I want to thank R. Walker for his constructive review and good suggestions. I am answering his comments in the following. For clarity, I repeat the original comment ([C]) at first and then the answer ([A]) and author's changes in manuscript [R] afterwards:

General Comments

[C]: Inclusion of ice shelves in global circulation models is a significant issue for the accuracy of climate projections. This study considers the impact of basal melting under the Ross Ice Shelf on the Southern Ocean by contrasting global ocean model experiments with and without melting in the sub-Ross cavity. The choice of a no-melt scenario that includes sub-ice-shelf bathymetry seems a little odd to me, as most ocean modeling that I'm aware of either includes ice shelves plus melting or excludes ice shelves from the domain. It should still be possible to get value from this experimental setup. However, I would have liked this manuscript to spend much more time on detailed discussion of the different experiments, particularly the relations between water properties and dynamics.

[A]: Initially I set up two experiments, one included ice shelves plus melting and the other excluded ice shelves from the domain. After preliminary analysis of simulation results, I realized that the sub-ice-shelf bathymetry gave significant contribution to the differences between the results from the two simulations. This difference in geometry changes local circulation and mixing and leads to changes of overall results compared to or even greater than that in basal melting under the Ross Ice Shelf. Under such conditions, it would be difficult to discuss the effect of basal melting under the Ross Ice Shelf. Hence a third experiment with no-melt scenario that includes sub-ice-shelf bathymetry was added and its results were used in the discussion instead of that from the experiment that excluded ice shelves from the domain. More discussions on the modeling results have been added.

[R] See [R] parts for specific comments.

[C]: General comment on figures) All units should be in axis labels, not only in the captions. Also, axes should be labeled with variable names. Figures 1, 2, 6, 7, 9, 10 should have a larger font size to be readable.

[A&R] These figures have been redrawn:

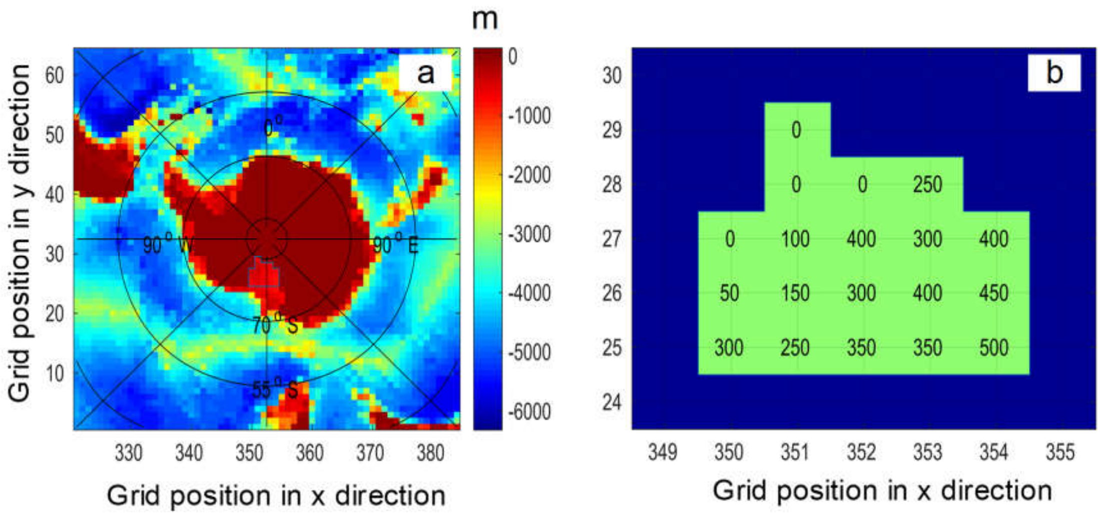

Fig. 1. (a) Bathymetry of the 6th cubed sphere face in the experiments and (b) cavity geometry of RIS in EI. The numbers on the axes indicate the positions of grids on the model domain.

Grid boxes shaded light green in (b) indicate the locations covered by RIS in the model and the numbers in (b) indicate the thickness of the water column in the cavity. The units of bathymetry and water column thickness in the cavity are in m.

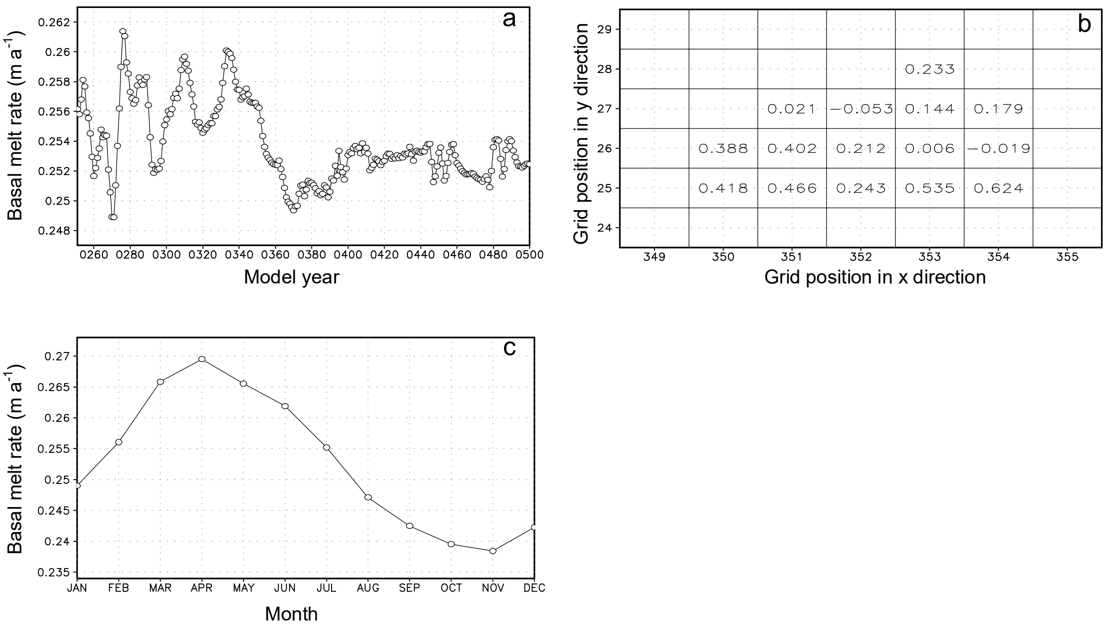

Fig. 2. Basal melting rates of RIS (m a^{-1}) in EI. (a) Variation of the annual and areal mean melting rate over the last 250 years. (b) Spatial distribution of the mean melting rate over the last 100 years. (c) Seasonal cycle averaged over the ice-shelf area and the last 100 years.

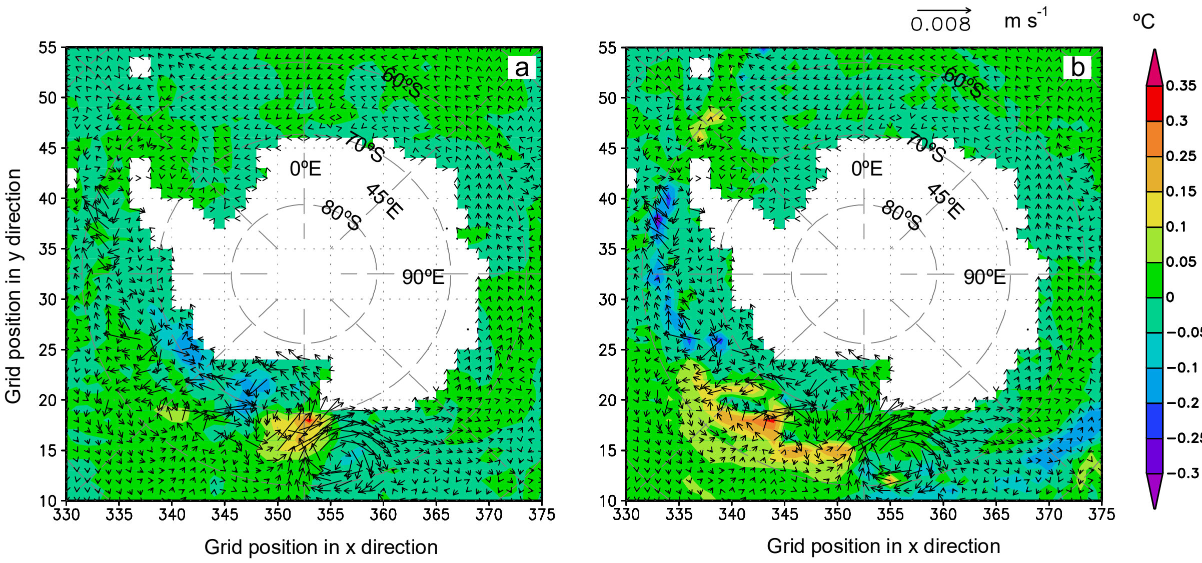

Fig. 6. Differences of sea surface temperature (shaded contours) and current (arrows) (EI minus EN). (a) March. (b) September. The units for temperature and current are °C and m s^{-1}, respectively

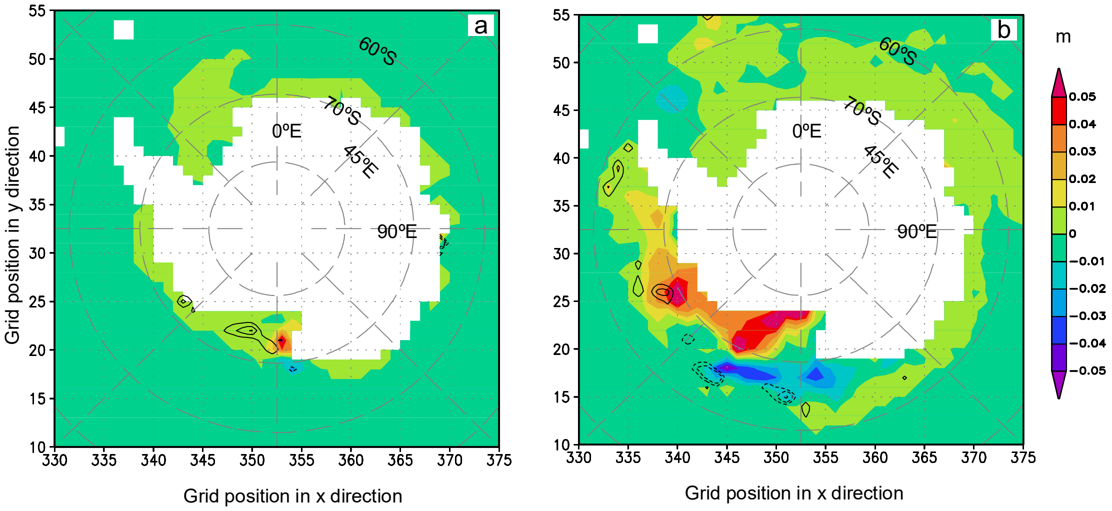

Fig. 7. Differences of sea ice concentration (SIC) and sea ice thickness (SIT) (EI minus EN). (a) March. (b) September. The differences of SIT are shaded. The contours in black represent the differences of SIC, in which contour intervals are 0.02 and 0.05 for (a) and (b), respectively, and lines of 0 are not plotted. The units for SIC and SIT are 100% and m, respectively.

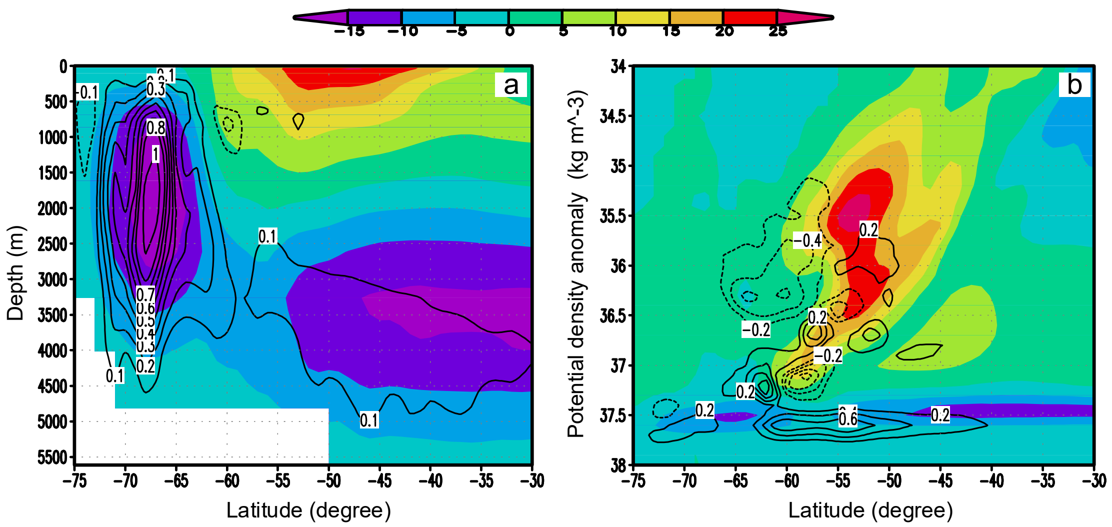

Fig. 9. Meridional transport stream function of EI (shaded contours) and its difference from EN (EI-EN, contours): (a) in depth-latitude space and (b) in density-latitude space. The contour intervals for the meridional transport stream function difference in (a) and (b) are 0.1 Sv and 0.2 Sv, respectively, and the 0 Sv line is not plotted.

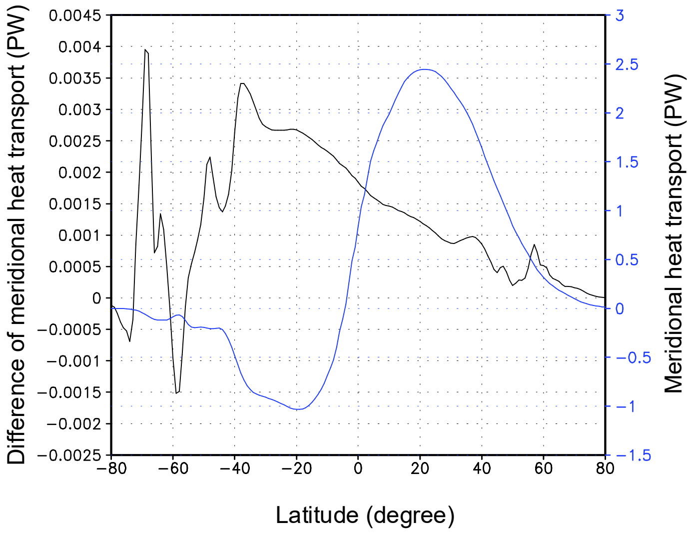

Fig. 10. Meridional heat transport for the global ocean from EI (blue line on the right vertical axis) and its deviation from EN (EI minus EN, black line on the left vertical axis). The units for the vertical and horizontal axes are PW and degrees, respectively.

Specific Comments

[C] Page 2: Line 9) "The equivalent freshwater flux..." This is unclear. Do you mean that the freshwater flux is equivalent to a particular melt rate over the ice shelves?

[A&R] Yes, I do. The sentence has been revised to be clear.

[C] Figure 1b) On my printout, this looks like green, not yellow.

[A&R] Sorry, I used a wrong word. It has been revised.

[c] Section 3.1) Is the first paragraph about both experiments or only EI?

[A&R] It's only about EI.

[C] 5:5) "The difference in the feature ..." This calls for more explanation.

[A&R] More explanation has been added: "Before longer time scale reaction of ocean has been set up, variation of local basal melting is large.

[C] 5:10) When listing the earlier results, it would be good to provide the actual numbers for comparison.

[A&R] The suggestion is accepted. A table listing the earlier results has been added:

Table 2. Basal melt rates averaged over the entire RIS in the work and other studies

Basal melt rates (m/a)	Source	Brief description
0.12 ± 0.03	Shabtaie and Bentley (1987)	Calculated from the measured ice flux into the Ross Ice Shelf and previous measurements
0.18-0.27	Hellmer and Jacobs (1995)	Calculated from a two-dimensional (y/z plane) channel flow model forced by density

		differences between the open boundaries and the interior cavity
0.25	Assmann et al. (2003)	Calculated from a circumpolar numerical model
0.082	Holland et al. (2003)	Calculated from a regional numerical model (MICOM)
0.13-0.15	Dinniman et al. (2007)	Calculated from a regional numerical model (ROMS)
0.15	Dinniman et al. (2011)	Calculated from the ROMS model
**0.6	Timmermann et al. (2012)	Calculated from a global finite element ocean model (FESOM)
0.0± 0.1 for Ross West 0.3 ± 0.1 for Ross East	Rignot et al. (2013)	Calculated from radar measurements and output products from the Regional Atmospheric and Climate Model RACMO2
0.14 ± 0.05	Depoorter et al. (2013)	Calculated from radar measurements and a regional climate model (for firn air content and compaction)
0.25 (without tidal forcing) 0.32 (with tidal forcing)	Arzeno et al. (2014)	Calculated from the ROMS model
0.11 ± 0.14 (converted from basal melt budget of RIS dM/dt in Table 3 with ice density 918 kg/m^3)	Moholdt et al. (2014)	derived from Lagrangian analysis of ICESat (NASA's Ice, Cloud and land Elevation Satellite) altimetry
0.24 (converted from basal melt in Gt/yr for the last year of simulation in R_MLT in Table 3 with RIS area 500 000 km^2 and ice density 918 kg/m^3)	Mathiot et al. (2017)	Calculated from a regional numerical model (NEMO)
0.25	This study	Calculated from quasi-equilibrium state of a global numerical modelling (MITgcm)

[C] 5:14) "The difference in seasonality …" Also could use more explanation.
[A&R] The suggestion is accepted. More explanation has been added: "The modelling system used by Holland et al. (2003) did not incorporate wind and sea ice and restoration of surface temperature and salinity was used."

[C] Figure 3) Write out the full names of the variables in the axis labels.
[A&R] Figure 3 has been redrawn:

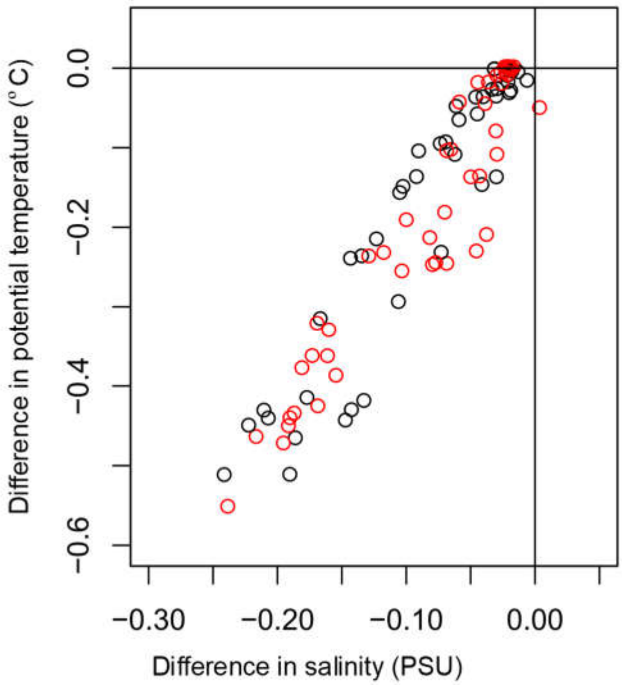

Fig. 3. Salinity difference-temperature difference distribution of water in the RIS cavity (EI minus EN). The horizontal axis is for salinity difference and the vertical axis is for temperature difference. The inflow anomaly and outflow anomaly are marked with red and black, respectively. The units for salinity and temperature are PSU and °C, respectively.

[C] 7:6) What latitudes are you considering to be the Southern Ocean?
[A&R] Ocean south of 35 °S is considered to be Southern Ocean. Explanation on it has been added in the text.

[C] 7:15) This could use a description of the complex mechanisms.
[A&R] The sentence has been removed.

[C] 7:17) What happens in the Southern Atlantic?
[A&R] In the Southern Atlantic Ocean, the salinity increases in water deeper than 4000 m. The analysis has been added in the text.

[C] 7:19) Why aren't you showing the figure? I don't think there's a limit on number of figures here.
[A&R] I rechecked the figure and realized that my previous analysis is not correct. The sentence related with the figure has been removed.

[C] Figure 4) This would be easier to read with the y-axis flipped so the surface is at the top of the graph.
[A&R] Figure 4 has been redrawn.

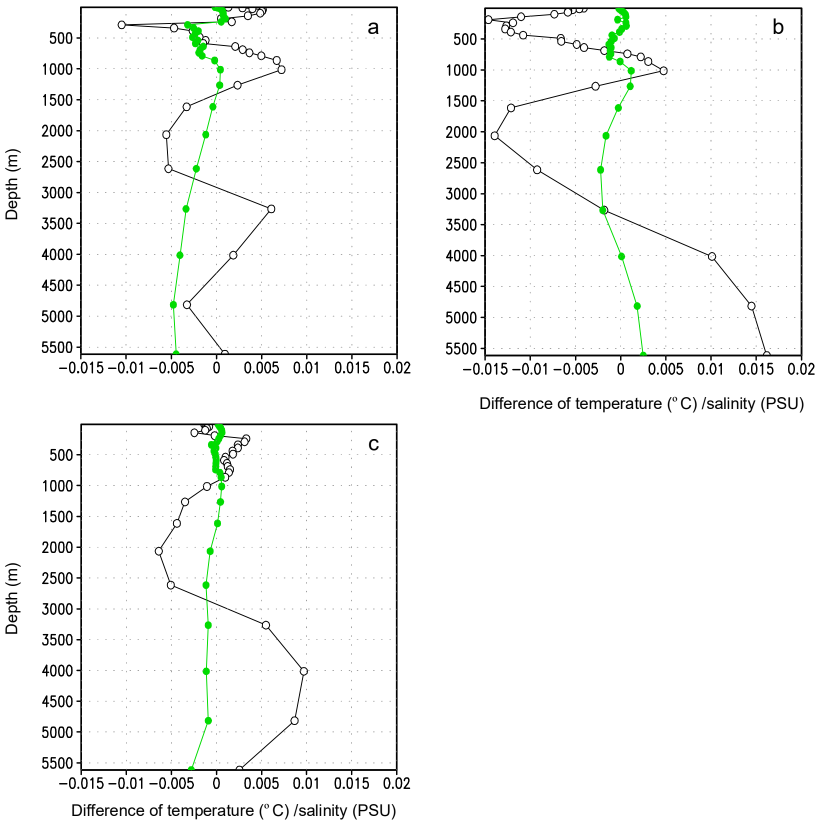

Fig. 4. Area-averaged differences of salinity (solid circle) and potential temperature (open circle) (EI minus EN). The horizontal axis represents the difference and the vertical axis represents ocean depth. (a) Southern Pacific Ocean. (b) Southern Atlantic Ocean. (c) Southern Indian Ocean. The units for salinity and temperature are PSU and °C, respectively.

[C] Figure 5) The color scale here doesn't show detail over most of the domain because of a few outliers under the Ross. Probably would be better to plot Ross separately or just discuss the values there in the text.

[A&R] The figure has been redrawn with new color scale.

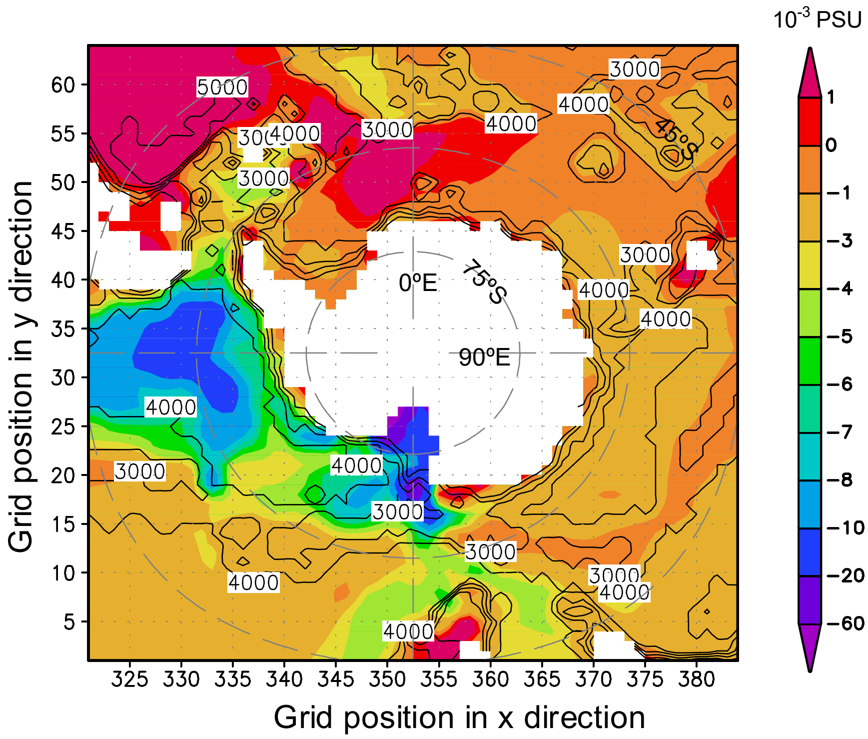

Fig. 5. Annual mean salinity differences (EI minus EN, shaded) at the sea bottom. The contour lines represent the water thickness with intervals of 1000 m. The unit for salinity is PSU.

[C] 9:7) Describe the specific bathymetry feature.
[A&R] There is a local low center in bathymetry. The detail has been added in the text.

[C] 9:16) It would be better to compare your output with Hellmer's for the case of ice-shelf melt being included. The difference you're describing here is more or less a matter of how you define the no-melt experiment setup.
[A] That is a good idea. The counterpart of Hellmer's for the case of ice-shelf melt being included could not be found in the article. I guess the cavity geometry contributes to the difference to a large part.

[C] Figures 6 and 7) The color scales for the subplots should be equal for (a) and (b). Also, the arrows in Figure 6 are very small and hard to read.
[A] The two figures have been redrawn. See my previous [R] parts.

[C] 11:2) Again, why not show the figure?
[A&R] The figure has been added (Fig. S4).

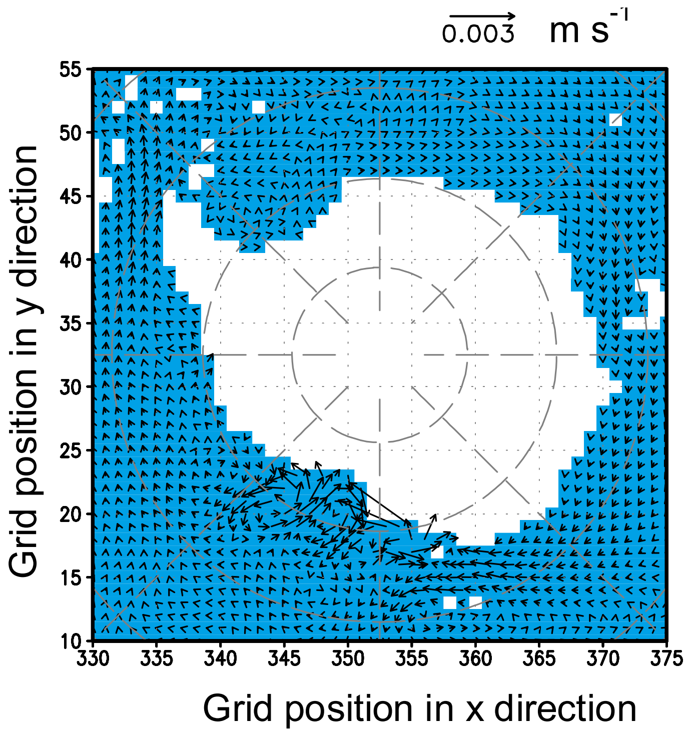

Fig. S4. Differences of annual mean ocean currents (EI minus EN) at 2065 m. The unit of velocity is m s^{-1}

[C] Figure 8) You may want to zoom in to show the gyres better.
[A&R] The figure has been redrawn.

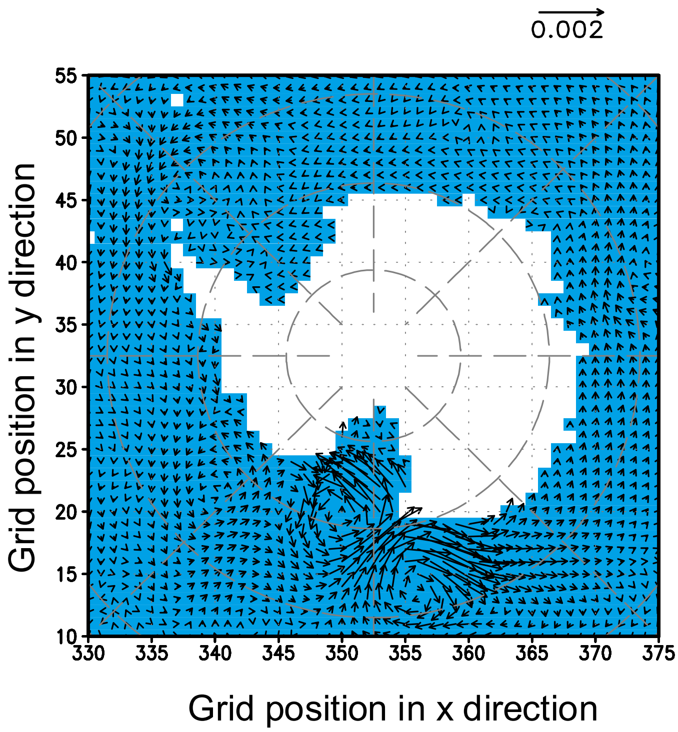

Fig. 8. Differences of annual mean depth-averaged ocean currents (EI minus EN). The unit of velocity is m s^{-1}.

[C] 11:15) Could use a reference for the recommendation.
[A&R] A reference has been added.
Ballarotta, M., Drijfhout, S., Kuhlbrodt, T., and Döös, K.: The residual circulation of the Southern Ocean: which spatio-temporal scales are needed? Ocean Modell., 64, 46–55, doi: 10.1016/j.ocemod.2013.01.005, 2013

[C] Figure 9) The contours of the difference overlying the EI shaded contours are hard to follow, at least for me. The difference could use its own subplot.
[A&R] The figure has been redrawn. See my previous [R] part.

[C] 12:18) It would be useful to compare the heat transport anomalies to the magnitude of the full heat transport.
[A] The suggestion is accepted.
[R] More analysis is added: Compared to the magnitude of the full heat transport, the maximum reduction of southward heat transport occurs around 71 $^{\circ}$S with a value about 6% whereas at most other latitudes the relative reduction is less than 1%.

[C]Figure 10) Cut “stream function” in caption.
[A&R] Corrected.

[C] 13:7) For consistency with the rest of the paper, this should be Southern Ocean.
[A&R] Corrected.

I want to thank X. Asay-Davis for his thorough review and good suggestions. I am answering his comments in the following. For clarity, I repeat the original comment ([C]) at first, then the answer ([A]) and author's changes in manuscript [R] afterwards:

General Comments

[C] This paper describes two global ocean-sea ice experiments run to quasi-equilibrium over 500 years, one with basal melting below the Ross Ice Shelf (RIS) and one without basal melting (but still with an ocean cavity below RIS). Most of the presented results examine differences between ocean and sea ice properties between the two experiments (results are typically averaged over the last 100 years of each experiment). Non-negligible differences in the horizontal and vertical distributions of temperature and salinity are found between the two experiments, leading to appreciable differences in both the meridional overturning circulation and meridional heat transport in the ocean. Differences in the surface and barotropic flow are also demonstrated, along with related changes in sea surface temperature, sea ice thickness and sea ice concentration.

The purpose of the study seems to be to show that freshwater fluxes from ice shelves have a significant impact on the Southern Ocean compared to a simulation without any freshwater fluxes. It seems unclear (and is not discussed in the manuscript) what the relevance of this study is to other modeling work or what this study might tell us about the melt-induced dynamics in the real world.

[A] The purpose of the study is to show the impacts of freshwater and latent heat fluxes from basal melting of Ross Ice Shelve on the Southern Ocean compared to a simulation without any basal melting. More discussions on the relevance of this study to other modeling work and on modeling results have been added.

[R] See the [R] part for specific comments.

[C] It has been known for some time in the Earth System Modeling community that some form or freshwater input into the deep ocean is required for adequate representation of deep ocean properties and of the meridional overturning circulation. Therefore all global Earth System Model (ESM) include some mechanism for freshwater input (typically surface “runoff” around Antarctica and Greenland), together with a mechanism for inducing overturning in polar regions (typically salinity restoring at the surface). No models I am aware of without sub-ice-shelf melting would leave out these mechanisms. Therefore, if the aim of this study is to show that current ESMs should be including the effects of ice-shelf melting in order to avoid inaccuracies in Southern Ocean properties, the “control” experiment (EN in the manuscript) should probably have been closer to a configuration used in ESMs: “runoff” at the surface to at least partially account for freshwater fluxes and no ice-shelf cavities.

[A] The numerical model of any kind used in scientific studies is a simplification and approximation of the real world, no matter how rough or elaborate it is. As have been pointed out in the review, in global ocean modelling the “runoff” can be tailored to reflect the freshwater input connected with basal melting of ice-shelf basing on assumptions. In this way, the latent heat flux is ignored. In addition, the difference in bathymetry with and without ice-shelf cavities changes local circulation and mixing and leads to changes of overall results compared to or even greater than that in basal melting under the Ross Ice Shelf. In the work, the “run off” is not used. The aim of this study is to investigate what differences may be led

by including the effects of ice-shelf melting under the Ross Ice Shelf to Southern Ocean properties. For this aim, the bathymetry is identical in the two experiments.
[R] See the [R] part for specific comments.

[C] If the purpose of the study is to show what features of the climate system are affected by the presence or absence of melting below RIS, there is another significant pitfall in this work. Very little effort is made to validate either the EI (with melting) or the EN (without melting) experiment against observations or previous modeling (except for the basal melt rate below RIS). This strikes me as highly problematic because the differences between the simulations is unlikely to tell us something about the real world if the base state (either EI or EN) that is being perturbed can be shown to be representative of the real world. Given the *very* coarse horizontal resolution (150 km) and rather coarse vertical resolution (not stated but seemingly around 50 m), it seems unlikely that the model will be able to capture the complex chain of processes by which water masses are transformed on the Ross continental shelf, within the Ross cavity, and off the continental slope where they mix into the deep ocean. These processes have been shown to require horizontal resolutions at least 30x higher than this simulation (see specific comments), allowing interactions between small-scale topographic features and narrow oceanic currents. Without these transformations being captured adequately or the model state having been validated against a broader set of observations, conclusions in this work about how basal melting affects the Southern Ocean are likely to only apply to this particular model configuration, and not to be representative of the real world.
[A] More efforts have been made to validate the EI experiment against previous work (for example, heat transport). The choice of model resolution is determined by the problem to study. The purpose of the study is to show what features of the climate system are affected in large scale by the presence or absence of melting below RIS. Under the current resolution, major features of bathymetry of RIS can be resolved and the influence of fresh water flux and latent heat flux due to basal melting of RIS can be represented. The influence of sub-grid processes on modeling results needs further study. Whether the conclusions in this work are model dependent or not also needs further work in the community. To approach the true result, more modelling work with different models are needed. Even most models give similar result, it is still possible that the result is not representative of the real world. Discussion on this have been added in the manuscript.
[R] See the [R] part for specific comments.

[C] The manuscript presents much of the results results with little deeper analysis, discussion or explanation (the exception is a more careful analysis changes in sea surface temperature and sea ice properties resulting from flow anomalies near RIS). Except for the dynamics at the ocean surface, little attempt is made to explain how water masses are transformed to reach various ocean depths. Basal melting is found to *decrease* the global overturning circulation, seemingly due to increased stabilization of the water column, in contradiction to know physical processes of Antarctic Bottom Water formation (known to occur in the Ross Sea region) that are thought to be an important driver of global ocean circulation. No discussion is included of potential shortcomings of the model at capturing or resolving ocean processes that would be relevant to these transformations.

I can only recommend this manuscript for publication after major revisions to address these shortcomings.
[A] More analysis and discussion on the results have been added in the revision version. AABW is formed in the Southern Ocean from surface water cooling in polynyas. With basal melting effect included, sea ice concentration in the Ross Sea increases and more salts are rejected to the ocean. Due to the adoption of boundary condition of restoring salinity in the simulations, the sea surface salinity increase from more ice freezing cannot be reflected in the model. Increased basal melting changes the shelf water characteristics and increases the stability of the water column, decreasing deep convection and the formation of denser bottom water (Hellmer, 2004). In the study of Kusahara and Hasumi (2013), it is found that if the basal melting of ice shelves is included, weakening of the thermohaline circulation driven by Antarctic dense water formation under warming climate conditions will be enhanced. During preparing the manuscript, I have tried to explain how water masses are transformed to reach various ocean depths. I inspected the time series of area-averaged difference in salinity and temperature at different levels for southern Atlantic Ocean, southern Pacific Ocean and southern Indian Ocean respectively. I also analyzed the lead/lag correlations between the fresh water flux from RIS basal melting and salinity of the Southern Ocean. But I have not got a clear picture. Since the time-dependent virtual tracers in the oceans can provide information on the ocean circulation, it would be a better way to make use of tracers to estimate pathways in the ocean. But I am not sure if this method is suitable for the case in the work.
[R] See the [R] part for specific comments.

[C] This paper would benefit from significant editing by a native English speaker. I have attempted to point out typos and grammatical errors where I have seen them (I include about 3 pages of such corrections). Additionally, the figures all need significant format-ting work before they are ready for publication, including labeling axes and increasing font sizes to make the labels more readable.
[A] Thanks so much for correcting the errors in language usage which have all been accepted. The manuscript will be edited by a native English speaker from Editage, a company supplying language services. All figures have been redrawn to meet the demand for publication.
[R] See the [R] part for specific comments.

Specific Comments
[C] p. 1 l. 6: In the field, BMR is typically used as an abbreviation of "basal melt rate". The incorporation of the Ross Ice Shelf into this abbreviation is confusing. I would suggest replacing "basal melting of Ross Ice Shelf (BMR)" with "basal melting below the Ross Ice Shelf (Ross BM)" and elsewhere replace "BMR" with "Ross BM" to avoid confusion. If you can come up with an alternative shorthand that will not be confused with "basal melt rate", that would be fine, too.
[A] The suggestion is accepted.
[R] The abbreviation "BMR" is replaced by "BMRIS" in the revised manuscript.

[C] p. 1 l. 12: I would suggest replacing "substantially" and "not so significant" with

something more quantitative if possible.
[A] The suggestion is accepted
[R] The sentence has been modified to “The extra freshwater flux decreases the salinity from 1500 m to the sea floor in the southern Pacific Ocean and the southern Indian Ocean with a maximum difference of nearly 0.005 PSU in the Pacific Ocean whereas the effect of concurrent heat flux is mainly confined to the middle layer of water body (roughly from 1500 m to 3000 m)”

[C] p. 1 l. 14: “local circulation anomalies”: In general, the abstract seems to treat the case of no basal melting as the control case and the case with basal melting as the modified experiment. I can understand this choice, since ocean models typically do not include ice-shelf cavities, though it seems strange from a physical standpoint to treat the less physical experiment as the control case. Here, the use of the word “anomalies” seems particularly strange to me, since it seems to imply “something that deviates from what is standard, normal, or expected”, whereas I would say the control case is the one more likely to deviate from the physical world. Perhaps another phrase such as “differences in local circulation) would be clearer.
[A] The suggestion is accepted.
[R] The “anomalies” has been used as little as possible.

[C] p. 1 l. 14: “with the help of ocean bathymetry”: This phrase seems rather vague to me. Maybe a better wording would be something like “The decreased density due to the effect of Ross BM, together with interactions with ocean bathymetry, creates local differences in circulation in the...”
[A] The suggestion is accepted.
[R] The sentence has been changed to “The decreased density due to the effect of BMRIS, together with the influence of ocean bathymetry, creates local differences in circulation in the Ross Sea and nearby water”

[C] p. 1 l. 22-24: The audience for The Cryosphere is aware of what ice sheets, ice shelves, icebergs, etc. are so I don’t think this level of introduction is necessary.
[A] The suggestion is accepted.
[R] The two sentences have been replaced with “Ice shelf melting, which accounts for 55% of the ice mass loss from Antarctica, is one of the main sources of freshwater input to the Antarctic coastal ocean (Mathiot et al.,2017)”.

[C] p. 1 l. 26: “beneath the currently stable Ross Ice Shelf”: The phrase “currently stable” is both grammatically problematic and confusing, because it implies a past or future instability in RIS that is not addressed here, nor is there any widely accepted likelihood of RIS instability in the community. I would remove this phrase.
p. 1 l. 26: “can be larger than 2500% of the overall…”: It is not clear that this fact or this reference is relevant to the rest of the paper, as you are not resolving melt channels in your simulations.
[A] The suggestions are accepted.

[R] The sentence has been removed.

[C] p. 2 l. 3: "Neglecting the sub-ice freshwater…for the Southern Ocean." While it is not stated here, the implication seems to be that common practice in ocean modeling of the Southern Ocean is to neglect sub-ice-shelf freshwater fluxes entirely, whereas this is not usually the case. Global (and I believe also regional Antarctic) ocean models without ice-shelf cavities still include an approximation of the total Antarctic freshwater input (melting + calving) but they almost universally do so by distributing the freshwater at the ocean surface and typically evenly around the continent. In my view, sub-ice-shelf freshwater fluxes aren't really "neglected" so much as they are estimated and distributed inaccurately. Here is one publication that discusses the differences in ocean model behavior depending on how freshwater fluxes are distributed: Mathiot, P., Jenkins, A., Harris, C., and Madec, G.: Explicit representation and parametrised impacts of under ice shelf seas in the z* coordinate ocean model NEMO 3.6, Geosci. Model Dev., 10, 2849-2874, https://doi.org/10.5194/gmd-10-2849-2017, 2017.
[A] To avoid misunderstanding, the sentences have been modified.
[R] The sentence has been changed to "The sub-ice freshwater input has various implications for the Southern Ocean."

[C] p. 2 l. 3-4: "These are pronounced in the Weddell…broad continental shelves". It is not clear to me that the Weddell and Ross Seas are the regions of Antarctica that would be most affected by neglecting freshwater fluxes. The large size of RIS and Filchner-Ronne Ice Shelf (FRIS) together with their relatively cold ice-shelf cavities do make them particularly important for AABW formation but other regions of Antarctica with warmer cavities have been shown to produce significant amounts of freshwater that impact Antarctic climate both locally and regionally in significant ways, see e.g.:
Nakayama, Y., R. Timmermann, C. B. Rodehacke, M. Schröder, and H. H. Hellmer (2014), Modeling the spreading of glacial meltwater from the Amundsen and Bellingshausen Seas, Geophys. Res. Lett., 41, 7942–7949, doi:10.1002/2014GL061600.
The Getz, Thwaites and Pine Island Ice Shelves, for example, each produce significantly more freshwater than RIS and nearly as much as FRIS, despite their significantly smaller areas:
Rignot, E., Jacobs, S., Mouginot, J., Scheuchl, B. Ice-shelf melting around Antarctica. Science. 2013 Jul 19;341(6143):266-70. doi: 10.1126/science.1235798.
[A] To resolve the smaller ice-shelves, model resolution must be improved greatly. Besides, the scenario would be different from the work if smaller ice-shelves are included.
[R] Discussion has been added in Part 4: "Ice shelves range in size from 500 000 km^2 (RIS) to around 100 km^2 (Ferrigno ice shelf). The current global ocean model configurations cannot resolve explicitly all the ice shelf cavities, especially for large scale simulation. As have been illustrated by some studies (for example, Rignot et al., 2013; Nakayama et al.,2014), small Ice Shelves can produce significantly more freshwater than RIS and impact Antarctic climate both locally and regionally in significant ways. Not all Ice Shelves are in stable state (some are thickening and some are thinning) (Rignot et al., 2013). To study the influences of stable Ice Shelf basal melting on the Southern Ocean in the long run, the RIS is included under the affordable model resolution for a long integration. But a model's horizontal resolution is

important not only in simulating the conditions underneath the ice shelf that lead to basal melt but also for the conditions in the open ocean that deliver heat to ice shelf cavities (Dinniman et al.,2016). Increasing the model resolution dramatically improves the representation of Circumpolar Deep Water on the Amundsen Sea continental shelf (Nakayama et al., 2014; Dinniman et al., 2015). So more work with finer resolution should be carried out to reduce the uncertainty in simulation of BMRIS effect on the Southern Ocean. Besides, the effects of other ice shelves, such as the Filcher-Ronne and so on, should also be evaluated."

[C] p. 2 l. 8-9: It would be good to supply a more complete list of estimates of basal melting. Here are a few more important ones:
Moholdt, G., L. Padman, and H. A. Fricker (2014), Basal mass budget of Ross and Filchner-Ronne ice shelves, Antarctica, derived from Lagrangian analysis of ICESat altimetry, J. Geophys. Res. Earth Surf., 119, 2361–2380, doi:10.1002/2014JF003171.
M. Depoorter, J. Bamber, J. Griggs, J. Lenaerts, S. Ligtenberg, M. van den Broeke, G. Moholdt. Calving fluxes and basal melt rates of Antarctic ice-shelves. Nature, 502 (7469) (2013), pp. 89-92
[A] The suggestion is accepted.
[R] Result from Moholdt et al. (2014) has been added in the manuscript.

[C] p. 2 l. 10: Other sources (Rignot et al 2013, Depoorter et al. 2013) estimate a significantly larger mean melt rate on the order of 0.8-0.9 m/a. Beckmann and Goosse, 2003 is not really an appropriate citation for the 0.5 m/a number, they are merely citing the Jacobs et al. 1996 estimate, converted from mSv to m/a. Given the significant improvements in satellite observations since 1996, I do not feel that number is particularly trustworthy.
[A] I agree.
[R] The number from Rignot et al 2013 has been used in the revision.

[C] p. 2 l. 11: "occurs at the base of the ice shelf edge": This is sometimes true, particularly for warm ice-shelf cavities. But the freshwater plume in cold cavities typically reaches neutral buoyancy at depths significantly below the ice-shelf edge:
Jacobs, S S, H H Helmer, C S M Doakea, A Jenkins, and R M Frolich. "Melting of Ice Shelves and the Mass Balance of Antarctica." Journal of Glaciology 38, no. 130 (1992): 375–87. doi:10.3198/1992JoG38-130-375-387.
For the purposes of the point you are making, it would be sufficient to say, "Since the injection of this freshwater occurs at depth rather than at the ocean surface..."
[A] The suggestion is accepted.
[R] The sentence has been revised as suggested.

[C] p. 2 l. 16-17: "can provide no direction information about sub-ice shelf circulation": This is not entirely true, as sub-ice-shelf observations include velocity measurements that can be used to infer at least some basic information about the sub-ice-shelf circulation. Temperature and salinity measurements can also be used to infer, through the fraction of Ice Shelf Water, the degree of interaction with the ice-shelf base, which also can provide information about

the broad sub-ice-shelf circulation. I would suggest toning this down to say that it is difficult to infer the sub-ice-shelf circulation from borehole observations.
[A] The suggestion is accepted.
[R] The sentence has been revised as suggested.

[C] p. 2. l. 15-29: The citations in this paragraph seems out of date and incomplete. These reviews provide many citations that could help to fill in the gaps:
Dinniman, Michael, Xylar Asay-Davis, Benjamin Galton-Fenzi, Paul Holland, Adrian Jenkins, and Ralph Timmermann. "Modeling Ice Shelf/Ocean Interaction in Antarctica: A Review." Oceanography 29, no. 4 (December 2016): 144 – 53. https://doi.org/10.5670/oceanog.2016.106.
Asay-Davis, Xylar S., Nicolas C. Jourdain, and Yoshihiro Nakayama. "Developments in Simulating and Parameterizing Interactions Between the Southern Ocean and the Antarctic Ice Sheet." Current Climate Change Reports, October 24, 2017, 1 – 14. https://doi.org/10.1007/s40641-017-0071-0.
I would suggest a complete rewrite of the paragraph with a more complete list of the numerical methods, domains, time periods covered, etc. In particular, there are several studies that have used the MITgcm with ice-shelf cavities in regional configurations to study Antarctica and the Southern Ocean. Since these use the same model as this study, it would seem like they might get particular emphasis here.
[A] The suggestion is accepted.
[R] The paragraph has been rewritten as: "The need for numerical modeling of ice shelf–ocean interactions is particularly acute due to a lack of extensive observational data, which results from the physical inaccessibility of the areas of interest. Besides, it is difficult to infer sub-ice-shelf circulation from borehole observations, creating a significant need for numerical models (Walker and Holland, 2007; Dinniman et al.,2016). As illustrated in Table 1, in ice shelf-sea ice-ocean coupled modeling, researchers use different types of ice shelf representations, such as dynamic ice-shelf geometry permitting two-dimensional flow (Grosfeld and Sandhager, 2004), simplified and computationally inexpensive representations that are nevertheless capable of handling significant changes to the shape of the sub-ice-shelf cavity as the shelf profile evolves (Walker and Holland, 2007), thermodynamics with fixed cavity techniques (Losch, 2008; Timmermann et al., 2012), and parameterized schemes for the interaction between ice shelves and the adjacent ocean (Beckmann and Goosse, 2003). The models are mostly circumpolar (Hellmer, 2004; Kusahara and Hasumi, 2013; Mathiot et al., 2017), regional (Galton-Fenzi et al., 2012), or two-dimensional in the yz-plane (Walker et al., 2009).

A few global models were also used for numerical studies. For example, Beckmann and Goosse (2003) studied the ice shelf basal melting effect using a global ocean-sea ice coupled model with a first order parameterization of ice shelf-ocean interaction. Losch (2008) introduced ice shelves into the Massachusetts Institute of Technology general circulation model (MITgcm) and conducted ISOMIP (Ice Shelf–Ocean Model Intercomparison Project) experiments and nearly global (excluding the Arctic Ocean) ocean circulation experiments. In these experiments, results with and without explicit modeling of ice shelf cavities were presented and the analysis was mainly focused on the Weddell Sea and circulation in the Filchner-Ronne Ice Shelf cavity. Timmermann et al. (2012) presented results of ice shelf basal mass loss from a global sea ice-ice shelf-ocean model based on the finite element method, in which the model was forced with daily data from the NCEP/NCAR reanalysis for the period 1958–2010. There are also numerous other recent modeling studies on ice shelves that employed regional, circumpolar, or global models; Asay-Davis et al. (2017) provided a thorough review of these studies. However, to research the effect of ice-shelf melting on the ocean in quasi-equilibrium, it is necessary to use a global model with thermodynamically active ice-shelf cavities and perform integration over hundreds of years. This type of research has not previously been conducted.

Table 1. An incomplete list of ice shelf-ocean coupled modelling

Publication	Ocean model	ice shelf implementation	domain and time periods covered
Beckmann and Goosse (2003)	Bremerhaven Regional Ice Ocean Simulations (BRIOS)	Parameterization	Circumpolar, 100 years
Grosfeld and Sandhager, (2004)	a rigid-lid, hydrostatic primitive equation model, formulated in spherical coordinates	Dynamic	900km x 700km in the horizontal, 300 years
Hellmer (2004)	Bremerhaven Regional Ice Ocean Simulations (BRIOS)	fixed cavity and thermodynamics	Circumpolar,20 years
Walker and Holland (2007)	A two-dimensional model in the yz-plane	simplified dynamic	600km x 1100m, 600 years
Losch (2008)	MIT general circulation model (MITgcm)	fixed cavity and thermodynamics	In ISOMIP (Ice Shelf–Ocean Model Intercomparison Project) experiment: from 0ºE to 15ºE and 80ºS to 70ºS, 10 000 days In (nearly) global ocean model (excluding the Arctic Ocean) experiment: 80ºN southward, 100 years
Timmermann et al. (2012)	Finite Element Sea-ice Ocean Model (FESOM)	fixed cavity and thermodynamics	Global, 53 years
Galton-Fenzi et al. (2012)	Regional Ocean Modeling System (ROMS)	fixed cavity and thermodynamics	Regional, 20 years
Kusahara and Hasumi (2013)	a sea ice-ocean coupled model, named COCO	fixed cavity and thermodynamics	Circumpolar,25 years for CTRL run and 38 additional years for ERA-INT case
Mathiot et al. (2017)	Nucleus for European Modelling of the Ocean (NEMO)	fixed cavity and thermodynamics	In academic case: from 0ºE to 15ºE and 80ºS to 70ºS, 10 000 days In real ocean application: circumpolar,

	10 years

"

[C] p. 2 l. 19: "dynamic": this could use further clarification. I think you mean dynamic ice-shelf geometry? How is this different from Walker and Holland (2007)?
[A] Yes, I mean dynamic ice-shelf geometry. Walker and Holland (2007) scheme is simpler and only permits one-dimensional flow.
[R] It has been revised to "dynamic ice-shelf geometry permitting two-dimensional flow"

[C] p. 2. l. 21: "fixed cavity and thermodynamics": The cavity geometry is fixed but the thermodynamics is not – melt rates evolve with changing ocean conditions.
[A] Thanks for pointing out the problem.
[R] "fixed cavity and thermodynamics" has been revised to "thermodynamics with fixed cavity".

[C] p. 2 l. 21: "parameterization": Again, more details on what this means would be helpful.
[A] The suggestion is accepted.
[R] The "parameterization" has been extended to "parameterization of the interaction between ice shelves and the adjacent ocean"

[C] p. 2 l. 22-23: What would the other options be besides the list given? Global? Indeed, there are several studies with global models (Losch, 2008; Helmer et al. 2012; Timmermann et al. 2012, etc.)
[A] Losch, 2008 and Timmermann et al. 2012 were mentioned in the paragraph. Helmer et al. 2012 used a regional model identical to that in Hellmer (2004) which had been mentioned.

[C] p. 2 l. 23: "two-dimensional" needs more clarification – one horizontal dimension and one vertical.
[A&R] "two-dimensional" has been revised to "two-dimensional in yz-plane".

[C] p. 2. l. 28-29: "At present, this kind of research has rarely been reported." I think it is fair to say that this has not been done before.
[A&R] The sentence has been changed to "At present, this kind of research has not been done before".

[C] p. 2 l. 30-p. 3 l. 6: Again, I think this paragraph is missing some important work. Many modeling efforts not mentioned here include the Ross Sea in larger regional or global models that are big enough to look at the effect of RIS on the Southern Ocean. Two examples are:
Timmermann, Ralph, and Hartmut H. Hellmer. "Southern Ocean Warming and Increased Ice Shelf Basal Melting in the Twenty-First and Twenty-Second Centuries Based on Coupled Ice-Ocean Finite-Element Modelling." Ocean Dynamics 63, no. 9–10 (October 2013): 1011–1026. https://doi.org/10.1007/s10236-013-0642-0.
Dinniman, Michael S., John M. Klinck, Eileen E. Hofmann, and Walker O. Smith. "Ef fects of Projected Changes in Wind, Atmospheric Temperature, and Freshwater Inflow on the Ross Sea." Journal of Climate, December 1, 2017. https://doi.org/10.1175/JCLID-17-0351.1.
You are correct that these models were not able to run for long enough times to look at

quasi-equilibrium effects

[A] Thanks for giving the references. Both articles focus on influences of warming atmosphere on Southern Ocean and Ice Shelf. There are not much information on the effect of RIS on the Southern Ocean.

[C] p. 3 l. 12: “will be an interesting topic”: I don’t think this belongs here, as it is a very subjective statement. I would remove this whole sentence.

[A&R] The statement has been removed.

[C] p. 3 l. 17-19: Both the topography data and the forcing data are not the most up-to-date versions, see references below. Both Bedmap2 (Fretwell et al. 2013) and RTOPO2 (Schaffer et al. 2016) have updated topography, though I am not sure whether these changes affect RIS specifically. There is a CORE-NYF.v2 data set (http://data1.gfdl.noaa.gov/nomads/forms/core/COREv2/CNYF_v2.html), which is a climatology from the interannual forcing described in Large and Yeager (2009). It would be worth explaining why these earlier versions were used instead of the more up-to-date versions.

Fretwell, P, H D Pritchard, D G Vaughan, J L Bamber, N E Barrand, R Bell, C Bianchi,et al. “Bedmap2: Improved Ice Bed, Surface and Thickness Datasets for Antarctica.” The Cryosphere 7, no. 1 (2013): 375–93. https://doi.org/10.5194/tc-7-375-2013.

Schaffer, Janin, Ralph Timmermann, Jan Erik Arndt, Steen Savstrup Kristensen, Christoph Mayer, Mathieu Morlighem, and Daniel Steinhage. “A Global, HighResolution Data Set of Ice Sheet Topography, Cavity Geometry, and Ocean Bathymetry.” Earth System Science Data 8, no. 2 (October 2016): 543–57. https://doi.org/10.5194/essd-8-543-2016.

Large, W. G., and S. G. Yeager. “The Global Climatology of an Interannually Varying Air–sea Flux Data Set.” Climate Dynamics 33, no. 2–3 (August 2009): 341–64. https://doi.org/10.1007/s00382-008-0441-3.

[A] Almost all the work was done in 2015, when the new version cavity geometry dataset hadn’t come out. The CORE-NYF.v2 data set was used and now I realized that the reference given in the manuscript was not accurate (on the website, it still says that “Details are provided in the Large and Yeager (2004) report”). There are differences in RIS cavity geometry between RTopo105b and RTOPO2 (Schaffer et al. 2016) and the model reflects these differences in 5 grids with difference of 50 m in thickness of water column in the cavity.

[R] The reference for CORE-NYF.v2 has been revised.

[C] p. 3 l. 17-19: How is “runoff” handled in each experiment (EI and EN)? I believe CORE specifies a runoff field that inputs freshwater into the Antarctic region equally around the continent and at the ocean surface at a level that is supposed to roughly match the surface accumulation over the continent (therefore accounting for the combined effect of runoff, sub-ice-shelf melting and calving, assuming AIS is in equilibrium). Was this runoff field included in your simulations?

[A] This runoff field was not used in both experiments.

[C] p. 3 l. 24-26: I would suggest making this sentence a footnote.

[A&R] It has been moved to footnote.

[C] p. 3. l. 27-28: Please explain the abbreviations “EI” and “EN”.
[A&R] The sentence has been revised to “The two experiments are denoted by EI (experiment with basal ice-shelf melting considered) and EN (experiment with no basal ice-shelf melting considered) respectively.

[C] p. 3 l. 29-30: More detail should be given about what the vertical resolution actually is. What is the resolution at the surface? At 1000 m depth? The coarsest resolution (at depth)? I suspect that, even with finer resolution in the upper 1000 m, 30 layers is inadequate to resolve the sub-ice-shelf plume in detail. Finer resolution would likely lead to a significantly different answer, see:
Losch, M. “Modeling Ice Shelf Cavities in a z Coordinate Ocean General Circulation Model.” Journal of Geophysical Research 113, no. C8 (August 2008): 1–15. https://doi.org/10.1029/2007JC004368.
Schodlok, Michael P., Dimitris Menemenlis, Eric Rignot, and Michael Studinger. “Sensitivity of the Ice-Shelf/Ocean System to the Sub-Ice-Shelf Cavity Shape Measured by NASA IceBridge in Pine Island Glacier, West Antarctica.” Annals of Glaciology 53, no. 60 (2012): 156–162. https://doi.org/10.3189/2012AoG60A073.
Schodlok, M. P., D. Menemenlis, and E. J. Rignot. “Ice Shelf Basal Melt Rates around Antarctica from Simulations and Observations.” Journal of Geophysical Research: Oceans 121, no. 2 (February 2016): 1085–1109. https://doi.org/10.1002/2015JC011117.
[A] The layer thicknesses are 10, 10, 15, 21, 28, 36, 45, 13 x 50, 100, 200, 300, 400, 500, 600, 700, and 3 x 800 m. According to Losch (2008), “Dz = 100 m appears to be the minimum vertical resolution that is required to resolve ice shelf-ocean processes.” The current vertical discretization meets that standard. The vertical resolution near the bottom is poor. This problem is partially alleviated by the partial cell treatment of topography (Adcroft et al., 1997).
Losch, M.: modelling ice shelf cavities in a z coordinate ocean general circulation model, J. Geophys. Res., 113, C08043, doi:10.1029/2007JC004368, 2008.
Adcroft, A., Hill, C., and Marshall, J.: Representation of topography by shaved cells in a height coordinate ocean model, Mon. Weather Rev.,125(9), 2293 – 2315, doi:10.1175/1520-0493(1997)125<2293:ROTBSC>2.0.CO;2, 1997.
[R] The detail about the vertical resolution has been added.

[C] p. 4 l. 2: “the horizontal resolution is about 150 km”. This is one of my biggest concerns about this work. I realize that long time integrations are expensive but this coarse resolution (coarser even than CMIP5 and CMIP6 models of the region) seems *far* too coarse to capture the relevant dynamics for the Antarctic region, most importantly the pathways for transporting freshwater from the RIS to the Southern Ocean. See the following paper for a discussion of the pathways and the resolution (~5 km) required to capture them:
Dinniman, Michael S., John M. Klinck, Eileen E. Hofmann, and Walker O. Smith. “Effects of Projected Changes in Wind, Atmospheric Temperature, and Freshwater Inflow on the Ross Sea.” Journal of Climate, December 1, 2017. https://doi.org/10.1175/JCLID-17-0351.1.
See this paper for a discussion of the inadequacy of CMIP5 models at capturing Antarctic

continental shelf processes:

Little, Christopher M., and Nathan M. Urban. "CMIP5 Temperature Biases and 21st Century Warming around the Antarctic Coast." Annals of Glaciology 57, no. 73 (September 2016): 69–78. https://doi.org/10.1017/aog.2016.25.

[A] In the history of numerical simulation, coarse resolution modelling was performed before finer work. As mentioned in the review, there are shortcomings in numerical modelling if the resolution is not capable of capturing critical processes. In my opinion, the current configuration is enough for capturing fundamental processes in large scale relating the effect of basal melting of RIS on the Southern Ocean. Smaller ice shelves are not studied in the manuscript.

[R] A short discussion has been added: "Ice shelves range in size from 500 000 km^2 (RIS) to around 100 km^2 (Ferrigno ice shelf). The current global ocean model configurations cannot resolve explicitly all the ice shelf cavities, especially for large scale simulation. As have been illustrated by some studies (for example, Rignot et al., 2013; Nakayama et al.,2014), small Ice Shelves can produce significantly more freshwater than RIS and impact Antarctic climate both locally and regionally in significant ways. Not all Ice Shelves are in stable state (some are thickening and some are thinning) (Rignot et al., 2013). To study the influences of stable Ice Shelf basal melting on the Southern Ocean in the long run, the RIS is included under the affordable model resolution for a long integration in the work. But a model's horizontal resolution is important not only in simulating the conditions underneath the ice shelf that lead to basal melt but also for the conditions in the open ocean that deliver heat to ice shelf cavities and identifying relevant water masses (Dinniman et al.,2016; Little and Urban, 2016). Increasing the model resolution dramatically improves the representation of Circumpolar Deep Water on the Amundsen Sea continental shelf (Nakayama et al., 2014; Dinniman et al., 2015). More work with finer resolution should be carried out to reduce the uncertainty in simulation of BMRIS effect on the Southern Ocean. Besides, the effects of other ice shelves, such as the Filcher-Ronne and so on, should also be evaluated."

[C] p. 4 Table 1: Please reformat values in scientific notation rather than "e" notation used in programming languages (e.g. $1.0 \ 10^{-4}$ if you are using LaTex). Here and elsewhere, "m/s" should be "m s^{-1}" and similarly "m/a" should be "m a^{-1}", etc.

[A&R] Those values have been reformatted in scientific notation.

[C] p. 4 Table 1: Could you explain the choice to use ISOMIP thermodynamics? Neglecting the velocity dependence of the heat- and salt-transfer coefficients has been shown to reduce the accuracy of melt fields, see discussions in:

Dansereau V, Heimbach P, Losch M. Simulation of subice shelf melt rates in a general circulation model: velocity-dependent transfer and the role of friction. Journal of Geophysical Research: Oceans. 2014;119(3):1765–90. https://doi.org/10.1002/2013JC008846.

Asay-Davis, Xylar S., Nicolas C. Jourdain, and Yoshihiro Nakayama. "Developments in Simulating and Parameterizing Interactions Between the Southern Ocean and the Antarctic Ice Sheet." Current Climate Change Reports, October 24, 2017, 1–14. https://doi.org/10.1007/s40641-017-0071-0.

[A] Although in most recent simulations models used have been updated from velocity-

independent to dependent formulations, the impact has not been well documented (except for Pine Island Ice Shelf and Larsen C ice shelf). Especially the analysis for RIS could not be found. Under the current coarse resolution, I am not convinced the velocity-dependent formulation can improve the result significantly.
[R] A brief discussion has been added: "In the work the ISOMIP thermodynamics, which neglects the velocity dependence of the heat- and salt-transfer coefficients, has been used. In the velocity-independent melt rate parameterizations, the impact of currents or tides on the distribution of sub-ice shelf melting is indirect, hence limited (Dansereau et al.,2014). If the velocity dependence of transfer coefficients is considered, just as most recent modelling with fine grids did (Dansereau et al.,2014; Asay-Davis et al.,2017), differences in melt rate patterns may are found. The differences in melt rate patterns may be bigger in higher resolution modelling since high boundary layer currents can be resolved better. "

[C] p. 4 Table 1: Could you explain why the Jenkins et al. (2001) form was not used? They show that this can lead to a drift away from the expected linear relationship between T and S over long timescales, which seems problematic given that this study is focused precisely on long timescales.
[A] For ISOMIP thermodynamics, the salinity uses a conservative boundary condition that implicitly includes both advective and diffusive fluxes; the advection of percolating meltwater into the ocean, which having an impact on the ice-ocean heat flux, is generally small and could be overlooked.

[C] p. 4 l. 11-12: Could you please explain the choice to remove the ice shelf cavity in the 4 grid boxes rather than thicken the cavity? What criterion was used to decide whether the cavity is too thin and should be set to zero? How does the cavity thickness in the model compare with that of the original RTOPO-1 data set, averaged over each grid cell? Was the cavity thickness increased in some cells to match some required threshold (e.g. the column is more than x cells thick)? If so, was the ice draft moved up or was the bathymetry moved down, or both? What is the area of the modeled cavity compare to the area in RTOPO-1 and what would you expect the effect of this difference to be (I would expect the modeled cavity is much smaller and that this would lead to a reduced freshwater flux but a similar melt rate to observations). In summary, more explanation of the method is needed.
[A] For the 4 grid boxes whose ice shelf cavity are removed, the thicknesses of water columns are less than 42 m which cannot be resolved with vertical grids of 50 m in size (starting from the 8th layer which is about 200 m below sea surface, the vertical grid size is 50 m). If the cavity is too thin to be resolved by the vertical grids, it will be set to zero. The cavity thickness in the model is smaller compared to that in the original RTOPO-1 data set with the maximum difference less than 50 m. The cavity thickness was not increased in some cells to match some required threshold. In RTOPO-1the area of cavity is 502024.1 km^2 whereas in the model it is only 476924.2 km^2 due to the coarse model resolution.
[R] More explanation of the method has been added.

[C] p. 4 l. 12: I believe "depth" actually refers to "water-column thickness". Is that correct? If so, please make this substitution.

[A&R] That is correct. It has been revised.

[C] p. 4 Fig. 1: "indicate grids where cavities are resolved". Since 4 grid boxes have water-column thicknesses of zero, I would argue those grid boxes don't resolve the cavity and should probably be removed from the figure or shaded differently.
[A&R] It has been revised to "indicate grids which are covered by RIS in the model".

[C] p. 4 Fig. 1: I am deeply concerned that RIS, the main focus of the study, is captured by only 15 grid cells and with seemingly 50 m vertical resolution and seemingly without partial bottom cells (though neither of these are discussed in the text). The introduction suggests that it is important to capture the sub-ice-shelf flow in models because it cannot be observed directly, but such coarse resolution seems entirely inadequate to do that job.
[A] About 80% of RIS area is resolved by the model. For grid boxes with ice base exceeding 200 m below the sea surface, the vertical grid size is 50 m. The partial bottom cells are used in the model. It's true that the model cannot capture the sub-ice-shelf flow well. The aim of the work is not to simulate the sub-ice-shelf flow.

[C] p. 5 l. 9-13: It would be helpful to have a figure, panel of a figure or table to compare these various melt rates. It would be useful to be more quantitative than "larger" and "smaller". It would also be important to separate results derived from modeling from those derived from satellite measurements. It is encouraging that the melt rate lies within the range of observational and previous model estimates. What about freshwater fluxes (given that the area of RIS in the model is probably significantly different from observations)? How do these compare with other studies?
[A] The suggestions are accepted. Since the model can capture about 80% of RIS area, the influence of reduced area is not large considering the uncertainties of RIS melting in observations and modelling.
[R] A table (Table 3) about basal melt rates averaged over the entire RIS in the work and other studies has been added in the revision version.

Table 3. Basal melt rates averaged over the entire RIS derived in this study and other studies

Basal melt rates (m/a)	Source	Brief description
0.12 ± 0.03	Shabtaie and Bentley (1987)	Calculated from the measured ice flux into the Ross Ice Shelf and previous measurements
0.18-0.27	Hellmer and Jacobs (1995)	Calculated from a two-dimensional (y/z plane) channel flow model forced by density differences between the open

		boundaries and the interior cavity
0.25	Assmann et al. (2003)	Calculated from a circumpolar numerical
0.082	Holland et al. (2003)	Calculated from a regional numerical model (MICOM)
0.13-0.15	Dinniman et al. (2007)	Calculated from a regional numerical model (ROMS)
0.15	Dinniman et al. (2011)	Calculated from the ROMS model
0.6	Timmermann et al. (2012)	Calculated from a global finite element ocean model (FESOM)
0.0± 0.1 for Ross West 0.3 ± 0.1 for Ross East	Rignot et al. (2013)	Calculated from radar measurements and output products from the Regional Atmospheric and Climate Model RACMO2
0.14 ± 0.05	Depoorter et al. (2013)	Calculated from radar measurements and a regional climate model (for firn air content and compaction)
0.25 (without tidal forcing) 0.32 (with tidal forcing)	Arzeno et al. (2014)	Calculated from the ROMS model
0.11 ± 0.14 (converted from basal melt budget of RIS dM/dt in Table 3 with ice density 918 kg/m^3)	Moholdt et al. (2014)	derived from Lagrangian analysis of ICESat (NASA's Ice, Cloud and land Elevation Satellite) altimetry
0.24 (converted from basal melt in Gt/yr for the last year of simulation in R_MLT in Table 3 with RIS	Mathiot et al. (2017)	Calculated from a regional numerical model (NEMO)

area 500 000 km2 and ice density 918 kg/m^3)		
0.25	This study	Calculated from quasi-equilibrium state of a global numerical modelling (MITgcm)

[C] p. 5 l. 13: What is meant by "net melt rate"?
[A&R] In Holland et al. (2003), "net melt rate" refers to the sum of "melt-only" rate and "freeze-only" rate. It's identical to the basal melt rate in the work. To avoid confusing, it has been changed to "basal melt rate".

[C] p. 5 l. 15: What is meant by "model system evolution stage"? Does this refer to the numerical methods used to discretize the equations of motion?
[A] That means stage during the process of modeled ocean adjustment.

[C] p. 6 l. 7-8: "salinity bias and temperature bias": I don't think "bias" is the correct word here, as this would assume that the control case (without melting) are the observations, which they most certainly are not. I would also suggest avoiding the word anomaly unless you make clearer why you have chosen the EN experiment to be the "control" (implying you expect it to be the "normal" case in some sense). I think the most correct term, free from value judgments, would simply be "difference". So the sentence should probably read something like "The relationship between salinity and temperature differences in RIS cavity water between the two experiments…"
[A&R] The suggestion is accepted and the sentence has been revised.

[C] p. 6 l. 7-11: This linear relationship between T and S resulting from melting is well known and is called the Gade line:
Gade, HG. "Melting of Ice in Sea Water: A Primitive Model with Application to the Antarctic Ice Shelf and Icebergs." Journal of Physical Oceanography 9 (1979): 189– 198.
It would be important to show if your line has the expected slope for a Gade line. Otherwise, it could indicate something is amiss with the sub-ice-shelf boundary conditions.
[A] This line reflects the relationship between difference of T and difference of S, it's not the Gade line.

[C] p. 6 l. 10: "ppt" should probably be "PSU", which is slightly different. I do not believe MITgcm uses ppt to measure salinity.
[A&R] The practical salinity scale is used in the model. In some publications using MITgcm, the salinity is unit-less. I have revised the unit to PSU.

[C] p. 6 l. 11: "there seems to be no significant influence on the inflow and outflow in the cavity": The only way I can make sense of this phrase is if "influence on" is changed to "difference between". Melting clearly has an influence on both the inflow and the outflow so it is clearly not correct to say there is no influence. I would suggest that this finding deserves more discussion. The only way to make sense of this is that, in quasi-equilibrium, a significant amount of outflowing freshwater recirculates into the cavity. This is a somewhat surprising finding and I think possibly a significant difference between these simulations and those at higher resolution (e.g. Nakayama et al. 2014, Dinniman et al. 2017):

Nakayama, Y., R. Timmermann, C. B. Rodehacke, M. Schröder, and H. H. Hellmer. "Modeling the Spreading of Glacial Meltwater from the Amundsen and Bellingshausen Seas." Geophysical Research Letters 41, no. 22 (November 2014): 7942 – 49. https://doi.org/10.1002/2014GL061600.

[A] As suggested, it would be safer to change the phrase "influence on" to "difference between". Under the current resolution, the model cannot catch circulation in the cavity in detail.

[R] The phrase "influence on" has been changed to "difference between".

[C] p. 7 Fig 3: "ppt" should be "PSU". Typically, we use degrees C instead of K in cryospheric research but that makes no difference for this particular plot.

[A&R] Accepted and revised.

[C] p. 7 l. 6-20: Most of this paragraph seems simply to describe Fig. 4 without providing any physical insight into why these differences occur. To a limited degree, it is helpful to have you point out the most salient features of each panel but it would be far more useful to get some understanding of why changes in salinity occur where they do (and similarly for temperature). Why are they so different?

[A] I agree with you. To get a clear picture behind Fig. 4 is a hard work that I've tried for quite some time.

[R] See [R] parts of the following three comments.

[C] p. 7 l. 13-15: It is not at all obvious to me how you are backing up the assertion that freshwater flux is more significant than heat flux. The way I would expect to see that is in the influence of each on density changes, which in turn affect large-scale overturning and mixing into the deeper ocean. But Fig. 4 provides no information about the effects on density. Given that T and S have completely different units, there seems to be no basis for comparing the relative importance of these differences on their own. The fact that temperature differences are more scattered does not seem in any obvious way to support the conclusion that heat fluxes are less influential on these differences.

[A] In polar oceans, salinity has larger influence on density variation than temperature. I have added a brief discussion on that.

[R] A brief discussion is added: "Using the International Thermodynamic Equation of Seawater-2010 (TEOS-10), the total differential in density ρ can be expressed as

$$d\rho = \frac{\partial \rho}{\partial \Theta}\Big|_{S_A,p} d\Theta + \frac{\partial \rho}{\partial S_A}\Big|_{\Theta,p} dS_A = \rho(-\alpha d\Theta + \beta dS_A),$$

where $\alpha = -\frac{1}{\rho}\frac{\partial \rho}{\partial \Theta}|_{S_A,p}$, $\beta = \frac{1}{\rho}\frac{\partial \rho}{\partial S_A}|_{\Theta,p}$; S_A is absolute salinity, Θ is conservative temperature, p is pressure, α is the coefficient of thermal expansion, and β is the coefficient of haline contraction. Using the Gibbs Seawater Oceanographic Toolbox in Fortran (https://github.com/TEOS-10/GSW-Fortran), such variables as S_A, Θ, α, β, and ρ can be easily computed. The S_A difference-Θ difference distribution of water in the RIS cavity (EI minus EN) is similar to that in Fig. 3. In polar oceans, β can be ten times larger than α (see Fig. S2). This implies that the change of density is dominated by that of salinity if temperature variation and salinity variation are in the same order. The added fresh water reduces the salinity in water near the RIS. This reduced salinity gives rise to a reduction in sea water density (Fig. S3).

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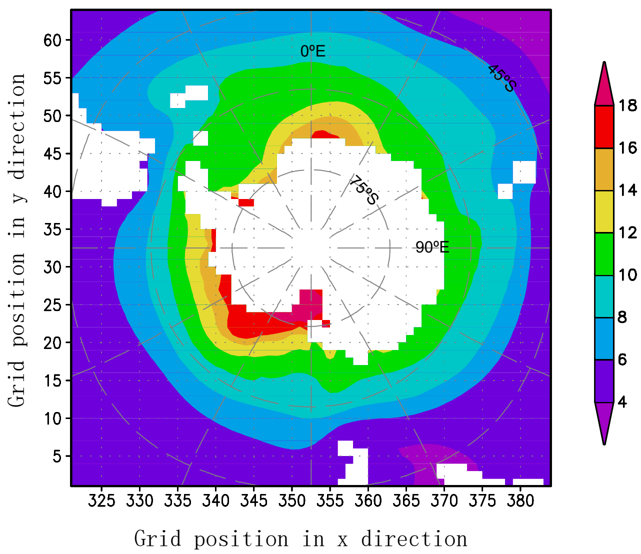

Fig. S2. Ratio of the coefficients of haline contraction and thermal expansion ($\beta\alpha^{-1}$) at 390 m in EN. The units of β and α are kg g^{-1} and $^{o}C^{-1}$ respectively.

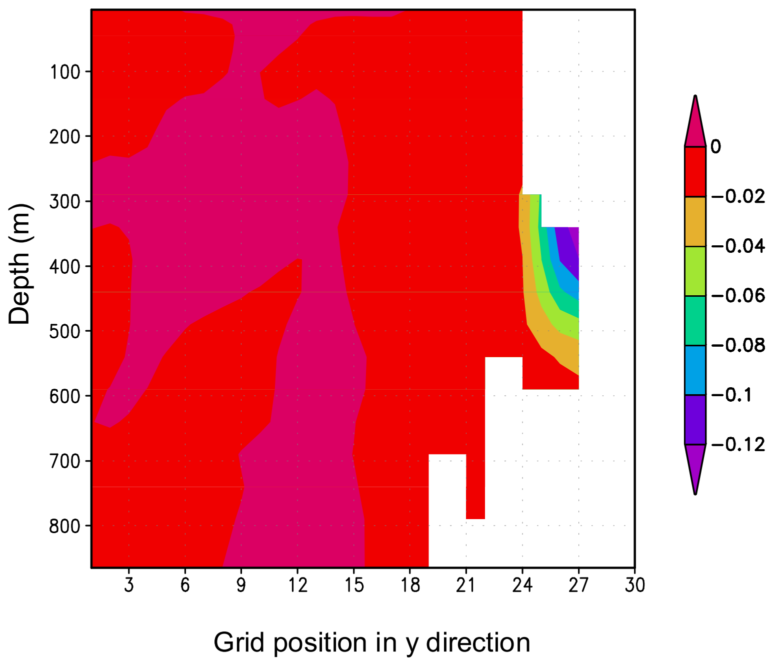

Fig. S3. Difference of density (EI-EN) in the cross-section along x=351. The contour interval is 0.02 kg m^{-3}."

[C] p. 7 l. 19: I think it would make sense to include the figure indicated by "Figure not shown", as I think the changes in the ACC would be an important finding.
[A&R] The ACC is also reduced at about 1000 m. The original analysis is not accurate. The related sentences have been removed.

[C] p. 7 l. 19-20: The discussion of Fig. 5 is so short that it is not at all clear what the figure is justified. I did not get any physical insight into the spatial pattern of freshening at the seafloor from the figure or the discussion here.
[A&R] The figure has been redrawn. Added discussion: The BMRIS has the biggest influence on bottom water in the Southern Pacific Ocean, especially the Ross Sea and its adjacent western (looking from the north) deep ocean. The signal of the BMRIS effect is weak in the Southern Atlantic Ocean compared to those in the Southern Pacific Ocean and the Southern Indian Ocean. This result agrees with the picture of the thermohaline circulation, in which the deep current moves southward in the Atlantic Ocean."

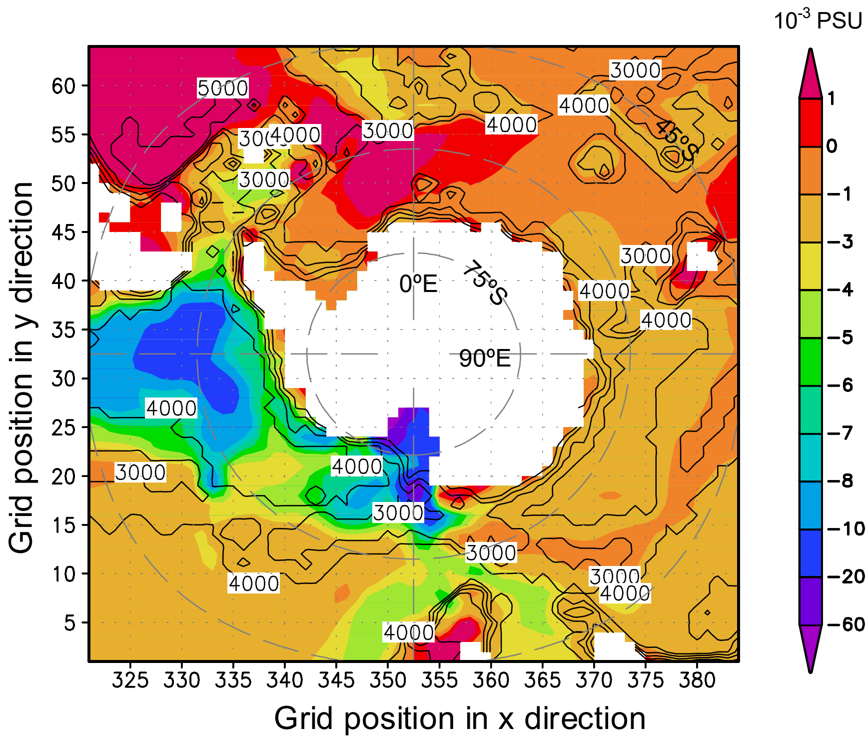

Fig. 5. Annual mean salinity differences (EI minus EN, shaded) at the sea bottom. The contour lines represent the water thickness with intervals of 1000 m. The unit for salinity is PSU.

[C] p. 8 Fig 4: The axis need descriptive labels including units. Tick mark labels should be larger. Caption should include the color of the curves (since figure will always be in color). There is no obvious reason that the x axes of the 3 panels are different, and this makes comparing the panels more difficult. The x axis is for both salinity and temperature differences? The depth axis should be inverted so that the deep ocean is down. It is also standard to have these depths be negative, indicating that they are elevations below sea level. What is the northern boundary of each of these regions? What longitudes separate them?

[A&R] Fig. 4 has been redrawn.

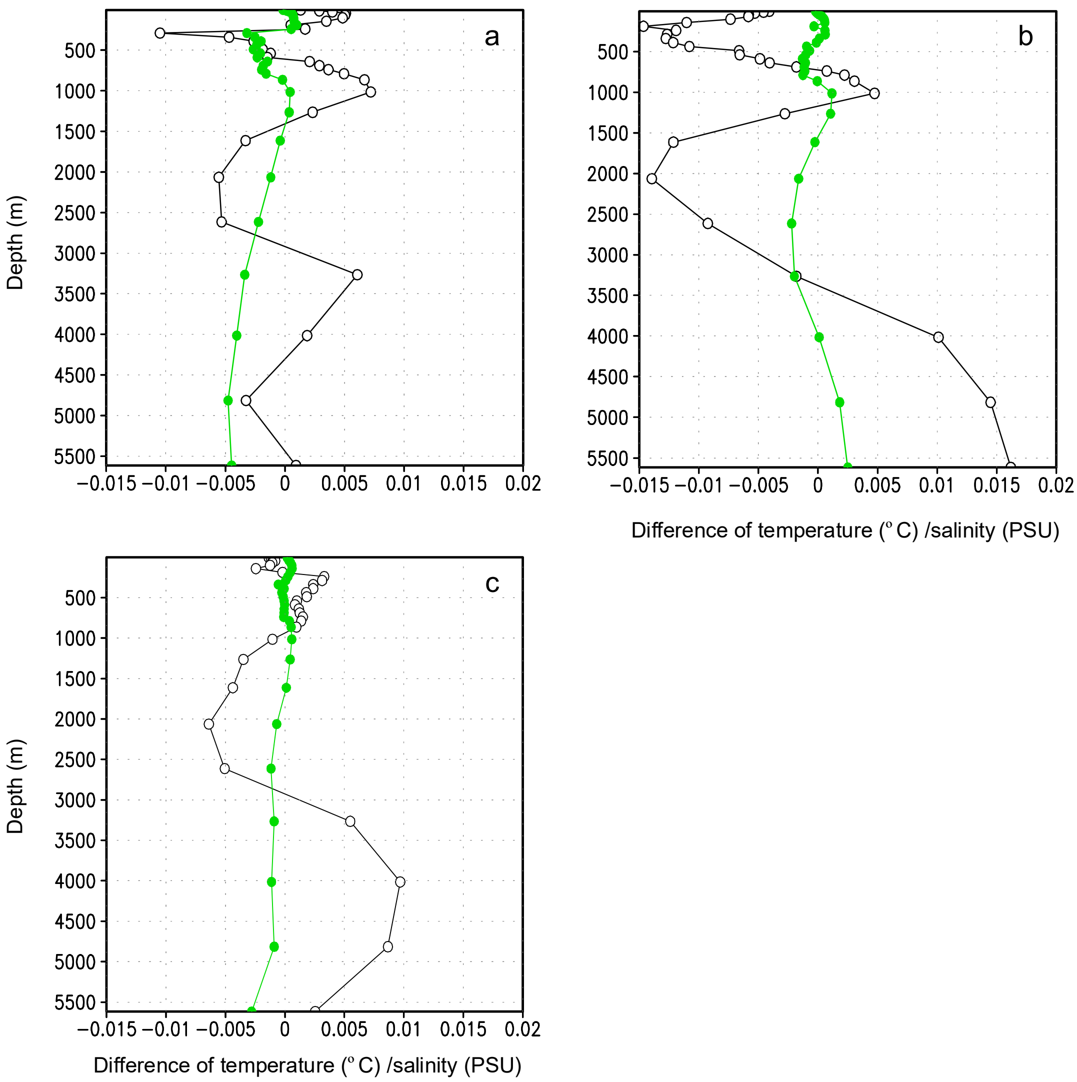

Fig. 4. Area-averaged differences of salinity (solid circle) and potential temperature (open circle) (EI minus EN). The horizontal axis represents the difference and the vertical axis represents ocean depth. (a) Southern Pacific Ocean. (b) Southern Atlantic Ocean. (c) Southern Indian Ocean. The units for salinity and temperature are PSU and °C, respectively.

The x axis is for both salinity and temperature differences. The northern boundary of each of these regions is 35 °S; the Southern Indian Ocean is from 19 °E to 145 °E; the Southern Pacific Ocean is from 146 °E to 290 °E; the Southern Atlantic Ocean is from 69 °W to 18 °E (Fig. S1).

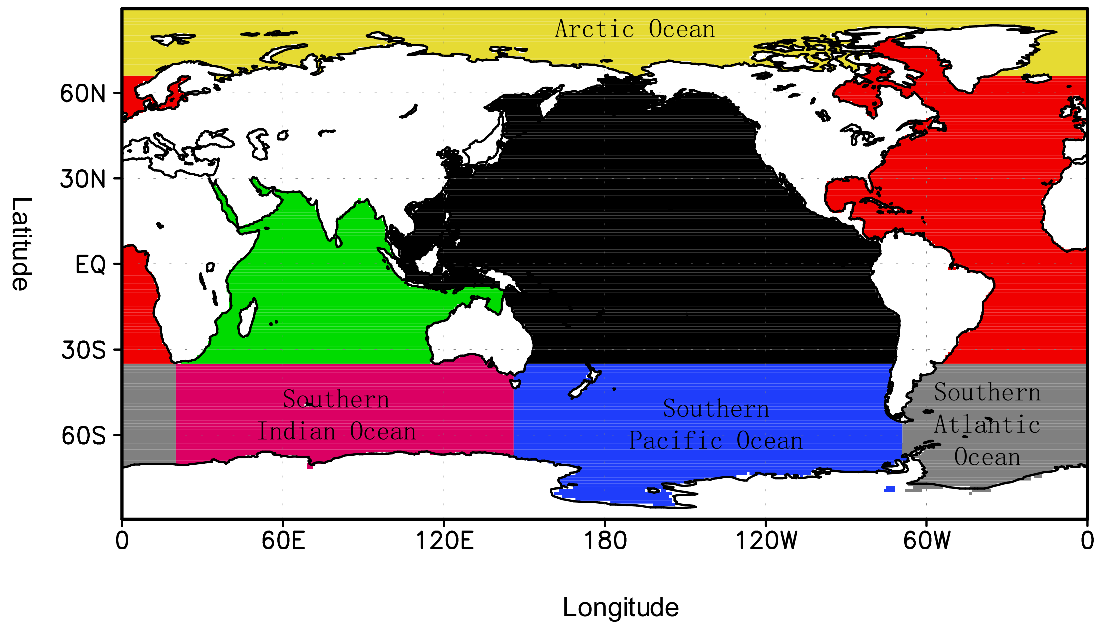

Fig. S1. Division of world ocean in 1 x 1 longitude-latitude grids.

[C] p. 9 Fig 5: This figure does not seem at all useful to me. The color contours are set such that all we can tell is the sign of the salinity difference (and that it is greater than -0.05 PSU) over the vast majority of the sea floor. A nonlinear color bar or one with many more contour values would be needed to make this figure at all useful.
[A&R] The figure has been redrawn (see my previous answer).

[C] p. 9 l. 5 "surface ocean": A careful point has been made in the manuscript that the freshwater flux is not at the ocean surface, so this should probably be "upper ocean".
[A&R] the phrase "surface ocean" has been revised to "upper ocean".

[C] p. 9 l. 5-p. 10 l. 2: This paragraph again refers to "anomalies", whereas I would encourage you to use "differences". Other than this small issue, I think this paragraph has some of the best analysis in the paper.
[A&R] I agree with your feeling about the difference between "anomaly" and "difference". But in some cases, it is inappropriate to use "difference" instead of "anomaly". For example, cold anomaly makes sense but cold difference does not, right? In cases "anomaly" can be replace with "difference", I have made substitution as far as possible.

[C] p. 9 l. 9-10: It's not clear to me what the difference between the warm advection anomaly and the warm SST anomaly is. It seems obvious that the one would cause the other but maybe I'm missing something.
[A] The advection involves flow field. The former can lead to the latter, but the latter cannot lead to the former without favorable flow condition.

[C] p. 9 l. 10-11: "The cold water from BMR is advected by the ACC westward": A couple of things here, the ACC flows eastward (which seems to be the direction most of the cold

difference is being advected) not westward. There is also the Antarctic Coastal Current (ACoC) that does flow westward on the continental shelf so maybe that's what is advecting a bit of the colder melt water to the west toward that SIT dipole?
[A&R] I used a wrong word. It should be "eastward" (looking from the South Pole. I am looking from North). I have changed the "westward" to "clockwise". Due to the coarse resolution, the model cannot reproduce the Antarctic Coastal Current (ACoC) well.

[C] p. 9 l. 15: I don't understand the cause of the increased SST near the sea-ice edge. Could you explain further why downwelling is associated with increased SST?
[A&R] The initial explanation is not accurate. The sentence has been revised to "This gives rise to piling up of warm water and increasing of SST in EI "

[C] p. 9 l. 16: It seems worth exploring in more detail *how* the results from the two studies are different, not just to point out that they are different and that they are simulating different conditions (transient vs. quasi-steady; cavity geometry vs. no cavities for the "control").
[A] The suggestion is accepted.
[R] revised: The feature of SIT difference in this work is quite different from that of Hellmer (2004), in which SIT in the Ross Sea gets thicker and there is no significant difference in SIT in the ocean area downstream the Ross Sea. In his work, the result of the 20th model year from a regional coupled ice-ocean model is given and the RIS cavity geometry is not included in the model bathymetry for the no sub-ice freshwater input experiment. Perhaps the differences in results between the two works are at least to a great deal due to the different treatments for the RIS cavity geometry in the no sub-ice melting experiments.

[C] p. 10 Fig 6: labels (tick marks, lat/lon, color bars) are all far too small. Please make them bigger and crisper. Please add more lines for lat and lon if possible so the reader can more easily find the lat/lon coordinates identified in the text.
[A&R] The figure has been redrawn.

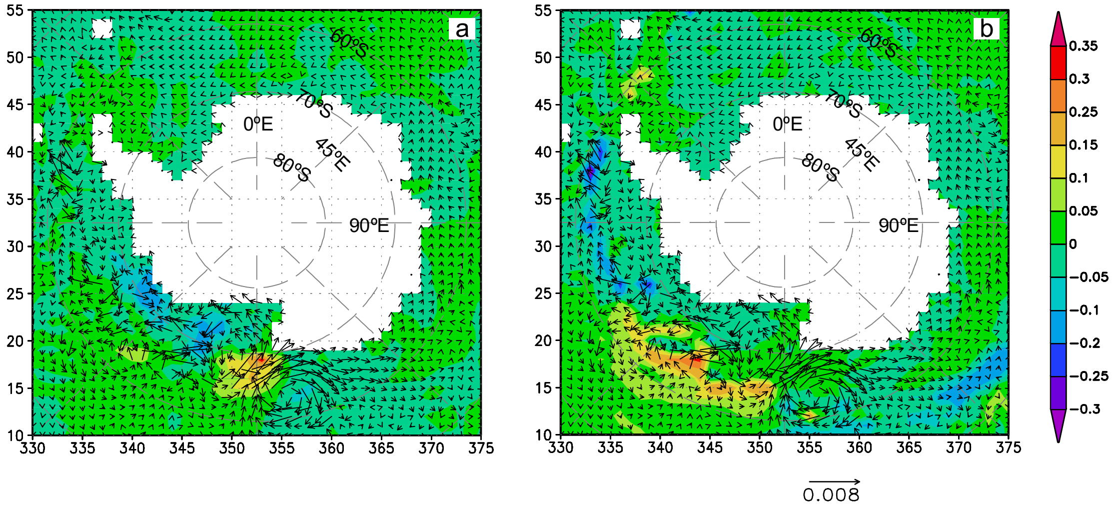

Fig. 6. Differences of sea surface temperature (shaded contours) and current (arrows) (EI minus EN). (a) March. (b) September. The units for temperature and current are °C and m s^{-1}, respectively.

[C] p. 11 l. 9-10: It seems entirely backwards to me that including basal melting would decrease the MOC. If the model were correctly producing more AABW from ice-shelf melting and subsequent climate and topographic interactions, there should be an increase in downwelling just off the Ross continental shelf break and an associated increase in southward transport in the upper ocean (by conservation of mass). This should lead to an increased MOC strength. This is my understand of the main contribution of Antarctic climate dynamics to the global ocean circulation. To me, the decreased MOC in your simulations with melt fluxes suggest that something is wrong in the simulations and AABW is not being produced. This would not be surprising at coarse resolution, since ESMs have a very hard time producing AABW for the right reasons at CMIP-type resolutions.
[A] I do not know what backwards mean here. Does it mean the result here has been proved to be out-of-date or wrong? Or does it mean the result is opposite to what you expect? My result supports studies such as Hellmer (2004) and Kusahara and Hasumi (2013), whose model resolutions are not coarse and their integrations are short compared to this work.

[C] p. 11 l. 13: The formation and spreading of AABW should be the cause (not the effect) here. Changes in AABW formation should be driving the changes in the MOC.
[A] I agree with you. The BMRIS influences AABW, which influences MOC subsequently. The results agree with the idea.

[C] p. 12 l. 4-6: I suggest you look further into these difference as part of this paper. It is precisely this kind of comparison with previous work that I feel is missing from this paper. Without more of this kind of validation work, it remains hard to trust the conclusions about the effects of melt fluxes on the ocean-sea ice system.
[A] The suggestion is accepted.
[A] addition: The strength and position of Subpolar Cell, Upper Cell and Lower Cell in this model resemble those in ACCESS and GFDL-MOM given in Farneti et al. (2015) much more. The strength and position of simulated Cells given in Farneti et al. (2015) are varied. The biggest discrepancy among the models exists in the strength of the anti-clockwise Lower Cell, which ranges from 20 Sv to zero. The simulated strength of the Lower Cell from EI is about 15 Sv (Fig. 9).

[C] p. 12 Fig. 9: I find it very hard to tell what is going on with the difference contours. The color plot is quite clear in most regions but hard to discern near the Antarctic the contours are hard to get the sign of, let alone the magnitude in the Antarctic. Maybe the figure should give more space to the region from -90 to -60 (i.e. a nonlinear x axis).
[A&R] The figure has been revised.

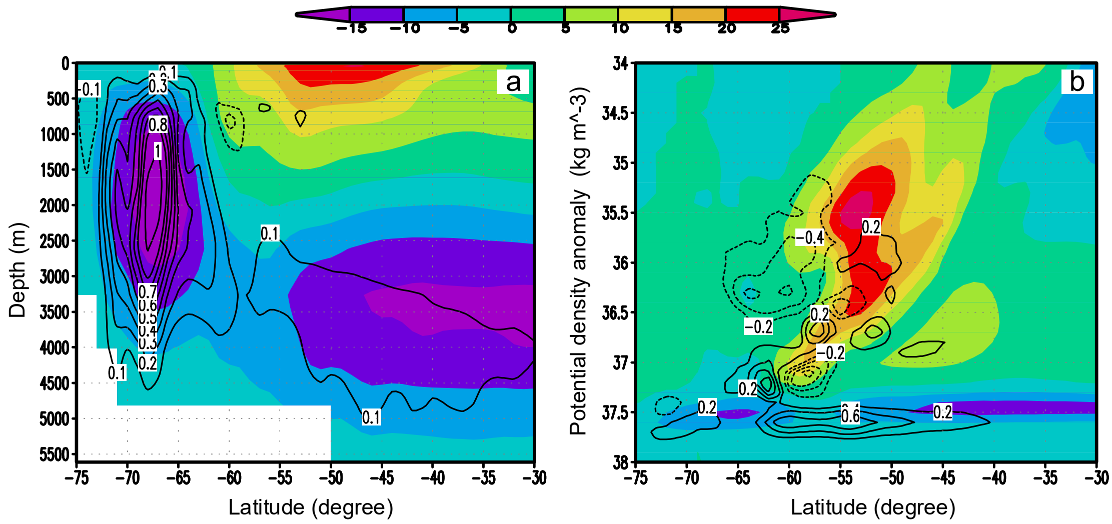

Fig. 9. Meridional transport stream function of EI (shaded contours) and its difference from EN (EI-EN, contours): (a) in depth-latitude space and (b) in density-latitude space. The contour intervals for the meridional transport stream function difference in (a) and (b) are 0.1 Sv and 0.2 Sv, respectively, and the 0 Sv line is not plotted.

[C] p. 12 l. 14: "contributes to northward heat transport anomaly": I find this confusing, since at least in the real world there should be a consistent southward transport of heat. In your simulations, you seem to see a mix of northward and southward transport do the "anomaly" is contributing to a reduction in southward heat transport at some latitudes and enhanced northward transport in others. Maybe "contributes to a reduction in southward heat transport"? Also, this needs some discussion. Consistent with my concern about the MOC above, it seems like you should be seeing steady southward heat transport in both cases and that southward heat transport should be enhanced by AABW formation, whereas you are seeing a consistent global reduction (with varying behavior in each ocean basin). The discussion of the individual basins is clearer in terms of describing enhanced or reduced transport.

[A] Yes, the "anomaly" is contributing to a reduction in southward heat transport at some latitudes and enhanced northward transport in others. I recalculate the heat transport with monthly averaged VT instead of V and T, the northward transport in the Southern Ocean vanishes. In the simulation result the AABW formation is reduced if the effect of BMRIS in included.

[R] The phrase "enhanced" or "reduced" is used instead of "anomaly" in situations describing transport change.

[C] p. 13 Fig 10: It would be helpful to compare the global MHT in 10a with observations, such as: Trenberth, Kevin E., and Julie M. Caron. "Estimates of Meridional Atmosphere and Ocean Heat Transports." Journal of Climate 14, no. 16 (August 1, 2001): 3433 – 43. https://doi.org/10.1175/1520-0442(2001)014<3433:EOMAAO>2.0.CO;2.

Eyeballing the comparison, the global MHT isn't too bad north of 40S but it is odd that you are seeing significant *northward* transport of heat between 60S and 40S, which is not consistent with observations.

[A] Thanks for giving the article. By using model output of monthly averaged VT directly instead of V and T, the calculated northward transport in the Southern Ocean vanishes and agrees with that of Trenberth and Caron (2001) better. Compared to Trenberth and Caron (2001), the curves of heat transport are not smooth and slopes in some latitudes are large for the individual basins. Since the heat transport for the individual basins are less reliable, analysis on them will be removed in the revision.
[R] Analysis on the heat transport for the individual basins have been removed. Analysis on comparing the global MHT with Trenberth and Caron (2001) has been added.

[C] p. 13 Conclusion and discussion: Overall, I find that this is mostly just a summary of the results with insufficient interpretation of the findings, discussion of the implications of this work for other modeling efforts and/or the behavior of the “real world” and insufficient introspection about what the missing processes and other shortcomings of the work might be.
[A] Yes, the initial conclusion and discussion needs improving.
[R] Some discussions have been added as given in previous [R] parts.

[C] p. 13 l. 9: “profoundly”: This is a very subjective term and I’m not sure it is supported by the results. The differences between simulations with and without RIS melting are detectable to be sure but the changes generally seem to be subtle rather than profound.
[A&R] The word is removed.

[C] p. 13 l. 9-p. 14 l. 2: My concerns about the “latent heat flux anomaly” and associated complexity of the temperature evolution remain the same as above. I do not think there has been sufficient analysis of the physical processes leading to the temperature evolution to conclude that they are even the result of the latent heat flux from ice-shelf melting. Instead, they are likely to result primarily from density changes, which are in turn primarily controlled by freshwater fluxes. Thus, I think the conclusion that the latent heat flux plays a secondary role is correct but I don’t think anything presented in this manuscript has supported that conclusion directly.
[A] I agree with you. In previous [R] part I have added some analysis on the influence of temperature and salinity on density.

[C] p. 14 l. 3-9: The manuscript did not present the circulation from either EI or EN or make any attempts to compare these with observations, so it is difficult to know how much (if any) credence can be given to the difference in circulation between the two experiments. That being said, Again I find the discussion of the surface processes to be among the most useful analysis in the paper.
[A] There are totally 91 boxes in the cavity. The current configuration cannot resolve circulation in the cavity in detail and there could be no favorable things to share.

[C] p. 14 l. 7: Again, the fact that basal melting stabilizes the water column and weakens overturning just seems to indicate that the processes we know to occur as part of AABW formation are missing from the model.

[A] Since the vertical resolution is coarse near the sea bottom, it is more possible that AABW formation is not depicted well than other models with finer resolution. But there are other models whose resolutions I believe are fine enough also give similar results.

[C] p. 14 l. 10-13: The discussion of fixed ice-shelf area seems unrelated to the manuscript and its findings. There is nothing to suggest that having dynamic ice-sheet geometry in this configuration would enhance our understanding of the quasi-equilibrium state of the ice sheet-ocean-sea ice system because: 1) the resolution of the ocean model is very much insufficient to supply realistic melt patterns to drive ice-sheet evolution; 2) the steady-state melting, if consistent with present-day observed melting, would be unlikely to drive any significant ice-sheet evolution because melt rates under RIS are very small. 3) the context in which melt-driven ice sheet dynamics are interesting are precisely those that are *not* in quasi-equilibrium.
p. 14 l. 14-19: I appreciated this discussion of possible future directions for the research.
[A&R] The suggestion is accepted and the paragraph on discussion of fixed ice-shelf area has been removed in the revised version.

[C] Typographical and Grammatical Corrections:
Title: The title would read better as “Modelling the effect of Ross Ice Shelf melting on the Southern Ocean in quasi-equilibrium”
[A&R] Accepted.

[C] p. 1 l. 6: “basal melting of Ross Ice Shelf” should be “basal melting of *the* Ross Ice Shelf”
p. 1 l. 19: remove “And, “. It is not necessary and is grammatically incorrect.
[A&R] Corrected.

[C] p. 1 l. 20: “accompanied accordingly”: This phrase doesn’t make sense. Perhaps you mean something like, “There is an accompanying northward anomaly in meridional heat transport at most latitudes of the global ocean”?
[A&R] Yes, that is what I want to express. It has been corrected.

[C] p. 1 l. 23: “Ices accumulated… are” should be “Ice accumulated … is”. Ice is only plural if there are multiple classes of ice or something along those lines, which doesn’t seem to be the case here.
p. 2 l. 11: 2 should be written out a “two”.
p. 2. l. 13: I suggest changing “regarding” to “of”.
[C] p. 2 l. 17: here and elsewhere “sub-ice shelf” should be “sub-ice-shelf”
p. 2 l. 19: “representation” should be “representations”
p. 2 l. 21: “parameterization should be “parameterized”
[A&R] Corrected.

[C] p. 2 l. 27: “In study such as modeling Ice Shelf melting effect on the Ocean…” this whole sentence is needs some significant grammatical work. Here’s my best guess at what is intended: “In studies that include the effect of ice-shelf melting on the ocean in quasi-

equilibrium, it is necessary to use a global model with thermodynamically active ice-shelf cavities and to perform integration over hundreds of years"
[A&R] Your guess is correct. It has been corrected.

[C] p. 3 l. 13-14: "assuming the RIS being in steady state" should be "assuming the RIS to be in steady state"
p. 3 l. 17: "should be "to get *the* RIS draft"
p. 3 l. 29 and 31: "1ooo" should be "1000" (zeros, not o's).
p. 3 l. 29: "To resolve the RIS vertically better" should be "To better vertically resolve the RIS"
p. 4 l. 3: "to that in" should be "to those in"
p. 4 l. 8-9: "and the Antarctic situates on the.." should be "with Antarctica situated on the..."
p. 4 l. 9: "the bathymetry of ocean around the Antarctica and cavity geometry of RIS is" should be "the ocean bathymetry around Antarctica and the cavity geometry of RIS are"
p. 4 l. 10: "grids" should be "grid cells" or "grid boxes". To me, the whole 64x64 face is a grid.
p. 4 l. 11: "of which 15 having cavities and being calculated basal melting" should be something like "of which 15 have nonzero cavity thickness and include basal melt calculations"
[A&R] Corrected.

[C] p. 4 Fig. 1: "(a)" and "(b)" should go before the phrases describing each panel rather than after.
[A&R] Corrected.

[C] p. 4 Fig. 1: "yellow shades in (b) indicate grids where cavities..." should probably be "grid boxes shaded light green indicate locations where cavities...". (To my eyes, the shading is light green, not yellow.)
[A&R] I used a wrong word. It has been corrected. Thanks.

[C] p. 5 l. 15: "modelling ice shelf" should be "modeled ice shelf". "lateral boundary" should be "lateral boundaries".
[A&R] Corrected.

[C] p. 5 Fig 2: The tick mark labels on the axes are too small to easily read. The melt-rate values are also somewhat small but perhaps large enough to read (but I see no reason to include so many empty cells around the 15 active cells. The 3 panels probably will need to be combined into a single figure for typesetting but I guess that's up to you and the journal to work out.
[A&R] The figure has been redrawn.

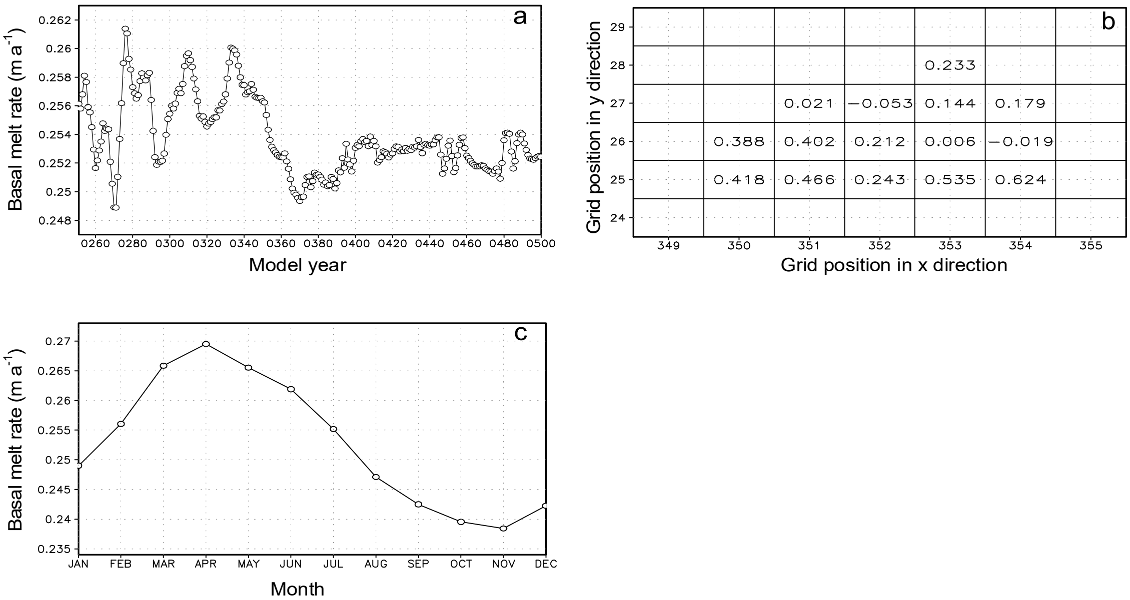

Fig. 2. Basal melting rates of RIS (m a^{-1}) in EI. (a) Variation of the annual and areal mean melting rate over the last 250 years. (b) Spatial distribution of the mean melting rate over the last 100 years. (c) Seasonal cycle averaged over the ice-shelf area and the last 100 years.

[C] p. 5 Fig 2: “annual mean areal average” should probably be something like “the annual and area mean”; “for the last 100 years’ mean” should be “for the mean over the last 100 years”; “areal mean averaged over the last 100 years” might be clearer as “averaged over the ice-shelf area and the last 100 years”.
p. 6 l. 6: “cold and fresh water are” should be “cold and fresh water *is*”
p. 6 l. 7: “become” should be “becomes”
p. 6 l. 7: “compared its counterpart” should be “compared *to* its counterpart”
[A&R] Corrected.

[C] p. 6 Fig 3: The axis labels should be more descriptive (not variable names) and should include units.
[A&R] The figure has been redrawn.

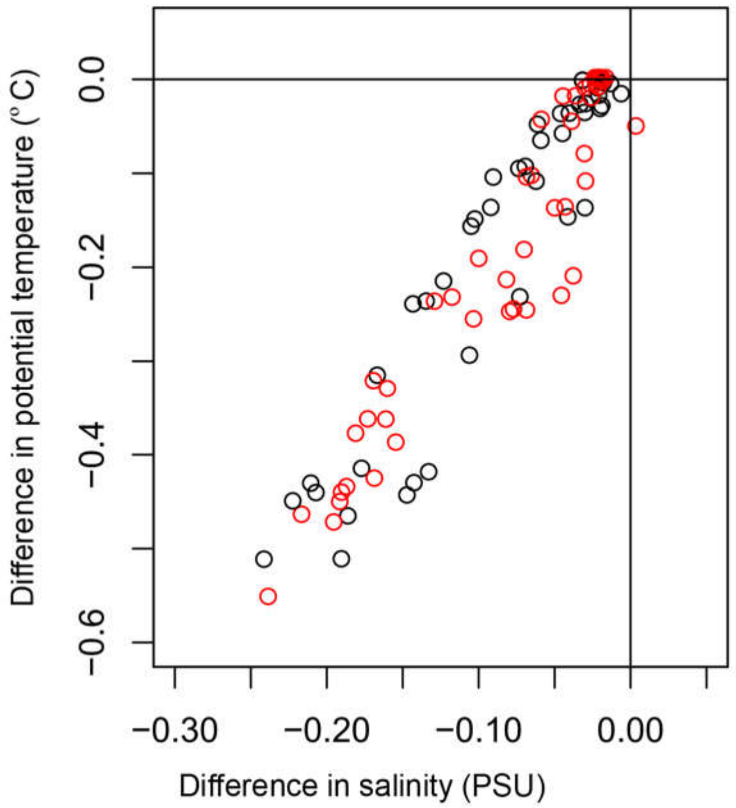

Fig. 3. Salinity difference-temperature difference distribution of water in the RIS cavity (EI minus EN). The horizontal axis is for salinity difference and the vertical axis is for temperature difference. The inflow difference and outflow difference are marked with red and black, respectively. The units for salinity and temperature are PSU and °C, respectively.

[C] p. 7 l. 1: "Figure 3. Figure 3." should just be "Figure 3"
p. 7 l. 6-20: There is no need to continually reference Fig. 4 here. It is clear that most of this text refers to that figure.
p. 7 l. 7: "from ocean surface" should be "from *the* ocean surface"
p. 7 l. 9: "freshening effect" should be "*the* freshening effect"
[A&R] Corrected.

[C] p. 7 l. 16: why 1005 m instead of just 1000 m?
[A&R] The model layer situates at 1005 m. The phrase "1005 m" has been revised to "about 1000 m"

[C] p. 7 l. 17-18: "This is due to that": this phrase is kind of confusing. I would suggest something like "This is due to the relatively stronger…at that level, which constrains…"
[A&R] It has been revised as suggested.

[C] p. 7 l. 19: "water in most area" should be "water in most of the area" p. 9 l. 16 and p. 10 l. 1: "the work" should be "this work"

[A&R] Corrected.

[C] p. 10 l. 12: “BMR effect” should be “the BMR effect” (or maybe “the Ross BM effect”, see earlier comment).
[A&R] It has been revised to “the BMRIS effect” (see earlier answer).
[C] p. 11 l. 1: No need to reference Fig. 8 again.
p. 11 l. 2: “Figures not shown” should just be “not shown”
p. 11 l. 3: “motion field” should be “flow field”
p. 11 l. 8: “by meridional transport” should be “by a meridional transport” or “by the meridional transport”
p. 11 l. 10 “here” should be lowercase or this should be made a separate sentence in parentheses (though The Cryosphere’s typographic editors discourage theses)
p. 11 l. 15 “the path” should be lowercase
p. 11 l. 15 “it’s” should be “it is”
p. 12 l. 2 “the calculation” should be lowercase
[A&R] Corrected.

[C] p. 12 Fig. 9: Axes need labels including units. All labels are too small to be readable.
[A&R] The figure has been redrawn. See previous answer.

[C] p. 12 l. 14: “contributes to northward” should be “contributes to the northward”
[A&R] Corrected.

[C] p. 13 Fig 10: the customary way of handling multiple y axes is to put one axis on the left of the figure and the other on the right. It is even more helpful if the axes are the same color as the curves they correspond with. As in all figures, the tick mark labels are far too small.
[A&R] The figure has been redrawn.

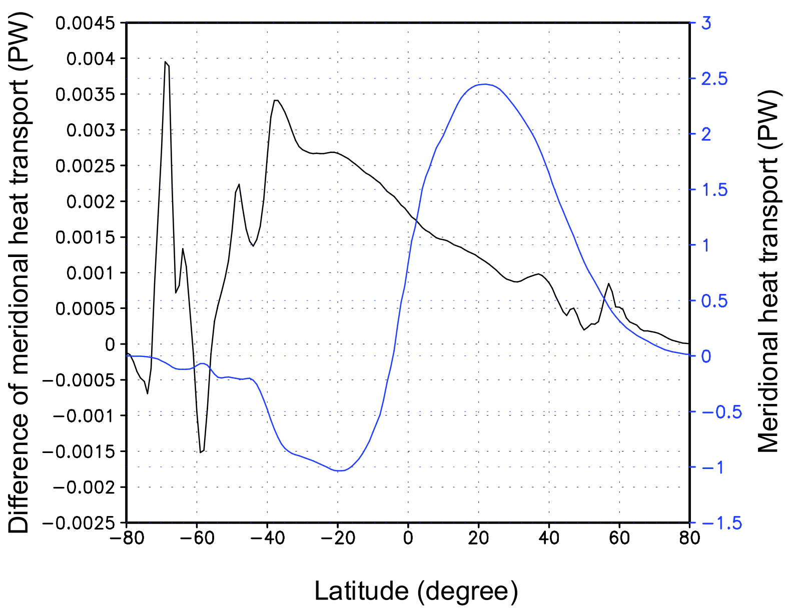

Fig. 10. Meridional heat transport for the global ocean from EI (blue line on the right vertical

axis) and its deviation from EN (EI minus EN, black line on the left vertical axis). The units for the vertical and horizontal axes are PW and degrees, respectively.

[C] p. 14 l. 7: “stables” should be “stabilizes”
[A&R] Corrected.

Modeling the effect of Ross Ice Shelf melting on the Southern Ocean in quasi-equilibrium

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Abstract. To study the influence of basal melting of the Ross Ice Shelf (BMRIS) on the Southern Ocean (ocean southward of 35° S) in quasi-equilibrium, numerical experiments with and without the BMRIS effect were performed using a global ocean-sea ice-ice shelf coupled model. In both experiments, the model started from a state of quasi-equilibrium ocean and was integrated for 500 years forced by CORE (Coordinated Ocean-ice Reference Experiment) normal year atmospheric fields. The simulation results of the last 100 years were analyzed. The melt rate averaged over the entire Ross Ice Shelf is 0.25 m a^{-1}, which is associated with a freshwater flux of 3.15 mSv (1 mSv = 10^3 m^3 s^{-1}). The extra freshwater flux decreases the salinity in the region from 1500 m depth to the sea floor in the southern Pacific and Indian Oceans, with a maximum difference of nearly 0.005 PSU in the Pacific Ocean. Conversely, the effect of concurrent heat flux is mainly confined to the middle depth layer (approximately 1500 m to 3000 m). The decreased density due to the BMRIS effect, together with the influence of ocean topography, creates local differences in circulation in the Ross Sea and nearby waters. Through advection by the Antarctic Circumpolar Current, the flux difference from BMRIS gives rise to an increase of sea ice thickness and sea ice concentration in the Ross Sea adjacent to the coast and ocean water to the east. Warm advection and accumulation of warm water associated with differences in local circulation decrease sea ice concentration on the margins of sea ice cover adjacent to open water in the Ross Sea in September. The decreased water density weakens the sub-polar cell as well as the lower cell in the global residual meridional overturning circulation. Moreover, we observe accompanying reduced southward meridional heat transport at most latitudes of the Southern Ocean.

1 Introduction

Ice shelf melting, which accounts for 55% of ice mass loss from Antarctica, is one of the main sources of freshwater to the Antarctic coastal ocean (Mathiot et al.,2017). Ice accumulated on ice sheets is mostly lost to the oceans by melting underneath the ice shelves or by calving of icebergs. Floating ice shelves around Antarctica are thinning substantially, driven primarily by melting at the ice-ocean interface (Rignot et al., 2013; Paolo et al., 2015). Ice shelf melting exceeds the calving flux (Rignot et al., 2013; Depoorter et al., 2013) and contributes significantly to the fresh water balance in ice shelf areas around Antarctica (Beckmann and Goosse, 2003). The circulation that occurs in sub-ice-shelf cavities is markedly different from that in the open ocean, consisting largely of thermohaline circulation forced by melting and freezing processes at the ice shelf base. This circulation is of more than local importance because it plays a key role in the production of Antarctic bottom water (AABW), a driver of global thermohaline circulation (Walker and Holland, 2007). The sub-ice freshwater input has various implications for the Southern Ocean. These are most pronounced in the Weddell and Ross Seas where large caverns are connected to broad continental shelves (Hellmer, 2004). Mass exchange between the Antarctic Ice Sheet and the Southern Ocean has drawn substantial research attention (Rowley et al., 2007; Kusahara and Hasumi, 2013).

Basal melting of the ice shelves has long been of interest because of its importance to the mass balance of the Antarctic ice sheet (Nost and Foldvik, 1994). The amount of basal melting from ice shelves has been estimated by many studies (for example, Hellmer and Jacobs (1995); Rignot et al. (2013); Moholdt et al. (2014); and others). Ice shelf basal melting is approximately 0.85 m a^{-1} over the circumpolar continental shelf area (Rignot et al., 2013), exceeding P–E (Precipitation minus Evaporation) by a factor of at least two (Beckmann and Goosse, 2003). Because injection of this freshwater occurs at depth rather than at the ocean surface, it has a different impact on the stability of the coastal ocean than P–E forcing. The quantification of basal mass loss under changing climate conditions is important for projections of the dynamics of Antarctic ice streams and ice shelves, as well as global sea level rise (Hellmer et al., 2012).

The need for numerical modeling of ice shelf–ocean interactions is particularly acute due to a lack of extensive observational data, which results from the physical inaccessibility of the areas of interest. Besides, it is difficult to infer sub-ice-shelf circulation from borehole observations, creating a significant need for numerical models (Walker and Holland, 2007; Dinniman et al.,2016). As illustrated in Table 1, in ice shelf-sea ice-ocean coupled modeling, researchers use different types of ice shelf representations, such as dynamic ice-shelf geometry permitting two-dimensional flow (Grosfeld and Sandhager, 2004), simplified and computationally inexpensive representations that are nevertheless capable of handling significant changes to the shape of the sub-ice-shelf cavity as the shelf profile evolves (Walker and Holland, 2007), thermodynamics with fixed cavity techniques (Losch, 2008; Timmermann et al., 2012), and parameterized schemes for the interaction between ice shelves and the adjacent ocean (Beckmann and Goosse, 2003). The models are mostly circumpolar (Hellmer, 2004; Kusahara and Hasumi, 2013; Mathiot et al., 2017), regional (Galton-Fenzi et al., 2012), or two-dimensional in the yz-plane (Walker et al., 2009).

A few global models were also used for numerical studies. For example, Beckmann and Goosse (2003) studied the ice shelf basal melting effect using a global ocean-sea ice coupled model with a first order parameterization of ice shelf-ocean interaction. Losch (2008) introduced ice shelves into the Massachusetts Institute of Technology general circulation model (MITgcm) and conducted ISOMIP (Ice Shelf–Ocean Model Intercomparison Project) experiments and nearly global (excluding the Arctic Ocean) ocean circulation experiments. In these experiments, results with and without explicit modeling of ice shelf cavities were presented and the analysis was mainly focused on the Weddell Sea and circulation in the Filchner-Ronne Ice Shelf cavity. Timmermann et al. (2012) presented results of ice shelf basal mass loss from a global sea ice-ice shelf-ocean model based on the finite element method, in which the model was forced with daily data from the NCEP/NCAR reanalysis for the period 1958–2010. There are also numerous other recent modeling studies on ice shelves that employed regional, circumpolar, or global models; Asay-Davis et al. (2017) provided a thorough review of these studies. However, to research the effect of ice-shelf melting on the ocean in quasi-equilibrium, it is necessary to use a global model with thermodynamically active ice-shelf cavities and perform integration over hundreds of years. This type of research has not previously been conducted.

The Antarctica possesses the majority of the world's ice shelves, of which the Ross Ice Shelf (RIS) has the largest area. Nost and Foldvik (1994) studied the circulation under the RIS with a simple analytical model. Using a two-dimensional channel flow model forced by thermohaline differences between the open boundaries and the interior cavity, Hellmer and Jacobs (1995) studied the flow under the RIS and estimated an ice shelf base loss rate of 18–27 cm a^{-1}. By comparing model estimates of oceanic CFC-12 concentrations along an ice shelf edge transect to field data collected during three cruises spanning 16 years, Reddy et al. (2010) estimated that the residence time of water in the RIS cavity is approximately 2.2 years and that basal melt rates for the ice shelf average 0.1 m a^{-1}. Arzeno et al. (2014) used data from two moorings deployed through RIS, ~6 and ~16 km south of the ice front east of Ross Island, and numerical models to show how the basal melting rate near the ice front depends on sub-ice-shelf ocean variability. However, these studies do not deepen our understanding of the influences of RIS on the Southern Ocean in quasi-equilibrium because the domains of the models employed were not sufficiently large and modeling results were significantly impacted by boundary conditions.

The marginal Ross Sea is an area of deep and bottom water formation. Approximately 25% of the total production rate of AABW comes from the Ross Sea, and basal melting of the ice shelves modifies the characteristics of water masses during the processes of AABW production along the Antarctic continental shelves (Budillon et al, 2011). Antarctic Bottom Water is distinctly colder and fresher than North Atlantic Deep Water and flows northward underneath it in the Atlantic at depths below 4000 m. In this study, we aim to estimate the effect of BMRIS on the Southern Ocean in quasi-equilibrium using a global ice shelf-sea ice-ocean coupled model. The model represents ice shelf-ocean interaction by assuming the RIS to be in a steady state, interacting with the ocean only through thermodynamics.

2 Model, datasets and experimental set up

MITgcm (Marshall et al., 1997) is used to carry out the numerical experiments and an Antarctic cavity geometry dataset (Timmermann et al., 2010) is used to obtain the RIS draft. CORE (Coordinated Ocean-ice Reference Experiment) normal year data (Large and Yeager, 2009) are used for atmospheric forcing fields. The MITgcm consists of packages such as atmosphere, ocean, sea ice, and ice shelf for flexible configuration. The parameterizations used in this study include the Gent-McWilliams-Redi eddy parameterization (Redi, 1982; Gent and McWilliams, 1990) and the non-local K-profile vertical mixing parameterization (Large et al., 1994). A sea ice model package with zero-layer thermodynamics (Hibler, 1980) and viscous-plastic rheology (Zhang and Hibler, 1997) is employed. A package of ice shelf thermodynamics (Losch, 2008) named '*shelfice*' is ready for use in the MITgcm[1].

Two experiments are implemented, one with RIS basal melting and one without, denoted as EI and EN, respectively. In both experiments, bathymetry of the RIS cavity is included. Both experiments start from a model restart state of one integration over 1000 years (Liu and Liu, 2012). To improve the vertical resolution of the RIS, that of the upper 1000 m is increased and that below 1500 m is coarsened, whilst maintaining the number of model layers at 30. The layer thicknesses are 10 (x 2), 15, 21, 28, 36, 45, 50 (x 13), 100, 200, 300, 400, 500, 600, 700, and 800 (x 3) m. The current vertical discretization meets the minimum vertical resolution required to resolve ice shelf-ocean processes, where the layer thickness is 100 m (Losch, 2008). The vertical resolution near the bottom is poor; however, this problem is somewhat alleviated by the partial cell treatment of topography (Adcroft et al., 1997). If the RIS cavity is too thin to be resolved by the vertical grids, it will be set to zero.

Vertical interpolation is used to obtain the model initial fields. Because the RIS was treated as land in the former integration covering more than 1000 years, the initial ocean states in the RIS cavity of the experiments are derived from extrapolation. Cubed sphere grids are used and the horizontal resolution is approximately 150 km. In the original dataset of Antarctic cavity geometry (Timmermann et al., 2010), the area of the cavity is 502024.1 km^2; however, in the model, it is only 476924.2 km^2 due to the coarse model resolution. This would lead to a reduced freshwater flux. Except for vertical layer division and the *shelfice* package, model parameters used here are identical to those in Liu and Liu (2012). The major parameters for the *shelfice* package used in EI are given in Table 2. The model has been integrated for 500 years for each configuration.

Under the current configuration, the whole model domain in the horizontal consists of six cubed sphere faces with Antarctica situated on the 6^{th} face. The ocean bathymetry around Antarctica and the cavity geometry of RIS are shown in Fig. 1. There are 64 x 64 grid cells on each cubed sphere face and the maximum depth of the Southern Ocean is over 6000 m (Fig. 1a). A total of 19 grid boxes are covered by the ice shelf, of which 15 have non-zero cavity thickness and include basal melt calculations in the model. The water-column thickness of the

[1] For more information on the MITgcm see the latest online document on the MIT website: http://mitgcm.org/public/r2_manual/latest/online_documents /manual.html.

RIS cavity ranges from 50 m to 500 m (Fig. 1b). For the four grid boxes whose ice shelf cavity are removed, the thicknesses of the water columns are less than 42 m, which cannot be resolved with vertical grid cells 50 m in size (from the 8th layer, which is approximately 200 m below the sea surface, the vertical grid size is 50 m). The cavity thickness in the model may be smaller than that in the original dataset with a maximum difference of less than 50 m.

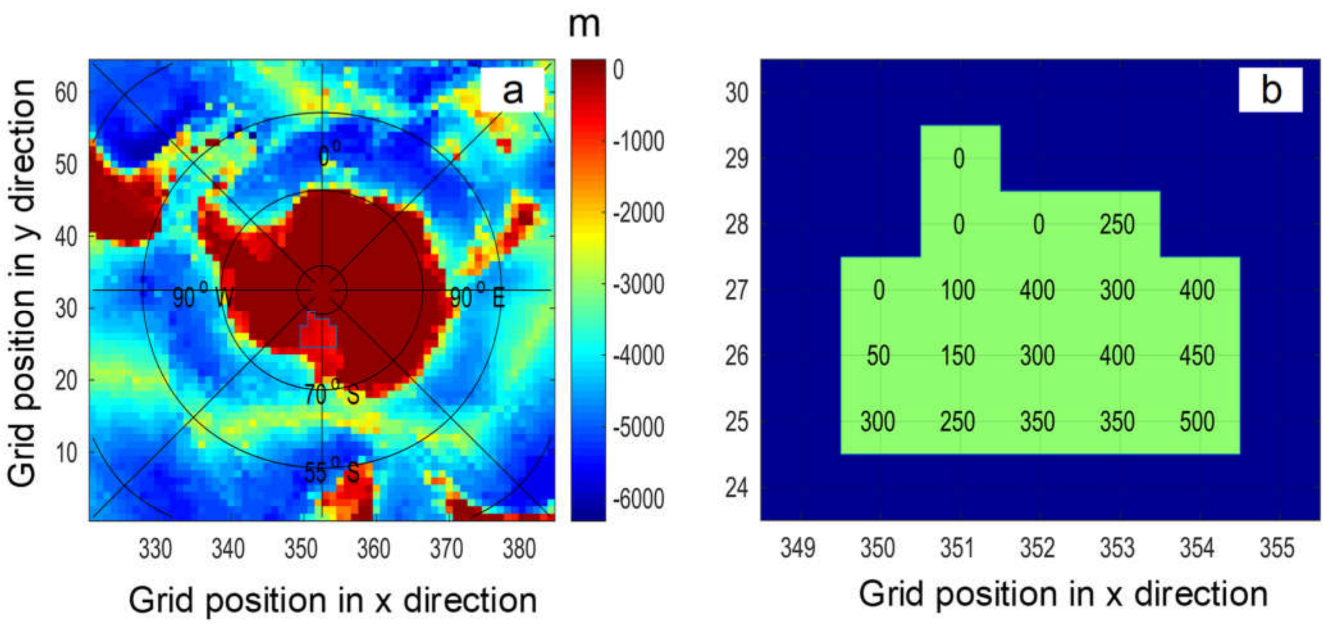

Fig. 1. **(a) Bathymetry of the 6th cubed sphere face in the experiments and (b) cavity geometry of RIS in EI. The numbers on the axes indicate the positions of grids on the model domain. Grid boxes shaded light green in (b) indicate the locations covered by RIS in the model and the numbers in (b) indicate the thickness of the water column in the cavity. The units of bathymetry and water column thickness in the cavity are in m.**

3 Results

3.1 Simulated basal melting of RIS and its local effects

There is significant interdecadal variability in the simulated basal melt rate, which is smaller in the last 100 years than in other periods (Fig.2a). This difference in the interdecadal variability may be due to the influence of ocean system adjustment processes. After approximately 400 years of adjustment, the ocean reaches a quasi-equilibrium state and the decadal variability becomes smaller. Therefore, in this study, only integration data of the last 100 years is used. In the simulation result, only 2 out of 15 grid boxes of RIS experience annual mean freezing and the largest melt occurs near the ice shelf front (Fig. 2b). As illustrated in Table 3, the melt rate averaged over the entire RIS is 0.25 m a^{-1}, which is comparable to the results of Hellmer and Jacobs (1995), Assmann et al. (2003), Arzeno et al. (2014), and Mathiot et al. (2017), but higher than that of Shabtaie and Bentley (1987), Holland et al. (2003), Dinniman et al. (2007, 2011), Depoorter et al. (2013), and Moholdt et al. (2014), and lower than that of Timmermann et al. (2012). There is no clear difference in the basal melt rate between Ross East and Ross

West, different from the result revealed by Rignot et al. (2013). The highest melt occurs in April (approximately 0.269 m a^{-1}) and the lowest melt occurs in November (approximately 0.238 m a^{-1}) (Fig. 2c). This differs from the results of Holland et al. (2003), in which the largest basal melt rate occurs in November. This difference in seasonality may be due to the combined effects of such factors as melting mechanisms in the modeled ice shelf, adjustment processes of the model system, atmospheric forcing, and the influence of boundary conditions. The modeling system used by Holland et al. (2003) did not incorporate wind and sea ice and the surface temperature and salinity was restored. In a two-year simulation after six years of spin up using a regional model, Dinniman et al. (2007) obtained a maximum basal melt rate in February and a minimum value in September.

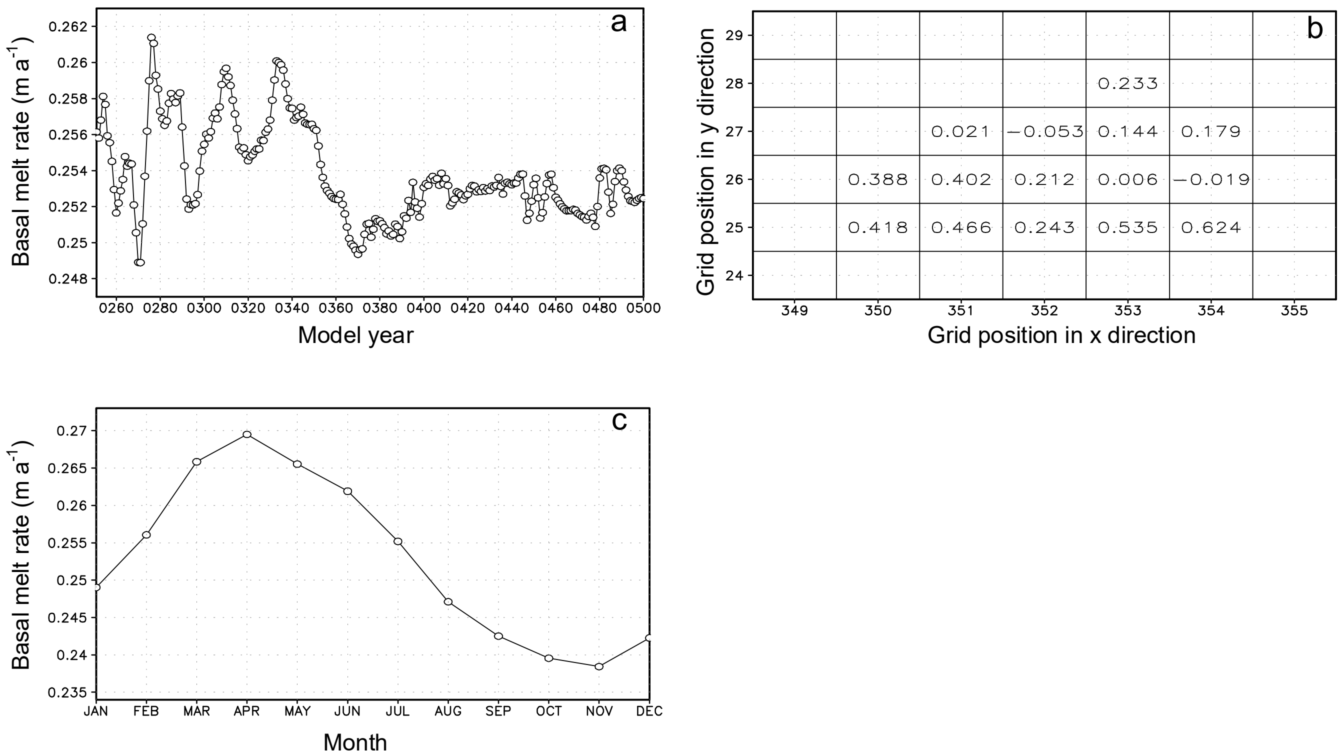

Fig. 2. Basal melting rates of RIS (m a^{-1}) in EI. (a) Variation of the annual and areal mean melting rate over the last 250 years. (b) Spatial distribution of the mean melting rate over the last 100 years. (c) Seasonal cycle averaged over the ice-shelf area and the last 100 years.

Due to the inclusion of ice shelf melting in EI, cold and fresh water is supplemented into the RIS cavity and the water there becomes colder and fresher than its counterpart in EN (Fig. 3). The relationship between salinity differences and temperature differences of RIS cavity water for the two experiments is quasi-linear, implying that larger salinity differences correspond to larger temperature differences. This is fundamentally governed by the latent heat formula in the model equations. The maximum decrease of water temperature and salinity in the cavity can reach 0.50 °C and 0.25 PSU, respectively, due to the RIS melting effect and there seems to be no significant difference in feature between inflow anomaly and outflow anomaly in the cavity (Fig. 3). This implies that, in quasi-equilibrium, a significant amount of outflowing freshwater recirculates into the cavity.

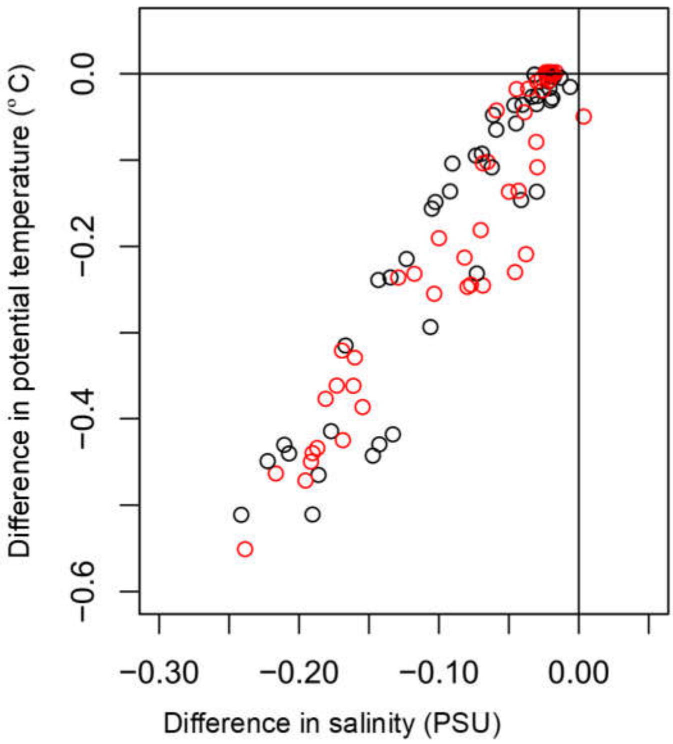

Fig. 3. Salinity difference-temperature difference distribution of water in the RIS cavity (EI minus EN). The horizontal axis is for salinity difference and the vertical axis is for temperature difference. The inflow anomaly and outflow anomaly are marked with red and black, respectively. The units for salinity and temperature are PSU and °C, respectively.

3.2 Influence of BMRIS on the Southern Ocean

BMRIS contributes to salinity changes in the Southern Ocean (ocean south of 35° S; separation of the global ocean in 1 x 1 longitude-latitude grids is shown in Fig. S1). The area-averaged salinity decreases in water deeper than 1500 m in the Southern Pacific Ocean and the Southern Indian Ocean(Fig. 4). In the Southern Atlantic Ocean, the salinity increases in water deeper than 4000 m. From the surface to 1500 m, the curves of salinity difference have similar shapes, whereas the curves of temperature difference do not. In the middle layer of the water body (approximately 1500–3000 m), the water in EI becomes colder and fresher due to the addition of cold and fresh water. In the deep ocean (deeper than 3100 m), the water in EI predominantly becomes warmer. In the shallow ocean (shallower than approximately 550 m), the temperature biases are more varied (see Fig. 4a-4c). At the sea bottom, water in most of the area south of 45° S becomes fresher (Fig. 5), which is consistent with the results from Fig. 4; large differences mostly appear in the cavity of RIS (Fig. 5). The BMRIS has the biggest influence on bottom water in the Southern Pacific Ocean, especially the Ross Sea and its adjacent western (looking from the north) deep ocean. The signal of the BMRIS effect is weak in the Southern Atlantic Ocean compared to those in the Southern Pacific Ocean and the Southern Indian Ocean. This result agrees with the results of thermohaline circulation, in which the deep current moves southward in the Atlantic Ocean.

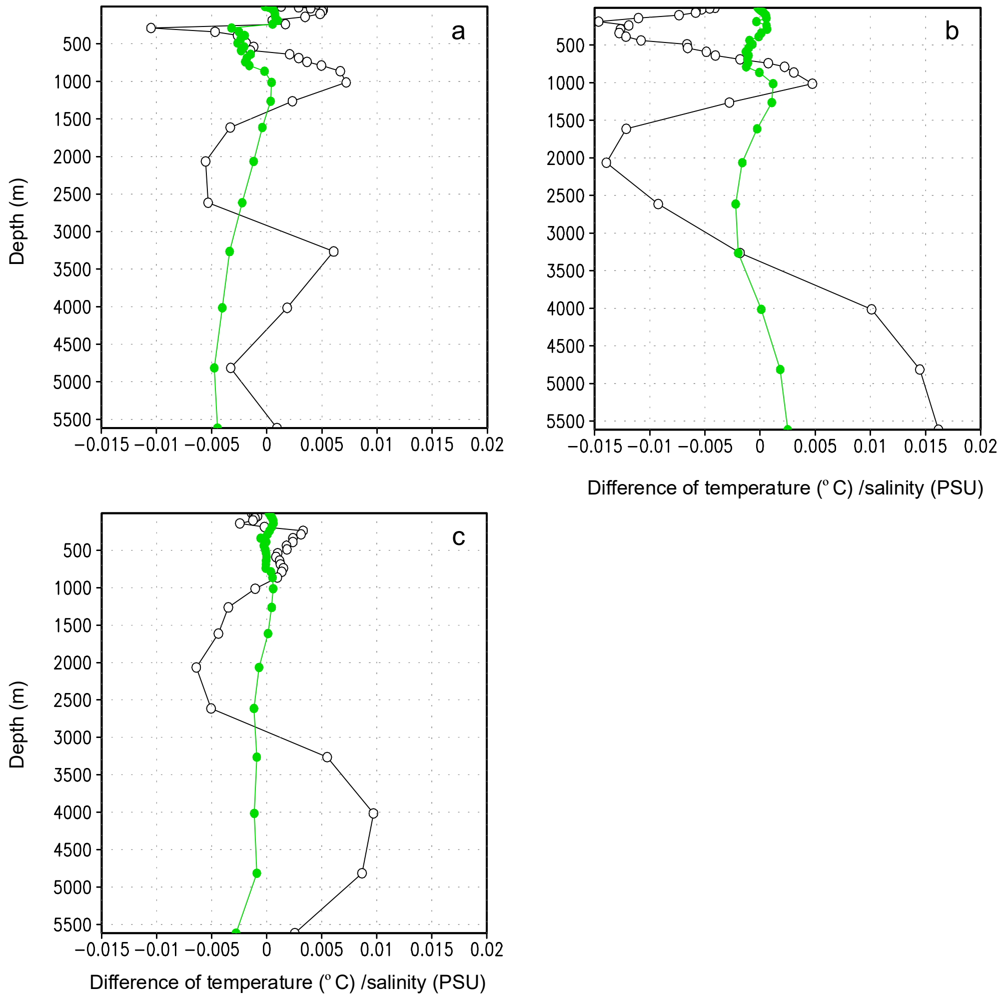

Fig. 4. Area-averaged differences of salinity (solid circle) and potential temperature (open circle) (EI minus EN). The horizontal axis represents the difference and the vertical axis represents ocean depth. (a) Southern Pacific Ocean. (b) Southern Atlantic Ocean. (c) Southern Indian Ocean. The units for salinity and temperature are PSU and °C, respectively.

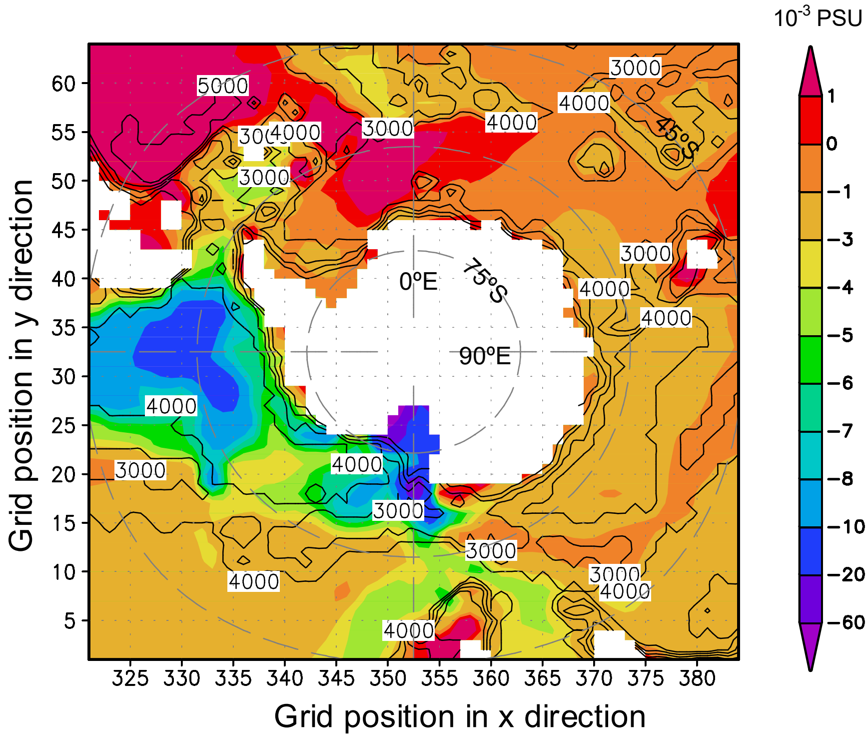

Fig. 5. Annual mean salinity differences (EI minus EN, shaded) at the sea bottom. The contour lines represent the water thickness with intervals of 1000 m. The unit for salinity is PSU.

Using the International Thermodynamic Equation of Seawater-2010 (TEOS-10), the total differential in density ρ can be expressed as

$$d\rho = \frac{\partial \rho}{\partial \Theta}|_{S_A,p}\, d\Theta + \frac{\partial \rho}{\partial S_A}|_{\Theta,p}\, dS_A = \rho(-\alpha d\Theta + \beta dS_A),$$

where $\alpha = -\frac{1}{\rho}\frac{\partial \rho}{\partial \Theta}|_{S_A,p}$, $\beta = \frac{1}{\rho}\frac{\partial \rho}{\partial S_A}|_{\Theta,p}$; S_A is absolute salinity, Θ is conservative temperature, p is pressure, α is the coefficient of thermal expansion, and β is the coefficient of haline contraction. Using the Gibbs Seawater Oceanographic Toolbox in Fortran (https://github.com/TEOS-10/GSW-Fortran), such variables as S_A, Θ, α, β, and ρ can be easily computed. The S_A difference-Θ difference distribution of water in the RIS cavity (EI minus EN) is similar to that in Fig. 3. In polar oceans, β can be ten times larger than α (see Fig. S2). This implies that the change of density is dominated by that of salinity if temperature variation and salinity variation are in the same order. The added fresh water reduces the salinity in water near the RIS. This reduced salinity gives rise to a reduction in sea water density (Fig. S3).

BMRIS therefore adds a freshwater flux of 3.15 mSv (1 mSv=10^3 m^3 s^{-1}) to the upper ocean. This surplus of fresh water decreases the ocean water density and generates anticlockwise circulation anomalies in the Ross Sea. In addition, due to the topography effect near the location (65° S, 170° E), a clockwise circulation anomaly is induced and superimposed on the Antarctic circumpolar current (ACC) in EI (Fig. 6). The two circulation anomalies work together to produce a warm advection anomaly near the location (67° S, 180° E). Associated with this warm advection anomaly is a warm sea surface temperature (SST) anomaly (Fig. 6a). The cold water from BMRIS is advected clockwise by ACC, which contributes to a cold SST anomaly, an anomalous surplus of sea ice concentration (SIC), and a sea ice thickness (SIT) surplus over a broad area (Figs. 6 and 7). In the austral winter, the sea ice extent increases due to decreased SST. The anticlockwise circulation anomaly associated with the low water density anomaly in the Ross Sea and the circulation anomaly in the north forms a convergence anomaly at the margins of the ice cover, approximately along the latitude circle of 62° S. This leads to warm water accumulation and SST increases in EI (Fig. 6b), as well as SIC and SIT decreases (Fig. 7b). These observed SIT differences contrast to those of Hellmer (2004), in which SIT in the Ross Sea increases and shows no significant difference in ocean areas downstream the Ross Sea. His study reports the results of the 20th model year from a regional coupled ice-ocean model and the RIS cavity geometry is not included in the model bathymetry for the no sub-ice freshwater input experiment. Thus, differences between these studies may largely be due to the different treatments of RIS cavity geometry in the no sub-ice melting experiments. In this study, the difference of quasi-equilibrium states is discussed and the magnitude of the SIT difference is far smaller than that reported in Hellmer (2004).

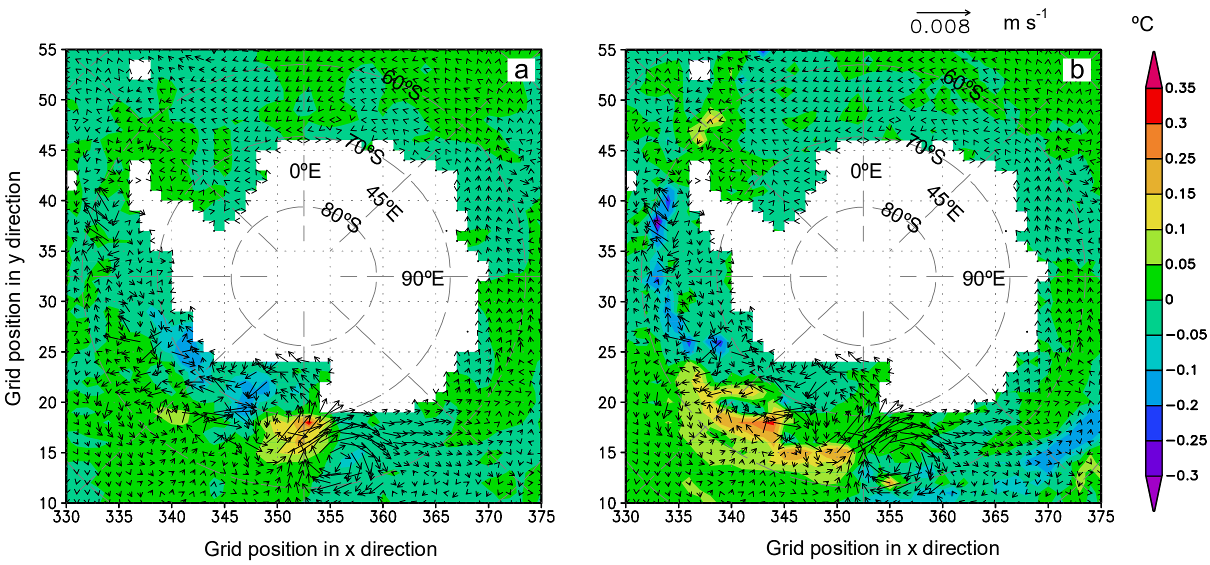

Fig. 6. Differences of sea surface temperature (shaded contours) and current (arrows) (EI minus EN). (a) March. (b) September. The units for temperature and current are °C and m s^{-1}, respectively.

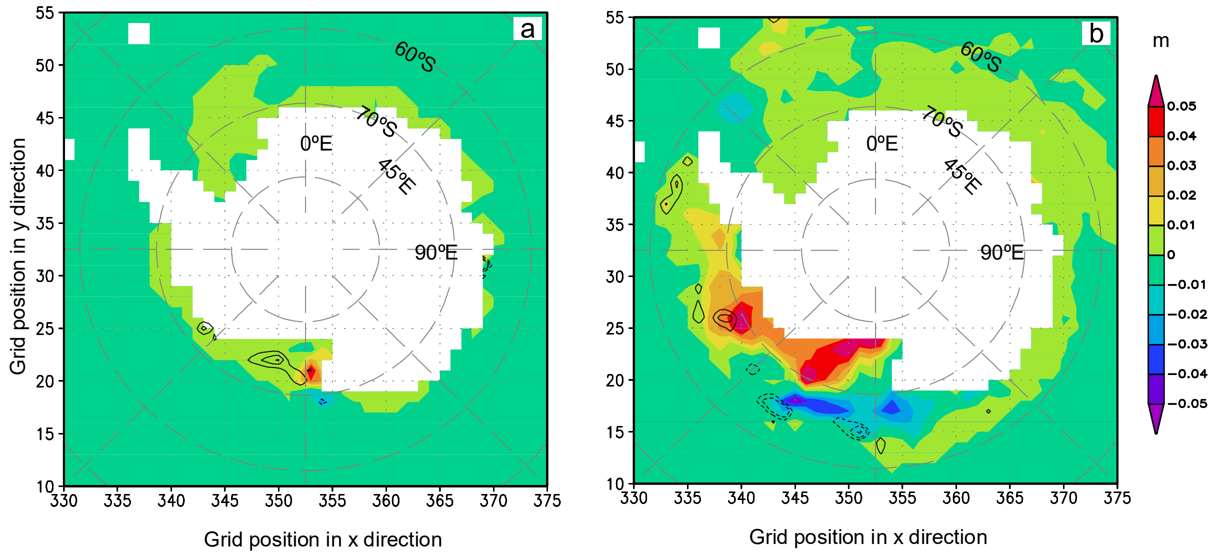

Fig. 7. Differences of sea ice concentration (SIC) and sea ice thickness (SIT) (EI minus EN). (a) March. (b) September. The differences of SIT are shaded. The contours in black represent the differences of SIC, in which contour intervals are 0.02 and 0.05 for (a) and (b), respectively, and lines of 0 are not plotted. The units for SIC and SIT are 100% and m, respectively.

Similar to the pattern of surface currents (Fig. 6), the ACC is weakened in the depth-averaged ocean currents in regions other than that north of the Ross Sea when the BMRIS effect is considered (Fig. 8). There are also two circulation anomalies near the Ross Sea. One is anti-clockwise and the other is clockwise. This circulation pattern is maintained until approximately 2000 m depth (Fig. S4), implying a combined influence of salinity difference from BMRIS and the characteristics of local bathymetry. As the density variation is dynamically linked with the flow, the ultimate pattern of ACC differences is the result of the mutual adjustment between the velocity and density fields.

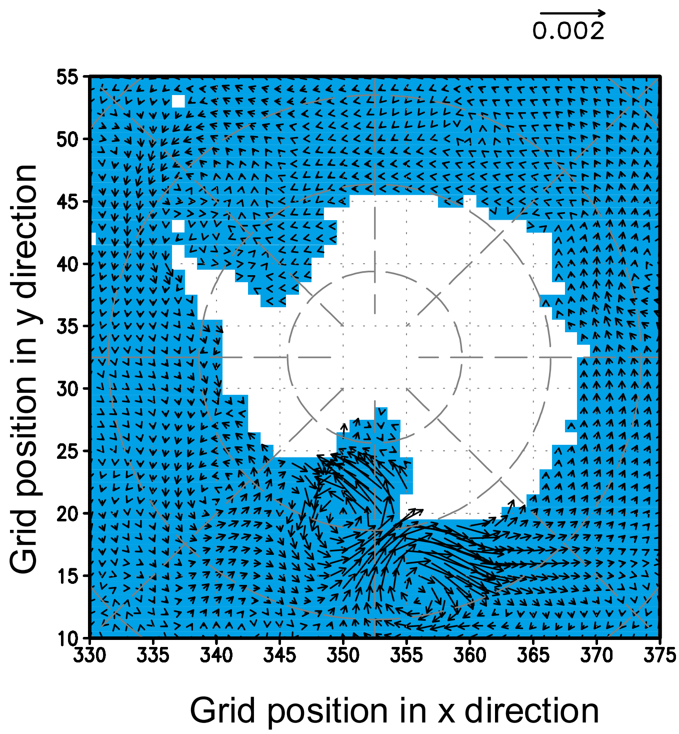

Fig. 8. Differences of annual mean depth-averaged ocean currents (EI minus EN). The unit of velocity is m s^{-1}.

The meridional overturning circulation (MOC), which is a system of surface and deep currents encompassing all ocean basins, is usually depicted by the meridional transport stream function. When the BMRIS effect is introduced, the strength of the Antarctic Subpolar Cell and Lower Cell weakens (Fig. 9a) (here, the cell names follow the convention of Farneti et al. (2015)). This is because the enrichment of fresh water from BMRIS decreases the water density and dampens the sink of surface dense water, thus significantly weakening the downward branch of MOC over the Antarctic continental slope. As a consequence, the formation and spreading of the AABW will also be influenced.

Because the meridional transport stream function in depth-latitude space cannot reflect real diapyncnal transport in the ocean (the path of overturning circulation may parallel the contour of potential density in some places), it is recommended that it be evaluated in density-latitude space (Ballarotta, et al., 2013). When zonal integration is performed along potential isopycnals, the positions and strength of cells in the meridional-isopycnal frame cannot always be traced back to their counterparts in depth-latitude space. As seen in Fig. 9b (the calculation of potential density follows the algorithm of Jackett et al. (2006) and the reference pressure used here is 2000 dbar), there are more isolated cells that have no counterparts in Fig. 9a. The strength and position of the Subpolar Cell, Upper Cell, and Lower Cell in this model much more closely resemble those in ACCESS and GFDL-MOM given in Farneti et al. (2015). The strength and position of simulated cells in Farneti et al. (2015) are variable; the biggest discrepancy among the models exists in the strength of the anti-clockwise Lower Cell, which ranges from 20 Sv to zero. The simulated strength of the Lower Cell from EI is approximately 15 Sv. In density-latitude space, the Subpolar Cell and Lower

Cell in the Southern Ocean also weakens (Fig. 9b).

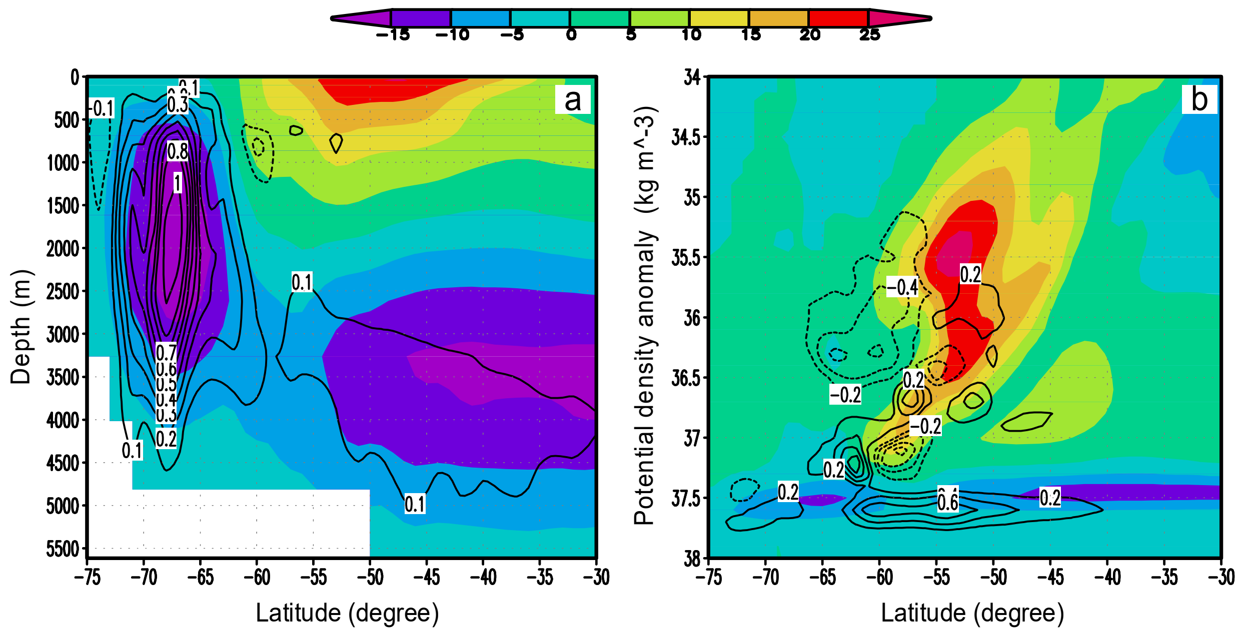

Fig. 9. Meridional transport stream function of EI (shaded contours) and its difference from EN (EI-EN, contours): (a) in depth-latitude space and (b) in density-latitude space. The contour intervals for the meridional transport stream function difference in (a) and (b) are 0.1 Sv and 0.2 Sv, respectively, and the 0 Sv line is not plotted.

The simulated heat transport in EI is similar to that derived from the NCEP reanalysis dataset given by Trenberth and Caron (2001) with the biggest difference located in latitudes around 55° S, where the simulated southward heat transport is approximately 0.2 PW weaker. The BMRIS contributes to the ocean heat transport anomaly by changing MOC. Considering the global ocean as one water body, the BMRIS contributes to reduced southward heat transport in most latitudes of the Southern Ocean; the maximum reduction occurs at approximately 70° S (Fig. 10). Compared to the magnitude of the full heat transport, the maximum reduction of southward heat transport occurs at 71° S with an approximate value of 6%, whereas the relative reduction is less than 1% at most other latitudes.

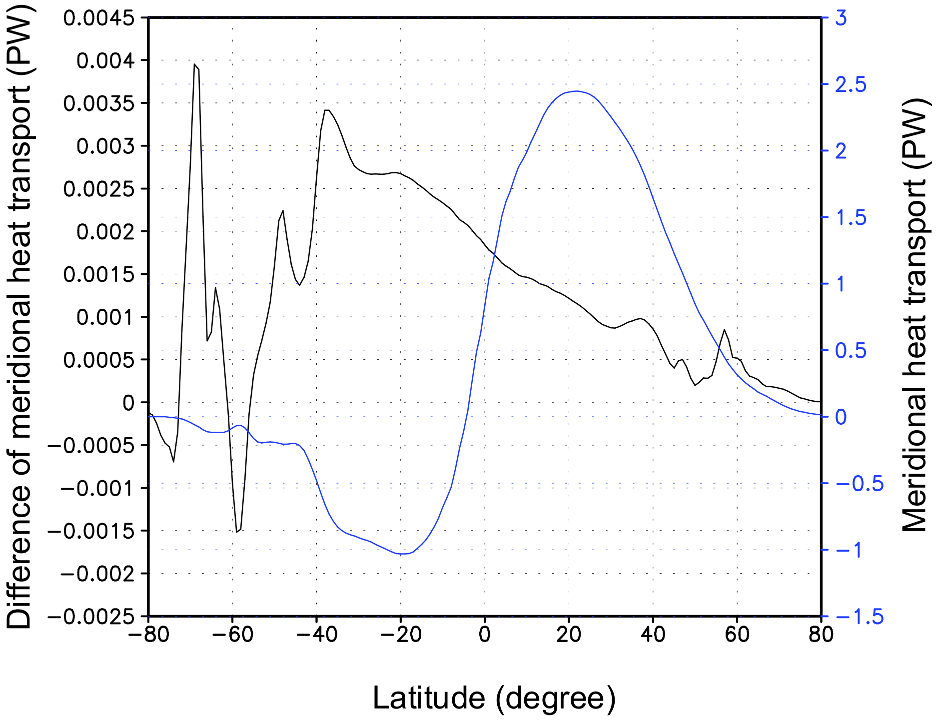

Fig. 10. Meridional heat transport for the global ocean from EI (blue line on the right vertical axis) and its deviation from EN (EI minus EN, black line on the left vertical axis). The units for the vertical and horizontal axes are PW and degrees, respectively.

4 Conclusion and discussion

Through numerical modeling, we studied the influences of BMRIS on the Southern Ocean in quasi-equilibrium. The aim of the study was to show that, through steady basal melting, the BMRIS leads to some interesting long-term phenomena. In quasi-equilibrium, the freshwater flux from BMRIS is 3.15 mSv, which is associated with a basal melt rate of 0.25 m a^{-1}. This freshwater decreases the salinity and density in the Antarctic Ocean. The decreased density from BMRIS together with the influence of ocean bathymetry generates local circulation differences in the Ross Sea and adjacent regions. The cold anomaly from BMRIS is advected clockwise by ACC and then increases sea ice thickness and sea ice concentration in the affected region. In quasi-equilibrium, the strength of ACC in most areas except the northern part of the Ross Sea is reduced. The density anomaly from BMRIS stabilizes the water near Antarctica and weakens the sub-polar cell as well as the lower cell in the global MOC, which is accompanied by reduced southward meridional heat transport in most latitudes of the Southern Ocean.

According to a simulation study by Beckmann and Goosse (2003), in which ice shelf basal melting was parameterized as a function of oceanic temperature on the shelf/slope area of the adjacent ocean as well as an effective area of interaction, the basal melt rate of RIS differs substantially with different atmospheric forcing fields. Atmospheric forcing resolution affects the delivery of ocean heat to Antarctic floating ice shelves; higher-resolution winds can lead to more heat being delivered to the ice shelf cavities from the adjacent ocean and an increased efficiency of heat transfer between water and ice (Dinniman et al., 2015). Thus, simulations with other atmospheric forcing fields may be useful to ascertain the effects of BMRIS on the Antarctic Ocean.

In this study, ISOMIP thermodynamics were used, which neglect the velocity dependence of heat- and salt-transfer coefficients. In velocity-independent melt rate parameterizations, the impact of currents or tides on the distribution of sub-ice-shelf melting is indirect, and therefore limited (Dansereau et al.,2014). If the velocity dependence of transfer coefficients is considered, as in the most recent modeling studies using fine grids (Dansereau et al.,2014; Asay-Davis et al.,2017), differences in melt rate patterns may be observed. These differences may be more significant in higher resolution modeling because of the improved resolution of high boundary layer currents.

Ice shelves range in size from 500 000 km^2 (RIS) to approximately 100 km^2 (Ferrigno ice shelf). Current global ocean model configurations cannot explicitly resolve all the ice shelf cavities, especially in large-scale simulations. As illustrated by some studies (for example, Rignot et al., 2013; Nakayama et al., 2014), small ice shelves can produce significantly more freshwater than RIS and impact the Antarctic climate both locally and regionally in significant ways. Not all ice shelves are in a stable state (some are thickening and some are thinning) (Rignot et al., 2013). To study the long-term influences of stable ice shelf basal melting on the Southern Ocean, the RIS was included with an appropriate model resolution for long integration in this study. However, model horizontal resolution is important not only for simulating the conditions underneath the ice shelf that lead to basal melting but also for the open-ocean conditions that deliver heat to ice shelf cavities and for identifying relevant water masses (Dinniman et al.,2016; Little and Urban, 2016). Increasing the model resolution dramatically improves the representation of Circumpolar Deep Water on the Amundsen Sea continental shelf (Nakayama et al., 2014; Dinniman et al., 2015). More research using a finer resolution should be conducted to reduce the uncertainty in the simulation of the BMRIS effect on the Southern Ocean. Moreover, the effects of other ice shelves, such as the Filcher-Ronne ice shelf, should also be evaluated.

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Table 1. An incomplete list of ice shelf-ocean coupled modeling studies

Publication	Ocean model	Ice shelf implementation	Domain and time periods covered
Beckmann and Goosse (2003)	Coupled Large-scale Ice Ocean (CLIO)	parameterization from an ice shelf-ocean interaction model	global, 100 years
Grosfeld and Sandhager, (2004)	Rigid-lid, hydrostatic primitive equation model, formulated in spherical coordinates	dynamic	900 km x 700 km in the horizontal, 300 years
Hellmer (2004)	Bremerhaven Regional Ice Ocean Simulations (BRIOS)	thermodynamics with fixed cavity	circumpolar, 20 years
Walker and Holland (2007)	A two-dimensional model in the yz-plane	simplified dynamic	600 km x 1100 m, 600 years
Losch (2008)	MIT general circulation model (MITgcm)	thermodynamics with fixed cavity	in ISOMIP (Ice Shelf–Ocean Model Intercomparison Project) experiment: from 0º E to 15º E and 80º S to 70º S, 10 000 days in (nearly) global ocean model (excluding the Arctic Ocean) experiment: 80º N southward, 100 years
Timmermann et al. (2012)	Finite Element Sea-ice Ocean Model (FESOM)	thermodynamics with fixed cavity	global, 53 years
Galton-Fenzi et al. (2012)	Regional Ocean Modeling System (ROMS)	thermodynamics with fixed cavity	regional, 20 years
Kusahara and Hasumi (2013)	Sea ice-ocean coupled model (COCO)	thermodynamics with fixed cavity	circumpolar, 25 years for CTRL run and 38 additional years for ERA-INT case
Mathiot et al. (2017)	Nucleus for European Modeling of the Ocean (NEMO)	thermodynamics with fixed cavity	in academic case: from 0º E to 15º E and 80º S to 70º S, 10 000 days in real ocean application: circumpolar, 10 years

Table 2. Major parameters for the *shelfice* package used in EI

Parameter	Value	Parameter	Value
Heat transfer coefficient that determines heat flux into ice shelf	10^{-4} m s^{-1}	Salinity transfer coefficient that determines the salt flux into the ice shelf	5.05 10^{-7} m s^{-1}
If a simple ISOMIP (Ice Shelf-Ocean Model Intercomparison Project) thermodynamics is used	yes	If conservative ice-ocean interface boundary condition following Jenkins et al. (2001) is used	no
If average over boundary layer width is used	yes	If slip condition for ice shelf is used	yes

Table 3. Basal melt rates averaged over the entire RIS derived in this study and other studies

Basal melt rates (m a^{-1})	Source	Brief description
0.12 ± 0.03	Shabtaie and Bentley (1987)	Calculated from the measured ice flux into the Ross Ice Shelf and previous measurements
0.18–0.27	Hellmer and Jacobs (1995)	Calculated from a two-dimensional (y-z plane) channel flow model forced by density differences between the open boundaries and the interior cavity
0.25	Assmann et al. (2003)	Calculated from a circumpolar numerical model
0.082	Holland et al. (2003)	Calculated from a regional numerical model (MICOM)
0.13–0.15	Dinniman et al. (2007)	Calculated from a regional numerical model (ROMS)
0.15	Dinniman et al. (2011)	Calculated from the ROMS model
0.6	Timmermann et al. (2012)	Calculated from a global finite element ocean model (FESOM)
0.0± 0.1 for Ross West 0.3 ± 0.1 for Ross East	Rignot et al. (2013)	Calculated from radar measurements and output products from the Regional Atmospheric and Climate Model RACMO2
0.14 ± 0.05	Depoorter et al. (2013)	Calculated from radar measurements and a regional climate model (for firn air content and compaction)
0.25 (without tidal forcing) 0.32 (with tidal forcing)	Arzeno et al. (2014)	Calculated from the ROMS model
0.11 ± 0.14 (converted from the basal melt budget of RIS dM/dt in Table 3 with an ice density of 918 kg m^{-3})	Moholdt et al. (2014)	Derived from Lagrangian analysis of ICESat (NASA's Ice, Cloud and Land Elevation Satellite) altimetry

0.24 (converted from basal melt in Gt a^{-1} for the last year of simulation in R_MLT in Table 3 with an RIS area of 500 000 km^2 and an ice density of 918 kg m^{-3})	Mathiot et al. (2017)	Calculated from a regional numerical model (NEMO)
0.25	This study	Calculated from quasi-equilibrium state of a global numerical model (MITgcm)