Response to Reviewers

Modelling the evolution of Thwaites Glacier over the 20th century

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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 2

Summary:

Bett et al., 2026 use a combination of aerial imagery analysis and coupled ice sheet-ocean modeling to generate a representation of Thwaites Glacier pre-1940s, when it is assumed to be in a stable state. Potential 1940s states are evaluated based on their ability to evolve into the present-day glacier under idealized forcings. This work makes use of observations to validate models of the historical and present day glacier. Ice damage and increased ocean forcing are analyzed as potential triggers for destabilization resulting in a glacier retreat pattern similar to observations of Thwaites Glacier in the present day. The authors find that healing the damage to the present day ice sheet is necessary to well represent the historical state.

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

General Comments:

This paper is interesting and overall quite well written. The main results seem sound and well reasoned, and the combination of coupled modeling with historical observations is nice to see. My main critique of the paper is that the methodology section remains convoluted, which makes it rather difficult to initially assess the experimental design and results. It would be very helpful to have a figure of some type to supplement the description of the initialization procedure and to distinguish the various experimental simulations. Perhaps a schematic or flow chart could be produced, but at the minimum it would be good to see a table identifying the various simulations. A naming convention for experiments would also help the audience to follow along when different simulations are discussed.

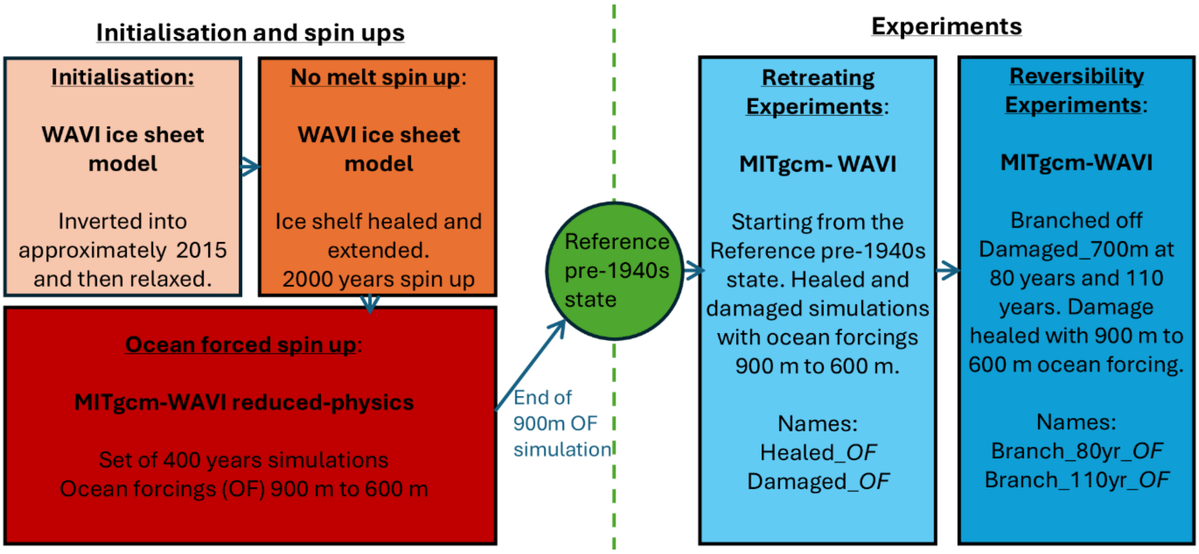
The schematic below will be added as an appendix in order to make the steps in the initialisation, spins up and experiment clearer (shown here below). As suggested a naming convention will be used for the simulations in the two different experiment sets in order aid clarity and the manuscript will be 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 shown below at L325 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 at L463 (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 the names of the 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.'*

Improvements to the explanation of the damage factor, specifically, and how it is applied is needed in the methods section. It is completely understandable to not implement a physics based damage model given the complexity of that challenge, as is true for many other studies. This approach to represent damage is interesting, but I think more detail is necessary, especially given that damage is an often ignored component of ice sheet physics in modeling studies and that the key results follow from its inclusion here. The assumption of damage being the primary source of viscosity enhancement is fair, but can you explain more regarding where the viscosity enhancement factor field comes from? Is there an inversion step to calculate viscosity as part of the initialization procedure? How are variations in viscosity due to temperature being calculated so as to be able to identify the component due to damage?

The viscosity enhancement factor field, which forms the basis for the damage field, does indeed come from an inversion step within the initialisation procedure. The description of this step will be expanded in the manuscript (L 168):

*'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...'*

The influence of temperature on strain-rate is calculated as provided by ***Cuffey and Paterson (2010).*** This will be noted in the manuscript (L 214):

*'During the ice model's initialisation into the 2015 state, a 'viscosity enhancement' factor field (E) is recovered, which represents all spatial variations in viscosity that cannot be explained by the influence of temperature on strain-rate **(as provided by Cuffey and Paterson (2010)).**'*

The figures in this paper are an integral component of the analysis as comparison to historical observations is done via visual inspection of photos. While I find the analysis to be successful, some of the figures would benefit from additional information provided, and generally all figures would benefit from some refinement. Specific suggestions are listed below.

Specific Comments:

Abstract

L10: Repetitive use of make/making, suggest changing

Thanks for the suggestion this will be changed:

*'Thwaites Glacier is rapidly evolving and could **produce** large sea-level contributions in the coming centuries, making it essential to understand the drivers of the ongoing ice loss.'*

L15-17: This sentence took me a few reads through to understand. It is quite dense and a bit confusing. I suggest breaking up the ideas here so that the model ensemble as methodology is addressed first. Then state the result afterwards that it was necessary to use an intact ice shelf to achieve the best fit to observations

We agree this sentence is confusing, this will be separated out into multiple sentences:

*'We use the MITgcm-WAVI coupled ocean-ice sheet model to create example quasi-steady pre-1940s configurations for Thwaites Glacier, including a most plausible pre-1940s state**. We find** that healing and extending the damaged ice shelf is necessary to achieve this.'*

L21: "eliminate these quasi-steady states" is an odd way to phrase this. Maybe "destabilize" is more clear?

This will be changed.

Introduction

L65: The large intact iceberg is not initially obvious. I think the discussion of the 1973 image could use a bit more detail. From what is written, it isn't obvious to me that we can assume the Thwaites Ice Shelf was undamaged for centuries.

A label will be added to the iceberg in Figure 1a in order to increase clarity. Extra detail will be added to the discussion of the 1973 image including to explain where the assumption of Thwaites Ice Shelf being undamaged for centuries comes from:

*'Crucially, a key feature of this image is a large intact iceberg near Thwaites's western ice shelf**, as labelled in Figure 1a. 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).'*

L66: Missing possessive apostrophe when describing western ice shelf

This will be fixed.

L102: It is unclear which paper, this manuscript or the 2024 paper, is being referenced for "These simulations retreat ..."

We agree this is confusing. This will be changed to:

*'**In this study,** simulations retreat...'*

Analysis of 1947 aerial imagery:

Generally super interesting.

Thank you!

Methods

L170: "outside of this area we apply a constant value C = 104 Pa m-⅓ a⅓"

Does this mean that constant friction is applied to grounded regions in the model that are floating in the present day?

Yes that is right. Text will edited to make this clearer:

'A 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****.'*

L175: Why is the Pine Island Glacier cavity modified?

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).****'*

L195: 20 days strikes me as a large timestep for the ice sheet model. What is your grid resolution? Is 20 days small enough to ensure solution convergence?

There is some nuance here which we did not explain clearly enough in the original manuscript: the ice thickness is timestepped (we will call this sub-timestepping here) on the ocean model timestep (i.e. 100s, alongside the ocean model), while the velocity is timestepped on the much longer 20 day timestep of the ice sheet model. By sub-timestepping the ice thickness, we can run a longer velocity timestep than would be otherwise expected without sacrificing convergence. Text will be added to make this point in the first paragraph in the model structure section (L 159):

'However, the ice thickness updates and melt rates are applied continuously (i.e. during these periods), on the shorter ocean model timestep, ***with this short ice thickness stepping aiding ice sheet model convergence (the ice velocity is timestepped on the much longer ice sheet timestep)****.'*

This sentence will be added to the first paragraph in the model structure section (L 160):

'No ice shelf melting is permitted on partially grounded ice sheet model cells, as in Bett et al. (2024) and as recommended by Seroussi and Morlighem (2018). ***A horizontal resolution of 2 km is used within both models in WAVI-MITgcm and a vertical resolution of 20 m in MITgcm.'***

L205: Why don't you initialize the model with the extended ice front? I would think that changing the geometry after initializing would introduce inconsistencies in the stress balance that can be avoided.

Ideally, we would want to initialise with the extended ice front into the pre-1940s state, but we lack the satellite observations from this period to do so. Instead, we initialise into the present day using the observations of surface thinning and velocity to create a present-day field of viscosity enhancements (damage) and basal sliding. Therefore, for this we also want to initialise using the present-day ice front. Initialising into the present-day state with the extended ice front, even if the ice in this area was thin, would affect these desired fields as there is not an extended ice front in the present day.

L207: extensive → extended

This will be fixed.

L213: More information regarding the calculation of damage is needed here.

Extra information will be added to describe the inversion procedure which calculates the viscosity enhancement factors which forms the basis for the damage field (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); Bett et al. (2024). **The inversion process generates fields of basal drag coefficients and viscosity enhancement factors. 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...'*

L225: Does damage evolve in time during simulations?

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 1. This is because the applied damage is linked to whether a grid cell is grounded or fully floating which does change during the simulation at each coupling period (which is also the ice sheet model time step). A sentence will be added to the near the end of the last paragraph in the section in order to help make this clearer (L 241):

*'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...'*

L243: What is the damage feedback? It seems to me that this is more of an applied forcing than a feedback.

This just notes that the applied damage forcing can be interpreted as a damage feedback occurring on a grid cell after it fully ungrounds, as this is when the damage forcing changes on the gridcell. This will be added:

‘Essentially for a damage intensity factor value ***of 1,*** *when a cell becomes fully ungrounded during the evolving simulations,* ***the increased applied damage forcing can be interpreted*** *as* ***assuming*** *an idealised instant* ***increasing*** *damage feedback occurs at that location* ***to the 2015 damage field value****.’*

Results

L276: The healed damage field is applied to grounded ice as well? I thought changes to ice damage were only applied to floating ice? Please make this more clear in the methods

Yes the healed damage field is always applied to grounded ice, but this field consists of the initialised damage field on the present day grounded ice area and then the averaged damage value past the present day grounding line. Text will be edited to make this clearer combined with other comment edits.

This sentence in the last paragraph of the damage methods section will be edited to help make this clear (L 238):

‘If the cell is grounded or partially grounded, then the value from the healed damaged field is used ***in all cases****.’*

The referenced sentence will also be edited to make this clear:

‘Therefore, **in addition to** the healed damage field **always being used for grounded ice**, **it is also used for** fully floating ice.’

L345: I would remove this statement regarding the passage taking longer to open up due to no melt on partially grounded cells. Applying melt to partially grounded cells has been shown to over-represent ice sheet response and perform less accurately on idealized model domains unless a sufficiently small spatial resolution is used (e.g. Seroussi & Morlighem, 2018). I would not use the choice of melt representation at the GL here to explain the retreat pattern you see in the model output. If your model is converging properly, this choice should not determine the GL behavior, but rather the applied melt rates and internal ice sheet dynamics will dictate how the GL evolves.

Seroussi, H. and Morlighem, M., 2018. Representation of basal melting at the grounding line in ice flow models. The Cryosphere, 12(10), pp.3085-3096.

This statement will be removed from this sentence as suggested.

L346: open up upstream →open upstream

This will be fixed.

4.3 Multiple quasi-steady states:

- The experimental design of these experiments isn’t clear to me

The experimental design for this section will be made clearer, by referring to the schematic in Appendix D and the new standardised simulations names will be introduced and used in describing the experimental design and results in the text.

Discussion

L580: Thwaites → Thwaites’s, possessive nouns in APA style

This will be fixed.

L602: ungrounding of eastern Thwaites pinning point → ungrounding of the eastern Thwaites pinning point

This will be fixed.

L603: Notably → Notably,

This will be fixed.

L612: Maybe use "tipping in the parameter space defined by thermocline height and damage" for added clarity

This will be changed.

L612-613: Some typos here with the citation Thom, 1975

The typos of the extra citation of (Thom,1975) (Line 612) and extra bracket on the remaining citation (Line 613) will be fixed.

L626: I would rephrase this sentence to avoid saying "state 2 is potentially the best". In your analysis of the options presented here, it is the best. The rest of this paragraph could also use a bit of editing. The argument is a bit hard to follow with the long sentence structure and additional context in parenthesis.

This sentence will be changed and the paragraph will be reworded in order to aid clarity:

'Having found these multiple quasi-steady states, we can now re-examine which of these three states is the most plausible ***candidate for the true*** *pre-1940s state. Using the available evidence of sediment cores from Thwaites Glacier (Clark et al., 2024) and the 1947 aerial imagery (USGS, 2018) - we find that* ***out of the three options S****tate 2 is ~~potentially~~ the best candidate for a pre-1940s Thwaites Glacier. The sediment core analysis suggests that there was an ocean passage upstream of the western pinning point prior to the 1940s****. This is not the case*** *in State 1, which was our original reference pre-1940s state,* ***but is the case in State 2 and State 3****.* ***Additionally, the sediment core analysis suggests*** *that western grounding line retreat may have occurred in the 1950s (Clark et al., 2024), so suggesting an advanced* ***1940s*** *grounding line position compared to the 1990s satellite observed grounding line position.* ***This is not the case*** *in State 3,* ***but is the case in State 1 and State 2****.* ***Therefore these two conditions together*** *leaves State 2 as the most plausible pre-1940s Thwaites Glacier state that we have found.'*

L682-685: The structure of this sentence is somewhat confusing with many different clauses. I suggest breaking it up or rephrasing.

This sentence will be broken up and editted:

*'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)).'*

L691-693: Summarizing what you did in this way undercuts the experimental design and your results. It begs the question of why you did not produce further simulations using state 2. I do not think that additional modeling work needs to be done for this work to be published, but I would reframe this summary of your results.

We agree that this paragraph (L 692-698) is not beneficial to the manuscript and will be removed.

L696: Remove "additionally"

This paragraph will be removed (see above).

L729-734: There are some grammar issues with this first sentence, revisit. It is unclear what "this model" refers to- the published studies cited here or the work described in this paper.

These will be fixed:

*'This suggestion of the importance of damage links with previous stud**ies** where Thwaites Glacier retreats for the extreme case of no ice shelf melting, ~~using this model~~ with **a** present-day geometrical configuration and highly damaged western ice shelf (Williams et al., 2026; Bett et al., 2024).'*

L745: Does this process refer to ice thickening or to damage healing?

The process referred to is damage healing, but this includes the process of less damaged ice moving into a location and not necessarily already damaged ice being healed. This will be clarified:

*'Crucially, our results suggest that any stabilisation of Thwaites Glacier near its current grounding line would require intact, undamaged ice to reground on the western pinning point, rather than just the simple direct thickening of existing damaged ice by reduced melt rates due to a cooling of the ocean. This process **of damage healing, either through the advection of less damaged ice into the ice shelf or by other means**, could have potentially occurred before...'*

Conclusions

L786: Maybe I'm missing something, but aren't changes in ice damage always applied to the model in these simulations as opposed to something that can come out of the simulation results? I don't understand how rapid acceleration can lead to increasing damage given the methodology.

The wording on this statement will be corrected:

*'**While we haven't modelled the dynamics in this study, we hypothesise that** this rapid acceleration led to increasing damage, thinning and weakening the ice shelf and so preventing any regrounding of the western pinning point.'*

L796: Remove "to advance", typo

This will be removed.

Throughout: Capitalize state when referencing the name of a specific model simulation- e.g. State 1

This will be fixed throughout the manuscript.

Figures

General: It would be helpful to increase the linewidth across all the figures for things like flow lines and grounding line locations.

This will be done.

Figure 1: Pinning points are labeled Eastern PP and Western PP in panel a. It would increase clarity to point these out in the caption with the abbreviation written in full.

This will be done. The following text will be added to the caption:

'The labels Western PP and Eastern PP refer to the Western/Eastern pinning point locations respectively.'

Is this figure supposed to have outlines of the attached iceberg from 1947 and 1966 included? The text makes it seem like there might be some information missing here.

Apologies for the confusion, this figure isn't meant to show these sketches. This sentence will be edited for clarity:

*'Crucially, a key feature of this image is a large intact iceberg near Thwaites' western ice shelf~~,~~ ~~with~~**. 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.'*

Figure 2: Super cool!

Thank you!

Figure 3: In the caption: model ice speed → modeled ice speed.

This will be changed to modelled.

Panels b, d, e: Suggest increasing linewidth showing ice fronts and GL location

This will be changed.

This is nitpicking, but subpanel labels in this figure do not match labels in previous figures, i.e. a vs a). It would be nice if figure style choices were consistent throughout the paper- notation choices, font sizes, etc.

Figures 1 and 2 will be updated to be consisted in labelling, with the other figures along with Figures 10 and 11.

Figure 4: I would increase the linewidth in all panels to make the solid lines easier to see.

This will be changed.

Are the present-day modeled values shown in this figure from the initialization in present-day step? Or a simulation modeled from pre-1940s to present-day?

The present-day grounding line in all panels and the present day modelled velocities in panel a) are form the initialization into the present-day. The caption will be edited to make this clear:

*'2015 **initialised** modelled ice flow (red arrows) and grounding line (black) are also shown.'*

Is the simulation shown in panel (d) using a healed ice shelf?

Yes that's is right. Text will be edited to make this clear:

*'d) Grounding line after 2000 years of ice-only spin up **with healed ice shelf** (purple), and the subsequent reduced-physics-model grounding lines after 400 years **for healed ice shelf and** ocean forcings of 900 m (blue), 800 m (green), 700 m (orange) and 600 m (red).'*

Figure 7: Grey grounding line is especially difficult to see across all panels

This will be thicken along with the other lines and changed to orange.

Figure 8: Maybe make the cross more prominent in panels b and c so that the starting point can be easily identified for each simulation.

The starting crosses and the stars for end locations of simulation where the grounding line is still changing will be made bold in order to make them more prominent. Where these simulations cross in b) they will staggered to make it clearer.

Figure 11: Caption is confusing, especially in the description of panel b.

We agree the sentence referring to b) about image mirroring is confusing and unhelpful. It will be removed from this figure caption and also figures 2 and 10 where similar sentences are used. Figure 11 caption will be reworked to refer to the newly defined Healed_600m simulation, which will aid clarity.

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