Chapter 6

Synthesis

Most of the interior ocean waters upwell to the surface through the Southern Ocean. Through this process these waters return carbon and nutrients to the surface and have therefore been identified as a critical component in controlling long-term changes in the global climate system (Knox and McElroy, 1984; Sarmiento and Toggweiler, 1984; Siegenthaler and Wenk, 1984; Marinov et al., 2006; Sigman et al., 2010). Yet, the processes that drive changes in this upwelling of deep waters have been less well understood and have been highly debated in scientific literature. We could make a first step towards a better comprehension of these processes by analyzing their observed changes over recent decades. Numerous studies have investigated the response of the Southern Ocean to changes in the wind-driven ocean circulation (e.g. Oke and England, 2004; Saenko et al., 2005; Fyfe and Saenko, 2006; Toggweiler and Russell, 2008; Sigmond et al., 2011; Thompson et al., 2011). However, many of the observed changes in temperature and salinity seem inconsistent with the response induced by the wind-driven ocean circulation. Alternatively, changes in the vertical exchange of water masses could be caused by changes in the marginally stable density stratification of the Southern Ocean (Watson and Naveira Garabato, 2006; Matear and Lenton, 2008; Morrison et al., 2011; Watson et al., 2015), which is controlled by the surface salinity (Sigman et al., 2004). In this dissertation, I investigated the recent changes in the surface freshwater fluxes over the Southern Ocean and the response of the Southern Ocean hydrography, circulation, and vertical exchange of heat and carbon to changes in these fluxes. With this synthesis, I intend to first summarize my main findings and conclusions (section 6.1), and then discuss the limitations of my results (section 6.2) as well as their implications in the context of long-term changes in the global climate system (section 6.3) that I introduced in chapter 1. This discussion will elucidate that sea-ice freshwater fluxes could play a crucial role in driving glacial–interglacial changes in the global carbon cycle and could entail a substantial risk in under- or overestimating feedbacks in projected future changes in the carbon cycle. At last, I will provide an outlook and suggestions for future research activities on this topic (section 6.4).

6.1 Findings & conclusions

I will here summarize the main findings and conclusions from my investigation of the research objectives that I posed in section 1.5:

(1) How large are sea-ice–ocean freshwater fluxes associated with sea-ice formation, transport, and melting in the Southern Ocean, and how do they compare to freshwater fluxes from the atmosphere and from land ice?

In chapter 2, we presented the first observation-based estimate of sea-ice–ocean freshwater fluxes associated with sea-ice formation, transport, and melting over the period 1982 to 2008. An analysis of this data set revealed that overall 410 $\pm$ 110 mSv of freshwater are removed and added to the Southern Ocean surface waters due to the formation and melting of sea ice. About 80 $\pm$ 20% (320 $\pm$ 70 mSv) of the freezing flux arises from the coastal ocean, where cold temperatures and a divergent sea-ice field fuel the ice production. About 40 $\pm$ 10% (130 $\pm$ 30 mSv) of this ice that is produced in the coastal ocean is transported to the north, towards the sea-ice edge, and melts there in the warmer surface waters. An additional 50 $\pm$ 50 mSv of sea ice probably form through snow-ice formation from the atmospheric flux and contribute to the total melting flux. Estimates of the net atmospheric freshwater flux vary substantially between 650 mSv in ERA-Interim (Dee et al., 2011) over the ocean south of 50° S and 350 mSv in satellite-derived HOAPS estimate (version 3.2; Andersson et al., 2010). South of the climatological mean sea-ice edge (1% mean annual ice concentration), the atmospheric freshwater flux from ERA-Interim amounts to about 200 mSv of which about 80 mSv fall in the coastal region and slightly oppose the sea-ice formation flux. The freshwater fluxes from land ice through basal and iceberg melting amount to about 46$\pm$6 mSv and 42$\pm$5 mSv, respectively (Depoorter et al., 2013). In summary, the seasonal melting and freezing fluxes from sea ice exceed both the land ice and the atmospheric flux substantially. In the coastal ocean, the northward export of freshwater by sea ice is balanced by the other two freshwater fluxes and in the open ocean the sea-ice freshwater flux exceeds the atmospheric flux substantially in certain regions. Therefore, sea ice provides the dominant freshwater flux in the seasonally ice covered region of the Southern Ocean.

(2) What is the contribution of sea-ice–ocean freshwater fluxes and their recent changes to the Southern Ocean's salinity distribution?

A simple box model approach taken in chapter 2 revealed that the northward transport of freshwater by sea ice increases the coastal-ocean salinity by about +0.15$\pm$0.06 g kg^{-1} and lowers the open-ocean salinity by about -0.33 ± 0.09 g kg^{-1}. The former can be regarded as the effect on AABW, i.e., the lower overturning cell, and the latter as the effect on AAIW and SAMW, i.e., the upper circulation cell. Therefore, the sea ice effectively re-allocates freshwater and buoyancy from the lower ocean circulation cell to the upper ocean circulation cell and increases the meridional and vertical salinity and density gradients. This northward transport of freshwater has substantially increased by about 20 $\pm$ 10% over the period 1982 to 2008 (or by +9$\pm$5 mSv per decade), which corresponds to a salinity decrease of about -0.02 ± 0.01 g kg^{-1} per decade in open-ocean surface waters and AAIW when using our box model estimate. The magnitude of this change agrees very well with the observed magnitude of change over recent decades (Wong et al., 1999; Helm et al., 2010; Durack et al., 2012). Largest freshening signals have been observed in the open-ocean Ross Sea surface waters and in the Pacific AAIW, coinciding with the largest changes in northward sea-ice freshwater transport. Our findings are further supported by the sensitivity experiments with the regional ocean model performed in chapter 4 that show a large-scale freshening of the open-ocean surface and intermediate waters in response to the observed sea-ice fluxes in the Pacific sector and also in parts of the Atlantic sector. While one would expect that the increased northward sea-ice transport counteracts the freshening induced by glacial meltwater in the coastal region, the model simulations suggest that also the vertical distribution of brine might play a role and actually freshen the surface waters as well. Yet, this coastal response in the model might be unrealistic and increasing melting from Antarctica remains the most likely reason for the coastal and AABW freshening.

(3) Is it possible to study the Southern Ocean response to observation-based changes in the surface freshwater fluxes in an ocean circulation model?

In chapter 3, I presented a regional ocean model for the Southern Ocean that is forced with observation-based surface freshwater, heat, and momentum fluxes. For this purpose, I implemented a number of modifications to the model's lateral boundary conditions in the north and south, its mixing scheme, and surface forcing in the sea-ice region. The model realistically simulates the general water-mass structure of the Southern Ocean, the ocean circulation, and the surface processes in the open ocean. Despite the major advances that I made throughout this thesis, large model biases remain in the coastal ocean and in the subsurface waters. Nevertheless, a good representation of the region of interest, i.e., the upwelling region, allows to study changes in the surface stratification induced by surface freshwater fluxes. While this flux-forced model cannot be used to study feedbacks between the ocean and the sea ice, land ice, or atmosphere, I can analyze the ocean's response to changes in the surface fluxes. I conclude that my approach of constraining an ocean model with observation based sea-ice–ocean freshwater fluxes provides a novel tool to study the effect of changes in the surface condition on the Southern Ocean. This approach circumvents many of the common problems in coupled ocean–ice models that are often overly sensitive to subtle inaccuracies in the atmospheric or sea-ice conditions, which can lead to an unrealistic water-mass structure in these models.

(4) How do Southern Ocean stratification, temperature, and circulation respond to recent changes in surface freshwater fluxes; and could increased northward freshwater transport provide an explanation for the observed surface stabilization and cooling?

The perturbation experiments that we presented in chapter 4 illustrate that the freshening associated with the recent increase in northward freshwater transport by sea ice considerably increased the surface density stratification of the open-ocean waters around the sea-ice edge in most of the

Pacific sector, and, to a lesser degree, also in the high-latitudes of the other ocean basins. This increased stratification reduces the upwelling of warm deep water into the surface layer in our simulations, resulting in a substantial cooling of the surface waters between the sea-ice edge and the Subantarctic Front in the Pacific sector and parts of the Atlantic sector. The cooling response of the model in this region shows a spatial pattern that is remarkably similar to the cooling derived from the to-date probably most complete observational ocean data set—the satellite observed sea-surface temperature record. At the subsurface, the model responds with a warming of CDW due to the reduced mixing of CDW into the surface layer. This response seems consistent with the trends derived from the few available observational subsurface data.

In contrast to the freshwater flux perturbation experiment, the simulated response to the observation-based changes in the surface wind stress exhibits a weak surface salinity and temperature increase in the high-latitude Pacific sector, a cooling of CDW, and a warming of AAIW and SAMW due to an increased overturning circulation and mixing. While the simulated response to surface wind stress changes south of the ACC frontal region is broadly inconsistent with observed changes, our simulations suggest that these changes might have contributed to the observed warming of the surface waters, AAIW, and SAMW north of the ACC frontal region. Therefore, we suggest that the observed surface cooling of large regions of the Southern Ocean high latitudes, which occurred despite global warming, is primarily caused by an increased sea-ice freshwater flux and an associated increased surface density stratification. Generally, we find opposing tendencies induced by the surface wind stress changes and freshwater flux changes in the simulated ocean hydrography and horizontal transport, with a relatively larger response induced by the freshwater flux perturbations. One exception is the meridional overturning circulation that strengthens in both perturbation experiments, consistent with the results by Morrison et al. (2011), and more strongly in the wind stress perturbation experiment. In summary, our simulations revealed that the upwelling of deep waters to the surface in the Southern Ocean is very sensitive to the freshwater fluxes from sea ice.

(5) What is the effect of changing surface freshwater fluxes on the release and uptake of CO_2 by the Southern Ocean and could this process provide an explanation why the Southern Ocean carbon sink did not saturate over recent decades despite an increase in westerly winds?

We analyzed the response of the surface CO_2 flux to the perturbations in sea-ice freshwater fluxes and surface wind stress in chapter 5. This analysis showed an increase of the net annual carbon uptake in the region between the sea-ice edge and the Subantarctic Front of 25% (0.06 PgC per year) in the sea-ice freshwater flux perturbation experiment and, surprisingly, an additional increase of 7% (0.02 PgC per year) in the wind stress perturbation experiment. We identified two major contributors to the increased carbon uptake in the freshwater flux perturbation experiment: One effect is that the surface cooling induced by the increased stratification increases the solubility of CO_2 in the seawater, which reduces the outgassing during all seasons. The other effect is a reduction in the upwelling of carbon-rich deep waters into the surface layer, which also reduces the natural release of CO_2 but only occurs during austral winter and spring. Both effects can be attributed to a decrease in upwelling in this simulation due to a reduced and shallower winter-time mixing. These two effects are countered by a reduced subduction of CO_2 into AAIW south of the SAF during summer and a reduced subduction into SAMW north of the SAF during winter, which originate from reduced mixing due to the increasing stratification. The surface wind stress response is more complex and has strong opposing seasonal and spatial tendencies. We find a strong increase in summer-time CO_2 uptake, which might however be a model-dependent result. This effect is mostly compensated by an increased winter-time outgassing in the Pacific sector that also compensates part of the reduction in outgassing from the freshwater flux perturbation in this region. Our study highlights that the freshening of the surface ocean induced by the sea ice could have strengthened the Southern Ocean carbon sink over recent decades, providing a potential explanation why observations show an observed strengthening of the Southern Ocean carbon sink over recent decades (Landschützer et al., 2015b) rather than a long-term saturation that was suggested by earlier studies (e.g. Le Quéré et al., 2007). These findings are in line with the results by Matear and Lenton (2008), who argue that increase surface buoyancy forcing might compensate for the wind-driven reduction in carbon uptake.

The overarching picture that arises from all three studies (chapters 2, 4, and 5) of my thesis suggests that the increased northward sea-ice transport in the Pacific sector of the Southern Ocean is a predominant driver of the observed changes in the region south of the Subantarctic Front over recent decades. This conclusion is supported by a consistent emerging signal from many different data sets that I have analyzed throughout this thesis, i.e., satellite-based sea-ice data, atmospheric reanalysis data, in-situ ocean salinity and temperature data, satellite-based sea-surface temperature data, and simulations with a regional ocean model. I argue that the importance of processes related to changes in sea-ice–ocean fluxes have not sufficiently been accounted for so far in the context of changes in the Southern Ocean system. My thesis revealed that sea ice is an active element in this system and probably in the climate system as a whole rather than simply an indicator of changes in the surface climate (Maksym, 2016). Through its dominant role in the surface freshwater balance, its changes can effectively alter the surface stratification and therefore the deep-to-surface exchange of heat and carbon—a process that was so far underestimated and has important implications for long-term changes in the global climate system (see section 6.3).

6.2 Limitations

While the research that I presented in this thesis provides substantial progress in quantifying the surface freshwater fluxes in the Southern Ocean and in understanding the ocean's response to changes in these fluxes, a number of limitations arise from data uncertainties, the methodological approach, and model shortcomings. I will here outline these limitations that should provide a basis for further investigations.

In this thesis, I focused on the response of the Southern Ocean to changes in surface freshwater fluxes from sea ice and, to some extent, to changes from land ice. However, there are reasonable grounds to believe that also the net atmospheric freshwater flux increased over the Southern Ocean in recent decades, because theoretical arguments and global model simulations support an increasing precipitation in this region with global warming (Knutti and Sedláček, 2013). While my findings suggest that a large portion of the observed freshening can be attributed to sea-ice freshwater fluxes, the changes in the atmospheric flux and their contribution to the freshening remain largely unconstrained. Most of the freshening from the sea ice occurs in the Pacific sector just north of the sea-ice edge and partly in the Atlantic, as well as in the intermediate waters that are predominantly formed in this region. Yet, observations also suggest freshening in other regions of the Southern Ocean and in lower latitudes, which could be induced by a changing atmospheric freshwater flux. A detailed assessment of the potential freshening induced by the atmospheric freshwater flux is to-date still hindered by the unavailability of reliable data. The uncertainty in such data is almost 50% for the spatially integrated mean flux (see section 3.5), and different data products disagree on the sign and magnitude of trends over the Southern Ocean (Bromwich et al., 2011). Due to these uncertainties and because the most reliable products do currently not show very large changes over recent decades (Bromwich et al., 2011; Nicolas and Bromwich, 2011), I did not further investigate this contribution in my dissertation.

A major caveat of this thesis arises from the large uncertainties in the observation-based sea-ice freshwater fluxes. While the sea-ice concentration from which I derived these fluxes is well constrained, the sea-ice thickness and the sea-ice drift products induce large spatial and temporal uncertainties. Currently, sea-ice thickness observations are still very sparse in time and space, which is mostly related to the challenges in retrieving satellite-based thickness. We combined the few observational products with a reanalysis product to assess the uncertainties in the mean sea-ice thickness distribution, which turned out to be a major source of uncertainty in the freshwater flux estimates. A largely unknown source of uncertainty remains the trend in sea-ice thickness, which purely originates from the reanalysis product in our estimates. Due to the non-linearity between the different variables in our calculations, it is difficult to attribute a specific fraction of the freshwater flux trend to the sea-ice thickness trend. However, a sensitivity test with a mean sea-ice thickness distribution revealed that the freshwater flux trends mostly arise from the trends in sea-ice drift. The sea-ice drift is a variable that could be estimated robustly in principle, given that these data can be derived from the long-term passive microwave satellite data. The major challenge for sea-ice drift data that we identified in our study presented in chapter 2 are the algorithms used to derive the sea-ice drift and the consistency between data from different satellite platforms. Therefore, such data sets must be handled with great care and the temporal inhomogeneities incorporate another major source of uncertainty when deriving long-term trends in sea-ice freshwater fluxes. At the same time, there is a large potential to substantially reduce uncertainties from sea-ice drift data by developing new algorithms, by adapting the algorithm parameters, time-steps, and resolution to the underlying data, and by treating consistent sensors and frequencies separately. The overall uncertainties in the sea-ice freshwater flux trends are as large as 40% to 50% in the spatially integrated fluxes and substantially larger on a grid box scale. In combination with an even larger uncertainty in the ocean salinity trends (P. Durack, personal communication), it is impossible to directly attribute a specific fraction of the freshening trend to the sea-ice freshwater fluxes. However, their spatial pattern and the order of magnitude of the trends agrees well.

Multiple limitations are associated with the simulated ocean response presented in chapters 4 and 5. Among these limitations are large persisting biases in the simulated temperature and salinity fields in the subsurface and in the coastal ocean around the Antarctic continent, which reside in the model despite major advances in the model developments. In the coastal ocean, the model has a too stable surface density stratification, which limits the mixing of waters on the continental shelf and reduces the subduction of AABW. This problem is most likely related to the brine plume parameterization, since it is less severe if the paramerization is switched off. However, if this parameterization was switched off, the representation of the open-ocean surface waters would be unrealistic because spurious, deep open-ocean convection destroys the water-mass structure. Therefore, we decided to use such a parameterization in these simulations with the downside of not being able to reliably assess the coastal ocean and AABW response. The brine plume parameterization would become obsolete if sufficient surface mixing occurred in the model, which is the main source of this issue. A second reason for the too stable surface ocean in the coastal region and the subsurface warm bias in the model is the prescribed surface heat flux from ERA-Interim, which underestimates the heat loss to the atmosphere in the high latitudes and therefore leads to a build up of the heat in the deep ocean. A third issue is the too salty and too shallow AAIW core and a too fresh surface ocean in the mean state. This issue might also be directly related to the insufficient surface mixing by the model. All three issues in the model might lead to a too high sensitivity to stratification changes and therefore an overestimation of the inferred surface temperature and carbon flux response. Hence, we have less confidence in the absolute magnitude of the response. Despite the biases, the model is able to generally reproduce the characteristic water-mass structure in the surface ocean of the upwelling region and spatial and temporal evolution of surface mixing processes, which indicates that it is able to reproduce the underlying upwelling mechanisms. The agreement of spatial patterns of the model response with the observed spatial pattern of trends provides further confidence that the simulated response provides valuable insights.

Another limitation in our simulations results from a too coarse resolution of the experiments to fully resolve meso-scale instabilities, which was applied due to constraints in the computation time. A consequence of this too coarse resolution is a too strong meridional overturning circulation in the mean state and a probably too sensitive response to changes in the surface wind stress. Moreover, it is very likely that the model underestimates the lateral dissipation of signals in temperature and salinity or other tracers due to the underrepresented lateral mixing by eddies. This issue is counteracted by the models resolution-dependent hyper-diffusion in the advection scheme. However, at the current state, it is not clear how large and how realistic the compensation from this lateral mixing process is. A fully eddy-resolving simulation will elucidate in the future how large the effects of resolution on the simulated responses are.

Finally, several limitations result from the experimental design of the model experiments. We perturbed the model with an instantaneous change in the forcing rather than imposing the real trend that gradually changes over time. This procedure is certainly a strong simplification and potentially leads to an overestimation of the magnitude of the response. However, it clearly illustrates the sensitivity of the model to changes in freshwater flux forcing relative to changes in the surface wind stress. Additionally, non-linearities between the variables could arise that might influence the response to a certain degree. Moreover, we did not perform any experiments related to changes in the surface heat flux or changes in the atmospheric pCO_2. Accounting for changes in the surface heat flux would potentially amplify the cooling around the sea-ice edge due to the ice-albedo feedback related with the expanding sea ice and amplify the warming of the lower latitude surface ocean, AAIW, and SAMW due to an increased uptake of anthropogenic heat. Similarly, the carbon sink would strengthen simply due to the increase in anthropogenic CO_2 in the atmosphere. A number of additional simulations could further clarify the relative magnitude of these changes compared to the changes in surface freshwater fluxes.

6.3 Implications

Throughout this thesis, I analyzed recent changes that are constraint by observational data and therefore provide a better ground to comprehend the important processes in the Southern Ocean, rather than past and potential future changes that can only be inferred from model and proxy data. However, my findings summarized in section 6.1 have direct implications for past and future changes that I will outline in this section.

My results suggest that an increased northward transport of sea ice makes the lower ocean circulation cell more salty and the upper circulation cell fresher. Thereby it strengthens the Southern Ocean halocline and the deep to surface ocean density gradient. In the long-term, this process decouples the deep ocean from the surface ocean and limits the exchange of waters between the two circulation cells. The upper circulation cell shoals and draws water from shallower depths. Therefore, less of the warm and carbon-rich deep waters enter the surface layer in the region between the sea-ice edge and the Subantarctic Front, which reduces the CO_2 and heat release to the atmosphere from these surface waters in the upwelling region and increases the net annual uptake of carbon. The deep waters that no longer upwell into the upper circulation cell probably enter the lower circulation instead through mixing between the dense shelf waters and CDW, essentially enhancing the volume and age of bottom water and the storage of carbon in the deep ocean. Ultimately, such a process could alter the long-term balance between the amount of carbon stored in the upper circulation cell and therefore the atmosphere, and the amount of carbon stored in the deep ocean.

The above interpretations are based on the most recent observed changes in the sea-ice freshwater fluxes that show an expansion of the sea ice and an increased northward transport. However, it is not yet clear whether these changes are a response to anthropogenic changes in the climate system or whether they are due to multi-decadal natural variability. If they were due to the anthropogenic forcing, one would expect that the current changes are a transient response due to an adjustment of the atmospheric circulation to changes in meridional temperature gradients (Haumann et al., 2014), and that the changes would reverse in future once the sea-ice region starts to warm and the sea ice starts to retreat as suggested by global climate model simulations. In any case, the current trends most likely reflect a cold phase of the high-latitude Southern Ocean with expanding sea ice. Therefore, this situation, rather reflects a cold glacial climate during which the sea ice extended to lower latitudes and sea-surface temperatures were colder (Gersonde et al., 2005; Wolff et al., 2006; Roche et al., 2012; Benz et al., 2016; Xiao et al., 2016), even though the current changes are probably less extreme. A critical difference between the present situation and the situation in a glacial climate might be the process that expands the sea-ice cover. The current increase is driven by increasing southerly winds that transport more freshwater towards the sea-ice edge and probably increase the coastal divergence, which leads to a stronger sea-ice formation. In a glacial climate, sea-ice formation is potentially enhanced by colder surface temperatures. Nevertheless, one would still expect an increasing northward freshwater transport since thicker ice would be transported northward. At the same time, an increasing sea-ice formation could strengthen the halocline even without an increasing northward transport, because the seasonal freezing and melting redistributes the salt vertically in the water column by mixing the salty winter-time waters deeper down than the fresher summer-time waters.

In contrast to many other mechanisms that have been suggested to cause the glacial–interglacial variations in the atmospheric CO_2 concentration, physical changes in the vertical exchange of water in the Southern Ocean have been identified to be consistent with proxy data (Toggweiler, 1999; Fischer et al., 2010; Sigman et al., 2010). Proxy data reveals a reduced export production (Jaccard et al., 2013) and a more complete nutrient utilization (Francois et al., 1997; Anderson et al., 2009) in the upwelling region during glacial states and an increased age of the deep waters around Antarctica derived from radiocarbon data (Skinner et al., 2010). All these data suggest a reduction in upwelling of deep carbon- and nutrient-rich waters to the surface. At the same time, δ^{13}C data suggest an enhanced volume of the lower circulation cell and a shoaling of the upper cell (Curry and Oppo, 2005; Lynch-Stieglitz et al., 2007). This change in ocean circulation is accompanied by a much saltier AABW in a glacial climate as inferred from pore water in sediment cores (Adkins et al., 2002), suggesting a major change surface freshwater balance. Today, AABW formation is mostly driven by cooling on the continental shelf as the freshwater fluxes in the coastal ocean balance and is enhanced by mixing with CDW. An enhanced glacial sea-ice formation and a reduced freshwater input from the Antarctic continent and the atmosphere could considerably shift the freshwater balance in the coastal ocean towards a higher salinity and therefore a salinity- rather than a temperature-driven AABW formation. Such a shift of the AABW formation mechanism towards a sea-ice brine-driven formation is also supported by the δ^{18}O data analyzed by Adkins et al. (2002).

The results that I presented in this thesis imply that glacial salinity, stratification, and circulation changes could be induced by increased sea-ice freshwater fluxes, which redistribute salt between the lower circulation cell and the upper circulation cell. Such a process would be very appealing since Antarctic sea-ice formation and extent are directly related to the Antarctic surface temperature that shows a striking correlation to the atmospheric CO_2 concentration (Petit et al., 1999; EPICA community members et al., 2004; Jouzel et al., 2007; Parrenin et al., 2013, see section 1.1.2;). Several mechanisms that involve either sea-ice or other buoyancy fluxes have been suggested by a number of studies (Gildor and Tziperman, 2000; Watson and Naveira Garabato, 2006; Bouttes et al., 2010, 2012; Ferrari et al., 2014; Sun et al., 2016), but none of them considers the addition of freshwater to the upwelling region from melting sea-ice as the process that drives the increasing stratification, except for the review by Fischer et al. (2010), who argue that such a mechanism could play a critical role. While sea-ice-driven changes in ocean stratification provide a hypothetical explanation for glacial-interglacial changes in the carbon cycle that seems consistent with proxy data, it remains unclear how much such an effect would contribute to the overall change in the atmospheric CO_2 concentration of 80 to 100 ppm.

The opposite effect to this hypothetical glacial situation could be expected for a warming Southern Ocean, such as during the deglaciation or a potential future climate. A retreat of the sea-ice edge and the northward transport would potentially degrade the halocline in the upwelling region giving rise to either facilitated upwelling from deeper levels or even convective instabilities during winter-time when the temperature stratification becomes statically unstable and overwhelms the stable salinity stratification. Since the subsurface waters are typically warmer the sea ice would retreat even faster, inducing a positive feedback that effectively lifts the carbon stored in the deep ocean to the surface. While this process could have led to a rapid release of CO_2 during the deglaciation, possible future implications are more complex. One aspect is that as soon as the atmospheric pCO_2 reaches a level above the pCO_2 of the deep waters, any additional upwelling would not lead to an additional release of natural CO_2 (Matear and Lenton, 2008). However, the higher CO_2 concentration of the upwelling waters from deeper levels would saturate the uptake of anthropogenic CO_2, similar to the mechanism suggested by Le Quéré et al. (2007) but induced by a weaker halocline. Therefore, decreasing sea-ice freshwater fluxes could substantial amplify global warming due to a reduced uptake of anthropogenic CO_2 and heat. These possible effects only concern the changes sea ice, but other processes like an increasing atmospheric freshwater flux (Liu and Curry, 2010; Knutti and Sedláček, 2013) and an increasing warming would stabilize the Southern Ocean surface waters (Manabe and Stouffer, 1993; Sarmiento et al., 1998). However, most of this stabilization would occur in lower latitudes, which limits the CO_2 subduction (Caldeira and Duffy, 2000) rather than its upwelling. In higher latitudes, temperature stratification during winter would still remain unstable, despite global warming, and increasing atmospheric and land ice fluxes will be critical to compensate for a sea-ice retreat in the upwelling region. Several recent studies suggested massive changes in the future land-ice flux (Golledge et al., 2015; Ritz et al., 2015; DeConto and Pollard, 2016) and their effects on the future ocean stratification in the upwelling region are to-date very uncertain (Fogwill et al., 2015). In summary, future changes in Southern Ocean stratification remain highly uncertain and incorporate a substantial risk for positive feedbacks on global warming.

6.4 Outlook & suggestions for further research

Our findings and their limitations and implications raise numerous questions that should be addressed in future research. Among the obvious issues to address is to further reduce the model biases. This goal could be achieved by further improving the model's vertical mixing scheme. However, one should note that the mixing problems that identified in this thesis are not unique to our model but apply to most existing numerical ocean models. Therefore, a general advance in the numerical representation of the strongly stabilizing summer-time surface boundary layer in the Southern Ocean should have high priority and has a high potential to reduce uncertainties in global model simulations. One of the suggestions is to account for the temporal decay of deep mixing events under stabilizing conditions, which occurs in reality due to inertial shear. Specific to the Southern Ocean ROMS setup, an advance in the treatment of the surface heat flux and a bias correction of the ERA-Interim surface heat flux would be desirable. Further improvements in the model would result from repeating the simulations at an eddy-resolving resolution of 0.1°. At last, running additional experiments in which also the heat flux and the atmospheric pCO_2 is perturbed and in which combined perturbations are applied might explain some of the discrepancies between the changes in our experiments and the observed changes. The latter suggestion might also be realized by running a hind-cast simulation with a temporally varying forcing field.

The substantial increase in data that is currently collected in the Southern Ocean will considerably reduce some of the large uncertainties in the surface freshwater fluxes and ocean salinity. Among these advances are new satellite platforms for continuous monitoring of sea-surface salinity (e.g. Gordon, 2016) and sea-ice thickness (e.g. Schwegmann et al., 2016) in time and space. At the same time, further improvements of existing algorithms that are used to derive sea-ice drift and sea-ice thickness from existing satellite data are urgently required to obtain more consistent and therefore more reliable time-series. The availability of subsurface physical and biogeochemical data will also considerably increase by the deployment of Argo floats in the Southern Ocean that are by now also able to collect data under sea ice (e.g. Riser et al., 2016). A further opportunity to better constrain the surface freshwater fluxes and their distribution in the ocean arises from the unique isotopic signature that can be derived from oxygen isotopes and ocean salinity (e.g. Jacobs et al., 2002; Meredith et al., 2013). A large number of seawater oxygen isotope data exist already in the Southern Ocean but not all are yet compiled in the global data base (Schmidt et al., 1999). Together with a large number of data collected during the Antarctic Circumnavigate Expedition, new constraints on the surface freshwater fluxes will emerge (Leonard et al., 2016). A more complete picture of the oxygen isotopic composition in the modern Southern Ocean could also help to gain insights into the shifts between the present day surface freshwater budget and the one of past glacial climates (e.g. Adkins et al., 2002). All these new data sets will provide fantastic opportunities to improve our understanding and monitoring of the Southern Ocean surface freshwater fluxes and the surface stratification.

In this thesis, I mostly focused on the physical response of temperature, salinity, stratification, and circulation, as well as the air–sea CO_2 flux. However, changing surface freshwater fluxes will also affect the heat uptake by the Southern Ocean or the upwelling of nutrients. The response of the ocean heat uptake is most likely rather complex. In our current model setup it is not possible to study changes in the heat uptake since the surface heat flux is prescribed and cannot adjust to changes in the surface ocean conditions. However, the cooling response suggest that both the sensible and the outgoing longwave radiative flux to the atmosphere would decrease in the high-latitudes. In lower latitudes, where the atmosphere becomes warmer than the surface ocean, the cooling of the surface ocean would result in an increased heat uptake. All these considerations would suggest an increased net heat uptake by the Southern Ocean in response to the increased stratification. Since most of the excess anthropogenic heat has been taken up by the Southern Ocean, this issue requires further investigation in future studies. Similar to the heat and the carbon, less nutrients would upwell to the surface ocean in response to an increasing stratification with potential consequences for the ecosystem. While less nutrients would be available for biological production, the increased stratification could still enhance biological production in the Southern Ocean because it reduces the light-limitation and the production is not nutrient limited (Eveleth et al., 2017). In the long-term, changes in Southern Ocean stratification could critically affect the global biological productivity because it depends on the return of nutrients to the surface ocean in the Southern Ocean (Marinov et al., 2006). Therefore, numerous open questions exist in terms of the ecosystem response, which might be sensitive to the processes reported in this thesis.

A pressing question that arises from the results presented in this thesis is why many of the observed changes are not reproduced in the historical simulations with global climate models. These model simulations suggest that a sea-ice retreat, a surface ocean warming, and a much weaker surface freshening occurred over recent decades. I propose that four potential explanations exist for this discrepancy that require further investigation. Firstly, the freshwater redistribution by sea ice in many global models is most likely poorly represented due to difficulties in the accurate representation of the sea-ice dynamics and atmospheric circulation over the sea-ice region (Haumann et al., 2014; Uotila et al., 2014; Lecomte et al., 2016). This issue could considerably affect the representation of the surface ocean density stratification in the models and could therefore explain some of the large biases in their water-mass structure. Secondly, global models might be too sensitive to changes in the surface wind stress that drives most of the response in these simulations, which might outweigh changes from surface freshwater fluxes. Thirdly, the issues in the mixing scheme that I identified in ROMS might also be present in several global models and could lead to model biases that affect their Southern Ocean response to climatic changes. Finally, it is still unclear whether the observed changes over recent decades are a response to the anthropogenic forcing or simply an expression of multi-decadal variability. While several of these issues might explain the discrepancies between some of the observed and simulated changes in the Southern Ocean, they might at the same time be a core reason for the large spread of the historical Southern

Ocean heat and CO_2 uptake in these simulations (Frölicher et al., 2015) and their inconsistency with proxy data of past changes (Sigman et al., 2004; Otto-Bliesner et al., 2007; Roche et al., 2012; Rojas, 2013).

If the current response of the models to changes in the sea-ice freshwater fluxes was underestimated, one would expect that also their response to future and past climatic changes in this process is not accurate. In order to test how reliable Southern Ocean stratification changes in global models are, I suggest to assess their surface freshwater budget in detail and use the currently available observational data to develop constraints that might reduce the uncertainties in their future projections. Additionally, one could replace sea-ice freshwater fluxes in a coupled global model with the observed fluxes to further investigate the current changes, but also the past and future changes by imposing idealized perturbations on the prescribed freshwater flux that resemble potential future or past climates as outlined in section 6.3. Further extending such experiments by additionally perturbing the glacial or atmospheric freshwater fluxes could provide valuable insights into the drivers of glacial–interglacial changes in the climate system and into the risks that are associated with future changes in the Southern Ocean density stratification.