Melt sensitivity of irreversible retreat of Pine Island Glacier

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Reply to referee #2 comments

We thank the referee for their helpful and thorough feedback on our manuscript. We have responded to their comments below. The referee comment is shown in black; our replies are shown in ***bold italic blue*** and the original and new content in the manuscript is given in quoted *italic blue* *with added/changed words underlined*.

Main points:

Would results have been different if you had readvanced the grounding line under cold conditions, as used for the relaxation 100 years, rather than the no melt? (described in methods L95-100, and L130-145). Would the grounding line still have advanced, and would the steady state have been the same? Do you think the position of the steady state has any impact on the retreat i.e. would results have been any different if you'd initially advanced using cold forcing only?

- **In our previous paper (Reed et al. 2023) we found steady-state grounding lines for a range of thermocline depths when starting from a present-day position, and showed that a steady-state at the ridge could only be achieved with a thermocline depth of at least 1100m (when using this melt parameterization), which is effectively zero melt (see Fig.4 for COLD1000 and COLD1200). As we wanted to start the simulation from an advanced position on the ridge, to agree with sediment core analysis (Smith et al., 2017), we decided to start with zero melt and then follow with a cold perturbation to ensure the ice shelf wasn't unreasonably thick. If we would have started with the cold conditions (e.g., thermocline 800m) this would have resulted in an advance only to the small bed rise ~18km downstream of the present-day position, rather than the larger ridge ~40km downstream.**

- **We will include more detail in the methods section.**

I think the paper would benefit from more details/discussion of the modelling choices made in the initial state. In particular:

- There are downstream basal drag values that cannot be obtained from the initialisation because they are under ice that is floating in the present day. The authors state that these are set to a constant value (L392 and Figure C1) but this value doesn't seem to be stated. What is the value and why/how was it chosen? And how does, or might, it affect the future simulations? How can you be confident the results aren't highly dependent on this choice?

- **We have added further details to Appendix C regarding this. However, our previous study showed limited impact when changing the basal slipperiness or friction law.**

- **Original** [389-392]: *"The spatially varying basal slipperiness (C) was derived for present-day grounded areas only and without data for the 1940s period we chose to set the downstream region to a constant value. Whilst a more realistic field may alter the timescales of retreat, we do not expect this to change the overall outcome of this study, as has been previously shown by Reed et al. (2023)."*

- **New**: *"The spatially varying basal slipperiness (C) was derived through the inversion process for present-day grounded areas only. Lacking data for the 1940s period, we chose to set the downstream region to a constant value of 0.05m yr^{-1} kPa^{-3}, which is an average value from the upstream fast flowing tributaries. Whilst a more realistic field may alter the timescales of retreat, we do not expect this to have a substantial impact on our results or change the overall outcome of this study, as has been previously shown in Reed et al. (2023)."*

- On L138 the authors state that the lack of advancement beyond the subglacial ridge is "aided by the fixed calving front" – can you speculate on what you'd expect if the calving front advanced? Would you expect a different steady state/more advance of the grounding line? How much of limitation is this fixed calving front for the study?

- **Previous studies suggest that the calving front position did not vary much between 5k years ago and 2013 (Larter et al. 2014, Arndt et al. 2018). Also, a slightly more advanced calving front compared to what we use in our study is not likely to provide much additional buttressing (Fig S4 in Fürst et al. 2016).**

- **We have added an additional statement to clarify this.**

- **Original** [138]: *"Hence, the subglacial ridge provides a steady-state position for PIG, which does not advance beyond it despite the absence of basal melting. This is also aided by the fixed calving front, which is not far from its 1940s position (Rignot, 2002; Arndt et al., 2018)."*

- **New**: "*Hence, the subglacial ridge provides a steady-state position for PIG, which does not advance beyond it despite the absence of basal melting. This is also aided by the fixed calving front, which is not far from its 1940s position (Rignot, 2002; Arndt et al., 2018). It is unlikely that a slightly more advanced calving front would provide much additional buttressing, (Fürst et al. 2016), so would have a limited impact on subsequent ice dynamics.*"

How realistic are the thermocline heights and prescribed melt rates?

- Can you give more context, either in "2.6 Perturbation experiments" or in the Discussion, for the thermocline profiles chosen? Can you comment on how extreme are some of these e.g. the standard warm profile using in WARM25 etc, and the really high melt profiles that allows unstable retreat after just 5 or so years of forcing? (introduced in 3.4 Mapping the stability regime). It is stated that thermocline depths of 1100-1200m are unrealistic, so discussing the realistic range of warm forcings would also help, maybe around L315-320.

- **The thermocline depths that we chose for our warm (600m) and cold (800m) forcing are based on the shallowest and deepest observations from Pine Island Bay in 2009 and 2012/3 respectively (Dutrieux et al., 2014; Webber et al., 2017). However, as these are summer observations, we cannot rule out colder conditions (deeper thermocline) during the winter months. Furthermore, future projections for a number of possible scenarios suggest a shoaling of the thermocline with a larger volume of CDW on the continental shelf, leading to increased basal melting beneath ice shelves (Naughten et al., 2023).**

- **We will add more detail regarding the thermocline profiles to the "Perturbation experiments" section and in the discussion.**

- In addition, on L38-40, you mention "shallow" and "deep" thermoclines– how shallow/deep? What was the depth here compared to those explored in this study?

- **Original** [37-41]: "*A shallow thermocline in the mid to late 2000s coincided with widespread acceleration (Mouginot et al., 2014), enhanced thinning (Konrad et al., 2017) and grounding-line retreat (Rignot et al., 2014). Conversely, a deep thermocline in 2012, following a strong La 40 Niña event in 2011, led to the lowest basal melt rates recorded in the ASE and likely caused a sector wide slow down (Mouginot et al., 2014; Dutrieux et al., 2014)*."

- **New**: "*A shallow thermocline (600m) in the mid to late 2000s coincided with widespread acceleration (Mouginot et al., 2014), enhanced thinning (Konrad et al., 2017) and grounding-line retreat (Rignot et al., 2014). Conversely, a deep thermocline (800m) in 2012, following a strong La 40 Niña event in 2011, caused the lowest basal melt rates recorded in the ASE and possibly led to reduced glacier acceleration across the sector (Mouginot et al., 2014; Dutrieux et al., 2014).*"

- L117-118: thermocline depth varies, but not this melt rate, correct? Can you put this choice of 100 m/a into context here? What do you think would happen if you explored changes to this melt rate as well as thermocline depth?

- **We chose to only vary the depth of the thermocline to be able to make direct comparisons with ocean observations/estimates (Dutrieux et al., 2014; Jenkins et al., 2018) and to be consistent with previous studies (e.g., De Rydt et al., 2014, 2016; Bradley et al. 2022).**

- **A melt rate of 100m/yr below the thermocline was based on previous estimates for this ice shelf (Bindschadler et al., 2011; Dutrieux et al., 2013; Shean et al., 2019).**

- **Another study which used a similar melt parameterization but also doubled the deep melt rate showed that this had a smaller impact compared to when the thermocline was raised (Favier et al., 2014). A modelling study of a glacier with a similar geometry has also shown that a tapering down of the melt rate close to the deep grounding lines could still lead to rapid grounding line retreat and mass loss (De Rydt et al., 2016).**

- **We will add this detail to the methods section.**

Minor points:

L60-61: "finished when the glacier stabilized at an ice plain in the early 1990s". How do the suggest timings fit together here, when put together with L45-50: "The glacier has been retreating across an ice plain since the early 1990s" and "the subsequent ice loss was unaffected by the reduced basal melt rate in the early 2000s"? It seems from this text that the glacier stabilized in the early 1990s but was also trigged to unstably retreat at that time too?

- **We have adjusted the wording in both places:**

- **Original** [44-46]: "*In the mid to late 1990s, while the flow of most ASE glaciers had slowed down, possibly in response to cooler ocean conditions (Mouginot et al., 2014; Dutrieux et al., 2014; Naughten et al., 2022), Pine Island Glacier (PIG) continued accelerating (Rignot et al., 2002; Mouginot et al., 2014) and thinning (Shepherd et al., 2001; Wingham et al., 2009). The glacier had been retreating across an ice plain since the early 1990s (Park et al., 2013; Corr et al., 2001), where its grounding line had been situated on the seaward side of a prominent seabed rise following an earlier slow down (Mouginot et al., 2014; Jenkins et al., 2010). Although the initial cause of this recent retreat is unknown, it is clear that the subsequent mass loss was unaffected by the reduced basal melt rate in the early 2000s (Dutrieux et al., 2014).*"

- **New**: "*Between the late-1990s and mid-2000s, while most ASE glaciers experienced reduced acceleration, possibly in response to cooler ocean conditions, Pine Island Glacier (PIG) continued accelerating and thinning. The glacier had been rapidly retreating across an ice plain since the early 1990s, where its grounding line had been situated on the seaward side of a prominent seabed rise following an earlier slow down. Although the initial cause of this recent retreat is unknown, it is clear that the subsequent mass loss was unaffected by reduced basal melt rates in the early 2000s*"

- **Original** [60-61]: "*This suggests that the retreat had entered an unstable and irreversible phase after the 1940s climate anomaly, which finished when the glacier stabilized at an ice plain in the early 1990s (De Rydt and Gudmundsson, 2016; Reed et al., 2023; Mouginot et al., 2014; Park et al., 2013).*"

- **New**: "*This suggests that the retreat had entered an unstable and irreversible phase after the 1940s climate anomaly, which had finished when the glacier reached a shallower section of bed around 1990.*"

Can you deduce anything from your results about whether the unstable retreat from the 1940s can be attributed to anthropogenic change or natural variability alone? It seems to me that no trend in warming is required to sustain the retreat – quite the opposite, in fact, because in many cases the ocean has to become colder than it originally was to halt the retreat. So does this lead you to conclude that this unstable retreat could be due to natural variability alone?

- **We know that following El Nino years there can be a significant shoaling of the thermocline in the Amundsen Sea so it's certainly possible that an increase in melting due to natural variability could have initiated PIG's retreat. However, we cannot comment on the exact cause because we have used a simplified depth-dependent melt**

parameterization here to mainly focus on the ice dynamical response. What we can say is that once the retreat started, there would need to have been a large decrease in basal melting to stop it. So, whether this was not possible because of anthropogenic change or other reasons, it is hard to say, and we will direct the reader to previous studies that have looked at the 1940s atmospheric conditions and causes in more detail (Holland et al., 2022, O'Connor et al., 2023).

- **We will include this detail in the discussion.**

L119-122: it may help the reader if you link to the thermocline plots in Figure 2b here.

- **Original**: *"In the cold experiments, the shallow zero melt layer extends down to 400 m depth and the deep layer begins at 800 m depth."*

- **New**: *"In the cold experiments, the shallow zero melt layer extends down to 400 m depth and the deep layer begins at 800 m depth (Fig. 2b)."*

L138-140: The initial state from the 1000 years of no melting is "not far from the 1940s position" and after relaxation for 100 years "the new state represents the approximate situation prior to the warm anomaly in the 1940s". I'm curious how well defined the 1940s state is in Smith et al. 2017, and whether it is clear that the relaxed state matches it more closely than the unrelaxed steady state?

- **Just to clarify, the "not far from the 1940s position" statement is referring to the calving front position (Rignot 2002), rather than the initial state.**

- **In Smith et al. 2017 they deduce that there was a small cavity upstream of ridge with "space for the sediment to accumulate before 1945" but no sea water incursion. Hence, we think that our relaxed state with a thinner ice shelf and small isolated upstream cavities is probably closer to the 1940s state than the unrelaxed state.**

Figure 3, middle row: these melt rates look a bit stripey here, why is that?

- **This is a feature of the depth-dependent melt parameterization that we use and the way the grounding line retreats non-uniformly. Adjacent regions of shallow/deeper ice shelf draft experience different degrees of melting, which then leaves an imprint in the advected ice downstream.**

Line 200: can you comment on the timescale of the retreat here? Is it consistent with what is observed in the 1970s, or a bit slower? Would you expect it to capture the timescale?

- **As we only have a few observations of grounding line position (e.g., 1945, 1970s, 1992+), we do not know the exact retreat history of PIG, but those observations suggest that around 1945 the inner cavity first opened to ocean waters, and that inner cavity then remained open in the years after. The grounding line continued to retreat but the ice shelf remained in contact with the ridge until the late 1970s. So, it took around 30 years for this to occur.**

- **In our experiments, the inner cavity opens around 11 years and then final ungrounding from the ridge occurs approximately 8-10 years later. So, our retreat occurs at a faster rate than observed. However, we are using a simplified melt forcing which doesn't consider any geometric or topographic feedbacks, which have been shown to delay retreat by 10 years (De Rydt et al., 2016). Furthermore, we are using approximate bed conditions and ice rheology inferred from present-day velocities, so we would also expect these parameters to impact the timescale.**

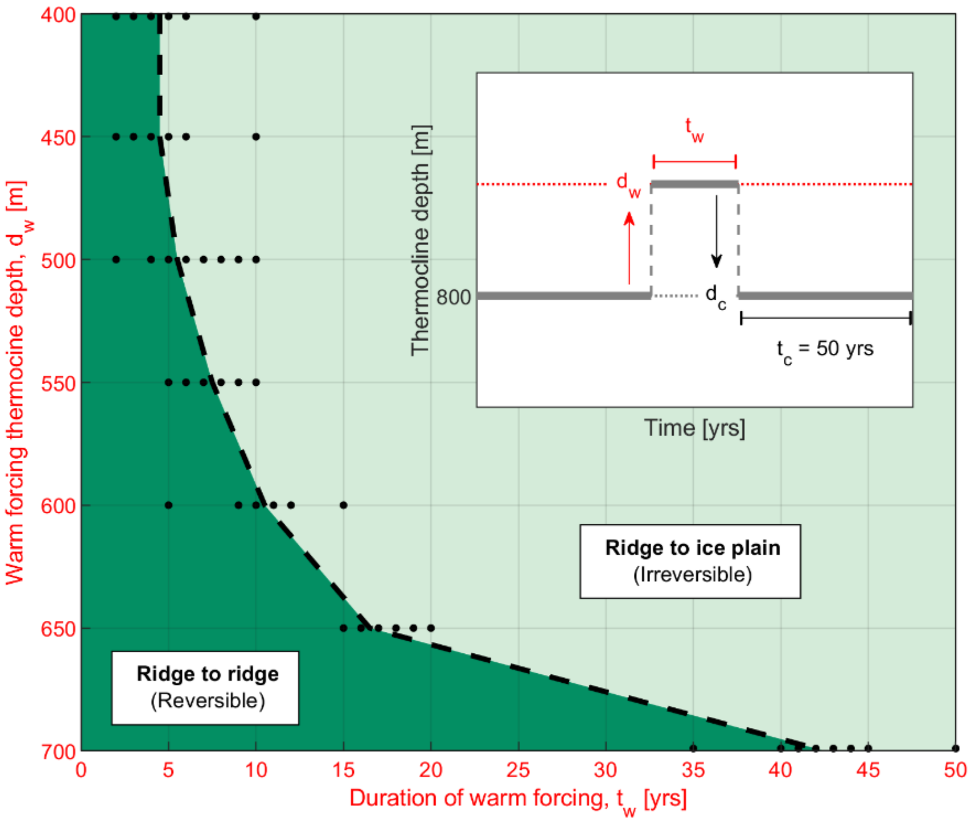
Figure 4, black dashed line indicates time of melting starting upstream of the ridge – but presumably just for cases WARM12and the cold cases? Please clarify.

➢ **Yes, that's right, the caption has now been corrected.**

- **Original**: *"The vertical black dashed line indicates the time of melting starting upstream of the ridge (11.3 yrs)."*
- **New**: *"The vertical black dashed line indicates the time of melting starting upstream of the ridge in the WARM25 experiment (12 yrs)."*

Figure 6: can't tell that the dashed line is dashed.

➢ **This has now been changed to a thicker black dashed line.**



L290-295: you note that the stabilisation on the prograde slope might have coincided with cold ocean conditions – but would they be necessary for stabilisation in your model, **or does it stabilise there even in warm conditions?**

➢ **The cold conditions are not necessary for stabilisation on the prograde slope, as we see at the end of the WARM25 simulation - there is a decrease in ice flux as the grounding line stops retreating at the upstream bed rise (ice plain). In our previous paper, we also show a number of steady-state grounding lines at this location for different melt conditions.**

L332: Bett et al, 2024, also use a coupled ice-ocean model and find that ocean melt around pinning points is a key control on the retreat.

➢ **This reference will be added**

Figure D1: Lines for t=12 years and t=25 years hard to distinguish.

➢ **The line colours have been changed**

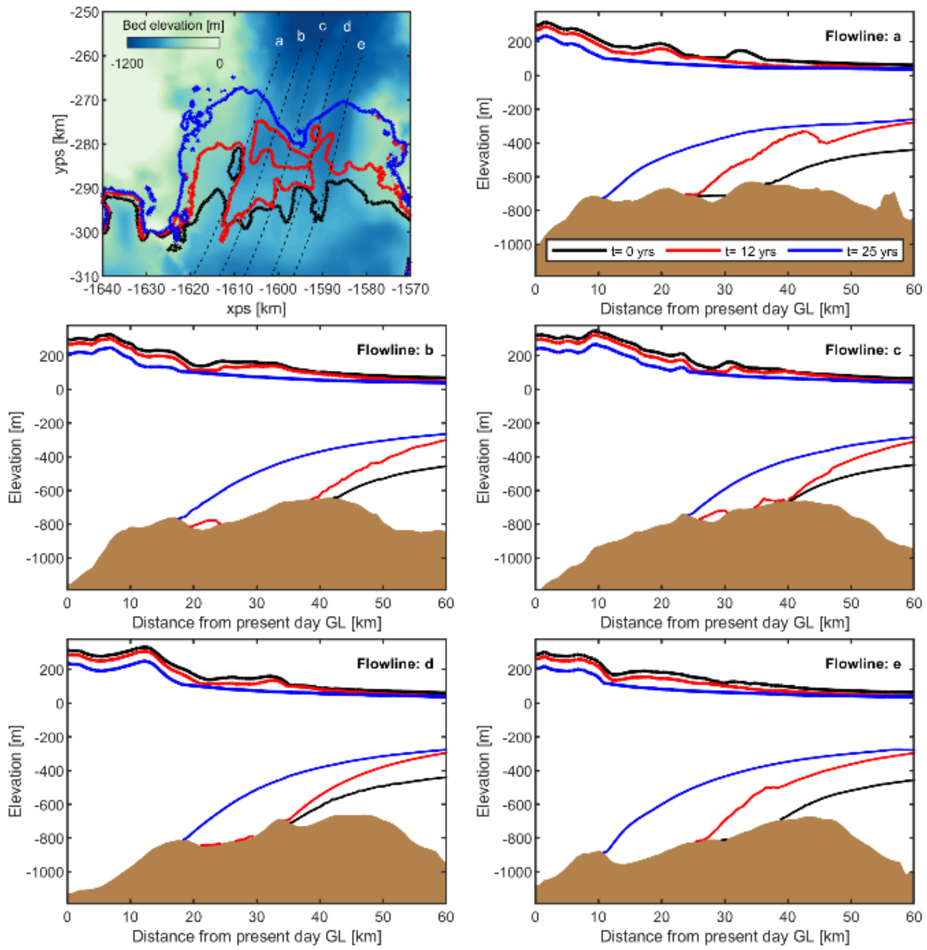


Figure E1: For the reversible cases the final state grows compared to the initial state – is the final grounding line position similar to the steady state or significantly more advance? Presumably not more advanced that the no melt case from the first steady state (after 1000 years of no melt)?

- **The final grounding line positions in the reversible cases (dc=1100 and dc=1200) are similar to the no melt (advance) case because the melt rate in both of these runs is very low.**

- **In Fig E1, at time=0 yrs we're showing the end of the initial relaxation stage (thermocline depth 800m), so there has already been some thinning and retreat in this case.**