Response to Reviewers

Coupled ice/ocean interactions during future retreat of West Antarctic ice streams in the Amundsen Sea sector

David T. Bett, Alexander T. Bradley, C. Rosie Williams, Paul R. Holland, Robert J. Arthern and Daniel N. Goldberg

Black: Reviewer comments. Blue: Authors' response. Where necessary to clarify our response, we have added proposed paper correction in italics, including new text as underlined where we are modifying existing text.

Response to Reviewer 1

Thanks for the detailed response to reviewers. The revised manuscript clearly addressed the questions and comments from reviewers. However, some of the descriptions need further improvement.

We thank the reviewer for the time taken in reading and reviewing the manuscript and providing helpful comments and suggestions that will improve the manuscript.

Here are some specific comments:

P3, L73: (Goldberg, 2011) -> Goldberg (2011)

This has been changed.

P3, L81: Measrues -> MEaSUREs

This has been changed.

P3, L83: How do you decide the grounding fraction? Do you use sub-grid parameterisation method to decide the fraction? If yes, I think you need to further clarify it here.

The sentence has been extended to including, 'using a sub-grid parametrization' along with the addition of references (L82):

'Partially grounded cells are utilised <u>using a sub-grid parametrization</u> to better represent the grounding line <u>(e.g., Arthern and Williams, 2017; Pattyn et al., 2006; Cornford et al., 2012; Seroussi et al., 2014)</u>, where the grounding fraction is used to proportionally apply the Weertman sliding drag coefficient.'

P5, L132: a 0.01 value -> a value of 0.01

This has been changed.

L242: shows -> show

This sentence has been expanded for clarity:

'However, as the simulation progresses, both sides of the ice shelf accelerate, reaching speeds of up to ~10 km/yr, but then <u>the whole ice shelf</u> shows signs of deceleration between 144 years and 180 years.'

L244: rapid melt rates -> high melt rates

This has been changed.

L254: are€?

This has been fixed.

L278: 'SLR than in the zero-melting case, increasing to ~0.3 mm/yr and ~0.1 mm/yr, in the warm case, respectively, ' -> 'SLR in the warm case than in the zero-melting case, increasing to ~0.3 mm/yr and ~0.1 mm/yr, respectively '

This sentence has been updated with reviewer's 2 suggestion (L 263). The sentence's arrangement has been kept, as it makes this point about both melting cases and not just the warm case, but the warm case's values are given as an example.

'In PIG and Smith areas, the rates of SLR with melting are approximately constant but are higher than the rates of SLR in the zero-melting case, increasing to ~0.3 mm/yr and ~0.1 mm/yr in the warm case, respectively'.

L283: I'm curious what is causing the noise?

Text has been added to expand on this point.

In all three areas 'noise' is present in the SLR rates, due to the instant effects of the evolving grounded ice fraction field, though this is harder to see for the Thwaites area due to the larger y-axis scale.

L293: 27% for all the three glaciers or you just talk about Thwaites here?

This value is when considering SLR from all three regions, which has now been clarified in the text (L 280).

L371-372: the new added sentence is not quite clear to me. 'the last pinning point' -> 'the last pinning point in group 'a''

This has been changed.

L385-387: "with an average pinning point duration over warm/cold matching pinning locations of ~6 years" -> "with an average pinning point duration of ~6 years over warm/cold matching pinning locations"

This has been changed.

L387: ungrounding times -> ungrounding timings

This has been changed.

L484: "Without this" ?

This has been clarified to be 'Without these model ensembles.' (L473)

L485: "the timings of pinning point ungroundings" -> 'the timing when pinning point becomes ungrounded'

This has been changed (L474):

'Without these model ensembles there is high uncertainty, for example, in SLR contributions and the timing of when pinning points become ungrounded.'

L493: recent observations of ??

This has now been clarified to be 'recent observations of grounding-line retreat rates.' (L482).

L580-584: here you mention 'they may have the greatest impact' in the no melt case twice. Please rephrase it. Again, in this paragraph, I don't recall the gap between the east and west of Thwaites Ice Shelf. Have you mentioned it earlier in the manuscript? What do you mean "these gaps cannot recover during the simulation"? It is hard to follow what you discuss here without a context. Correct me if I have missed it somewhere.

Second mention of 'may have the greatest impact' has been removed (L 564). The gaps in the ice extent between the east and west of Thwaites ice shelf are now explicitly mentioned in the Methods section (L 88-89).

Response to Reviewer 2

The revision of the manuscript "Coupled ice/ocean interactions during the future retreat of West Antarctic ice streams in the Amundsen Sea Sector" is much improved compared to the initial submission, with extensive clarifications on the models and processes applied as well as additional discussion of the limitations of the study and how it compares to previous work.

We thank the reviewer for the time taken in reading and reviewing the manuscript and for providing helpful comments and suggestions that will improve the manuscript.

The main limitation of the new version is that the calculation of total melt includes regions that have thinned significantly and reached the threshold of 50 meters beyond which ice shelves won't thin further and for which the sub-ice shelf melt is actually not melting the ice shelves. While I understand this is a feature of the model that is common to many similar models, accounting for melt in these regions (where melt is actually not applied) is not correct, and these total melt values should be post-processed afterwards to correct it in regions where there is no more melt. The authors claim in their response that the impact is small, but the correct solution is to post-process that value afterwards.

The inclusion of melting on cells which have reached the minimum thickness has only a very small effect on the total melt timeseries for each area (Figure R1). Therefore, their inclusion or not has no material effect on the plots and conclusions taken from the total melting trends. In addition, it is important to clarify that melting is actually occurring in these cells. The melting is being calculated and the meltwater is cooling and freshening the ocean. The only limitation is that this melting is not permitted to thin the ice. This melting is therefore having an oceanographic effect, and it is also partly having a glaciological effect; while melting on these cells doesn't result in the ice thinning, it does stop the ice in these cells from thickening away from the minimum ice thickness value. These points are now discussed on lines 275.

'In addition, while the effect of the inclusion is small, we do include ice shelf melting that occurs on ice that has reached the minimum thickness, as while this melting is not allowed to thin the ice

further it still has a partial glaciological effect, by stopping the ice from thickening. Furthermore, this melting still has an oceanographic effect in the simulation by cooling and freshening the ocean.'

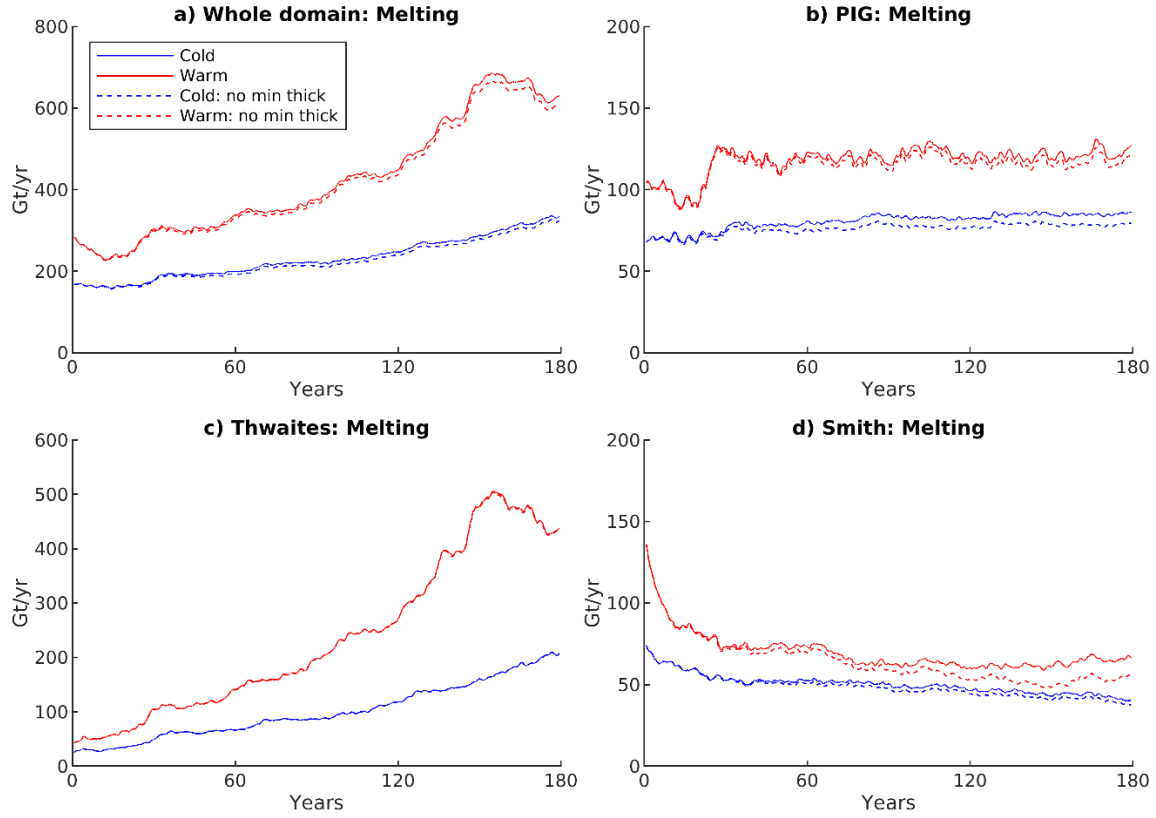

Figure R1: Timeseries of total melting shown for the cold (blue) and warm (red) cases, when including all grid cells (solid lines) and when excluding melt on grid cells at the minimum thickness (dashed lines). Timeseries are shown for the whole domain (a), the PIG area (b), the Thwaites area (c) and the Smith area (d).

Another thing that could be better discussed in the decrease in total melt and SLR found for Thwaites Glacier over the last ~30 years, to understand what causes these decreases at the end of the simulations in and warm case.

We thank the reviewer for pointing this out and we welcome the opportunity to expand the text to explain this feature of the simulation. Thwaites Glacier retreats on to a shallower and less slippery ridge towards the end of the warm case's simulation (as shown in Figure 5d), which corresponds with the reduction in SLR rate from the Thwaites area. Text has been added to explicitly point out this in the manuscript (L319-322), as shown below:

'Towards the end of the warm case simulation, the grounding line experiences rapid retreat (Figure 5b) across a deep and slippery bed section (Figure 5d-e) before slowing down as it encounters a ridge of shallower and less slippery bed (Figure 5d-e), where it remains until the end of the simulation. These features explain the large variations in the Thwaites area SLR rate in the last ~50 years of the

simulation (Figure 4b). In particular, the retreat onto the shallower and less slippery ridge at the end of the warm simulation decreases the ice flux across the grounding line and corresponds with the Thwaites region's decreasing SLR rate during the last 25 years of the simulation.'

In addition, as Thwaites retreats on to the shallower ridge, i.e. the bed depth at the grounding line increases, the ice shelf area reduces. Thus, a smaller area of ice shelf is exposed to the warmest water, reducing the ice shelf melting. Text has been added (L 424) to point out the decrease in melting at the end of simulation and text has been added to explain the reason why (L432).

'Figure 9a shows the evolution of total melt flux from the Thwaites Ice Shelf in the warm case, for both the entire ice shelf and for ice below 600 m depth only, which is the thermocline depth in this case. For the majority of the simulation, the total melt flux from the entire ice shelf increases, but it decreases during the last 25 years.'

'However, towards the end of the simulation the groundling line retreats slowly onto a shallower ridge (Figure 5d), where the shallowing grounding line depth decreases the ice shelf area below 600 m, and subsequently decreases the total amount of melting below 600 m.'

I continue to think that the title is misleading since the scenarios are highly idealized and do not represent "the future retreat" of that region.

We have discussed other options for the manuscript title, and we still believe that including the word 'future' is appropriate, as the ice model is initialized using present day ice velocities and rates of ice thickness changes. The oceanographic boundary conditions that are applied represent the present-day range in oceanographic conditions and are clearly explained in the abstract and manuscript. Therefore, while the simulations do not represent 'the future retreat' that is expected to occur, it does represent retreat that occurs in the future. The title has been edited to remove the word 'the':

'Coupled ice/ocean interactions during ~~the~~ future retreat of West Antarctic ice streams in the Amundsen Sea sector'.

Below are some technical comments line by line (lines refer to the manuscript including track changes):

l. 1: As mentioned above, I continue to think the title is misleading

Please see response above.

l.17: "that is approximately quadratic in time" -> "that evolves approximately quadratically over time"

This has been changed.

l.35: "has a unconfined" -> "has an unconfined": also if it is unconfined, it should be less impacted by changes in the ice shelf, so I am confused here

This has been changed. The sentence has been changed to 'largely unconfined' and we have added 'but' for clarity:

'Of particular concern is Thwaites Glacier, which has a largely unconfined ice shelf, but whose current pinning point on its eastern ice shelf appears to be weakening and has been predicted to unground within decades (Wild et al., 2022).'

l.48, l.56 and other: "e.g." -> "e.g.,"

This has been changed in all locations.

l.79: "basal sliding drag": I would use basal drag or basal sliding but not both (this comes up many times in the text)

This term was expanded out from 'basal drag' due to a reviewer suggestion to stop the potential confusion with the ice shelf melting drag coefficient used in the ice shelf melting calculations.

l.81: "Measures" -> "MEaSUREs"

This has been changed.

l.83: Add some references about the partial cell basal sliding

References have now been added to this sentence:

'Partially grounded cells are utilised using a sub-grid parametrization to better represent the grounding line (e.g., Pattyn et al., 2006; Cornford et al., 2012; Seroussi et al., 2014), where the grounding fraction is used to proportionally apply the Weertman sliding drag coefficient.'

l.85: "remains fixed" -> "remain fixed"

This has been changed.

l.85: You should add a figure showing the deviation of ice thickness and velocity from present in an appendix

A new appendix has been added (L 601) and referred to (L87) in regard to the changes of ice thickness and surface ice speed after the relaxation period of the ice model, when compared to present day observations.

l.110: "2009 and 2012" -> "in 2009 and 2012"

This has been changed.

l.110: "has temperature" -> "has a temperature"

This has been changed.

l.147: "to evolve" –> "to evolve continuously"

This has been changed.

l.161: "exists is" -> "is"

This has been changed.

l.168: "of Amundsen Sea" -> "of the Amundsen Sea"

This has been changed.

Fig.1 caption: "coloured regions" -> "coloured contours"

This has been changed.

l.231: Consider changing the title of section 3.1

The title for section 3.1 has been changed to 'Simulated evolution of the Amundsen Sea sector'.

Fig.3: Add a scale (like 100 km) on one of the subplots. Also, the log scale should be used for the velocity

These changes have been made to figure 3.

Fig.3 caption: "Starting" -> "Initial"

This has been changed.

l.240: I thought this pinning point was called the Eastern Ice Rise

To be consistent in terminology in the manuscript it is just referred to as a pinning point located on the current eastern Thwaites ice shelf.

l. 255: "above" -> "a-d" (twice)

This has been changed.

l.268: You should add that in the case of Pine Island there is no SLR contribution but instead some mass gain in the no melt case

New text has been added to make this point (L 254):

'In the PIG area there is a negative SLR contribution for the zero-melting case (mass gain), though the contribution from PIG is dependent on the particular choice of bathymetry deepening that is implemented (Appendix B).'

l.277: "obtain" is not clear

This sentence has been changed to increase clarity (L263).

l.293-296: How does that compare to previous studies?

This figure refers to the difference between warm and cold scenarios, as a fraction of the total SLR in the model for the whole domain, which is ~27% in this study. In the discussion section, we compare against a previous coupled model study (Seroussi et al., 2017) for the Thwaites area and find a larger sensitivity to a realistic range of ocean forcings, in the shorter and longer term. However, we feel that it would be misleading to compare the specific SLR percentages differences, as previous studies perform different experiments such as applying different ranges of oceanographic conditions, and varying increases in the temperature of the boundary conditions, rather than raising or lowering the thermocline as done in this study.

Fig.5: the purple lines are hard to see, maybe a different color or thickner lines would be better. I would also use thicker lines for grounding line positions

The contours have been changed to red in the subplots (a, b, d, e) in order to help with the clarity of these plots, while the contour for final extent of the grounding line retreat in the warm case has been changed to magenta in subplot (d , e).

l.329: "Weertman C basal sliding drag coefficient" -> "Weertman drag coefficient" or something a bit more natural

This has been changed to *'Weertman C drag coefficient'* as suggested (L 313).

l.329" "area of initially grounded ice" -> "ice area initially grounded"

This sentence has been updated:

'Figures 5d and 5e show the bed depth and 'Weertman C' drag coefficient over the ice area that is initially grounded.'

l.340-341: This is for specific areas and for the slowly retreating regions mostly. My first impression looking at the overall patterns in Fig.5 a and b is that they are very similar. Then looking in more details we start to see changes, but the overall retreat rate is similar suggesting this is not controlled by the ocean thermal forcing but by the geometry of the glacier.

This statement has now been clarified and expanded (L329):

'There are very large percentage increases in grounding-line retreat rates in ~~for these~~ two clear bands on the retreated area (Figure 5c), where two bands of slow retreat rates in the cold case are not present in the warm case.'

l.386: remove "warm/cold"

This has been removed.

l.398: remove "strong"

We believe the reviewer is referring to l. 445 in the tracked changes document. This word has been removed.

l.445-447: As mentioned above, I think it is not correct to include the melt applied in the regions not allowed to think because the thickness has reached the minimum imposed. I understand this is feature of the melt that cannot be changed, which is ok. But the calculation of the melt should be corrected or post-processed to only include it in the areas that are actually seeing the melt happening. The correction might be very small (which would be great so conclusions would not change), but at the moment it is adding some "random" melt never used to thin the ice, so I don't think this is correct, especially since it should be possible to calculate it afterwards without rerunning the entire simulation.

Please see response above.

Fig.9a and b: It would be good to talk more about the decrease in melt and area below 600 m in the last ~30 years of simulations, to explain why this is happening after a long period of regular increase.

Please see response above.

l.469: "over 160 years of the time period" -> "over the first 160 years"?

This has been changed.

l.473: "sooner": sooner than what?

This is referring to the simulations in the previous ice only study and this text has been added to clarify this: 'than in the simulations of this previous study.' (L 449).

l.493: mention what observations you are talking about

This has now been clarified to be 'recent observations of grounding-line retreat rates.'(L482)

l.517: “increasing ice area at depth” is not clear (the area at depth is not really increasing since it was always there even if grounded). The following explanation on l.518 is much more clear so maybe remove this first part.

First part has been removed as suggested (L495).

l.554f: “affect” -> “effect”

This has been changed.

l.564: remove “ice shelf”

This has been removed.

l.567: “determine level” -> “determine the level”

This has been changed.

l.572: “sensitively” -> “sensitivity”

This has been changed.

l.581: remove comma after mask

This has been removed.

l.583: remove “in the region”

We believe that this comment refers to l.593. This has been removed.

References

Arthern, R. J. and Williams, C. R.: The sensitivity of West Antarctica to the submarine melting feedback, Geophysical Research Letters, 44, 2352-2359, https://doi.org/10.1002/2017GL072514, 2017.
Cornford, S. L., Gladstone, R. M., and Payne, A. J.: Resolution requirements for grounding-line modelling: sensitivity to basal drag and ice-shelf buttressing, Annals of Glaciology, 53, 97-105, 10.3189/2012AoG60A148, 2012.
Pattyn, F., Huyghe, A., De Brabander, S., and De Smedt, B.: Role of transition zones in marine ice sheet dynamics, Journal of Geophysical Research: Earth Surface, 111, https://doi.org/10.1029/2005JF000394, 2006.
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