We would like to thank our two referees for their helpful comments and suggestions. We appreciate the time and effort that went into their review of our article and hope our explanations and actions taken upon their comments will satisfy the expectations of referees and editor.

Answers to Roger Stevens' comments:

GENERAL COMMENTS

Numerical models are the ideal tool for undertaking experiments on complex natural systems when attempting to understand the mechanics of the system and how it might change into the future. This paper presents the results of a set of numerical model experiments on one of Earth's major state changes, i.e. the freezing in autumn and winter of the Southern Ocean adjacent to the Antarctic Continent. What is more, Southern Ocean sea ice is baffling in that its extent has been increasing even as global air temperatures have increased. This paper investigates how much of the expansion of sea ice extent is caused by increased freshwater runoff from the Continent. The paper is therefore of interest not only for scientific reasons but also because of the politics surrounding global warming and this "poster child" for climate change sceptics. The paper is well written and easy to understand. The investigation into how the spatial distribution of fresh water input changes sea ice is interesting. That there could exist a maximum freshwater input for sea ice extent increase (and above which extent decreases) is also an interesting result.

SPECIFIC COMMENTS

I think the experimental method is reasonable and the choice of NEMO/LIM is a good one. My major question relates to the authors' choice of LIM version 2 rather than version 3. I realize that LIM2 is favoured by ocean modellers because it is more economical on computer time but this research is focusing on sea ice (and the waters that interact with it) rather than the ocean generally. In this application LIM version 3 seems to offer some advantages over the earlier version. The most important of these is accounting for ice rafting and also frazil ice growth. Both of these processes are important for Southern Ocean sea ice (and less so for Arctic Ocean sea ice). The paper reports that one of the consequences of increased runoff is thinner, more mobile ice. Rafting is common, possibly ubiquitous, in thin Southern Ocean sea ice (Worby et al, 2008) and can occur in relatively mild convergent conditions compared to those encountered by sea ice impacting land, ice shelves, or land-fast ice. The results show that the most thickening of ice from ridging occurs in highly convergent regions, e.g. western Ross Sea. It is possible that the model underestimates dynamic ice thickening in other regions because of the lack of rafting in LIM2. It may have been interesting to run a simulation where increased freshwater is added to all the Southern Ocean, i.e. approximating increased precipitation. This would isolate the thermodynamic contribution of increased freshwater to the ice extent increase. However, I realize that these suggestions would require re-running the model and so are not feasible. It would be desirable to explain why LIM2 was preferred to LIM3. The simulated winter ice concentration is higher than that of satellite observations as seen in the supplementary material. The model will report high ice concentration of very thin ice while the passive microwave observations will have problems distinguishing very thin ice from open water. However, thin ice also melts more quickly in spring and summer so I am not sure that the authors' argument is correct, i.e. that the higher winter ice concentration in the simulation accounts for the larger spring/early summer sea ice extent that the model produces. Extent includes open water south of the ice edge so maybe total ice area would give a better comparison? Using total ice area has its own problems of course. Also in the supplementary material the authors state that the quarter degree resolution is sufficient to capture most of the important aspects of atmosphere, ocean and thus the sea ice. I would agree with them in most respects but I wonder if they looked at how well the atmospheric forcing captured the katabatic winds which are so important for the formation of latent heat polynyas and therefore bottom water production?

We agree with the referee that a more sophisticated sea ice model might have been more suitable for a model study focused on sea ice properties and their variability. We do also agree that the new features of LIM3 sea ice model might make it a better choice than LIM2, to a great extent. More than based on computational cost, our decision to remain on the “old” but well-tested LIM2 was motivated by the state of the LIM3 code at the time we started the research project that includes the simulations presented here (second half of 2014). Our modelling group at CMCC, as part of the NEMO system team, was aware of weaknesses of the LIM3 code available since 2009 (Vancoppenolle et al. 2009a,b) that might have a large impact on the Southern Ocean sea ice and water masses (as salt rejection during ice formation). The group closely followed the evolution of the new LIM code toward the updated version by Rousset et al. 2015. This new code has been released in July 2015, integrated into the most-recent stable version of NEMO (version 3.6). Tests, tuning and then analysis of the LIM3 performances in comparison to LIM2 have been conducted, starting from the coarse 1-degree global configuration (see Uotila et al., in review) and, only later, for the eddy-permitting configuration.
Following the development of the NEMO code, we do plan to continue our modeling study of the Antarctic sea ice and runoff effect using the more complete NEMO3.6 which includes the new LIM3 sea ice model, but also modules for iceberg and ice shelf cavities.

Rousset C., M. Vancoppenolle, G. Madec, T. Fichefet, S. Flavoni, A. Barthélemy, R. Benshila, J. Chanut, C. Levy, S. Masson, and F. Vivier: The Louvain-La-Neuve sea ice model LIM3.6: global and regional capabilities. Geosci. Model Dev., 8, 2991–3005, 2015. doi:10.5194/gmd-8-2991-2015

Uotila, P., Iovino, D., Vancoppenolle, M., Lensu, M., and Rousset, C.: On the influence of sea-ice physics in multi-decadal ocean-ice hindcasts, Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-187, in review, 2016.

Vancoppenolle, M., Fichefet, T., Goosse, H., Bouillon, S., Madec, G., and Maqueda, M. A.: Simulating the mass balance and salinity of Arctic and Antarctic sea ice: I. Model description and validation, Ocean Model., 27, 33–53, 2009a.

Vancoppenolle, M., Fichefet, T., and Goosse, H.: Simulating the mass balance and salinity of Arctic and Antarctic sea ice: II. Sensitivity to salinity processes, Ocean Model., 27, 54–69, 2009b

TECHNICAL CORRECTIONS Poor grammar in places, e.g. page 8 lines 1: “In the central and eastern Weddell Sea, the fresh water addition causes the ice to thickened thermodynamically in S3.” I think that “thickened” should be either “thicken” or “be thickened”.

We apologize for the mistakes. We carefully checked the text and hope to have corrected and eliminated all typographical and grammatical errors.

Answers to Anonymous Referee #2's comments :

This paper examines the model response of sea ice to the supply of additional freshwater at the surface of the ocean around Antarctica. The model used is NEMO, forced by global atmospheric reanalysis data with LIM2 sea ice model. Five scenarios are examined and compared with a control run. The scenarios include cases where the fresh water “runoff” is distributed uniformly around the coast of Antarctica, and others with regional maxima that approximately coincide with major ice shelves. In a third category the runoff is applied offshore, to mimic iceberg drift. The total magnitude of the runoff also differs between most of the simulations. The authors conclude that fresh water input increases sea ice extent and volume, up to a “turning point” value whereupon the sea ice trend is inverted. They also find that their experiments are sensitive to the distribution of fresh water runoff at the ocean surface. The paper is well written and readable and makes a useful contribution. One of the more interesting aspects of this paper is that the authors segregate the response of the sea ice into a thermodynamic and a dynamic components. I congratulate the authors on this part of their discussion.

MAIN COMMENTS

1. This is a topic of current interest, as evidenced by the fact that at least two highly relevant papers have appeared in the literature in the time that this article has been in process. Some details of the present paper need to acknowledge the publication of these two studies. They are

Merino, N. J. Le Sommer, G. Durand, N. Jourdain, G. Madec, P. Matthiot and J. Tournadre, (2016) Antarctic icebergs melt over the Southern Ocean: climatology and impact on sea-ice. Ocean Modelling, 104, 99-110, doi:10.1016/j.ocemod.2016.05.001

Pauling, A.G., C. M. Bitz, I. J. Smith, and P. J. Langhorne, (2016) The response of the Southern Ocean and Antarctic sea ice to fresh water from ice shelves in an Earth System Model. J. Climate, 29, 1655–1672. doi: http://dx.doi.org/10.1175/JCLI-D-15- 0501.1

We thank the referee for suggesting these new publications. We added the mentioned articles to the list of previous studies. Section 1. includes now the following text: “*Merino et al. (2016) used an iceberg model coupled to a sea ice-ocean model to establish a seasonal climatology of iceberg melt for the Southern Ocean and find that the iceberg melt water leads to higher sea ice concentration and thickness, with exception of the Amundsen/Bellingshausen Sea area. Pauling et al. (2016) employed an Earth-system model to investigate the Southern Ocean sea ice response to artificially augmented freshwater input. They tested the sensibility to higher freshwater additions than current estimates and previous studies and compare an iceberg model-based surface distribution with a coastal distribution at depth. They conclude that the effect of the different distributions on the mixed layer depth is contrary but the sea ice response is similar in both cases.*”

2. An interesting aspect is the hypothesis that a large amount of freshwater will reduce the sea ice. I am not sure I understand why this is the case. In addition, as the conclusion is based on one experiment, and as I could not see a clear pattern in the qualitative behaviour of the system with increasing freshwater flux, my opinion is that the authors need to work a little harder to be convincing.

We agree with the referee that the “turning point” conclusion based on only one experiment might be not solid enough. Therefore, we refrain from any statements presenting turning point as a fact. However, we find the results from that experiment very interesting and contrary to our expectations. This prompts us to show our findings and suggest a possible interpretation of them with the due caution.

As to the question why there may be a turning point, we offer a possible explanation at the end of

Section 3.2 p.10, which we have adapted after reconsidering the involved processes: "*During autumn the sea ice production of S5 surpasses that of S2, since the lower surface salinity facilitates ice formation. However, during winter and spring S2 features higher ice production values, because the influence of the offshore areas, particularly the northeastern Weddell and Ross Seas, becomes dominant. As a possible underlying mechanism, we suggest that the increased velocity is not limited to the coastal current but spreads to the subpolar gyres. A stronger circulation in a cyclonic gyre causes increased upwelling in the gyre's center due to the increased Ekman transport at the surface. In the Weddell and Ross Seas, this would cause a local increase of surface temperatures and salinities (SSS). In S5, SST and especially SSS in the winter mean is higher than in S2 in the northeastern Weddell Sea and northeastern Ross Sea (figures of the SST and SSS difference between experiments S2 and S5 are provided as Supplement S2). In consequence ice production is reduced and ice melt furthered. A reduced sea ice cover, especially in the regions close to the winter ice edge, leads to a higher heat uptake from solar radiation during the summer, triggering a positive feedback loop (Stammerjohn et al., 2012).*
*Additionaly, there is a second way, the increased speed of the coastal ice drift can contribute to the difference in sea ice volume and extent between S2 and S5: it shortens the period of time available for thermal growth and it can strengthen the mechanical processes thickening the ice in areas of convergence. Depending on the regional geometry and the ice drift pattern, either the thermodynamic or the dynamic effect on the sea ice thickness prevails and leads to thinner or thicker sea ice, respectively. While in WRoS, the sea ice in S5 is thicker than in S2 due to compression against the shoreline, the thermodynamic effect is of greater influence in WWeS, where large areas feature thinner ice in S5 (Figure 2h and q).*"
And summarize again in the Conclusions (Section 5):"*Based on this we think it probable that a turning point in the sea ice response to freshwater forcing exists and offer the following mechanism as a possible explanation: The coastal freshwater input changes the SSH slope and increases not only the velocities in the coastal current, but also of the subpolar gyres. Due to the increased Ekman transport more warm and saline water wells up in the gyres' centres., SST (and SSS) will increase and lead to enhanced melting of the northward advected sea ice and reduced local ice production during autumn and winter. The reduced sea ice cover allows higher shortwave radiation absorption by the ocean and triggers a positive feedback loop. Also, the freshwater-induced acceleration of the coastal current leads to thinner sea ice, when the time available for thermodynamical growth is reduced strongly. This is especially relevant for the Weddell Sea, while in the western Ross Sea all performed experiments result in dynamically thickened sea ice.*"

3. In relation to this, please can you explain why the simulations of sea ice are considered to represent sea ice behaviour, while the simulation period of 10 years is too short for the water characteristics to reach equilibrium (see e.g. p. 2, line 28-33). Are you saying that you are investigating sea ice response processes and therefore do not need to reach equilibrium? If this is the case, I am not sure I understand how you may conclude that there is a reversal of behaviour when more than a certain amount of fresh water (undetermined from these experiments) is added to the system. How can you tell that this is not due to variability between runs? This may require more explanation of the known behaviour of the model. The existence of a turning point based on evidence of a single simulation requires additional argument for its existence.
The response times of ocean surface and deeper layers of the ocean to changes from the surface differ strongly. We are confident that the surface and the sea ice reaches near-equilibrium state within a fraction of the simulation period. We consider especially the differences between experiments to be reliable and due to the differences in runoff input since they present the only source of variability

between the runs. For these two reasons, we think the results trustworthy, although the ocean at depth is not in an equilibrium state.
With the complexity of today's ocean models and the short run period of our experiments it is possible that the difference we see between experiments S2 and S5 does not proof a turning point, however to the authors of this article the proposed explanation seems the most probable. The suggestion is not based on the result of one experiment, but on the difference we observe between two experiments. However, we agree with the referee that before stating the existence of this turning point as a fact further investigation is needed. We slightly altered the wording to enhance the speculative character of our suggestions.

4. How was the seasonal variation in ice shelf "runoff" decided (see Fig 1e)?
There is not much known about the seasonality of Antarctic runoff. However seasonality can be expected for both, iceberg meltwater and basal melting. In the first case the seasonality is strong (e.g. Merino et al., 2016) since the ocean surface heats up in summer. In the latter case uncertainties are large, but in winter the dense water formation in coastal polynyas inhibits warm water intrusions under the ice shelves and therefore a higher heat flux into the cavities can be expected during the summer. The runoff in our reference run is obtained from the DRAKKAR group (Bourdalle-Badie and Treguier 2006), who adapted the figures given by Dai and Trenberth (2002) and Jacobs et al. (1992) for the ORCA025 grid.

5. Development in time and variability on p. 9: How much is know about variability between model runs when there has not been a repeat of an experiment? Perhaps this is well known for the model and could be briefly explained to the reader.
The model variability is low and a repeat of any experiment is expected to give the same results, since the runtime of only ten years does not give the small numerical errors the time to grow into variability of any significance.

6. Comments 2-5 lead me to be unconvinced by the authors' conclusion that (the small) freshwater input they apply causes the sea ice to expand, while a larger input inverts the trend. This needs to be very carefully re-evaluated.
We agree that the presented experiments do not proof the existence of a turning point in the sea ice response. However, we are of the opinion that they strongly suggest such a behaviour. The differences in output between our experiment S2 and S5 are not random, but the result of the differences in the model input. We checked our wording to avoid misrepresentation of the turning point as a hard fact.

TECHNICAL COMMENTS
p. 2, line 9-10: Merino et al and Pauling et al (2016) need to be added to the previous studies.
We added Merino et al. (2016) and Pauling et al. (2016) to the previous studies. We added the following text in Section 1: "*Merino et al. (2016) used an iceberg model coupled to a sea ice-ocean model to establish a seasonal climatology of iceberg melt for the Southern Ocean and find that the iceberg melt water leads to higher sea ice concentration and thickness, with exception of the Amundsen/Bellingshausen Sea area. Pauling et al. (2016) employed an Earth-system model to investigate the Southern Ocean sea ice response to artificially augmented, constant freshwater input. They tested the sensibility to higher freshwater additions than current estimates and previous studies and compare an iceberg model-based surface distribution with a coastal distribution at depth. They conclude that the effect of the different distributions on the mixed layer depth is contrary but the sea ice*

*response is similar in both cases.*"

We added the following passages to section 3.3: " *increase in Antarctic runoff leads to an increase in sea ice in accordance with e.g. Bintanja et al. (2013), Bintanja et al. (2015) and Pauling et al. (2016).*"

"*While Pauling et al. (2016) with even higher amounts of fresh water addition did not conclude the existence of a turning point, their experiment with the highest amount of fresh water yields the lowest seasonal linear trends for the sea ice, while the lowest fresh water amount in summer and winter yields the least negative and in autumn even a positive trend (their Figure 11).* "

"*In particular, as also Merino et al. (2016) found, considering an idealized freshwater discharge from icebergs strongly impacts sea ice thickness*"

"*Pauling et al. (2016) recently found the depth distribution of additional fresh water in the Southern Ocean to be of small effect on the sea ice.*"

p. 2, line 24-25: Note that Pauling et al (2016) have added fresh water spatially distributed according to ice shelves, and at the depth of the ice shelf. However their simulations did not vary in magnitude through the year.

Mentioned in the newly added text (see answer above).

p. 2, line 28-33: (as main comment) Please can you explain why the simulations of sea ice are considered to represent sea ice behaviour, while the simulation period of 10 years is too short for the water characteristics to reach equilibrium. Are you saying that you are investigating sea ice response processes and therefore do not need to reach equilibrium? If this is the case, I am not sure I understand how you may conclude that there is a reversal of behaviour when more than a certain amount of fresh water (undetermined from these experiments) is added to the system. How can you tell that this is not due to variability between runs? This may require more explanation of the known behaviour of the model. The existence of a turning point based on evidence of a single simulation requires additional argument for its existence.

Answered above (Main comments #2 and #3)

p. 4, line 5-6: Was Dai and Trenberth (2002) applied in all other parts of the globe, apart from Antarctica? Was the seasonal variation used (see Fig 1a – actually I think it is 1e) from Dai and Trenberth (2002)? If so how do you justify using the seasonal behaviour for river runoff to represent melting ice shelves?

The runoff data in the reference run is obtained from the DRAKKAR group (Bourdalle-Badie and Treguier, 2006) and is based on Dai and Trenberth (2002) for all the globe except Antarctica, where it relies on Jacobs et. al. (1992). The seasonal cycle of the Antarctic runoff was introduced by the DRAKKAR group. To more clearly explain this, we changed the description in the article to: "*The river run-off data is a monthly climatology based on the studies of Dai and Trenberth (2002) and Jacobs et al. (1992) and adapted for the ORCA025 grid by the DRAKKAR group (Bourdalle-Badie and Treguier, 2006).*" and added the references.

The melt of the Antarctic glacial ice in the Southern ocean is primarily dependent on the water temperature. For the basal melt of the ice shelves the main question is therefore how much warm water can intrude onto the continental shelves. In winter, deep convection linked to polynya activity hinders the warm water intrusions and thus higher melt rates can be expected in the summer months. Also for iceberg melt the seasonal dependence is strong due to the surface warming (Merino et al., 2016). We admit that there is limited knowledge of the seasonal cycle of the Antarctic 'runoff'. The runoff in our study therefore may not be correct in amplitude or shape, but some seasonal variation of the meltwater may be expected.

p. 4: Table 1 is very useful but has not been referred to in the text. It would be useful to refer to it in section 2.2.
A reference was added in the text p.4, l. 16. "*A short overview over the experiments and their differences is also given in Table 1*."

p. 4, lines 12-33: I think that the subfigures of Fig. 1 have been mislabeled.
Yes, we apologize for the mix-up. The mistake is now corrected.

p. 4-5: Experiment design – please note that Merino et al (2016) and Pauling et al (2016) both conduct experiments with fresh water distributed to mimic iceberg melt.
In this section, we describe only our own experiments. However, both mentioned studies are now added with mention of the iceberg model-derived distribution in the introduction chapter.

p. 5, line 20 onwards: This is a very interesting discussion regarding the influence of additional fresh water at the surface on the SSH, the velocity and thus on sea ice thickness. I was confused about how changes in the direction of the velocity were taken into account? Does the right hand column of Fig 2 show speed not velocity?
The right hand column of Figure 2 shows the velocity differences as arrows underlaid by the difference in speed following the colour scale.

p. 5: Spatial Response Patterns: How can you have a high confidence interval in the difference when, at each time step, there are only two quantities? Is it time-averaged?
The confidence level was determined using the Student's t-test for dependent data samples. The 'sampling period' was limited to the 10*6 monthly means April-September 2004-2013.

Fig 2 is for the "winter" months. Which months are "winter"?
We do refer to 'winter' as the 6-month period from April to September as mentioned p. 5, l. 14. A short statement was added there to improve clarity. "*In the following, the word winter referring to a specific time period will mean the months April-September.*"

p. 6: line 9-10: Is a salinity-dependent freezing point coded in the model?
Yes, in the LIM2 sea ice model, the freezing temperature of seawater depends on salinity, linearly with an empirical constant.

p. 6, line 23 + p.7, lines 14, 27, 28, + p. 8, line 12, + p. 13 line 23: use of the word "acceleration" when I think you mean "faster speed"
Yes, not in all cases the words accelerated/acceleration were used in their proper sense. We corrected the phrasing where necessary.

p. 7, line 26: please mark Princess Martha Coast on a map.
Princess Martha Coast was marked on the map in Fig. 1b)

p. 8, line 10: please mark Filchner/Ronne Ice Shelf on a map
We consider the Filchner/Ronne Ice Shelf to be a well known feature of the Antarctic geography like e.g. the Ross Ice Shelf, Amundsen Sea and Antarctic Peninsula. We are afraid readers unfamiliar with the main features of the Antarctic geography will have to refer to a map from another source.

p. 9, line 10-12: Why are the larger amplitude anomalies in 2009-2011? Why are the anomalies smaller in 2012-2013?
We cannot answer this question completely. As mentioned in the article, regional time series show that the difference occurs in the Amundsen, Bellingshausen and western Weddell Seas. We therefore assume that the atmospheric circulation features a regional shift in those years that has a much stronger effect on the experiments with regionally varied runoff than on the experiments with uniform coastal runoff.

p. 10, line 9-15: We are not shown the surface salinity or the SST so it is difficult to follow this discussion. Could the essential elements be presented in a figure?
Figures of the difference in SSS and SST between runs S2 and S5 are added as Supplements S2. In the article that fact is now mentioned: "*(figures of the SST and SSS difference between experiments S2 and S5 are provided as Supplement S2)*".

p. 11, line 13 & line 16: I believe it is more appropriate to state as estimates 6 – 24% and 5 – 23% .
We agree and rounded the given percentages.

p. 13, line 23: Stammerjohn et al (2012) have shown that there is strong correspondence between anomalies in the timings of sea ice retreat and subsequent advance, and you may wish to refer to this paper. Stammerjohn, S., R. Massom, D. Rind, and D. Martinson (2012), Regions of rapid sea ice change: An inter-hemispheric seasonal comparison, Geophys. Res. Lett., 39, L06501, doi:10.1029/2012GL050874.
We thank the referee for the suggestion. The reference was added in the article: "*A reduced sea ice cover, especially in the regions close to the winter ice edge, leads to a higher heat uptake from solar radiation during the summer, triggering a positive feedback loop (Stammerjohn et al., 2012).* "

p. 13, line 23: Why would there be sea ice melt in winter? Is there evidence for this in the model runs?
If the SST is above the freezing point, sea ice melts. In the weakly stratified Southern Ocean heat can be transported to the surface with relative ease. In the Weddell Sea this has lead to the occurrence of the well-known Weddell polynya in the 1970s. Here, ice is advected northward into regions that still retain heat from the summer months. To improve understanding, the wording was changed. "*If the stratification of the offshore water column is increased, SST will increase during summer and lead to enhanced melting of the northward advected sea ice and reduced local ice production*."

p. 14, line 2: replace "lose density" with "density reduces"
The wording has been changed. "*the dense shelf waters become warmer, fresher and hence less dense.*"

p. 14, line 12-13: Some experiments have been done by Pauling et al (2016).
The study by Pauling et al. 2016 has been added in the Introduction chapter and the section 3.3.

Fig 1: I did not understand the caption at all. I also think that the sub-figures are mislabeled. Please give a key for regions 1-10 in a).
Yes, the subplots were mislabelled. The mistake was corrected. A key for the regions was added in the figure caption.

Fig 2: Do you mean speed rather than velocity? What months are represented? How is the t-test performed when it is the difference between only 2 quantities?
In the right hand column the colour scale refers to speed, while the arrows depict velocity. A short explanatory text was added to the caption. "*The colors underlaying the velocity arrows indicate speed.*" The 'winter' period in our article always refers to the months April-September. The t-test for dependent samples is performed on the time series of the two quantities. The 'sampling period' was limited to the 10*6 monthly means April-September 2004-2013.

Fig 3 b, d, f.: Are the large jumps in values between month 1 and month 12 expected?
They correspond to what is also visible in the time series in a), c), e) and are not beyond what is expected. The strong seasonal cycle of the runoff addition may play a role here and cause a stronger seasonal signal in the sea ice properties.

# Impacts of Antarctic runoff changes on the Southern Ocean sea ice in an eddy-permitting sea ice-ocean model

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**Abstract.** In a warming climate ~~climate~~, observations indicate that the sea ice extent around Antarctica has increased over the last decades. One of the suggested explanations is the stabilizing effect of increased mass loss of the Antarctic ice sheet. We investigated the sea ice response to changes in the amount and especially the spatial distribution of freshwater. We performed a sensitivity study by comparing a set of numerical simulations with additional supply of water at the Antarctic ocean surface. Here, we analyse the response of the sea ice cover and the on-shelf water column to variations in the amount and distribution of the prescribed surface freshwater flux.

Our results confirm that an increase in fresh water input can increase the sea ice extent. However, a very strong increase of freshwater will eventually invert the trend. Our experiments suggest that the spatial distribution of the freshwater is of great influence. It affects sea ice dynamics and can strongly alter regional sea ice concentration and thickness. For strong regional contrasts in the freshwater addition the local change in sea ice is dominated by the dynamic response, which generally opposes the thermodynamic response. Furthermore, we find that additional coastal runoff generally leads to fresher and warmer dense shelf waters. Comparing our results with the observed trend, we estimate that the current increase of fresh water originating from the Antarctic Ice Sheet contributes between 5% and 24% to the trend observed in the sea ice extent.

## 1 Introduction

In an environment of global warming, the sea ice extent in the Southern Ocean shows an increase in the satellite data collected since 1979. The positive circumpolar trend is the sum of partly opposing regional trends of the same order of magnitude (Parkinson and Cavalieri, 2012). Several mechanisms have been proposed to explain the expanding Antarctic sea ice. Many studies attribute the increase of sea ice to changes in the circumpolar wind field. The strengthening of the circumpolar westerly winds alters the sea ice drift patterns and could result in the regionally different trends observed in the sea ice cover (e. g. Thompson and Solomon, 2002; Liu et al., 2004; Lefebvre and Goosse, 2005; Turner et al., 2009). An increase of precipitation over the Southern Ocean has influence on surface salinity, albedo of ice covered areas and ice thickness by submersion and could also be a possible contributor to the observed increase in Antarctic sea ice extent (Liu and Curry, 2010).

Zhang (2007) and Goosse and Zunz (2014) suggested that the trends in the Antarctic sea ice extent could be explained as the result of a feedback between the sea ice and the upper ocean stratification. Also Bintanja et al. (2013) attributes the change in sea ice to a fresher surface layer, but sees the cause in an enhanced Antarctic ice sheet melting.

The mass loss of Antarctic ice sheets by basal melt has recently been found to be accelerating (Jacobs et al., 2011; Pritchard et al., 2012) leading to the freshening of the mixed layer and thus to a stronger stratification of the water column. This shields the surface more effectively from the heat stored in the deeper layers of the ocean and therefore sea ice melt is reduced and sea ice growth is furthered. The importance of adding glacial melt water from the Antarctic continent to the Southern Ocean in simulations to account for ice-shelf melt water has been indicated by e.g. Hellmer (2004) and Stössel et al. (2007). However, so far, only few studies have been conducted to investigate the effect that changing Antarctic melt water provokes in the Southern Ocean sea ice.

Bintanja et al. (2013) used a global coupled climate model to test the sensitivity of the Southern Ocean sea ice to an increase in Antarctic melt water and came to the conclusion that, while winds may be responsible for the regional trends, the circumpolar trend in sea ice is due to the increase of Antarctic melt water. With the CMIP5 ensemble Swart and Fyfe (2013) tested the influence of ice sheet melt on the sea ice area trends and concluded, that for realistic amounts of meltwater the effects on the ice are small and that the freshwater addition is unlikely to reproduce the spatial pattern of the observed trends. More recently, Bintanja et al. (2015) simulated the impact of projected Antarctic mass loss on the future sea ice trends with a climate model and found that additional freshwater decelerates the negative ice area trend in the simulations and in higher amounts can even invert it. Zunz and Goosse (2015) investigated the dependence of the forecasting skill of an Earth-system model on the freshwater input. Their results show a strong dependency on the initial state and in consequence they express the opinion that neither atmospheric nor freshwater trends cause the current sea ice trends, but that the ocean's preconditioning of the 1970s lead to surface cooling and sea ice expansion.

Merino et al. (2016) used an iceberg model coupled to a sea ice-ocean model to establish a seasonal climatology of iceberg melt for the Southern Ocean and find that the iceberg melt water leads to higher sea ice concentration and thickness, with exception of the Amundsen/Bellingshausen Sea area. Pauling et al. (2016) employed an Earth-system model to investigate the Southern Ocean sea ice response to artificially augmented, constant freshwater input. They tested the sensibility to higher freshwater additions than current estimates and previous studies and compare an iceberg model-based surface distribution with a coastal distribution at depth. They conclude that the effect of the different distributions on the mixed layer depth is contrary but the sea ice response is similar in both cases.

With exception of the most recent publications, the~~These~~ previous studies ~~generally~~ use very crude renderings of the spatial distribution of the freshwater addition. Our study aims to investigate the sensitivity of sea ice properties ~~including the dynamic response~~ to changes in the amount and especially the spatial distribution of fresh water input at surface including also the dynamic response of the sea ice-ocean system. We focus on the differences between a widely-used uniform runoff distribution around Antarctica and more complex spatially varying distributions. In our study, we employ an eddy-permitting ocean-sea ice model. Six experiments are carried out with differing spatial distribution and magnitude of the Antarctic freshwater flux at surface. Specifically, we study the response of sea ice concentration, thickness, velocity and production and deduce the development of sea ice extent and volume. The development of the on-shelf water column and the dense shelf water at the main sites of dense shelf water formation are presented, although the simulation period of 10 years is ~~too short~~not sufficient for the water characteristics to reach equilibrium. While these changes do not directly correspond to the trends in sea ice extent observed around Antarctica in recent decades, they tell us how the sea ice reacts to spatially limited changes in the freshwater input and thus give us a measure of what to expect as a sea ice response to observed changes in the runoff and offer explanations for observed changes in sea ice and water properties.

## 2 Methods

### 2.1 Model description

The presented numerical calculations are based on version 3.4 of NEMO (Nucleus for European Modelling of the Ocean) global general circulation model (Madec et al., 2012). The ocean and sea ice components are run on a global ORCA tripolar grid (an isotropic Mercator grid in the Southern Hemisphere, matched to a quasi-isotropic bipolar grid in the Northern Hemisphere with poles at 107°W and 73°E). The horizontal resolution is 0.25° (approximately 27.75 km) at the Equator and increases with latitude to be e.g. ≈10 km at 70°S (1442 grid points × 1021 grid points). The vertical grid has 75 levels, the spacing of which increases with a double tanh function of depth from 1m near the surface to 205m at the bottom, with partial steps representing the bottom topography (Barnier et al., 2006).

The model bathymetry is based on the combination of ETOPO1 data set (Amante and Eakins, 2009) in the open ocean and GEBCO (IOC, IHO and BODC, 2003) in coastal regions. Hand editing is performed in a few key areas.

The ocean general circulation model OPA is a finite difference, hydrostatic, primitive equation ocean general circulation model and uses a linear free surface and an energy and enstrophy conserving momentum advection scheme. The horizontal viscosity is bi-Laplacian with a value of $1.8\times10^{11}$ $m^4$ $s^{-1}$ at the Equator, reducing poleward as the cube of the maximum grid cell size. Tracer advection uses a total variance dissipation (TVD) scheme (Zalesak, 1979). Laplacian lateral tracer mixing is along isoneutral surfaces with a coefficient of 300 $m^2$ $s^{-1}$. The vertical mixing of tracers and momentum is parameterized using the turbulent kinetic energy (TKE) scheme. Subgrid-scale vertical mixing processes are represented by a background vertical eddy diffusivity of $1\times10^{-5}$ $m^2$ $s^{-1}$ and a globally constant background viscosity of $1\times10^{-4}$ $m^2$ $s^{-1}$. The bottom friction is quadratic. A diffusive bottom boundary layer scheme is included.

The sea ice component is the Louvain-la-Neuve Sea Ice Model, LIM2 (Fichefet and Morales Maqueda, 1997), which includes the representation of both the thermodynamic and dynamic processes. It accounts for sensible heat storage within the ice. The vertical heat conduction is calculated assuming two layers of ice and a snow layer on top. Sub-grid scale thickness distributions are thereby accounted for by use of an effective conductivity. The model also includes the conversion of snow to ice if the ice surface is depressed under the sea surface by the snow load. The ice dynamics are calculated according to external forcing from wind stress, ocean stress and sea surface tilt and internal ice stresses using C grid formulation (Bouillon et al., 2009). The elastic-viscous-plastic (EVP) formulation of ice dynamics by Hunke and Dukowicz (1997) is used.

The model is forced with ERA-Interim global atmospheric reanalysis (Dee et al., 2011), with 0.75°×0.75° spatial resolution. The turbulent variables are given as 3-hour mean values, while the radiative fluxes and precipitation are given as daily mean. The surface boundary conditions are prescribed to the model using the CORE bulk formulation proposed by Large and Yeager (2004). The forcing routine and the ice model are called every 5 time steps of the ocean model (every 90 minutes).

A suite of simulations is presented in this manuscript: a control run (hereafter CTR) and five sensitivity experiments (S1-S5). CTR was started from a state of rest in January 1979 and run for 35 years. Initial conditions for temperature and salinity are derived from the World Ocean Atlas 2013 climatological fields (Zweng et al., 2013; Locarnini et al., 2013), merged with PHC2.1 climatology over the Arctic region. The initial condition for the sea ice was inferred from the NSIDC Bootstrap products for January 1989. All freshwater experiments are branched off from CTR in January 2004 and run for ten years. In these simulations, we changed the amount and/or distribution of the Antarctic runoff; all other settings are identical to CTR.

The river run-off data is a monthly climatology based on~~from~~ the studies of Dai and Trenberth (2002) and Jacobs et al. (1992) and adapted for the ORCA025 grid by the DRAKKAR group (Bourdalle-Badie and Treguier, 2006). It includes 109 major rivers and a coastal runoff and has a mean value of 1.26 Sv. The fresh water is added to the surface with zero salinity and at sea surface temperature. In the areas of freshwater addition, the vertical diffusion is enhanced (mixing coefficient: 2×10-3 m2 s-1) over a depth of 15 m. In the Southern Ocean, the runoff field is modified, as described in the next section. The runoff follows a seasonal cycle, which is unaltered relative to the mean amount in S1-S5 (Figure 1a).

No surface restoring for tracers was used in the simulations. The simulation was run without any constraint on the freshwater budget.

### 2.2 Experiment design

To test the response of sea ice to changes in the melting of glacial ice around Antarctica, we present five sensitivity experiments in this study, where the surface freshwater input is modified in its magnitude and spatial distribution. Ice shelves and icebergs are not explicitly resolved in our configuration; therefore any source of melt water is represented in the runoff field. A short overview over the experiments and their differences is also given in Table 1.

The CTR total runoff represents a continental discharge of 2610 Gt $yr^{-1}$, and is uniformly distributed along the Antarctic coastline (Figure 1b), as commonly done in ocean models. The value is close to observation-based estimates of 2760 Gt $yr^{-1}$ by Rignot et al. (2013), 2775 Gt $yr^{-1}$ by Depoorter et al. (2013), and 2260 Gt $yr^{-1}$ by Liu et al. (2015), that include both basal melt and iceberg contributions. For information on the general performance of CTR please refer to the Supplement S1~~supplementary material~~.

In the first sensitivity experiment, S1, the magnitude of fresh water input is increased by 5% adding 130 Gt yr$^{-1}$, and is spatially constant as in CTR (Figure 1b). A comparison between the simulations allows us to study the effect of increased runoff without interference of other factors. The amount of increase is a conservative choice within the range of recent estimations of Antarctic mass loss (e. g. Shepherd et al., 2012; Vaughan et al., 2013; Wouters et al., 2013; Velicogna et al., 2014).

S2 simulation introduces a more realistic uneven spatial distribution of the runoff based on estimates of basal melt and calving by Rignot et al. (2013). The runoff, still distributed close to the coastline, varies in magnitude by region (Figure 1c). In some areas (mainly East Antarctica), it is reduced compared to CTR, while in other areas (e.g. Weddell Sea and Amundsen Sea) it is strongly increased. The total freshwater flux is increased by 150 Gt yr$^{-1}$ compared to CTR.

S3 takes into account that not all the fresh water entering the ocean is added at the coastline. With a spatial distribution similar to S2, only a reduced amount of runoff (1670 Gt yr$^{-1)}$ is distributed close to the coastline to represent ice shelf melt.~~coastline to represent ice shelf melt.~~ 1090 Gt yr$^{-1}$ are widely distributed (with four levels of flux intensity) in the Southern Ocean to represent icebergs melting in the open ocean (Figure 1d). The shape of this distribution is loosely based on iceberg drift and melt studies, e.g. Gladstone et al. (2001), Silva et al. (2006) and Jongma et al. (2008). The total amount of runoff is 2760 Gt yr$^{-1}$ as in S2.

S4 features a more extreme distribution of runoff that focuses on the key areas of dense water formation. Since the sea ice formation processes over the Antarctic continental shelves are essential factors in the formation of dense shelf water and consequently of the bottom water of the world ocean, the effect of runoff on the water column in these areas is of special interest. The S4 runoff adds 420 Gt yr$^{-1}$ to the CTR runoff, but distributes it all in only three locations: in front of the Filchner/Ronne Ice Shelf in the Weddell Sea (230 Gt yr$^{-1}$), in front of the Ross Ice Shelf in the Ross Sea (120 Gt yr$^{-1}$) and in front of the Amery Ice Shelf in Prydz Bay (60 Gt yr$^{-1}$) (Figure 1e). The total of the runoff is 3030 Gt yr$^{-1}$.

S5 is designed to study the effect of the accelerated melting of Antarctic ice shelves. It starts with the freshwater distribution of S2, but the runoff amount increases from 2760 Gt yr$^{-1}$ in 2004 to 3310 Gt yr$^{-1}$ in 2013 in 4 steps (137 Gt yr$^{-1}$ every 2 years).

## 3 Sea ice

In this section, the impact of modifications in the freshwater supply on the sea ice is analyzed by comparing the sensitivity experiments with CTR. In the comparison, we focus on the austral winter period from April to September, since the sea ice values in CTR are closest to observations during these months (see Supplement S1~~supplementary material~~ for a detailed description of CTR results). In the following, the word winter referring to a specific time period will mean the months April-September.

In Sect. 3.1, we analyse the resulting differences in sea ice concentration, thickness and velocity for all runoff scenarios and in Sect. 3.2 we discuss the time series of ice extent, volume and ice production. Our results regarding the sea ice properties are set in relation to previous model studies and observations in Sect. 3.3.

### 3.1 Spatial response patterns

Since sea ice concentration in CTR (Figure 2a) is already high during the winter months, there is only limited leeway for it to increase in the sensitivity runs. The maximum changes are found in the marginal ice zone (Figure 2, left column). The variability of the differences between scenarios S1-S5 and CTR is comparatively high, so areas with a high statistical confidence level are limited. Changes of the sea ice thickness (Figure 2, middle column) generally exhibit a similar, but spatially more coherent pattern compared to the changes in sea ice concentration: areas of higher (lower) concentration yield thicker (thinner) sea ice. The longer-lasting character of the changes in thickness reduces the variability and increases the areas of statistical significance compared to the changes in concentration. Also the sea ice velocity is affected by the changes in runoff. The addition of fresh water affects the sea surface height (SSH). A change in the SSH slope influences the surface current of the ocean and the sea ice drift. Therefore, changes in the runoff scenario directly affect sea ice properties by both thermodynamic and dynamic processes. The velocity of the sea ice is altered by changes in the fresh water input and in consequence affects the ice thickness due to dynamic compaction. The areas featuring a high statistical confidence level for the changes in sea ice velocity (Figure 2, right column) are predominantly found along the coastline. Here, the runoff addition per area is highest in the sensitivity experiments and the coastal current distributes the added fresh water within a narrow band circling the continent. Most of the offshore velocities show seemingly erratic changes induced by the highly variable fronts and eddies in the Antarctic Circumpolar Current.

#### 3.1.1 S1: Response to a simple runoff increase

In S1, the sea ice concentration features small changes from CTR, except for an increase at the tip of the Antarctic Peninsula (Figure 2d). Also the changes in ice thickness are small, but increases dominate in the western Ross Sea, west of and at the tip of the Antarctic Peninsula, and in the central Weddell Sea (Figure 2e). The main areas of sea ice thinning are the eastern Ross Sea and the southwestern Weddell Sea. The addition of freshwater, by decreasing the surface salinity, increases the freezing temperature and inhibits heat transport from below and is expected to increase the ice cover. However we have to consider the ice dynamics in order to explain local maxima and especially decreases in either concentration or thickness. In S1, the freshwater increase along the coastline strengthens the coastal current and the coastal sea ice drift is slightly sped up compared to CTR (Figure 2f). The faster ice drift leaves some areas with younger and thus thinner ice. In areas with a more complex coastline geometry, it causes stronger convergence and compaction of the ice, thus creating higher ice concentrations and thicker ice.

### 3.1.2 S2: Response to strong regional runoff variations

The runoff distribution used in S2 introduces regionally-varied coastal surface freshwater fluxes. The responses of the sea ice properties can therefore be expected to be strongly region-dependent. The sea ice concentration (Figure 2g) features changes of high statistical confidence in the coastal area. Increases in ice concentration and thickness (Figure 2h) occur in the eastern Weddell Sea, in the western Ross Sea, close to the coast of East Antarctica, and east of the tip of the Antarctic Peninsula. Areas of strongly reduced sea ice are located adjacent to the coast of the Amundsen and eastern Ross Seas and in the southern Weddell Sea. Since in S2, the freshwater input is varied regionally along the coastline also the ice drift velocities are altered dependent on the location (Figure 2i). Compared to CTR, the westward ice drift is ~~accelerated~~faster along the coast of the Amundsen and Ross seas. From the Prydz Bay to the southern Weddell Sea it is slower than in CTR. From here, sea ice speeds up compared to CTR, moving northward along the Antarctic Peninsula, to slow down again on the western side of the peninsula toward the Bellingshausen Sea. In S2, the changes in sea ice velocity cause most of the local changes in sea ice concentration and thickness.

To investigate the mechanisms controlling regional sea ice behaviour in S2 in more detail, we subdivided the widely-used 5 regions of the Southern Ocean (e.g. Parkinson and Cavalieri, 2008, 2012) into 10 regions (Figure 1b~~a~~). With the exception of the western and eastern Weddell regions, which both have a width of 40° in longitude, all regions span 35°. A northern limit was also employed, chosen individually for every region, in a way to include areas under the influence of the westward coastal current, while excluding most of the areas with eastward sea ice drift.

The compilation of the regional differences in runoff and sea ice characteristics between S2 and CTR (Table 2) confirms, that the regional thermodynamic response to an increase (decrease) of runoff is an increase (decrease) of sea ice production. Only the western Ross Sea region (WRoS) is an exception to this rule, because here the increase of the runoff along the southern coastline is exceeded by the reduction of runoff along the north-south directed western coastline (Figure 1c~~b~~). For the sea ice production, however, the southern coastline is of greater influence because of frequent polynya activity due to southerly winds.

The change in sea ice presence (concentration, thickness and volume) in most regions is contrary to the thermodynamic response. This is strong evidence that the impact on regional sea ice presence in S2 is determined by the response of the sea ice dynamics, and that regional thermodynamics play only a minor role. The differences in the sea ice velocities change the regional import and export rates of sea ice. Therefore, given strong regional contrasts of the freshwater addition, the dynamic response decides the development of sea ice presence in the area. In the S2 experiment, two regions show a different behaviour: the Wilkes Land (WiL) and the Bellingshausen Sea (BeS) sectors (Table 2). Both feature an increase in runoff, sea ice production, sea ice concentration and thickness. In WiL, the coastal current is dominated by the larger scale situation; the strong acceleration experienced in the Amundsen and Ross Seas, is inverted while circling East Antarctica (Figure 2i). WiL is the only East Antarctic region where fresh water input is increased compared to CTR, but in spite of this the coastal current is losing speed. Therefore, both thermodynamic and dynamic response favour increased sea ice presence in the region.

In the BeS sector, the coastal current is least pronounced and current speeds are lowest of all regions in CTR (Figure 2c). In S2, the current speeds are even weaker in this region (Figure 2i). Sea ice drift therefore is of low importance. BeS is the only region where the local thermodynamic response dominates the change in sea ice presence seen in S2.

#### 3.1.3 S3: Response to wide-spread runoff addition

S3 features a widespread increase in sea ice concentration and thickness compared to CTR (Figure 2j-k), which is caused by higher local sea ice production. The addition of freshwater, by decreasing the surface salinity, increases the freezing temperature and inhibits heat transport from below. Since in S3 only a part of the freshwater is added at the Antarctic shoreline, the coastal runoff is decreased compared to CTR in most areas and the coastal current is decelerated (Figure 2l), with the maximum deceleration along the Princess Martha Coast (Figure 1b), in the eastern Weddell Sea. Only from the Amundsen Sea to the Ross Ice Shelf front, we find coastal velocities ~~accelerated compared to~~faster than in CTR. In the Amundsen Sea, the ~~acceleration~~increased speed leads to a sea ice depletion, because the ice is younger and the export from the region is increased. In the western Ross Sea, the increased velocities (Figure 3) lead to thicker sea ice (Figure 2, middle column) due to enhanced accumulation and compaction of the sea ice against the coastline in the southwestern corner of the Ross Sea. Additionally, a sea ice convergence is created by the contrast between the runoff addition at the southern and at the western coastline of the Ross Sea (Figure 1d~~e~~) causing the ice drift to slow.

In the central and eastern Weddell Sea, the fresh water addition causes the ice to thicken~~ed~~ thermodynamically in S3. In the western Weddell Sea, sea ice thickness is increased (Figure 2k), contrary to the ice concentration (Figure 2j). The increased sea ice presence over the northern part of the Weddell Gyre inhibits the northward export east of the Antarctic Peninsula (Figure 2l) and leads to dynamic compaction there.

#### 3.1.4 S4: Response to regional runoff addition

In S4, the changes in the sea ice variables feature a pattern similar to the pattern of S1 (Figure 2m-o). The strongest increase of both ice concentrations and thickness occurs around the tip of the Antarctic Peninsula and in the western Ross Sea, since the strengthened coastal current leads to more dynamical compaction in these areas. A decrease of ice thickness is found to the southeast of the peninsula (Figure 2n), which can be attributed to the fact that the ice is younger. In S4, additionally a decrease of sea ice concentration occurs at the Filchner/Ronne Ice Shelf front (Figure 2m). Since the runoff addition is regional and confined to the fronts of the Filchner/Ronne, Ross and Amery ice shelves, the coastal ice velocities increase in the Weddell Sea (Figure 2o) and deplete the area of ice. In Prydz Bay, we find a similar ~~acceleration~~speed increase and a local decrease of ice concentration. In the Ross Sea, the coastline geometry has a blocking effect.

### 3.1.5 S5: Response to runoff increase with time

S5 features a very similar spatial pattern of changes in sea ice concentration, thickness and velocity as S2 (Figure 2p-r), since the spatial distribution of runoff is the same and only the amount of freshwater is increased over time. In sea ice velocity, S5 differs from CTR as S2 does (Figure 2r), although the drift velocity along the coast is generally higher than in S2. This leads to the dynamical effects, like the thickening in the western Ross Sea or the depletion of sea ice in the Amundsen and the southern Weddell Seas, to increase compared to S2. However, in the offshore area of the eastern Weddell Sea the sea ice thickness and concentration are predominantly reduced instead of increased compared to CTR. A similar behaviour is evident in the offshore eastern Ross Sea for the sea ice thickness. The total of the sea ice cover is decreased compared to S2. The reasons lie in the surface warming of extensive areas and are discussed further in Sect. 3.2.

In summary, all scenarios confirm that the increase in drift velocity in areas of a strong contrast in freshwater addition prevails against local thermodynamic effects and lead to thinner sea ice in lower concentrations in the region. This is the expected case for the southern Weddell Sea and the Amundsen Sea, which are located downstream of areas where less runoff addition is expected. In regions downstream of high additional freshwater flux, the increased velocities can have the opposite effect on ice thickness, when encountering obstacles like headlands. The dynamic compression is enhanced and the sea ice increases in thickness. In the western Ross Sea, this effect is very efficient. It occurs also at other locations e.g. the tip of the Antarctic Peninsula in the Weddell Sea.

## 3.2 Development in time and variability

In this section, we assess the time-dependency of the effects of the freshwater additions in the different experiments as well as their effect on the seasonal cycle of sea ice extent, volume and production. The time series of the sea ice variables over the course of the 10-year integration period are presented in Figure 3 with the addition of the mean seasonal cycles of the variables.

The differences in sea ice extent (Figure 3a-b) between all scenarios (S1-S5) and CTR are very small compared to the extent's seasonal amplitude (equal to $1.7\times10^7$ km$^2$). However, while the interannual and seasonal variability of the differences in ice extent is high, all scenarios result in a higher sea ice extent than CTR in the mean over the simulated period (Figure 3b). S1 diverges from CTR only to a small extent, and although the increase of ice extent prevails over the 10-year integration period, there are many occasions when S1 features a smaller sea ice extent than CTR. The magnitude of difference in ice extent between S2 and CTR is comparable with those of S1, but with distinct events of larger (smaller) ice extent in winter 2009-2011 (2012-2013).

S3 and S4 show a more substantial increase in sea ice extent. In S3, the widespread distribution of additional freshwater causes the sea ice to thermodynamically thicken and increases its concentration. In S4, the dominant factor is the dynamic compression due to more convergent ice drift. In both cases the increased ice thickness extends the ice's lifespan. Therefore, the sea ice extent is increased and most effectively during the austral summer.

S5 features similar results as S2, but in comparison it yields a smaller sea ice extent than S2 in the mean. The main contribution to this decrease comes from the eastern Weddell Sea and the Cosmonaut Sea, where S5 features thinner and less concentrated ice at the ice edge in connection with a higher sea surface temperature (SST; see Supplement S2 for a figure of the SST difference~~SST~~).

As seen for the sea ice extent, the differences of the sea ice volume between simulations and CTR (Figure 3c-d) are small compared to the volume's seasonal amplitude ($1.4\times10^4$ km$^3$). The S1 ice volume is generally comparable to CTR from February to May, but tends to increased values from June to January. The S2/S5 differences to CTR in ice volume feature a larger interannual variability. During the first seven years the volume generally surpasses that of CTR, but drops to lower values during 2011 to return to an increasing trend in the last two years. In the 10-year mean, the seasonal cycle of S2 and S5 shows a larger volume than CTR, except in the late summer and early autumn. S3 produces higher sea ice volumes than CTR and all other scenarios through almost the entire simulated period, due to the widespread increase in both sea ice concentration and thickness. Similar to S2 and S5, the initial strong increase is interrupted in 2011 when a sudden drop in ice volume occurs, although the ice volume of S3 remains higher than in CTR. These experiments featuring a drop in ice volume in 2011 share a strongly regional distribution of runoff, indicating that the source also is regional, probably of atmospheric origin. The main contributing regions are the Amundsen, Bellinghausen and western Weddell Seas. S4, like S1, seems unaffected by the 2011 event and features distinctly increased ice volumes compared to CTR. The difference is comparatively small in the end of summer and reaches maximum values in spring.

Figures 3e-f show the changes in sea ice production caused by the runoff alterations. Again, the differences in sea ice production (Figure 3e) are small compared to the seasonal amplitude ($1.6\times10^6$ m$^3$ s$^{-1}$) of the ice production. All scenarios feature a sea ice production larger than CTR from autumn to spring, but in contrast also the summer melting is higher in S1-S5 than in CTR. In S1, the changes are smallest and of a similar magnitude as their variability, while S3 diverges from CTR to the greatest extent and maintains a distinctly higher ice production even late in the year. While a strong stratification and a decoupled surface layer lead to cold surface waters and high ice production during the freezing period, in summer the heat uptake by the ocean is distributed in a shallower layer. Thus SST is higher and sea ice melt is enhanced. This behaviour is strengthened by a positive feedback loop (Stammerjohn et al., 2012) as long as the ocean gains heat.

During autumn the sea ice production of S5 surpasses that of S2, since the lower surface salinity facilitates ice formation. However, during winter and spring S2 features higher ice production values, because the influence of the offshore areas, particularly the northeastern Weddell and Ross Seas, becomes dominant. ~~Once the fresher surface water has been advected offshore, the stronger stratification leads to a shallow surface layer. The heat uptake during the melting period therefore leads to higher temperatures, e~~As a possible underlying mechanism, we suggest that the increased velocity is not limited to the coastal current but spreads to the subpolar gyres. A stronger circulation in a cyclonic gyre causes increased upwelling in the gyre's center due to the increased Ekman transport at the surface. In the Weddell and Ross Seas, this would cause a local increase of surface temperatures and salinities (SSS). In S5, SST and especially SSS in the winter mean is higher than in S2 in the northeastern Weddell Sea and northeastern Ross Sea (figures of the SST and SSS difference between experiments S2 and S5 are provided as Supplement S2). In consequence ice production is reduced and ice melt furthered. A reduced sea ice cover, especially in the regions close to the winter ice edge, leads to a higher heat uptake from solar radiation during the summer, triggering a positive feedback loop (Stammerjohn et al., 2012). ~~In S5, SST in the winter mean is higher than in S2 in the northeastern Weddell Sea and northeastern Ross Sea.~~ ~~Those higher temperatures are remnants of the summer heat uptake and lead to faster ice melt during winter.~~

~~Another factor responsible for the difference between S2 and S5 is dynamics related.~~ Additionaly, there is a second way, t~~T~~he increased speed of the coastal ice drift can contribute to the difference in sea ice volume and extent between S2 and S5~~affect the sea ice thickness twofold~~: it shortens the period of time available for thermal growth and it can strengthen the mechanical processes thickening the ice in areas of convergence. Depending on the regional geometry and the ice drift pattern, either the thermodynamic or the dynamic effect on the sea ice thickness prevails and leads to thinner or thicker sea ice, respectively. While in WRoS, the sea ice in S5 is thicker than in S2 due to compression against the shoreline, the thermodynamic effect is of greater influence in WWeS, where large areas feature thinner ice in S5 (Figure 2h and q).

### 3.3 Comparison with previous studies and observed trend

All sensitivity experiments have a higher amount of runoff compared to CTR that results in more sea ice. On a hemispheric scale, the experiments S1-S4 confirm the expectation that an increase in Antarctic runoff leads to an increase in sea ice in accordance with e.g. Bintanja et al. (2013), ~~and~~ Bintanja et al. (2015) and Pauling et al. (2016). However, comparing S2 and S5 shows that S5 (although with larger runoff) results in slightly less sea ice production, volume and extent. This suggests that there may be~~is~~ a turning point ~~(indeterminable from the experiments conducted for this study)~~ in the sea ice response, where the amount of added freshwater exceeds the amount that leads to an increase in sea ice, and instead leads to a decrease (transient or not). Further study is required to verify the existence of such a turning point and possibly for its determination. While Pauling et al. (2016) with even higher amounts of fresh water addition did not conclude the existence of a turning point, their experiment with the highest amount of fresh water yields the lowest seasonal linear trends for the sea ice, while the lowest fresh water amount in summer and winter yields the least negative and in autumn even a positive trend (their Figure 11).

The differences in runoff input applied in our simulations do not directly relate to the changes in Antarctic melt water estimated for the recent decades. An abrupt shift of freshwater sources from one region to another (as a comparison of CTR and S2 symbolizes) is unlikely, the increasing ocean temperatures are more likely to induce a slow but region-dependent increase of freshwater input. Similar to these natural processes is the difference between S2 and S5, where the (relative) spatial distribution of the Antarctic runoff does not differ, but the amount is increased. However, since the increase in S5 is much faster than observed and the runoff amount surpasses current estimates of Antarctic mass loss (70-290 Gt $yr^{-1}$; Rignot et al., 2008; Joughin and Alley, 2011; Shepherd et al., 2012; Vaughan et al., 2013; Wouters et al., 2013; Rignot et al., 2013;

Velicogna et al., 2014), a comparison with the recently observed hemispheric trend yields no similarities: S5 exceeds a turning point and results in less sea ice than S2. However, most regional trends are strengthened in S5 compared to S2 and only in the eastern Weddell Sea and the Cosmonaut Sea regions the ice extent of S5 is closer to CTR than that of S2.

S1 and CTR also differ in amount of fresh water but not in its distribution. Although the runoff distribution in the two simulations is far from realistic, a comparison of our results with the observed sea ice trend is possible under some assumptions. Due to the abrupt runoff change in the simulations, a curve of the form $y \sim (a \times x)^b$ was fitted to the resulting differences in sea ice extent and projected for the duration of 35 years. For S1 (with a=0.0011 and b= 0.7469), this resulted in an increase of the ice extent by $5.62 \times 10^4$ km$^2$ after 35 years due to 130 Gt yr$^{-1}$ of additional Antarctic freshwater. Using the range of the available mass loss estimates (70-290 Gt yr$^{-1}$) and the observed change of $5.25 \times 10^5$ km$^2$ ($15 \times 10^3$ km$^2$ yr$^{-1}$; Parkinson and Cavalieri, 2012), the simulated increase of sea ice extent in S1 corresponds to 6~~5.8~~-24~~3.9~~% of the observed increase (assuming a linear dependency on the runoff amount).

A similar comparison of the differences between S4 and CTR (with a=0.0086 and b=0.4165) yields $1.71 \times 10^5$ km$^2$ after 35 years. Considering the runoff addition (420 Gt yr$^{-1}$) in the simulation and the range of current estimates of Antarctic mass loss, we obtain a 5~~.4~~-23~~2.5~~% runoff contribution to the currently observed trend in sea ice extent. Considering the differences in distribution of the additional fresh water between the experiments S1 and S4, the closeness of the obtained percentages gives the result some convincibility.

Like Swart and Fyfe (2013), we find the simulated trends in sea ice extent to be smaller than the observed trend for runoff amounts close to observations and do not see the runoff as the main driving force of the circumpolar trend like Bintanja et al. (2013). However, we argue that the melt water increase currently contributes a roughly estimated 5-24% of the observed increase in sea ice extent and is thus not negligible.

We find the spatial distribution of the freshwater addition of high influence on the sea ice cover, as Zunz and Goosse (2015) suspected. In particular, as also Merino et al. (2016) found, considering an idealized freshwater discharge from icebergs strongly impacts sea ice thickness, which in turn affects ice dynamics and longevity. Considering the effect that the spatial distribution of runoff has on sea ice, it seems important for modelling purposes to use a meltwater distribution as close to observations as possible. A re-adjustment of the sea ice parameters may be necessary to overcome the bias from tuning with a spatially unrealistic addition of freshwater.

Of course, in contrast to our idealized experiments, the fresh water from ice sheets and icebergs basal melt does not enter the ocean only at the surface in the real world, but at tens or hundreds of meters depth. However, this approximation, still widely-used and to some extent imposed by the ocean model used, is applied in our study. Pauling et al. (2016) recently found the depth distribution of additional fresh water in the Southern Ocean to be of small effect on the sea ice. ~~although we expect it to be of influence on the mean state and variability of the sea-ice.~~ Also, this study neglects the heat fluxes associated with the melting of glacial ice.

## 4. On-shelf water characteristics

In this section, the influence of the different runoff scenarios on the on-shelf waters is presented for three locations, which are key regions for bottom water formation: the Weddell Sea, the Ross Sea and the Prydz Bay. The areas are limited for the Weddell Sea to west of 38° W and south of 71.7° S, for the Ross Sea to west of 170° W and south of 71.7° S and for Prydz Bay to between 70° E and 80° E and south of 66.4° S. The regions are further limited to areas shallower than 550m depth to avoid strong influences from the deep ocean at the shelf break while including the outflow of dense water across the sills. Our comparison between S1-S5 and CTR focuses on the winter period (from April to September), when the dense shelf water is formed (Foldvik and Gammelsrød, 1988; Fahrbach et al., 1995).

In the mean vertical profiles of temperature, salinity and density computed in all three regions (Figure 4a-c, g-i, m-o), we find a warming (cooling) of the waters at 300-500m depth corresponding to the freshening (salinification) of the upper water column. Strong spatial variations in freshwater addition may cause local deviations from this behaviour, due to advection. For example, in the Weddell Sea, despite the local strong addition of fresh water, S2 and S5 feature slightly saltier waters than CTR in the 100-300m depth interval, due to the preconditioning of the waters by the decreased runoff along the coastline of East Antarctica.

The evolution in time of the winter means of water properties at the 550m-isobath is presented for the simulated decade in Figure 4(d-f, j-l, p-r). The range of temperatures, salinities and densities at 550m depth between the simulations widens throughout the decade and the diverging trends can be expected to continue in subsequent years. The most extreme discrepancies of temperature and salinity in 2013 occur in the Ross Sea, where S5 features temperatures 1.4 K higher and salinities 0.09 psu higher than CTR. The highest discrepancy in density in 2013, however, occurs in the Weddell Sea, where the water in S3 is 0.06 kg $m^{-3}$ denser than in CTR.

In the Weddell Sea and in Prydz Bay, the S3 scenario mimicking an iceberg drift pattern yields much cooler and consequently also denser shelf waters. The surface salinity of S3 is increased compared to CTR in these locations and the water column is destabilized, because the coastal freshwater input is reduced in the region upstream (East Antarctica). Only in very few locations, the coastal freshwater input of S3 is larger than that of CTR (Figure 1 d). The most substantial increase of runoff occurs in the Amundsen Sea area, which is upstream of the Ross Sea shelf. Therefore, in S3, we see a subsurface warming and increased stability of the water column compared to CTR in the Ross Sea.

Also S2 results in denser shelf waters than S5 in the Weddell Sea and in Prydz Bay, while in the Ross Sea, S5 creates denser water than S2. On the Ross Sea shelf, the density contrast between the surface and 500m depth is stronger than in the Weddell Sea or in Prydz Bay in our simulations. The waters at depths of 300-500 m are warmer and saltier than at the other two locations due to warm water intruding upon the shelf (the simulation tends to overestimate warm water access due to its limited resolution of the bathymetry), and at the surface the salinity is lower due to the strong fresh water input in the Amundsen and Ross Seas. Therefore, the surface is decoupled more effectively from the sub-surface waters in the Ross Sea. The surface freshening does not translate to a freshening of the entire water column, but instead leads to increased sea ice formation and eventually salt accumulation in the deeper water column. Thus, S5, the simulation with more freshwater input, creates the more saline and therefore denser shelf waters.

In contrast, S1 and S4 result in fresher shelf water than CTR in the Ross Sea. The freshening, however, mostly occurs in the last years of the simulated decade and is largely due to the destabilisation of the water column. Compared to CTR, S1 and S4 feature colder temperatures at 500m depth and higher salinities at the surface. Only S1 and S4 feature the same response in the dense shelf water in all three locations: temperatures are higher, salinities lower and densities decreased. In the Weddell and Ross Sea, S4 features the largest drop in salinity and consequentially density of all scenarios. In Prydz Bay, S2 and S5 feature a higher loss of salinity and density because here the water column is very unstable and the surface addition of fresh water easily translates to a freshening of the entire water column.

Our results regarding the formation of dense shelf water are in accordance with the findings of Hellmer (2004). Both studies support the idea that addition of fresh water leads to reduced density of the shelf waters, stronger stability of the water column and increased sea ice thickness (S1, S4). However, if aspects of spatially varying addition and subtraction of melt water come into play (as in S2, S3, S5), the processes become more complex and the preconditioning of the waters in upstream regions can cause results to differ locally.

## 5. Conclusions

To assess the impact of increased Antarctic freshwater fluxes at the surface on sea ice properties and dense water formation in the Southern Ocean, five simulations with varying freshwater forcing were performed and compared to the control run. We used the NEMO v3.4 ocean model coupled with the LIM2 sea ice model in a global configuration with horizontal resolution of 1/4°.

Our results confirm that the sea ice extent (and volume) increases for moderate increases of the runoff amount. The strongest freshwater forcing we used, however, leads to a decrease in sea ice volume and extent compared to other experiments. Based on this we think it probable that a turning point in the sea ice response to freshwater forcing exists and offer the following mechanism as a possible explanation: ~~If the stratification of the offshore water column is increased~~The coastal freshwater input changes the SSH slope and increases not only the velocities in the coastal current, but also of the subpolar gyres. Due to the increased Ekman transport more warm and saline water wells up in the gyres' centres., SST (and SSS) will increase ~~during summer~~ and lead to enhanced ~~sea ice~~ melting of the northward advected sea ice and reduced local ice production during autumn and winter. The reduced sea ice cover~~,~~ allows higher shortwave radiation absorption by the ocean and trigger~~ings~~ a positive feedback loop. Also, the freshwater-induced acceleration of the coastal current leads to thinner sea ice, when the time available for thermodynamical growth is reduced strongly. This is especially relevant for the Weddell Sea, while in the western Ross Sea all performed experiments result in dynamically thickened sea ice.

For strong regional alterations of runoff addition, the dynamic response in our simulations proved to be stronger than the thermodynamic response in most cases. The region with additional runoff is depleted of sea ice since the coastal current is accelerated, and sea ice export from the region increases. The spatial distribution of freshwater addition is therefore of great importance.

Our results emphasize that the addition of freshwater induces a warming in the sub-surface waters due to the stronger stratification and the inhibited vertical heat exchange. On the continental shelves around Antarctica, the characteristics of the dense bottom waters are therefore subject to strong changes. In our experiments, the dense shelf water characteristics do not reach an equilibrium within the 10-year simulation period, but it is evident that for simple increases in the runoff the dense shelf waters become warmer,~~ and~~ fresher~~,~~ and hence ~~lose~~less dense~~ity~~. However, in regions downstream of reduced freshwater input at the coast, the water column is less stable and in consequence waters generated on the shelf are denser (colder and more saline).

We conclude that the increase of Antarctic melt water currently contributes to the positive trend in sea ice extent, but rough calculations limit its role to 5-24% of the observed increase. Changes in the runoff regional distribution can also induce regional variations in sea ice, as e.g. occurs in the Amundsen Sea, where the strong basal melt processes effectively reduce the sea ice cover and export more sea ice to the eastern Ross Sea. Generally, our experiments suggest that the spatial distribution of runoff around the Antarctic continent is of high importance for the sea ice cover and the stratification of the Southern Ocean. Numerical applications may highly benefit from realistic distributions of Antarctic runoff.

It is worth noting that the impact on shelf water properties, simulated in our experiments, is due to fresh water, that enters the ocean only through the surface. These results may change with the additional water distributed at non-zero depth, for better representing calving and basal melting of the ice shelves. The freshening of underlying layers would decrease stability and impact the mixed layer depth. Also the influence of the heat fluxes associated with melting the glacial ice has not been considered in this study.

**Acknowledgments**

This study was performed in the framework of Climatically driven changes of Antarctic sea ice and their role in the climate system (CATARSI) project as part of the Italian National Program for Research in Antarctica (PNRA). The financial support of the Italian Ministry of Education, University and Research, and Ministry for Environment, Land and Sea (also through the project GEMINA) is gratefully acknowledged.

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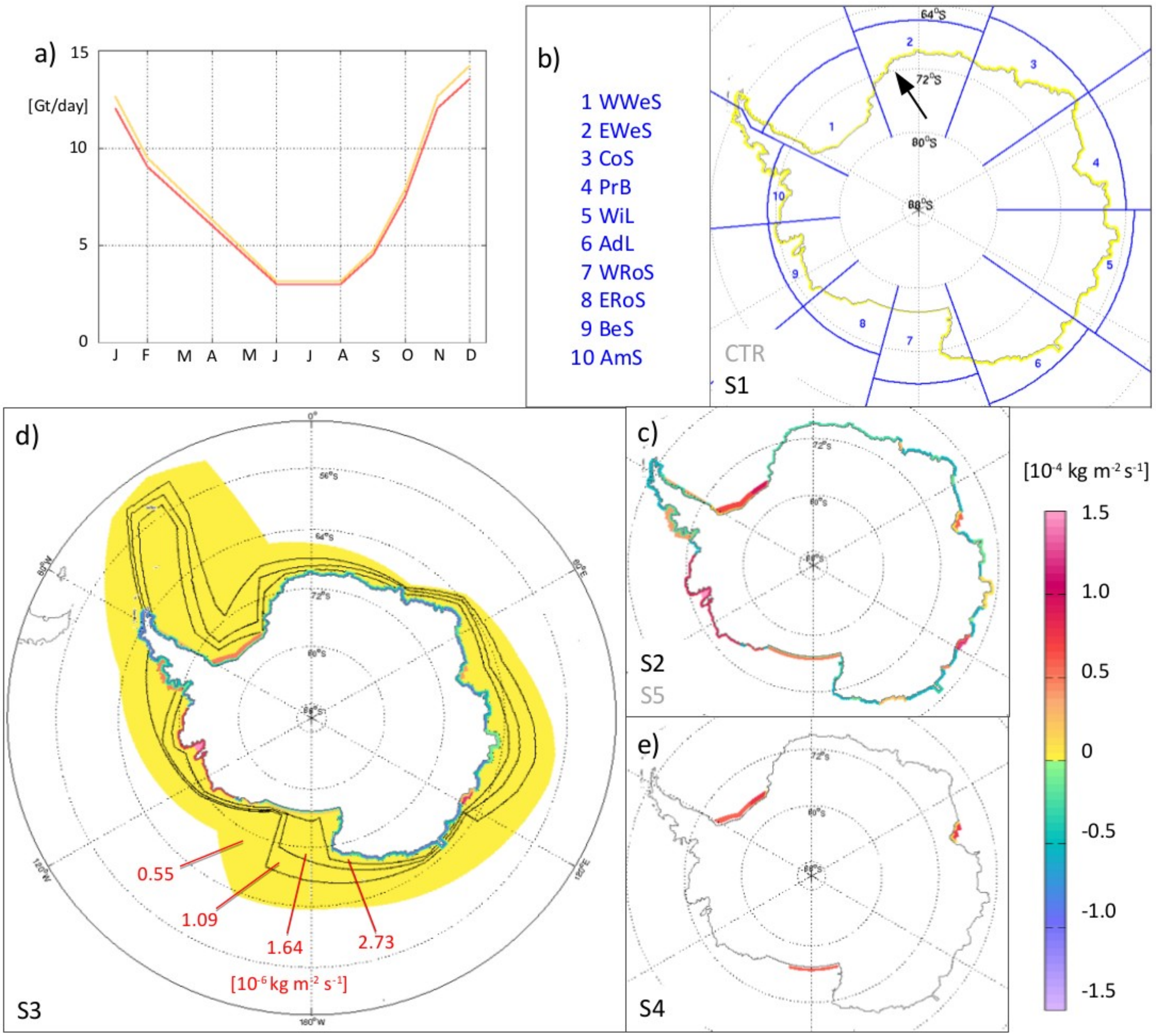


Figure 1: a) Seasonal cycle of the runoff, exemplary for CTR (red) and S1 (yellow); b-e) Runoff distributions for the scenarios as differences from the CTR runoff. The numbers vary with the seasonal cycle; shown is the mean for the winter half of the year (April-September). CTR (S5) has a similar distribution to S1 (S2) but different values; b~~a~~) also depicts the location of Princess Martha coast marked with a black arrow and the definition of the regions used in the article~~. e) Seasonal cycle of the runoff, exemplary for CTR (red) and S1 (yellow).~~: 1 WWeS – Western Weddell Sea, 2 EWeS – Eastern Weddell Sea, 3 CoS - Cosmonaut Sea, 4 PrB – Prydz Bay, 5 WiL – Wilkes Land, 6 AdL – Adelie Land, 7 WRoS – Western Ross Sea, 8 ERoS – Eastern Ross Sea, 9 AmS – Amundsen Sea, 10 BeS – Bellingshausen Sea.

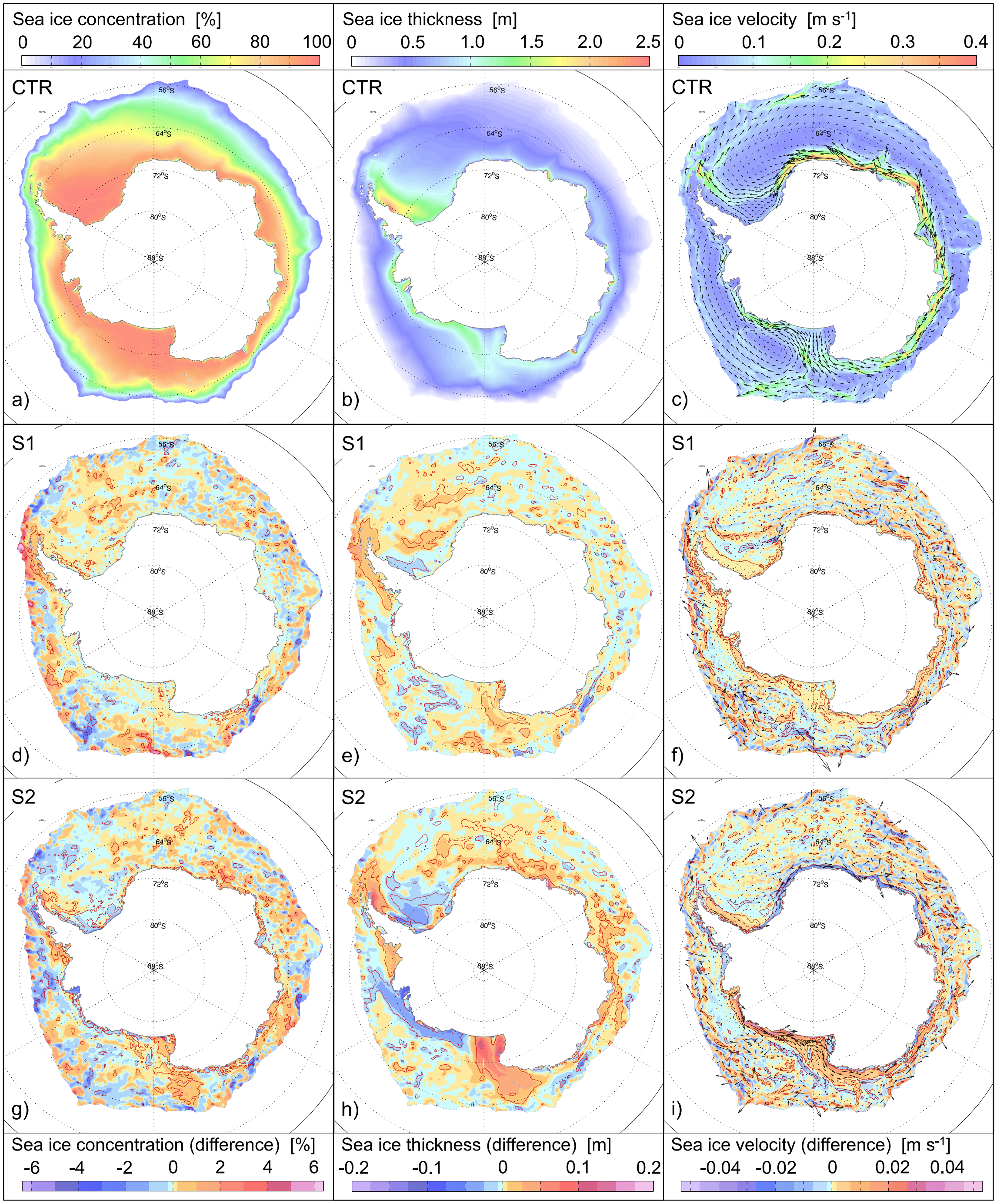


**Figure 2: Maps of a) winter sea ice concentration, b) thickness, and c) velocity in CTR averaged over the years 2004-2013. b-r) Difference of ice concentration (left), thickness (middle), and velocity (right) between respective scenario and CTR. The colors underlaying the velocity arrows indicate speed. Dark red contours encompass the areas where the significance of the difference surpasses the 99% confidence-level of the Student t-test for dependent samples.**

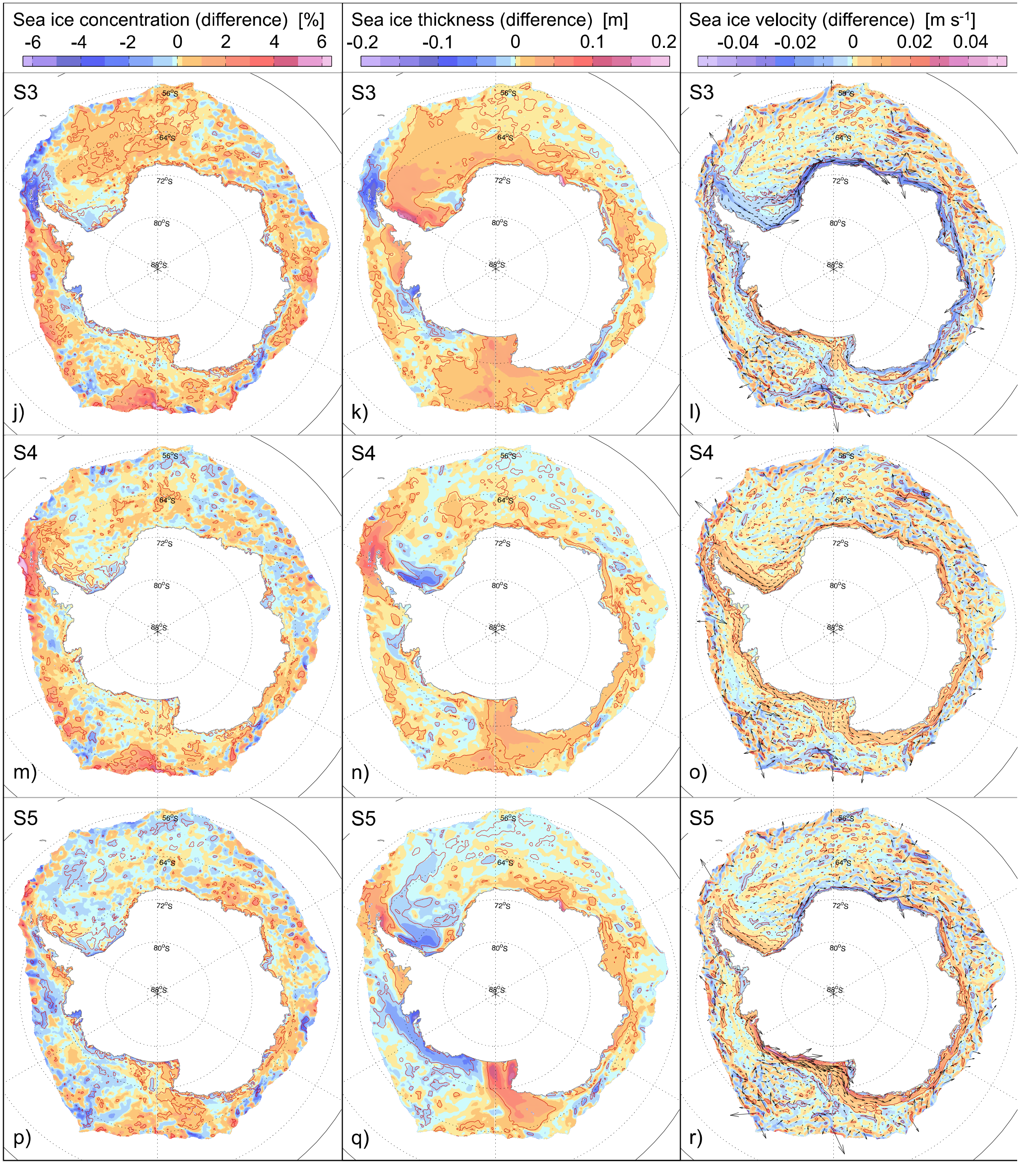


**Figure 2 (continued).**

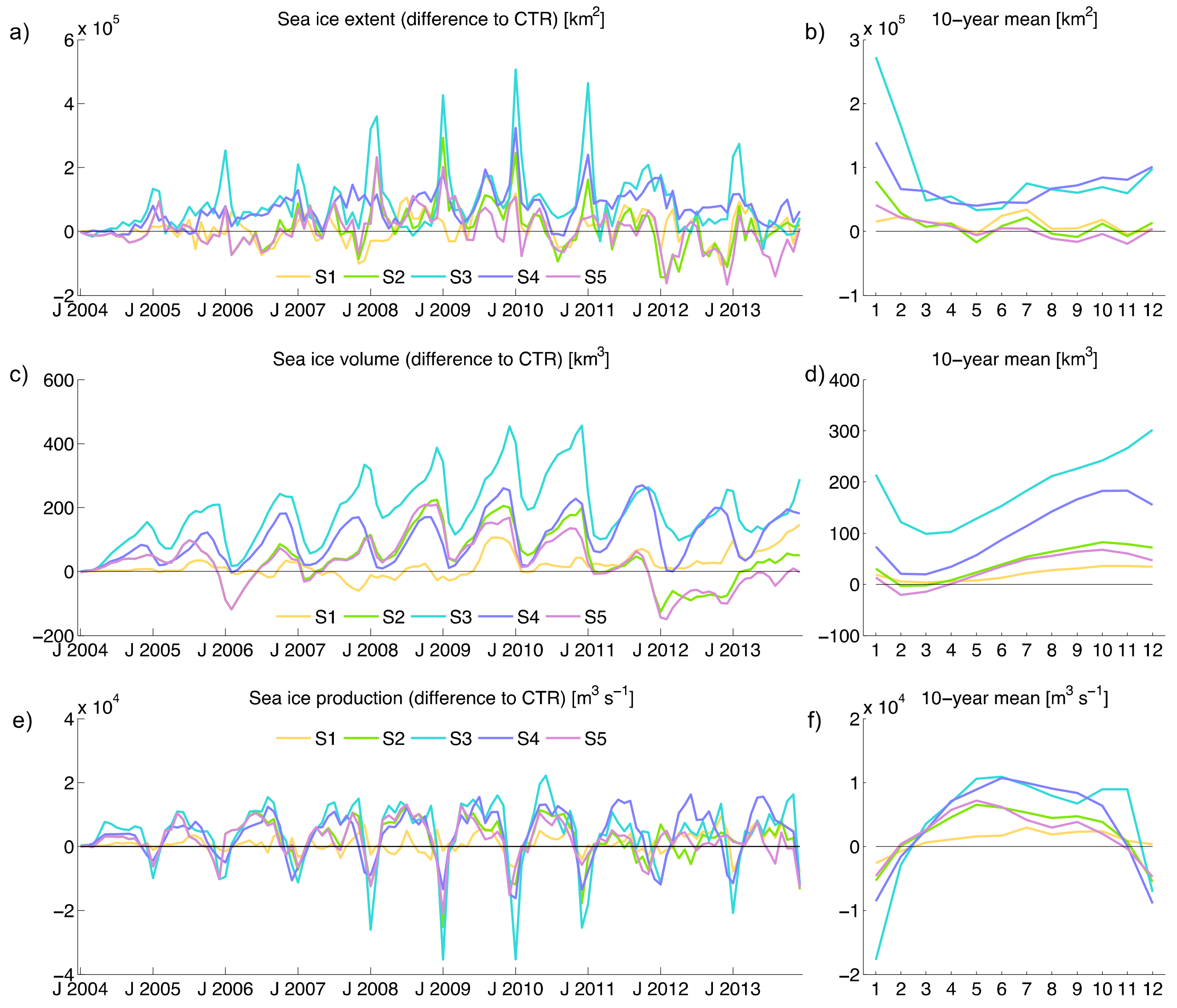


**Figure 3: Time series of the differences of (a-b) sea ice extent, (c-d) sea ice volume and (e-f) sea ice production between respective scenario and CTR, monthly values for 2004-2013 (left column), monthly values averaged over the 10-year period (right column).**

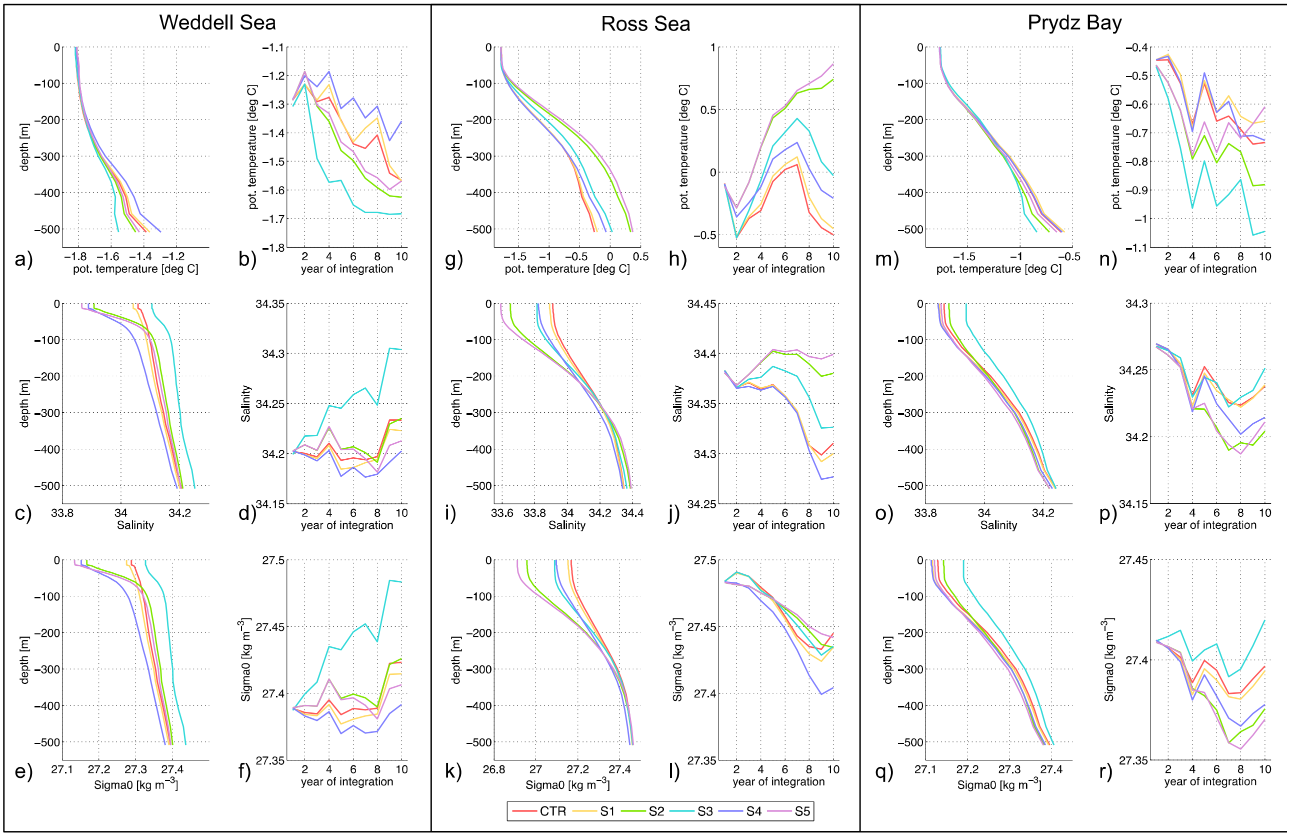


**Figure 4. Mean vertical profile ≤550 m depth (left) and annual mean values at the 550m isobath (right) of potential temperature, salinity and sigma0 in April-September in the a-f) Weddell Sea, g-l) Ross Sea and m-r) Prydz Bay.**

**Table 1: Main features of the experiments.**

| Simulation | Runoff amount [Gt $yr^{-1}$] | Runoff distribution |
|---|---|---|
| CTR | 2610 | Uniform, coastal |
| S1 | 2740 | Uniform, coastal |
| S2 | 2760 | Regional, coastal |
| S3 | 2760 | Regional, including offshore distribution |
| S4 | 3030 | Additional coastal runoff at major ice shelves |
| S5 | 2760-3030 | Regional, coastal, increasing in 4 steps |

**Table 2. Differences between S2 and CTR computed as winter mean over the selected regions for the 2004-2013 period. Positive numbers are printed in bold font.**

| Region | Runoff [Mt] | Ice production [$km^3\ d^{-1}$] | Ice concentration [%] | Ice thickness [cm] | Ice volume [$km^3$] |
|---|---|---|---|---|---|
| West. Weddell Sea (WWeS) | **30** | **0.17** | -0.1 | -1.0 | -14 |
| East. Weddell Sea (EWeS) | -8.4 | -0.07 | **0.04** | **0.6** | **5.0** |
| Cosmonaut Sea (CoS) | -16 | -0.05 | **0.3** | **1.1** | **6.8** |
| Prydz Bay (PrB) | -8.1 | -0.005 | **0.04** | **0.6** | **4.2** |
| Wilkes Land (WiL) | **1.1** | **0.02** | **0.02** | **0.8** | **4.0** |
| Adelie Land (AdL) | -13 | -0.06 | -0.06 | **0.3** | **2.0** |
| West. Ross Sea (WRoS) | -0.84 | **0.24** | **0.17** | **3.7** | **37** |
| East. Ross Sea (ERoS) | **8.4** | **0.15** | -0.16 | -1.6 | -10 |
| Amundsen Sea (AmS) | **42.7** | **0.15** | -0.34 | -3.3 | -11 |
| Bellingshausen Sea (BeS) | **0.9** | **0.016** | **0.29** | **1.8** | **2.8** |

## Contents



## Supplement S1 Control run

Here, we present results from the control run (CTR). To get an overview over the model's performance, we compare them to observations of sea ice (Cavalieri et al., 1996) and ocean temperature and salinity (Orsi and Whitworth, 2005). For the sea ice characteristics, the main focus is on the last decade (2004-2013), since it will be used for the comparison in Section 3. For the water characteristics, the model data from the year corresponding to the observation was used.

### S1.1 Sea ice characteristics

The modeled sea ice concentration around Antarctica is compared with data obtained from passive microwave data sensors (Cavalieri et al., 1996) in Figure S1a-d. The model result matches the observations very well. It successfully reproduces the spatial distribution for both the minimum sea ice extent in March and the maximum sea ice extent in September. In March, a sea ice maximum is found in the western Weddell Sea. Also the Ross and Amundsen Seas feature large remnants of the ice cover, while less sea ice is found along the coastline of East Antarctica. However, the March ice concentration in the simulation tends to be lower than in the satellite data.

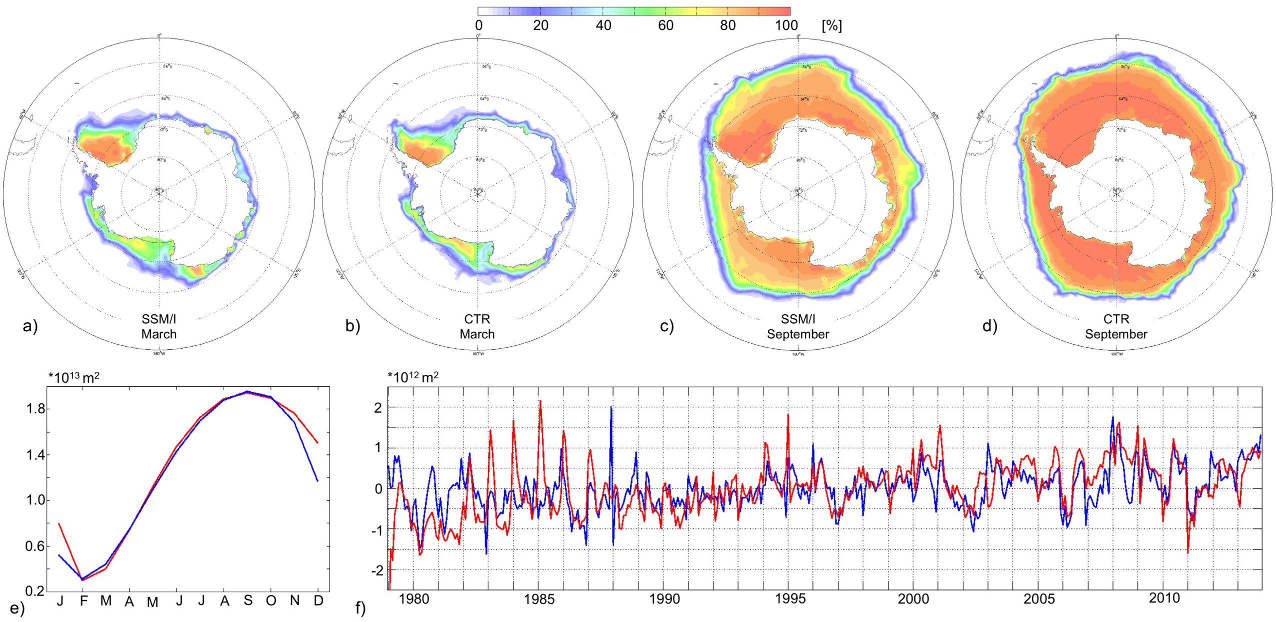


Figure S1: a-d) Sea ice concentrations, mean 2004-2013; e) mean seasonal cycle of sea ice extent 1979-2013 and f) divergence from mean seasonal cycle of sea ice extent, SSM/I observations (blue) and CTR (red).

In September, the model features a sea ice outline that matches the observed shape very well. We find northward outcrops of the sea ice east of the South Sandwich Islands (approx. 27° W), west of the southward bend of the Southwest Indian Ridge (approx. 15° E), close to the Kerguelen Plateau (approx. 80° E), at the eastern margin of the d'Urville Sea (approx. 155° E), and east of the Pacific Antarctic Ridge (approx. 152° W). While the observed sea ice covered area is matched very well by the model, the sea ice concentrations in September are slightly overestimated.
The confines of the sea ice covered area in winter are defined by the Antarctic circumpolar current (ACC). The warm surface temperatures of the ACC melt the ice and thus inhibit sea ice expansion. The larger discrepancies between model and observation can therefore be mainly attributed to the resolution of the bathymetry, which steers the ocean currents.

A time series of the sea ice extent for both, simulation and observation is calculated from the sea ice concentration data using a threshold of 15%. The mean seasonal cycle of the sea ice extent (Figure 2e) shows that CTR very well captures amplitude and range of the seasonal changes. The extremes in summer and winter are very close to the observations and also during the freezing period, the simulated sea ice extent does not differ far from the observations. Only during the melting season, the simulation features a considerably higher sea ice extent than observed. This indicates a delay in the onset of sea ice melting that can be explained by the overestimation of ice concentrations in winter. It is compensated by much faster melting toward the end of summer, which is due to a shallower summer mixed layer of the model leading to an overestimation of ocean surface temperatures.
A time series of the deviations of the sea ice extent from the mean seasonal cycle (Figure 2f) features periods of large discrepancies during the first decade. Thereafter, the differences between CTR and observations in the sea ice extent are smaller and the short-term anomalies of the sea ice extent show similar fluctuations in CTR and in the satellite observations.
The initially high but later diminished discrepancies between simulation and observation indicate that after 10 years the model is close to equilibrium. In the period 1989-2013, the short-term fluctuations of the sea ice extent predominantly seem to be caused by similar events in model and observation. Although resolution remains an ever-present challenge in sea ice modeling, the 0.25° resolution of the model proves high enough to transmit the most important fluctuations of atmosphere and ocean to the sea ice.
The trend for the sea ice extent calculated for the period 1989-2013 from the simulation (31.000 $km^2$ $yr^{-1}$) matches the corresponding trend from the observations (25.000 $km^2$ $yr^{-1}$) fairly well. However, the simulation's trend decreases for later (shorter) periods and turns even slightly negative for the last decade. Since this behavior is not seen in the observations, the model is evidently missing an aspect of the development of the sea ice extent and the atmosphere (in the simulation) can not by itself account for the change. It is therefore a likely assumption that changes (increase) in the Antarctic runoff, a probable driving force behind the positive trend, are the missing piece in the puzzle.

For other sea ice characteristics there is still only sparse data available and a comprehensive comparison between model results and observations is not yet possible. However, the sea ice thickness of CTR (Figure 3a) is close to expectations. Typically the highest sea ice thicknesses are found close to the continent, while the areas farther offshore are covered with thinner ice. In the Weddell and Ross Seas, we can see the northward transport of the sea ice leaving traces in the thickness distribution. The coastal westward drift (Figure 3b) leads to dynamic build up of the sea ice thickness on the eastern flanks of the coastline while the western flanks are typically accompanied by a minimum in ice thickness.

The long-term mean sea ice velocities are strongly influenced by the ocean surface velocities. In the ocean, the westward coastal current following the continental shelf break is connected to the eastward ACC by the cyclonic subpolar gyres. In the Ross Sea, we find the Ross Gyre not only exporting sea ice northward on its western branch, but also causing southward drift of sea ice on its eastern branch, although to a much smaller extent. The Weddell Gyre has a less well-defined eastern, southward branch, due to its greater variability, and there is no southward ice drift visible in the long-term mean.

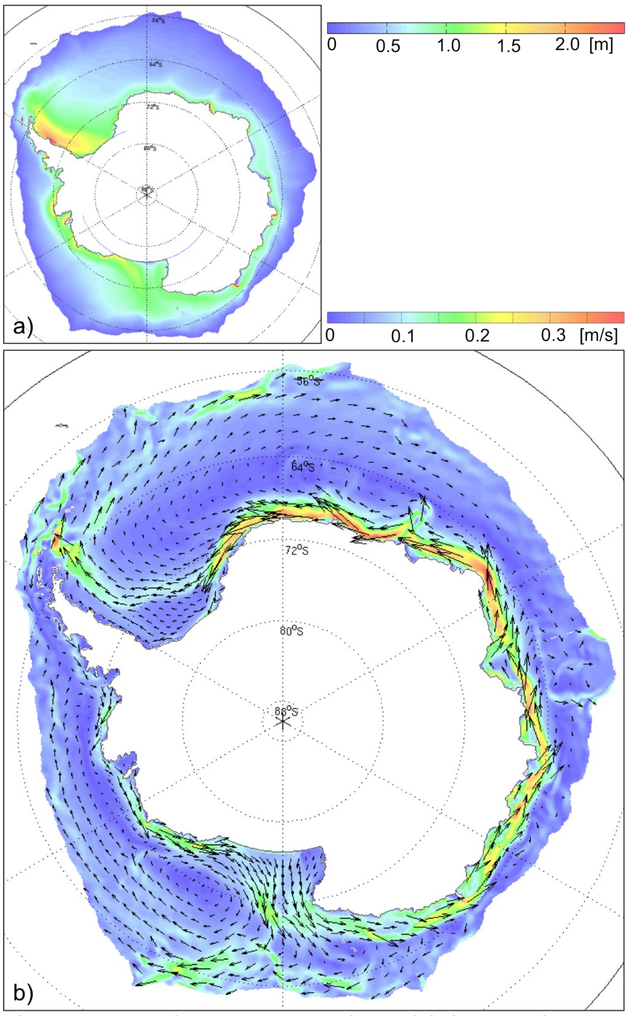

Figure S2: a) Mean sea ice thickness in CTR, April-September 2004-2013. b) Mean sea ice velocity in CTR, April-September 2004-2013.

S1.2 Water characteristics

In this chapter, salinity and potential temperature of CTR are compared to observations on two vertical sections through the Weddell and the Ross Seas. The measurements were taken during 1995 and 1992, respectively, and are compared to the annual mean of the corresponding year from the simulation.

The salinity and temperature section of CTR in the Weddell Sea from 15° W, 75° S to 37° W, 30° S is compared to the World Ocean Circulation Experiment (WOCE) Southern Ocean Atlas (Orsi and Whitworth, 2005) section A23. The comparison shows, that the model performs very well in reproducing the general characteristics of the different water masses. In the south close to the Antarctic continent, we find very cold and fresh waters at the surface with minimum temperatures close to the freezing point. Below the surface layer, we find slightly warmer and more saline waters, the Warm Deep Water (WDW), with a maximum in temperatures and salinity at ca. 400 m depth. With salinities slightly over 34.7 and temperatures reaching 1.4° C the simulation overestimates the maximum of the WDW. Below the WDW, salinity and temperature decrease again toward the bottom, where salinities below 34.66 and temperatures below -0.7° C are reached in the simulation. Compared to the observation the model’s bottom values are slightly too high.

In the north, the surface waters are several degrees warmer than in the south and temperatures decrease with depth, reaching -0.4° C at the bottom. Salinities, however, increase with depth in the upper ocean and we find a maximum of over 34.76 at depths of 1500-2000 m, below which salinities slightly decrease again to less than 34.66 at the bottom.

The slight overestimation of salinity and temperature of the WDW in the Weddell Gyre can be attributed to the fact that the coarser model topography allows the waters of the ACC to mix more easily with those of the gyre over the South Scotia Ridge.

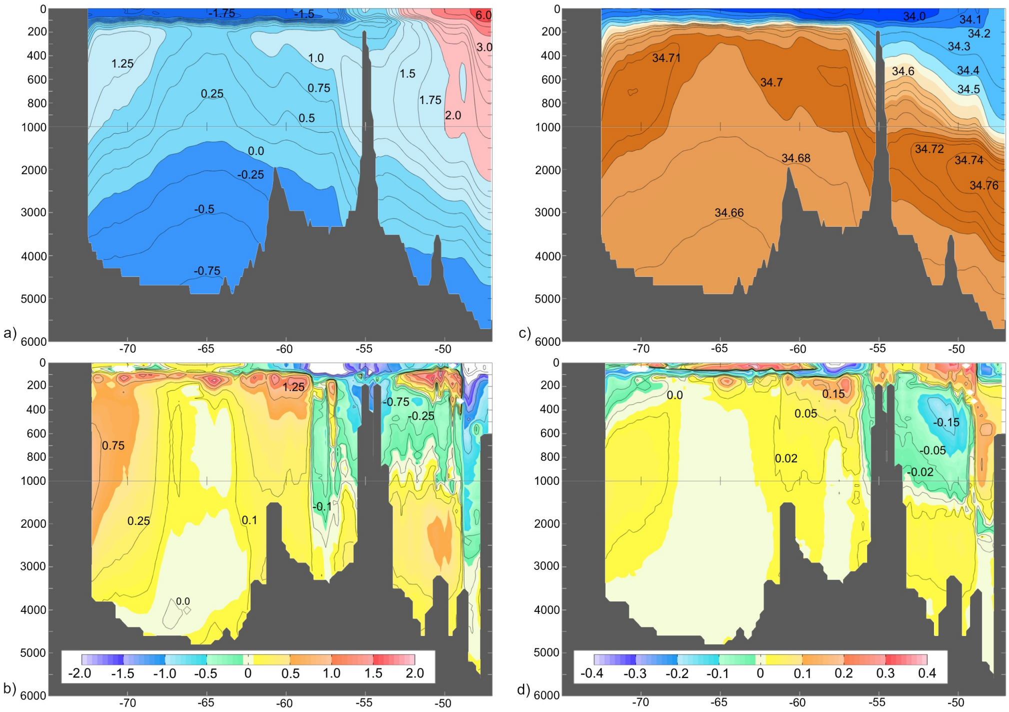


Figure S3: Section through the Weddell Sea (WOCE A23). a) CTR pot. temperature, b) difference to observed pot. temperature (Orsi and Whitworth, 2005), c) CTR salinity, d) difference to observed salinity (Orsi and Whitworth, 2005).

Also the bottom water in the Weddell Basin is slightly too warm and too saline. Apart from deficiencies in the topography of the South Scotia Ridge, that might let the dense water escape more easily into the open ocean, it is a common problem for OGCMs to correctly reproduce the modification of dense shelf water and ensuing formation of bottom water. While sinking down along the continental slope, the dense waters lose their characteristics too fast due to the model's limitations in resolution.

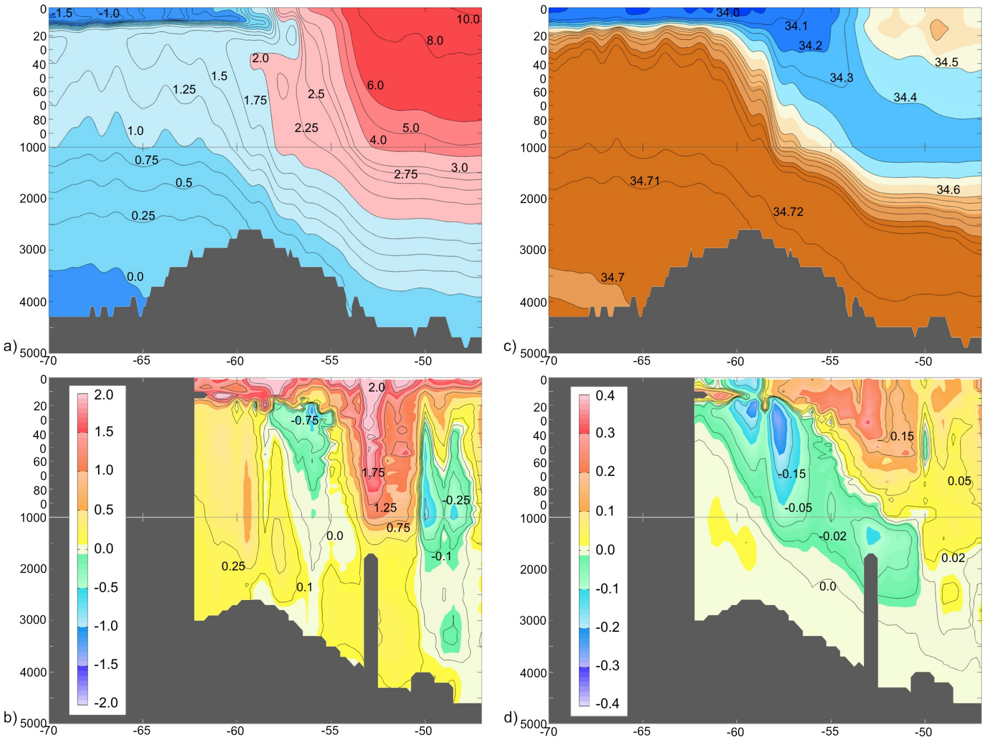


Figure S4: Section at 150° W (WOCE P16). a) CTR pot. temperature, b) difference to observed pot. temperature (Orsi and Whitworth, 2005), c) CTR salinity, d) difference to observed salinity (Orsi and Whitworth, 2005).

Another section of salinity and potential temperature in the eastern Ross Sea at 150° W also shows very good agreement between model and observation (WOCE section P16) (Figure 5). At the surface, we find cold and fresh ($S \approx 34.0$) waters close to the Antarctic continent and warm, slightly saltier ($S \approx 34.5$) waters in the north. At the bottom, we see the saline ($S > 34.7$) and relatively cold ($T < 0.8°$ C) waters from Antarctica spill over the topographic obstacle of the Pacific Antarctic Ridge into the world ocean. In the simulation, the bottom waters retained in the southern basin close to the Antarctic continent with temperatures of approx. 0.9° C and salinities of approx. 34.7 are slightly warmer and more saline than in the observation. As in the Weddell Sea, two processes can contribute to this: First, the coarseness of the bathymetry in the model allows the dense water to escape more easily from the basin, and second, the resolution of the model hinders the production of the dense deep waters.

Supplement S2 Difference between experiments S2 and S5 in SST and SSS

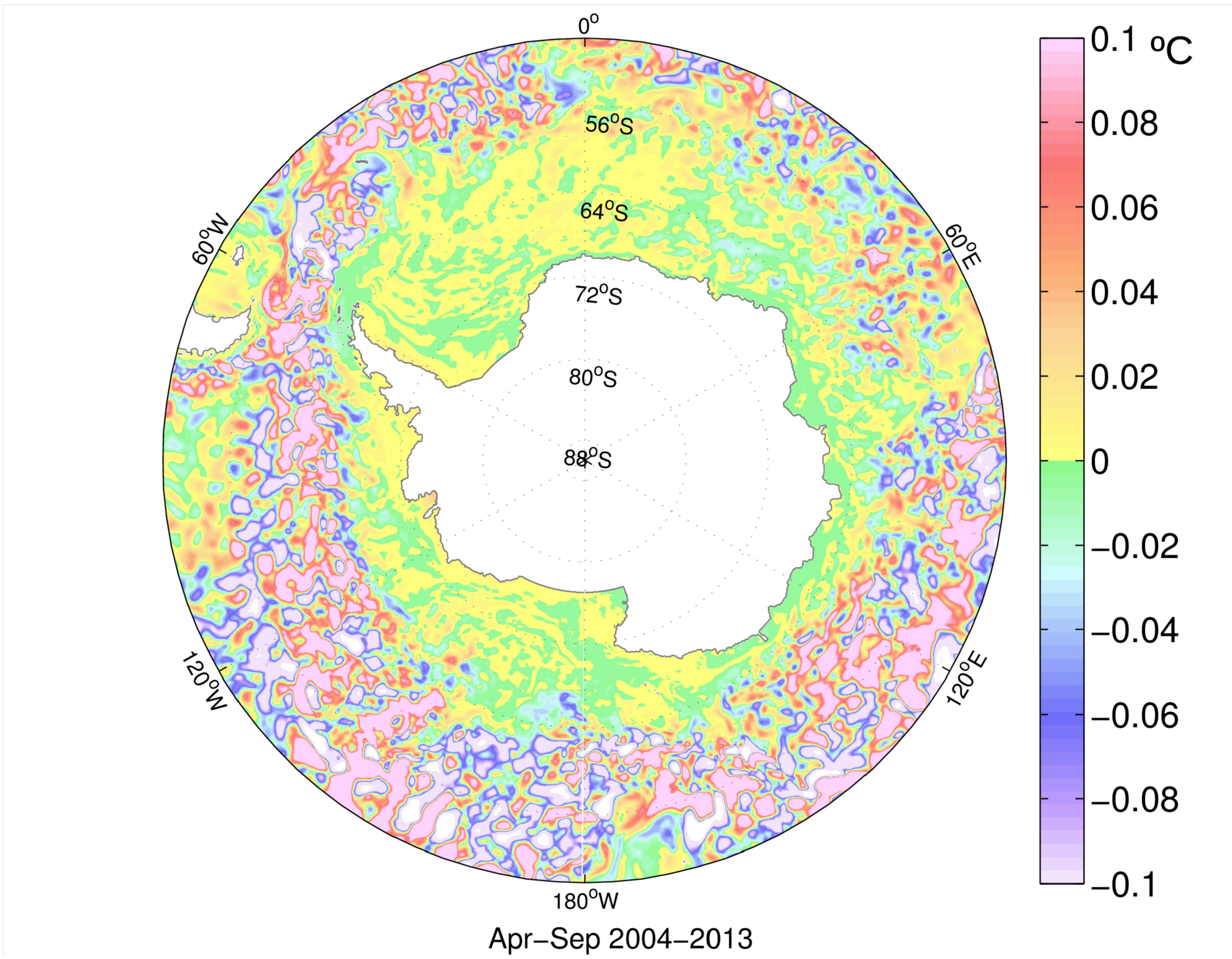


Figure S5: Difference of 10-year mean winter sea surface temperatures between experiments S2 and S5.

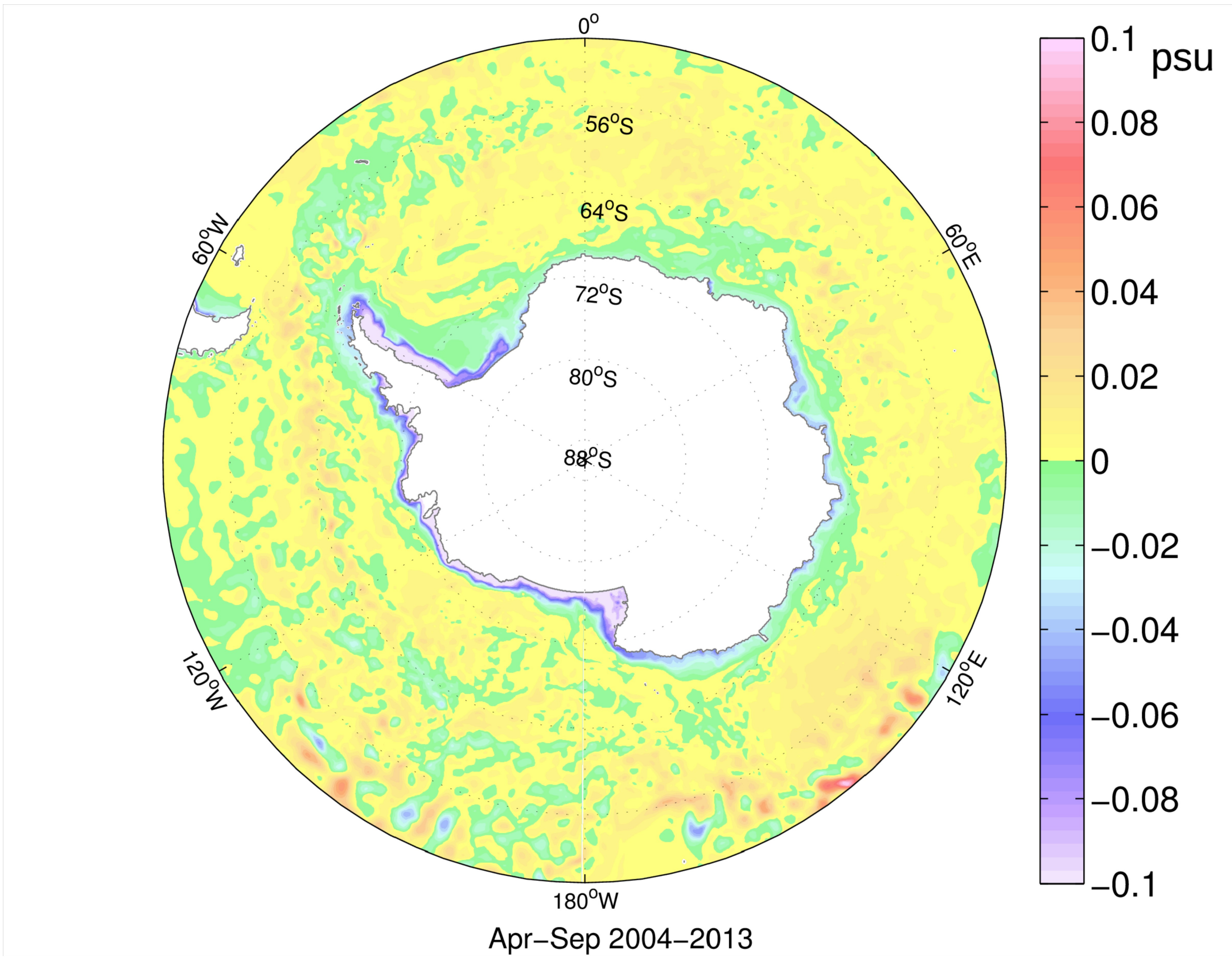


Figure S6: Difference of 10-year mean winter sea surface salinities between experiments S2 and S5.