

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 (p. 2, l. 32 – p. 3, l. 5): “*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. They 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 effect of artificially augmented, constant freshwater input on sea ice. They tested the sensibility to freshwater additions from current estimates to much larger values (3000 Gt yr<sup>-1</sup>) and compared an iceberg model-based surface distribution with a coastal distribution at the depth of the ice shelf front. Their model experiments show that enhancing the freshwater input by an amount within the range of estimates of the Antarctic mass imbalance does not significantly affect sea ice area, magnitude or trend. Further, their results show the sea ice response to be insensitive to the depth of freshwater injection.*”

In Section 4, we compare our findings with their results:

(p. 11, l. 24) “*On a hemispheric scale, they 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), Bintanja et al. (2015) and Pauling et al. (2016).*”

(p. 12, l. 20) “*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.*”

(p. 13, l. 9-16) “*Pauling et al. (2016) performed experiments with freshwater addition larger than estimates (up to 3000 Gt yr<sup>-1</sup> increase) with a fully coupled model. Using two different freshwater*

*distributions (ice shelf melt in front of ice shelves and at the depth of the front, and iceberg melt at the surface over a wide area), they found that the total sea ice area increases significantly under the large freshwater enhancement. In accordance with the similarities we see between our experiments S2-High and S3-High after 10 years of integration, their experiments show that the spatial distributions of the freshwater input have no significant influence on the sea ice response. However, S2-High and S3-High feature divergent behaviour on seasonal time scales. As Pauling et al. (2016) point out, differences in the model complexity (as forced vs. fully coupled configurations) and in their physics could lead to diverging results.”*

*(p. 13, l. 21) “The effect on the sea ice may be small as Pauling et al. (2016) recently found for the depth distribution of additional fresh water in the Southern Ocean.”*

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. Since we find the results from that experiment very interesting and contrary to our expectations, we conducted two more simulations with larger freshwater addition in two different spatial distributions. The sea ice response in these runs strengthens the robustness of our model results. Under these 2 “extreme” runoff forcings, our model reproduces the same principal result supporting the hypothesis that sea ice extent and volume can decrease despite an increased freshwater addition.

The revised manuscript includes the new experiments, with consequent changes to the text.

The name S2-Incr is now used to identify the run previously-called S5. The new experiments with larger freshwater addition are named S2-High and S3-High and are based on runoff spatial distribution of S2 and S3, respectively. Figure 1 now includes the new experiments. We extracted S5 (now S2-Incr) from the Figures 2, 3 and 5 (formerly Figure 4) and included a new Figure 4, setting the ice extent and volume of the new runs in context with CTR, S2 and S3. Also, we changed the text at several locations, the most important of which follow:

In the Abstract (p. 1, l. 15):

*“Only for “extreme” freshwater additions, our experiments show a negative development of the sea ice extent.”*

In Section 1 (p. 3, l. 18-21):

*“Three additional experiments with enhanced freshwater amounts exceeding the range of current estimates (70-290 Gt yr<sup>-1</sup>; (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), allow us to gain insight in possible future sea ice changes.”*

In Section 2.1 (p. 4, l. 20):

*“A suite of simulations is presented in this manuscript: a control run (hereafter CTR) and seven sensitivity experiments (S1-S4, S2-Incr, S2-High and S3-High).”*

In Section 2.2 (p. 6, l. 7-12):

*“We present three additional experiments in which the amount of additional fresh water exceeds the range of current Antarctic mass loss estimates. These runs are an attempt to determine how much fresh water is required to have a significant effect on the sea ice area trend, in our model. The spatial runoff distribution in the experiments S2-Incr and S2-High is based on S2 simulation, while the experiment S3-High follows the S3 distribution including the widespread offshore freshwater addition. In S2-Incr, the runoff increases from 2760 Gt yr<sup>-1</sup> in 2004 to 3310 Gt yr<sup>-1</sup> in 2013 in 4 steps (137 Gt yr<sup>-1</sup> every 2 years). In S2-High and S3-High, a constant freshwater input of 3310 Gt yr<sup>-1</sup> is added around Antarctica*

*in different spatial distributions.”*

In Section 3.1 and 3.2, we removed the paragraphs referring to S5.

We turned Section 3.3 into an independent Section 4, where we added the following text (p. 12, l. 25 – p. 13, l. 18):

*“Our three additional experiments, where the freshwater input (up to 550 Gt yr<sup>-1</sup>) is beyond the range of current estimates, are an attempt to determine how an “extreme” amount of fresh water in our model configuration impacts the sea ice extent. The experiments S2-High and S3-High were motivated by the results of S2-Incr, with the objective to verify and understand the unexpected circumstance that more fresh water can cause a decrease in sea ice (as in the comparison of S2-Incr with S2). As described in Sect. 2.2, S2-Incr and S2-High differ from S2 in the amount of additional fresh water, but are based on the same spatial distribution, and S3-High features the same freshwater enhancement as S2-High, but with the S3 spatial distribution that also mimics iceberg melt. Compared to S2 and S3, the amount of Antarctic fresh water is increased by 20% in S2-High and S3-High (the 20% increase is reached in 2012 in S2-Incr). Our model results suggest that the sea ice trend is dependent on the amount of fresh water added to the Southern Ocean. In fact, in response to “extreme” freshwater addition in our model, sea ice starts to decrease (Figure 5).*

*In all three experiments, there is a reduction of the sea ice extent and a loss of ice volume apparent in comparison with their respective base experiment (S2 or S3) toward the end of the simulated decade. The seasonal mean (Figure 5) still bears the imprint of a negative trend in both sea ice extent and volume in S2-High and S3-High. The ice loss occurs primarily in the Weddell Sea and is linked to a destabilisation of the water column. The faster coastal current, as dynamic response of the ocean to freshwater input (as in Figure 2), leads to increased Ekman pumping and offshore upwelling. Increased salinities and temperatures at the surface can enhance ice melt or reduce ice formation. Once a reduction of sea ice occurs, a positive feedback loop between sea ice cover and ocean heat uptake from shortwave radiation is triggered (Stammerjohn et al., 2012).*

*Our results with “extreme” freshwater input suggest that sea ice trend is sensitive to the amount of fresh water and to the method by which it is added. Pauling et al. (2016) performed experiments with freshwater addition larger than estimates (up to 3000 Gt yr<sup>-1</sup> increase) with a fully coupled model. Using two different freshwater distributions (ice shelf melt in front of ice shelves and at the depth of the front, and iceberg melt at the surface over a wide area), they found that the total sea ice area increases significantly under the large freshwater enhancement. In accordance with the similarities we see between our experiments S2-High and S3-High after 10 years of integration, their experiments show that the spatial distributions of the freshwater input have no significant influence on the sea ice response. However, S2-High and S3-High feature divergent behaviour on seasonal time scales. As Pauling et al. (2016) point out, differences in the model complexity (as forced vs. fully coupled configurations) and in their physics could lead to diverging results. With the low stability of the Southern Ocean water column, small differences in the chosen parameterizations, e.g. in the vertical mixing, can have a large effect on the sea ice. This is especially known for the Weddell Sea, which is the main region of sea ice loss in our experiments.”*

In Section 5 (formerly 4), we removed the paragraphs referring to S5.

In the concluding Section 6 (formerly 5; p. 15, l. 10):

*“However, we find a strong dependency on the amount of freshwater addition, as in our model large amounts of fresh water can affect the sea ice trend inversely. Our experiments with the strongest freshwater forcing result in a decrease in sea ice extent and volume.”*

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.

We performed our sensitivity experiments with the aim to analyse the very-short-term response of the sea ice and upper ocean to an idealized “perturbation” of the system. The 10 years of integration are not sufficient to let the ocean reach equilibrium after the disturbance at the surface. Comparing the model results to the reference simulation within this time window, we investigate the sea ice behaviour and the feedbacks with the water masses (mainly on the continental shelf areas) under an imposed “climate change” (as may currently be observed in the real sea ice/ocean), not the state the system would have reached after re-finding its balance. For this, we are more interested in the qualitative response and the underlying processes than a quantitative assessment and an exact reproduction of observations.

We compare experiments, which differ only in the addition of freshwater. The different results are reliably caused by the differences in runoff input.

We agree with the referee that a stronger corroboration of the mentioned turning point by additional experiments is beneficial. We performed two additional experiments with even higher freshwater addition, which both resulted in sea ice loss, thus substantiating the possible reversal of the sea ice trend (at least in our model). (See also answer to Main comments #2)

In Section 2.2, we added the following text: “The sensitivity experiments are run from 2004 to 2013. The 10-year period is not sufficient to let the 3D ocean reach equilibrium after the disturbance at the surface. However, this study only aims to examine the very-short-term response of the sea ice and upper ocean system to the imposed idealized changes in the Southern Ocean freshening, via the comparison to the CTR run. “

#### 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 applied in our reference run (CTR) is derived from the river runoff dataset by Dai and Trenberth (2002) and Dai et al. (2009) for the major rivers, while the Antarctic coastal freshwater discharge is based on estimates by Jacobs et al. (1992). Bourdalle-Badie and Treguier (2006), who joint the two datasets and adapted them to the ORCA025 model grid, also applied a *pseudo* annual cycle to the Antarctic contribution, with the maximum of ~0.15 Sv in December/January and the minimum of 0.04 Sv in June/August.

Bourdalle-Badie, R. and Treguier, A.-M.: A climatology of runoff for the global ocean-ice model ORCA025, Report, MercatorOcean, MOO-RP-425-365-MER, 2006.

Dai, A., T. Qian, K. E. Trenberth, and J. D Milliman, 2009: Changes in continental freshwater discharge from 1948-2004. *J. Climate*, **22**, 2773-2791.

Dai, A., and K. E. Trenberth, 2002: Estimates of freshwater discharge from continents: Latitudinal and seasonal variations. *J. Hydrometeorol.*, **3**, 660-687.

Jacobs S. S., H. H. Hellmer, C. S. M. Doake, A. Jenkins, R. M. Frolich (1992), Melting of ice shelves and the mass balance of Antarctica, *J. Glacio.* **38**, 375-387.

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.

In the article, we refer to the variability of the change effected in a sea ice property, i.e. whether a (detrended) time series has a high or low standard deviation.

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 conducted further experiments to substantiate our results (see Main comments #2 and #3). We would like to mention here, that there are no changes in the initial conditions in our experiments or any other introductions of randomness. We do not consider the results of a singular experiment. We always compare two experiments that only differ in the freshwater input. The differences in output between our experiments are therefore not random, but the result of the changes introduced by the modifications of the freshwater.

#### TECHNICAL COMMENTS

p. 2, line 9-10: Merino et al and Pauling et al (2016) need to be added to the previous studies.

As suggested, we included the studies by Merino et al. (2016) and Pauling et al. (2016) in the revisited manuscript. We added the following text in Section 1 (p. 2, l. 32 – p. 3, l. 5): “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. They 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 effect of artificially augmented, constant freshwater input on sea ice. They tested the sensibility to freshwater additions from current estimates to much larger values (3000 Gt yr<sup>-1</sup>) and compared an iceberg model-based surface distribution with a coastal distribution at the depth of the ice shelf front. Their model experiments show that enhancing the freshwater input by an amount within the range of estimates of the Antarctic mass imbalance does not significantly affect sea ice area, magnitude or trend. Further, their results show the sea ice response to be insensitive to the depth of fresh water injection.”

We discuss the consistency of the sea ice response in our sensitivity runs and experiments by Pauling et al. (2016) in Section 4 (p. 13, l. 8-18): “Our results with “extreme” freshwater input suggest that sea ice trend is sensitive to the amount of freshwater and to the method by which it is added. Pauling et al. (2016) performed experiments with freshwater addition larger than estimates (up to 3000 Gt yr<sup>-1</sup> increase) with a fully coupled model. Using two different freshwater distributions (ice shelf melt in front

of ice shelves and at the depth of the front, and iceberg melt at the surface over a wide area), they found that the total sea ice area increases significantly under the large freshwater enhancement. In accordance with the similarities we see between our experiments S2-High and S3-High after 10 years of integration, their experiments show that the spatial distributions of the freshwater input have no significant influence on the sea ice response. However, S2-High and S3-High feature divergent behaviour on seasonal time scales. As they point out, differences in the model complexity (as forced vs. fully coupled configurations) and in their physics could lead to diverging results. With the low stability of the Southern Ocean water column, small differences in the chosen parameterizations, e.g. in the vertical mixing, can have a large effect on the sea ice. This is especially known for the Weddell Sea, which is the main region of sea ice loss in our experiments. “

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.

The fact that their fresh water addition was constant is now mentioned in the text.

In the Introduction (Section 1, p. 2, l. 34), we say: “Pauling et al. (2016) employed an Earth-system model to investigate the effect of artificially augmented, constant freshwater input on sea ice.”

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?

For most of the global domain the river runoff is a monthly climatology derived from the freshwater discharge dataset by Dai and Trenberth (2002) and Dai et al. (2009). Their dataset includes the river outflow for the largest 925 ocean-reaching rivers on global scale. The following plot (Figure 1 in Dai et al. 2009) shows the locations of the gauge stations used in their study. Unfortunately, their estimate of the global freshwater discharge excludes an estimate of the freshwater flux from Antarctica, as reported in Section 4. in their manuscript “...our estimates of the continental discharge include runoff from all land areas except Antarctica...” The contribution of Antarctica freshwater applied in our reference simulation relies on estimates of  $2613 \text{ kg y}^{-1}$  ( $0.0829 \text{ Sv}$ ) by Jacobs et. al. (1992). Bourdalle-Badie and Treguier (2006) distributed the Antarctic freshwater contribution as a uniform flux along the coastal points around the Antarctic continent and applied a *pseudo* annual cycle to it (as described in our answer to comment #4).

To more clearly explain this, we changed the description of the runoff data set in Section 2. as follow: “The runoff data is a monthly climatology derived from the Global River Flow and Continental

Discharge Data Set (Dai and Trenberth, 2002; Dai et al., 2009) for the major rivers and estimates by Jacobs et al. (1992) for the Antarctic coastal freshwater discharge. It has been adapted to the ORCA025 grid and applied along the land mask (Bourdalle-Badie and Treguier, 2006).” We 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.

We added the following sentence in Section 2.2 (p. 5, l. 11). “*A short overview of 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 suggested studies are now added with mention of the iceberg model-derived distribution in the Introduction (Section 1.) and our findings are compared with their results in Section 4 (formerly 3.3). (See also Main comment #1).

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 column of Figure 2 shows the differences in sea ice velocity between a single sensitivity run and CTR as arrows and the corresponding differences in vector magnitude (speed) as filled coloured contours. We modified the figure caption as follows:

(p. 21) “Figure 2: Maps of winter sea ice a) concentration, b) thickness, and c) velocity in CTR averaged over April - September 2004 – 2013. b-r) Difference of ice concentration (left), thickness (middle), and velocity (right) between respective experiment and CTR. The colors underlying the velocity arrows indicate the difference in vector magnitude (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.”

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 now clearly stated in Section 3, p. 6, l. 20: “*In the following, the word winter referring to a specific time period identifies the period 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 (Vancoppenolle et al., 2012).

Vancoppenolle, M., Bouillon, S., Fichefet, T., Goosse, H., Lecomte, O., Morales Maqueda, M. A., and Madec, G.: The Louvain-la-Neuve sea ice model, Notes du pole de modélisation, Institut Pierre-Simon Laplace (IPSL), Paris, France, no. 31, ISSN No 1288-1619, 2012.

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 that we cannot mark all the place names mentioned in the manuscript within our Figure 1. We therefore kindly ask readers unfamiliar with the main features of the Antarctic geography 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?

Since the question of the experiment S5 (now S2-Incr) has in the meantime changed character and the manuscript has been adapted to include the new runs, we decided not to include the figure in the article. However, we are happy to include figures of the differences in SSS and SST between the runs S2-High and S2, and S3-High and S3 here in our response (Figure R1). We hope that this serves as helpful illustration beyond the scope of the article itself.

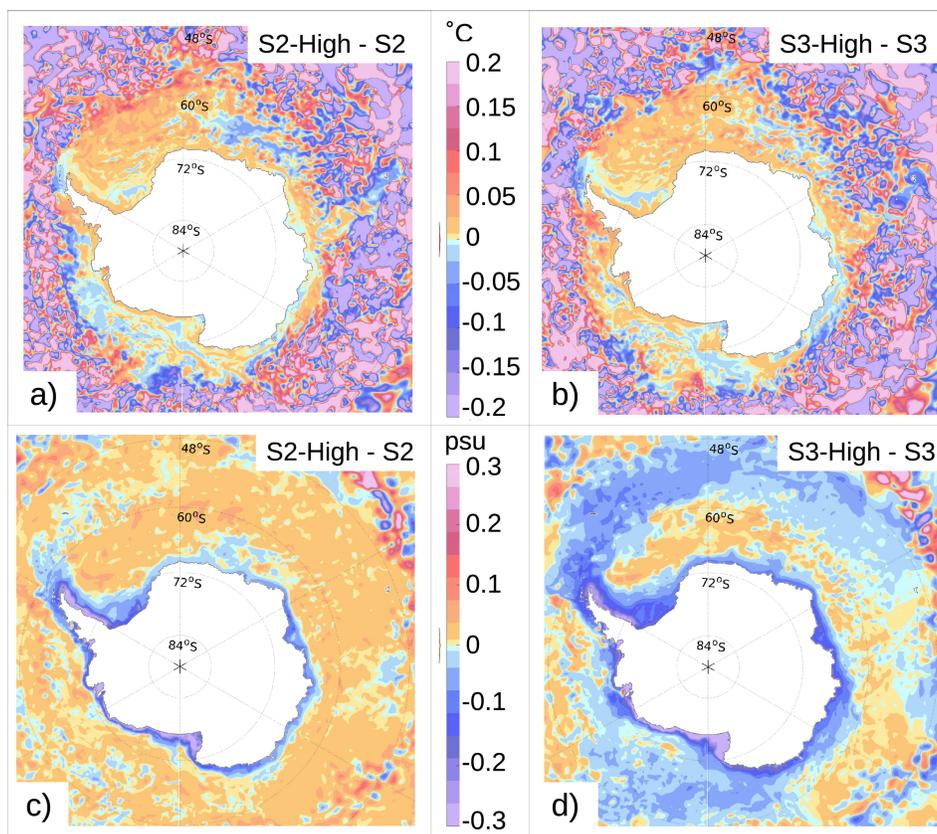


Figure R1: Maps of sea surface a-b) temperature and c-d) salinity averaged over April - September 2011 – 2013 between the named experiment and its base experiment.

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.](#)

[In Section 3.2 \(p. 11, l. 17\): “This behaviour is strengthened by a positive feedback loop \(Stammerjohn et al., 2012\) as long as the ocean gains heat.”](#)

[In Section 4 \(p. 13 l. 7\): “Once a reduction of sea ice occurs, a positive feedback loop between sea ice cover and ocean heat uptake from shortwave radiation is triggered \(Stammerjohn et al., 2012\).”](#)

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. This part of the text was removed due to the changes involved with the new experiments (see Main comment #2)

p. 14, line 2: replace “lose density” with “density reduces”

The wording has been changed to (p. 15, l. 23) “*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 Section 1 and Section 3.3. (See also Main comments #1)

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 column of Figure 2, the colour scale refers to speed, while the arrows depict velocity. A short explanatory text was added to the caption. “The colours underlying the velocity arrows indicate the difference in vector magnitude (speed).”

The 'winter' period in our article always refers to the months April-September. The period is now also mentioned in the figure texts (where relevant). 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. Obviously, any trends in the time series will also leave an imprint here. Also, 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~~ freshwater changes on the ~~Southern Ocean~~ Antarctic sea ice in an eddy-permitting sea ice-ocean model

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10 **Abstract.** In a warming ~~climate~~ climate, ~~satellite data~~ 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. ~~Here, We~~ investigated the sea ice response to changes in ~~both~~ the amount and ~~especially~~ the spatial distribution of freshwater ~~input to the ocean~~. ~~We performed a sensitivity study~~ by comparing a set of numerical ~~sensitivity~~ 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.

15 Our results confirm that ~~enhancing the an increase in~~ fresh-water input can increase the sea ice extent. ~~Only for “extreme” freshwater additions~~, our ~~experiments show a negative development ofn inversion of the sea ice extent trend~~. ~~However, a very strong increase of freshwater will eventually invert the trend. Our experiments suggest~~ We find that the spatial distribution of the fresh water is of great influence ~~on sea ice concentration and thickness as- I~~ it affects sea ice dynamics and

20 ~~thermodynamics. can strongly alter regional sea ice concentration and thickness~~. For strong regional contrasts in the freshwater addition the ~~dynamic response dominates 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 ~~currently~~ contributes between 5% and 24% to the trend observed in

25 the sea ice extent.

## 1 Introduction

30 Sea ice is one of the key components of the polar climate system controlling air-ocean exchange and driving deep ocean convection. Even though in situ observations show a prevailing atmospheric and oceanic warming trend, satellite-based observations indicate that Antarctic sea ice has been expanding over the past few decades (e.g. Collins et al. 2013). 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 net (circumpolar-averaged) trend is the sum of partly opposing regional trends of the same order of magnitude (Parkinson and Cavalieri, 2012). The causes of this positive trend in a generally warming world are still debated. Several mechanisms have been proposed to explain the expanding Antarctic sea ice. Many studies, for example, 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-can 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, 2015) investigated the sensitivity of Antarctic sea ice to an increase of freshwater flux intended to reproduce current sources from Antarctic ice shelf melt. Bintanja et al. (2013) suggested that including realistic changes in the Antarctic ice sheet mass in a coupled climate model can lead to a better simulation of the evolution of the sea ice in the Southern Ocean. In their study, with a freshwater increaseflux of 250 Gt yr<sup>-1</sup> under constant year 2000 forcing, sea ice concentration increased up to 10 % over a ~30year period, suggesting that the net sea ice trend is dominated by the increased ice-shelf melt, while winds may be responsible for the regional trends. Bintanja et al. (2015) then assessed the effect of increased (basal) melt rate of the Antarctic ice sheet and the associated freshwater flux on future sea-ice trends in a RCP8.5 scenario. In their coupled simulations, projected mass losses of the Antarctic ice sheet impact the future sea-ice trend: an additional additional-freshwater forcing (120 Gt yr<sup>-1</sup>) significantly is necessary offsets the sea ice area decline and is even able to reverse thethe sign of the sea ice trend to positive values in the strongest freshwater forcing scenario (120 Gt yr<sup>-1</sup>).

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 On the other hand, Swart and Fyfe (2013) showed that an accelerating rate of freshwater forcing, with a magnitude constrained by observations, in unlikely to impact significantly the Antarctic sea ice trends simulated by the CMIP5 models, 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 opinions~~ suggest 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~~ They 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 effect of Southern Ocean sea ice response to artificially augmented, constant freshwater input on sea ice. They tested the sensibility to higher freshwater additions from than current estimates to much larger values (3000 Gt yr<sup>-1</sup>) and previous studies and compared an iceberg model-based surface distribution with a coastal distribution at the depth of the ice shelf front. Their model experiments show that enhancing the freshwater input by an amount within the range of estimates of the Antarctic mass imbalance does not significantly affect sea ice area, magnitude or trend. Further, their results show the sea ice response to be insensitive to the depth of freshwater injection. ~~sea ice response to be insensitive to the depth of fresh water injection.~~

~~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. Generally, the previous studies use very crude renderings of the spatial distribution of the freshwater addition. Here, ~~We~~ 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-Four~~ experiments are carried out with differing spatial distribution and magnitude of the Antarctic freshwater flux at surface are analysed with respect to. Specifically, we study the response of sea ice concentration, thickness, and velocity in space, and extent, volume and production over time. ~~and deduce~~ In addition, ~~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 dynamically and thermodynamically to spatially limited changes in the freshwater input. Thus, they provide ~~and thus give us~~ a measure of what to expect as a sea ice response to observed changes in the runoff, and also offer explanations for observed changes in sea ice and water properties.

Three additional experiments with ~~additional~~enhanced freshwater amounts exceeding the range of current estimates (~~that vary from 70-290 Gt yr<sup>-1</sup>~~; (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), allow us to gain insight in possible future sea ice changes ~~and shortcomings of simple distributions widely used in climate modelling.~~

## 5 2 Methods

### 2.1 Model description

10 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 is a finite difference, hydrostatic, primitive equation ocean general circulation model. Our configuration employs ~~are run on~~ a global ORCA025 tripolar grid (Madec and Imbard, 1996) ~~whose 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.  $\approx 10$  km at 70°S (1442 grid points  $\times$  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).

15 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.

20 The ~~ocean general circulation model OPA is a finite difference, hydrostatic, primitive equation ocean general circulation model and model~~ uses a linear free surface and an energy and enstrophy conserving momentum advection scheme. The horizontal viscosity is bi-Laplacian with a value of  $1.8 \times 10^{11} \text{ m}^4 \text{ s}^{-1}$  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  $300 \text{ m}^2 \text{ s}^{-1}$ . 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  $1 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$  and a globally constant background viscosity of  $1 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ . The bottom friction is quadratic. A diffusive bottom boundary layer scheme is included.

25 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  
30 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).

5 | A suite of simulations is presented in this manuscript: a control run (hereafter CTR) and ~~five-seven~~ sensitivity experiments (S1-S4, [S2-Incr](#), [S2-High](#) and [S3-High5](#)). 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  
10 | 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 runoff data is a monthly climatology derived from the Global River Flow and Continental Discharge Data Set \(Dai and Trenberth, 2002; Dai et al., 2009\) for the major rivers and estimates by Jacobs et al. \(1992\) for the Antarctic coastal freshwater discharge. It has been adapted to the ORCA025 grid and applied along the land mask \(Bourdalle-Badie and Treguier, 2006\). The river runoff data is a monthly climatology derived from Dai and Trenberth \(2002\) and applied along the land mask by the DRAKKAR group.](#) It includes 109 major rivers and a coastal runoff ~~and has a~~ [with a global](#) mean value of 1.26 Sv. The fresh water is added ~~at~~ the surface with zero salinity and at sea surface temperature. In the areas of freshwater addition, the vertical diffusion is enhanced (mixing coefficient:  $2 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$ ) over a depth of 15 m. In the Southern Ocean, ~~we vary~~ the runoff field ~~is modified between simulations~~, as described in the next section. The runoff follows a seasonal  
15 | cycle, which is unaltered relative to the mean amount in [S1-S5 all experiments](#) (Figure 1a). No surface restoring for tracers was used in the simulations. The simulation was run without any constraint on the freshwater budget.  
20 |

## 2.2 Experiment design

To test the response of sea ice to changes in the melting of glacial ice around Antarctica, we present ~~five-seven~~ sensitivity experiments in this study, where the surface freshwater input is modified in its magnitude and spatial distribution. ~~It is worth mentioning that our study does not attempt to closely reproduce reality, but aims to investigate the response of our ocean-sea ice system to an additional forcing.~~ Ice shelves and icebergs are not explicitly resolved in our configuration; therefore any source of melt water is represented in the runoff field. ~~The sensitivity experiments are run from 2004 to 2013. The 10-year period is not sufficient to let the 3D ocean reach equilibrium after the disturbance at the surface. However, this study only aims to examine the very-short-term response of the sea ice and upper ocean system to the imposed idealized changes in the Southern Ocean freshening, via the comparison to the CTR run. A short overview over~~ [the experiments and their differences is also given in Table 1.](#)  
25 |  
30 |

The CTR total runoff represents a continental discharge of 2610 Gt yr<sup>-1</sup>, 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<sup>-1</sup>

by Rignot et al. (2013), 2775 Gt yr<sup>-1</sup> by Depoorter et al. (2013), and 2260 Gt yr<sup>-1</sup> 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 supplementary material.

In the first sensitivity experiment, S1, the magnitude of fresh-water input is increased by 5% adding 130 Gt yr<sup>-1</sup>, 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<sup>-1</sup> compared to CTR.

S3 takes into account that ~~not all the~~ fresh water ~~does not~~ entering the ocean ~~exclusively is added~~ at the coastline. Meltwater input from icebergs is introduced offshore over a much wider area. With a spatial distribution similar to S2, Only a reduced amount of runoff (1670 Gt yr<sup>-1</sup>) is distributed close to the Antarctic coastline to represent ice shelf melt (following the S2 distribution), while 1090 Gt yr<sup>-1</sup> are associated to the iceberg freshwater release (Rignot et al., 2013), and are widely distributed ~~(with four levels of flux intensity)~~ in the Southern Ocean ~~(with four levels of flux intensity) 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<sup>-1</sup> 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<sup>-1</sup> 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<sup>-1</sup>), in front of the Ross Ice Shelf in the Ross Sea (120 Gt yr<sup>-1</sup>) and in front of the Amery Ice Shelf in Prydz Bay (60 Gt yr<sup>-1</sup>) (Figure 1e). The total of the runoff is 3030 Gt yr<sup>-1</sup>.

We present three additional experiments in which the amount of additional fresh water exceeds the range of current Antarctic mass loss estimates. These runs are an attempt to determine how much fresh water is required to have a significant effect on the sea ice area trend, in our model. The spatial runoff distribution in the experiments S2-Incr and S2-High is based on S2 simulation, while the experiment S3-High follows the S3 distribution including the widespread offshore freshwater addition.  
In S2-Incr, the runoff increases from 2760 Gt yr<sup>-1</sup> in 2004 to 3310 Gt yr<sup>-1</sup> in 2013 in 4 steps (137 Gt yr<sup>-1</sup> every 2 years). In S2-High and S3-High, a constant freshwater input of 3310 Gt yr<sup>-1</sup> is added around Antarctica in different spatial distributions. 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<sup>-1</sup> in 2004 to 3310 Gt yr<sup>-1</sup> in 2013 in 4 steps (137 Gt yr<sup>-1</sup> every 2 years).

### 3 Sea ice ~~response to freshwater modifications~~enhancement

In this section, the impact of modifications in the freshwater supply on the sea ice is analyzed by comparing the sensitivity experiments S1-S4 with the reference simulation CTR. Overall, CTR properly reproduces the mean state of upper-layer ocean and sea ice. The seasonal cycle and spatial distribution of sea ice concentration compare well with satellite observations. Temperature and salinity are close to observations from the World Ocean Circulation Experiment (Orsi and Whitworth, 2005; see supplementary material for a more detailed description of CTR results).

In the comparison, we focus our analysis on the ~~6-month austral winter~~ period from April to September ~~when, since~~ the sea ice ~~values properites~~ in CTR are closest to observations ~~during these months (see supplementary material for a detailed description of CTR results)~~. In the following, the word winter referring to a specific time period identifies the period months April to September.

In Sect. 3.1, we analyse the ~~response of resulting differences in~~ sea ice concentration, thickness and velocity to artificial freshwater enhancement in the experiments S1-S4; while 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 reaches its maximum in CTR (Figure 2a) is already high during the winter months (Figure 2a or CTR), there is only limited leeway for it to increase under additional freshwater input 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 experiments S1-S4 and CTR is comparatively high (Figure 3), 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 s~~Sea ice velocity is also 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 amount of additional fresh water runoff scenario directly affect sea ice properties by both thermodynamic and dynamic processes. The changes in sea ice velocity of the sea ice is altered caused by changes in the fresh-water input modify and in consequence affects the ice thickness due to the advection speed and 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, ~~w. H~~here; the runoff addition per area is highest higher in the sensitivity experiments and the coastal current distributes it the added fresh water primarily within a narrow band around 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

5 In the S1 experiment, the sea ice concentration and thickness features small changes from CTR. The former shows a more relevant, except for an increase at the tip of the Antarctic Peninsula (Figure 2d). The latter thickens mainly 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), while larger. The main areas of sea ice thinning are in the eastern Ross Sea and the southwestern Weddell Sea. The surface freshening addition of freshwater, by the enhanced runoff decreasing the surface salinity, increases the ocean stratification, which freezing temperature and inhibits vertical heat transport from the deeper ocean below to the surface. The SST cools and the freezing temperature increases, both of which are and is expected to increase the ice formation and 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 resulting in 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 more closely the mechanisms controlling regional sea ice behaviour in S2 in more detail, we subdivided the widely-used 5 sectoregions of the Southern Ocean (e.g. Parkinson and Cavalieri, 2008, 2012) into 10 regions (Figure 1ba). 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 1**cb**). 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 strongly suggests evidence~~ that the impact on ~~regional~~ sea ice presence in S2 is locally 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-impact~~ the regional ~~import and export~~ rates of sea ice import and export. Therefore, given strong regional contrasts of the freshwater addition, the dynamic response decides the development of sea ice presence in the area. ~~In-With~~ the S2 freshwater input experiment, two regions show a ~~distinct~~ 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 the lowest of all regions in CTR (Figure 2c). ~~In-The 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 clearly 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, b~~By decreasing the surface salinity, the enhanced runoff increases the freezing temperature and inhibits heat transport from below. Since in S3 only a part of the fresh water 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 c~~Coastal velocities are accelerated compared to faster than in CTR only from the Amundsen Sea to the Ross Ice Shelf front. 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 1**de**) causing the ice drift to slow.

In the central and eastern Weddell Sea, the fresh-water addition causes the ice to thicken<sup>ed</sup> 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.

### 5 3.1.4 S4: Response to regional runoff addition

The response of sea ice properties to modified runoff in S4 (Figure 2m-o) shows~~In S4, the changes in the sea ice variables feature a pattern similar to the~~ pattern to that of S1 (Figure 2m~~d~~-o~~f~~). 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~~ those areas. ~~A decrease of ice thickness~~ Thinner sea ice is found to the southeast of the peninsula (Figure 2n), which can be attributed to the fact that the ice is younger. ~~In S4, a~~ Additionally, a decrease of sea ice concentration occurs at the Filchner/Ronne Ice Shelf front (Figure 2m). In this simulation, Since the extra runoff ~~addition~~ is regionally distributed and confined to the fronts of the Filchner/Ronne Ice Shelf (Weddell Sea), Ross and the Amery Ice Shelves (Prydz Bay) and the Ross Ice Shelf (Ross Sea).; In the Weddell Sea, the coastal ice velocities increase in the Weddell Sea (Figure 2o) and deplete the area of ice. In Prydz Bay, we find a similar accelerations<sup>speed increase</sup> and a local decrease of ice concentration. In the Ross Sea, the coastline geometry has a blocking effect on sea ice advected by the coastal current.

### 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, the sea ice response in our sensitivity experiments S1-S4 supports the hypothesis that artificial freshwater addition causes the sea ice to expand over time. The additional Antarctic runoff generally leads to an increase of the sea ice. Furthermore, our model results show all scenarios confirm that, in areas of a strong contrast in freshwater addition, the increase in drift velocity in areas of a strong contrast in freshwater addition prevails against local thermodynamic effects and regionally, an enhanced freshwater supply can lead to thinner sea ice and in lower sea ice concentrations in the region. This is the expected case for the southern Weddell Sea and the Amundsen Sea, characterized by high mass loss and which are located downstream of areas where less runoff addition is expected. In regions located downstream of high large additional freshwater flux, where ocean the increased velocities are increased, the sea ice can thicken due to enhanced dynamic compression 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 evident very efficient in the western Ross Sea, but 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 extra freshwater input additions in the different experiments as well as its effect on the seasonal cycle of sea ice extent, volume and production. The time series of the sea ice variables properties over the course of the 10-year integration period are presented, together with their mean seasonal cycles, over the 10-year integration period 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 the sensitivity runs (S1-S45) and CTR are very small compared to the extent's seasonal amplitude (equal to  $1.7 \times 10^7$  km<sup>2</sup>), and present a marked. However, while the interannual and seasonal variability. However, in all experiments, the additional fresh water enhances the monthly-averaged value 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 compared to CTR (Figure 3b). The S1 sea ice extent diverges from CTR only to a small extent degree, 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 fresh water 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 [lengthens](#) 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). As seen for the sea ice extent, the differences of the sea ice volume between sensitivity runs and CTR (Figure 3c-d) are small compared to the volume's seasonal amplitude ( $1.4 \times 10^4 \text{ km}^3$ ). 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 represent](#) an increasing trend in the last two [simulated](#) years. In the 10-year mean, the seasonal cycle of S2 ~~and S5~~ shows a larger volume than CTR, except in [February and March](#) ~~the late summer and early autumn~~. S3 produces higher sea ice volumes [compared to than](#) CTR and all other [scenarios experiments](#) 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 [sea ice volume a](#) suddenly [drops in ice volume occurs down](#), although [the ice volume of S3 remains](#) higher than ~~in~~ CTR. These [two](#) experiments featuring a drop in ice volume in 2011 share a strongly regional distribution of runoff, [suggesting indicating](#) that ~~other the source also is~~ regional [factor may be in play](#), 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 ( $1.6 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ ) of the ice production. All [scenarios shown experimets](#) feature a sea ice production larger than CTR from autumn to spring, but in contrast ~~also~~ the summer melting is [also](#) higher in S1-S54 than in CTR. In S1, the changes are [the](#) 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, eAs 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. Additionally, 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 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).

### **3.34. Comparison with previous studies and observed trend**

Our numerical study primarily aims to investigate the response of sea ice to artificially-increased freshwater input and whether the ice response depends on the freshwater spatial distribution. All our sensitivity experiments S1-S4 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 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 fresh water applied in our simulations compared to CTR 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 ~~andwith~~ S2 ~~or~~ S3 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<sup>-1</sup>; 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  $5.62 \times 10^4 \text{ km}^2$  after 35 years due to  $130 \text{ Gt yr}^{-1}$  of additional Antarctic fresh water. Using the range of the available mass loss estimates (70-290 Gt yr<sup>-1</sup>; 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) and the observed change of  $5.25 \times 10^5 \text{ km}^2$  ( $15 \times 10^3 \text{ km}^2 \text{ yr}^{-1}$ ; Parkinson and Cavalieri, 2012), the simulated increase of sea ice extent in S1 corresponds to ~~65.8~~ ~~-243.9~~% 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  $1.71 \times 10^5 \text{ km}^2$  after 35 years. Considering the runoff addition ( $420 \text{ Gt yr}^{-1}$ ) in the simulation and the range of current estimates of Antarctic mass loss, we obtain a ~~5.4~~ ~~-232.5~~% 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 lends~~ the result some ~~convincibility~~~~credibility~~.

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 fresh water.

Our three additional experiments, where the freshwater input (up to 550 Gt yr<sup>-1</sup>) is beyond the range of current estimates, are an attempt to determine how an “extreme” amount of fresh water in our model configuration impacts the sea ice extent. The experiments S2-High and S3-High were motivated by the results of S2-Incr, with the objective to verify and understand the unexpected circumstance that more fresh water can cause a decrease in sea ice (as in the comparison of S2-Incr with S2). As described in Sect. 2.2, S2-Incr and S2-High differ from S2 in the amount of additional fresh water, but are based on the same spatial distribution, and S3-High features the same freshwater enhancement as S2-High, but with the S3 spatial distribution that also mimics iceberg melt. Compared to S2 and S3, the amount of Antarctic fresh water is increased by 20 % in S2-High and S3-High (the 20 % increase is reached in 2012 in S2-Incr). Our model results suggest that the sea ice trend is dependent on the amount of fresh water added to the Southern Ocean. In fact, in response to “extreme” freshwater addition in our model, sea ice starts to decrease (Figure 5).

In all three experiments, there is a reduction of the sea ice extent and a loss of ice volume apparent in comparison with their respective base experiment (S2 or S3) toward the end of the simulated decade. The seasonal mean (Figure 5) still bears the imprint of a negative trend in both sea ice extent and volume in S2-High and S3-High. The ice loss occurs primarily in the Weddell Sea and is linked to a destabilisation of the water column. The faster coastal current, as dynamic response of the ocean to freshwater input (as in Figure 2), leads to increased Ekman pumping and offshore upwelling. Increased salinities and temperatures at the surface can enhance ice melt or reduce ice formation. Once a reduction of sea ice occurs, a positive feedback loop between sea ice cover and ocean heat uptake from shortwave radiation is triggered (Stammerjohn et al., 2012).

Our results with “extreme” freshwater input suggest that sea ice trend is sensitive to the amount of fresh water and to the method by which it is added. Pauling et al. (2016) performed experiments with freshwater addition larger than estimates (up to 3000 Gt yr<sup>-1</sup> increase) with a fully coupled model. Using two different freshwater distributions (ice shelf melt in front of ice shelves and at the depth of the front, and iceberg melt at the surface over a wide area), they found that the total sea ice area increases significantly under the large freshwater enhancement. In accordance with the similarities we see between our experiments S2-High and S3-High after 10 years of integration, their experiments show that the spatial distributions of the freshwater input have no significant influence on the sea ice response. However, S2-High and S3-High feature divergent behaviour on seasonal time scales. As Pauling et al. (2016) point out, differences in the model complexity (as forced vs. fully coupled configurations) and in their physics could lead to diverging results. With the low stability of the Southern Ocean water column, small differences in the chosen parameterizations, e.g. in the vertical mixing, can have a large effect on the sea ice. This is especially known for the Weddell Sea, which is the main region of sea ice loss in our experiments.

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. ~~The effect on the sea ice may be small as Pauling et al. (2016) recently found for 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, [which however makes it more comparable to the other studies.](#)

#### 4.5. On-shelf water characteristics

In this section, the influence of the [different S1-S4 runoff scenarios freshwater additions](#) 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-S4](#) 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-features](#) 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-S2](#) features temperatures [1.42 K°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<sup>-3</sup> denser than in CTR.

In the Weddell Sea and in Prydz Bay, the [S3-scenario freshwater distribution](#) 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 [scenario experiments](#). In Prydz Bay, S2 and S5 features 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.

## 56. Conclusions

We have investigated the hypothesis that increasing freshening of the Southern Ocean could explain the Antarctic sea ice expansion. 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 A set of coupled ocean-sea ice simulations with varying freshwater forcing were performed and compared to the control run in order to assess the impact of enhanced surface freshening on sea ice properties and dense water formation in the Southern Ocean. We used the NEMOv3.4 ocean model coupled with the LIM2 sea ice model in a global configuration with horizontal resolution of  $1/4^\circ$ .

Our results confirm that the sea ice extent (and volume) increases for moderate increases of the runoff amount. [The artificial addition of Antarctic freshwater input produces an increasing ocean stratification, which inhibits the vertical transport of warmer water from depth to the ocean surface and in all cases SSTs cool, resulting in increased sea ice formation.](#) For moderate However, we find [find a strong dependency on the amount of freshwater addition, as in our model large amounts of fresh water can affect the sea ice trend inversely. Our experiments with the strongest freshwater forcing result in a decrease in sea ice extent and volume.](#) that very large amount of freshwater might affect also the sea ice trend, a strong dependency on the amount of freshwater addition as our experiments with the strongest freshwater forcing lead to a decrease in sea ice extent and volume.

For moderate enhancements amounts of fresh water, ~~the spatial distribution of the added freshwater addition proves to be of great influence, since it affects the dynamic response of ocean and sea ice.~~ For moderate enhancements of fresh water, the spatial distribution of the added water proves to be of great influence, since it affects the dynamic response of ocean and sea ice. ~~It also found that, in our model, very large amount of freshwater can affect the sea ice trend, as our experiments with the strongest freshwater forcing lead to a decrease in sea ice extent and volume. The impact on the sea ice trend is also reproduced in coupled simulations where the negative trend in sea ice area (seen for example in the CMIP5 simulations) is reversed into a small positive trend (e.g. Bintanja et al. 2013, 2015). 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 triggerings 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 is 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~~ influence on the sea ice response.

Our results emphasize that the addition of fresh water locally 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 ~~loseless~~ density. 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).

Our results suggest ~~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 of runoff can also induce regional variations in sea ice, as e.g. occurs in the Amundsen Sea, where the strong basal melt processes add a high amount of fresh water to the ocean. The dynamic response is an acceleration of coastal current and sea ice, which effectively reduces the sea ice cover, and exports more sea ice to the eastern Ross Sea. Generally, ~~our experiments~~ we conclude 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 [water masses](#). Numerical applications may highly benefit from realistic distributions of Antarctic runoff.

It is worth noting that the impact on [local ocean and shelf water sea ice properties](#), simulated in our experiments, is due to fresh-water [input](#), 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.

## 10 Acknowledgments

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## References

Amante, C. and Eakins, B. W.: ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis, NOAA Technical Memorandum NESDIS NGDC-24, 19 pp., 2009.

20 **Barnier, B., Madec, G., Penduff, T., Molines, J.-M., Treguier, A.-M., Le Sommer, J., Beckmann, A., Biastoch, A., Böning, C., Dengg, J., Derval, C., Durand, E., Gulev, S., Remy, E., Talandier, C., Theeten, S., Maltrud, M., McClean, J., and De Cuevas, B.: Impact of partial steps and momentum advection schemes in a global ocean circulation model at eddy-permitting resolution, *Ocean Dyn.*, **56**, 543–567, 2006.**

Bintanja, R., van Oldenborgh, G. J., Drijfhout, S. S., Wouters, B., and Katsman, C. A.: Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion. *Nature Geoscience*, 6(5), 376-379, 2013.

25 Bintanja, R., van Oldenborgh, G. J., and Katsman, C. A.: The effect of increased fresh water from Antarctic ice shelves on future trends in Antarctic sea ice, *Ann. of Glaciology*, 56(69), 120-126, 2015.

Bouillon, S., Morales Maqueda, M. A., Legat, V., and Fichefet, T.: An elastic-viscous-plastic sea ice model formulated on Arakawa B and C grids, *Ocean Modelling*, 27:174–184, 2009.

30 [Bourdalle-Badie, R. and Treguier, A. M.: A climatology of runoff for the global ocean-ice model ORCA025. Mercator-Ocean report, MOO-RP-425-365-MER, 2006.](#)

[Collins, M., Knutti, R., J. Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A. J. and Wehner, M.: Long-term climate change: Projections, commitments](#)

- and irreversibility. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Doschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, 1029-1136, 2013.
- 5 Dai, A. and Trenberth, K. E.: Estimates of freshwater discharge from continents: Latitudinal and seasonal variations. *J. Hydrometeorol.*, 3, 660-687, 2002.
- [Dai, A., Qian, T., Trenberth, K. E., and Milliman, J. D.: Changes in continental freshwater discharge from 1948-2004. \*J. Climate\*, 22, 2773-2791, 2009.](#)
- Dee, **D. P. et al.**, **The ERA-Interim reanalysis: Configuration and performance of the data assimilation system**. *Q. J. R. Meteorol. Soc.*, 137, 553–597, 2011.
- 10 Depoorter, M. A., Bamber, J. L., Griggs, J. A., Lenaerts, J. T. M., Ligtnerberg, S. R. M., van den Broeke, M. R., and Moholdt, G.: Calving fluxes and basal melt rates of Antarctic ice shelves. *Nature* 502, 89-92, 2013.
- Fichefet, T. and Morales Maqueda, M. A.: Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics, *J. Geophys. Res.*, 102:12609–12646, 1997.
- Gladstone, R. M., Bigg, G. R., and Nicholls, K. W.: Iceberg trajectory modelling and meltwater injection in the Southern  
15 Ocean, *Journal of Geophysical Research*, 106, C9, 19903-19915, 2001.
- Goosse, H. and Zunz, V.: Decadal trends in the Antarctic sea ice extent ultimately controlled by ice–ocean feedback, *The Cryosphere*, 8, 453-470, 2014.
- Hellmer, H. H., 2004: Impact of Antarctic ice shelf basal melting on sea ice and deep ocean properties, *Geophys. Res. Lett.*, 31, L10307.
- 20 Hunke, E. C. and Dukowicz, J. K.: An elastic–viscous–plastic model for sea ice dynamics, *J. Phys. Oceanography*, 27:1849–1867, 1997.
- IOC, IHO, and BODC: Centenary Edition of the GEBCO Digital Atlas, published on CD-ROM on behalf of the Intergovernmental Oceanographic Commission and the International Hydrographic Organization as part of the General Bathymetric Chart of the Oceans, British Oceanographic Data Centre, Liverpool, UK, 2003.
- 25 [Jacobs, S. S., Hellmer, H. H., Doake, C. S. M., Jenkins, A. and Frölich, R. M.: Melting of ice shelves and the mass balance of Antarctica, \*J. Glaciol.\*, 38 \(130\), 375–387, 1992.](#)
- Jacobs, S. S., Jenkins, A., Giulivi, C. F., and Dutrieux, P.: Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf, *Nature Geoscience*, 4(8), 519-523, 2011.
- 30 **Jongma, J. I., Driesschaert, E., Fichefet, T., Goosse, H., and Renssen, H.: The effect of dynamic–thermodynamic icebergs on the Southern Ocean climate in a three-dimensional model. *Ocean Modelling*, 26, 104-113, 2008.**
- Joughin, I. and Alley, R. B.: Stability of the West Antarctic ice sheet in a warming world, *Nature Geoscience*, 4, 506–513, 2011.

- Large, W.G. and Yeager, S.G.: Diurnal to decadal global forcing for ocean and seaice models: the data sets and flux climatologies, Technical Report NCAR/TN460+ STR, CGD Division of the National Centre for Atmospheric Research (NCAR), 2004.
- Lefebvre, W. and Goosse, H.: Influence of the Southern Annular Mode on the sea ice-ocean system: The role of the thermal and mechanical forcing, *Ocean Sci.*, 1, 145–157, 2005.
- Liu, J. and Curry, J. A.: Accelerated warming of the Southern Ocean and its impacts on the hydrological cycle and sea ice. *Proc. Natl Acad. Sci. USA (PNAS)*, 107(34), 14 987–14 992, 2010.**
- Liu, J., Curry, J. A., and Martinson, D. G.: Interpretation of recent Antarctic sea ice variability, *Geophys. Res. Lett.* 31, L02205, 2004.
- 10 Liu, Y., Moore, J. C., Cheng, X., Gladstone, R. M., Bassis, J. N., Liu, H., Wen, J., and Hui, F.: Ocean-driven thinning enhances iceberg calving and retreat of Antarctic ice shelves, *PNAS*, 112, 11, 3263-3268, 2015.
- Locarnini, R. A., Mishonov, A. V., Antonov, J. I., Boyer, T. P., Garcia, H. E., Baranova, O. K., Zweng, M. M., Paver, C. R., Reagan, J. R., Johnson, D. R., Hamilton, M., and Seidov, D.: World Ocean Atlas 2013, Volume 1: Temperature, S. Levitus, Ed., A. Mishonov Technical Ed.; NOAA Atlas NESDIS 73, Silver Spring, MD, 40 pp., 2013.
- 15 [Madec, G. and Imbard, M.: A global ocean mesh to overcome the north pole singularity. \*Climate Dynamics\*, 12, 381-388, 1996.](#)
- Madec, G., and the NEMO team: Nemo ocean engine – Version 3.4. Technical Report ISSN No 1288–1619, Pole de modelisation de l’Institut PierreSimon Laplace No 27, 2012.
- [Merino, N., Le Sommer, J., Durand, G., Jourdain, N. C., Madec, G., Mathiot, P. and Tournadre, J.: Antarctic icebergs melt over the Southern Ocean: Climatology and impact on sea ice. \*Ocean Modelling\*, 104, 99-110, 2016.](#)
- 20 [Orsi, A. H. and Whitworth III, T.: Hydrographic Atlas of the World Ocean Circulation Experiment \(WOCE\). In: M. Sparrow, P. Chapman, and J. Gould \(Eds\) Southern Ocean, International WOCE Project Office, Southampton, UK, Vol. 1, 2005.](#)
- Parkinson, C. L. and Cavalieri, D. J.: Antarctic sea ice variability and trends, 1979–2010. *The Cryosphere*, 6, 871-880, 2012.
- [Pauling, A. G., Bitz, C. M., Smith, I. J. and Langhorne, P. J.: The Response of the Southern Ocean and Antarctic Sea Ice to Fresh Water from Ice Shelves in an Earth System Model. \*Journal of Climate\*, doi:10.1175/JCLI-D-15-0501.1, 2016.](#)
- 25 Pritchard, H. D., Ligtenberg, S. R. M., Fricker, H. A., Vaughan, D. G., van den Broeke, M. R., and Padman, L.: Antarctic ice-sheet loss driven by basal melting of ice shelves, *Nature*, 484, 7395, 502-505, 2012.
- Rignot, E., Bamber, J. L., van den Broeke, M. R., Davis, C., Li, Y., van de Berg, W. J., and van Meijgaard, E.: Recent Antarctic ice mass loss from radar interferometry and regional climate modelling, *Nature Geosci*, 1, 106-110, 2008.
- 30 Rignot, E., Jacobs, S., Mouginot, J. and Scheuchl, B.: Ice-shelf melting around Antarctica, *Science*, 341, 6143, 266-270, 2013.
- Shepherd, A. et al.: A reconciled estimate of ice-sheet mass balance, *Science*, 338, 1183-1189, 2012.

Silva, T. A. M., Bigg, G. R., and Nicholls, K. W.: **Contribution of giant icebergs to the Southern Ocean freshwater flux, *Journal of Geophysical Research*, 111, C03004, 2006.**

[Stammerjohn, S., Massom, R., Rind, D. and Martinson, D.: Regions of rapid sea ice change: An inter-hemispheric seasonal comparison, \*Geophys. Res. Letters\*, 39, L06501, 2012.](#)

5 Stössel, A., Stössel, M. M., and Kim, J.-T.: High-resolution sea ice in long-term global ocean GCM integrations, *Ocean Modell.*, 16, 206–223, 2007.

Swart, N. C. and Fyfe, J. C.: The influence of recent Antarctic ice sheet retreat on simulated sea ice area trends, *Geophysical Research Letters*, 40(16), 4328-4332, 2013.

10 Thompson, D. W. J. and Solomon, S.: Interpretation of recent Southern Hemisphere climate change, *Science*, 296, 895-899, 2002.

Turner, J., Comiso, J. C., Marshall, G. J., Lachlan-Cope, T. A., Bracegirdle, T., Maksym, T., Meredith, M., Wang, Z., and Orr, A.: Non-annular atmospheric circulation change induced by stratospheric ozone depletion and its role in the recent increase of Antarctic sea ice extent, *Geophys. Res. Lett.*, 36, L08502, 2009.

15 Vaughan, D. G. et al.: Observations: Cryosphere, in *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker et al., Cambridge Univ. Press, Cambridge, U. K, 2013.

Velicogna, I., Sutterley, T. C., and van den Broeke, M. R.: Regional acceleration in ice mass loss from Greenland and Antarctica using GRACE time-variable gravity data. *J. Geophys. Res. Space Physics*, 119, 8130–8137, 2014.

20 Wouters, B., Bamber, J. L., van den Broeke, M. R., Lenaerts, J. T. M., and Sasgen, I.: Limits in detecting acceleration of ice sheet mass loss due to climate variability, *Nature Geosci.*, 6, 8, 613-616, 2013.

Zalesak, S.T.: Fully multidimensional flux-corrected transport algorithms for fluids, *J. Comp. Physics*, 31, 335-362, 1979.

Zhang, J.: Increasing Antarctic sea ice under warming atmospheric and oceanic conditions, *J. Climate*, 20, 2515-2529, 2007.

Zunz, V. and Goosse, H.: Influence of freshwater input on the skill of decadal forecast of sea ice in the Southern Ocean, *The Cryosphere*, 9, 541-556, 2015.

25 Zweng, M. M., Reagan, J. R., Antonov, J. I., Locarnini, R. A., Mishonov, A. V., Boyer, T. P., Garcia, H. E., Baranova, O. K., Johnson, D. R., Seidov, D., and Biddle, M. M.: *World Ocean Atlas 2013, Volume 2: Salinity*, S. Levitus, Ed., A. Mishonov Technical Ed.; NOAA Atlas NESDIS 74, Silver Spring, MD, 39 pp. , 2013.

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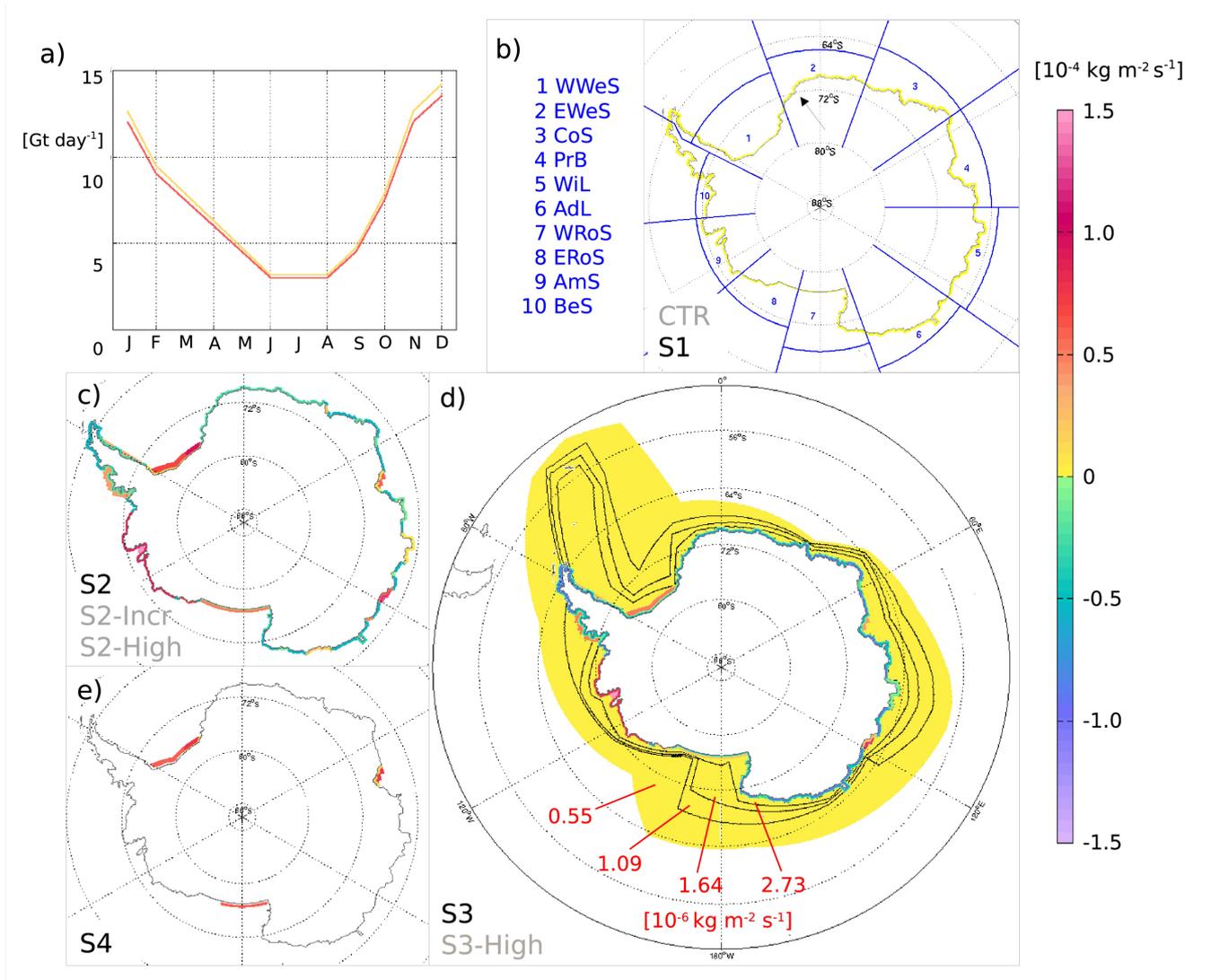
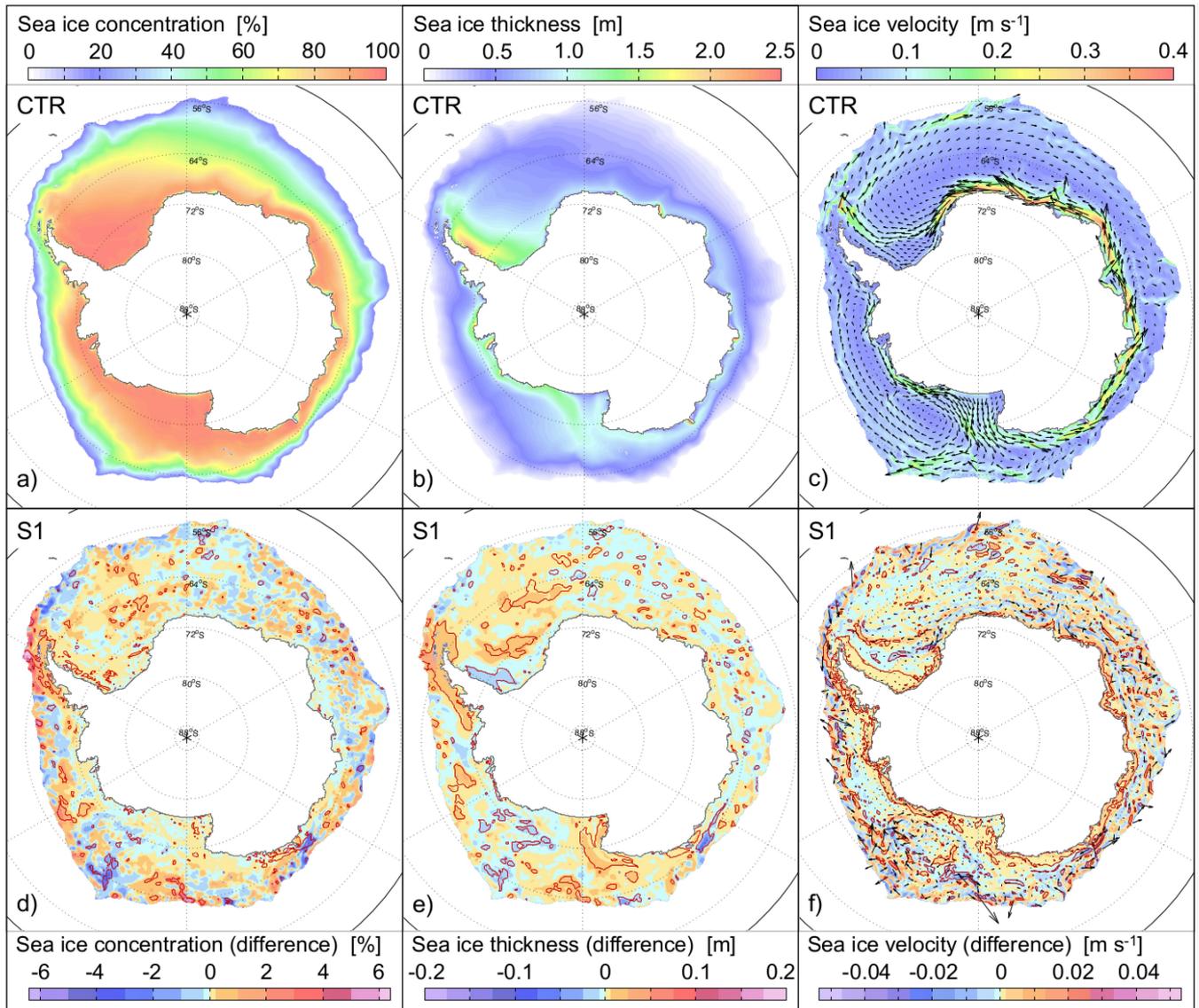


Figure 1: a) Seasonal cycle of the runoff, exemplary for CTR (red) and S1 (yellow); b-e) Runoff distributions for the scenarios as differences from the CTR runoff. The numbers vary with the seasonal cycle; shown is the mean for the winter half of the year (April-September). CTR (S2-Incr, S2-HighS5) has a similar distribution to S1 (S2) but different values; **ba) 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 – Adelle Land, 7 WRoS – Western Ross Sea, 8 ERoS – Eastern Ross Sea, 9 AmS – Amundsen Sea, 10 BeS – Bellingshausen Sea.



5 **Figure 2: Maps of a) winter sea ice a) concentration, b) thickness, and c) velocity in CTR averaged over the years April - September 2004 – 2013. b-r) Difference of ice concentration (left), thickness (middle), and velocity (right) between respective scenario experiment and CTR. The colors underlying underlying the velocity arrows indicate the difference in vector magnitude (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.**

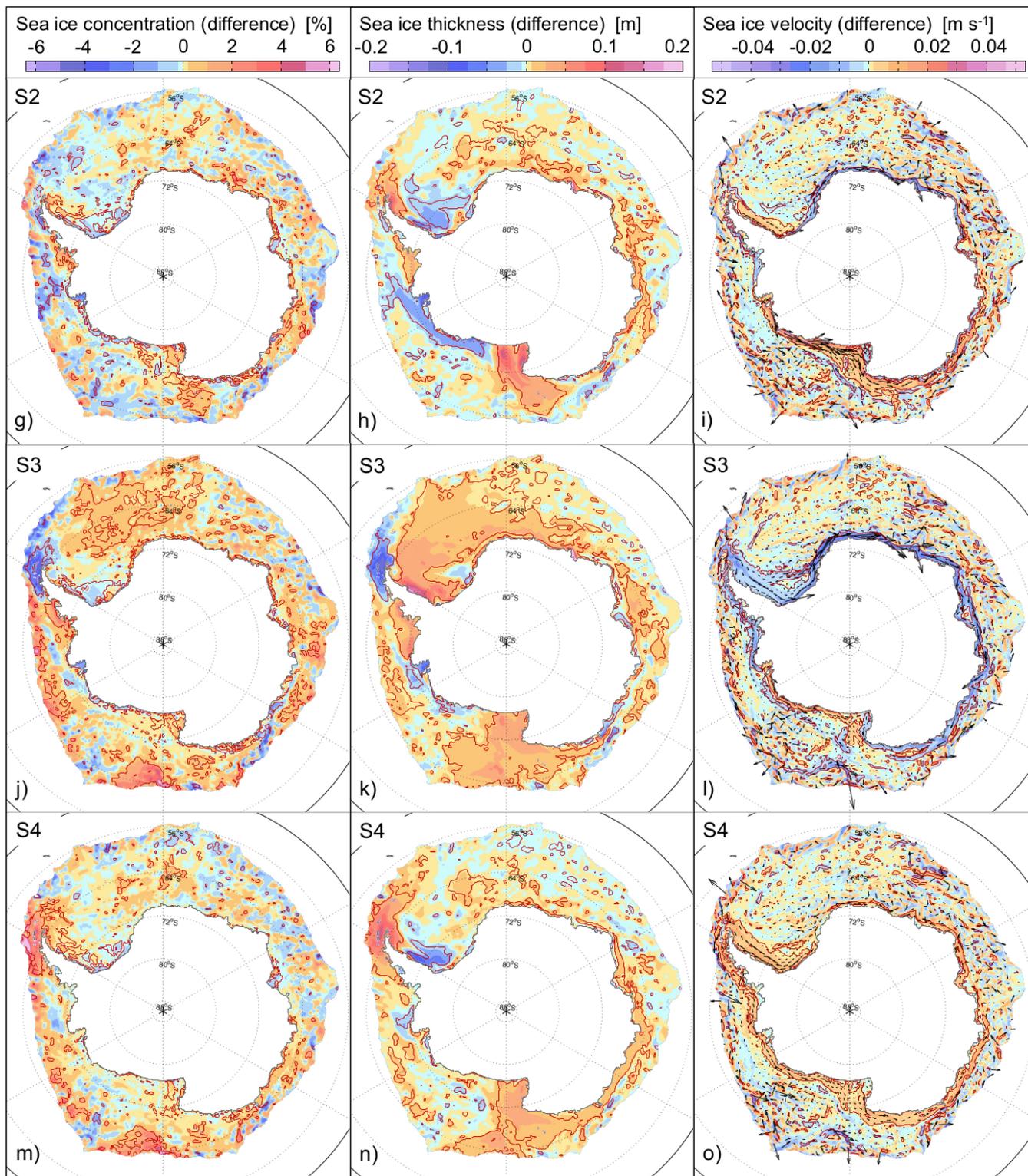


Figure 2 (continued).

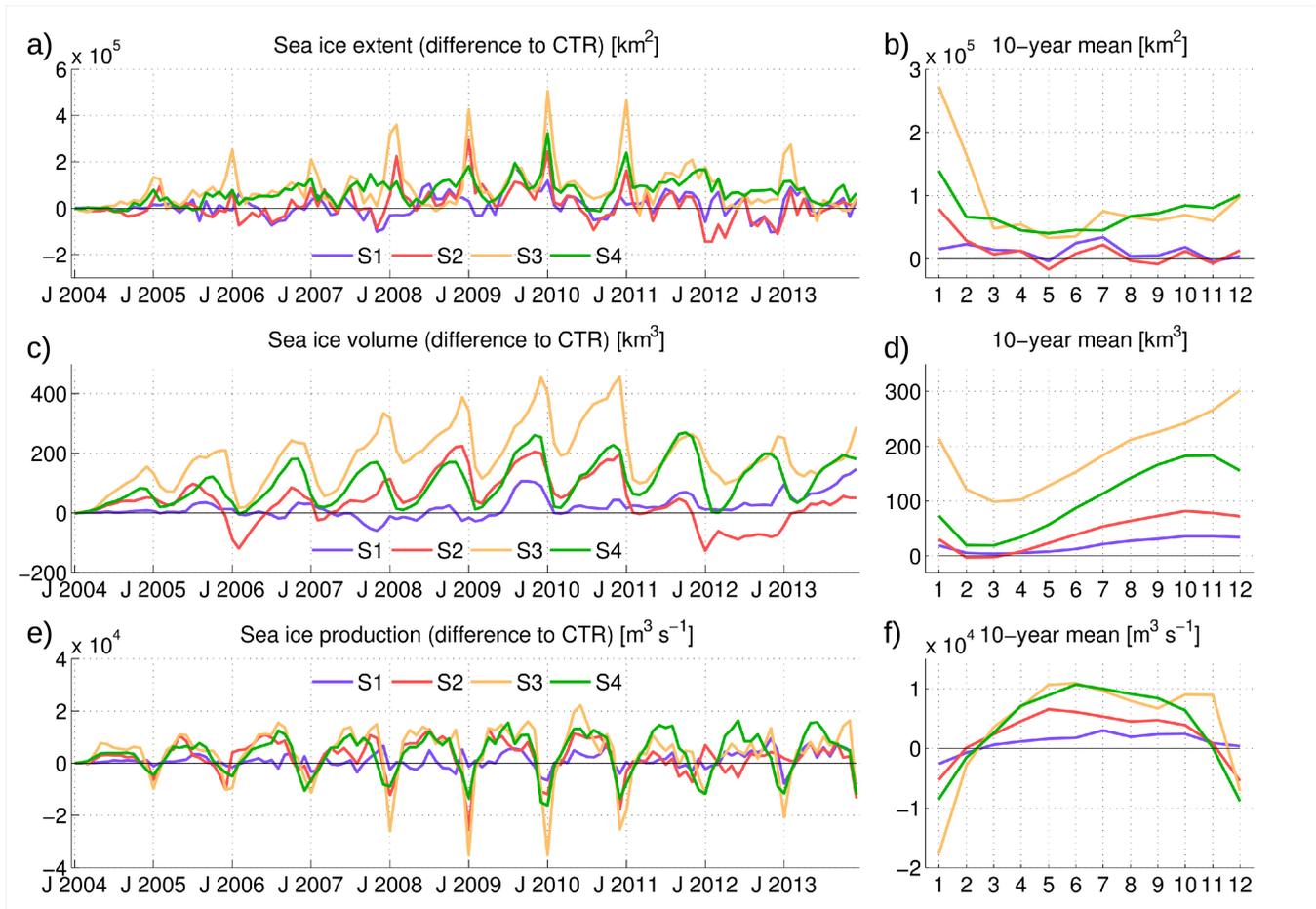
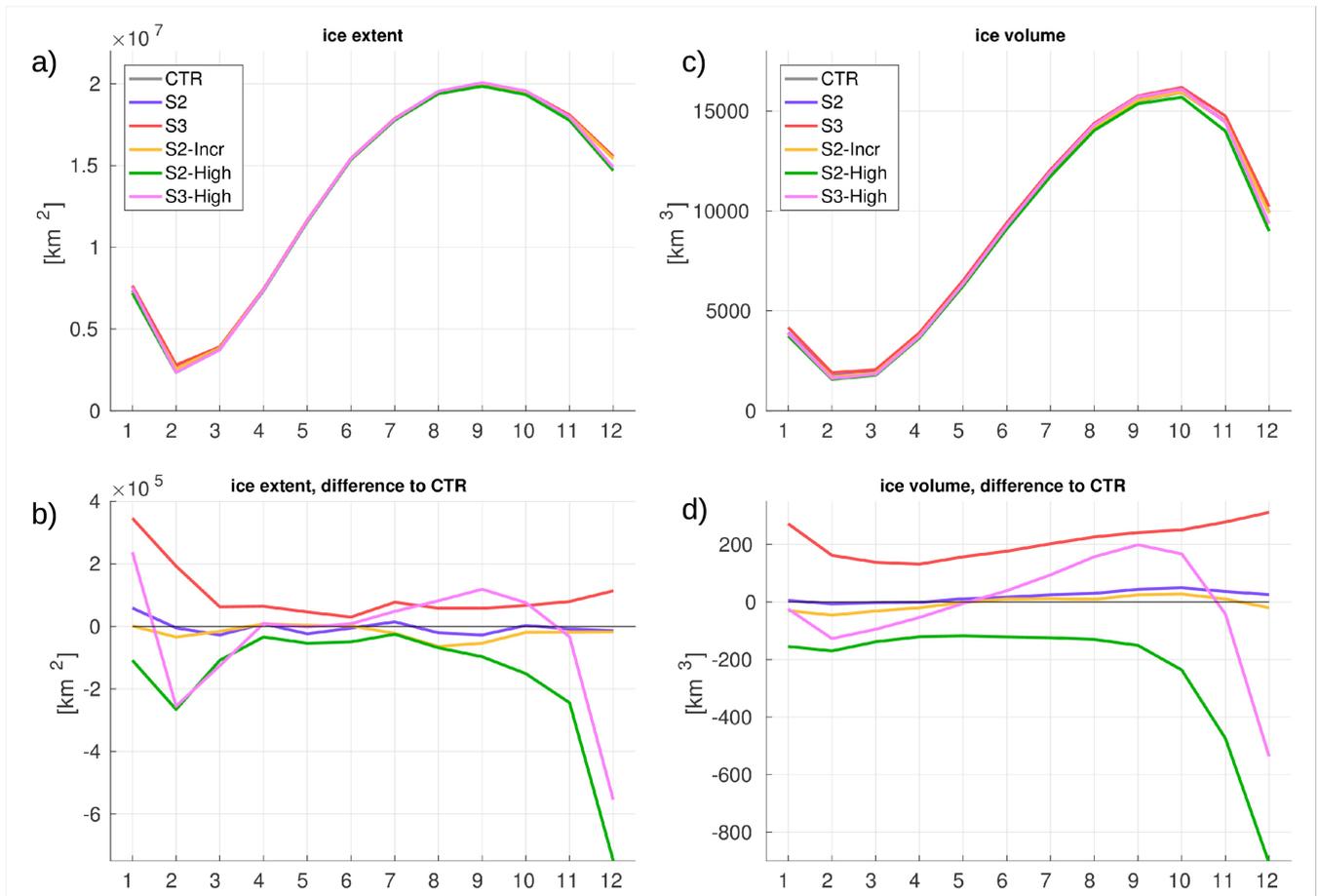
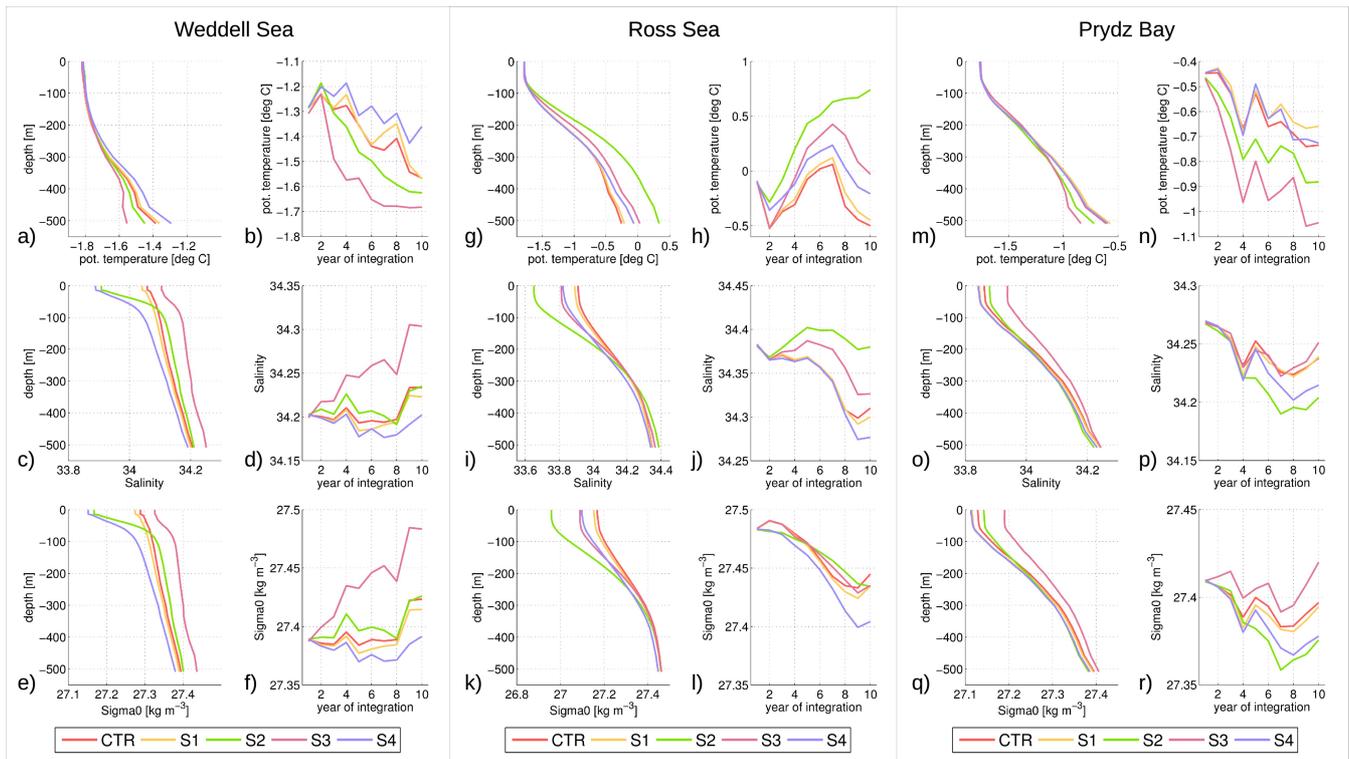


Figure 3: Time series of the differences of (a-b) sea ice extent, (c-d) sea ice volume and (e-f) sea ice production between respective scenario-experiment and CTR, monthly values for 2004-2013 (left column), monthly values averaged over the 10-year period (right column).

5



**Figure 4: Mean seasonal cycle of a) sea ice extent, b) differences to CTR in sea ice extent, c) sea ice volume and d) differences to CTR in sea ice volume for 2011-2013.**



**Figure 45.** Mean vertical profile  $\leq 550$  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.**

<b>Simulation</b>	<b>Runoff amount [Gt yr<sup>-1</sup>]</b>	<b>Runoff distribution</b>
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
<a href="#">S5</a> <a href="#">S2-Incr</a>	<a href="#">2760-3030</a> <a href="#">2760-3310</a>	Regional, coastal, increasing in 4 steps
<a href="#">S2-High</a>	<a href="#">3310</a>	<a href="#">Regional, coastal</a>
<a href="#">S3-High</a>	<a href="#">3310</a>	<a href="#">Regional, including offshore distribution</a>

Table 2. Differences between S2 and CTR computed as ~~winter~~ mean over the selected regions for ~~April – September~~the 2004 – 4-2013 period. Positive numbers are printed in bold font.

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