Chapter 4

Recent changes of Southern Ocean waters induced by sea-ice freshwater fluxes*

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Abstract

This study investigates the sources of recent changes in the Southern Ocean hydrography and circulation by forcing a regional ocean circulation model with recent observational constraints on changes in surface fluxes from sea ice and land ice and with atmospheric reanalysis data. Sensitivity experiments support the hypothesis that the freshening of open-ocean surface and intermediate waters is caused by an increased northward freshwater transport by sea ice. In the model, this freshening signal increases the surface density stratification of the open-ocean waters between the sea-ice edge and the Subantarctic Front, which results in a significant surface cooling and subsurface warming due to a reduced mixing of warmer deep waters into the surface layer and smaller heat capacity of the mixed layer. A remarkable agreement between the satellite-observed and simulated surface cooling suggests that this surface cooling occurs primarily due to an increased sea-ice freshwater flux. In contrast, the surface salinity and temperature weakly increase in response to the momentum flux changes. Overall, we find opposing tendencies induced by the surface wind stress changes and freshwater flux changes in the ocean hydrography and transport with the circumpolar current. One exception is the meridional overturning circulation that strengthens in both cases, but additionally shoals in the freshwater flux perturbation experiment. We conclude that the upwelling of deep waters in the Southern Ocean is greatly sensitive to the freshwater transport to the sea-ice edge and that this process is a major driver of changes observed over recent decades in the Southern Ocean surface waters south of the frontal region and water masses formed in this region.

4.1 Introduction

Observations of the Southern Ocean waters reveal pronounced changes in temperature and salinity over recent decades (e.g. Böning et al., 2008; Jones et al., 2016). Understanding these changes and their driving forces is of major concern because they may reflect or lead to changes in the vertical exchange of water masses between the surface and the deep ocean, which in turn influences the Southern Ocean's ability to take up carbon and heat from the atmosphere (Frölicher et al., 2015; Landschützer et al., 2015b). Therefore, such changes in the Southern Ocean could feedback on global climatic changes in the long-term (Knox and McElroy, 1984; Sarmiento and Toggweiler, 1984; Siegenthaler and Wenk, 1984; Sigman et al., 2010) and amplify or diminish global warming (Manabe and Stouffer, 1993; Sarmiento et al., 1998; Caldeira and Duffy, 2000). A detailed process understanding and an attribution of recent hydrographic changes to either surface freshwater, heat, or momentum flux changes has yet been limited by the availability of reliable surface flux data. In this study, we make use of most recent observation-based estimates in surface freshwater fluxes from sea ice (Haumann et al., 2016b) and land ice (Depoorter et al., 2013; Sutterley et al., 2014; Paolo et al., 2015) to investigate the response of the Southern Ocean salinity, temperature, density stratification, and circulation to the suggested changes in these fluxes and contrast this response with wind-induced ocean circulation and mixing changes, and observed changes.

The observed recent changes in the Southern Ocean have not been spatially uniform but instead exhibit vertical and horizontal patterns that relate to the characteristic water masses. Large areas of the high-latitude surface ocean (south of the Subantarctic Front) experienced a substantial surface freshening (Jacobs et al., 2002; Jacobs and Giulivi, 2010; Durack et al., 2012), and—despite global warming—a significant and persistent surface cooling (Fan et al., 2014; Armour et al., 2016) and sea-ice expansion (Comiso and Nishio, 2008; Stammerjohn et al., 2008) over recent decades. These signals at surface largely originate from the Pacific sector. In other sectors, the surface ocean has freshened less and experienced a slight warming. A stronger warming occurred in lower latitudes. At the subsurface, a pronounced freshening (Wong et al., 1999; Böning et al., 2008; Helm et al., 2010; Schmidtko and Johnson, 2012) and warming (Gille, 2002; Böning et al., 2008; Schmidtko and Johnson, 2012) of Antarctic Intermediate Water (AAIW) and Subantarctic Mode Water (SAMW) occurred in the open ocean. Along the Antarctic continental shelf, warming (Schmidtko et al., 2014; Cook et al., 2016) and freshening (Jacobs and Giulivi, 2010; Hellmer et al., 2011; Schmidtko et al., 2014) occurred in many regions. This signal potentially also propagated into the Antarctic Bottom Water (AABW) that is subducted from the continental shelf region (Jullion et al., 2013; Purkey and Johnson, 2013). All these changes in the water mass properties suggest either substantial changes ocean circulation, ocean mixing, surface freshwater or heat fluxes, or a combination of these factors.

The observed strengthening (Marshall, 2003; Thompson et al., 2011; Lee and Feldstein, 2013) and possible shift (Fyfe et al., 2007; Cai et al., 2010) of the westerly surface winds over the Southern Ocean might have led to changes in wind-driven ocean circulation and mixing. In the subsurface, the observed warming of AAIW and SAMW in the Atlantic and Indian Ocean sectors has been related to a poleward shift of the ACC (Gille, 2008; Sokolov and Rintoul, 2009b; Meijers et al., 2011). Yet, large zonal (Freeman et al., 2016) and potentially temporal variations (Landschützer et al., 2015b) in these meridional shifts have occurred over recent decades that are related to zonal asymmetries in the atmospheric circulation changes (Turner et al., 2009; Hosking et al., 2013; Haumann et al., 2014). Together with an increased heat uptake from the atmosphere due to global warming (Cai et al., 2010; Armour et al., 2016), these processes could explain large portions of the observed warming of AAIW and SAMW, but not the observed freshening (Meijers et al., 2011). An increase in the meridional overturning circulation, as suggested by coarse resolution global climate models (Oke and England, 2004; Saenko et al., 2005; Fyfe and Saenko, 2006), would only initially cool and presumably freshen the surface waters (Sen Gupta et al., 2009; Thompson et al., 2011; Ferreira et al., 2015; Kostov et al., 2016; Seviour et al., 2016). On time-scales longer a few month to several years, the surface waters warm and become more salty due to increased upwelling deep waters, which would be inconsistent with the observed changes. High-resolution modeling experiments (Hallberg and Gnanadesikan, 2006; Farneti et al., 2010; Meredith et al., 2012; Patara et al., 2016) and observational studies (Böning et al., 2008; Hogg et al., 2015) suggest that the overturning circulation is much less sensitive to changes in the surface winds than initially thought. In the absence of changes in the overturning circulation, a delayed and reduced warming would still be expected because the upwelling deep waters did not yet experience global warming Armour et al. (2016). However, the observed surface cooling, sea-ice expansion, and broad-scale freshening over recent decades cannot be explained by the historical anthropogenic forcing in current global climate models (Wong et al., 1999; Helm et al., 2010; Bitz and Polvani, 2012; Haumann et al., 2014). Consequently, the origin of these changes proposes a major conundrum.

Changes in Southern Ocean salinity and temperature fields could result from changes in vertical density stratification that either enhance or reduce the vertical exchange of heat and salt (Gordon and Huber, 1984; Martinson, 1990; Hasselmann, 1991; Manabe and Stouffer, 1993; Bitz et al., 2006). Such changes in stratification would result from changes in the surface buoyancy forcing. While the surface ocean stratification north of the frontal region is mostly sensitive to surface heat flux changes (Manabe and Stouffer, 1993; Sarmiento et al., 1998), south of the frontal region it is predominantly controlled by surface freshwater fluxes (Sigman et al., 2004; Stewart et al., 2016). Therefore, a more stable halocline in the in the high-latitude Southern Ocean could induce a surface cooling and freshening of the surface waters and warmer and saltier deep waters (Gordon and Huber, 1984; Martinson, 1990; Bitz et al., 2006; Zhang, 2007; Bintanja et al., 2013; Goosse and Zunz, 2014)—a figure that is consistent with recently observed changes in the Southern Ocean. Observations in the Southern Ocean high latitudes indeed show such an increased surface density stratification due to a strengthening of the halocline (de Lavergne et al., 2014), which would imply an increased surface freshwater forcing in the upwelling region.

While observational evidence has been small, numerous modeling studies have suggested a surface freshening and cooling in the Southern Ocean could be induced by an increased surface freshwater flux from either the atmosphere (Zhang, 2007; Liu and Curry, 2010), glacial melt (Hellmer, 2004; Bintanja et al., 2013; Pauling et al., 2016), or northward transport of sea ice (Pollard and Thompson, 1994; Kirkman and Bitz, 2011; Goosse and Zunz, 2014). Global models suggest that atmospheric surface freshwater fluxes increase over the Southern Ocean with global warming (Liu and Curry, 2010; Knutti and Sedláček, 2013). However, over recent decades, very little change is observed in most reliable estimates of reanalysis and satellite-derived products (Bromwich et al., 2011; Nicolas and Bromwich, 2011), leaving a large uncertainty on atmospheric changes. Glacial meltwater discharge has considerably increased in the South Pacific sector due to increased grounding line fluxes (Sutterley et al., 2014) and increased ice shelf-thinning (Paolo et al., 2015) presumably due to warming of coastal waters (Spence et al., 2014; Cook et al., 2016). However, this meltwater largely acts to freshen the coastal ocean and presumably AABW (Hellmer, 2004; Jacobs and Giulivi, 2010; Purkey and Johnson, 2013; Kusahara and Hasumi, 2014; Nakayama et al., 2014; Pauling et al., 2016). Most recent observation-based estimates of northward transport of freshwater by sea ice suggest that these changes would be largely sufficient to explain most of the open ocean freshening of the surface waters and AAIW (Haumann et al., 2016b), with possible contributions to the increased surface stratification, surface cooling, and subsurface warming.

In this study, we explore the hypothesis that sea-ice changes drive a large-scale freshening of the open-ocean surface and intermediate waters and land-ice changes mostly the coastal and bottom waters as was previously implied from changes in the surface freshwater fluxes. We will then analyze if such a freshening induces an increased density stratification that could contribute to the observed surface cooling and subsurface warming in the Southern Ocean. For the purpose of this investigation, we will perturb a regional ocean circulation model with the observation-based magnitude and spatial pattern of changes in sea-ice and glacial freshwater fluxes. In order to place our results in context, we will run an additional experiment with an observation-based momentum flux perturbation and compare our results to observed changes in ocean temperature and salinity.

4.2 Model, experimental design & data

We here use the eddy permitting version (5 to 25 km horizontal resolution) of the Regional Ocean Modeling System (ROMS) that has been adapted for the Southern Ocean region south of 24° S as described in detail in section 3. The model is forced at the surface with climatological mean observation-based fluxes from the atmosphere, sea ice, and land ice. Therefore, it is suitable for studying the response of the ocean to perturbations in these fluxes, which is the aim of this study, but not to study feedback mechanisms. As discussed in detail in section 3.7, this mostly free running model in the interior ocean basin is generally able to reproduce the Southern Ocean circulation and water mass structure, but also suffers from some considerable biases. These biases involve a too weak surface mixing in summer, a too salty, warm, and shallow AAIW, a too fresh coastal ocean, and a too warm and salty deep ocean. Potential effects of these biases on our results are discussed in section 4.4.

After a spin-up simulation of 40 years, the model shows only very little drift in the ocean circulation and surface properties. Some model drift remains at the subsurface (see section 3.6). We account for this drift by running a control experiment that continues after the spin-up simulation for another 40 years using the climatological mean forcing. In addition to this control simulation, we run three perturbation experiments for 40 years. Each of these perturbation experiments uses the climatological mean forcing except for one respective variable that is perturbed according to observation-based estimates of changes over recent decades. Throughout the control and the perturbation experiments we add the restoring fluxes of heat and freshwater from the last ten years of the spin-up simulation to the surface forcing and restrict restoring to both surface temperature and salinity fields to the boundary region between 24° S and 40° S to prevent the model from drifting at the boundary. Therefore, the perturbations in the regions of interest (south of 40° S) are not influenced by the restoring of the model.

In one experiment, we only perturb the sea-ice melting and freezing fluxes (Haumann et al., 2016b,a). We estimate daily trends by calculating the trend in the net sea-ice production from a 11-day running mean window for each grid point over the period 1982 to 2008. Calculating the trend from the melting and freezing fluxes separately rather than using the net flux would have led to very large over- or underestimations and a very noisy product as these flux components have a much higher uncertainty (Haumann et al., 2016b). Even though the actual observational period is shorter, we multiplied the resulting trend by 35 years to obtain a magnitude that is comparable in terms of its time period to the wind perturbation (see below). The resulting annual perturbation (Figure 4.1a) agrees well with the original net sea-ice freshwater flux changes.

In a second experiment, we also perturb the sea-ice freshwater fluxes but additionally increase the glacial meltwater discharge from the Antarctic continent. The mean ice-shelf melting fluxes originate from Depoorter et al. (2013), who estimated a total discharge due to basal melting of 1454 Gt yr^{-1} for the year 2009. For the spin-up simulation and the control experiment we re-

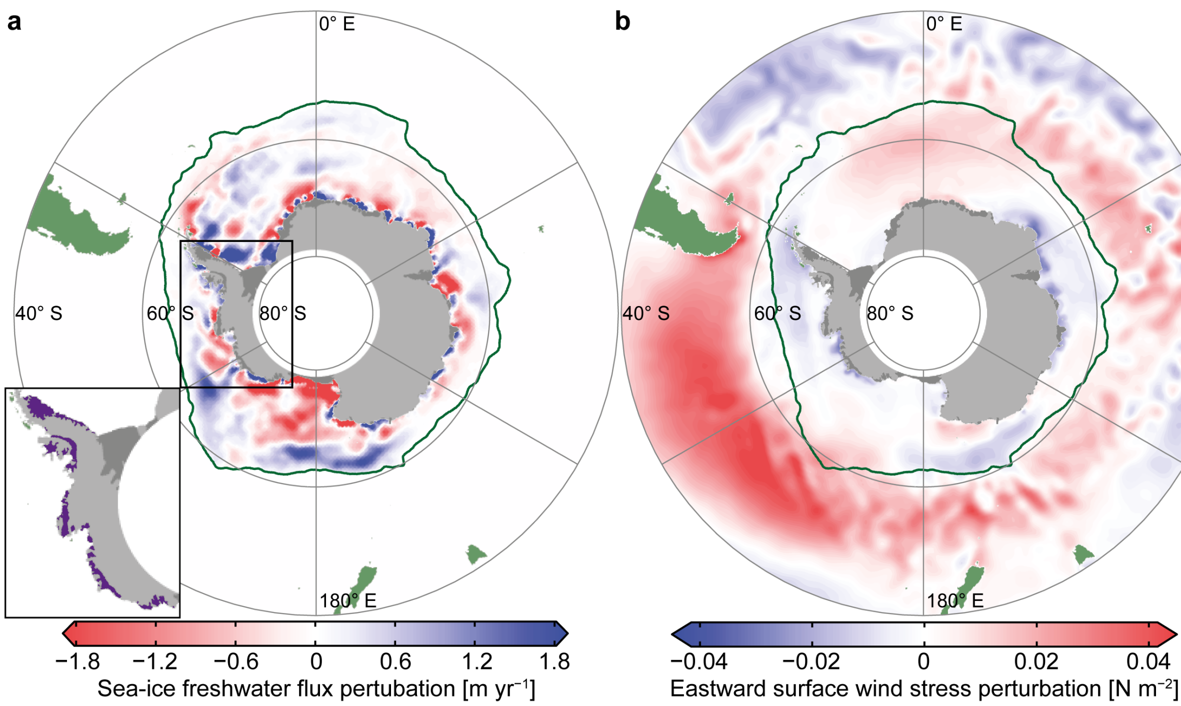

Figure 4.1 Observation-based surface freshwater flux and wind perturbations: (**a**) Surface freshwater flux perturbation from sea ice and land ice (purple in inset). (**b**) Eastward surface wind stress perturbation from ERA-Interim. Green contour line: climatological mean sea-ice edge. Black contour line: Antarctic continental shelf (shallower than 1000 m).

calculate these fluxes by reducing the discharge in the sector between 165° W and 60° W (inset in Figure 4.1a), i.e. the West Antarctic Ice Sheet, where most of the change over the recent decades occurred. Removing the contributions of changes in the grounding line flux (Sutterley et al., 2014) and the ice-shelf thinning (Paolo et al., 2015) since 1992, we approximate the discharge to about 860 Gt yr^{-1} for the spin-up and control simulations. For the perturbation experiment, we increase this flux to 1755 Gt yr^{-1}, to approximately mimic the year 2014. The decrease and increase has been scaled with the mean discharge of each ice shelf, so that ice shelves with a high discharge in 2009 experience the largest changes. We do not run experiments where we perturb the freshwater fluxes from ice berg melting or the atmosphere, as there is, to the authors knowledge, no observation-based evidence for considerable changes in these fluxes. The most reliable reanalysis product and observational estimates suggest that the atmospheric flux over the Southern Ocean did not change much over the recent decades (Bromwich et al., 2011; Nicolas and Bromwich, 2011).

We run a third experiment, in which we perturb both the eastward and northward surface wind stress in the forcing. Therefore, we calculate the monthly trends from the ERA-Interim atmospheric forcing data (see section 3.5.1; Dee et al., 2011) for each grid point over the period 1979 to 2014 and multiply the trends by the 35-year period (Figure 4.1b, note that only the eastward momentum stress is shown for illustration). These perturbations are than added to the climatological mean fluxes.

For the analysis, we calculate temporal averages from the last 20 years of each experiment and compare these to the last 20 years of the control experiment. Therefore, these differences correspond to an ocean response after 20 to 40 years after the perturbation has been applied. However, we expect that the response to the perturbation will be considerably larger than a response that could be expected in the real world over such a time period, since the forcing was perturbed instantaneously rather than gradually over time. Nevertheless, the relative change between the different perturbation experiments and the spatial pattern of these changes reveal valuable insights into drivers of the observed changes.

We will compare our model results to observation based changes from multiple data sets. These comprise an estimate of sea-surface salinity trends over the period 1950 to 2000 from ocean data (Durack and Wijffels, 2010; Durack et al., 2012), sea-surface temperature trends over the period 1982 to 2014 from the NOAA Optimum Interpolation SST from AVHRR satellite data (Reynolds et al., 2007), and sea-surface height trends over the period 1992 to 2011 from AVISO satellite data (produced by Ssalto/Duacs and distributed by AVISO with support from Cnes, http://www.aviso.altimetry.fr/duacs). We compare the sea-surface temperature and salinity trend estimates to those from the upper five layers (about 50 m) in the EN4 Objective analyses, which is derived from quality controlled ocean profile data (version 4.2.0; 1979–2014; Ingleby and Huddleston, 2007; Good et al., 2013). The same data set is also used to derive subsurface trends in ocean salinity and temperature. Trends are estimated based on a least-squares linear regression analysis. For a better comparison between all data sets and the model results, we scale all trends to a 30 year period, irrespective of their observational period. It should be noted that in the sea-ice covered region all observational products suffer from a summer-time bias and only very little data is available. Therefore, these trend estimates have very large uncertainties and are largely unreliable along the Antarctic coast. Nevertheless, they provide a good overview of observed changes in the Southern Ocean that have been evaluated more carefully by numerous previous studies (see section 4.1).

4.3 Results

We will first discuss the simulated Southern Ocean salinity response to the changes in surface freshwater fluxes from sea and land ice. This discussion serves the purpose of validating the findings by Haumann et al. (2016b), who used a simple box-model approach to infer salinity changes induced by the surface flux changes rather than an ocean circulation model used here. Subsequently, we will investigate their effect on the vertical density stratification and temperature. Throughout this discussion, we will contrast the response to freshwater flux changes with the response to surface wind stress changes. Moreover, we will compare our simulations to observation-based estimates of temperature and salinity changes to identify the potential sources of the observed changes. At last, we will analyze the response of the vertically integrated transport and zonal mean meridional overturning circulation to these changes in the surface fluxes to further understand how these changes relate to changes in water mass properties.

4.3.1 Salinity response

The simulated surface salinity responds with a broad-scale open-ocean freshening (Figure 4.2a) to the observation-based changes in northward sea-ice freshwater transport (Figure 4.1a). The largest response occurs in the South Pacific sector, directly downstream of the increased northward sea-ice transport in the Ross Sea. This anomaly partly propagates through Drake Passage into the South Atlantic and is partly subducted into the AAIW and SAMW layers (Figure 4.3a). The spatial patterns of these surface and subsurface salinity changes in the open ocean broadly agree with the observed spatial patterns (Figures 4.2d–e and 4.3d). However, the response of the simulated salinity is considerably larger at the surface and weaker at the subsurface compared to the observed estimates. These differences could partly be related to a too weak subduction of freshwater into AAIW and SAMW in the model and partly due to compensations by other changes. Surprisingly, the coastal ocean also freshens substantially at the surface despite an increased northward export of freshwater by sea ice (Figure 4.1). The main reason of this surface freshening is an increased freezing and melting cycle in the forcing data and the mixing parameterization in the model that mixes the brine from the sea-ice formation deeper in the water column. Sensitivity experiments with this mixing parameterization showed that this result is not very robust and therefore, at the current stage of model development, we cannot reliably interpret changes in the coastal ocean.

Adding the glacial meltwater perturbation to the model did not considerably change the results (Figure 4.2b), since the freshwater flux perturbation is considerably smaller than the vertical freshwater redistribution flux by the changing sea-ice melting and freezing cycle in the model. Nevertheless, we conclude that the additional glacial meltwater cannot be the driving force of the open-ocean salinity trends because its magnitude is too small for such a broad scale freshening, consistent with another recent study (Pauling et al., 2016). As the coastal ocean response seems to be a model dependent result, we will focus in this study rather on the open-ocean response from the sea-ice forcing which is induced by the increased northward transport. In summary, the model's response to recent changes in surface freshwater fluxes from sea ice supports the conclusion by Haumann et al. (2016b) that sea-ice changes could explain the observed freshening of the open ocean surface and intermediate waters and the coastal freshening seems to be more complex than previously thought.

In contrast to the surface freshwater flux perturbations, the surface wind stress perturbation leads to a broad-scale sea-surface salinity increase in most of the low- and high-latitude surface ocean (Figure 4.2c). Largest changes occur in the south-eastern Pacific, where an increased upwelling of salty deep waters through transport and mixing enhances the surface salinity and

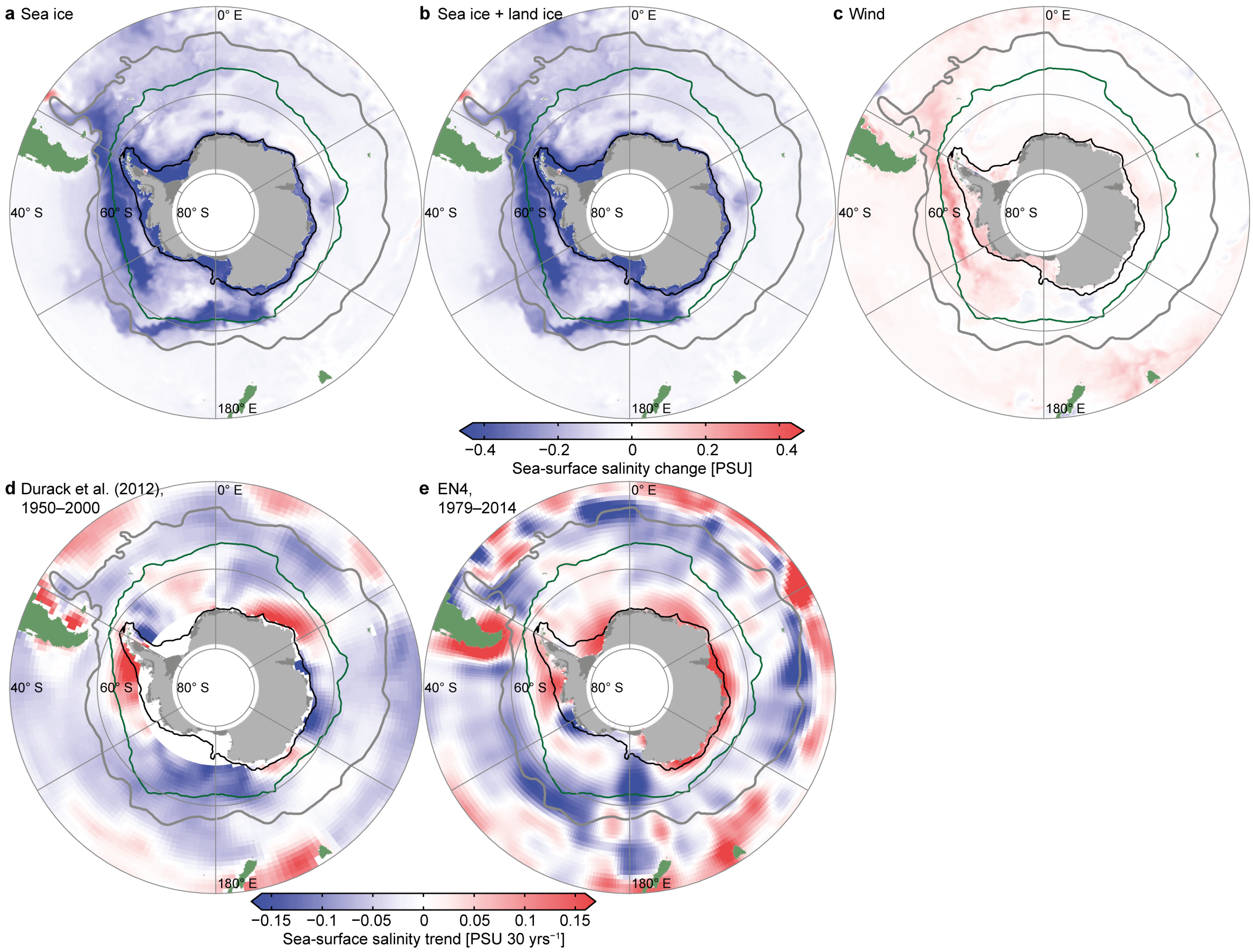

Figure 4.2 Sea-surface salinity response: Response to the sea-ice freshwater flux perturbation (**a**), to the combined sea-ice and land-ice freshwater flux perturbations (**b**), and to the surface wind stress perturbation (**c**). Shown are the differences of the last 20 years of a 40-year perturbation experiment to a control simulation with constant forcing. (**d**) Observed sea-surface salinity trends from Durack et al. (2012, 1950–2000), scaled to a 30 year period. (**e**) Observed salinity trends derived from the upper 50 m of the EN4 Objective analyses (1979–2014; Ingleby and Huddleston, 2007; Good et al., 2013), scaled to a 30 year period. Green contour line: climatological mean sea-ice edge; gray contour line: Subantarctic Front (Orsi et al., 1995); black contour line: Antarctic continental shelf (shallower than 1000 m).

slightly reduces the subsurface salinity of Circumpolar Deep Water (CDW; Figure 4.3c). The salty surface anomaly is also subducted into AAIW and SAMW, slightly counteracting the freshening of these waters from the surface freshwater fluxes. An increased salinity occurs over large areas of the continental shelf and is most pronounced in the South Pacific sector in response to enhanced easterly winds (Figure 4.1b) that increase the advection and mixing of salty CDW onto the continental shelf, consistent with the results by Spence et al. (2014). This process further counteracts the freshening of the continental shelf waters from the freshwater perturbation. In conclusion, the wind-driven response of the salinity due changes in ocean transport and mixing processes opposes the salinity changes induced by the surface freshwater fluxes. However, the magnitude of the salinity response to the surface wind stress perturbation is much weaker than the response to the surface freshwater fluxes. Therefore, our simulations suggest that the overall observed salinity changes in the higher latitude Southern Ocean are largely due to the changes in the surface freshwater fluxes from sea ice, with regional exceptions depending on the strength of each forcing.

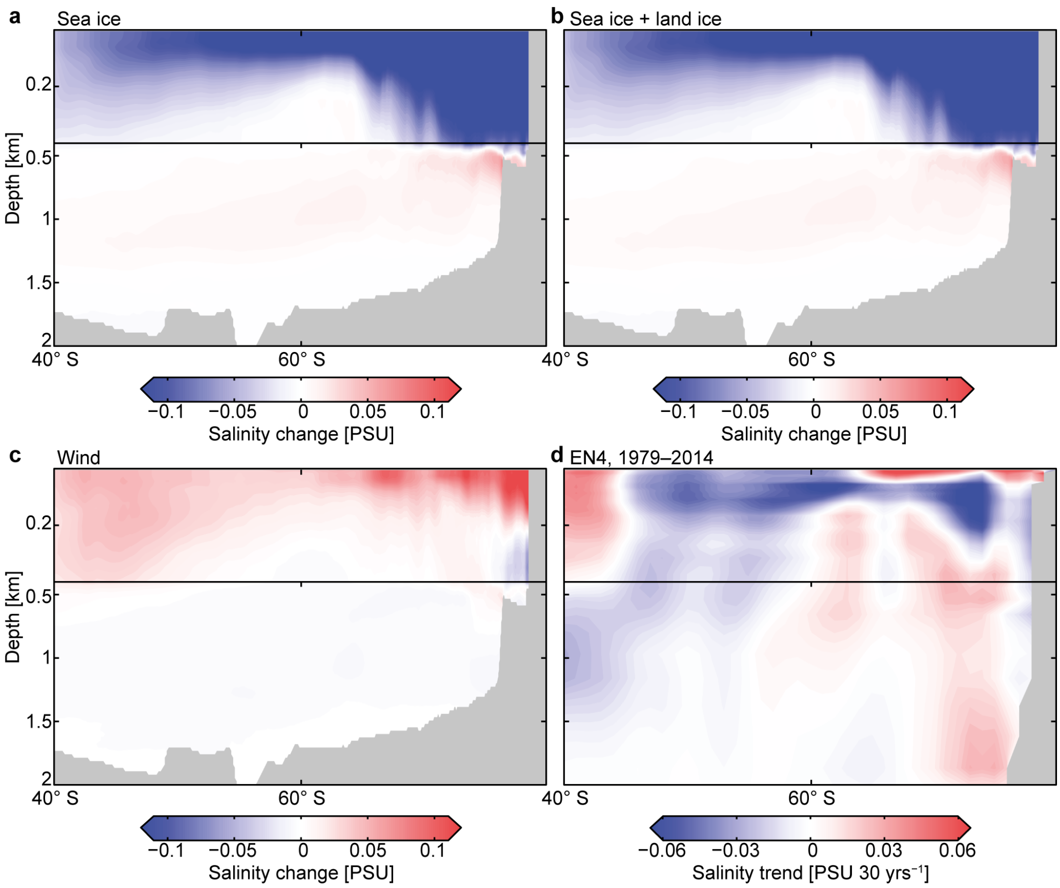

Figure 4.3 Zonal mean subsurface salinity response: Response to the sea-ice freshwater flux perturbation (**a**), ot the combined sea-ice and land-ice freshwater flux perturbations (**b**), and to the surface wind stress perturbation (**c**). Shown are the differences of the last 20 years of a 40-year perturbation experiment to a control simulation with constant forcing. (**d**) Observed salinity trends derived from the EN4 Objective analyses (1979–2014; Ingleby and Huddleston, 2007; Good et al., 2013), scaled to a 30 year period.

4.3.2 Stratification response

South of the ACC frontal region the stable surface density stratification is mostly established by the vertical salinity profile (Stewart et al., 2016) since the vertical temperature stratification becomes seasonally unstable. At such low temperatures the vertical density stratification is much more sensitive to changes in salinity due to the non-linearities in the equation of state (Turner, 1973; Sigman et al., 2004). Therefore, the strong changes in surface salinity induced by the sea-ice and land-ice freshwater fluxes imply considerable changes in the surface density stratification south of the ACC frontal region with a decreasing effect further to the north where temperature starts to dominate the density stratification. Indeed, the surface ocean freshening induced by the sea-ice freshwater fluxes induces a sharp increase in surface density stratification adjacent to the sea-ice edge, where the coldest waters, a very marginal stability, and deep mixing occur during

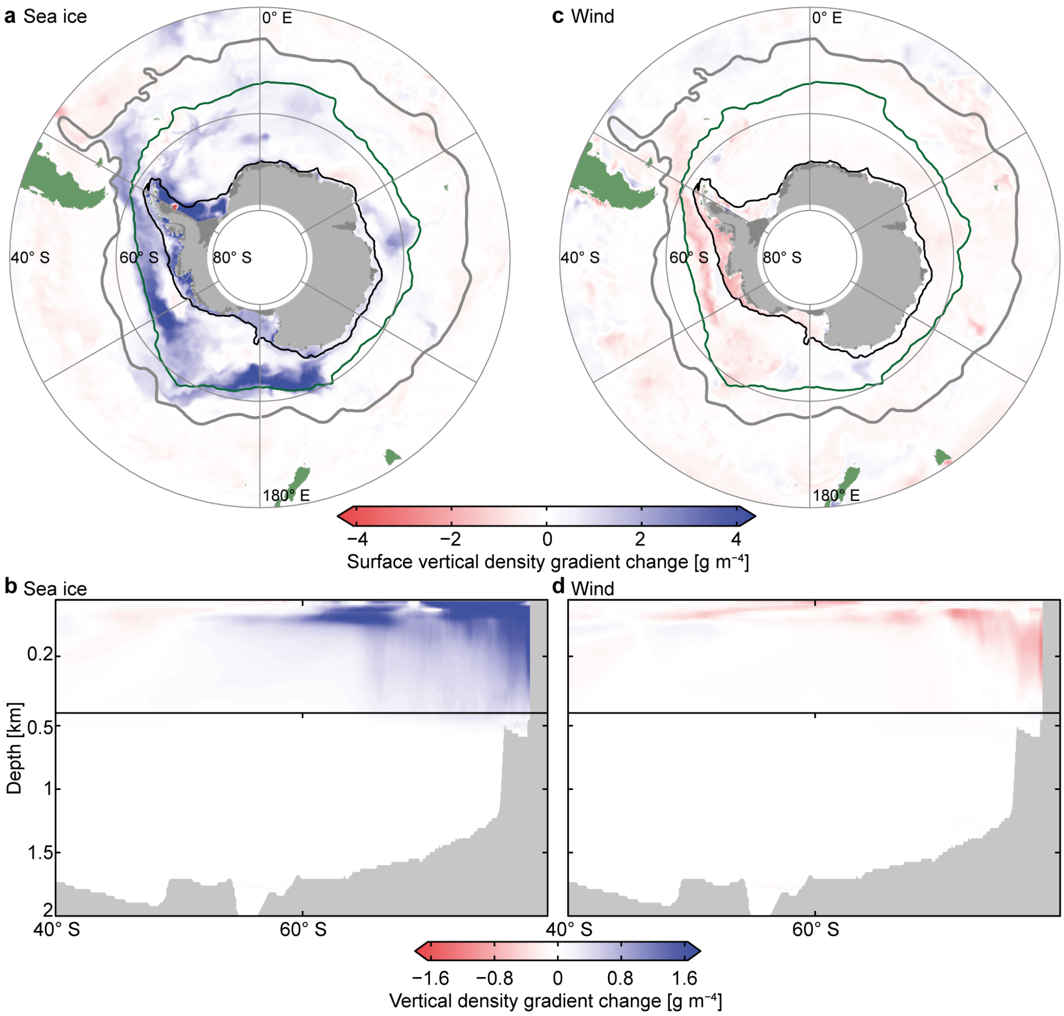

Figure 4.4 Density stratification response: Response to the sea-ice freshwater flux perturbation (**a–b**), and to the surface wind stress perturbation (**c–d**). Positive values denote a stabilizing ocean and negative values a destabilizing ocean. Upper two panels: averaged over the top 100 m. Lower two panels: zonal mean. Shown are the differences of the last 20 years of a 40-year perturbation experiment to a control simulation with constant forcing. Green contour line: climatological mean sea-ice edge; gray contour line: Subantarctic Front (Orsi et al., 1995); black contour line: Antarctic continental shelf (shallower than 1000 m).

winter-time (Figure 4.4a–b). Further to the north, this effect vanishes. In the coastal ocean, a very strong stabilization occurs due to the increased melting and freezing cycle, explaining the strong freshening at the surface. As discussed above, whether or not this coastal stabilization is realistically represented in the model is debatable, as it depends on the mixing parameterization of brine to the subsurface in the model. Nevertheless, the increased northward transport of freshwater stabilizes the ocean in the upwelling region around the sea-ice edge. The surface wind stress perturbation shows a much weaker response due to the surface salinity increase that slightly oppose the freshwater response (Figure 4.4).

4.3.3 Temperature response

As a response to the considerable increase in surface density stratification induced by the sea-ice freshwater perturbation in the upwelling region, we expect an influence on vertical temperature profile due a reduction in the upwelling of CDW that is several degrees warmer than the surface waters south of the ACC frontal region. The sea-surface temperature response to this perturbation reveals a strong cooling between the sea-ice edge and the Subantarctic Front (SAF) in the entire Pacific sector and parts of the Atlantic sector (Figure 4.5a). This surface cooling is, in terms of its spatial pattern, strikingly consistent with the satellite derived cooling trends in this region (Figure 4.5d). However, the simulated magnitude from this perturbation alone is considerably larger than the observed trend. If the warming from the surface wind stress perturbation in this region is considered as well (Figure 4.5c), both effects together seem to agree very well with the observed magnitude of the cooling. Moreover, the surface wind stress response reveals that a large fraction of the surface warming observed in the lower latitudes can be attributed to wind-driven changes in ocean circulation and mixing. In the high-latitude Atlantic sector and parts of the Indian Ocean sector the wind stress perturbation results in a weak cooling south of the SAF. This cooling can be attributed to a reduction of the meridional gradient in the wind stress along the sea-ice edge in this region, as it can be depicted from Figure 4.1b. Very little cooling is found south of the sea-ice edge, because these waters are very close to their natural limit of the freezing point temperature and actual temperature trends could only occur during summer. But at that time of the year the surface layer is strongly stratified and very little subsurface heat enters the surface layer. In summary, our simulations suggest that most of the observed cooling in the Pacific and western Atlantic sectors of the Southern Ocean surface waters results from increased northward freshwater transport by sea ice, which reduces the upwelling of warm CDW due to an increased density stratification. Surface wind stress changes partly counteract this signal and are probably responsible for sea-surface temperature changes in the other regions of the Southern Ocean.

The strong cooling signal in the Pacific sector occurs right at the sea-ice edge and provides probably a positive feedback on the sea-ice cover changes. Such a feedback mechanism cannot be studied directly with our model simulations. However, they might have contributed considerably to the observed persistent expansion of the sea ice as suggested by Goosse and Zunz (2014). Our simulations suggest that an increased sea-ice advection to the sea-ice edge in the Ross Sea could effectively prolong the period of seasonal sea-ice cover since the sea-surface temperature and therefore the melting is reduced or delayed and freezing might occur earlier. To obtain a surface cooling, the location of the freshwater input is critical because it can only be initiated if a surface freshening occurs in the upwelling region between the sea-ice edge and the SAF, where the surface temperatures are critically influenced by the subsurface heat flux. If the surface freshening

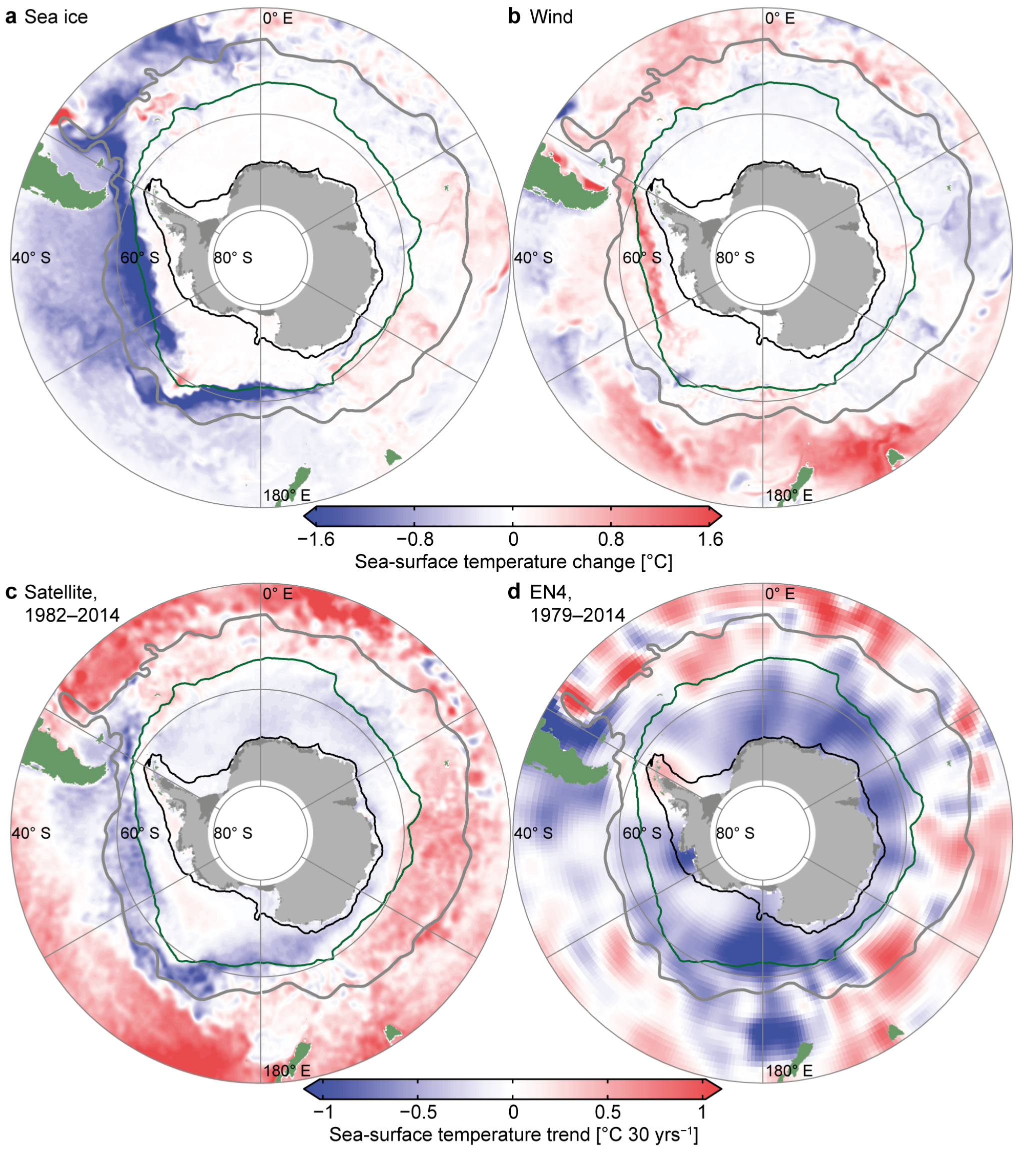

Figure 4.5 Sea-surface temperature response: Response to the sea-ice freshwater flux perturbation (**a**), and to the surface wind stress perturbation (**b**). Shown are the differences of the last 20 years of a 40-year perturbation experiment to a control simulation with constant forcing. (**c**) Observed sea-surface temperature trends derived from the AVHRR satellite data (1982–2014; Reynolds et al., 2007), scaled to a 30 year period. (**d**) Observed temperature trends derived from the upper 50 m of the EN4 Objective analyses (1979–2014; Ingleby and Huddleston, 2007; Good et al., 2013), scaled to a 30 year period. Green contour line: climatological mean sea-ice edge; gray contour line: Subantarctic Front (Orsi et al., 1995); black contour line: Antarctic continental shelf (shallower than 1000 m).

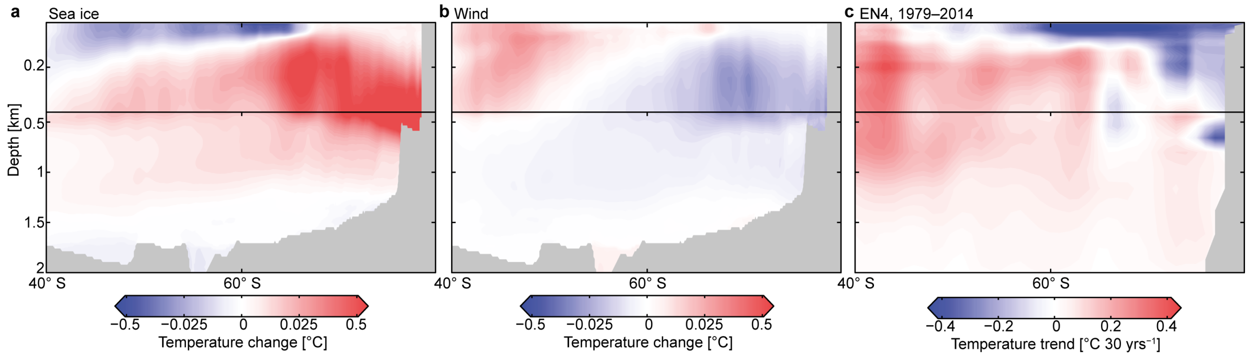

Figure 4.6 Zonal mean subsurface temperature response: Response to the sea-ice freshwater flux perturbation (**a**), and to the surface wind stress perturbation (**b**). Shown are the differences of the last 20 years of a 40-year perturbation experiment to a control simulation with constant forcing. (**c**) Observed temperature trends derived from the EN4 Objective analyses (1979–2014; Ingleby and Huddleston, 2007; Good et al., 2013), scaled to a 30 year period.

occurred further to the north, it would not considerably change the surface temperature because it had not much influence on the density stratification in these warmer regions and because the upwelling of deep waters is drastically reduced further to the north. Nevertheless, a surface cooling occurs north of the SAF in the freshwater perturbation experiment (Figure 4.5a). This cooling can be explained by a northward transport of the anomaly that originates from south of the SAF, which is an essential process in terms of the heat uptake from the atmosphere by these waters and subsequent subduction into AAIW and SAMW (Armour et al., 2016).

The observation-based estimates of zonal mean temperature changes in the Southern Ocean (Figure 4.6d) suggest that the surface cooling only occurs in the upper 100 m of the water column and are therefore, in contrast to the subsurface warming, probably not related to meridional shifts of the ACC. The distinct cooling of this surface layer around the sea-ice edge in the zonal mean profile also occurs in the sea-ice freshwater perturbation experiment (Figure 4.6a). In the surface layer south of the sea-ice edge, cooling is mostly absent in any of the model experiments. However, the observational data from EN4 suggests that also a strong cooling occurred south of the sea-ice edge. Comparing the EN4 surface layer trends with the satellite derived trends (Figures 4.5d–e) and other observational studies (de Lavergne et al., 2014; Schmidtko et al., 2014), suggests that this trend in EN4 might also be unrealistically large. This discrepancy in the observational data south of the sea-ice edge is certainly related to the sparse coverage of this region with oceanographic data. At the subsurface, the observational profiles suggest a warming of CDW, AAIW, and SAMW. The CDW warming is consistent with a reduced upwelling of heat into the surface layer as a result of the increased surface stabilization in the upwelling region from the sea-ice freshwater fluxes (Figure 4.6a). The model probably overestimates this CDW warming due to the overly strong stabilization of the coastal ocean from both the sea-ice and land-ice perturbations and an insufficient heat loss in the coastal ocean. The surface wind stress counteracts this warming of CDW and dominates the warming of AAIW and SAMW further to the north (Figure 4.6b). In conclusion, the response of the subsurface ocean temperature also shows opposing effects induced by the freshwater perturbation and the surface wind stress perturbation, and the former dominates changes in the high latitudes, whereas the latter changes become comparably larger in the low latitudes.

4.3.4 Circulation response

Since the changes in the density structure associated with the freshwater perturbation as well as the wind stress changes presumably influence the ocean circulation, we proceed to analyze the circulation response to these forcing changes. Similar to the changes in temperature and salinity, we find opposing tendencies imposed on the circulation by the freshwater and wind perturbation experiments. Figures 4.7b–c show that the freshwater perturbation tends to increase the sea-surface height south of the frontal region and therefore reduces the meridional sea-surface height gradient in the Southern Ocean, which is a consequence of a decrease in density in the surface

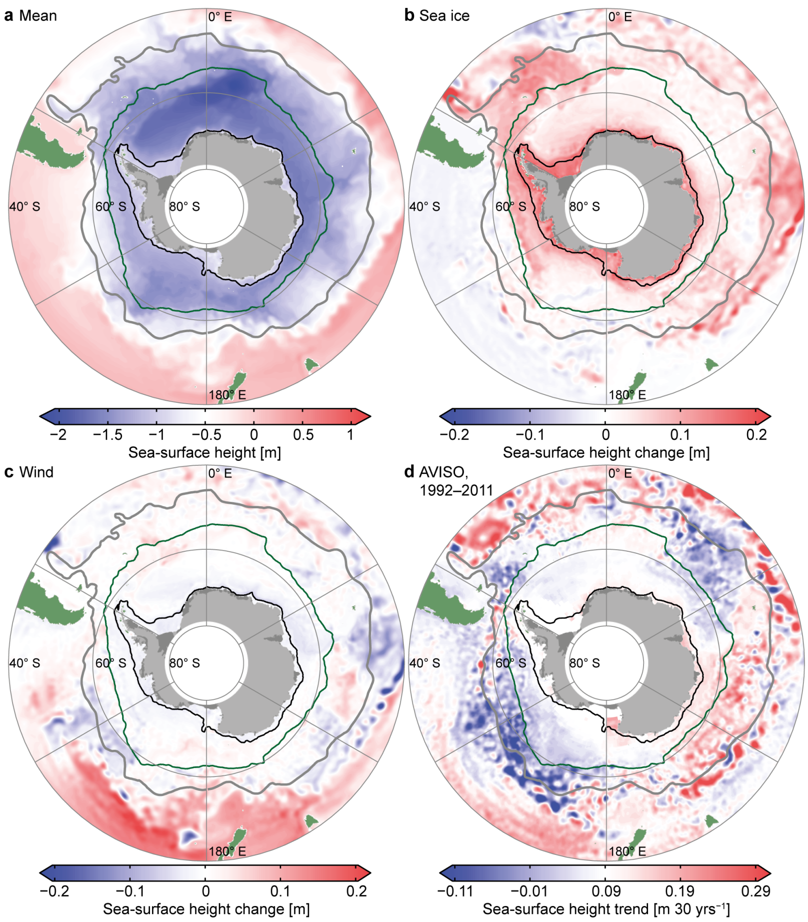

Figure 4.7 Sea-surface height response: Mean simulated sea-surface height (**a**), response to the sea-ice freshwater flux perturbation (**b**), and the response to the surface wind stress perturbation (**c**). The responses show the differences of the last 20 years of a 40-year perturbation experiment to a control simulation with constant forcing. (**d**) Observation-based sea-surface height trend from AVISO satellite data (produced by Ssalto/Duacs and distributed by AVISO with support from Cnes, http://www.aviso.altimetry.fr/duacs) over the period 1992 to 2011, scaled to a 30 year period. Green contour line: climatological mean sea-ice edge; gray contour line: Subantarctic Front (Orsi et al., 1995); black contour line: Antarctic continental shelf (shallower than 1000 m).

waters due to the surface freshening. In contrast, the wind stress perturbation experiment shows little response in the high latitudes but a strong sea-surface height increase in the low latitudes, especially in the Pacific sector. This response results in an increase in the meridional sea-surface height gradient, which incorporates an increasing ACC transport of 1.9 Sv. The freshwater perturbation decreases the ACC transport by about 3.3 Sv. Therefore, almost no change or a slight decrease would occur in the net transport consistent with observational data that show very little long-term changes in the ACC transport (Meredith et al., 2011b; Koenig et al., 2014). The reduction in density on the Antarctic continental shelf and therefore an increase in the sea-surface height (Figure 4.7b) appears from the freshwater flux perturbation experiment. This finding is consistent with the results by Rye et al. (2014), who find an increasing sea-surface height around most of the Antarctic continental margin in response to increased glacial meltwater. However, due to the difficulties of ROMS to accurately simulate the continental shelf process at its current state, this response might not be reliable in our simulations.

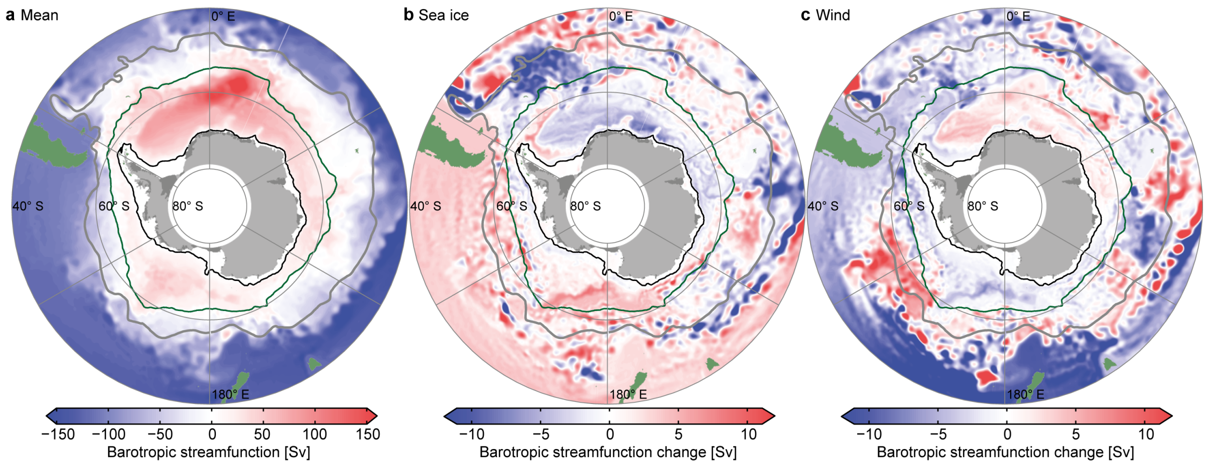

Figure 4.8 Barotropic streamfunction response: Mean simulated barotropic streamfunction (**a**), the response to the sea-ice freshwater flux perturbation (**b**), and the response to the surface wind stress perturbation (**c**). The responses show the differences of the last 20 years of a 40-year perturbation experiment to a control simulation with constant forcing. Green contour line: climatological mean sea-ice edge; gray contour line: Subantarctic Front (Orsi et al., 1995); black contour line: Antarctic continental shelf (shallower than 1000 m).

The model simulations suggest changes in the gyre circulation. One of the most prominent features in the wind stress perturbation experiment is a spin-up of the subtropical gyre in the South Pacific that can be depicted from both changes in sea-surface height and the barotropic streamfunction (Figures 4.7 and 4.8). This finding is consistent with the observed changes in sea-surface height (Figures 4.7d). However, observational estimates of changes in the sea-surface height from the AVISO satellite data only exist since 1992. Therefore, the observation based changes reflect a much shorter period and might deviate considerably from the simulated response. In the higher latitudes, the changes in the barotropic streamfunction reveal changes in the subpolar gyre circulation (Figure 4.8). The wind stress perturbation spins up the Ross Sea gyre and expands it north-eastward. This change is consistent with the observed deepening and expansion of the Amundsen Sea Low (Haumann et al., 2014). In the Weddell Sea, the wind stress perturbation leads to a slight spin-up and contraction of the Weddell Sea gyre, which seems to be partly counteracted by the freshwater flux perturbation.

The meridional overturning circulation in the model strengthens in response to the surface wind stress perturbation, especially the upper circulation cell (Figure 4.9c). It is likely that the model overestimates this response, as it is not fully eddy-resolving. Consistent with results by Morrison et al. (2011), the meridional overturning circulation also weakly strengthens with an increased surface freshwater forcing in high-latitudes (Figure 4.9b). The explanation for a strengthening of the upper circulation cell is probably provided by the finding that these freshwater fluxes are an important contributor to the AAIW formation process. The slight increase in the overturning in our model would actually bring more deep water to the surface and counteract the changes induced by the increased stratification. Therefore, the cooling of the surface waters can only result from an increased stratification and reduced mixing, rather than through changes in vertical advection. Furthermore, a weak shoaling of the upper circulation cell and an expansion of the lower circulation cell in our simulation (Figure 4.9b) suggest that the upwelled waters are advected from a shallower depth. A shoaling of the upper circulation cell and AAIW over recent decades is also consistent with the findings by Schmidtko and Johnson (2012). While most of the simulated response shows opposing effects induced by the freshwater and wind perturbations, the meridional overturning circulation strengthens in both cases. This finding is in line with a few observation-based estimates that suggest an increased subduction of AAIW and SAMW over recent decades (Waugh et al., 2013; Waugh, 2014), which would be supported by both an increased northward sea-ice freshwater transport and increased meridional surface wind stress gradient in our simulations.

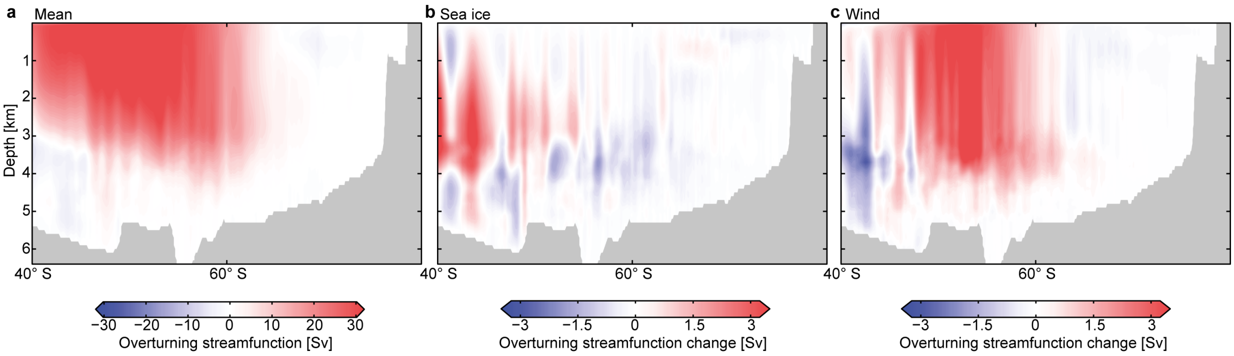

Figure 4.9 Zonal mean meridional overturning response: Mean of the simulated meridional overturning circulation (**a**), response to the combined sea-ice and land-ice freshwater flux perturbations (**b**), and response to the surface wind stress perturbation (**c**). The responses show the differences of the last 20 years of a 40-year perturbation experiment to a control simulation with constant forcing. Note that apparent vertical lines are artifacts from interpolating the transport from the model's σ-coordinates to depth-levels.

4.4 Discussion

While our simulations show a strong agreement with observed changes in temperature and salinity of the Southern Ocean, several limitations arise from model biases, the experimental design, and uncertainties in the forcing data. One limitation is that we performed these simulations at an eddy-permitting but not fully eddy-resolving resolution of 5 to 25 km and about 18 km in the ACC region. Since ROMS does not include a parameterization of mesoscale instabilities, the response of the overturning circulation and therefore the wind stress response is most likely too sensitive and the horizontal mixing of tracers and their anomalies is too small in the model. Another limitation is the large model bias in the coastal ocean around Antarctica. This bias prevent us at the current state of the model development to reliably analyze the effect of the perturbations on the observed changes over the continental shelf and the AABW. The model has a far too stable density stratification over the continental shelf region, which reduces the advection of the anomalies to the subsurface and leaves a too strong response at the surface. Similar problems, but not as severe, occur in the subduction of AAIW and SAMW. Therefore, the freshening and cooling response at the surface in the open ocean might be exaggerated and the freshening response of AAIW and SAMW underestimated. A further exaggeration of the response might result from the experimental design, because we instantaneously increase the forcing rather than applying a gradual increase. Moreover, at the current stage, we did not run a combined wind stress and freshwater perturbation experiment that might reveal some non-linear effects between the changes. Such a simulation should be additionally performed in future efforts. Finally, we did not run perturbation experiments where we change the surface heat flux. However, our simulations reveal that most of the changes in the Southern Ocean south of the ACC frontal region can be explained without changes in the surface heat flux. Additional cooling in might be induced along the expanding sea-ice edge by the ice–albedo feedback. North of the frontal regions, our simulations show a much weaker warming of AAIW and SAMW than suggested by observations. This discrepancy can most likely be explained by the increased heat uptake through AAIW and SAMW over recent decades (Frölicher et al., 2015), which is not included in our simulations as the surface heat flux is fixed.

Our simulations suggest that the upwelling of CDW into the surface waters south of the SAF, as well as the properties of the surface waters and the water masses formed in this region strongly depend on the northward transport of freshwater by sea-ice into this region. Such a high sensitivity of the upwelling to buoyancy-driven stratification changes, and freshwater flux changes in particular, is consistent with earlier idealized model experiments (Watson and Naveira Garabato, 2006; Morrison et al., 2011; Watson et al., 2015), theoretical considerations (Ferrari et al., 2014), and ocean proxy data of glacial–interglacial changes (Francois et al., 1997; Adkins et al., 2002; Sigman et al., 2004). Our results suggest that the sea-ice freshwater transport into this upwelling region is the dominant surface buoyancy flux that controls stratification changes in this region, which could provide an explanation for a more stratified ocean in the upwelling region during cold climates and a less stratified ocean during warm climates. The sea-ice transport effectively removes freshwater from the lower circulation cell and adds it to the upper circulation cell, making the deep ocean saltier and the upper ocean fresher during increased sea-ice formation and transport (Haumann et al., 2016b). Our results support the theory that such changes occurred over recent decades. However, this effect might be reversed in the coming decades if the sea-ice region warms and sea ice retreats.

We here argue that the recent changes in Southern Ocean temperature and salinity are to a large extent driven by the sea-ice changes. These sea-ice changes have been previously attributed to changes in southerly winds, which increased the northward transport of sea-ice and led to a sea-ice expansion (Haumann, 2011; Holland and Kwok, 2012; Haumann et al., 2014). Therefore, the freshwater flux changes are indirectly induced by the changes in the surface winds and the atmospheric circulation changes are the overall driver of all these changes. Our simulations, in which we do not run a coupled sea-ice or atmosphere model, enabled us to disentangle the wind-induced freshwater flux changes from the wind-induced ocean circulation and mixing changes. A critical factor for the observed increase in the northward sea-ice transport in the Ross Sea is the zonal asymmetry in the atmospheric circulation changes (Haumann et al., 2014, 2016b). To date, it is still strongly debated whether these zonally asymmetric changes result from natural variability or anthropogenic sources (Ding et al., 2012; Fan et al., 2014; Haumann et al., 2014; Li et al., 2014; Meehl et al., 2016; Hobbs et al., 2016), which is the result of a rather short observational record in combination with difficulties of global models to reproduce these changes and a potentially large multi-decadal variability. Yet, proxy data (Thomas and Abram, 2016) and a recent ocean reanalysis product (Giese et al., 2016) suggest that the changes in sea-ice and surface temperature in the Ross Sea might have persisted over a much longer time-period. Therefore, the Southern Ocean surface freshening, cooling, and sea-ice expansion might also be an initial response to the anthropogenic forcing that lasts for several decades as the differential warming of high and low latitudes and ozone depletion could induce zonally asymmetric circulation changes that are not captured by climate models (Haumann et al., 2014). A further reason for the under-representation or absence of the surface cooling and freshening in climate models might be their poor representation of the sea-ice transport (Uotila et al., 2014; Lecomte et al., 2016). We argue that models that do not accurately capture this process would not be able to reproduce the recent cooling of the high-latitude Southern Ocean, independent of a natural or anthropogenic cause.

4.5 Summary & conclusions

In this study, we investigated the sensitivity of the Southern Ocean salinity, temperature, density stratification, and circulation to recently observed changes in surface freshwater fluxes from sea ice and land ice, as well as changes in the surface wind stress. We find a freshening of the open-ocean surface and intermediate waters in the Pacific and Atlantic sectors that is consistent with observed changes. This freshening considerably increases the surface density stratification between the sea-ice edge and the Subantarctic Front in the Pacific sector, which reduces the upwelling of warm and salty deep waters into the surface layer. As a consequence, the simulations show a strong surface cooling and a subsurface warming. The spatial pattern of the surface cooling agrees remarkably well with the satellite-observed cooling of this region in recent decades that occurred despite a globally warming surface ocean. Therefore, our analysis suggests that this cooling signal is driven by an increased northward transport of freshwater by sea ice into the upwelling region.

The response of temperature and salinity to surface wind stress changes slightly opposes the sea-ice freshwater flux induced changes in most regions. While they are much weaker south of the Subantarctic Front, in lower latitudes these changes and potentially surface heat flux changes dominate the observed warming of surface waters, AAIW, and SAMW. This warming increases the meridional density gradient and enhance the ACC transport in our simulations. However, the freshwater fluxes reduce both the meridional density gradient and ACC transport due to the high-latitude surface freshening. Therefore, the net effect of these two processes would lead to a weaker sensitivity of ACC transport changes to the hydrographic changes.

The response to changes in land-ice freshwater fluxes is much weaker in our simulations than an apparent vertical redistribution of freshwater from freezing and melting of sea ice along the Antarctic coast. However, this latter response might be a model specific result that depends on the surface mixing parameterization, leaving no conclusive answer on the source of changes observed over the continental shelf from our simulations. Therefore, at the current state of the model development, we cannot robustly estimate changes over the continental shelf and in AABW.

We conclude that the observed changes between the Subantarctic Front and the sea-ice edge, as well as in the water masses formed in this region, are largely induced by changes in surface freshwater fluxes from sea ice. This conclusion is consistent with the earlier findings by Pollard and Thompson (1994) and Kirkman and Bitz (2011) that sea-ice transport could delay global warming in the high-latitude Southern Ocean. We argue that this process led to the observed surface cooling of the Southern Ocean over recent decades. Since this cooling occurs mostly around the sea-ice edge, it could provide an important positive feedback that probably contributed to recently observed expansion of Antarctic sea ice, in line with the arguments by Goosse and Zunz (2014). While the freshwater anomalies propagate from the sea-ice edge region across the frontal region into the AAIW and SAMW, the cooling signal most likely vanishes more quickly in reality due to an anomalous uptake of heat towards the north (Armour et al., 2016). Therefore, our results promote an at first sight counter-intuitive, more effective ocean heat uptake due the increased surface stratification from the surface freshwater fluxes. This effect can mostly be explained by our finding that the increased freshwater fluxes lead to a shallower upwelling and therefore to a reduced upwelling of CDW but not to a reduced subduction of AAIW and SAMW. In fact, the overturning circulation weakly increases in our simulations in response to the freshwater forcing consistent with the model experiments by Morrison et al. (2011). Therefore, both buoyancy- and wind-driven changes in the upper overturning circulation cell are consistent with observed strengthening of this cell (Waugh et al., 2013; Waugh, 2014). Our results imply that the upwelling of warm, salty, and carbon- and nutrient-rich deep waters in the Southern Ocean is highly sensitive to stratification changes induced by freshwater fluxes from sea ice—a finding that could provide a possible explanation for an increasing vertical density stratification during glacial climates (Sigman et al., 2010).

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