiFS Project, 2003), which is extrapolated to depth according to Morel and Berthon (1989) and used for all phytoplankton functional types, and the fields of a global model simulation with CESM1.2 for iron, ammonium, and dissolved nutrients (Yang et al., 2017).

The experimental design is the same as the one presented in chapter 4 (Haumann et al., 2017). The model is spun up with the climatological mean forcing for 40 years until the ocean circulation and the surface ocean are stable in time. Hereafter, we perform a set of three simulations of 40 years that are each restarted from the model spin-up simulation. One simulation is a simple control simulation using the same climatological forcing as the model spin up. In a second simulation, the freshwater flux forcing from sea ice is perturbed using the data set by Haumann et al. (2016b,a, Figure 5.1a) and in a third simulation only the surface momentum forcing (ERA-Interim, 1979–2014; Dee et al., 2011) is perturbed (Figure 5.1b). All perturbations vary throughout the year. Therefore, the sea-ice melting flux perturbation is mostly added in summer and the freezing flux perturbation in winter. The surface wind stress perturbation is more zonally symmetric during austral summer and zonally asymmetric during winter (Figure 5.1c–f). We averaged the last 20 years in all three simulations and subtracted the control simulation from the two perturbation experiments. We note that the atmospheric pCO_2 is kept constant throughout the

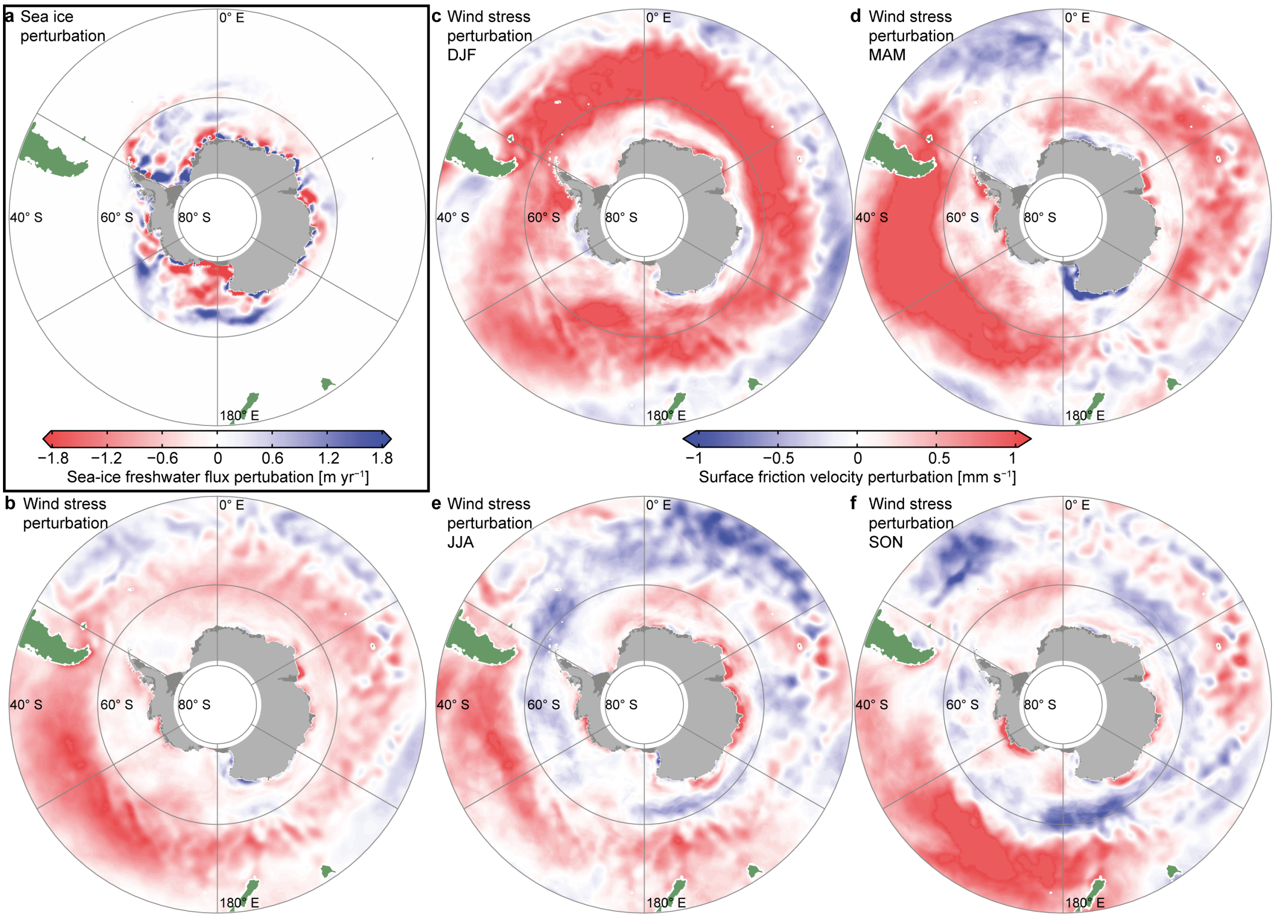

Figure 5.1 Perturbation of sea-ice freshwater flux and wind stress surface forcing: (**a**) Sea-ice freshwater flux change. (**b–f**) Surface friction velocity change: annual mean (**b**), austral summer (DJF, **c**), autumn (MAM, **d**), winter (JJA, **e**), spring (SON, **f**).

simulations. Therefore, our simulations do not reflect any changes associated with the increase in atmospheric pCO_2 over recent decades, but include the mean uptake of anthropogenic CO_2 by the ocean.

We here analyze the spatially integrated surface CO_2 flux and its spatial and temporal changes. Additionally, we decompose the signal by estimating the contribution from changes in surface temperature to the air-sea pCO_2 gradient, and residual changes that result mostly from changes in dissolved inorganic carbon (DIC) and alkalinity (Alk) as well as biological production. The thermal contribution is approximated according to Takahashi et al. (2002):

$$\Delta pCO_2^T = pCO_2^O(\exp^{0.0423\cdot\Delta SST} - 1). \tag{5.1}$$

Here, pCO_2^O denotes the mean surface ocean pCO_2 and ΔSST the change in sea-surface temperature. We will compare our results to observation-based estimates from Landschützer et al. (1982–2014; 2015b, expanded as in Le Quéré et al. (2016)). Moreover, we will use the location of the SAF as estimated by Orsi et al. (1995) and an Argo and CTD profile derived mixed layer depth product (de Boyer Montégut et al., 2004).

5.3 Results

The Southern Ocean south of 30° S takes up 1.5 PgC yr^{-1} in our simulations. This value is higher than the observation-based estimate of 1.0 PgC yr^{-1}. Figures 5.2a–b illustrate that the spatial pattern of the surface CO_2 flux in the model agrees well with the observed spatial pattern, with high CO_2 uptake north of the SAF (around 50° S; Orsi et al., 1995) and CO_2 release between the SAF and the annual mean sea-ice edge (around 65° S) where carbon-rich waters upwell to the surface. South of the SAF, the model overestimates the carbon uptake compared to the observational product by 0.55 PgC yr^{-1}, which is the main reason for the overall discrepancy. This overestimation is caused by a too strong summer-time uptake in the model that is mostly driven by biological production (Figure 5.2c). The band between the SAF and the sea-ice edge experiences a very large seasonal cycle with strong CO_2 release during austral winter and spring and uptake during austral summer (Figure 5.2c–f). In some regions of this band, the uptake in the model outweighs the winter-time outgassing. The outgassing is associated with dynamical upwelling of CDW into

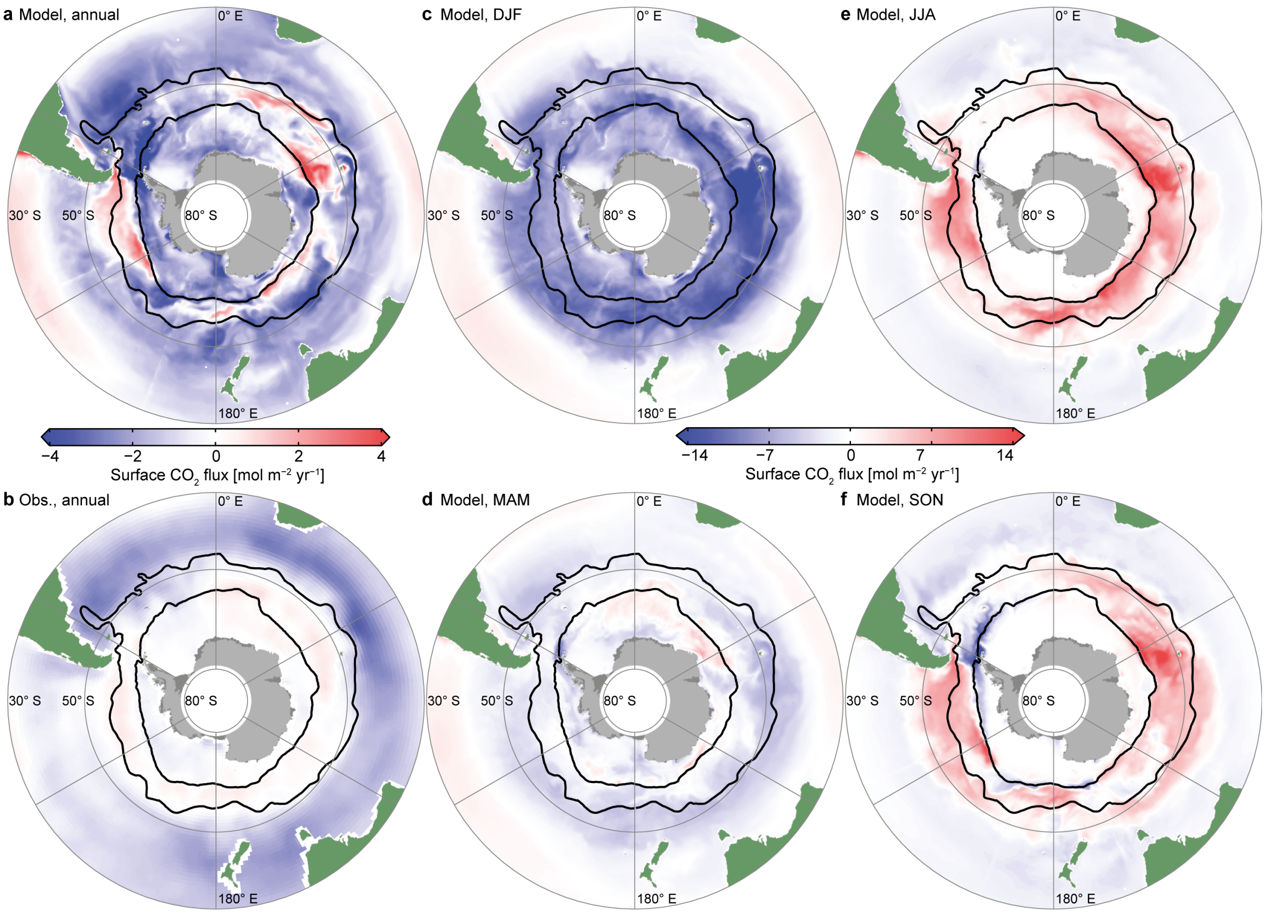

Figure 5.2 Simulated and observed surface CO_2 flux: (**a**) Simulated annual mean surface CO_2 flux. (**b**) Observation-based annual mean surface CO_2 flux (1982–2014; Landschützer et al., 2015b, expanded as in Le Quéré et al. (2016)). Seasonal means of the simulated surface CO_2 flux for austral summer (DJF, **c**), autumn (MAM, **d**), winter (JJA, **e**), and spring (SON, **f**). Positive values (red) show outgassing and negative values (blue) uptake by the ocean. The thick black lines denote the SAF and annual mean sea-ice edge (10% sea-ice concentration).

the surface waters, which are subsequently subducted in the same band as AAIW (Sallée et al., 2010a). The spatial gradients and the seasonal cycle are generally much stronger in the model than in the observation based product. This difference can partly be attributed to the strong spatial and temporal smoothing induced by the method to derive the observational data (personal communication P. Landschützer and N. Gruber). Overall, the model produces the characteristic spatial and temporal evolution of surface CO_2 fluxes very well, but probably overestimates the magnitude of the fluxes.

In the sea-ice freshwater flux perturbation experiment, the surface freshwater flux around the sea-ice edge in the Pacific sector increases substantially due to the increased northward transport of freshwater by sea ice in this region (Figure 5.1a; Haumann et al., 2016b). In response, the model simulates a strong anomalous net annual CO_2 uptake in the Pacific sector that is confined

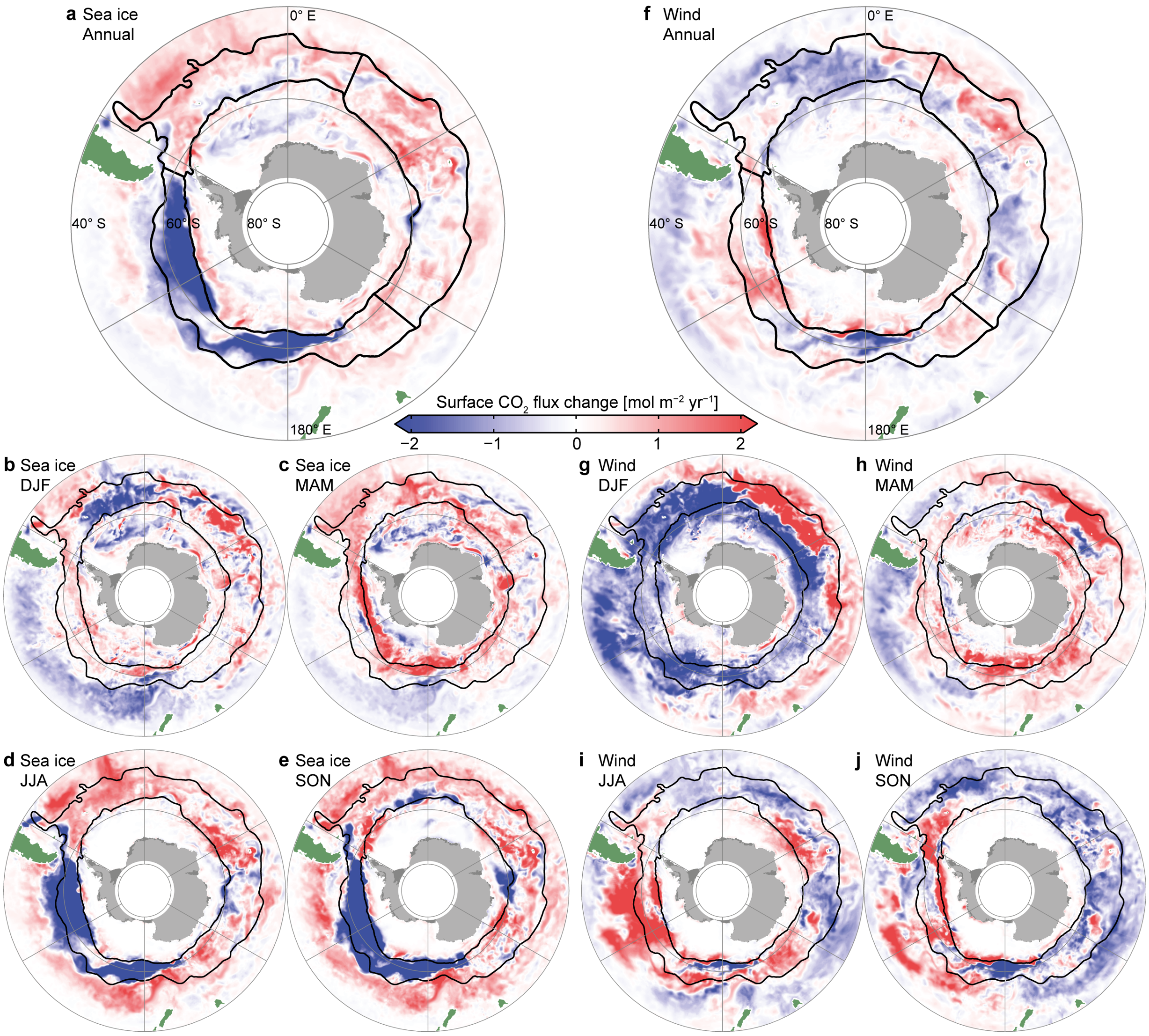

Figure 5.3 Surface CO_2 flux response to freshwater flux and wind perturbation: Annual mean (**a,f**), austral summer (DJF, **b,g**), autumn (MAM, **c,h**), winter (JJA, **d,i**), and spring (SON, **e,j**) response of the surface CO_2 flux to the sea-ice freshwater flux perturbation (**a–e**) and surface wind stress perturbation (**f–j**). The thick black lines denote the SAF and annual mean sea-ice edge (10% sea-ice concentration). This band is divided into the Pacific, Atlantic, and Indian Ocean sectors.

to the region between the sea-ice edge and the SAF, where the net annual uptake increases by 0.13 PgC yr^{-1} (Figure 5.3a). This anomalous uptake is counteracted by anomalous net annual CO_2 release of 0.02 PgC yr^{-1} in the Atlantic and 0.04 PgC yr^{-1} in the Indian Ocean sectors. As a result, the net annual uptake of CO_2 in this band increases by about 25%. An additional anomalous carbon release occurs north and south of this band in all three sectors. Splitting the results into the seasonal responses (Figure 5.3b–e), reveals that the signal originates from austral winter and spring and therefore results from a reduction in outgassing.

The response to the surface wind stress perturbation shows less extreme changes in the net annual CO_2 flux, which are zonally asymmetric (Figure 5.3f), consistent with the zonally asymmetric changes in the surface wind forcing (Figure 5.1b). In many regions, they oppose the changes induced by the surface freshwater flux perturbation. An anomalous net annual CO_2 release of 0.01 PgC yr^{-1} occurs in the Pacific sector between the sea-ice edge and the SAF, which is outbalanced by an anomalous net annual CO_2 uptake of 0.03 PgC yr^{-1} in this same band in the other two sectors together. The seasonal changes reveal that this weak net annual response is the result of strong opposing seasonal changes (Figures 5.3g–j). During austral summer, strong enhanced uptake occurs in most of the Southern Ocean except for the lower latitudes in the Atlantic and Indian Ocean sectors, where the CO_2 uptake is reduced. Especially in the Pacific sector, this picture is reversed during austral winter and to some extent also during austral spring, when the wind perturbation experiment reveals a strongly enhanced CO_2 release in this sector. This signal is opposed by a reduced CO_2 release in the Atlantic and Indian Ocean sectors during austral winter and spring. In summary, both the sea-ice freshwater flux and surface wind stress perturbation experiments lead to a spatially and temporally very complex response of the surface CO_2 flux, whereas the response to the sea-ice freshwater flux changes is stronger than the one to the wind stress forcing. Summing both effects together, the Southern Ocean CO_2 uptake strengthens by 0.09 PgC yr^{-1} south of 50° S, which is opposed by a reduction in the uptake by 0.05 PgC yr^{-1} north of 50° S.

To better understand the drivers of these changes, we decompose the surface pCO_2 gradient between the atmosphere (pCO_2^A) and the ocean ($\Delta pCO_2 = pCO_2^O - pCO_2^A$) into the thermal and non-thermal components (see section 5.2). The air–sea gradient (Figure 5.4a,d) shows very similar changes as the surface CO_2 flux (Figure 5.3a,f), except for the sea-ice region where the gas-exchange is reduced by the sea-ice cover. The observed ΔpCO_2 trend differs regionally from the simulated changes. However, the general picture of an enhanced uptake around the sea-ice edge and a reduced uptake north of the SAF seems to be a consistent feature in both the observed and simulated changes. The enhanced uptake of between the sea-ice edge and the SAF in our simulations mostly results from the surface cooling induced by the sea-ice freshwater fluxes (Figure 5.4b), which is consistent with the observed trend, even though the observed trend is much weaker (Figure 5.4h). The non-thermal component suggests a reduced outgassing directly at the sea-ice edge in some regions and an enhanced outgassing or reduced uptake north and south of this region due to the sea-ice freshwater flux changes (Figure 5.4c). North of the sea-ice edge the thermal and the non-thermal contributions oppose each other, which can also be seen in the observed trends. Overall the sea-ice freshwater flux changes have a much larger effect on the air–sea CO_2 gradient in our simulations than the surface wind stress changes.

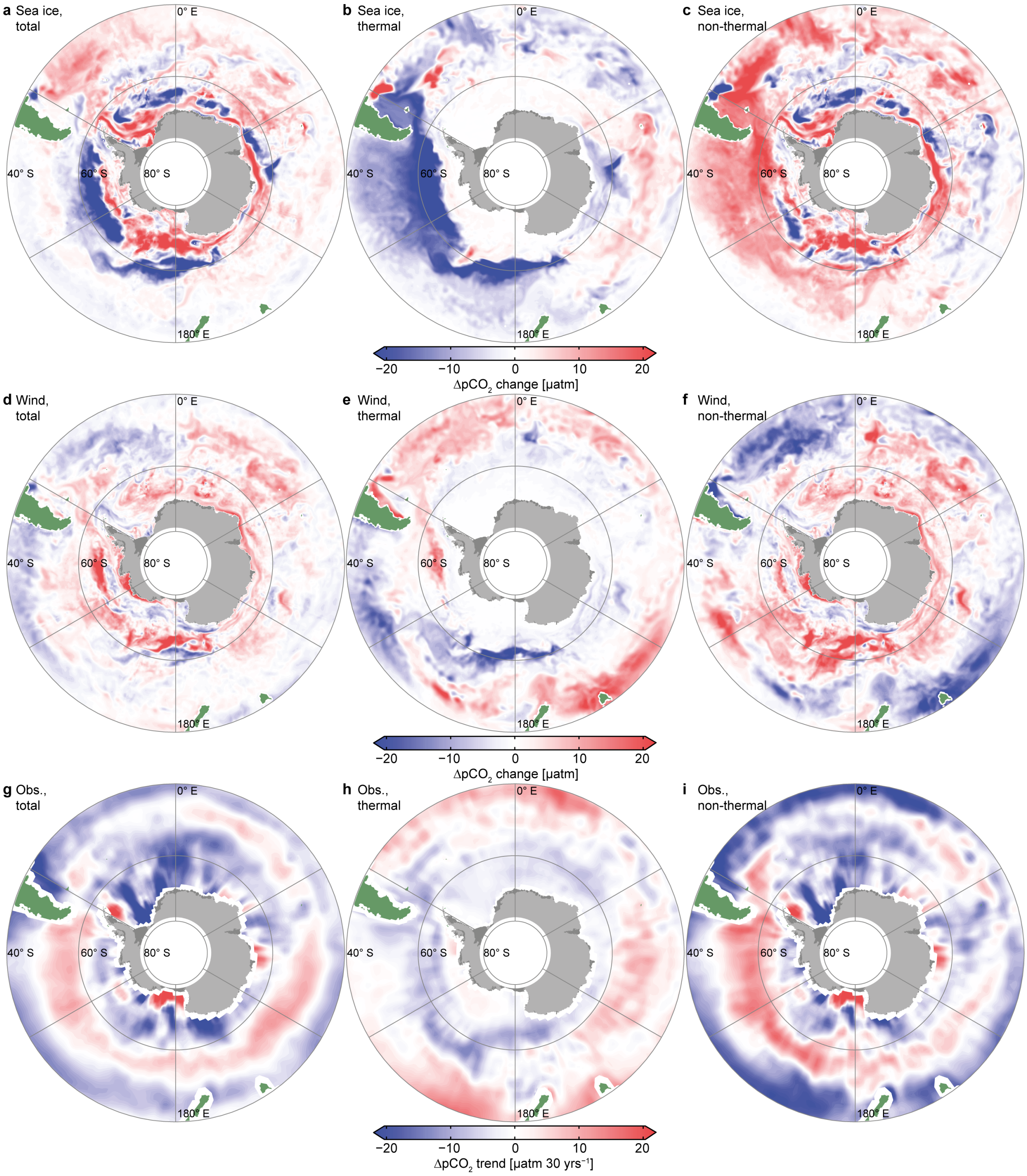

Figure 5.4 Observed and simulated ΔpCO_2 changes and its thermal and non-thermal contributions: (**a–c**) Simulated ΔpCO_2 change due to the sea-ice freshwater flux perturbation. (**d–f**) Simulated ΔpCO_2 change due to the surface wind stress perturbation. (**g–i**) Observed trends derived from the period 1982–2014 Landschützer et al. (2015b, expanded as in Le Quéré et al. (2016)), scaled to a 30-year period. The middle column (**b,e,h**) shows the respective thermal contribution and the right column (**c,f,i**) the respective non-thermal contribution.

The surface cooling that is responsible for a most of the enhanced CO_2 uptake in the sea-ice freshwater flux experiment is driven by an increased stratification and a reduced mixed-layer depth in the Pacific sector. This enhanced stratification and shoaling of the mixing is illustrated in Figure 5.5. While most of the freshwater flux perturbation is added to the surface ocean during the melting period in summer, the response of the reduced surface mixing occurs in winter. We argue that the main reason is that the surface freshwater in summer pre-conditions the surface ocean. Therefore, the erosion of the stable summer-time halocline by the surface cooling and increasing winds between May and September is much slower and the mixing is more shallow (Figure 5.5c). As a consequence, the upwelling of warmer CDW into the surface layer is reduced during winter-time. In comparison, the surface wind stress perturbation only leads to a small increase in winter-time mixing.

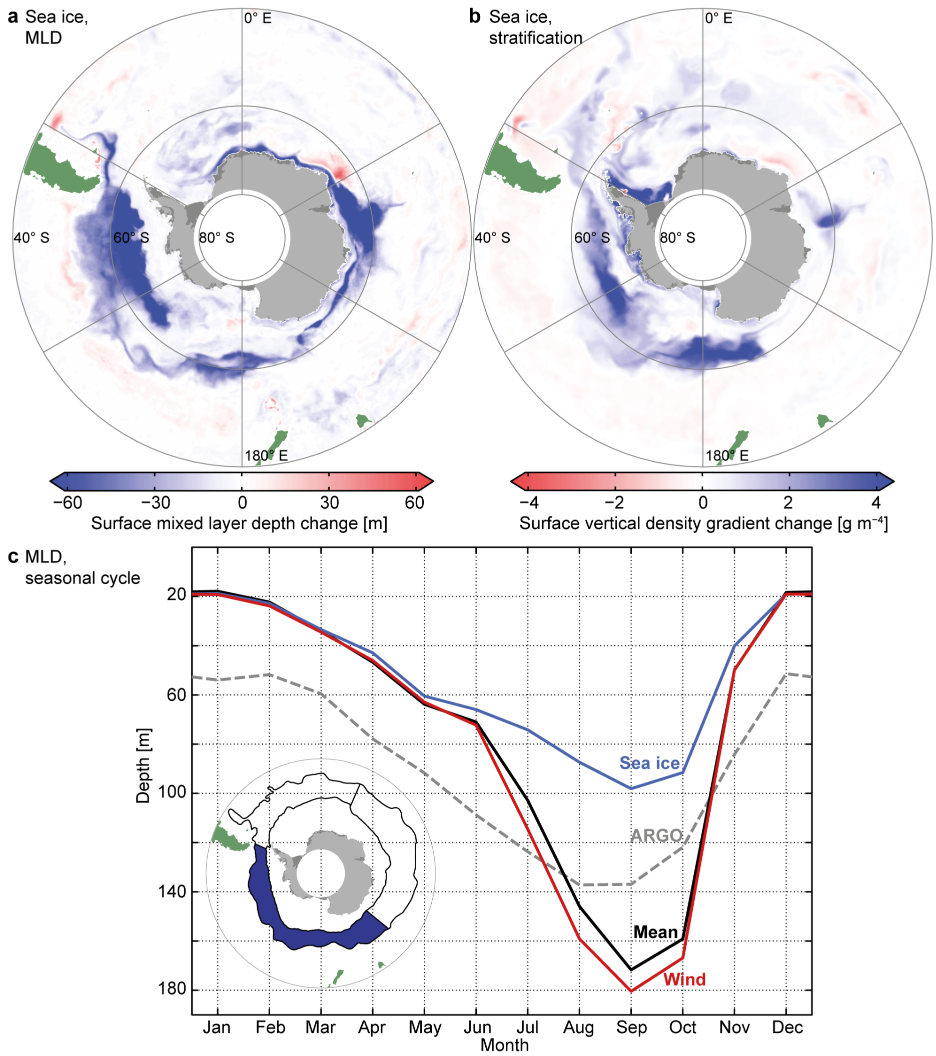

Figure 5.5 Surface stratification and mixed-layer depth response: (**a**) Change of the surface density gradient (averaged over the top 100 m) and (**b**) surface mixed-layer depth to the sea-ice freshwater flux perturbation. (**c**) Seasonal cycle of the spatially averaged mixed-layer depth between the sea-ice edge and the SAF in the Pacific sector. The averaging region is displayed in blue in the inset. Black line: mean of the control simulation, blue line: sea-ice freshwater flux experiment, red: surface wind stress experiment, gray dashed line: mean of the observed mixed-layer depth from ARGO data (de Boyer Montégut et al., 2004).

The causes for the response in the non-thermal component of the ΔpCO_2 to the sea-ice freshwater flux perturbation can be further investigated by considering the opposing seasonal changes in this component (Figure 5.6). During summer and autumn, when the high-latitude Southern Ocean takes up CO_2, the surface stabilization in the Pacific sector reduces the subduction of CO_2 into the subsurface, which increases the surface ocean pCO_2. This process would lead to a reduction in the CO_2 uptake during summer and autumn if it were not for the surface cooling that partly compensates for this effect. During winter and spring this situation is reversed in the region between the sea-ice edge and the SAF in the Pacific sector, when a reduction of upwelling of CDW that is rich in dissolved inorganic carbon (DIC) lowers the surface pCO_2 in this region. North of the SAF, where waters are subducted with SAMW during winter the subduction of CO_2 decreases. Consequently, the increased stability from the sea-ice freshwater flux omits upwelling of DIC-rich CDW during winter and, at the same time, hinders the subduction of CO_2 with AAIW and SAMW during all seasons.

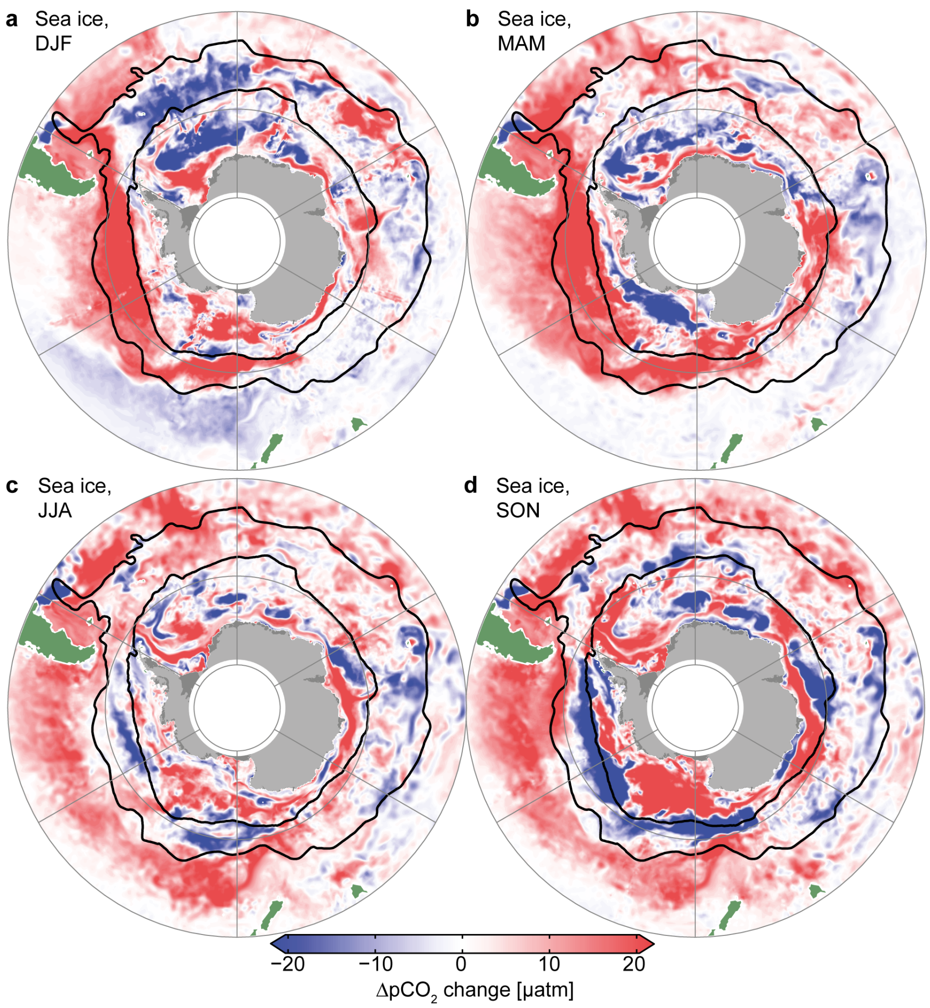

Figure 5.6 Seasonal response of non-thermal ΔpCO_2 changes to sea-ice freshwater fluxes: For the austral summer (DJF, **a**), autumn (MAM, **b**), winter (JJA, **c**), and spring (SON, **d**). The thick black lines denote the SAF and annual mean sea-ice edge (10% sea-ice concentration).

5.4 Discussion and conclusions

In this study, we analyzed the sensitivity of the Southern Ocean surface CO_2 fluxes to an increased surface stratification from recent changes in sea-ice–ocean surface freshwater fluxes. We find that the increased stratification in the region between the sea-ice edge and the SAF drives a substantial reduction in the release of natural CO_2. There are two major reasons for the reduced CO_2 release. Firstly, the increased stratification cools the surface ocean throughout the year, which increases the solubility of CO_2 in the seawater and reduces the outgassing. Secondly, a reduced and shallower mixing during austral winter reduces the upwelling of DIC-rich waters into the surface layer. These two effects are opposed by a reduction in subduction of CO_2 from the surface layer into AAIW during summer and a reduced subduction into SAMW north of the SAF during winter. Consistent with the study by Matear and Lenton (2008), we find a net strengthening of the CO_2 uptake in response to the surface freshwater fluxes. They also argue that the net effect of reduced outgassing and reduced uptake will depend on the background atmospheric CO_2 concentration. Therefore, a much higher atmospheric CO_2 concentration in a future climate could reverse the net effect (Manabe and Stouffer, 1993; Sarmiento et al., 1998; Lovenduski and Ito, 2009; Bernardello et al., 2014b) and a much lower atmospheric CO_2 concentration in a past climate could have led to a much stronger reduction in CO_2 release in response to an increasing stratification than today.

Our findings are limited to the response to changes in sea-ice–ocean freshwater fluxes that dominated the recent observed freshening in the upwelling region of the open Southern Ocean (Haumann et al., 2016b). However, we did not consider potential changes in the atmospheric freshwater flux or additional glacial meltwater from Antarctica. Both these fluxes are expected to increase substantially in a warming climate (Knutti and Sedláček, 2013; Golledge et al., 2015). Our study highlights that the location of the additional freshwater is a critical aspect for the CO_2 flux response. Sea-ice freshwater fluxes at the sea-ice edge due to increased northward transport are very effective in changing the CO_2 flux as they stabilize a region of major vertical water-mass exchange, i.e., the region between the sea-ice edge and the SAF. South of the sea-ice edge the vertical exchange is strongly reduced due to the isolating sea-ice layer that prevents strong surface cooling in winter and deep mixed layers (Gordon and Huber, 1984; Martinson, 1990). North of the SAF, the surface ocean stratification is very stable due to warmer surface waters preventing the upwelling of deep waters. The increased sea-ice freshwater transport into this region over recent decades is mainly driven by changes in the atmospheric circulation (Haumann et al., 2014). Whether or not such an increase will continue in future, is uncertain as global climate models simulate sea-ice decline over recent decades and in future. A decreasing future sea-ice cover could reverse the effects and lead to an enhanced outgassing of natural CO_2 due to a decrease in the vertical stability of the water column around the sea-ice edge. In contrast, during cold glacial climates an expanded sea-ice cover and an associated increased sea-ice freshwater flux could enhance the stratification in the upwelling region and reduce the outgassing of natural CO_2 (Fischer et al., 2010; Sigman et al., 2010). Consequently, this mechanism could provide an explanation for co-varying glacial–interglacial changes in the atmospheric CO_2 concentration and Antarctic surface temperature (Petit et al., 1999; Parrenin et al., 2013).

We contrasted our results with effects induced by surface wind stress changes from the period 1979 to 2014. While multiple studies have previously investigated the effects of increasing winds over the Southern Ocean (e.g. Le Quéré et al., 2007; Lovenduski et al., 2007, 2008; Lenton et al., 2009; Dufour et al., 2013; Hauck et al., 2013), they mostly studied the response to changes in the Southern Annular Mode. Here, we use a perturbation that accounts for spatial and seasonal variations in the wind changes as reconstructed by ERA-Interim reanalysis data. We find strongly opposing tendencies in the surface CO_2 flux changes with an increased summer-time uptake and an increased winter-time release. The increased winter-time release is a consequence of increasing upwelling of DIC-rich waters in the Pacific sector and the other sectors rather show a reduction in CO_2 release, which is associated with zonally asymmetric circulation changes during winter (Figure 5.1). The summer-time increased uptake in our simulations is probably associated with a higher subduction of CO_2 from increased biological productivity (Hauck et al., 2013) and stronger subduction into SAMW (Iudicone et al., 2011). This interpretation of contrasting seasonal responses to changes in surface winds is consistent with the findings by Hauck et al. (2013). However, in our simulations the increased summer-time uptake is larger than increased winter-time release, which might be a model dependent result, since our model overestimates the summer-time CO_2 uptake. In conclusions, these results illustrate that the paradigm of a saturating Southern Ocean carbon sink with increasing winds is more complex than previously thought and might not hold for the changes over recent decades due to opposing seasonal and spatial variations in the wind-response.

We conclude that the recent finding that the Southern Ocean carbon sink did not saturate despite increasing winds (Landschützer et al., 2015b) could be explained by an increasing stratification from sea-ice freshwater fluxes on the one hand, and a more complex response to surface wind stress changes than previously thought on the other hand. The net response of these two changes together in our simulations would result in a reduced outgassing or enhanced uptake in higher latitudes, i.e., south of the SAF, and a reduced uptake in lower latitudes, i.e. north of the SAF. However, these changes have to be understood on top of the background increase in atmospheric CO_2 concentrations that we did not account for in our simulations. Therefore, the reduced uptake north of the SAF would result in a reduction in the uptake of anthropogenic CO_2, which is compensated by a reduction in release of natural CO_2 south of the SAF. This figure is consistent with the long-term trends in Southern Ocean CO_2 uptake over the period 1982 to 2014 derived from sparse observational data.

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