Melt sensitivity of irreversible retreat of Pine Island Glacier

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Reply to referee #1 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 comments:

l.101: What **adjustments** where made to the ice shelf **thickness**? What part of the ice shelf was impacted? And what was the magnitude of this correction? Some **overall numbers** should be added to the text.

- **The thickness adjustments were personally provided by Mathieu Morlighem (and were later incorporated into Bedmachine v3). The region affected was the ice plain area, which was grounded in the 1990s. The maximum change to ice thickness was a decrease of ~250m in a small isolated region, but typically decreases were 80-100m across the ice plain area.**

- **Original** [100-101]: *"Some adjustments were made to the ice-shelf thickness near the grounding line to ensure the hydrostatic floating condition was met for our geometry"*

- **New**: *"Some small adjustments were made to the ice-shelf thickness in the ice plain area to ensure the hydrostatic floating condition was met for the PIG ice shelf. These updated data were provided by Mathieu Morlighem and later incorporated into Bedmachine v3. The maximum change was a thickness decrease of 250m, but generally there were decreases of between 80m and 100m."*

l.104: Additional information should be added here to understand what is done to the **friction** in the part of the domain that was grounded in 1940 (and therefore a friction coefficient is needed) but is not grounded during the satellite area (and thefore cannot be inferred with observations). How was this friction chosen? Also, given there is a large uncertainty in these values, what is the impact on the results presented?

- **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)."*

l.133: why was a period of **1000 years** chosen to simulated the grounding line advance? And why was the melt set-up to **zero instead of cold conditions**? I am sure a number of conditions could lead to a more or less similarly advanced position, so I am curious why such conditions were chosen?

- **We used 1000 years to ensure a quasi-steady state was reached, which could then be used as a starting point for our perturbation experiments. The initial advance to the ridge is effectively finished after 100-150 years, and this is followed by only small changes to the ice shelf thickness and a small advance of the grounding line in the smaller eastern cavity.**

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

l.143: similarly to my question about the grounding line advance, why was a period of **100 years** chosen for the initial grounding line retreat?

- **The relaxation simulation, with a deep thermocline of 800m, was run to ensure there was a more realistic ice shelf draft before the warmer scenario started (otherwise a very thick ice shelf would lead to initially large melt rates). As with the advance case, 100 years was chosen to ensure a quasi-steady state was reached with this new forcing. Most of the thinning and grounding line retreat occurs within the first 10-20 years, with only small changes afterwards.**

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

Fig.6: the small inset showing the thermocline depth and its timing is very useful to understand the experiments and should be **provided earlier** (for example in the description of **experiments**) for improved clarity.

- **We will include this figure earlier in the manuscript.**

l.267: the experiments performed show this behavior for Pine Island Glacier but **not that it could happen to other places** at the same time, so this statement should be toned down.

- **Original** [265-267]: *"Our modelling results combined with observations demonstrate that glacier flow and mass loss can be sensitive to changes in ocean conditions, when grounded on a topographic high, and this can happen simultaneously across multiple glaciers."*

- **New**: *"Our modelling results combined with observations demonstrate that glacier flow and mass loss can be sensitive to changes in ocean conditions, when grounded on a topographic high, and we would expect other glaciers to respond similarly if they are in a comparable configuration."*

l.321: How does the retreat and possible readvance from this ridge compare to the present day conditions investigated in previous studies such as **Favier et al. 2014 or Seroussi et al. 2014?**

- **Similar to our results, in both the Favier et al. 2014 ("F14") study and Seroussi et al., 2014 ("S14") study they show a 30-40 km retreat across a retrograde slope when there is high melting at the grounding line. They also see a propagation of thinning and acceleration upstream of the grounding line, not just confined to the ice shelf.**

- **In the F14 study, once the grounding line retreats across the retrograde bed, the imbalance decreases, as we also see in our results. In their full Stokes simulations, a readvance is only possible when melt rates are 5-10% of the control run, or 5-10m/yr melting below the thermocline (compared to 100m/yr in the control). Similarly, we only achieve readvance once melt is reduced to less than 10%.**

- **Both studies suggest that a temporary increase in ice shelf basal melting can lead to acceleration and irreversible retreat, despite returning to previous conditions.**

- **We will include these studies in our discussion.**

Technical comments:

l.40: there was not much slow down reported in Mouginot et al. 2014 outside of the Eastern Thwaites ice shelf, maybe less acceleration or relatively stagnant conditions, but **not really a sector wide slowdown** and the **discharge kept acceleration at least remained constant.**

- **Original** [39-41]: *"Conversely, a deep thermocline in 2012, following a strong La 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**: *"Conversely, a deep thermocline in 2012 (800m), following a strong La 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)."*

l.83: why not use the **actual velocity at the divide** instead of zero? It is unlikely the velocity changed much during this period.

- ➢ **The velocity at the ice divide is small (~10s m/yr) with a high relative error (>5m/yr) and so we do not expect this to hugely impact the fast-flowing (1000s m/yr) central trunk of PIG.**

l.92: What is the **refinement**? It would be good to put an actual number to get at least the order of magnitude in the text.

- **Original** [90-92]: *"For cold and warm transient experiments (Sect. 2.6) a further time-dependent mesh refinement was applied around the grounding line, adapting the mesh as the geometry evolved, to ensure element sizes were less than 500 m in the area of transition from grounded to floating ice"*

- **New**: *"For the cold and warm transient experiments (Sect. 2.6) a further time-dependent mesh refinement was applied around the grounding line, adapting the mesh as the geometry evolved every half a year. This refinement ensured 500m mesh elements within 5000m of the grounding line, and 250m elements within 2000m of the grounding line."*

Fig.1: the blue line for A-B on panel 1 is hard to see

- **Original**: *"(d) Corresponding flowline profiles for the location shown in dashed blue in a, with the flow direction from A to B"*

- **New**: *"(d) Corresponding flowline profiles for the location shown as a thick black dashed line in a, with the flow direction from A to B"*

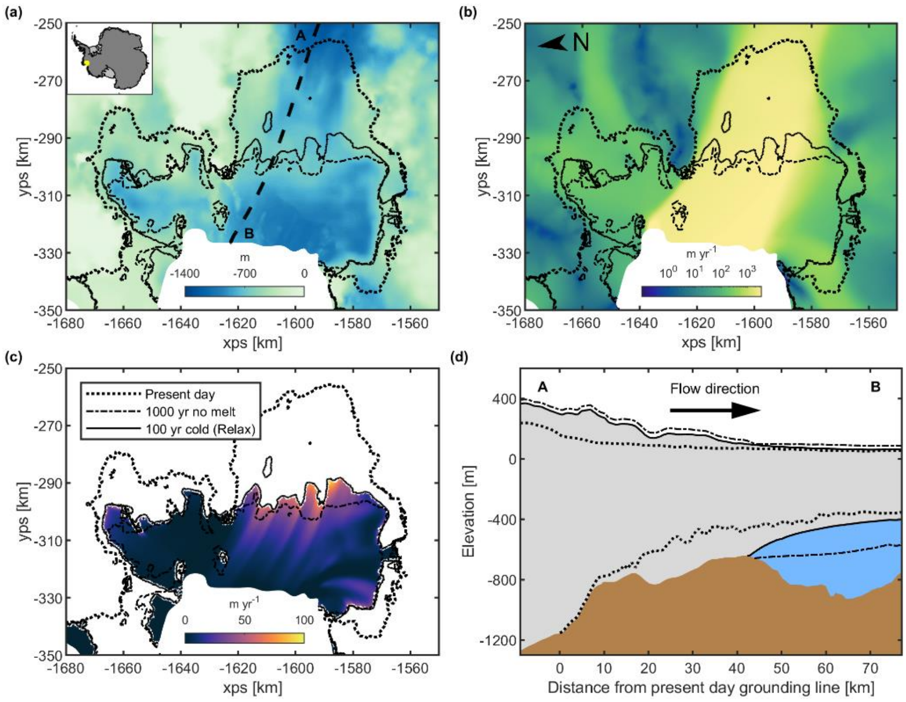

Fig.2 caption: Why grounding line is displayed on panel c?

- **Original**: *"Depth-dependent melt-rate parameterization for the cold (blue) and warm (red) forcing (b) and bed elevation with overlain grounding line (c). Basal melt at the start of the perturbation experiments for the cold parameterization (d) and the warm parameterization (e)."*

- **New**: *"(b) Depth-dependent melt-rate parameterization for the cold (blue) and warm (red) forcing. Bed elevation (c), basal melt for the cold parameterization (d) and basal melt for the warm parameterization (e) at the start of the perturbation experiments. In (c) – (e) the grounding line is shown as a thick black line, and model boundary as a thin black line."*

Table 1 and text lines 172-179 : it would be great to add the **total number of experiments** performed as part of the **WARMvar** and **CODLvar** cases. Were all the possible combinations tested? If not which ones were tested and how was that decided?

- **Original** [172-177]: *"The final set of experiments test the sensitivity of irreversible retreat for a wider suite of forcing conditions (WARMvar and COLDvar). All model simulations start at the ridge and consist of a period of warm forcing, followed by cold forcing. This allowed us to test whether any retreat was irreversible or not. We first experimented with the warm anomaly, by changing the duration of forcing (0 to 50 years) and the thermocline depth (400 to 700 m), where each of the experiments was followed by a 50 year period of cold forcing with an 800 m thermocline depth. The next experiment varied the cold forcing, after an initial warm anomaly, by changing the cold duration (0 to 50 years) and the thermocline depth (800 to 1200 m)"*

- **New**: *"The final set of experiments test the sensitivity of irreversible retreat for a wider suite of forcing conditions (WARMvar and COLDvar). All model simulations start at the ridge and consist of a period of warm forcing, followed by cold forcing. This allowed us to test whether any retreat was irreversible or not. We first experimented with the warm anomaly, by changing the duration of forcing (between 0 and 50 years) and the thermocline depth (400 to 700 m), where each of the warm forcing periods was followed by a 50 year period of cold forcing with an 800 m thermocline depth. There were 46 WARMvar model simulations in total, where we initially used increments of 5 years, and then narrowed this to every 1 year to find the irreversible transition year. The next experiment varied the cold forcing, after an initial warm anomaly for 12 years, by changing the cold thermocline depth (800 to 1200 m) and finding which simulation led to reversible retreat. These five simulations all ran for 100 years."*

To include in Table 1:

Experiment	Warm duration	Warm thermocline	Cold duration	Cold thermocline
	(t_w) [yrs]	(d_w) [m]	(t_c) [yrs]	(d_c) [m]
…	…	…	…	…
WARMvar	2, 3, 4, 5, 6, 10	400	50	800
	2, 3, 4, 5, 6, 10	450	50	800
	2, 4, 5, 6, 7, 8, 9, 10	500	50	800
	5, 6, 7, 8, 9, 10	550	50	800
	5, 9, 10, 11, 12, 15	600	50	800
	15, 16, 17, 18, 19, 20	650	50	800
	35, 40, 41, 42, 43, 44, 45, 50	700	50	800
COLDvar	12	600	100	800
	12	600	100	900
	12	600	100	1000
	12	600	100	1100
	12	600	100	1200

Fig.3: it would be good to add the **years** at the top of the corresponding columns

- ➢ **This has been changed:**

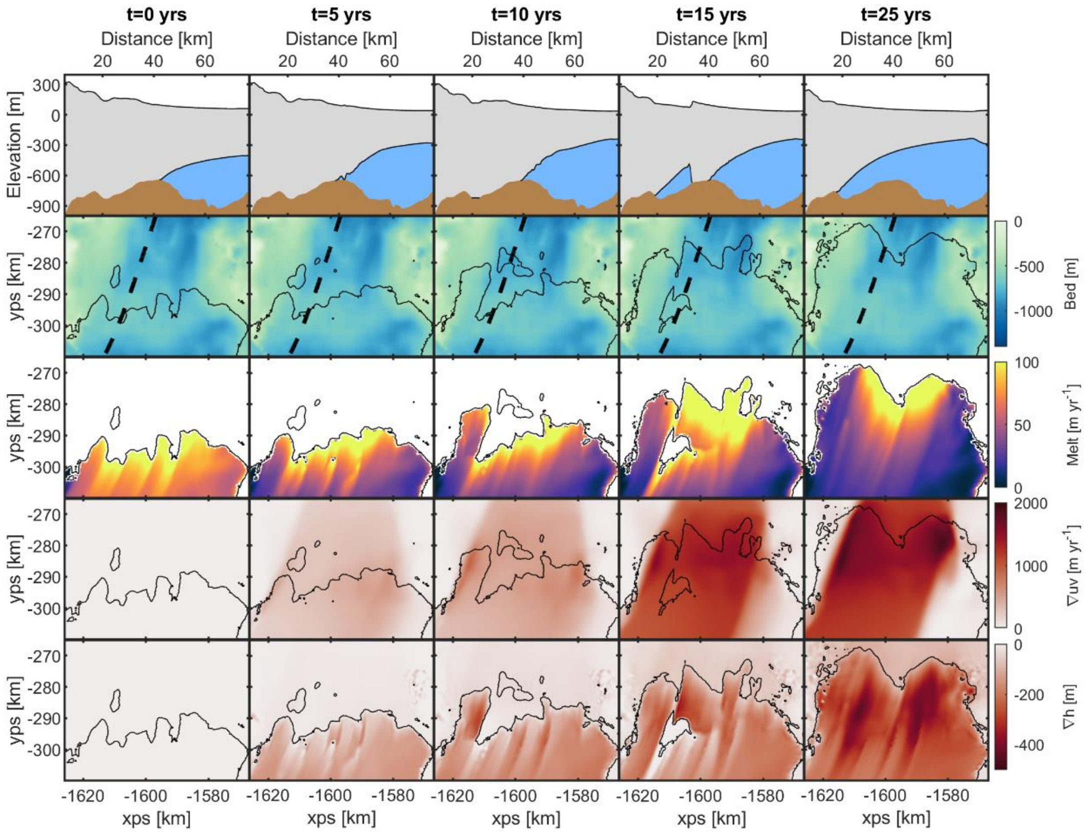

Fig.4 caption: for which experiement are the **vertical black dashed lines**?

- ➢ **These lines (and caption) have 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)."

l.220: "there is A continued retreat"

- ➢ **Will be corrected**

l.300: It looks like the glacier continues to lose mass, so what does "**stabilized**" mean in this context?

- **Original** [299-300]: *"The irreversible retreat would have been unaffected by a reverse of ocean conditions in the following years and PIG continued losing mass through the 1970s and 1980s (Jenkins et al., 2010; Mouginot et al., 2014). The glacier then stabilized when it reached an ice plain in the 1990s. This demonstrates that although an increase in basal melt is the initial cause of mass imbalance and retreat, it can be the dynamical response that becomes the dominant driver of mass loss once the forcing is removed."*
- **New**: *"The irreversible retreat would have been unaffected by a reverse of ocean conditions in the following years and PIG continued losing mass through the 1970s and 1980s (Jenkins et al., 2010; Mouginot et al., 2014). Eventually, the ice shelf detaches from the ridge and the grounding line retreats to an upstream ice plain, which leads to a reduction in ice flux across the grounding line (Mouginot et al., 2014). This sequence of events demonstrates that although an increase in basal melt is the initial cause of mass imbalance and retreat, it can be the dynamical response that becomes the dominant driver of mass loss once the forcing is removed. The glacier only stops retreating when it reaches a shallow section of bed upstream."*