*Response to the specific comments and corrections from the Editors*

*(Comments from reviewer are in italics; our responses are indicated in bold typeface)*

**Thank you very much for editor's and reviewers' comments.**

**The main updates for the revised manuscripts are:**

- **New sections (4.1) in discussion.**
- **New paragraphs included in sections 3.1, 3.2, and 4.2.**
- **New Figures (3 and 9).**
- **3 Tables now included in the main text.**
- **LMELT is now defined as a reference run.**

**We feel that the changes we made in response to the reviewers' comments have strengthened the paper and made the manuscript more readable. We hope that we have satisfactorily responded to all comments, which can be found here below.**

*Editor's comment*

*General comments:*

** 2-57: Rewrite the 2nd paragraph in section 2, especially the "We carry out two sensitivity simulations for 32 year" ... seeing that you carry out 1 control run plus 3 sensitivity runs.*

**Revised as suggested.**

** Fig 1: Can you provide a sub-figure showing the same info as in main figure 1 but at increased "zoom" for the BA area?*

**Revised as suggested.**

** 3-63ff: What is the scientific motivation for the choices for the values of the transfer coefficients for the 3 "modified" scenarios, especially for HMELT?*

**We include additional discussion explaining the meaning of 3 sensitivity experiments Line 159-178.**

** Remove Tab S2 and include text in short form in text body.*

*--> Agree with Ref #3 about the confusing naming of "LMELT" vs "CTRL". --> Swap.*

**Revised as suggested.**

** Overall the detail provided for the model description should be broadened to allow the reader to understand the process implications of the ice-shelf melt, i.e., in terms of the evolution of the ice shelves within the model and the near-coastal ocean and sea ice.*

**Following suggestions from all reviewers, in '2 Model' we now provide further details about the sea ice model and the ocean-ice shelf interaction, and mention that we keep the ice shelf cavity geometry time-invariant. Our effort to improve FESOM with regard to onshore flow of water of open ocean origin and thus the warming of shelf waters in AS and BS is described in detail in a separate paragraph 4.1 Experiment design and its application.**

** Section 3.1 Model Evaluation is relatively brief, especially with note to the evolution of the ice shelves and sea ice for the 4 different simulations. Suggest to expand.*

**Following editor's suggestion, we now include time series of integrated basal melt flux from AS and BS ice shelves in the revised manuscript (Fig. 3 in the revised manuscript). We also include time series of sea ice extent in the supplementary material and include additional discussions (Lines 149-155).**

** Similarly, sections 4 and to some degree 5 are very brief. I suggest you expand these. For example, there are no timeseries figures/detailed info from your model runs... which might be helpful to understand the mechanisms of the spread and modification of the meltwater. Also what secondary processes does the appearance of the meltwater trigger within the model?*

**We now include additional discussion in Section 4 about the choice of heat and salt transfer coefficients (Lines 158-178). We also include time series figure of integrated ice shelf melt rates from the AS and BS ice shelves (Fig. 3 in the revised manuscript) and include additional discussion on the time evolution and secondary processes, which is triggered by the appearance of the melt water injection (Lines 192-198). We also include more discussions in the section 5 (Line 217-220).**

*Spread modification of the melt water Cite Nakayama et al., 2014 write about the mechanism of the coastal freshening and the reason.Other time series??*

**Revised as suggested. We also include Figs. 3, 9, S1 including two timeseries figures.**

** By which criteria have tables and figures been moved into supplemental material?*

*I would prefer all be included in the main paper.*

**Revised as suggested.**

** Fig 1: Can you provide a sub-figure showing the same info as in main figure 1 tighten.*

**We include increased "zoom" as suggested above in the revised manuscript.**

*Importantly pls explore if the code can be open source.*

**Revised as suggested.**

*Minor comments:*

*1-7: Correct "Amundsen and Bellingshausen Seas" to "Amundsen and Bellingshausen seas".*

**Revised as suggested.**

*1-18 and throughout ms: Correct "e.g." to "e.g.,"."Ross, and Weddell Seas"*

**Revised as suggested.**

*1-19: Change "Their recent high basal melt rates coincide with a few glaciological observations,"that show evidence for" to "Against the backdrop of increased basal melt give evidence of".*

**Revised as suggested.**

*1-21: Change "There exist a few other evidences" to "There have been few studies".*

**Revised as suggested.**

*4-93: Naming of "RS basin": The respective area indicated in Fig 1 appears to be outside the Ross Sea. Pls verity correctness of naming of RS Basin.*

**Revised as suggested.**

*4-118: Correct "east Antarctic" to "East Antarctic".*

**Revised as suggested.**

*5-125: Correct "east Antarctic" to "East Antarctic".*

**Revised as suggested.**

*5-134: Correct the citation to be an in text citation.*

**Revised as suggested.**

*5-135: Change "and long response time scales of 15-20 years" to "and slow response of 15-20 years".*

**Revised as suggested.**

*5-144: Correct "0.035 g kg^-^1" to "0.0035 g kg^-^1".*

**This sentence is removed in the revised manuscript.**

*5-145: Correct "0.016 g kg^-^1" to "0.0016 g kg^-^1".*

**This sentence is removed in the revised manuscript.**

*Fig2 caption: Correct "Ross, and Weddell Seas" to "Ross, and Weddell seas".*

**Revised as suggested.**

*Reviewers' comments:*

*Reviewer #1 (Remarks to the Author):*

*In this study the authors use the finite element ocean/sea ice/ice shelf FESOM model to study the impact of increased basal melting of the ice shelves in the Amundsen (AS) and Bellingshausen (BS) Seas on the hydrography of the entire Antarctic continental shelf and the condition of Antarctic Bottom Water (AABW) just off the continental shelf. This is done through examining four 32 year long simulations where the ice shelf basal melt rates are increased between simulations by modifying the transfer coefficients between the ice and the water underneath. The freshening signal not only propagates onto the Ross Sea continental shelf, but within the time frame of these simulations also makes its way around almost the entire continent onto the Weddell Sea continental shelf. The increased melt scenarios also impact the AABW off the Ross Sea and have slight impacts on AABW elsewhere. I thought the paper was generally clear and well written. The impacts of increasing ice shelf basal melt in the AS and BS on Antarctic continental shelf waters and AABW are an important problem and, in my opinion, well worth the attention of the Cryosphere. FESOM, with its high resolution on the Antarctic continental shelf (including under the ice shelf cavities) and slope, explicit ice shelves, and global domain (so no worries about lateral boundary conditions) is a fantastic tool to study this question.*

*My only negative general comment is relatively minor, but I do think there are some warnings about the applicability of these results that should be included. The LMELT results are using what the authors think the heat and salt transfer coefficients should be, but this results in low basal melting compared to observations. No mention is made of why they think the melting is low compared to* *current day conditions: Is this because of unknown ice/ocean interaction physics or is there a problem with the representation of water masses on the continental shelf? If it's an issue with the water masses, does this influence the rate at which meltwater advects (due to lateral density gradients) in the coastal current over the continental shelf? Also, the HMELT increased melting is not due to changes in the AS/BS shelf conditions, as they presumably are in the real world since the mid-20th century, but rather numerical manipulation of the ice/ocean transfer coefficients. Does this have an impact on the results?*

**In the revised manuscript, we include a discussion explaining the reason why the melting is low compared to observations for LMELT. We also elaborate on the physical meaning of changing turbulent heat and salt transfer coefficient (Lines 158-178).**

*I have some other specific comments and suggestions below, but most of these are very minor and should be easily dealt with by the authors.*

*Specific comments*

*Abstract, line 3: The abstract states that the long term impact of enhanced melting of the Amundsen Sea ice shelves "on the Southern Ocean hydrography has not been well investigated". However, there have been several studies of this (e.g. Fogwill et al., 2015; Golledge et al., 2019; Lago and England, 2019), just not with models setup as nicely as the FESOM model used here (i.e. explicit ice shelves and high resolution around Antarctica). I think it would be helpful to mention some of the other studies in the Introduction, but also include mention of why the model used here is better suited for examining this question.*

**Revised as suggested (Line 40-42).**

*Abstract, line 7 and line 155: See comments below about the propagation of the melt- water, but suggest changing "propagates further" to "can propagate further".*

**Revised as suggested.**

*First paragraph of model section: Even though the authors mention the ice/ocean heat/salt transfer coefficients in the next paragraph, I think it would be helpful to readers not familiar with FESOM to explicitly mention in this paragraph that FESOM does simulate the melting/freezing of the base of the floating ice shelves.*

**Revised as suggested.**

*Should also explicitly mention that FESOM does have a dynamic sea ice model.*

**Revised as suggested.**

*Lines 71-73: I think it would be helpful if the authors added a figure about the simulated sea ice extent to the Supplement.*
**As suggested, we included a figure of simulated sea ice extent (Fig. S1).**

*Lines 124-126: The HMELT case shows the propagation of the freshening signal as described here, but it's often hard to see if there has been a propagation of the signal in the other cases. For example, the red and orange lines in Figure 6c do not stay below zero until ~ year 15 and then go back above zero for a good portion of the time past year 20. In 6d, one could argue that the red and orange lines do not stay below zero until almost the end of the period. This is why I suggested the change in line 7 of the Abstract/line 155.*
**Thank you for your suggestion and we revised the manuscript as suggested.**

*Line 151: I think it's a bit much to say this paper is investigating the impact of the meltwater on "the Southern Ocean hydrography". It is looking at some aspects of the hydrography (Antarctic continental shelf conditions and changes in AABW), but not at all the broad scale water masses that are involved in the Southern Ocean. Suggest changing "Southern Ocean hydrography" to something a little more focused.*
**Revised as suggested (Line 206).**

*Technical corrections*
*Line 15: To avoid confusion from some readers about ice shelf vs. grounded ice contributions to sea level rise, suggest changing "ongoing sea level rise and ocean freshening" to "ongoing ocean freshening as well as to sea level rise".*
**Revised as suggested.**

*Line 21: Suggest changing "There exist a few other evidences" to "There is some evidence".*
**Revised following editor's comment.**

*Line 35: Suggest changing "focuses" to "of a focus".*
**Revised as suggested.**

*Lines 60 and 61: Are the transfer coefficients set to constants as in Hellmer and Olbers or functions of the friction velocity as in Holland and Jenkins? From other FESOM ice shelf papers, I assume they are functions of the friction velocity, but I can't tell from how it is written here.*

**We calculated the ice shelf melt rate following Holland and Jenkins 1999. We revised the manuscript as in Line 64-68.**

*Line 82: From Rignot et al. (2013), I get 664 Gt/yr (not 459) for their estimate of the basal melt of the combined AS and BS (numbers 5-18 in Table S3) ice shelves.*
**This is from Supplementary Table in Rignot et al., 2013. This is the steady state melt rate ($B_{SS}$) assuming zero thickening or thinning. My calculation was based on the table I received from personal communication and recalculated the number (461 Gt/yr) based on their publication. To clarify, we revised as the manuscript (Line 94-95).**

*Line 83: Change "at that the time in the middle" to "in the middle".*
**Revised as suggested.**

*Lines 87-88 and Figure 3: If the Figure 3 plots are mean bottom salinity, then how does this show that the salinity at 200-m depth is stable? Is "bottom" over the continental shelf in the figure defined at 200-m?*
**Thank you for pointing this out. We removed this sentence in the revised manuscript.**

*Line 89: Suggest changing "the RS continental shelf further along the east Antarctic coast and towards" to "the RS continental shelf and then further along the east Antarctic coast as well as towards".*
**Revised as suggested.**

*Line 92: Typo, "Fig .3" should be "Fig. 3".*
**Revised as suggested.**

*Line 101: Suggest changing "Despite underestimated" to "Despite being underestimated".*
**This sentence is removed in the revised manuscript.**

*Line 143: Typo, "0.030" should be "0.0030" and "0.048" should be "0.0048" (assuming Table S4 is correct).*
**Revised as suggested.**

*Line 167: Add "on" after "commented".*
**Revised as suggested.**

*Figure 2: Why does the temperature scale top out at 1.0C? The Schmidtko et al. observations have the mean BS temperature > 1.0, and thus it's hard to make comparisons between the model and the observations in the AS and BS continental shelves.*

**In the revised manuscript, we decided to remove this figure. Instead, we included a few sentences describing oceanographic features well captured and not well captured in the model simulation (Line 83-89)**

*Table S1: What are the units for the sea ice salt concentration and is the value here correct? Timmermann et al. (2009) has it as 5 (psu or g/kg).*

**Thank you for pointing this out. This value here is not correct and sea ice salt concentration is 5 (g/kg) as pointed out.**

*Table S3: I don't understand what "16" and "17" are in the references. I assume one is Depoorter et al. and one is Rignot et al., but can't tell which is which.*

**Thank you for pointing this out. We revised the manuscript as suggested.**

*Reviewer #2 (Remarks to the Author):*

*Many satellite and oceanographic observations revealed that Antarctic Ice sheets and the Southern Ocean have been changing in recent decades. The interaction between Antarctic ice sheets/shelves and the Southern Ocean is one of the most important topics in the climate sciences. This study investigates pathways of ice-shelf meltwater from the West Antarctic ice shelves and its role on the Southern Ocean conditions, using a series of sea-ice/ice-shelf/ocean simulations. In my reading, the results of this study will be a valuable contribution to the Antarctic sciences. I recommend publication in The Cryosphere after addressing the comments listed below.*

**Thank you very much for encouraging and insightful comments.**

*I have two major comments.*

*(1) This paper used numerical experiments with different levels of basal melting (by tuning the transfer coefficients) to explain the observed changes (e.g., lines 97-104). In my reading, the results from CTRL (or CTRL-LMELT) shows a transition from the LMELT conditions and are not suitable for explaining the observed changes. The transition timescale is useful information, but the comparison of the Southern Ocean water properties between the model and observation in the present manuscript may be misleading.*

**We think that PRS-LMELT (previously CTRL-LMELT) possibly explains some of the observed changes. We revised the manuscript as in (Line 158-178). We also decided to remove figures comparing data and observations. We now show the LMELT case rather than the PRS case and we think it is sufficient to cite Schmitko et al., 2014 for comparison.**

*(2) Although there are sentences about the impact of the meltwater on AABW formation in the remote regions (Cape Darnley and Weddell Sea) in abstract and discussion (lines 9-11 and158-159), Figure 5d-f show no pronounced change in the bottom water properties. I understand the idea, but the simulations didn't support it.*

**I agree that our results do not fully support this idea. We revised the manuscript as in Line 11-12 and 213-214.**

*Specific comments:*

*(3) lines 31-34: Wrong and missing citations Kusahara et al. (2017) is a modeling study of dense shelf water, not ice-shelf meltwater. Kusahara and Hasumi (2013, JGR-Oceans) performed virtual (meltwater) tracer experiments in idealized warming climates, showing that increased basal meltwater from the Amundsen and Bellingshausen Seas causes the bottom water freshening in the Ross Sea and Australia- Antarctic Basins.*

**Thank you for pointing out. We removed Kusahara et al., 2017. We also included Kusahara and Hasumi 2013 and state that virtual (meltwater) tracer experiments in idealized warming climates show that increased basal meltwater from the Amundsen and Bellingshausen Seas causes the bottom water freshening in the Ross Sea.**

*(4) lines 38-40 Please briefly explain what kind of model development allows the longer integration.*

**Revised as suggested (Line 43-44).**

*(5) The description of ice-ocean interaction is missing.*

**We revised the manuscript as in Line 62-64.**

*(6) I think that 10-years spin-up is short.*

**We revised the manuscript as in Line 69-70.**

*(7) Lines 97-104 and Fig. S2a What is the mechanism of the bottom water warming in the Ross Sea?*

**We revised the manuscript as in Line 123-124.**

*(8) All map figures need longitude and latitude information (at least one panel).*

**We included lat-lon information on Figure 1.**

*(9) The manuscript is not so long. I suggest merging the supplementary material into the main text to increase readability.*

**As suggested, we moved all the tables to the revised manuscript but kept a few figures in the supplementary.**

*Reviewer #3 (Xylar Davis )*

*I realized just after submitting my review that I had not completed the first 3 bullet points, which should have read:*

*This manuscript explores the impacts of changes in freshwater fluxes from the Amund- sen Sea (AS) and Bellingshausen Sea (BS) on the Ross continental shelf, depper Ross Sea (RS) and other Antarctic regions. Major findings are that:*

** Freshwater reaches the Ross continental shelf in one year, the deeper Ross Sea within ∼5 years, the region near the Amery Ice Shelf after ∼5-10 years and the Weddell Sea in ∼10-15 years.*

** For the most significant amounts of melting, on the order of 10 times currently observed melt rates in the AB region, freshwater reaches the Weddell Sea much more quickly (∼10 years into the simulation) and the amount of freshwater reaching the Weddell continental shelf is enough to reduce the salinity there by a non-negligible amount.*

** In simulations with AS and BS melt rates comparable to or less than present-day, meltwater may reach the Weddell Sea after ∼30 years but its impact on salinity are difficult to distinguish from temporal (and perhaps ensemble) variability*

*General Comments:*

*Main points:*

*- Freshwater from the Amundsen and Bellingshausen (AB) Seas is shown to reach the Ross continental shelf in XXX years, the deeper Ross Sea within XXX years, the region near the Amery Ice Shelf after XXX years and the Weddell Sea in XXX years.*

*- For the most significant amounts of melting, on the order of 10 times currently observed melt rates in the AB region, freshwater reaches the Weddell Sea much more quickly (~10 years into the simulation) and the amount of freshwater reaching the Weddell continental shelf is enough to reduce the salinity there by a non-negligible amount.*

*- In simulations with AB melt rates comparable to or less than present-day, meltwater may reach the Weddell Sea after ~30 years but its impact on salinity are difficult to distinguish from temporal (and perhaps ensemble) variability*

*- I get the impression in several places in the text that the experiments were designed (and perhaps the manuscript was originally written) with LMELT as the intended control experiment, and that perhaps a later decision was made that CTRL should be the control because its melt rates are most comparable to observations. Differences are repeatedly taken with respect to LMELT, rather than CTRL and the coefficients used in LMELT are stated to be the ones commonly used in other FESOM simulations. I would urge you to consider explicitly renaming LMELT to CTRL and CTRL to something else because this would seem more consistent with the manuscript as written. Several specific comments point out in more detail where this inconsistency arises.*

**Following the reviewer's suggestion, we decided to consider LMELT as a reference simulation. The CTRL case is now renamed as PRS because the latter represents ice shelf melt rates closer to the current observations. We also state that we regard LMELT as the reference simulation. The manuscript is revised as Line 64-68.**

*The manuscript seems short for TC, especially the discussion section (see below). It sometimes reads as if it were intended for a journal that requires a shorter page count. This may explain why several tables that are referenced repeatedly in the text are included in the supplement rather than the main manuscript. I am not aware of a limit on tables or figures that require putting so many tables in the supplement. In particular, values from Table S4 are repeated (in multiple places) in the text, which would presumably not be necessary if that table were in the main text.*

**Following the reviewer's suggestion, we moved all tables to the main text.**

*Speaking of which, there is a lot of redundancy both within the text vs. in tables and between the results, discussion, and conclusion sections. I have pointed out where I find this redundancy in the specific comments. This redundancy comes at the expense of what could have been a broader discussion of the results that synthesizes the findings in a somewhat more qualitative fashion and talks about their broader implications based on observed and projected changes in AB melting, impacts of freshening on both the Ross continental shelf, deeper Ross Sea and elsewhere, etc.*

**Following the reviewer's suggestion in the specific comments, we moved all tables to the main text. See other responses to the specific comments.**

*Colormaps are not very intuitive and are not friendly to readers with color blindness. The manuscript preparation guidelines include the following: "For maps and charts, please keep colour blindness in mind and avoid the parallel usage of green and red. For a list of colour scales that are illegible to a significant number of readers, please visit ColorBrewer 2.0." In addition to concerns about color blindness, the colormaps used in this manuscript suffer from alternate banding of bright and dark* *colors that make it difficult for a reader to intuitively tell higher from lower values of the field. (In the terminology of color theory, they are not perceptually uniform). I would recommend that you consider using perceptually uniform colormaps such as those from cmocean (https://matplotlib.org/cmocean/) or Scientific Colour Maps (http://www.fabiocrameri.ch/colourmaps.php). The colormap in Fig. 2a, b is the only one in the paper that seems reasonably perceptually uniform. I believe these colormaps are available in a format that can be imported into ParaVeiw, the tool that I'm pretty sure you are using for this visualization.*

**In the revised manuscript, we only use perceptually uniform colormaps.**

*I submitted my review well after Reviewer #1's review became available and I feel the need to reiterate a point that she or he made. I fully agree that the paper does not sufficiently discuss the implications of changing heat- and salt-transfer coefficients to vary melt rates. Previous work, cited in this manuscript, have adjusted these coefficients and explored the sensitivity of AS and BS melting to these parameters. But these previous simulations did not, in my understanding, use adjustment of these parameters to change melt rates as a proxy for physical changes in the ocean state (e.g. ocean warming or thermocline shoaling). The implications of using parameter tuning to force melting needs some more discussion. One part of this discussion could presumably be that this approach makes it possible to explore changes to the ocean state (reduced salinity in this case) without complicating the simulation with other changes in state (e.g. changes in surface forcing) that would also impact the ocean state.*

**In the revised manuscript, we included a more comprehensive discussion (Line 158-178).**

*A small note: The Cryosphere no longer requires, at least to the best of my knowledge, that the figures and tables be placed at the end of the text during the review process. My request for future manuscripts would be that you include the figures in the text during review and move them to the end only at the point where typesetting occurs (if requested). I review manuscripts electronically and flipping back between the text and the figures and captions gets quite tedious, even more so when I also have to flip back and forth between the main text and the supplement.*

**I consider changing the format for future submissions. For this submission, however, I will keep the same format and, thus, page numbers as it can be easily compared with the previous submission. Thank you for your suggestion.**

*Specific Comments:*

*l. 60: "the coefficients are chosen following previous studies": The values for these coefficients are never explicitly stated.*

**We calculated ice shelf melt rate based on Holland and Jenkins 1999. The only difference is that the drag coefficient at the ice shelf base is set to $2.5*10^{-3}$. We emphasize this point in the revised manuscript.**

*l. 61: "while they are set to 3-times larger values for the CTRL case": As mentioned above, it isn't clear why you chose this to be the control. If this was chosen because melt rates match observations better than for your other simulations, it would be important to state this.*
**As suggested, we now use LMELT as our reference simulation.**

*Also, as Reviewer #1 points out, it would be somewhat troubling if these larger values of the coefficients are required to compensate for a cooler-than-observed ocean state in this region. If this is the case, it would be worthy of discussion if not, it would be worth discussing why the values used in previous simulations are not the appropriate ones in this case.*
**We also include additional discussion in the revised manuscript on the choice of turbulent heat and salt transfer coefficients (Line 158-178).**

*l. 62: "is a convenient way to force the ocean model": As I mentioned in the general comments, I think this approach is okay for showing the sensitivity of melting to unknown parameters but shouldn't be treated as an easy substitute for ocean warming, increased inflow of CDW, thermocline shoaling, etc. This needs some more discussion either here or in the discussion section.*
**Please note, the purpose of this paper is to show the impact of increased AS and BS ice shelf basal melting on the hydrography of downstream Antarctic marginal seas and less on the impact of ocean warming, increased on-shore flow and/or thermocline shoaling on basal melt rates in AS and BS. However, we included additional discussion on this point (Line 158-178).**

*l. 71: "(Mazloff et al., 2010; Renault et al., 2011)": Could you quote the observed values (preferably with uncertainties) from these sources? Otherwise, it's hard for the unacquainted TC reader to know how reasonable FESOM's Drake Passage transport is.*
**Revised as suggested.**

*l. 73-74, 76: "The bottom temperature on the continental shelf is mostly close to the freezing point except for regions with CDW intrusions onto the AS and BS continental shelves (Figs. 2 and S1)": I guess Fig. S1 is included here because a reader could be expected to deduce from C in Fig. 2 and C - L in Fig. S1 what L would look like, but this seems a little too indirect to me. I would remove the reference to Fig. S1. Similarly, for the reference to Fig. S1 on l. 76.*
**Revised as suggested.**

*l. 76: “These features are present both in the observations and the model results”: The salinity gradient you talk about in AS and BS seems to me to be much more visible in the model results than the observations.*

**As suggested, we note this point in the revised manuscript (Line 87-89).**

*Also, it seems like this is a good place for a discussion of features are not being captured well by the model and what their implications might be.*

**As suggested, we also included a sentence describing what is not being well captured in the model simulation (Line 87-89).**

*l. 87: I think Reviewer #1 may have also pointed this out, but Fig. 3 shows bottom salinity, so it’s a bit confusing that the text refers to this figure when comparing salinity at 200 m depth.*

**This sentence is now removed.**

*l. 101: “Despite [being] underestimated by ~50% in magnitude..”: Are these really underestimated? You’re simulating a different process, changing coefficients in the melt parameterization that lead to an instantaneous jump in meltwater production, than the melt increase seen in observations, so would you expect quantitative agreement with observations? I would reword this to make clear that the process is different and the additional meltwater you see simply is about half of that seen over the last 50 years without stating anything about underestimating.*

**We revised the manuscript as suggested (Line 115-124)**

*l. 108-109: “...introduced with heat and salt transfer coefficients being set to 2-times and 30-times larger values, respectively.” If you continue to use your current CTRL, these values should be compared with it instead of LMELT (i.e. 2⁄3 and 10 times the CTRL values, respectively). However, you are clearly treating LMELT as the control experiment throughout this section.*

**Following the reviewer’s suggestion, we now use LMELT as our reference simulation.**

*l. 111: “We subtract the LMELT results from MMELT, CTRL, and HMELT”: Again, you are using LMELT as the control run.*

**See previous reply.**

*l. 114-115: “For MMELT-LMELT, the salinity decrease is confined mostly to the AS, BS, and RS continental shelves with a freshening of 0.025 g kg −1 and 0.0030 g kg −1 for the RS continental shelf and RS bottom basin, respectively (Table S4).” This seems like a restatement of the table. As* *stated below, this table would make more sense if it were moved into the text and the text were modified to provide a broader explanation of the implications of these numbers rather than just restating them.*

**As suggested, we moved this table into the main text. Although we still keep these numbers in the results section, we modified the text to provide a broader explanation (Line 180-204).**

*l. 118, 120: "...WS with values of 0.045, 0.0048, 0.0078, and 0.0035 for the RS shelf..." and "...CTRL case amounting to 0.14, 0.0015, 0.035, and 0.016 for the RS shelf...": These numbers need units and would be better left in the table rather than repeated in the text, as in my previous comment. Instead, the text should presumably discuss the implications of these numbers in a more qualitative way.*

**Revised as suggested.**

*l. 132: "could be strongly affected": Could you please elaborate on what you mean by "strongly affected"? What would the effects be? The discussion is currently rather thin but expanding on these effects would help to flesh it out.*

**Revised as suggested (Line 199-203).**

*l. 139-140 and the remaining paragraph: "We also note that magnitudes of freshening caused by glacial meltwater from ice shelves in the AS and BS represent linear and nonlinear behaviors." I think this end phrase is unnecessarily vague. It would be much better, and would flesh out the discussion more, if you discussed what these linear and nonlinear behaviors are rather than simply calling them behaviors. You go on to state the quantitative amounts of melting under various conditions (again, numbers better left to a table) but you do not explain clearly what the linear behaviors are and differentiate them from the nonlinear ones, nor do you explore why some are linear while others are nonlinear. The discussion section is not an appropriate place for the long lists of numbers you have here. These should only be in tables, and should referred to in the results section, whereas the discussion section should focus on a more qualitative synthesis of the results and their broader implications.*

**Revised as suggested (Line 180-191).**

*l. 159-160: "We also show that magnitudes of freshening caused by glacial meltwater from the AS and BS represent linear and nonlinear behaviors": This statement isn't very useful to the reader. Can you talk about what these linear and nonlinear behaviors are?*

**Revised as suggested (Line 214-217).**

*l. 164-165, 174-175: "upon request", "The model code, processing tools, and raw model output are difficult to make publicly available, and the authors recommend contacting the corresponding author for those interested in accessing the data.": I would strongly encourage you to work out the logistics of making the specific code (not just a repository but a specific DOI on a site like Zenodo) available. Having code available only on request really hampers open science and model development. Not recording in the paper exactly which version of the code was used further hampers reproducability. I realize this is a bit of extra work and sometimes requires getting premission from the developers but it is worth the effort to the broader community. I ask you to reconsider. I realize that data sets are harder to make available but I would encourage you to see if a database like Pangaea, Open Science Framework or the Earth System Grid might be an appropriate place to host your data in a public forum. Again, the lack of data availability really sets back open science.*

**As suggested, we upload grid data and model output into a server in our institute.**

*Figs. 1, 2c,d, 3, 4, and 5: As mentioned in the general comments, I would encourage the authors to look at alternative, perceptually unifrom colormaps.*

**Revised as suggested.**

*Fig. 2a, b: If you end up switching to using LMELT as the reference simulation as I have recommended, it may be more appropriate to plot that one here. Also, the obs. plots are really tiny and hard to compare. It would be helpful to have bias plots (CTRL - Obs) in addition.*

**As we would like to show that the model is capable of simulating the hydrographic spatial structures in consistent with observations, we decided to remove observations from Figure 2. Instead, we cite these figures in the manuscript and further include a sentence discussing what features the model can and cannot reproduce (Line 87-89).**

*Fig. 2c, d: It would likely make sense to move these panels to another figure to make more room for expanding the first two panels of this figure.*

**Revised as suggested.**

*Fig. 3: As in the text, it seems like you are treating the LMELT as the control run here, since differences are C-L, not L-C.*

**Following the reviewer's suggestion, we now use LMELT as the reference simulation.**

*Table S1: It seems like the ice shelf-ocean drag coefficient is missing. I would also suggest putting the control values of the heat- and salt-transfer coefficients here. Are there any other parameter* *values related to the ice shelf-ocean interface or boundary layer that you did not include? Is there a good reason this should be in the supplement rather than the main text? I don't have strong feelings either way, but as a reader I often don't download the supplement if I don't need to.*

**As suggested, we now include the value of ice shelf-ocean drag coefficient in this table. Other parameters are the same as Holland and Jenkins 1999. We also move this table to the main text.**

*Table S2: This data seems too simple to be worth having a table, and the text repeated in each entry seems unnecessary.*

**This table is removed.**

*Table S3: As Reviewer 1 pointed out, references 16 and 17 need to be replaced with the proper reference or shortcuts of some kind. Maybe these were the numbers of the references when this paper was submitted to another journal with another citation format?*

**Revised as suggested.**

*Table S4: This table belongs in the main manuscript. This is also a case where LMELT, rather than CTRL, seems to be treated as the control run. The formatting of the leftmost column is hard to follow as the spacing between adjacent lines in the same entry and between table rows is the same (hopefully typesetting will fix this).*

**Revised as suggested.**

*Figs. S1 and S2: Once again, by taking CTRL - LMELT rather than the other way around, it seems like LMELT is the control run.*

**We now use LMELT as the reference simulation.**

*Typographical and grammatical corrections:*

*l. 13: "based on satellite-based" sounds a bit redundant so I'd suggest changing "based on" to something like "as shown by"*

**Revised as suggested.**

*l. 19: "Their" probably refers to ice shelves in AS and BS, but this is not entirely clear from the context, so I would make this explicit.*

**Revised as suggested.**

*l. 19: The comma after "observations" should be removed.*

**Revised as suggested.**

*l. 21: "evidences" should be something like "lines of evidence"*
**Revised following editor's comment.**

*l. 31: "Kusahara and Hasumi (2014); Dinniman et al. (2016); Kusahara et al. (2017)": I don't think explicit ("citet" in LaTex) citations should be combined in this way. I would reword the sentence so these become parenthetical citations, e.g. "Using circum-Antarctic or global domains, several studies (Kusahara and Hasumi 2014; Dinniman et al. 2016; Kusahara et al. 2017) also showed..." If you want to keep them more as they are, I think you need to put "and" before "Kusahara et al.".*
**Revised as suggested.**

*l. 34: "are developed" should be "have been devleoped"*
**Revised as suggested.**

*l. 38: "(FESOM) (Timmermann..." should be "(FESOM; Timmermann..."*
**Revised as suggested.**

*l. 61: "3-times" should be "three times"*
**Revised as suggested.**

*l. 76: "both in" should be "in both"*
**Revised as suggested.**

*l. 80-81: "(Depoorter et al., 2013; Rignot et al., 2013) (Table S3)" might be more cleanly formatted as "(Table S3; Depoorter et al., 2013; Rignot et al., 2013)" or by rephrasing so that the satellite estimates are mentioned earlier (with references) than the CTRL results.*
**Revised as suggested.**

*l. 83: "LMELT case" should either be "the LMELT case" or just "LMELT". I would suggest rephrasing this whole sentence: "...may represent better the melt rates at that the time in the middle of the last century"*
**Revised as suggested.**

*l. 84: "largely" should be something like "significantly"*
**Revised as suggested.**

*l. 85: "flown" should be "flowed"*

**Revised as suggested.**

*l. 89-90: The citations would be better formatted as "(Fig. 2; Nakayama et al., 2014; Dinniman et al., 2016)"*

**Revised as suggested.**

*l. 97: "RS dense shelf water observed for about 50 years shows" should be something like "Fifty years of observations of RS dense shelf water show..."*

**Revised as suggested.**

*l. 99: "(RSBW) (Purkey and Johnson, 2013)" should be "(RSBW; Purkey and Johnson, 2013)", although this is confusing since the citation isn't about RSBW but rather its warming and freshending so it might be best to reword the sentence so the citations and the abbreviation can be separated.*

**We removed all the abbreviations for RSBW in the revised manuscript.**

*l. 100: "RSBW shows warming and freshening of ~0.1 ◦ C and ~0.01 g kg −1 , respectively" mighty be better as "RSBW experiences a ~0.1 ◦ C warming and a ~0.01 g kg −1 freshening". (Sorry for the formatting.)*

**Revised as suggested.**

*l. 101: "Despite underestimated by ~50% in magnitude": something is missing here and this should maybe be "Despite being underestimated by ~50% in magnitude"*

**This sentence is removed.**

*l. 107: "focusing on both small (200-m depth) and large (bottom) depths": I find this wording confusing and I think it would work just as well as "focusing on both 200 meters depth and the sea floor" (or "ocean bottom" if you prefer).*

**Revised as suggested.**

*l. 108: "introduced with heat and salt transfer coefficients being set to..."*

**Revised as suggested.**

*l. 132: no comma is needed after "affected"*

**This sentence is removed.**

*l. 134-135: "...the idea presented by (e.g. Beckmann and Timmermann, 2001)": This should be "...the idea presented by e.g. Beckmann and Timmermann (2001)". You might want "...by, e.g., Beckmann..." but I don't think the commas are required.*

**Revised as suggested.**

*l. 137-138: "However, considering the magnitude of the salinity decrease in the CTRL experiment, circum-Antarctic freshening could possibly be possibly undergoing be underway."*

**Revised as suggested.**

*l. 141: "enhances" should be "is enhanced"*

**Revised as suggested.**

*l. 154: "existing" would be better as something like "recent"*

**Revised as suggested.**

*l. 155: "We further show...propagates further downstream": It's a little jarring to have "further" twice in this sentence so I'd suggest starting with something like "In addition, we show"*

**Revised as suggested.**

*l. 166: "All authors commented on the manuscript."*

**Revised as suggested.**

# Impact of West Antarctic Ice Shelf melting on the Southern Ocean Hydrography

Yoshihiro Nakayama[1,2], Ralph Timmermann[2], and Hartmut H. Hellmer[2]
[1]Institute of Low Temperature Science, Hokkaido University, Japan
[2]Alfred Wegener Institute, Bremerhaven, Germany
**Correspondence:** Yoshihiro Nakayama (Yoshihiro.Nakayama@lowtem.hokudai.ac.jp)

**Abstract.** Previous studies show accelerations of West Antarctic glaciers, implying that basal melt rates of these glaciers were previously small and increased in the middle of the 20th century. This enhanced melting is a likely source of the observed Ross Sea (RS) freshening, but its long-term impact on the Southern Ocean hydrography has not been well investigated. Here, we conduct coupled sea-ice/ice-shelf/ocean simulations with different levels of ice shelf melting from West Antarctic glaciers. Freshening of RS shelf and bottom water is simulated with enhanced West Antarctic ice shelf melting, while no significant changes in shelf water properties are simulated when West Antarctic ice shelf melting is small. We further show that the freshening caused by glacial meltwater from ice shelves in the Amundsen and Bellingshausen seas can propagate further downstream along the East Antarctic coast into the Weddell Sea. The freshening signal propagates onto the RS continental shelf within a year of model simulation, while it takes roughly 5-10 years and 10-15 years to propagate into the region off Cape Darnley and into the Weddell Sea, respectively. This advection of freshening modulates the shelf water properties and possibly impacts the production of Antarctic Bottom Water if the enhanced melting of West Antarctic ice shelves continues for a longer period.

## 1 Introduction

Ice shelves in the Amundsen Sea (AS) and Bellingshausen Sea (BS) are melting and thinning rapidly, shown by satellite-based estimates of the last ∼20 years (Depoorter et al., 2013; Rignot et al., 2013; Paolo et al., 2015), contributing significantly to ongoing ocean freshening and sea level rise through a high discharge of grounded ice (Shepherd et al., 2012; Rignot et al., 2013). The main cause for high basal melt rates is the relatively warm Circumpolar Deep Water (CDW, about 0.5–1.5 °C, located below ∼300–500 m depth), which flows via submarine glacial troughs from the continental shelf break into the ice shelf cavities (e.g. Jacobs et al., 1996; Nakayama et al., 2013; Dutrieux et al., 2014; Webber et al., 2017; Jenkins et al., 2018). Against the backdrop of increased basal melt giving evidence of a sustained increase of ice discharge for most glaciers in the eastern AS since 1973 (e.g. Ferrigno et al., 1993; Lucchita and Rosanova, 1997; Rignot, 1998; Mouginot et al., 2014), there have been few studies implying that basal melt rates of these glaciers were previously small and started increasing from the middle of the 20th century (Hillenbrand et al., 2017; Smith et al., 2017).

In the Ross Sea (RS), shelf water is freshening, leading to a change in the Antarctic Bottom Water (AABW) properties (Jacobs et al., 2002; Jacobs and Giulivi, 2010). Since the salinity decrease leads to a change in AABW characteristics formed in the RS (Jacobs et al., 2002; Aoki et al., 2005; Rintoul, 2007; Jacobs and Giulivi, 2010) and may influence the global thermohaline circulation, understanding the possible link between the melting of West Antarctic ice shelves and RS freshening is important for assessing long-term changes in the Southern Ocean.

Nakayama et al. (2014a) showed the spreading pathways of glacial meltwater from ice shelves in the AS and BS, which may end up on the RS continental shelf. However, due to the difficulties in a realistic representation of Southern Ocean hydrography as well as basal melt rates, their global model simulations were limited to 10 years. Using circum-Antarctic or global domains, a few studies (Kusahara and Hasumi, 2014; Dinniman et al., 2016) also showed pathways of glacial meltwater using passive tracers, confirming that glacial meltwater from the AS and BS ice shelves flows westwards onto the RS continental shelf. Kusahara and Hasumi (2013) also performed meltwater tracer experiments in idealized warming climates, showing that increased basal meltwater from the AS and BS causes the bottom water freshening in the RS. However, the impact of the glacial melt from ice shelves in the AS and BS on the Antarctic coastal ocean has not been investigated. Recently, many ocean simulations have been designed for studying oceanographic conditions in the Amundsen Sea, but they employ regional models with more of a focus on CDW intrusions onto the Amundsen Sea continental shelf (e.g. Thoma et al., 2008; Schodlok et al., 2012; Assmann et al., 2013; St-Laurent et al., 2015; Kimura et al., 2017; Nakayama et al., 2017, 2018; Webber et al., 2019). Using global models, the impact of enhanced ice shelf melting on the global deep water circulation has been investigated (Fogwill et al., 2015; Golledge et al., 2019; Lago and England, 2019), but their model resolutions are coarse and the impact of glacial meltwater propagation in the Antarctic marginal seas has not been investigated.

After the development of the global Finite-Element Sea-ice/ice-shelf/Ocean Model (FESOM; Timmermann et al. (2012); Nakayama et al. (2014a)) including model grid refinement in the Antarctic Peninsula region and adjustment of sea ice model parameters, we are now able to carry out longer integration of our simulation with more realistic hydrographic representations of the Antarctic coastal regions. In this study, we conduct 32-year simulations to analyze the impact of glacial meltwater on the Southern Ocean. We also conduct sensitivity experiments with different ice shelf melt rates in the AS and BS.

## 2 Model

Here, we investigate ocean states using FESOM (Timmermann et al., 2012; Nakayama et al., 2014a), which includes dynamic/thermodynamic sea-ice (Timmermann et al., 2009) and thermodynamic ice shelf (Timmermann et al., 2012) capabilities. Ice shelf draft, cavity geometry, and global ocean bathymetry are derived from the RTopo-1 dataset (Timmermann et al., 2010). We use a tetrahedral mesh with a horizontal spacing of ∼100 km along non-Antarctic coasts, refined to ∼20 km along the Antarctic coast, 10-20 km under the large ice shelves in the RS and Weddell Sea (WS), and ∼5 km in the central AS and BS (Fig. 1). We apply a hybrid vertical coordinate system with 46 layers and a z-level discretization in the mid- and low-latitude ocean basins. The top 21 layers along the Antarctic coast are terrain-following (sigma coordinate) for depths shallower than 650 m. In the z-coordinate region, bottom nodes are allowed to deviate from their nominal layer depth to allow for a correct representation of bottom topography, similar to the shaved-cell approach in finite-difference models. A Gaussian function with a width depending on the model's horizontal resolution is applied to smooth ice shelf draft and sea-floor topography in the sigma-coordinate region. Ocean bathymetry south of 55°S of the global model is shown in Fig. 1. Unlike the previous study (Nakayama et al., 2014a), no restoring is applied to any region of our model domain. The model parameters used in this study are summarized in Table 1. We assume a steady state for ice shelf thickness and cavity geometry and compute the ice shelf basal mass loss using the three-equation approach (Hellmer and Olbers, 1989) with the parametrization suggested in Holland and Jenkins (1999).

We carry out four simulations for 32 years using the ERA-Interim reanalysis product (1979-2010) (Dee et al., 2011) by changing the heat and salt transfer coefficients at the interface between ocean and those ice shelves fringing the AS and BS. For the LMELT case, these coefficients are calculated following (Holland and Jenkins, 1999) but the drag coefficient at the ice shelf base is set to 0.0025. The coefficients are set to values three-times larger for the present (PRS) case, as the simulated ice shelf melt rates are close to present observations (Table 2). We regard the LMELT case as our reference simulation. We conduct a model spin-up of 10 years (1979-1988) using the LMELT set up. We note that ice-shelf basal mass loss for most ice shelves stabilizes within the first 5 years of model integration (Timmermann et al., 2012). The PRS case represents the transient response of the ocean to a step change of AS and BS ice shelf melting. We further conduct two other sensitivity experiments (MMELT and HMELT), which are discussed in section 3.2. To track the basal meltwater, we use a virtual passive tracer, which is released at the same rate as the glacial melt only from ice shelves in the AS and BS.

# 3 Results

## 3.1 Model Evaluation

Both LMELT and PRS produce many features of ocean circulation, water mass properties, and sea-ice distribution in good agreement with observations. The integrated transport of the Ross Gyre is ∼30 Sv (1Sv=$10^6$ $m^3$ $s^{-1}$) and the Antarctic Circumpolar Current (ACC) carries ∼160 Sv through Drake Passage. Based on oceanographic observations, the estimates of ACC transports through Drake Passage are 145.0 ±8.8 and 137.9±10.5 Sv for two different vertical sections (Renault et al., 2011). Using ocean state estimate, Mazloff et al. (2010) estimated the transport of the ACC to be 153±5.0 Sv. The simulated austral winter (September) sea-ice extent is similar to observations, slightly overestimated by 0.2 million $km^2$ (Cavalieri et al., 2006; Spreen et al., 2008), while the austral summer (March) sea-ice extent is underestimated by 1.2 million $km^2$ (Fig. S1). The time series of sea ice extent also show similar variability compared to observations (Fig. S1c). The bottom temperature on the continental shelf is mostly close to the freezing point except for regions with CDW intrusions onto the continental shelves (Fig. 2). Bottom salinity shows local salinity maxima towards the western WS and RS, and a zonal-shelf gradient with higher salinity at the eastern side in the AS and BS (Fig. 2). These features are present in both the observations (Figs. 1A-B in Schmidtko et al. (2014) and Fig. 2 in Jenkins et al. (2016)) and the model results. Despite general hydrographic features being well reproduced, on-shelf CDW temperature is underestimated in the AS and the BS roughly by 0.5 °C and the salinity gradients in AS and BS seem to be more pronounced in observations.

As a result of the different heat and salt transfer coefficients, the total ice shelf basal mass losses are 192 Gt yr$^{-1}$ and 336 Gt yr$^{-1}$ in the AS, and 155 Gt yr$^{-1}$ and 260 Gt yr$^{-1}$ in the BS for LMELT and PRS, respectively (Table 2). For the AS and BS, the PRS loss rates are slightly lower than satellite-based estimates between 2003-2009 (Table 2; Depoorter et al. (2013); Rignot et al. (2013)). The total LMELT loss rate of all AS and BS ice shelves is 347 Gt yr$^{-1}$, which is ∼110 Gt yr$^{-1}$ smaller than the steady state melt rates (assuming zero thickening) of 461 Gt yr$^{-1}$ estimated based on 2006-2007 ice shelf configurations (Supplementary Table in Rignot et al. (2013)). However, LMELT may represent better the melt rates in the middle of the last century, considering the fact that ice shelf cavity geometry should have evolved significantly since then (Jenkins et al., 2010a; Smith et al., 2017) and West Antarctic glaciers should have flowed much slower at the time (Mouginot et al., 2014). Time series of integrated basal melt flux of all ice shelves in the AS and BS show some variability for both LMELT and PRS. For LMELT, melt flux decreases from 1979 to 2000, takes the minimum value of ∼240 Gt yr$^{-1}$ in 2001, and increases until the end of the simulation (Fig. 3a). This temporal variability is similar to the PRS case. Thus, the total basal melt flux difference between LMELT and PRS does not show large temporal variability and remains similar at the value of 250 Gt yr$^{-1}$ (Fig. 3b).

For the LMELT case, the impact of freshening is small as no significant changes in shelf water properties occur during the model integration, e.g., RS shelf salinity at the bottom remains stable (Fig. 4). Comparing PRS and LMELT, near-bottom CDW potential temperature and salinity in the AS and BS are higher by ∼0.3 °C and ∼0.02 in PRS than in LMELT (Figs. S2 and 4), respectively, and salinity is lower mostly elsewhere for model year 32 (Fig. S2). Both LMELT and PRS show glacial meltwater spreading downstream onto the the RS continental shelf and then further along the East Antarctic coast as well as eastward to the northwestern WS within the ACC (Fig. 5; Nakayama et al. (2014a); Dinniman et al. (2016)). In response to enhanced ice shelf melting, PRS shows glacial meltwater spreading further downstream (Fig. 5b). The simulated bottom salinity difference between LMELT and PRS shows a freshening along the western AS coast (year 5, Fig. 4c), which spreads further onto the RS continental shelf (year 10-32, Fig. 4). This freshening extends down to the bottom of the RS as a result of the formation and descent of dense shelf water. We note that the RS is the only location where a large amount of glacial melt from the AS and BS reaches the deep ocean (Fig. 6). For PRS, 19% and 36% of the total glacial meltwater tracer from ice shelves in the AS and BS descend to depths of 700-1600m and 1600m-bottom, respectively, most of which are found in the deep RS after 32 years of simulation (Fig. 6).

We now compare the PRS results with recent observations. Fifty years of observations of RS dense shelf water show a salinity decline of 0.03 g kg$^{-1}$ per decade (Jacobs et al., 2002; Jacobs and Giulivi, 2010). Warming and freshening of Ross Sea Bottom Water (Purkey and Johnson, 2013) extend further westward off the Adélie Land (Aoki et al., 2005; Rintoul, 2007) and Ross Sea Bottom Water experiences a ∼0.1°C warming and a ∼0.01 g kg$^{-1}$ freshening between 1992-2011 at 180°E along the S04P section (Purkey and Johnson, 2013). Despite that we simulate the response of the Southern Ocean to an instantaneous jump in meltwater production in the AS and BS, these features are reproduced in PRS, as the RS dense shelf water freshens by ∼0.045 g kg$^{-1}$ over 20 years (Fig. 4i, Table 3). This dense shelf water descends to the deep ocean causing a simulated Ross Sea Bottom Water warming and freshening of ∼0.02°C and ∼0.005 g kg$^{-1}$, respectively, over 32 years (see the black arrow in Fig. S3). This Ross Sea Bottom Water warming occurs along with the warming of the Antarctic Slope Current by 0.1-0.2°C (Fig. S3; ∼1000-2000 m depth).

### 3.2 Spreading of glacial meltwater from West Antarctic ice shelves

We conduct two additional sensitivity experiments and investigate the impact of enhanced ice shelf melting in the AS and BS focusing on both 200 meters depth and the seafloor. Medium and high rates of ice shelf melting (referred to MMELT and HMELT, respectively) are introduced with heat and salt transfer coefficients being set to 2-times and 30-times larger values, respectively. The total ice shelf basal mass losses are 280 Gt $yr^{-1}$ and 592 Gt $yr^{-1}$ in the AS, and 218 Gt $yr^{-1}$ and 445 Gt $yr^{-1}$ in the BS for MMELT and HMELT, respectively (Table 2).

We subtract the LMELT results from MMELT, PRS, and HMELT and use the last-2-year temporally averaged fields to investigate the impact of enhanced ice shelf melting. We calculate spatial averages for the regions indicated in Fig. 1 but using regions shallower than 1000 m and deeper than 2500 m for on-shelf 200-m and bottom spatially averaged salinity, respectively (Table 3). For MMELT-LMELT, the salinity decrease is confined mostly to the AS, BS, and RS continental shelves with a freshening of 0.025 g $kg^{-1}$ and 0.0030 g $kg^{-1}$ for the RS continental shelf and deep RS, respectively (Table 3). Freshening in other regions is small at 200-m depth amounting to 0.0038 g $kg^{-1}$ and 0.0003 g $kg^{-1}$ for the continental shelf off Cape Darnley (CD) and the WS continental shelf, respectively (Table 3). For the PRS-LMELT case, the freshwater signal extends along the East Antarctic coast to the WS with values of 0.045 g $kg^{-1}$, 0.0048 g $kg^{-1}$, 0.0078 g $kg^{-1}$, and 0.0035 g $kg^{-1}$ for the RS shelf, deep RS, off CD, and WS shelf regions, respectively (Fig. 7, Table 3). For the HMELT-LMELT case, the spatial freshening pattern remains similar to the PRS case amounting to 0.14 g $kg^{-1}$, 0.0015 g $kg^{-1}$, 0.035 g $kg^{-1}$, and 0.016 g $kg^{-1}$ for the RS shelf, deep RS, off CD, and WS shelf regions, respectively (Fig. 7, Table 3).

Our experiments clearly show the timescales for the freshening signal to reach other regions around the Antarctic continent. For all cases, the freshening signal propagates onto the RS continental shelf within a year of model simulation (Fig. 8). It takes roughly 5 more years for this freshening signal to become visible in the deeper part of the RS (Fig. 8). Another branch of the freshening signal further propagates near the surface along the East Antarctic coast taking roughly 5-10 years and 10-15 years to propagate into the region off CD and into the WS, respectively. Since the salinity decrease continues even after model year 32 in these regions (Figs. 8 c and d), it seems to take a long time (over 32 years) for the Southern Ocean to adjust to the new state of enhanced ice shelf melting in the AS and BS.

Previous studies show that sea ice surrounding Antarctica expanded before 2016 and this expansion has been attributed to atmosphere changes (e.g., Turner et al. (2009)) as well as accelerated basal melting of Antarctic ice shelves (Bintanja et al., 2013). Follow-up studies, however, demonstrated that the amount of freshwater required for such water column stabilization to expand sea ice extent is at least an order of magnitude greater than ice shelf melt over the observational period (Swart and Fyfe, 2013; Pauling et al., 2016). We also note that the simulated impact of glacial meltwater spreading on sea ice is small. For example, austral winter (September) sea-ice extent difference between LMELT and HMELT is less than 0.1 million $km^2$ for the last year of our model simulations.

## 4 Discussion

### 4.1 Experiment design and its application

Some studies suggest that strong El Niño-Southern Oscillation in the 1940s induced anomalous on-shore CDW intrusions and triggered simultaneous groundline retreats of West Antarctic ice shelves (Steig et al., 2013; Jenkins et al., 2016; Hillenbrand et al., 2017). This likely enlarged ice shelf cavities, created stable sub-ice shelf circulations, and sustained high ice shelf melt rates in the AS until the present day. We aim to investigate the impact of enhanced ice shelf melting in the AS and BS on the Southern Ocean hydrography. However, it is difficult to design different ice shelf cavity geometry or grounding line locations to force our simulations with different levels of ice shelf melt rates. Previous studies adjusted their turbulent heat and salt exchange coefficients for the following reasons: (1) the model simulation has a bias in the water mass characteristics caused by processes not implemented or resolved in the model, e.g., ocean mixing and tidal forcing; (2) the basal melting parameterization includes uncertainty, e.g., treatment of mixed layer at the ice-ocean interface, bottom drag coefficient, etc. (Jenkins et al., 2010b); (3) the basal melt rate is sensitive to not well-known ice shelf cavity geometry including channels, grounding line location, and ocean mixing induced by a steep ice base near grounding lines. Thus, in this study, we adjust turbulent heat and salt exchange coefficients and force our model with a step-wise increase of ice shelf melting in the AS and BS. Although it may be oversimplified to assume a step-wise increase in basal melting, we emphasize that the focus of our model study is on the spreading of the AS and BS glacial melt and its impact on the downstream hydrography, which shows some similarities with observations.

We note that simulated ice shelf melt rates of the AS and BS regions in LMELT are lower than present-day estimates, although we use cavity geometry from present-day configurations. This is likely caused by the fact that (1) a horizontal resolutions of ∼5 km and smoothed ice shelf drafts do not allow good representations of ice shelf cavities especially steep slopes near grounding lines, where ice shelf melting peaks with strong vertical velocity and mixing (e.g., Nakayama et al. (2019); Shean et al. (2019)) and (2) the FESOM simulation has a bias in water mass characteristics and simulates on-shelf CDW intrusions possibly weaker than observations (Nakayama et al., 2014b).

### 4.2 Response to the enhanced ice shelf melting

We show that magnitudes of freshening caused by glacial meltwater from ice shelves in the AS and BS represent linear and nonlinear behaviors. For the RS shelf and deep RS, magnitudes of freshening linearly increase as ice shelf melting in the AS and BS is enhanced (total melt rate difference in Table 3). For example, for MMELT, PRS, and HMELT basal melting increases by 150 Gt yr$^{-1}$, 250 Gt yr$^{-1}$, and 695 Gt yr$^{-1}$ and simulated RS shelf region freshens by 0.025 g kg$^{-1}$, 0.045 g kg$^{-1}$, and 0.14 g kg$^{-1}$, respectively. Similarly, a linear relation can be found for the deep RS (Table 3). On-shelf freshening in the RS shelf extends along the East Antarctic coast and into the WS, similar to the idea presented by Beckmann and Timmermann (2001). Freshening off the CD and in the WS, however, responds differently. Weak (or almost no) freshening is simulated for MMELT and PRS, and enhanced freshening is only simulated in the HMELT case (Table. 3). This implies that the large-scale freshening becomes significant only when ice loss in the AS and BS region is high. Due to much stronger seasonal and interannual variability in the near-surface layers and a slow response of 15-20 years (Figs. 8c and d), we are likely not able to extract the effect of enhanced ice shelf melting from the existing observations in these regions. However, considering the magnitude of the salinity decrease today, circum-Antarctic freshening could be underway.

Such response of Antarctic coastal regions can not be explained solely by an increase of ice shelf melt rates alone. Instead we consider the freshening to be a result of the strengthening of the westward flowing coastal current due to a strong density gradient (caused by shelf water salinity) across the Antarctic Slope Front (Nakayama et al. (2014a)). For the HMELT case, the development of strong density gradients is simulated in the BS, AS, and RS, along the East Antarctic coast, and in the WS (Fig. 9c). However, for other cases, strong density gradients are simulated only in the BS, AS, and RS (Figs. 9a-b) and in a limited region along the East Antarctic coast (Fig. 9).

We also note that enhanced ice shelf melting modifies the properties of RS shelf water (Figs. 7 and 8), possibly with consequences for the global thermohaline circulation. For example, Fogwill et al. (2015) show that enhanced ice shelf melting in the AS region may lead to a significant decrease in the rate of AABW formation. In HMELT, however, properties of Ross Sea surface and bottom water converge towards the end of the simulation with a freshening of $\sim$0.12 and $\sim$0.015, respectively, rather than showing a rapid drawdown (Fig. 8). Further investigations with longer model integration are required to investigate the impact of enhanced ice shelf melting on deep water properties.

## 5 Conclusions

In this study, we conduct four 32-year simulations with different levels of ice shelf melting in the AS and BS to investigate the impact of glacial meltwater on the Antarctic continental shelf hydrography. The total ice shelf mass losses from the AS and BS are 346 Gt yr$^{-1}$, 497 Gt yr$^{-1}$, 596 Gt yr$^{-1}$, and 1036 Gt yr$^{-1}$ for LMELT, MMELT, PRS, and HMELT, respectively (Tables 1 and 2). We show that the LMELT result represents a quasi-steady state without significant change in RS shelf water salinity (Fig. 4), and the PRS result shows a RS continental shelf and deep ocean freshening with some similarities to recent observations (Fig. 4). In addition, we show that glacial meltwater from the AS and BS can propagate further downstream along the East Antarctic coast leading to salinity decreases off CD and in the WS (Figs. 7 and 8). The freshening signal propagates onto the RS continental shelf within a year of model simulation, while it takes roughly 5-10 years and 10-15 years to propagate into the region off Cape Darnley and into the Weddell Sea, respectively. This modulates the shelf water properties and may impact the production of AABW if the enhanced melting of West Antarctic ice shelves continues for a longer period. We also show that the amount of freshening observed in the Ross Sea surface and bottom waters increases linearly as the freshwater flux from ice shelf melting in the AS and BS increases (Table 3). However, for regions further downstream, off CD and in the WS, the impact of freshening can be detected only when ice loss in the AS and BS is high. Such response of the Antarctic coastal regions is likely related to the development of a strong cross-slope front density gradient caused by lower shelf water salinity, and thus a more vigorous westward flowing coastal current. Considering the spatial and temporal scales of AS and BS glacial meltwater spreading around Antarctica, further investigations and model developments are required for understanding the impact of West Antarctic ice shelf melting on the circum-Antarctic and global ocean.

*Code availability.* Model codes presented in this study are available in https://fesom.de.

*Data availability.* The model grid and output are provided in http://www.lowtem.hokudai.ac.jp/wwwod/nakayama/.

*Author contributions.* YN prepared the manuscript, conducted ocean simulations. RT and HH helped interpreting the results. All authors commented on the manuscript.

*Competing interests.* The authors declare no competing interests.

*Acknowledgements.* We thank Dmitry Sidorenko and Lukrecia Stulic for their numerical and technical support and Sunke Schmidtko for sharing the observed data. Alex Gardner, Andrew Thompson, Dimitris Menemenlis, Eric Rignot, Surendra Adhikari, Stan Jacobs, and Shigeru Aoki provided helpful comments and suggestions. Simulations were carried out at the Supercomputing Division, Information Technology Center at University of Tokyo and at the North-German Supercomputing Alliance (HLRN). We acknowledge funding by the Helmholtz Climate Initiative REKLIM (Regional Climate Change), a joint research project of the Helmholtz Association of German Research Centres (HGF). This work was also supported by the fund from Grant in Aids for Scientific Research (19K23447) of the Japanese Ministry of Education, Culture, Sports, Science and Technology. The model code, processing tools, and raw model output are difficult to make publicly available, and the authors recommend contacting the corresponding author for those interested in accessing the data.

## References


Aoki, S., Rintoul, S. R., Ushio, S., Watanabe, S., and Bindoff, N. L.: Freshening of the Adélie Land Bottom water near 140 E, Geophysical Research Letters, 32, 2005.

Assmann, K., Jenkins, A., Shoosmith, D., Walker, D., Jacobs, S., and Nicholls, K.: Variability of Circumpolar Deep Water transport onto the Amundsen Sea continental shelf through a shelf break trough, J. Geophys. Res., 118, 6603–6620, 2013.

Beckmann, A. and Timmermann, R.: Circumpolar influences on the Weddell Sea: Indication of an Antarctic circumpolar coastal wave, Journal of Climate, 14, 3785–3792, 2001.

Bintanja, R., Van Oldenborgh, G., Drijfhout, S., Wouters, B., and Katsman, C.: Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion, Nature Geoscience, 6, 376–379, 2013.

Cavalieri, D., Parkinson, C., Gloersen, P., and Zwally, H.: Sea ice concentrations from Nimbus-7 SMMR and DMSP SSM/I passive microwave data, January 1979-June 2006, 2006.

Dee, D., Uppala, S., Simmons, A., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M., Balsamo, G., Bauer, P., et al.: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society, 137, 553–597, 2011.

Depoorter, M., Bamber, J., Griggs, J., Lenaerts, J., Ligtenberg, S., van den Broeke, M., and Moholdt, G.: Calving fluxes and basal melt rates of Antarctic ice shelves, Nature, 502, 89–92, 2013.

Dinniman, M. S., Asay-Davis, X. S., Galton-Fenzi, B. K., Holland, P. R., Jenkins, A., and Timmermann, R.: Modeling ice shelf/ocean interaction in Antarctica: A review, Oceanography, 29, 144–153, 2016.

Dutrieux, P., De Rydt, J., Jenkins, A., Holland, P. R., Ha, H. K., Lee, S. H., Steig, E. J., Ding, Q., Abrahamsen, E. P., and Schröder, M.: Strong sensitivity of Pine Island ice-shelf melting to climatic variability, Science, 343, 174–178, 2014.

Ferrigno, J. G., Lucchitta, B. K., Mullins, K., Allison, A., Allen, R., and Gould, W.: Velocity measurements and changes in position of Thwaites Glacier/iceberg tongue from aerial photography, Landsat images and NOAA AVHRR data, Annals of Glaciology, 17, 239–244, 1993.

Fogwill, C., Phipps, S., Turney, C., and Golledge, N.: Sensitivity of the Southern Ocean to enhanced regional Antarctic ice sheet meltwater input, Earth's Future, 3, 317–329, 2015.

Golledge, N. R., Keller, E. D., Gomez, N., Naughten, K. A., Bernales, J., Trusel, L. D., and Edwards, T. L.: Global environmental consequences of twenty-first-century ice-sheet melt, Nature, 566, 65–72, 2019.

Hellmer, H. and Olbers, D.: A two-dimensional model for the thermohaline circulation under an ice shelf, Antarctic Science, 1, 325–336, 1989.

Hillenbrand, C.-D., Smith, J. A., Hodell, D. A., Greaves, M., Poole, C. R., Kender, S., Williams, M., Andersen, T. J., Jernas, P. E., Elderfield, H., et al.: West Antarctic Ice Sheet retreat driven by Holocene warm water incursions, Nature, 547, 43–48, 2017.

Holland, D. M. and Jenkins, A.: Modeling thermodynamic ice-ocean interactions at the base of an ice shelf, J. Phys. Oceanogr., 29, 1787–1800, 1999.

Jacobs, S. S. and Giulivi, C. F.: Large multidecadal salinity trends near the Pacific-Antarctic continental margin, J. Clim., 23, 4508–4524, 2010.

Jacobs, S. S., Hellmer, H. H., and Jenkins, A.: Antarctic ice sheet melting in the Southeast Pacific, Geophys. Res. Lett., 23, 957–960, 1996.

Jacobs, S. S., Giulivi, C. F., and Mele, P. A.: Freshening of the Ross Sea during the late 20th century, Science, 297, 386–389, 2002.

Jenkins, A., Dutrieux, P., Jacobs, S. S., McPhail, S. D., Perrett, J. R., Webb, A. T., and White, D.: Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat, Nat. Geosci., 3, 468–472, 2010a.

Jenkins, A., Nicholls, K. W., and Corr, H. F.: Observation and parameterization of ablation at the base of Ronne Ice Shelf, Antarctica, Journal of Physical Oceanography, 40, 2298–2312, 2010b.

Jenkins, A., Dutrieux, P., Jacobs, S., Steig, E. J., Gudmundsson, G. H., Smith, J., and Heywood, K. J.: Decadal ocean forcing and Antarctic Ice Sheet response: Lessons from the Amundsen Sea, Oceanography, 29, 106–117, 2016.

Jenkins, A., Shoosmith, D., Dutrieux, P., Jacobs, S., Kim, T. W., Lee, S. H., Ha, H. K., and Stammerjohn, S.: West AntarcticIce Sheet retreat in the Amundsen Sea driven by decadal oceanic variability, Nature Geoscience, 11, 733, 2018.

Kimura, S., Jenkins, A., Regan, H., Holland, P. R., Assmann, K. M., Whitt, D. B., Van Wessem, M., van de Berg, W. J., Reijmer, C. H., and Dutrieux, P.: Oceanographic Controls on the Variability of Ice-Shelf Basal Melting and Circulation of Glacial Meltwater in the Amundsen Sea Embayment, Antarctica, Journal of Geophysical Research: Oceans, 122, 10 131–10 155, 2017.

Kusahara, K. and Hasumi, H.: Modeling Antarctic ice shelf responses to future climate changes and impacts on the ocean, J. Geophys. Res., 118, 2454–2475, 2013.

Kusahara, K. and Hasumi, H.: Pathways of basal meltwater from Antarctic ice shelves: A model study, J. Geophys. Res. Lett., 2014.

Lago, V. and England, M. H.: Projected Slowdown of Antarctic Bottom Water Formation in Response to Amplified Meltwater Contributions, Journal of Climate, 32, 6319–6335, 2019.

Lucchita, B. K. and Rosanova, C. E.: Velocities of Pine Island and Thwaites glaciers, West Antarctica, from ERS-1 SAR images, 1997.

Mazloff, M. R., Heimbach, P., and Wunsch, C.: An eddy-permitting Southern Ocean state estimate, Journal of Physical Oceanography, 40, 880–899, 2010.

Mouginot, J., Rignot, E., and Scheuchl, B.: Sustained increase in ice discharge from the Amundsen Sea Embayment, West Antarctica, from 1973 to 2013, Geophysical Research Letters, 41, 1576–1584, 2014.

Nakayama, Y., Schröder, M., and Hellmer, H. H.: From Circumpolar Deep Water to the glacial meltwater plume on the eastern Amundsen Shelf, Deep Sea Res. I, 77, 50–62, 2013.

Nakayama, Y., Timmermann, R., Rodehacke, C. B., Schröder, M., and Hellmer, H. H.: Modeling the spreading of glacial meltwater from the Amundsen and Bellingshausen Seas, Geophysical Research Letters, 41, 7942–7949, 2014a.

Nakayama, Y., Timmermann, R., Schröder, M., and Hellmer, H.: On the difficulty of modeling Circumpolar Deep Water intrusions onto the Amundsen Sea continental shelf, Ocean Modelling, 84, 26–34, 2014b.

Nakayama, Y., Menemenlis, D., Schodlok, M., and Rignot, E.: Amundsen and Bellingshausen Seas simulation with optimized ocean, sea ice, and thermodynamic ice shelf model parameters, Journal of Geophysical Research: Oceans, 122, 6180–6195, 2017.

Nakayama, Y., Menemenlis, D., Zhang, H., Schodlok, M., and Rignot, E.: Origin of Circumpolar Deep Water intruding onto the Amundsen and Bellingshausen Sea continental shelves, Nature communications, 9, 3403, 2018.

Nakayama, Y., Manucharyan, G., Zhang, H., Dutrieux, P., Torres, H. S., Klein, P., Seroussi, H., Schodlok, M., Rignot, E., and Menemenlis, D.: Pathways of ocean heat towards Pine Island and Thwaites grounding lines, Scientific reports, 9, 1–9, 2019.

Paolo, F. S., Fricker, H. A., and Padman, L.: Volume loss from Antarctic ice shelves is accelerating, Science, 348, 327–331, 2015.

Pauling, A. G., Bitz, C. M., Smith, I. J., and Langhorne, P. J.: The response of the Southern Ocean and Antarctic sea ice to freshwater from ice shelves in an Earth system model, Journal of Climate, 29, 1655–1672, 2016.

Purkey, S. G. and Johnson, G. C.: Antarctic Bottom Water warming and freshening: Contributions to sea level rise, ocean freshwater budgets, and global heat gain, Journal of Climate, 26, 6105–6122, 2013.

Renault, A., Provost, C., Sennéchael, N., Barré, N., and Kartavtseff, A.: Two full-depth velocity sections in the Drake Passage in 2006?Transport estimates, Deep Sea Research Part II: Topical Studies in Oceanography, 58, 2572–2591, 2011.

Rignot, E., Jacobs, S. S., Mouginot, J., and Scheuchl, B.: Ice-shelf melting around Antarctica, Science Express, 341, 226–270, 2013.

Rignot, E. J.: Fast recession of a West Antarctic glacier, Science, 281, 549, 1998.

Rintoul, S. R.: Rapid freshening of Antarctic Bottom Water formed in the Indian and Pacific oceans, Geophys. Res. Lett., 34, L06 606, 2007.

Schmidtko, S., Heywood, K. J., Thompson, A. F., and Aoki, S.: Multidecadal warming of Antarctic waters, Science, 346, 1227–1231, 2014.

Schodlok, M. P., Menemenlis, D., Rignot, E., and Studinger, M.: Sensitivity of the ice shelf ocean system to the sub-ice shelf cavity shape measured by NASA IceBridge in Pine Island Glacier, West Antarctica, Ann. Glaciol., 53, 156–162, 2012.

Shean, D. E., Joughin, I. R., Dutrieux, P., Smith, B. E., and Berthier, E.: Ice shelf basal melt rates from a high-resolution digital elevation model (DEM) record for Pine Island Glacier, Antarctica, The Cryosphere, 13, 2633–2656, 2019.

Shepherd, A., Ivins, E., Geruo, A., Barletta, V., Bentley, M., Bettadpur, S., Briggs, K., Bromwich, D., Forsberg, R., Galin, N., et al.: A reconciled estimate of ice-sheet mass balance, Science, 338, 1183–1189, 2012.

Smith, J., Andersen, T. J., Shortt, M., Gaffney, A., Truffer, M., Stanton, T., Bindschadler, R., Dutrieux, P., Jenkins, A., Hillenbrand, C.-D., et al.: Sub-ice-shelf sediments record history of twentieth-century retreat of Pine Island Glacier, Nature, 541, 77–80, 2017.

Spreen, G., Kaleschke, L., and Heygster, G.: Sea ice remote sensing using AMSR-E 89-GHz channels, Journal of Geophysical Research: Oceans, 113, 2008.

St-Laurent, P., Klinck, J., and Dinniman, M.: Impact of local winter cooling on the melt of Pine Island Glacier, Antarctica, Journal of Geophysical Research: Oceans, 120, 6718–6732, 2015.

Steig, E. J., Ding, Q., White, J. W., Küttel, M., Rupper, S. B., Neumann, T. A., Neff, P. D., Gallant, A. J., Mayewski, P. A., Taylor, K. C., et al.: Recent climate and ice-sheet changes in West Antarctica compared with the past 2,000 years, Nature Geoscience, 6, 372–375, 2013.

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

Thoma, M., Jenkins, A., Holland, D., and Jacobs, S.: Modelling Circumpolar Deep Water intrusions on the Amundsen Sea continental shelf, Antarctica, Geophys. Res. Lett., 35, 2008.

Timmermann, R., Danilov, S., Schröter, J., Böning, C., Sidorenko, D., and Rollenhagen, K.: Ocean circulation and sea ice distribution in a finite element global sea ice–ocean model, Ocean Model., 27, 114–129, 2009.

Timmermann, R., Brocq, A. L., Deen, T., Domack, E., Dutrieux, P., Galton-Fenzi, B., Hellmer, H., Humbert, A., Jansen, D., Jenkins, A., et al.: A consistent data set of Antarctic Ice Sheet topography, cavity geometry, and global bathymetry, Earth System Science Data, 2, 261–273, 2010.

Timmermann, R., Wang, Q., and Hellmer, H.: Ice-shelf basal melting in a global finite-element sea-ice/ice-shelf/ocean model, Ann. Glaciol., 53, 303–314, 2012.

Turner, J., Comiso, J. C., Marshall, G. J., Lachlan-Cope, T. A., Bracegirdle, T., Maksym, T., Meredith, M. P., 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, Geophysical research letters, 36, 2009.

Webber, B. G., Heywood, K. J., Stevens, D. P., Dutrieux, P., Abrahamsen, E. P., Jenkins, A., Jacobs, S. S., Ha, H. K., Lee, S. H., and Kim, T. W.: Mechanisms driving variability in the ocean forcing of Pine Island Glacier, Nature Communications, 8, 14 507, 2017.

Webber, B. G., Heywood, K. J., Stevens, D. P., and Assmann, K. M.: The impact of overturning and horizontal circulation in Pine Island Trough on ice shelf melt in the eastern Amundsen Sea, Journal of Physical Oceanography, 49, 63–83, 2019.

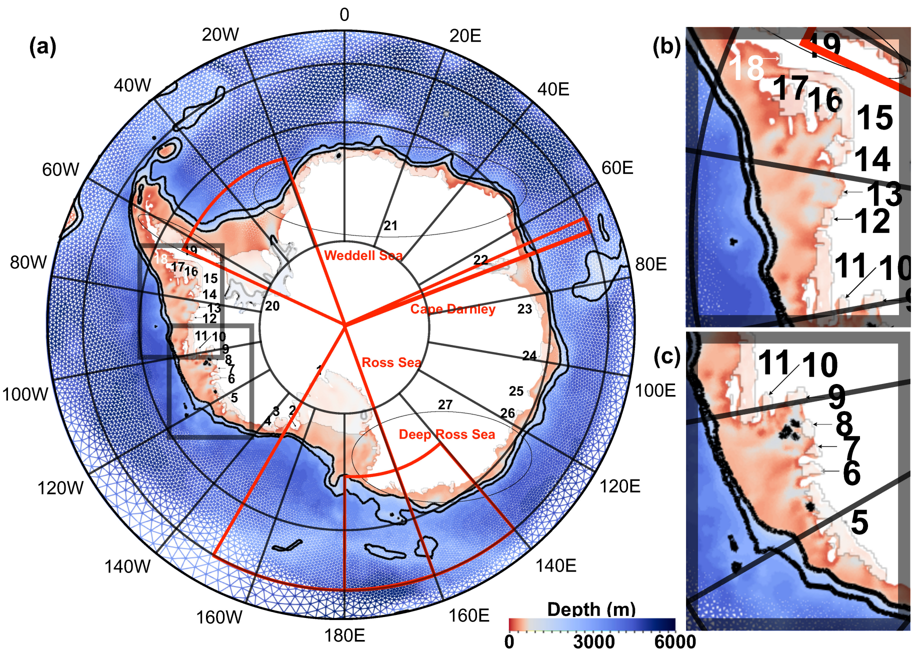


**Figure 1.** (a) Horizontal grid (triangles) and model bathymetry (color) south of 55ºS in the global model. The bathymetry contours of 1000 m and 2500 m are shown as black lines. Locations of ice shelves are indicated by numbers summarized in Table 3. Basal melt rates are integrated for several ice shelves in the WS and East Antarctica, bordered by ellipses, for model-data comparison (Table 3). The regions enclosed by red lines represent the RS, deep RS, CD, and WS, in which spatially averaged water mass characteristics are calculated (Table 4 and Fig. 8). Close-ups for the Bellingshausen and Amundsen seas enclosed by the black boxes in (a) is shown in (b) and (c), respectively.

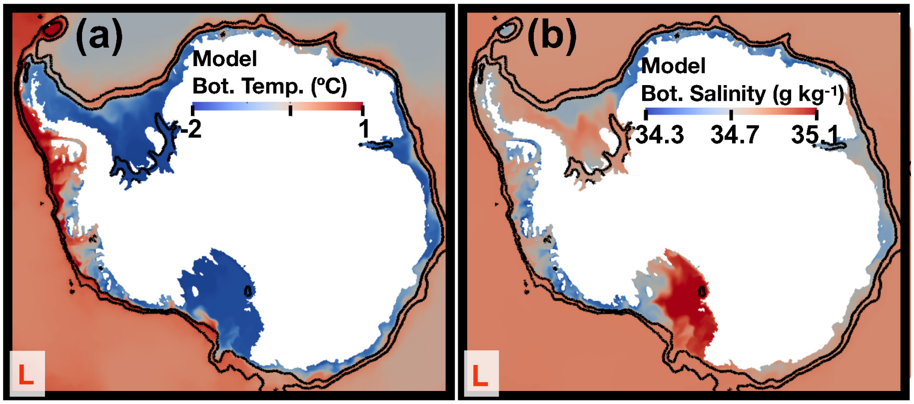


**Figure 2.** January mean bottom properties for (a) potential temperature and (b) absolute salinity for the LMELT case for model year 32. The bathymetry contours of 1000 m and 2500 m are shown as black lines.

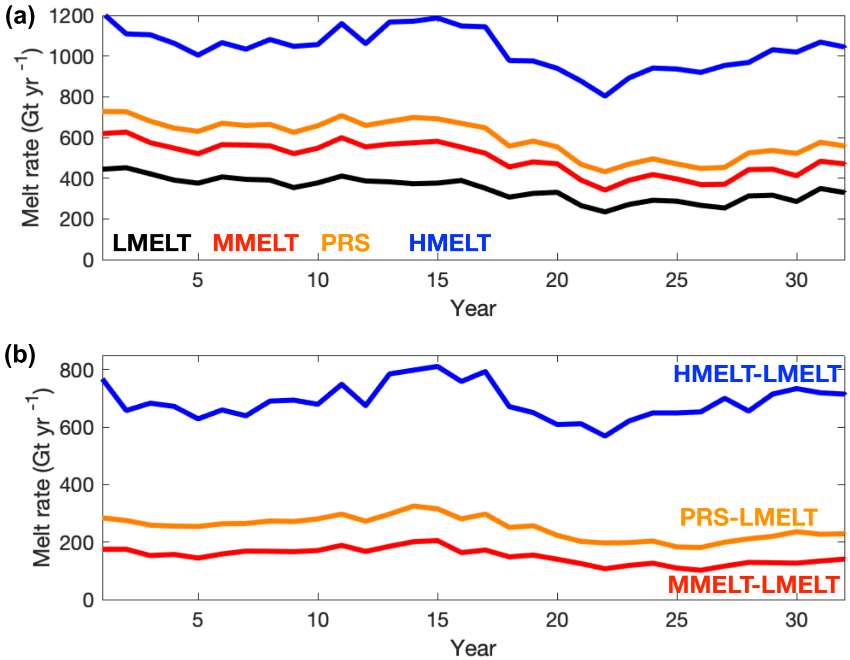


**Figure 3.** Time series of area integrated annual mean melt rates for (a) Amundsen and Bellingshausen seas for LMELT, MMELT, PRS, and HMELT. (b) Difference of integrated annual mean melt rates for AS and BS ice shelves between HMELT and LMELT (blue), PRS and LMELT (orange), and MMELT and LMELT (red).

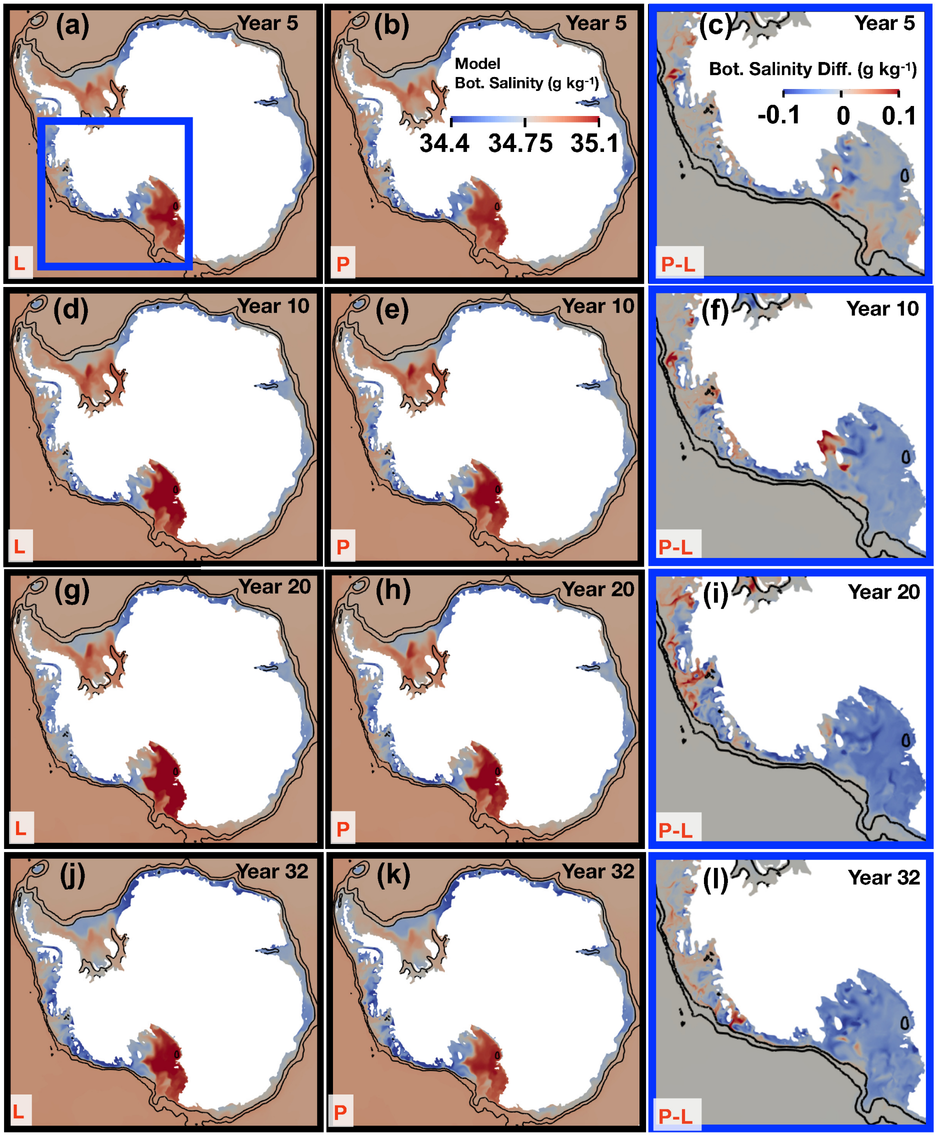


**Figure 4.** January mean bottom absolute salinity for LMELT (L) and PRS (P) and the differences (P-L) for years 5, 10, 20, and 32. The differences are shown for the region enclosed by the blue box in (a). The bathymetry contours of 1000 m and 2500 m are shown as black lines.

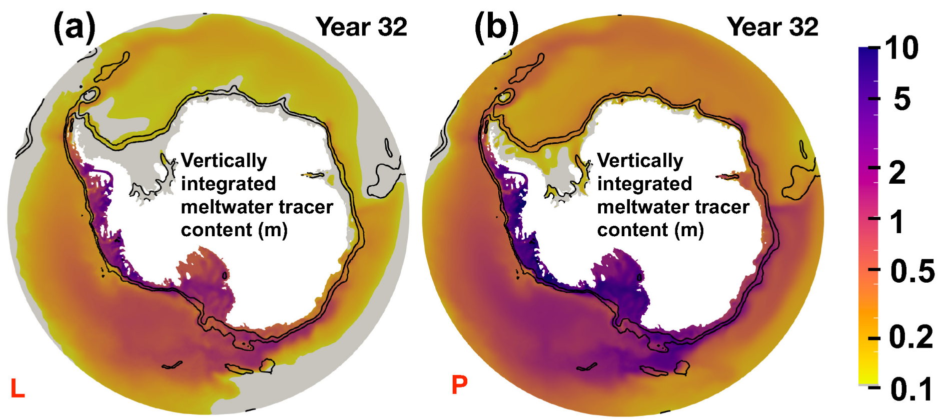


**Figure 5.** January mean vertically integrated tracer contents representing the glacial meltwater only from ice shelves in the AS and BS for (a) LMELT and (b) PRS cases for year 32. The letters P and L at the bottom left of each panel indicate PRS and LMELT, respectively. The bathymetry contours of 1000 m and 2500 m are shown as black lines. Values lower than 0.1 are indicated in gray.

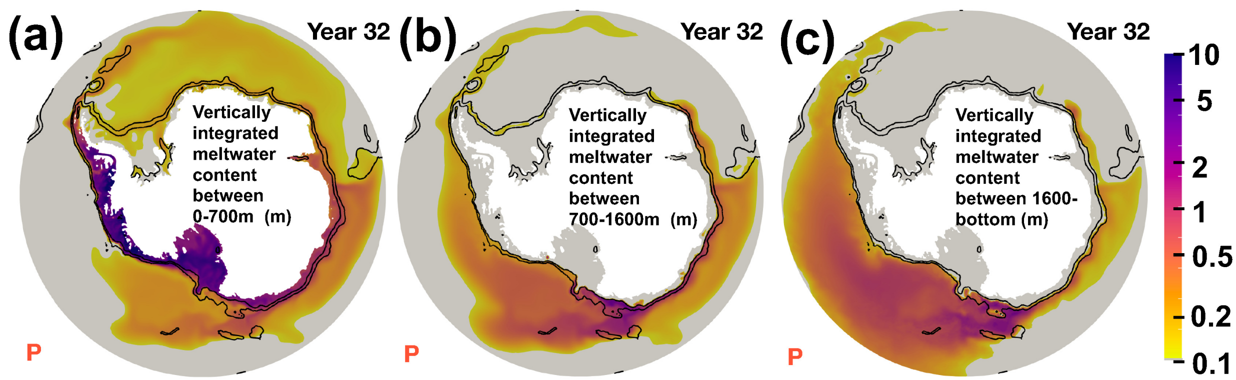


**Figure 6.** January mean vertically integrated glacial meltwater content between (a) 0-700 m, (b) 700-1600 m, and (c) 1600 m to bottom of year 32 for PRS case (P). The bathymetry contours of 1000 m and 2500 m are shown as black lines. Values lower than 0.1 are indicated with gray.

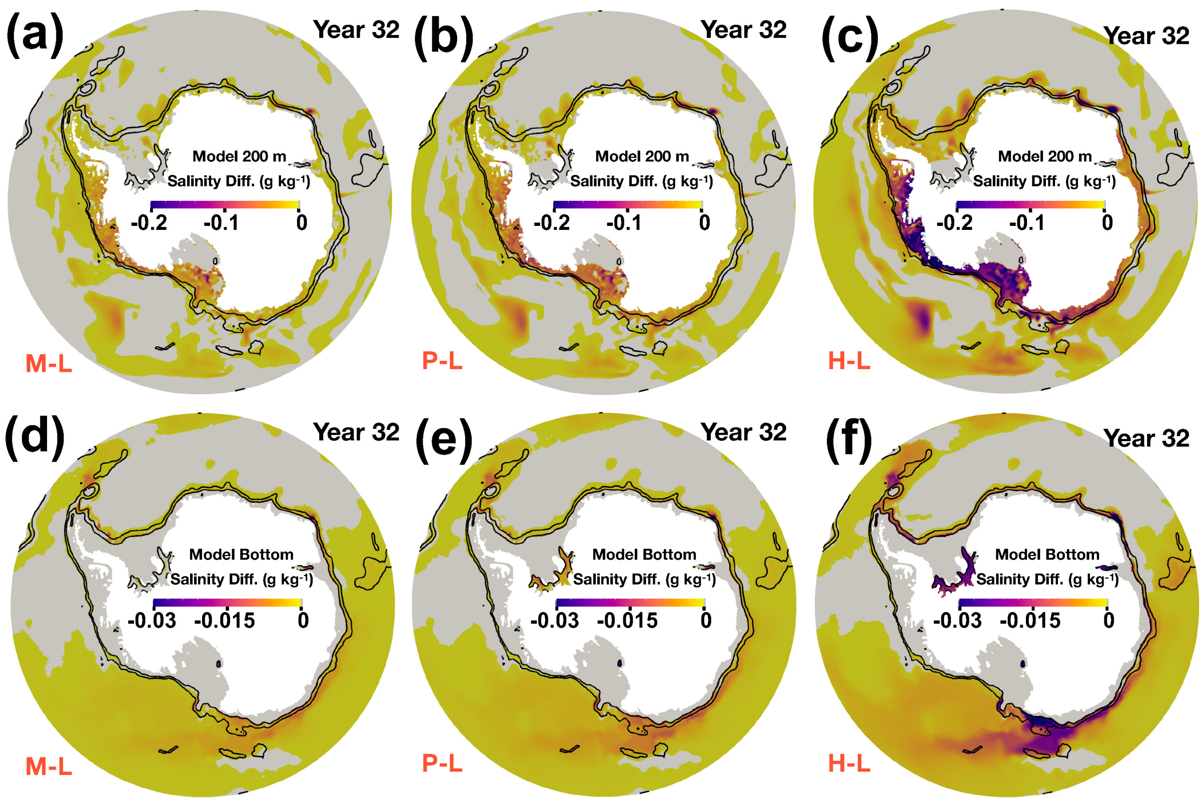


**Figure 7.** January mean absolute salinity differences MMELT-LMELT (M-L) for year 32 at (a) 200-m depth and (d) bottom. Same for PRS-LMELT (P-L), and HMELT-LMELT (H-L) shown in (b, e) and (c, f), respectively. Bottom properties are only shown for regions deeper than 1500m. The bathymetry contours of 1000 m and 2500 m are shown as black lines. Positive values are indicated in gray.

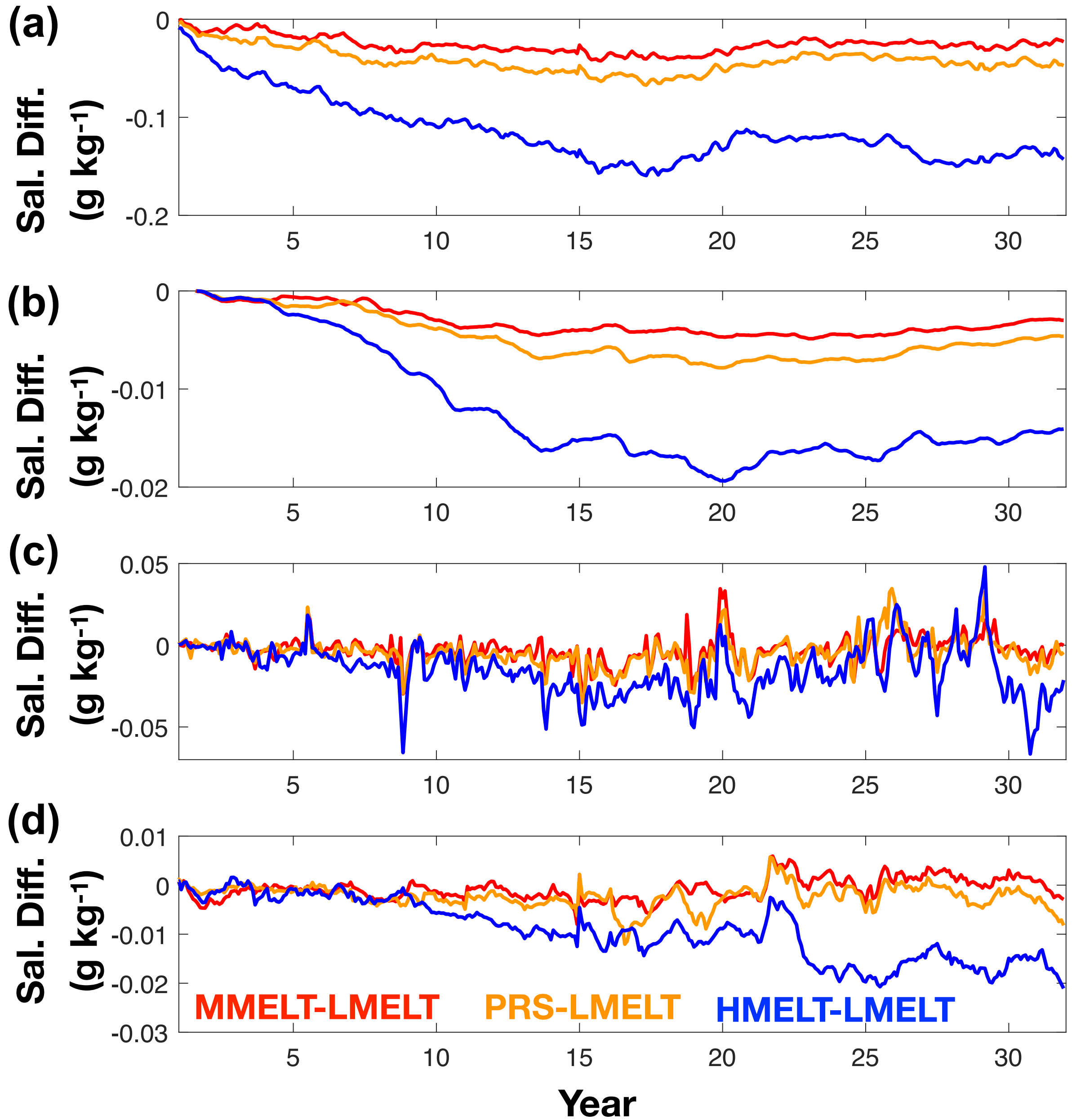


**Figure 8.** Time series of spatially averaged salinity difference over (a) RS continental shelf at 200-m depth, (b) deep RS bottom, (c) continental shelf off CD at 200-m depth, and (d) WS continental shelf at 200-m depth. Spatial averages have been calculated for the regions indicated in Fig. 1 but using regions shallower than 1000 m and deeper than 2500 m for on-shelf 200-m spatially averaged and bottom spatially averaged salinity, respectively (Table 4). LMELT fields are subtracted from HMELT (blue), PRS (orange), and MMELT (red) fields to calculate the differences.

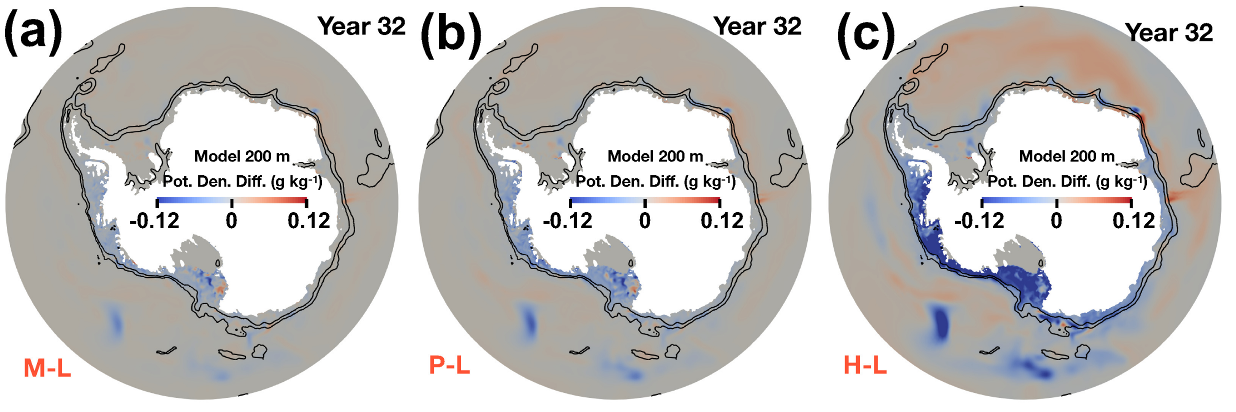


**Figure 9.** January mean potential density difference for (a) MMELT-LMELT (M-L), PRS-LMELT (P-L), and (c) HMELT-LMELT (H-L) for year 32 at 200-m depth. The bathymetry contours of 1000 m and 2500 m are shown as black lines.

**Table 1.** Model parameters used for the simulations in this study. Horizontal diffusivity and viscosity are scaled by area. For example, a grid element with an area of $5.8\times10^9$ $m^2$ or a 1.5° triangular grid yields a viscosity of $6.0\times10^4$ $m^2$ $s^{-1}$ and a diffusivity of about $1.8\times10^3$ $m^2$ $s^{-1}$.

| Parameter | |
|---|---|
| Horizontal diffusivity scaling factor ($m^2$ $s^{-1}$) | $1.8\times10^3$ |
| Background horizontal viscosity scaling factor ($m^2$ $s^{-1}$) | $6.0\times10^4$ |
| Scaling reference area ($m^2$) | $5.8\times10^9$ |
| Background vertical diffusivity ($m^2$ $s^{-1}$) | $5.0\times10^{-5}$ |
| Background vertical viscosity ($m^2$ $s^{-1}$) | $1.0\times10^{-3}$ |
| Bottom drag coefficient | $2.5\times10^{-3}$ |
| Air/sea ice drag coefficient | $2.5\times10^{-3}$ |
| Sea ice/ocean drag coefficient | $5.0\times10^{-3}$ |
| Sea ice salt concentration (g $kg^{-1}$) | 5.0 |
| Drag coefficient at ice shelf base | $2.5\times10^{-3}$ |
| Lead closing (m) | 0.1 |
| Ice strength (N m-2) | $1.5\times10^4$ |
| Sea ice dry albedo | 0.75 |
| Sea ice wet albedo | 0.68 |
| Snow dry albedo | 0.85 |
| Snow wet albedo | 0.77 |

**Table 2.** Antarctic ice shelf basal mass loss from LMELT, MMELT, PRS and HMELT and satellite-based estimates [Depoorter et al., 2013, Rignot et al., 2013]. Ice shelf locations are indicated by numbers in Fig. 1. For some ice shelf regions in the Weddell Sea and East Antarctica ((19)-(22) and (24)-(27), respectively), basal melt rates are accumulated for several ice shelves and compared to the satellite-based estimates as indicated in Fig. 1. Turbulent heat and salt exchange coefficients for ice shelves in AS and BS (bold) are increased for sensitivity experiments.

| Name | LMELT (Gt yr$^{-1}$) | MMELT (Gt yr$^{-1}$) | PRS (Gt yr$^{-1}$) | HMELT (Gt yr$^{-1}$) | Satellite-based estimates (Gt yr$^{-1}$) | References |
|---|---|---|---|---|---|---|
| (1) Ross | 110.2 | 110.5 | 110.3 | 110.7 | 14-82 | Rignot et al., 2013, Depoorter et al., 2013 |
| (2) Withrow | 0.1 | 0.1 | 0.1 | 0.1 | -0.1-0.7 | Rignot et al., 2013 |
| (3) Swinburne-Salzberger | 16.5 | 15.6 | 14.9 | 12.8 | 19-26 | Rignot et al., 2013 |
| (4) Nickerson-Land | 3.0 | 2.9 | 2.8 | 2.7 | 5-11 | Rignot et al., 2013 |
| **(5) Getz** | 93.3 | 139.4 | 168.3 | 309.4 | 117-159 | Rignot et al., 2013, Depoorter et al., 2013 |
| **(6) Dotson** | 13.1 | 19.6 | 23.2 | 33.1 | 41-49 | Rignot et al., 2013 |
| **(7) Crosson** | 3.5 | 4.7 | 5.3 | 5.8 | 35-43 | Rignot et al., 2013 |
| **(8) Thwaites** | 15.2 | 22.2 | 27.0 | 48.3 | 91-105 | Rignot et al., 2013 |
| **(9) Pine Island** | 28.3 | 42.2 | 52.6 | 103.4 | 81-109 | Rignot et al., 2013, Depoorter et al., 2013 |
| **(10) Cosgrove** | 10.3 | 15.9 | 20.3 | 37.2 | 7-11 | Rignot et al., 2013 |
| **(11) Abbot** | 28.5 | 35.5 | 39.4 | 54.5 | 33-97 | Rignot et al., 2013, Depoorter et al., 2013 |
| **(12) Venable** | 2.4 | 3.6 | 4.2 | 7.3 | 17-21 | Rignot et al., 2013 |
| **(13) Ferrigno** | 0.1 | 0.1 | 0.2 | 0.7 | 3-7 | Rignot et al., 2013 |
| **(14) Stange** | 23.6 | 34.6 | 41.9 | 79,1 | 22-34 | Rignot et al., 2013 |
| **(15) George VI** | 104.4 | 147.7 | 176.8 | 298.7 | 72-160 | Rignot et al., 2013, Depoorter et al., 2013 |
| **(16) Bach** | 4.7 | 7.0 | 8.9 | 17.4 | 9-11 | Rignot et al., 2013 |
| **(17) Wilkins** | 19.3 | 25.1 | 28.3 | 41.4 | 1-35 | Rignot et al., 2013 |
| **(18) Wordie** | 0.1 | 0.3 | 0.4 | 1.7 | 4-10 | Rignot et al., 2013 |
| (19) Larsen B-G | 36.4 | 36.6 | 36.0 | 35.3 | -59-134 | Rignot et al., 2013, Depoorter et al., 2013 |
| (20) Filchner-Ronne | 108.5 | 106.9 | 107.8 | 109.1 | 10-200 | Rignot et al., 2013, Depoorter et al., 2013 |
| (21) Brunt-Downer | 101.3 | 101.2 | 101.0 | 100.1 | 40-162 | Rignot et al., 2013 |
| (22) Amery-Publication | 64.8 | 64.3 | 63.8 | 62.1 | 12-62 | Rignot et al., 2013, Depoorter et al., 2013 |
| (23) West | 14.6 | 14.7 | 14.8 | 15.0 | 17-37 | Rignot et al., 2013 |
| (24) Shackleton-Glenzer | 22.1 | 22.3 | 22.3 | 22.2 | 61-97 | Rignot et al., 2013 |
| (25) Vincennes | 1.1 | 1.1 | 1.1 | 1.0 | 3-7 | Rignot et al., 2013 |
| (26) Totten-Moscow Univ. | 9.7 | 9.6 | 9.6 | 9.7 | 83-99 | Rignot et al., 2013 |
| (27) Holmes-Drygalski | 23.4 | 22.2 | 21.3 | 18.4 | 33-72 | Rignot et al., 2013 |
| Amundsen Sea (5-11) | 192.2 | 280.0 | 336.0 | 591.7 | 405-573 | Rignot et al., 2013, Depoorter et al., 2013 |
| Bellingshausen Sea (12-18) | 154.6 | 218.1 | 260.3 | 444.7 | 128-278 | Rignot et al., 2013, Depoorter et al., 2013 |
| Antarctic total | 837.4 | 976.3 | 1068.0 | 1480.1 | 1263-1737 | Rignot et al., 2013, Depoorter et al., 2013 |

**Table 3.** Differences of mean Antarctic ice shelf melt rate and spatially averaged salinity for different regions for the last 2 years of model simulations. The LMELT field is subtracted from HMELT, PRS, and MMELT fields to calculate the differences. We calculate spatial averages for the regions indicated in Fig. 1 but using regions shallower than 1000 m and regions deeper than 2500 m for on-shelf 200-m spatially averaged and bottom spatially averaged salinity, respectively.

| | HMELT-LMELT | PRS-LMELT | MMELT-LMELT |
|---|---|---|---|
| Total melt rate difference (Gt yr$^{-1}$) | 643 | 231 | 138 |
| RS continental shelf salinity difference at 200-m depth (g kg$^{-1}$) | -0.14 | -0.045 | -0.025 |
| Deep RS salinity difference at bottom (g kg$^{-1}$) | -0.015 | -0.0048 | -0.0030 |
| Continental shelf region off Cape Darnley salinity difference at 200-m depth (g kg$^{-1}$) | -0.035 | -0.0078 | -0.0038 |
| Weddell Sea continental shelf salinity difference at 200-m depth (g kg$^{-1}$) | -0.016 | -0.0035 | -0.0003 |