Response to Reviewers

Modelling the evolution of Thwaites Glacier over the 20th century

David T. Bett, Alexander T. Bradley, Bertie W.J Miles, C. Rosie Williams, Paul R. Holland, Robert J. Arthern.

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

Response to Reviewer 1

General comments:

Bett et al. successfully use coupled ice sheet-ocean modelling and historical observations to investigate the response of Thwaites Glacier to idealised perturbations in ocean forcing and ice-shelf damage. The authors find that an advanced glacier is only achievable with an extended ice front and 'healed' ice-shelf damage, allowing the western ice shelf to ground on a shallow bathymetric high. When ocean conditions are altered, the glacier retreats towards its present-day state and beyond, at a rate that increases with added damage. The authors also demonstrate 'ice piracy', with eastern Thwaites starved of ice during retreat, which could explain observed thinning despite low melt rates. Reversibility experiments indicate several different quasi-steady states depending on the level of ice-shelf damage and ocean forcing, highlighting the complex feedbacks that may have governed glacier evolution over the 20th century. These results have direct relevance for other modelling studies focussed on the evolution of Thwaites, whether initialised from its present-day damaged state or a historic undamaged configuration.

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

Specific comments:

Overall, the manuscript is generally well-written, but some sentences need to be reworded, and descriptions of model simulations could be condensed to help readability. I recommend using experiment names for the different simulations to help the reader keep track of what is being discussed and reduce the amount of words being used to describe damage and ocean forcing. The repeated use of 'ocean-only forced case' is also potentially confusing given the concurrent use of 'ice-only simulation'.

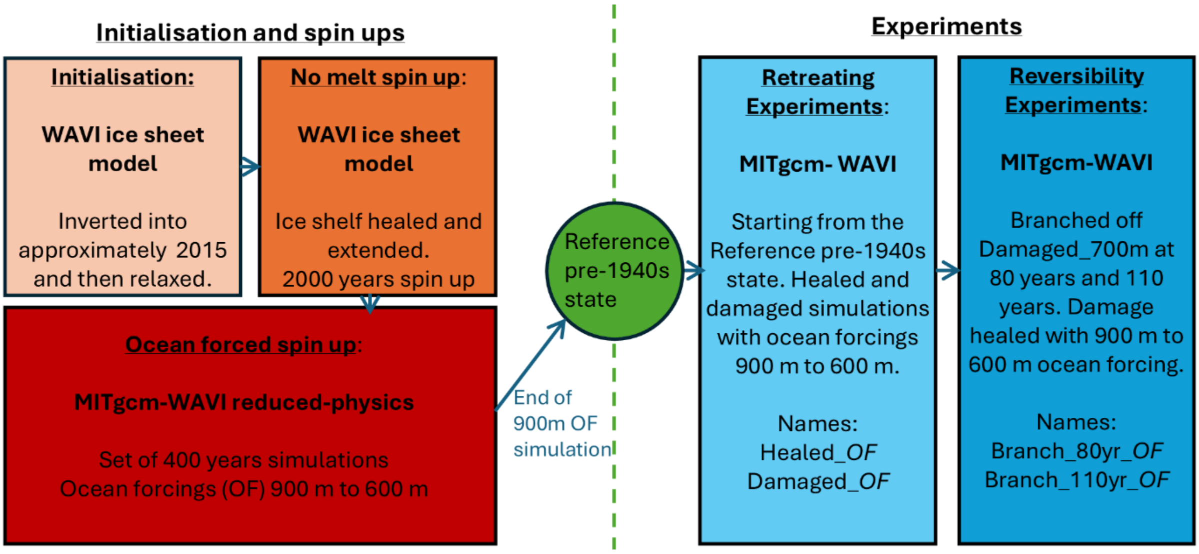
An appendix schematic (Appendix D) will also be added to aid clarity and is shown below. As suggested a naming convention will be used for the simulations in the two different experiment sets in order aid clarity and the manuscript will be edited to refer to these. For the retreating experiments the naming convention of Healed_OF and Damaged_OF will be introduced in a new paragraph at L 325 (shown below) and used, where OF stands for ocean forcing e.g. Healed_600m, so it is clear what damage and ocean forcings are being applied in each simulation. For the reversibility experiments the naming convention of Branch_80yr_OF and Branch_110yr_OF will be introduced (shown below) and used to make it clear the time of branched off and the ocean forcings applied for each simulation.

New paragraph at L 325:

'In this section we will examine full-physics coupled model simulations starting from the reference pre-1940s state for two different levels of floating ice damage forcing, with damage intensity set to 0 (referred to as healed) and 1 (referred to as damaged), along with ocean forcings in the range 900 m to 600 m (Appendix D). The specific simulations within this simulation set will be referred by "Healed_OF" and "Damaged_OF", depending on the damage and ocean forcing (OF) that is applied.'

Introducing next new simulations sets at L 463:

'The specific simulations within these new sets of simulations will be referred to as "Branch_80yr_OF" and "Branch_110yr_OF", depending on the ocean forcing (OF) that is applied in each case.'



*'**Figure D1:** Flow chart showing the steps in the initialisation and spin up used to create the reference pre-1940s state, which is the starting point for two sets of experiments. Details of the initialisation can be found in Section 3.2. Details and results of the spin up sets are found in Section 4.1. Results of the retreating and reversibility experiments are shown in Section 4.2 and Section 4.3 respectively.'*

Whilst the authors state this is an example 1940s configuration, the title frames the work as modelling Thwaites' evolution over the 20th century. However, given the idealised nature of both the ocean and damage forcing, this characterisation seems difficult to justify. The authors show that healing the ice-shelf damage is required to advance the grounding line, but the impact of the initialisation procedure, whereby the model is matched to present-day velocities and surface elevation changes, remains unclear. The model setup is also insufficiently described for both the full and reduced physics configurations; this detail could be included in an appendix. Similarly, the damage calculation methodology lacks sufficient detail, despite being central to the study.

While we agree that the ocean and damage forcings used in this manuscript are idealised, we are keen to stress that the final pre-1940s state created in these simulations matches all available observations and we therefore believe it is justified to refer to '20th century' in the title. However, we agree that the idealised nature of our experiments means that we are not modelling the exact behaviour as it happened or producing a reconstruction; therefore, as mentioned below the title will be adjusted to *'**Exploring** Thwaites Glacier over the 20th century **using a coupled ice-ocean model**'.*

There are no satellite observations for pre-1940s Thwaites Glacier, so in order to constrain the ice model fields of basal drag coefficients (C) and viscosity enhancement factors (E) an inversion using present day observations is needed. The inversion process description will be expanded in the manuscript in order to aid clarity on the inversion process (L168). These viscosity enhancement factors (E) from the inversion form the basis for the damage field (after specified assumptions), rather than the damage field being calculated directly.

*'The WAVI ice sheet model is initialised to match the near present-day Amundsen Sea glaciers, taking into account both the approximately 2015 surface elevation change signal (Smith et al., 2020) and the surface ice velocities (Mouginot et al., 2017a, b) in the inversion process, as described by Arthern et al. (2015) and Bett et al. (2024). **The inversion process generates fields of basal drag coefficients (C) and viscosity enhancement factors (E). During this iterative procedure incremental adjustments are made to these fields in order to minimise a cost function. Therefore**, a Weertman basal drag coefficient field (C) is inferred under…'*

There are tuneable parameters in the initialisation method which would affect the resulting viscosity enhancement factors (E) and so the damage field. The initialisation procedure produces 2D fields of the basal drag coefficient and the viscosity enhancement factor (E), as described above. The problem solved to determine these fields is ill-posed -- there is no unique solution. The tuneable parameters used in the inversion method determine the balance between the two resulting fields e.g. the balance between E and basal drag that match the observations. The key here is that we select an initial state with a small misfit between observations. In other work, we find that different initialisation parameters result in different fields of E and drag, but with very similar misfit metrics (Williams et al., 2026 – accepted). To "tune" these, or to select which is better to use, you then need additional observations. Both this, and the computation of multiple initial states, is outside the scope of this study, not least because the coupled simulations are so expensive in compute and time. This will be noted in the manuscript as a limitation of the study at L174:

'The sensitivity to the initial state is not explored in this study, due to the expense in time and computer resources of the coupled ice-ocean simulations.'

Both the reduced-physics coupled model and the full-physics coupled model are still WAVI-MITgcm. The only differences are the different coupling/ice model/ocean model timesteps and the use of a spatially and temporally adaptive ocean lateral eddy viscosity in the reduced-physics version. The paragraph (L190) explaining the types of simulations will be edited and improved in order to make clear the differences between these two types of simulations. Additionally, text will be added to state the resolutions used in the models at L 185, along with introducing the timesteps used the full-physics version earlier at this location.

The reversibility experiments section requires further justification. It is unclear whether 250-year simulations are sufficient to characterise tipping point behaviour or map the stability landscape meaningfully. Furthermore, buttressing from other sources, notably Crosson Ice Shelf and Bear Island, receives only brief mention in the discussion, despite their potentially significant influence on Thwaites dynamics.

We agree that much longer simulations are required to truly map out the underlying stability landscape. However, the discussion using this framing is valuable as the simulations shown here cover policy relevant timescales. The simulations are limited in run length, due to computational and time expenses caused by the complex nature of these ice-ocean coupled simulations. Wording will be edited in the paragraph where this is discussed (L608) to make clear that only suggestions are made to the underlining stability landscape instead of determining it. A sentence will also be added to note that much longer simulations are required to truly map the underling stability landscape out (L616):

'However, we note that much longer simulations are required to truly map out the stability landscape of Thwaites Glacier.'

While we show that the western pinning point provides the primary buttressing, other sources of buttressing are indeed still important, and will be expanded where advancing Thwaites Glacier is discussed. These extras sources of buttressing are interacting with the process of advancing Thwaites grounding line, especially as these other sources of buttressing cause feedbacks with the western pinning point. Where these other sources of buttressing enable a thicker ice shelf, leading to a larger pinning point area, which again provides more buttressing. Additionally in order for the grounding line to advance and not just be steady at the near present day location, smaller pinning points need to be able to form on the ridge west of the western pinning point as part of the advancement process. This step will also be impacted by the buttressing provided by the interaction with Bear Island and Crosson ice shelf. The processes that occur during advancement will be expanded in the manuscript.

Extra details will be added when describing the advance in Section 4.1 L298:

*'In this edited setup, the ice first regrounds on the western pinning point**<u>, then ice flows out into the extended area interacting with Crosson Ice Shelf and Bear Island providing secondary buttressing and further thickening the ice shelf, which feedbacks back onto the western pinning point. After this smaller pinning points form on the ridge south-west of the bathymetric high</u>** and then the main grounding line advances from the 2015 position to encompass the western bathymetric high **<u>and the smaller pinning points</u>** (Figure 4c).'*

L755:

'In this study we find that simply prescribing the healing and extending of the floating ice shelf in the 2015 state allows for a regrounding of the western pinning point in an extreme no-melt case

*to provide sufficient buttressing**, along with interacting secondary sources,** for the main grounding line to re-advance onto the bathymetric high.'*

And the sentence in the conclusion will be edited L779:

*'We found that healing the ice damage on the western Thwaites Ice Shelf and extending the static ice front were needed, both supported by observations, so that the buttressing provided by a regrounded western pinning point **and interacting secondary sources** was sufficient to create an initial advanced quasi-steady state.'*

The figures could be improved, particularly regarding distinguishing east versus west Thwaites and the pinning points under discussion.

We have responded to the specific figure suggestions below.

Technical comments:

L1: The title is not very specific or descriptive for this study, there is no mention of ice-shelf damage, which you show is one of the key drivers of historical retreat

In this study we highlight several key processes including ice shelf melting induced pinning point ungrounding, ice shelf damage and ice piracy, along with analysing satellite and 1947 aerial imagery and exploring different quasi-steady states. We therefore feel that a broader scoped title fits the manuscript better as we would struggle to create a title that described all these specific parts. Otherwise if we focus the title on just ice damage, this would downplay the impact of other processes and results. However, we agree that the ocean and ice damage forcings used in the modelling study are idealised and have changed the title to recognise that we are exploring rather than explicitly modelling exactly the 20th century. Additionally to be more descriptive it will be added that an ice-ocean coupled model is used. This edited title will be suggested:

*'~~Modelling the evolution of~~ **Exploring** Thwaites Glacier over the 20th century **using a coupled ice-ocean model**'*

L20: "demonstrating the potential for tipping points in the Thwaites system" - do you mean tipping points in the historical position or in a future state?

This will be changed to *'demonstrating the potential for tipping points in the **historical** Thwaites system'.*

L40: "modelled to occur"?

This will be changed to "modelled".

L66-67: Reword this sentence because it sounds like you're referring to the "sketched outlines" in the "image" in figure 1.

This sentence will be split into two to make this clearer:

*'Crucially, a key feature of this image is a large intact iceberg near Thwaites' western ice shelf**.** **S**ketched outlines for 1947 (Ferrigno et al., 1993) and for 1966 (Williams and Carter, 1976) suggest that this intact iceberg was attached to the western Thwaites Ice Shelf.'*

L68: "relatively undamaged for centuries" - are you assuming this from flow speeds of km's per year and the length of the iceberg in the 1973 image?

Yes, that is right. This will be expanded and clarified:

*'...**S**ketched outlines for 1947 (Ferrigno et al., 1993) and for 1966 (Williams and Carter, 1976) suggest that this intact iceberg was attached to the western Thwaites Ice Shelf. **If this iceberg was the historical ice tongue,** then such a long **(~150 km)** and cohesive ice tongue**, combined with the 1973 Thwaites western ice tongue speed of ~2 km/yr (Mouginot et al., 2014),** suggests that Thwaites Ice Shelf was relatively undamaged for **at the least several decades** prior to sometime before the 1973 image. **However, the already damaged 1973 western ice tongue speed is very likely an over estimation of the ice speed of this more intact historical tongue and so the Thwaites Ice Shelf could have even been undamaged for centuries prior. Furthermore other changes in buttressing are suggested to have occurred before 1973 with** sediment core analysis suggesting that the western pinning point of Thwaites Glacier ungrounded in the 1940s (Clark et al., 2024), coinciding with the ungrounding of nearby Pine Island Glacier (Smith et al., 2017), with possible grounding line retreat occurring in western Thwaites during the 1950s (Clark et al., 2024).'*

L71-74: This sentence seems out of place, I would expect this at the end of your introduction.

This sentence will be adapted and moved to the last paragraph in the introduction where this section is referred to:

*'The paper proceeds as follows**: i**n section 2 we **analyse aerial images of Thwaites Ice Shelf taken in 1947 during the U.S. operation Highjump (USGS, 2018) and compare them to the earliest available satellite image from 1973. This provides insight into the configuration of Thwaites Ice Shelf prior to the major changes that ensued** ~~the 1947 imagery to provide new insight into the history of Thwaites~~.*

L76-77: "Changes in ... melting" compared to when?

This sentence will be expanded:

*'Changes in oceanic melting are the ultimate cause of Amundsen Sea glaciers' thinning and retreat (Shepherd et al., 2004), though it is uncertain how and why melting has changed **compared to a potential historical period where the glaciers were quasi-steady**.'*

L78: modified Circumpolar Deep Water (mCDW)?

This will be fixed.

L90: Remove 'the' before 'increasing': "the effect of the increasing ice damage on ice flow speed"

This will be fixed.

L98: Why have you switched from using "ocean-ice sheet model" in line 15 to "ice/ocean" here and throughout the paper? (e.g., 105, 147, 189, ...). Then in line 101 you use "coupled ice-ocean model".

Thank you for spotting this and this will be made consistent and referred to as "coupled ice-ocean model" throughout the manuscript.

L98: Remove the extra "coupled" before "model"

This will be fixed.

L98: As you only use idealised ocean boundary conditions (and forcing?), is it correct to say the simulations are over the "20th century"?

In this manuscript we use all available observations of Thwaites Glacier over the 20th century. However, as the ocean boundary conditions are idealised, throughout the manuscript references of 700m and 600m being equivalent to present average and present day warm respectively will be removed (L 459, L512, L 561, L619). Additionally to match the changes in the manuscript title this will be changed to 'exploring the 20th century'.

'To do so, we employ a coupled ice-ocean model, with additional idealised ice damage forcing and perform simulations ***exploring*** *the 20th century.'*

And changed on line L133:

'We will use the evidence of the 1947 imagery and the 1973 satellite image, including the inference of an extended, less-damaged western ice shelf, to constrain our modelling ~~*of*~~ ***to explore*** *the 20th century evolution of Thwaites Glacier.'*

L102: Does "These simulations" refer to the simulations mentioned in line 98? (i.e., not in Bett et al. 2024?)

They refer to the simulations in this study and the sentence will be clarified:

*'**In this study** simulations retreat to and past...'*

L112-113: Put this sentence after the next one. Introduce figure 2 first, then say that the lines are approximate and you can identify key features.

These sentences will be swapped as suggested.

L119: Change "is much more advanced" to "has a longer extent" or "with an ice front that is much more advanced".

This will be changed to "has a longer extent".

L120-121: Difficult to see where the "main western ice shelf" is in Fig 2 – Can you add a 1973 coastline to aid visualisation?

After your suggestion, adding an ice front has been explored. A western ice-shelf ice-front line will be added to figure 1a and linked to the plots Western Ice tongue label and this same line will be shown in the central image of figure 2. However, this ice front is subjective as to where this would lie, due to the varying degrees of damage that exist on the western ice shelf in this image. This line will be added to the captions of both figures:

'Purple line shows a western Thwaites ice-front, though this location is subjective due to the varying degrees of damage that exist there.'

L125-126: If the main 1940s grounding line was more advanced (as you suggest later in the paper), could the damage in (g) and (f) be due to fracturing at the grounding lines and pinning point, respectively, as we see in present day (e.g., Wang et al. 2025, Wild et al. 2022)? Or is this more indicative of shear margin damage?

This is a good point, which we are happy to expand on. We think the damage in image (g) is indicative of a shear margin because the damage is confine to a narrow band with a full distinctive rifting pattern. If this damage feature was mainly due to general fracturing near the grounding line, we would expect a wider more divergent pattern of damage than the one observed in this image. However, in (f) it is likely that fracturing due to the interaction with the western pinning point is likely combing with the shear margin shown in (g). Extra text will be added:

'Instead, the 1947 imagery shows an ***area of damage between*** *the (f) and (g) locations further west, on a flow line passing through the western pinning point.* ***The damage in (g) appears to be indicative of a shear margin, with the observed damage confined to a narrow band with a full distinctive rifting pattern, while if this was mainly due to general fracturing near a grounding line we would expect a more divergent pattern of damage. However, a wider band of damage is observed in (f) without such distinct features, and this is likely due to the shear margin in (g) interacting with the western pinning point causing additional fracturing. This*** *suggests a ~15 km eastward migration of the shear margin by 1973.'*

L129: What is the uncertainty in 1940s image location? How does it compare with the 15 km between possible shear margin locations?

The uncertainty of the 1947 aerial imagery locations has been assessed by comparing against key features like Mount Murphy and the Bear peninsular. For the possible shear margin feature the uncertainty is reduced as the westward shift in this feature compared to the 1973 image shows up on two separate flight lines and the shift distance ~15 km is quite large e.g. in comparison to the total flight line length ~100 km and if the flight lines were off this much it would show up in the comparison to regions key features. These sentences will be added at the end of the previous paragraph (L 126) in order to add these points:

'The images in (f) and (g) are located on two separate flight lines, which both align, providing independent observational evidence of this shear margin shift, thereby increasing our confidence in this having taken place. Additionally, the flight lines align with the region's key features like Mount Murphy and the suggested distance of the shift of ~15 km is large enough where if this shift was due to an artifact it would show up in the comparison with these key features.'

L130-131: Refer to figure 1 here

This will be added.

L157-160: What is the duration of the coupling period for velocities, if it is the same as the timestep does it vary throughout the simulation or remain constant? How often are the melt rates given to the ice model, is that on the ocean model timestep?

Text will be added to address these questions at this location:

*'However, the ice thickness updates **and melt rates are applied** continuously (i.e. during these periods), on the shorter ocean model timestep. **A constant coupling period/ ice sheet model timestep of 20 days and an ocean model timestep of 100 seconds are used in the full-physics coupled model simulations**.'*

L162: and Kohler, Pope? Do you keep present-day 'damage' on Crosson and Dotson ice shelves?

The missed glacier names will be added. While we focus on Thwaites ice shelf in this study the healing process is applied to all ice shelves and text will be edited to make this clear in the damage methods section (L 229):

*'This value is then applied as the maximum damage value past the present-day grounding line on the initially floating ice **for all ice shelves in the model domain**.'*

L162: You use "PIG" here but haven't said what that is beforehand.

This will be defined on its first use.

L164: Put "e.g.," inside the citation brackets

This will be fixed.

L168-169: Does the ice-sheet model include the surface/thickness elevation change (as well as velocities) in the inversion process?

Yes that is right and this will clarified in the text:

*'The WAVI ice sheet model is initialised to match the present-day Amundsen Sea glaciers, taking into account both the **approximately 2015** surface elevation change signal (Smith et al., 2020) and the surface ice velocities (Mouginot et al., 2017a, b) **in the inversion process**, as described by **Arthern et al. (2015) and Bett et al. (2024)**).'*

L169: Fix citation formatting

Format of citation has been fixed to '…, as described by Arthern et al. (2015) and Bett et al. (2024)'.

L170: What is this C value representative of, how did you select it? Unless I missed it, I couldn't find it in Bett et al. (2024).

This value is chosen as an approximate typical value for C values generated in the main ice streams in the initialisation procedure. We will edit the text to note this:

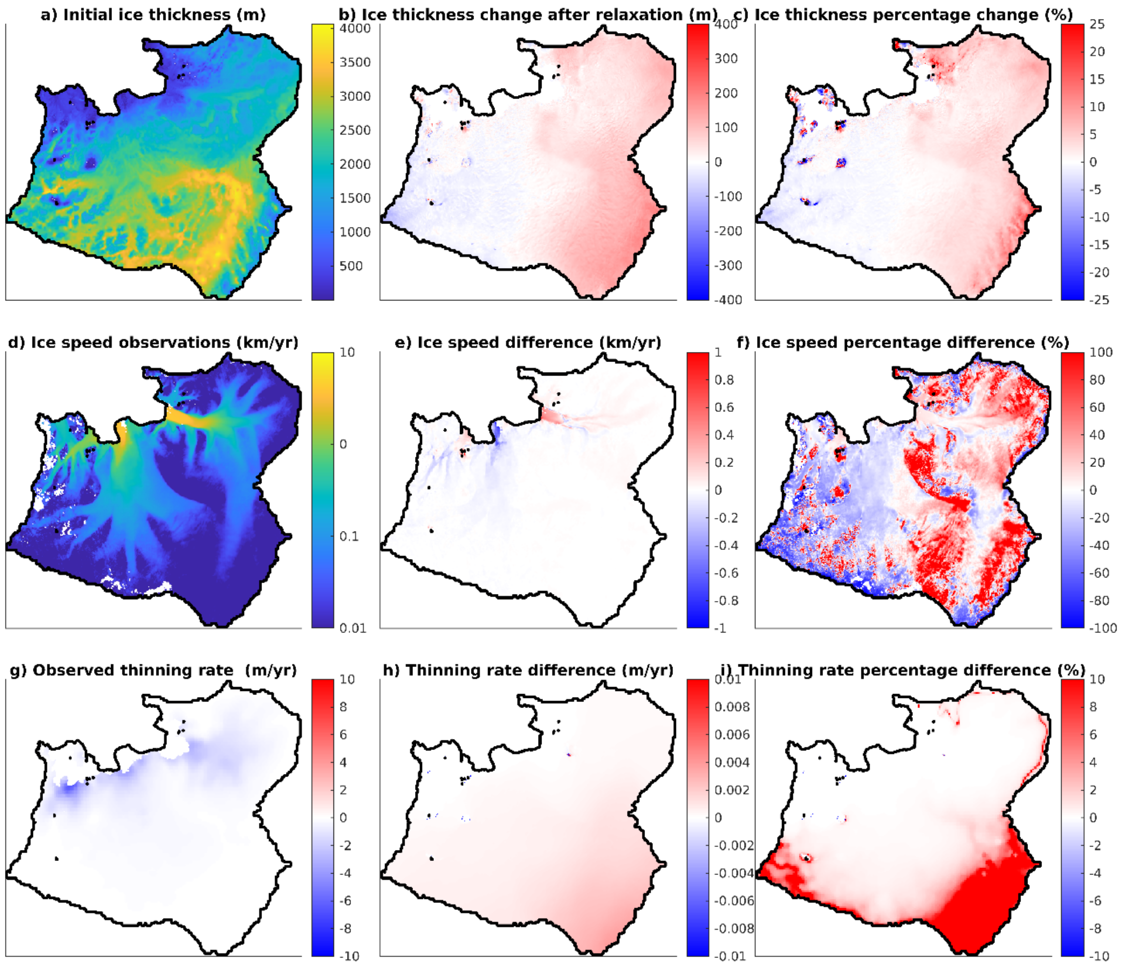
'Weertman basal drag coefficient field (C) is inferred under the 2015 grounded ice extent during this initialisation, but for any ice that grounds outside of this area we apply a constant value

*$C=10^4$ Pa $m^{-1/3}$ $a^{1/3}$, as in Bett et al. (2024)**, with this value chosen as an order of magnitude estimate in broad agreement with C values in the main ice streams**.'*

L172: What is the match with observations after the relaxation step?

An appendix will be added to show the absolute and percentage difference between ice thickness, speed and surface thinning rate observations with the model state after the relaxation step. For reference, we show this new appendix figure and appendix text below:

'As part of the ice sheet model initialisation, the relaxation step, which is applied after the inversion step as described in section 3.2, results in much better agreement with surface thinning rate observations (Figure A1 h, i), at the cost of relatively small differences in ice surface speeds (Figure A1 e, f) and ice thickness (Figure A1 b, c).'



*'**Figure A1:** (a) Ice thickness from the BedMachine V3 dataset (Morlighem et al., 2020; Morlighem, 2022) before initialisation relaxation step. (b) Changes in ice thickness from initialisation relaxation step. (c) Percentage changes in ice thickness after relaxation step. (d) Surface ice speed from MEaSUREs 2014/2015 (Mouginot et al., 2017a, b). (e) Model ice speed difference to observations after the relaxation step. (f) Model ice speed percentage difference to observations after the relaxation step. g) Observed surface elevation change signal for approximately 2015 (Smith et al., 2020) over target grounded cells for the relaxation step. h) Model surface elevation change difference over target grounded cells after relaxation step. i)*

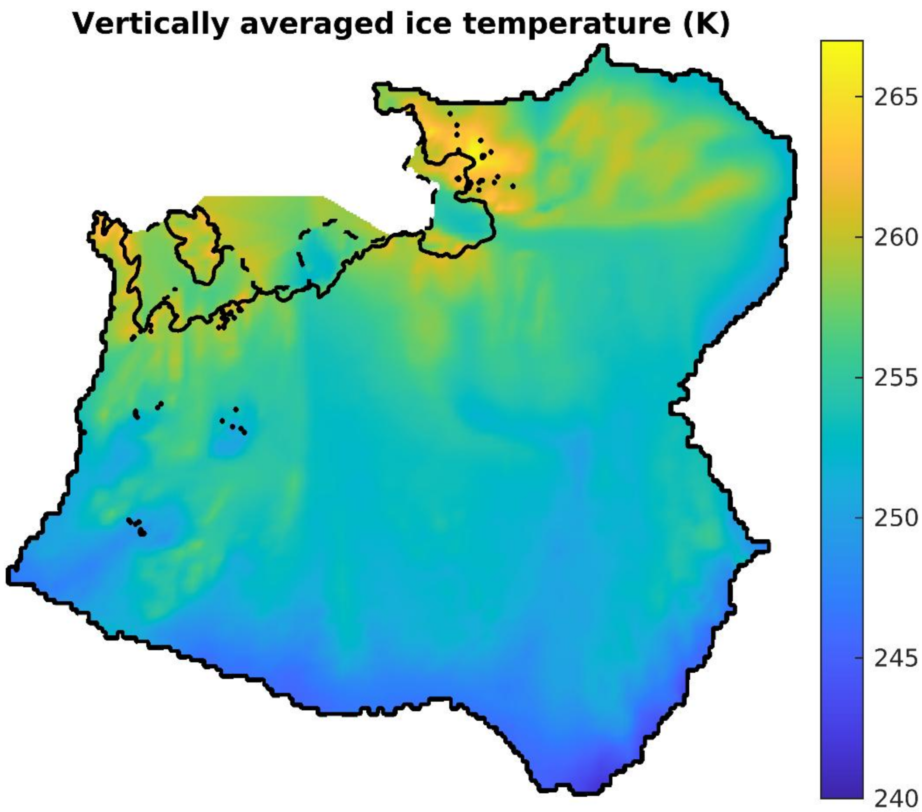
Model surface elevation change percentage change over target grounded cells after relaxation step. All plots shown for the full ice domain.'

L174: Is this temperature field what you later refer to in line 214 in the calculation of the viscosity enhancement factor? Could you show a plot of the field in an appendix/supplement?

This figure will be added as an appendix showing the vertical average of the temp field used and the full 3D temperature field will be included in the supporting data on publication.

The following text will be included in the Appendix:

'An updated ice temperature field generated using the BISICLES ice sheet model (Trevers et al., 2024), is used in the WAVI ice sheet model in this study. The vertically averaged temperature field is shown in Figure B1, with the full field included within the data availability.'



'Figure B1: *Vertically averaged temperature field generated using the BISICLES ice sheet model (Trevers et al., 2024), shown over the full WAVI Amundsen Section domain including the extended Thwaites ice front. WAVI's present day model ice front (black dashed line) and grounding line (black solid line) are shown.'*

This sentence has been added to the data availability statement:

'The ice temperature field used in this study will be available on Zenodo upon publication of the paper.'

L175: Why have you changed the bathymetry for Pine Island Glacier cavity?

While this study doesn't focus on Pine Island Glacier (PIG), the Bedmachine V3 bathymetry has a common issue of the water column under the PIG ice shelf is too thin, which other studies have faced (e.g Bett et al., 2024, Reed et al., 2026 ...). Incorporating data from auto-sub tracks taken under this ice shelf alleviates this issue and this change is included for completeness of model setup, even though this study doesn't focus on this part of the model's domain. A sentence will be added to note this:

'The bathymetry is based on Bedmachine V3 (Morlighem et al., 2020; Morlighem, 2022), but with the Pine Island Glacier cavity modified to match the field of Dutrieux et al. (2014). ***Though PIG is not the focus of this study this modification is made in order to alleviate the common issue of a too thin water column in the highly uncertain region close to PIG's grounding line (e.g. Bett et al., 2024).****'*

L188: You mention different types of "simulations" but then call them different "models" in the next sentence which is a bit confusing.

This will be fixed: 'models' will be changed to 'simulation types' in the following sentences in this paragraph.

L188: What is the reduced-physics coupled model, is it still WAVI-MITgcm? You've written "see below" but this doesn't seem to be described anywhere, unless the only difference is the eddy viscosity. Also, is the full-physics coupled model also WAVI-MITgcm?

The reduced-physics coupled model is still WAVI-MITgcm and that will be made clear in the manuscript. This paragraph will be edited throughout to improve clarity and to make clear the differences between these two types of simulations.

L190: Remove the extra "initial"

This will be fixed.

L198: It might be helpful to mention this coupling period in line 157-158 (see earlier comment)

This will be added.

L207: Why a thickness of 50m?

A small thickness initial value was chosen so that this choice of thickness didn't e.g. artificially cause the glacier to advance in the initial ice only spin up. We wanted the area to be flushed with new ice in the ice only spin and for the ice thickness to be set by the model. Text will be added:

'Therefore, post-initialisation, for our historical Thwaites simulations we extend out the fixed ice front to an idealised pre-1940s historical extent. ***This new ice*** *initially has* ***an*** *ice thickness of 50 m.* ***This thin layer was chosen to avoid artificially affecting the ice only spin up****.'*

L208: What does this mean: "removing restrictions that would have been placed by attempting to explicitly recreate the convoluted pre-1940s ice front"

If we tried to explicitly force the 1947 ice front, we would be applying restrictions on where the main ice outflow could flow to, whereas instead using an idealised extended ice front allows the ice sheet model to decide this. This sentence will be reworded for clarity:

*‘Using the evidence from the 1947 imagery and 1973 satellite image as a guide, an idealised extended ice front is chosen (Figure 3b). **We choose to apply an idealised ice front, rather than attempt to explicitly retreat the precise detail of the 1940s ice front, to not bias ice flow directions, which would be applied in the latter case.** ~~removing restrictions that would have been placed by attempting to explicitly recreate the convoluted pre-1940s ice front and enabling the model to determine where the main outflows are within the area.~~’*

L213: How is this “viscosity enhancement factor (E)” calculated?

The viscosity enhancement factor (E) is calculated during the initialisation procedure, along with the basal drag. As outlined in Arthern et al. (2015), during this iterative procedure, incremental adjustments are made to fields of these parameters in order to minimise a cost function. As previously mentioned in response to above comment, text will be added to explain this method in the earlier model structure section in the paragraph which mentions the WAVI ice sheet model initialisation (L168):

*‘The WAVI ice sheet model is initialised to match the near present-day Amundsen Sea glaciers, taking into account both the approximately 2015 surface elevation change signal (Smith et al., 2020) and the surface ice velocities (Mouginot et al., 2017a, b) in the inversion process, as described by Arthern et al. (2015) and Bett et al. (2024). **The inversion process generates fields of basal drag coefficients (C) and viscosity enhancement factors (E). During this iterative procedure incremental adjustments are made to these fields in order to minimise a cost function. Therefore**, a Weertman basal drag coefficient field (C) is inferred under…’*

L215: So, assuming “damage is the primary source of viscosity enhancement”, using E=1-D, more damage yields lower viscosity (and vice versa)?

Yes that is right. A sentence to this effect will be added to this clear:

*‘In this study we assume that ice damage (D) is the primary source of viscosity enhancement, and we refer to D = 1-E as ice damage from now on. **Therefore, for example higher damage equals lower viscosity.**’*

L216: If you are using Bedmachine (2015) geometry in the initialisation, would it better to say the ‘2015 state’ rather than ‘present-day’, particularly if the 2015 and 2024 damage fields are different. In Fig 1 you show a highly damaged (non-existent) western tongue but presumably that isn’t what your damage field in Fig 3 represents? Can you include a picture of the approximate 2015 state in a supplement? This should then show a damaged shear margin that coincides with your damage field in Fig 3d.

As suggested a satellite image of the 2015 state will be included as an Appendix:

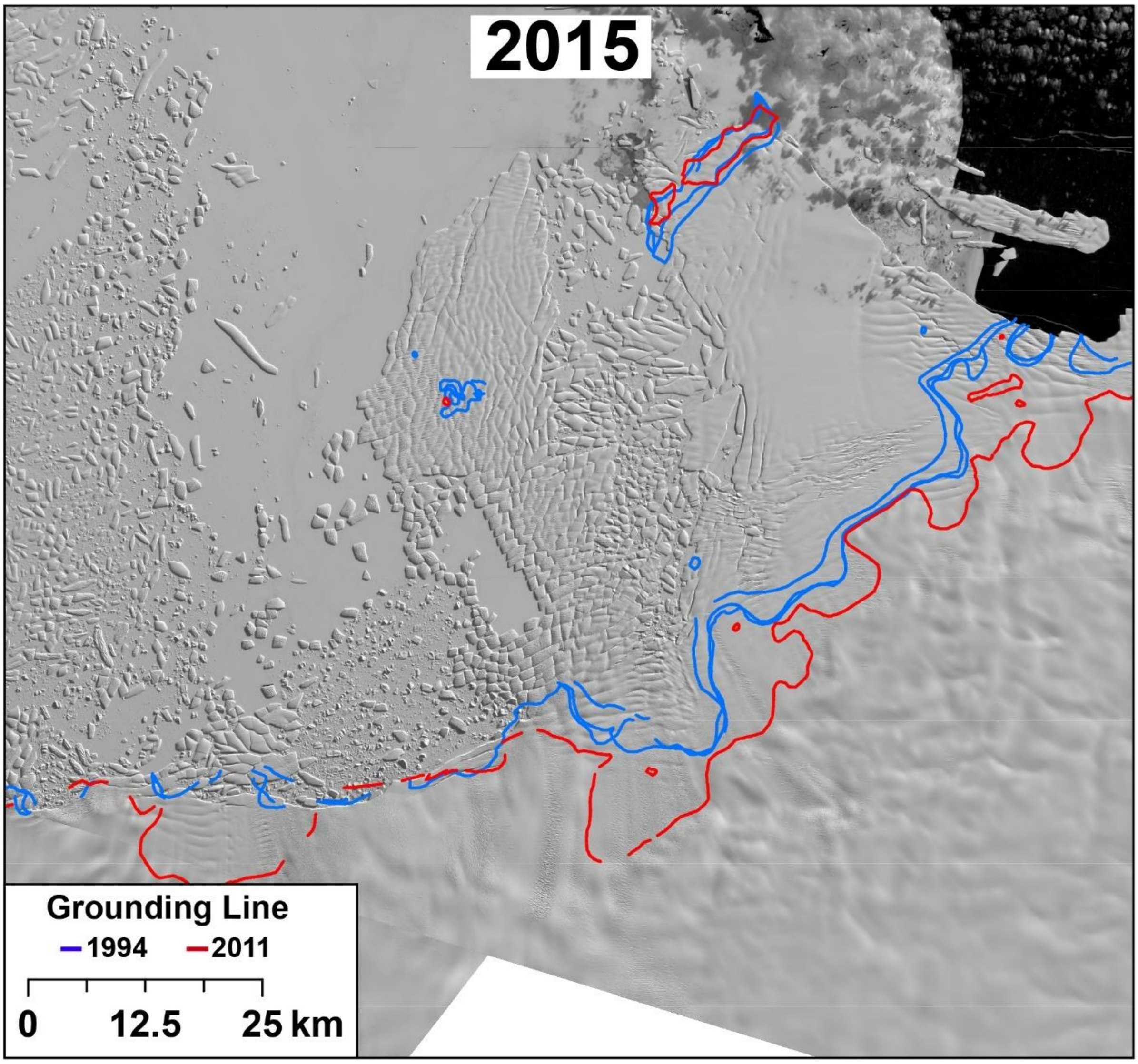


Figure C1: Landsat-8 satellite image of Thwaites Glacier in 2015. Grounding line positions in 1994 and 2011 from Rignot et al. (2016) are shown as blue and red lines, respectively.

Additionally, as suggested, when referring specifically to the initialised model state throughout the manuscript "present day" will be replaced by "2015".

L217: Are the "high damage values" close to 1?

The high damage values in the present-day shear margin are in the range 0.7-1, with a wider range more generally on the western ice shelf. The shear margin damage value will be noted in the text:

*'In this generated field there are high damage values in the western Thwaites Ice Shelf and particularly on the shear margin between eastern and western Thwaites Ice Shelf **in the range of 0.7-1** (Figure 3d), as might be expected (Figure 1b).'*

L218: "as might be expected (Figure 1b)" – but the image you show in Fig1b shows a non-existent western ice shelf with virtually no shear margin

This will be changed to reference the new 2015 satellite image appendix:

'In this generated field there are high damage values in the western Thwaites Ice Shelf and particularly on the shear margin between eastern and western Thwaites Ice Shelf in the range of 0.7-1 (Figure 3d), as might be expected ***in 2015 (Appendix C).****'*

L220: Are there tunable parameters in the model initialisation that would impact the resulting damage field?

Yes there are tuneable parameters in the initialisation method which would affect the resulting damage field. The initialisation procedure produces 2D fields of the basal drag coefficient and the viscosity enhancement factor (E), as described above. The problem solved to determine these fields is ill-posed -- there is no unique solution. The tuneable parameters used in the inversion method determine the balance between the two resulting fields e.g. the balance between E and basal drag that match the observations. The key here is that we select an initial state with a small misfit between observations. In other work, we find that different initialisation parameters result in different fields of E and drag, but with very similar misfit metrics (Williams et al., 2026 – accepted). To "tune" these, or to select which is better to use, you then need additional observations. Both this, and the computation of multiple initial states, is outside the scope of this study, not least because the coupled simulations are so expensive in compute and time. As previously mention in response to above comment this will be noted in the manuscript at L174:

'The sensitivity to the initial state is not explored in this study, due to the expense in time and computer resources of the coupled ice-ocean simulations.'

L225: Change 'our' to 'the': "During our evolving..."

This will be fixed.

L225-227: Needs rewording, it is difficult to understand what you are saying here. I presume the "plus" doesn't mean you are adding something to the present-day damage field, but refers to the other simulation.

This will be edited for clarity:

'During ***the*** *evolving ice-ocean simulations we use this* ***2015*** *damage field,* ***as well as*** *a "healed" ice shelf damage field****. The healed ice shelf damage field is used*** *to represent the historical conditions seen in the 1947 aerial imagery and the iceberg on the 1973 satellite image, in which the ice shelf was much less damaged compared to the present day.'*

L227-228: I'm not sure what you mean here, "1 decimal point rounded average damage..." – can you make it clearer

This text will be edited:

'Therefore, the ***spatial*** *average* ***of the inversion's*** *damage* ***field*** *on the initial* ***2015*** *grounded ice* ***area*** *is calculated* ***and the 1 decimal point rounded value of this is used*** *(0.2).'*

L228: Are you assuming that the average grounded present-day damage is a maximum damage value for the 1940s?

Yes, we assume that the present-day grounded ice damage average intensity is comparable to the average damage on the historical ice shelf and we then use this value as the maximum value of damage for the healed ice shelf field past the present-day grounding line position. Text will added to make this assumption clear:

*'To assign a damage value for the new "healed" field**, we make the assumption that 2015 grounded ice damage average intensity is comparable to the average damage on the historical ice shelf.**'*

L236-237: Does the damage change over time ("each coupling period")?

The present day and healed damage fields themselves (Figure 3d,e) are fixed in time, but the applied damage in a simulation does evolve in time, at each coupling period, if the damage intensity factor is above 0. This is because the applied damage is linked to whether a grid cell is grounded or fully floating which does change during the simulation. A sentence will be added to the near the end of the last paragraph (L 240) in the section in order to help make this clearer:

*'If the damage intensity factor is 1 then the present-day damage value is applied to the fully ungrounded cell, if it is 0 then the healed damage value is applied. **Therefore, while the 2015 and healed damage fields themselves are fixed, the applied damage in a "damaged" simulation will evolve with the evolving grounded ice field at the coupling period.** Essentially...'*

L238-242: This is a little confusing and doesn't explain what you're doing in your later experiments.

To aid clarity this paragraph will be generally edited to focus on the two damage intensity values used in the later experiments, which are 0 and 1. Also that we only use these two values in the study will also be explicitly stated in this paragraph as well (L 240).

*'The precise value within this range depends on a 'damage intensity factor' that we choose **and in this study we only use the values 0 (healed) or 1 (damaged).**'*

L245: Where does "see below" refer to?

This will be removed.

L262: Is the damage intensity factor ever set to values other than 0 or 1?

In this study only the values 0 and 1 are applied and as above this will be made clear in the paragraph describing the damage intensity factor.

L264: Is the healing of the ice shelves instantaneous?

Yes and that it is instantly will be mentioned here.

L269: The present-day configuration is the state after initialisation (inversion and relaxation)?

That is right and this will be made clear:

*'We start by considering the **2015** configuration, **which has been initialised into 2015 and subsequently relaxed,** with the modelled present-day ice flow...'*

L271: Why is there a reference to Holland et al. 2023 here, when you are showing your model result?

This sentence will be edited to say that this result is consistent with Holland et al. (2023):

*'The corresponding melt rates are shown in Figure 4b, with high melt rates in the western Thwaites inlet (Figure 1) and low melt rates in the eastern Thwaites, **which is consistent with** Holland et al. (2023)…'*

L272: "Thwaites retreats" - Do you mean different examples of retreat?

This is a typo. Sentence will be fixed:

*'To probe the processes responsible for Thwaites **retreating** into this **near** present-day state…'*

L274: As you refer to the "reference pre-1940s" case throughout the paper, can you use experiment names to help the reader keep track of the different simulations? Try to include the thermocline depth and damage value in the name. A summary table would help too.

As suggested experiments names will be used which refer to damage and thermocline height in the name (as discussed above). The "reference pre-1940s state" name will still be used, but it will be shown in a new appendix schematic (Appendix D) clearly showing that this is the starting state for the retreating experiment simulations.

L296: "unedited ice geometry" - Can you just say 2015 geometry (or ice front)? Unless you are changing other geometric variables?

This will be changed:

*'In the ~~unedited ice~~ **2015** geometry from the present-day initialisation there…'*

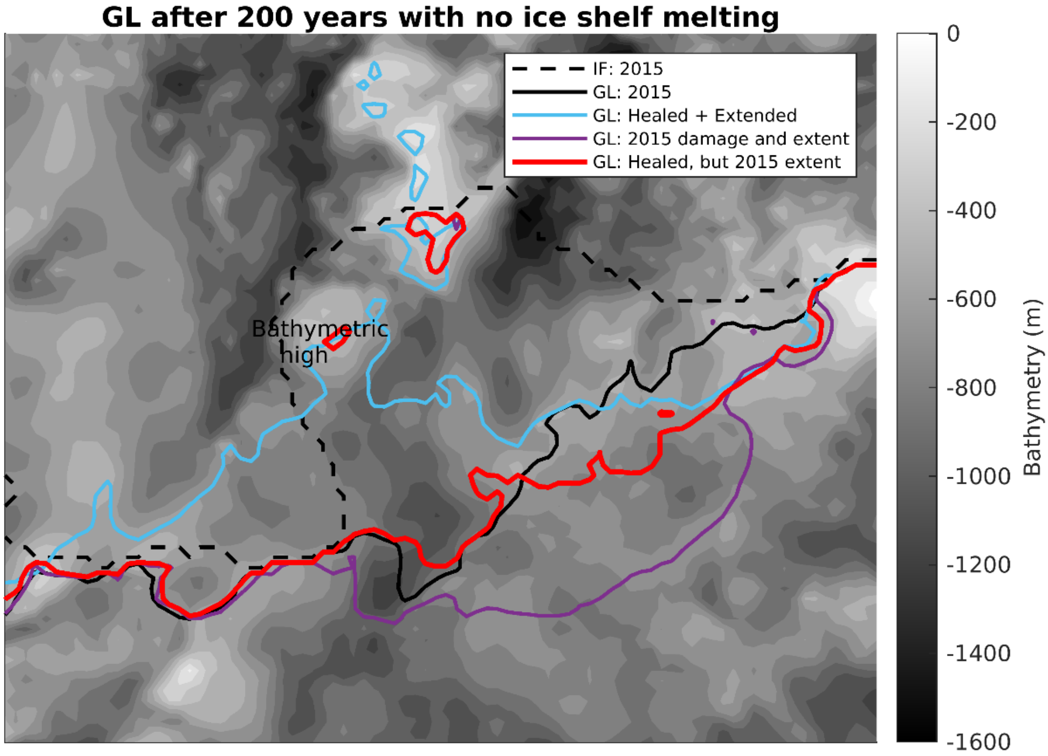
L298: Same as the above comment, does "edited setup" just mean the extended ice front and healing? Can you make this more explicit/obvious?

This will be changed.

*'In this ~~edited~~ **healed and extended** setup, the ice first regrounds on the western pinning…'*

L300-302: Although you do not show it, have you tested whether only healing or extending the ice front (both with no melting) causes advance?

Yes this is an interesting question and here is what we find, but we choose not to include this in the manuscript though because it adds too much complexity. For interest included below is the grounding line after 200 years of a no melt simulation with healed ice damage but 2015 ice extent, using the WAVI ice model only. In this case a much smaller pinning point forms than in the full healed and extended case, due to restrictions of imposed ice front meaning that flow west of the Thwaites inlet is unable to reach the pinning point. Additionally, this reduced ice front doesn't have the interaction from Crosson and Bear Island, nor has the area where additional smaller pinning points form in the advancing process (see comment further on). Therefore, it also doesn't have the feedbacks that occur between these features and the western pinning point. Alone this much smaller western pinning point is not enough to cause advance and instead a slow retreat is still occurring at the end of the 200 years in the east. This case doesn't retreat as far after 200 years, as than in the 2015 damage and extent case where no pinning point forms at all.



L309: Remove "as labelled in Figure 4c"

This will be removed.

L335: "levels of damage" - Do you consider damage fields between intensity factor of 0 and 1?

In this study we only consider two levels of damage and this sentence will be changed to "two levels of damage".

L339: The ramping up of the damage over 5 years is just for the second case? Does it ramp up from the 'healed' case to present-day damage?

This will be fixed:

'In both cases the ocean boundary forcing is instantaneously changed, and ***additionally*** *the ice damage ramps up over 5 years* ***in the second case from the healed ice shelf to 2015 damage*** *and we observe the subsequent evolution from the reference pre-1940s simulation.'*

L353: Remove extra bracket at the end of citation.

This will be fixed.

L353: Add 'a': "We also observe a separate slow ..."

This will be fixed.

L362: Can you rename this subtitle to be like 4.2.1, such as: "Retreating Thwaites Glacier with ocean melting and damage"

As suggested 4.2.1 will be renamed to be 'Retreating Thwaites Glacier with ocean melting and ice damage'. However, this was essentially the title for 4.2, so 4.2 will now be renamed to be 'Retreating Thwaites Glacier simulations'.

L365-366: Clear up the wording slightly, maybe: "During the damage plus ocean forced simulation, there is faster grounding-line retreat back to the observed 1996 position…"

The suggested change will be made.

L366: Why is there a smaller modelled grounding line on the east ridge in the 1940s state compared to observed 1996 and present day?

The reference 1940s state begins from the 2015 initialisation and then is generated after the subsequent steps of healing, extending and spin ups, so it has no knowledge of the 1996 grounding line. In a comparison the reference 1940s eastern grounding position is slightly more retreated that the 1996 eastern grounding line. Text will be added near L 390 where the eastern grounding line comparison to retreating simulations occurs in order to note this:

*'After this initial rapid retreat, both cases have grounding lines that pause around the observed 1996 grounding line position (Figures 6c and 6d), although there is a difference in the spatial pattern of the retreat, with the **Healed_600m** case retreating eastern Thwaites beyond the 1996 grounding line, by the time the western retreat has occurred. This is because the **Healed_600m** case takes a long time to unground the western pinning point and during this time a slow eastern retreat occurs**. However it should be noted that the eastern grounding position of the starting reference 1940s state is slightly more retreated than the eastern 1996 grounding line, which will affect this.** After the initial western retreat,…'*

L384: "initial pinning point" - which one?

This will be fixed: *'**western** pinning point'.*

L385: Refer to fig 6a here

This will be referenced.

L388: Use "observed" instead of "real"

This will be changed.

L391-393: Please improve the wording of this sentence, particularly: "… have a large retreat focussed on…"

This sentence will be changed to:

'After the initial western retreat, both simulations retreat east of the Thwaites inlet, while also further retreating in the west to the 2015 model grounding line…'

L400-401: Is the model initialisation method (surface elevation change) causing this retreat to happen?

This retreat referred to here occurs in the east, after the increase in ocean-forcing and in the second case damage-forcing as well from the reference pre-1940s case with 900m ocean-forcing applied and healed ice shelf. The direct effect of the surface elevation change used in the initialisation method only occurs if starting from the present-day initialised state and this thinning signal is removed after the model is spun up to get to the quasi-steady reference pre-1940s state. Therefore, the present-day thinning signal is not explicitly represented in the pre-1940s state. However, the present-day thinning signal may be indirectly affecting the reference pre-1940s state through fields like the basal sliding and ice shelf damage which are set during the present day initialisation.

L401: It is difficult to distinguish in Fig 6a,b where the 'east' and 'west' regions are that you are describing. Is it either side of the inlet?

East and West labels will be added to Figure 6a,b. Additionally, this is now mentioned on the first sentence of this paragraph (L396):

*'The large grounding line retreat in eastern Thwaites (**east of the Thwaites inlet**, Figure 6a,b), after passing through the present-day grounding line,…'*

and in the previous sections last paragraph (L 391):

'After the initial western retreat, both simulations retreat **east of the Thwaites inlet**,…'

Furthermore the paragraph referring to the east/west while describing the ice piracy (L 431) and referring to Figure 7, will be made more clear that in this paragraph it is referring to east/west of the shown boundary line.

L409: Move the reference to Fig 4a earlier in the sentence, into line 407 after "Thwaites Ice Shelf"

This will be moved.

L434: Is this the increase in flux around 85 years?

Yes that's right. This will be noted:

*'We see an overall increase in ice flux after the retreat **(at ~85 years)**, agreeing…'*

L438: Change "present day/future" to "present day and future"

This will be changed.

L441: Why is there a reference to Bett et al., (2024) here? If you are referring to the similar result in that paper, you should say that

This sentence will be updated:

*'…and all newly formed eastern pinning points have ungrounded**, as shown in** Bett et al. (2024).'*

L451-452: Is it true that you "vary ice damage and ocean forcing through time" or is it just separate instantaneous changes as shown in Figure 8?

In these simulations ice damage and ocean forcing varying in time during these simulations, but as you point out it is instantaneous changes to these forcings. Sentence will be edited to better reflect this:

*'To probe the existence of other steady states, we conduct a suite of reversibility experiments, in which we **instantaneously change** ice damage and ocean forcing **at set** times.'*

L459: Why do you start your reversibility simulations from the 700m simulation and not the 600m?

We chose the 700m simulation to aid in finding new quasi steady states quickly, as this was the highest ocean forcing that remains on the ridge in the initial reduced physics simulation; the 600m ocean forcing could equally have been used. Text will be edited to make this reason clear:

'The methodology is as follows: to search for new quasi-steady historical configurations, we start with the Damaged_700m simulation, which has damage intensity factor set to 1 and has a slightly cooler ocean forcing 700 m thermocline height. ***This was chosen as this is the warmest ocean forcing case that remains on the ridge by the end of the initial reduced physics spin ups (Figure 4d), to potentially aid the progression to a new quasi-steady state.****'*

L466-467: Remove the extra "initial"

This will be removed.

L477: This opening sentence was confusing to read at first "…with ice damage retreat…". Consider rewording this. Maybe: "All simulations starting…ice damage at time zero retreat past…"

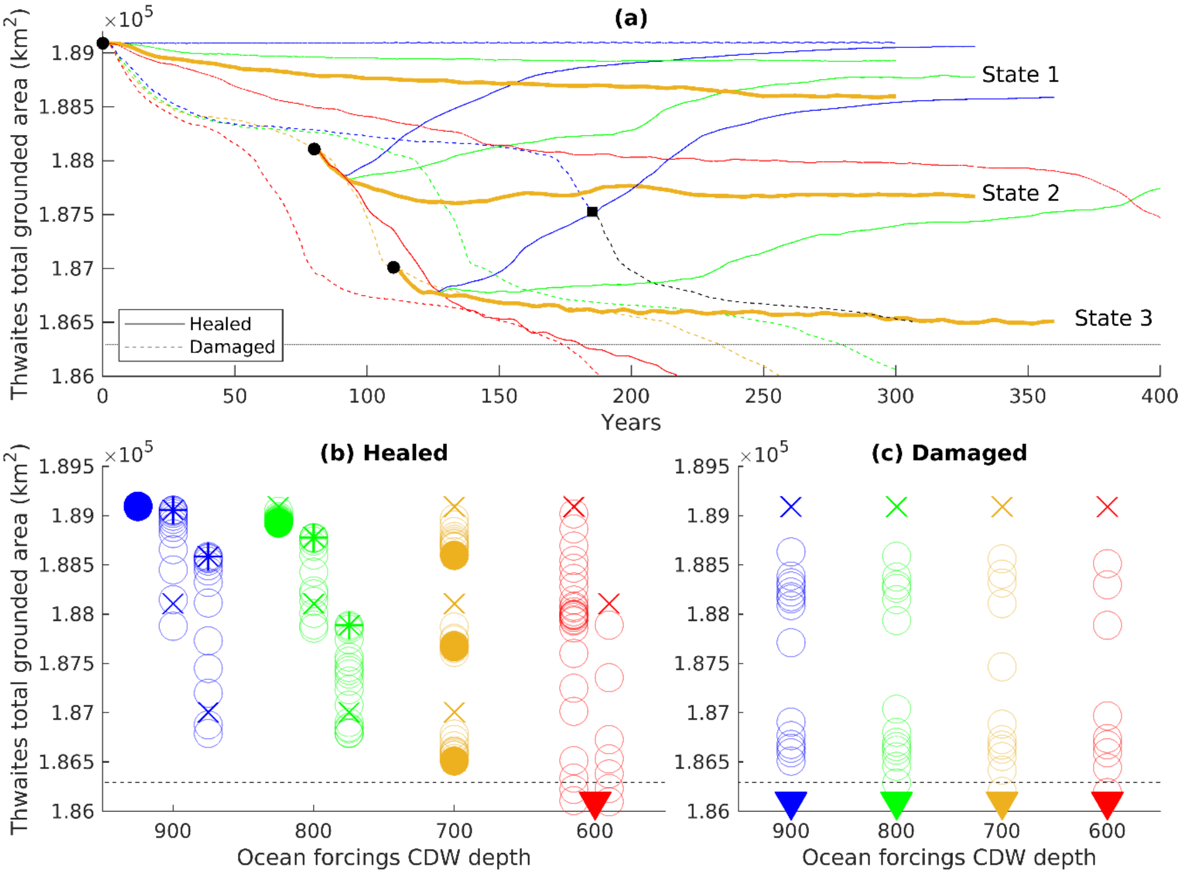
This sentence will be edited:

'All simulations starting from the reference pre-1940s state, ***and forced*** *with* ***2015*** *ice damage* ***from time zero****, retreat past the present-day grounding line extent (dashed lines in Figure 8a).'*

L477: All simulations with damage retreat past present-day except 900m?

The damaged 900 m case is only shown up to 185 years in Figure 8, as in this case the ocean model crashes during the modelled grounding line retreat that occurs during this time, for the default ocean model timestep in this extreme case of very low ice shelf melting and high damage forcing. To the show the full ocean forcings for the 2015 damage, a combination of two simulations will be used: The previously included simulation will be supplemented beyond 185 years by a new simulation with these forcings but with a smaller ocean timestep. This combined simulation will be included in Figure 8a and Figure 8c. This new simulation is still running (progress of new simulation shown below as a black dashed line with the transition marked with black square here but will be all blue dashed line in the revised manuscript), but we expect it to follow the same pattern of the other 2015 damage forced cases, where it will eventually retreat through the 2015 grounding line extent. The finished simulation will be added at the next revision/final paper. Text will be added to the figure caption to make clear that the results of the case in question are from a combination of two simulations with different ocean timesteps:

'The Damaged_900m case shown here in (a, c) consists of two simulations: 1) The standard case running up 185 years, 2) starting from the end of the first simulation, but now with a shorter ocean model timestep of 50 seconds.'



L480: Does “undamaged” also mean “healed” because there are two different words being used here

These will be changed to “healed”.

L480-481: Remove the extra “state”

This sentence will be edited and “state” changed to “grounding line location”:

*‘For future reference, we refer to the quasi-steady state, **which is** in the reference pre-1940s ~~state~~ **grounding line location** and maintained by the **healed** simulations, as ‘State 1’ (Figure 8a).’*

L488: CDW “depth” instead of “thickness”?

Thank you for spotting this and this will be fixed throughout the manuscript.

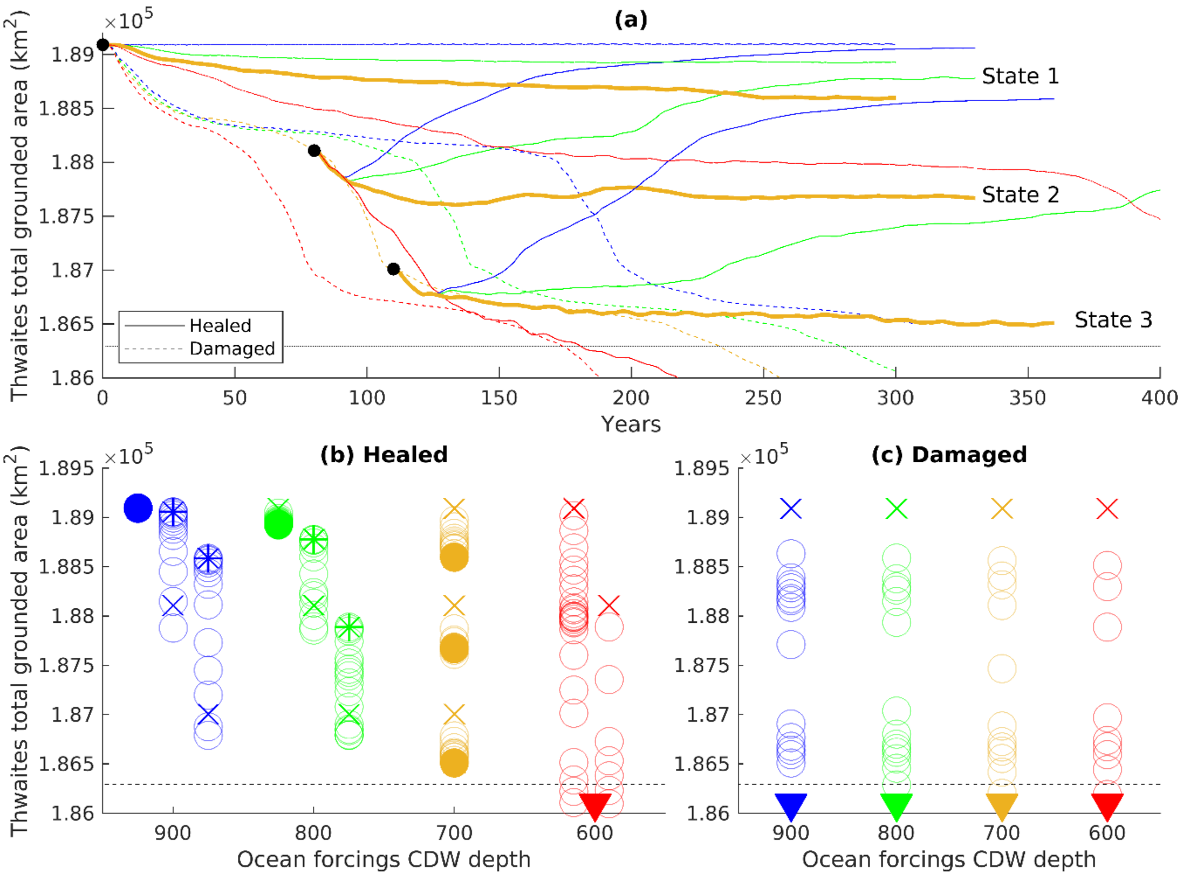
L495: You say that both coldest cases trend to state 1, but from Fig 8a, it looks like the 800m case readvances to state 2. I can see in panel 8b that you have solid circles (quasi-steady state) at state 1 but you haven’t referred to this in the text. Would it be helpful to refer to Fig 8 b,cearlier?

References to Figure 8b or 8c will be added earlier in the text to L 478, L489, L496.

This simulation advances to state 2 at the end of the run but is still continuing to advance. We see from the 80 years branched 800 m healed case, that at this grounded area value and ocean forcing it continues to advance to state 1 given time. The full advance from the year 110 branch for the 800 m isn't shown due to runtime it would take, as it would likely take a further ~200 years. Text will be added to this paragraph:

*'If we continue along the retreating **Damaged_700m simulation**, we get similar results for the set of simulations branched after 110 years **(Branch_110yr_OF)**, in a state close to the 1990s grounding line. Again, we see that the two coldest cases re-advance to produce earlier states and both appear to trend to State 1**. The Branch_110yr_800m simulation though only reaches State 2 by the end of the simulation but is still advancing and will reach State 1 eventually, as it has crossed into grounding line area covered by the Branch_80yr_800m simulation (which does advance to State 1 by the end of that simulation). In contrast** the **Branch_110yr_700m simulation** obtains a new quasi-steady state, State 3 **(Figure 8a, Figure 8b)**.'*

However, we ran this case for another ~50 years so that it reaches the edge of the plot in order to increase the overlap in the grounded areas from the 80 year branch and 110 year branch of the 800m ocean forcing case, which will be included in an updated figure:



L499: How do you know that the three states could have been "applicable for the pre-1940s period" if you haven't run the simulations from those states to present day?

Apologies for the unclear wording. This is meant to be pointing out that Thwaites had the possibility of being in any of these quasi-steady states pre-1940s. Wording will be changed to make this clearer:

*'States 1-3 all have the same ice damage state (healed) and ocean forcing (700 m thermocline), but are 3 independent quasi-steady states, any of which **<u>had the possibility of being the state</u>** ~~could have been applicable~~ for the pre-1940s period.'*

L502: This is the first time you mention the duration of these simulations, did all reversed simulations run for 250 years?

Yes all branched/reversed simulations run for 250 years, except for the Branch_110yr_800m simulation, which will now be extended to 300 years, due to the response above. This will be noted when these simulations are first introduced near L465:

*'The branching sets are simulated for **<u>250 years (except for Branch_110yr_800m which is simulated for 300 years)</u>** ~~several centuries~~ and are forced with a range of ocean forcings, with thermocline depths between 900m-600m, such that 4 coloured lines emerge from each branching point **<u>in Figure 8a</u>** (but all solid lines – healed ice).'*

L503: Are the "ocean only forced" simulations the same as those you've called "healed" in Fig 8? It's confusing having different phrases for all these model runs.

As suggested standardised simulation names will be made and referred to and also a schematic of the experiments setup will be added to appendix D.

L514: What do you mean by "within the area we are considering"?

This will be clarified that we are only considering the area close to the 2015 grounding line:

*'In summary, with a healed ice shelf these simulations suggest a quasi-steady stability landscape where cooler thermocline depths of 900 m and 800 m have one quasi-steady grounding line at the fully advanced State 1, then intermediate present-day 700 m forcing has three quasi-steady grounding lines (states 1-3), and finally the warmest 600 m thermocline height leads to no steady grounding lines **<u>close to or advanced from the 2015 position</u>** ~~within the area we are considering~~ (Figure 8b).'*

L514: Fig 8b: How long were the simulations in 8b run for? Because the solid circles for 900 and 800 do not match the final grounded area in 8a for simulations run from 110 years

In Figure 8b all simulations from 8a are shown, but stars (instead of solid circles) note the end of a simulations if the grounding line is still changing, which e.g. is the case for simulation branched from 110 years. This will be added to the caption of the figure:

*'b) Scatter of grounded area against ocean forcing applied, where the cross demotes the starting point for a simulation, open circles are plotted every 20 years, **<u>stars denote the end locations of simulation where the grounding line is still changing,</u>** and a solid circle indicates a quasi-steady state; a solid arrow indicates no steady state was found.'*

The solid circles for the 900 m and 800 m cases are taken from the simulation starting from 0 years, as these simulations have a steady grounding line at the end of the simulations and VAF that is more adjusted to the ocean forcing and grounding line. The other simulations for these forcings are trending towards these grounding lines, but require longer simulations. Figure 8b will be edited (as shown above in previous response), so for cases where simulations that overlap (900 m, 800 m and 600 m) the separate simulations will be staggered so the different simulations can be clearly seen.

L521: Add 'the': "with the grounding line"

This will be fixed.

L545: “westward shift” instead of “western shift”

This will be fixed.

L558: “varying degrees of damage” - unless I have misunderstood the simulations, you only considered two states of damage: present-day “damaged” and a “healed” state. “Varying degrees” sounds like you have modelled more than two.

This sentence will be edited for clarity:

*‘Once a **reference** historical state was found, simulations were set off from this state with **healed or 2015 floating ice** damage **intensities applied** and **multiple** ocean forcings.’*

L562: What “threshold”? Does this refer to the 600m thermocline depth?

Yes that is right. It will be changed to “ocean forcing threshold” to make this clearer.

L565-566: Does MITgcm produce reasonable melt rates at the grounding-line?

This sentence refers to how we apply melting close the grounding line of the WAVI ice sheet model, rather than the bulk melt rate over the whole shelf. In this study we follow the recommendation of Seroussi and Morlighem (2018), where no melting is allowed on partially grounded cells.

However, this comment prompted us to note that we did not include 2015 Thwaites Ice Shelf MITgcm total melt flux for comparison in the original manuscript and we will correct that in the updated manuscript in the text and in Figure 4. The pattern of melting in the 2015 geometry matches observations of low melt rates in eastern Thwaites (Davis et al., 2023) and modelled high melt rates in Thwaites inlet (e.g. Holland et al., 2023). Unfortunately, there are currently no ocean observations in the high melting region of Thwaites ice shelf and estimates of melting here are highly uncertain. The modelled melt rate in the 2015 geometry with 700 m ocean forcing is 12 Gt/yr (Figure 4b) which is lower than in other studies with a comparable CDW layer depth (e.g. Holland et al., 2023), though we use a cooler winter water layer here. This will all be noted where the 2015 geometry melt field is discussed (L 270): .

*‘The corresponding melt rates are shown in Figure 4b, with high melt rates in the western Thwaites inlet (Figure 1) and low melt rates in the eastern Thwaites**, which is consistent with** Holland et al. (2023) **and observations of suppressed melt rates in eastern Thwaites (Davis et al., 2023). The modelled total Thwaites Ice Shelf melt flux in the 2015 geometry with 700 m ocean forcing is 12 Gt/yr (Figure 4b), which is lower than in Holland et al. (2023) for comparative thermocline depth, though we use a cooler Winter Water layer here.**’*

L568: Is this needed: “with another study finding”?

This will be removed and replaced with “and”.

L570-571: Is it only the change in ocean currents driving these higher melt rates, or is there contribution from deeper grounding lines as they retreat?

Yes there are other factors contributing to the higher melt rates. This will be fixed to:

*‘During this ungrounding process we find a change in the ocean meltwater currents as the ocean passageway opens, with the current switching direction and **contributing to** driving high melt rates upstream from the western pinning point.’*

L578: Add ‘is’: “as is visible”

This will be fixed.

L579: Capitalise “figure”

This will be fixed.

L584: Were they “projections” in Bett et al. (2024) if they used idealised ocean forcing?

This will be changed to “simulations”.

L589: Remove the extra “:” after the citation.

This will be fixed.

L606: “evolution” instead of “shape”

This will be changed.

L612: Remove the out of place citation

This will be fixed.

L613: Remove the extra bracket in front of the citation

This will be fixed.

L610-615: Running simulations for only 250 years doesn’t give you enough information about tipping points or stability. I also don’t think this is “complex behaviour”: you applied warmer ocean temperatures to a weaker ice shelf which caused it to retreat, and when you reduced those temperatures and strengthened the ice it re-advanced.

You are right that we only run 250 years simulations instead of the thousands of years of simulation required to truly attempt to map out the stability landscape of Thwaites. This is why we only note that this “hints at the complex underlying stability landscape”. This will be made clear with text edits to this paragraph (see below).

We disagree, however, that the behaviour is not “complex” (though of course this is a subjective term). Our study shows that with a healed ice shelf, the extremes of ocean forcing can cause it to either to advance or retreat, with in-between ocean forcing having several of quasi-steady grounding locations. Our key point is that where Thwaites lands in this complex stability landscape depends on the history of the glacier rather than just the ocean forcing applied. The simplest conceptual model by Thom 1975, often used to illustrate tipping behaviour, only has two stable steady states. Beyond this complex stability landscape for a headed ice shelf, additional complexity comes from the extra dimension of ice shelf damage. The 2015 floating damage field removes all of these quasi-stable grounding lines. In fact, this axis is itself part of the evolving dynamical system rather than a forcing, as used in this study, complicating matters further. Text will be added to make clear the complex behaviour we are referring to:

‘It seems clear that the simplest conceptual models of tipping such as cusp catastrophes, and even butterfly catastrophes (Thom, 1975) may struggle to represent the complex behaviour

suggested *by our numerical simulations**. This is because while in this study we show that with a healed ice shelf the extremes of ocean forcing can cause it to advance or retreat, inter-between ocean forcings lead to multiple quasi-steady states. This means that where Thwaites Glacier lies within this shown quasi-steady landscape can depend on the history of the glacier and not just the ocean forcing. Furthermore the 2015 floating ice damage field removes all of these quasi-steady states, but this is complicated further as this damage axis is actually part of the evolving dynamical system rather than a forcing, as applied in this study.** ~~Indeed,~~ The search for quasi-steady states was not exhaustive, so it is possible there could be more. This* ***suggests*** *that the underlying stability landscape for Thwaites Glacier is not simple, and this glacier may exhibit a complex, non-linear response to climatic forcing.* ***However, we note that much longer simulations are required to truly map out the stability landscape of Thwaites Glacier****.'*

L626: Remove the dash after second citation

This will be removed.

L641: Change "damage/calving" to "damage and calving"

This will be changed.

L676: Should "Figure 11 c,d,g" be e,f,g?

Thank you for spotting this and this will be fixed.

L679: What do you mean by "shown here"? Figure 11h?

The reference to Figure 11h will be moved from the end of the sentence to right after "shown here".

L679: Do you mean an "eastward" movement?

This will be fixed.

L684: So, the damage visible in Fig 11b could be rifts caused at the grounding-line and not a shear margin?

As discussed above in a previous comment we believe the damage shown in Figure 11b is indicative of a shear margin, rather than a general fracturing simply due to a grounding line. However, comparative shear margin features in present day PIG do start at the grounding line (e.g. Lhermitte et al., 2020). Therefore, this shear margin feature can be used as an indication of the location of the grounding line. This will be clarified in the text:

'Additionally, the shear margin with a distinctive rifting pattern shown in the 1947 imagery appears to start at its intersection with the flight line (Figures 11b and 11c). ***This*** *could suggest that the grounding line is located here at the time of the imagery, as other such recurring rifting features start near the grounding line, for example* ***where the shear margins of PIG intercept the grounding line*** *(e.g. Lhermitte et al., 2020).'*

L690: This wording is confusing: "1940s to the present day and even before the 1973 satellite image"

For clarity the additional reference to the 1973 image will be removed.

'This all suggests a fundamental change in the configuration of Thwaites Ice Shelf has occurred from the 1940s to the present day ~~and even before the 1973 satellite image~~.'

L697: I don't think you can say that you've focussed on the "stability landscape" of Thwaites Glacier considering the short model simulations

Due to a comment from the other reviewer the paragraph that contains this sentence will be removed.

L715: "quasi-steady states" not "steady states"

This will be fixed.

L750: This is the first time you mention other sources of buttressing on Thwaites Glacier. Is there any buttressing being provided by Bear Island or Crosson ice shelf during your different simulations, and is this likely to have a bigger or smaller impact compared to the small pinning points?

Where the main source of buttressing is located can be shown using the retreating simulations. In the ocean forcing simulation it takes ~400 years of increased melt rates for the rapid retreat to be trigged, as it takes this long for the western pinning point to unground. If the key buttressing came from the Crosson and Bear Island interaction, this part of the ice shelf would have thinned in a much shorter time scale, reducing this buttressing and triggering retreat. However while not the primary source of buttressing there still will be buttressing being provided by the Crosson and Bear Island interaction. This will be made clear when taking about advancing Thwaites as described in later comment.

L755-756: You say "In this study we find..." that only healing the present-day ice shelf and no melt is enough to advance the grounding line, but in lines 300-301 (see above comment) you say both healing and extension are required.

This will be changed to "healing and extending".

L770-: The present-tense in this conclusion is a little confusing (e.g., "The next step is to run..." on line 782 sounds like future work)

Our actions described in the conclusions paragraph will be changed to past tense.

L779: How do you know that it is the western pinning point grounding that allows the grounding line to advance rather than buttressing from Crosson or Bear island?

We have shown that the western pinning point is the primary source of buttressing, as discussed in the previous comment. However other sources of buttressing are indeed still important and are interacting with the process of advancing Thwaites grounding line, especially as these other sources of buttressing cause feedbacks with the Western Pinning point. Where these other sources of buttressing enable a thicker ice shelf, leading to a larger pinning point area, which again provides more buttressing. Additionally in order for the grounding line to advance and not just be steady at the near present day location, smaller pinning points need to be able to form on the ridge west of the western pinning point as part of the advancement process. This step will also be impacted by the buttressing provided by the interaction with Bear Island and Crosson ice shelf. The processes that occur during advancement will be expanded in the manuscript (as previously mentioned above):

Extra details will be added when describing the advance in Section 4.1 L298:

*'In this edited setup, the ice first regrounds on the western pinning point**, then ice flows out into the extended area interacting with Crosson Ice Shelf and Bear Island providing secondary buttressing and further thickening the ice shelf, which feedbacks back onto the western pinning point. After this smaller pinning points form on the ridge south-west of the bathymetric high** and then the main grounding line advances from the 2015 position to encompass the western bathymetric high **and these smaller pinning points** (Figure 4c).'*

L755:

*'In this study we find that simply prescribing the healing and extending of the floating ice shelf in the 2015 state allows for a regrounding of the western pinning point in an extreme no-melt case to provide sufficient buttressing**, along with interacting secondary sources,** for the main grounding line to re-advance onto the bathymetric high.'*

And the sentence in the conclusion will be edited L779:

*'We found that healing the ice damage on the western Thwaites Ice Shelf and extending the static ice front were needed, both supported by observations, so that the buttressing provided by a regrounded western pinning point **and interacting secondary sources** was sufficient to create an initial advanced quasi-steady state.'*

L786: Where did you show that the "acceleration led to increasing damage"? I don't recall this.

This will be changed to

'While we haven't modelled the dynamics in this study, we hypothesise that this rapid acceleration…'

L798: Add '-day': "present-day grounding line"

This will be fixed.

Figures:

Fig 1: The yellow 2009 GL is not very visible and it probably isn't needed anyway. Can you add ice front locations to help show the outlines of floating shelves (e.g., MacGregor et al. 2012). In the caption add a note that the distance arrow shows the width of the iceberg/previous ice shelf and is used again in fig 2.

We will remove the yellow 2009 grounding line and a western ice front line will be added, as described above.

Fig 2: Make orange flight lines more visible. Does the dashed arrow (64 km) refer to the distance between 'a' and 'e', rather than anything on the background image? If it is not too messy, add outlines of shelves in the centre panel.

We will make the orange flight lines more visible and a western ice front line will be added, as described above. We will add a line to the caption to make it clear that the dashed arrow is referring to the distance between a and e.

Fig 3: The thick dashed lines showing zoom boxes dominate the subplots and get confused with other model outlines and features. Would the colormap in (d) and (e) be better as a red-white-blue to show the positive and negative values clearer? The caption says the ice damage is saturated to 1 and -1, does this mean there are values outside of this range?

The dashed zoom boxes lines will be made thinner, while the grounding and ice front lines will be made thicker, so that zoom boxes don't dominate the subplots. The colormap in (d and (e) will be swapped to a divergent green-white-orange colormap.

There can be negative values outside of this range, as damage (D) = 1-E. Where E (the viscosity enhancement factor) is E>0, so while D is limited to 1 (equivalent to zero viscosity) it can be smaller than -1 as there is no limit on increased viscosity. For example, there are a couple of cells within the range -10 to -1, but for plot viewability and with a focus on the positive damage values the plot is saturated to -1 to 1. This will be clarified in the caption:

*'(d-e) Thwaites ice damage field saturated to range of 1 to -1, **where larger negative values are possible** (as described in section 3.4),....'*

Fig 4: Include arrows in the legend in (a). For (c) and (d) it is not immediately clear what these lines are, can you add 'GL' to the legend labels or title.

GL will be added to legend labels and arrows will be added to an additional legend in a).

Fig 5: Mention in the caption that the melt rates are on a log scale. The cyan grounding line is quite hard to see.

This will be added to the caption. Cyan line will be thickened in order to make it easier to see.

Fig 6: In (c) and (d), put the coloured arrows and grounding lines in a legend. In the corners of c,e and d,f respectively add t=455 yrs, and t=85 years. For (c) and (d) consider using a different colormap or not having white for the thickest grounded ice and thickness below 250m. Why do you exclude thickness less than 250m? The lines in (a) and (b) might be more visible if thicker.

Grounding lines will be added to (d) and the colours arrows will be added to a legend in (c) in order to spread them out. The time labels will be added to Figures 6 c,e,d,f. All lines will be made thicker.

Thickness below 250 m was excluded in order to focus the range to highlight the main ice shelf outflow location in each case and highlight the good match of the damaged ice shelf with recent observations of the ice shelf in Figure 6d. This choice also highlights the effective ice front created by the high damage applied past the 2015 ice front in the Damaged_600m simulation shown, where essentially a 250 m thickness simple calving law is used to visualise this. We agree that is confusing that there is white for both thickness below 250m and above 600m in these plots and it would actually be better for the thickness below 250 m to be shown. Therefore, an additional colourmap of pale blues will be added for thicknesses below 250 m attached to the original black-white colourmap for 250 m -600 m. This will keep the effective visualisation, will add extra information for below 250 m thickness and avoids the confusion of two white area. For consistently this will also be used in similar plot in Figures 4,6,9,10 and 11.

Captions will be edited to reflect that these plots will be plotted for below 600 m and using pale blue colormap for below 250 m.

Fig 7: Do you need to say “Plotted over approximate area shown in Figure 3b by green dashed box” (also mentioned in other figures).

This sentence was added in order to help the reader locate the smaller plot area, but it is not the exact same area as shown in Figure 3b as the cut off of these plots (Figure 4, 5, 6, 7) changes in latitude. This sentence will be change on all the figures where it is mentioned to make this clearer and hopefully more helpful:

‘Plotted over **the longitudinal extent** shown in Figure 3b by **the** green dashed box’

There is similar sentence for Figure 9 and 10 relating to the red box in Figure 3a. These will be removed as these plots cover a larger and maybe this help isn’t needed.

Fig 8: Remove 950, 850 etc from the x-axis. Add a small legend in 8a for the solid and dashed lines with “Healed” and “Damaged”, or “Ocean only” and “Ocean and damage” (whichever is consistent)

The 950, 850 etc from the x axis will be removed. As suggested a legend to Fig 8a will be added, showing a solid grey line for “Healed” and a dashed grey line for “Damaged”.

Fig 9: Panel (f) needs the title fixing

This will be fixed.

Fig 11: Can you put consistent label formatting on these panels

This will be fixed.

Arthern, R. J., Hindmarsh, R. C. A., and Williams, C. R.: Flow speed within the Antarctic ice sheet and its controls inferred from satellite observations, Journal of Geophysical Research: Earth Surface, 120, 1171-1188, https://doi.org/10.1002/2014JF003239, 2015.
Bett, D. T., Bradley, A. T., Williams, C. R., Holland, P. R., Arthern, R. J., and Goldberg, D. N.: Coupled ice–ocean interactions during future retreat of West Antarctic ice streams in the Amundsen Sea sector, The Cryosphere, 18, 2653-2675, 10.5194/tc-18-2653-2024, 2024.
Clark, R. W., Wellner, J. S., Hillenbrand, C.-D., Totten, R. L., Smith, J. A., Miller, L. E., Larter, R. D., Hogan, K. A., Graham, A. G. C., Nitsche, F. O., Lehrmann, A. A., Lepp, A. P., Kirkham, J. D., Fitzgerald, V. T., Garcia-Barrera, G., Ehrmann, W., and Wacker, L.: Synchronous retreat of Thwaites and Pine Island glaciers in response to external forcings in the presatellite era, Proceedings of the National Academy of Sciences, 121, e2211711120, doi:10.1073/pnas.2211711120, 2024.
Davis, P. E. D., Nicholls, K. W., Holland, D. M., Schmidt, B. E., Washam, P., Riverman, K. L., Arthern, R. J., Vaňková, I., Eayrs, C., Smith, J. A., Anker, P. G. D., Mullen, A. D., Dichek, D., Lawrence, J. D., Meister, M. M., Clyne, E., Basinski-Ferris, A., Rignot, E., Queste, B. Y., Boehme, L., Heywood, K. J., Anandakrishnan, S., and Makinson, K.: Suppressed basal melting in the eastern Thwaites Glacier grounding zone, Nature, 614, 479-485, 10.1038/s41586-022-05586-0, 2023.
Dutrieux, P., De Rydt, J., Jenkins, A., Holland, P. R., Ha, H. K., Lee, S. H., Steig, E. J., Ding, Q., Abrahamsen, E. P., and Schröder, M.: Strong Sensitivity of Pine Island Ice-Shelf Melting to Climatic Variability, Science, 343, 174-178, 10.1126/science.1244341, 2014.

Ferrigno, J. G., Lucchitta, B. K., Mullins, K. F., Allison, A. L., Allen, R. J., and Gould, W. G.: Velocity measurements and changes in position of Thwaites Glacier/iceberg tongue from aerial photography, Landsat images and NOAA AVHRR data, Annals of Glaciology, 17, 239-244, 10.3189/S0260305500012908, 1993.
Holland, P. R., Bevan, S. L., and Luckman, A. J.: Strong Ocean Melting Feedback During the Recent Retreat of Thwaites Glacier, Geophysical Research Letters, 50, e2023GL103088, https://doi.org/10.1029/2023GL103088, 2023.
Morlighem, M.: MEaSUREs BedMachine Antarctica, Version 3 [dataset], https://doi.org/10.5067/FPSU0V1MWUB6, 2022.
Morlighem, M., Rignot, E., Binder, T., Blankenship, D., Drews, R., Eagles, G., Eisen, O., Ferraccioli, F., Forsberg, R., Fretwell, P., Goel, V., Greenbaum, J. S., Gudmundsson, H., Guo, J., Helm, V., Hofstede, C., Howat, I., Humbert, A., Jokat, W., Karlsson, N. B., Lee, W. S., Matsuoka, K., Millan, R., Mouginot, J., Paden, J., Pattyn, F., Roberts, J., Rosier, S., Ruppel, A., Seroussi, H., Smith, E. C., Steinhage, D., Sun, B., Broeke, M. R. v. d., Ommen, T. D. v., Wessem, M. v., and Young, D. A.: Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet, Nature Geoscience, 13, 132-137, 10.1038/s41561-019-0510-8, 2020.
Mouginot, J., Rignot, E., and Scheuchl, B.: Sustained increase in ice discharge from the Amundsen Sea Embayment, West Antarctica, from 1973 to 2013, Geophysical Research Letters, 41, 1576-1584, https://doi.org/10.1002/2013GL059069, 2014.
Mouginot, J., Scheuchl, B., and Rignot, E.: MEaSUREs Annual Antarctic Ice Velocity Maps, Version 1 [dataset], https://doi.org/10.5067/9T4EPQXTJYW9, 2017a.
Mouginot, J., Rignot, E., Scheuchl, B., and Millan, R.: Comprehensive Annual Ice Sheet Velocity Mapping Using Landsat-8, Sentinel-1, and RADARSAT-2 Data, 10.3390/rs9040364, 2017b.
Reed, B., De Rydt, J., Naughten, K. A., and Goldberg, D. N.: Calibration of a coupled ice sheet-ocean model using observations of ice dynamics and basal melt in West Antarctica, EGUsphere, 2026, 1-39, 10.5194/egusphere-2026-931, 2026.
Rignot, E., Mouginot, J., and Scheuchl, B.: MEaSUREs Antarctic Grounding Line from Differential Satellite Radar Interferometry, Version 2, NASA National Snow and Ice Data Center Distributed Active Archive Center [dataset], 10.5067/IKBWW4RYHF1Q, 2016.
Seroussi, H. and Morlighem, M.: Representation of basal melting at the grounding line in ice flow models, The Cryosphere, 12, 3085-3096, 10.5194/tc-12-3085-2018, 2018.
Shepherd, A., Wingham, D., and Rignot, E.: Warm ocean is eroding West Antarctic Ice Sheet, Geophysical Research Letters, 31, https://doi.org/10.1029/2004GL021106, 2004.
Smith, B., Fricker, H. A., Gardner, A. S., Medley, B., Nilsson, J., Paolo, F. S., Holschuh, N., Adusumilli, S., Brunt, K., Csatho, B., Harbeck, K., Markus, T., Neumann, T., Siegfried, M. R., and Zwally, H. J.: Pervasive ice sheet mass loss reflects competing ocean and atmosphere processes, Science, 368, 1239-1242, 10.1126/science.aaz5845, 2020.
Smith, J. A., Andersen, T. J., Shortt, M., Gaffney, A. M., Truffer, M., Stanton, T. P., Bindschadler, R., Dutrieux, P., Jenkins, A., Hillenbrand, C. D., Ehrmann, W., Corr, H. F. J., Farley, N., Crowhurst, S., and Vaughan, D. G.: Sub-ice-shelf sediments record history of twentieth-century retreat of Pine Island Glacier, Nature, 541, 77-80, 10.1038/nature20136, 2017.
Thom, R.: Structural stability and morphogenesis; an outline of a general theory of models, 1975.
Trevers, M., Cornford, S. L., Payne, A. J., Gasson, E., and Bevan, S. L.: Retreat of Thwaites Glacier Triggered by its Neighbours, 10.22541/essoar.170957499.97583808/v1, 2024.
Williams, C., Trevers, M., Sun, S., Holland, P., Bett, D., Arthern, R., and Bradley, A.: Mass loss from Thwaites Glacier continues even without ocean melting, PREPRINT (Version 1) available at Research Square 10.21203/rs.3.rs-8660051/v1, 2026.
Williams, R. S. and Carter, W. D.: ERTS-1: a new window on our planet, 929, US Government Printing Office1976.