Dear Emily Hill and co-authors,

I am most delighted to inform you that the pending review report is in and that the reviewer very much appreciates your ‘genuine efforts to address [the] comments’. At this stage, the reviewer mostly asks for editorial changes. Comments appear constructive and many of them come with pre-formulated suggestions for text modifications.

In light of this positive report, I invite you to address these comments during this step of minor revisions. I expect a fast iteration.

Yours Sincerely,

Johannes Fürst

Dear Johannes Fürst,

Thank you for inviting us to address these minor revisions. We have made a conscious and thorough effort to implement all of these reviewer comments, including taking on board pre-formulated text modifications.

Please find included below the reviewer comments in black and our response in blue.

With best wishes,
Emily Hill, Benoît Urruty, Ronja Reese and co-authors

Review of a manuscript "The stability of present-day Antarctic grounding lines Part A: No indication of marine ice sheet instability in the current geometry" by Hill et al.

This manuscript had two rounds of reviews. I would like to thank the authors for their genuine efforts to address my comments. The manuscript is substantially improved. Considering its high-profile, it would be better to make it clear as possible. It appears that the authors continue to treat the ice-sheet geometry as the only characteristic of the ice sheet behaviour (e.g., line 439 "As our experiments aimed to assess the stability of the observed grounding lines in their current geometry. . . "), yet the state of an ice sheet and its behaviour depends on the forcing in the equal measure. My comments are of editorial nature and their purpose is to clarify remaining inconsistencies, and not to criticize the authors. The comments are not separated in "major" or "minor"; they just follow the text. By no means I want to put words in the authors' mouth. They should take the suggested text as suggestions and modify it in a way they find appropriate. On the other hand, I have no objections if they decide to use it verbatim.

Thanks for the additional review comments. We have made a conscious effort to address all of your comments. See our responses and changes that have been made in the manuscript below.

Title: it'd be clearer if you add "... under steady-state climate conditions..." so it reads

"The stability of present-day Antarctic grounding lines under steady-state [present-day] climate conditions Part A: No indication of marine ice sheet instability in the current geometry".

My suggestion would be either to remove "marine ice-sheet instability" from the title; if your prefer to keep it, then have something like

"The stability of present-day Antarctic grounding lines Part A: No indication of marine ice sheet instability in the current geometry under steady-state [present-day] climate conditions"

because that's the experiments your performed. Though in your response you state that there are different versions of interpretation of marine ice-sheet instability, my understanding is that in your study you consider stability of a steady state, or something close to it, because for PISM simulations the forcing is the same - RACMO and PICO fields that do not change in time, apart from the periods when perturbations are applied and removed.

It is true that in all our experiments the climate conditions are steady, i.e. fixed through time, but our PISM ice sheet state is not in a steady state, which is a key difference between this and the other models. In fact, Part B shows that the steady state the PISM configuration evolves toward under steady climate conditions has a substantially retreated grounding line in WAIS. Also the climate conditions used between the three models are also different so we feel that adding this to the title could cause confusion to the reader. Also the title already spans two lines, and adding more words makes it incomprehensible.

We do however acknowledge that having a steady climate means that we do not consider so-called noise-induced tipping that the reviewer appears to indirectly refer to in their comments on the steady versus variable climate conditions (here and below). We think that adding this directly as a caveat to the discussion is easier for the reader to understand than indirectly implying it by adding "steady climate conditions" in the title and other places. We added the following text "Another point to make is that in our study here we consider only steady climate conditions in our experiments. Studies have shown that variability in the climate can cause noise-induced tipping which causes a system to transgress towards a qualitatively different state before the actual tipping point is crossed (e.g., Ashwin et al., 2012). Future work would benefit from incorporating time varying climate conditions to explore the possibility of noise-induced tipping in the real Antarctic Ice Sheet."

Abstract requires more clarifications and a brief but clear description what has been done in a study it could be something along the lines:

"Theoretical and numerical work has shown that under certain circumstances grounding lines of marine-type ice sheets can enter phases of irreversible advance and retreat – a process typically described as the marine ice sheet instability (MISI). Instances of such irreversible retreat have been found in several simulations of the Antarctic Ice Sheet under atmospheric and oceanic forcing that were meant to represent past or future climate conditions. However, it has not been assessed whether the currently observed ice-sheet geometry can maintain a steady state configuration, if the climate forcing similar to the present-day would remain constant, and whether such a steady state is stable. Here, we conduct a systematic numerical stability analysis of the present-day Antarctic Ice Sheet configuration using climate conditions that are similar to the observed ones with three state-of-the-art ice-sheet models, Ua, Elmer/Ice, and PISM. For the first two models, we construct steady-state configurations by modifying the surface ac- cumulation simulated with RACMO and sub-ice-shelf melt rates parametrized with PICO and in such a way that if the modified fields kept constant in time, the simulated grounding lines remain at the observed present-day positions. The third model, PISM, uses spin-up procedure and historical forcing such that its transient state is close to the observed one. To assess the stability of these simulated states, we apply short-term perturbations to submarine melting that causes the grounding-line migration, which is reversed after the perturbations are removed. Our results indicate that were these climate conditions remained constant in time the grounding line positions would remain at or very close to their present-day positions. Our results suggest that the simulated grounding-line retreat under drastically different climate conditions used in previous studies is not an indication of the marine ice-sheet instability."

We have not taken this new abstract verbatim but agree that the model set-up and initial states used could have been explained more clearly. We have added some sentences to that effect and the new abstract is included below. We did not want to include the second to last sentence of your proposed rewrite of the Abstract because stating "if climate conditions remained constant in time..positions would remain close to present-day positions" (paraphrased), because this contradicts the findings of our Part B experiments, which clearly show (as mentioned above), that under steady (present-day) climate conditions, the ice sheet eventually evolves towards a 'retreated' state. We are not sure what is meant by 'drastically different climate conditions', and because this is a qualitative description we feel that it would be confusing to the reader, especially given that we do not make comparisons to climate conditions used in other studies elsewhere in the manuscript.

The last sentence of the current version – "However, our accompanying paper (Part B, Reese et al., 2022) shows that if the grounding-lines retreat further inland, under present-day climate forcing, it may lead to the eventual irreversible collapse of some marine regions of West Antarctica."– is confusing because it contradicts the rest of the abstract. In my view, it is unnecessary, and the two parts of your study, A and B, could stand on their own.

Perhaps it is true that they could stand alone, but at present they are referenced to one another with Part A and B and so it seems appropriate to make a reference to Part B in the abstract. This statement is also not intended to be contradictory to the rest of the abstract. It would however, contradict this sentence suggested by the reviewer "Our results indicate that were these climate conditions remained constant in time the grounding line positions would remain at or very close to their present-day positions". As we discuss in the reply above, this statement is not what our experiments are showing and we do not claim this as a conclusion anywhere in the manuscript either. We have made an effort to reformulate the sentence about our Part B results to make this clearer to the reader. See our revised abstract below.

"Theoretical and numerical work has shown that under certain circumstances grounding lines of marine-type ice sheets can enter phases of irreversible advance and retreat driven by the marine ice sheet instability (MISI). Instances of such irreversible retreat have been found in several simulations of the Antarctic Ice Sheet. However, it has not been assessed whether the Antarctic grounding lines are already undergoing MISI in their current position. Here, we conduct a systematic numerical stability analysis using three state-of-the-art ice-sheet models, Ua, Elmer/Ice, and PISM. For the first two models, we construct steady-state initial configurations whereby the simulated grounding lines remain at the observed present-day positions through time. The third model, PISM, uses a spin-up procedure and historical forcing such that its transient state is close to the observed one. To assess the stability of these simulated states, we apply short-term perturbations to submarine melting. Our results show that the grounding lines around Antarctica migrate slightly away from their initial position while the perturbation is applied, and then revert once the perturbation is removed. This indicates that present-day retreat of Antarctic grounding lines is not yet irreversible or self-sustained. However, our accompanying paper (Part B, Reese et al., 2022) shows that if the grounding-lines retreat further inland, under present-day climate forcing, it may lead to the eventual irreversible collapse of some marine regions of West Antarctica."

Introduction:

Though the rebuttal states that "We however only use "stable/unstable" when referring to a steady state. . . " the first sentence of Introduction states "Retreat of the Antarctic ground- ing lines, i.e. the zones where the grounded ice sheet becomes so thin that it floats, could <u>destabilise</u> large marine regions of the ice sheet. . . " (emphasis is mine). Both sentences in the first paragraph need to be modified. Also references to Weertman (1974) and Schoof (2007) in the context of these sentences are incorrect – they considered idealized configurations, and had nothing (apart from a motivation) to do with Antarctic grounding lines and their retreats.

The first paragraph of the introduction has been revised. References to Weertman and Schoof have been removed.

The first sentence of the second paragraph (line 18) is incorrect, because " instability" is not a mechanism, it's a property either of a steady state or a time-variant trajectory (i.e., a limit cycle).

Weertman (1974) and Schoof (2012) discussed it specifically as a property of a steady state, and not in “the sense of having a self-enhancing, irreversible grounding line retreat due to a positive feedback mechanism related to the ice dynamics ” as you describe in the rebuttal. (It is not until line 36 that you mention the “positive feedback”sense.) The Introduction sentences up to one in line 23 (starting with “For marine, laterally uniform ice sheets with constant conditions. . . “) could say that the results of numerical studies with climate forcings (either varying in time or constant) that are substantially different than observed today show irreversible retreat of the grounding lines.

We agree with the reviewer that technically MISI is not a mechanism, but a property of a steady state or a time-variant trajectory. However, and importantly, across the literature it is referred to as a mechanism and we want to stay consistent with this. To align with this, and to address your comment further down about ‘describing how this self-reinforcing positive-feedback’ operates, we have moved the sentences from Line 36 up to the start of this second paragraph in the introduction. This now makes it clear from the outset what we are referring to when we say “positive self-reinforcing mechanism”

We have also changed the second sentence of the second paragraph to “The existence of MISI means that a shift in the position of the grounding line can cause it to cross a critical threshold (or `tipping point'), beyond which the system is driven towards a different steady state”

Line 27: the sentence “However, in the case of laterally confined ice shelves that buttress the inland grounded ice, the MISI mechanism becomes more complex.” is incorrect for the same reason as above – the MISI is not a mechanism. A simple modification for it could be to replace “the MISI mechanism” with “the situation” or something similar.

We changed the sentence to now refer to ‘feedback mechanism’ instead of MISI.

Line 33: the sentence “Critically, this means. . . ”is disconnected from the sentences above it, because they describe steady-state studies, and this sentence refers to “observed retreat”– an unsteady behaviour.

For simplicity, we have removed these two sentences.

Line 36: It would be helpful if you describe how this “self-reinforcing, positive feedback” operates. I suspect that it is based on the Schoof’s (2007) formula of the ice flux at grounding line. If that is the case, then that refers back to the use of the MISI in the sense of stability of steady states. Also, studies referenced in lines 28-33 show that this formula is valid only for laterally unconfined marine ice sheets.

See comment above, we have moved these sentences earlier in the introduction to make it clear what we mean by “self-reinforcing, positive feedback”. It is also discussed on line 25 in the previous version of the manuscript. In our understanding, this “self-reinforcing, positive feedback” is exactly how Schoof 2007 links to the "transient" MISI understanding of today.

Lines 39: the sentence “For example Rosier et al. (2021). . . ” is very similar to those in lines 20-23. It is better to remove/modify those and keep this one.

Sentences from lines 20-23 have now been incorporated at line 39.

Lines 44-54: the second sentences of these two “However, to date there has not been a systematic analysis to determine whether the currently observed changes in grounding line position are reversible. In this paper we use a systematic modelling approach to assess whether the current retreat of the Antarctic grounding lines is due to an ongoing positive feedback mechanism related to MISI.” is incorrect. This is because you do not assess whether the observed changes are reversible or not: you have created alternative, steady, states and assessed the reversibility of small perturbations from them. As you correctly point out later (lines 140-143), the present day ice sheet (and not only its geometry) is not in a steady state; and its current behaviour is not a perturbation from the steady state, or at the very least, you do not have evidence that indicates that it is a perturbation. The last sentence of this paragraph is incorrect as well for the same reason. This paragraph could state something like:

“Previous studies have argued that sections of the West Antarctic Ice Sheet may already be undergoing self-sustained unstable retreat (Joughin et al., 2014; Favier et al., 2014; Rignot et al., 2014). However, to date there has not been a systematic analysis whether, if the climate conditions close to the present-day ones kept constant, (1) the present day ice-sheet configu- ration could attain a steady state and (2) is stable or unstable. Our modelling approach is outlined at the beginning of Sect. 2. Briefly, we perform numerical experiments using three state-of-the-art ice sheet models, Elmer/Ice (Gagliardini et al., 2013), o`a (Gudmundsson, 2020) and the Parallel Ice Sheet Model (PISM; Bueler and Brown, 2009; Winkelmann et al., 2011), by applying a perturbation to our initial model forcing, that all closely replicate the current geometry and velocity of the Antarctic Ice Sheet. Our results indicate that (1) there exist climate conditions, such that were they held constant in time, the present-day ice-sheet geometry is in (or close to) a steady state with respect to them; and (2) this steady state is stable with respect to small perturbations in the model forcing.”

We appreciate the suggested change to the text. Crucially though, changing the text in this manner would lead to inconsistencies in the manuscript. The detailed explanation of our methodology at the beginning of Section 2 would no longer make sense if we were to reformulate the paragraph in this way. This would require an entire reformulation of our approach throughout the entire manuscript.

However, you are right that we cannot assess whether the observed changes are reversible or not, but we can only make inferences about how the present-day retreat of the grounding lines may not be due to MISI. To that effect we have rephrased the section of the paragraph to remove the sentence “In this paper we use a systematic modelling approach to assess whether the current retreat of the Antarctic grounding lines is due to an ongoing positive feedback mechanism related to MISI”. The new paragraph now reads as below:

“Previous studies have suggested that present-day retreat in regions of the West Antarctic Ice Sheet could mean that irreversible retreat has begun (Joughin et al., 2014; Rignot et al., 2014). However, to date there has not yet been a systematic analysis to assess whether irreversible retreat of Antarctic grounding lines is already underway. In this paper we use a systematic modelling approach to assess whether, under steady climate conditions, the grounding line positions of the Antarctic Ice Sheet are reversible with respect to a small-amplitude perturbation away from their current positions. Our modelling approach is outlined in detail at the beginning of Sect. 2. Briefly, we perform numerical experiments using three state-of-the-art ice sheet models, Elmer/Ice (Gagliardini et al., 2013), Ua (Gudmundsson, 2020) and the Parallel Ice Sheet Model (PISM; Bueler and Brown, 2009; Winkelmann et al., 2011) by applying a small but numerically significant perturbation to our initial model states, that all closely replicate the current geometry and velocity of the Antarctic Ice Sheet. If we find the grounding lines to either revert back to their former position (if the state is steady), or stay within the vicinity (if drifting through time), then this would indicate that current retreat of Antarctic grounding lines is unlikely to be due to an ongoing positive feedback mechanism, i.e. related to MISI."

Line 55: the first sentence is factually incorrect for the reasons described above. This paragraph can mention the companion paper and a different approach/forcing used in it.

The first sentence has been rephrased to "A follow-on question to the stability of the Antarctic grounding lines is: could the currently observed retreat driven by present-day climate conditions, eventually commit the grounding lines to undergo irreversible retreat?"

Methods

Lines 92-103: your results are still conditioned on steady states: in the case of the PISM simulations, it is forcing that is steady.

We agree that the climate forcing in PISM is steady, but the ice sheet state is not. We feel that this is a key distinction between the experiments conducted with Elmer/Ice and Ua and the experiments conducted with PISM. To make this clear throughout the manuscript we have stated where the climate forcing is steady but the ice sheet state is not. For example in Section 2.3.2 (describing the initial state in PISM) we state "During the control run the present-day climate conditions (2015) are held constant and so the climate forcing itself is steady, but the ice sheet state itself is not in a steady-state (ice thickness changes through time are not equal to zero)."

Line 158: My suggestion would be to move figs S1-S3 to the main text. Fig. S1 does not have units.

We do not think adding an extra three figures into the main text is justified, it will make it too long, and detract from the main results of the paper. The figures are the first to appear in the supplementary document, which is easy to access for all readers. Units have been added to Fig. S1.

Discussion:

Lines 404-415: The last sentence of the first paragraph is over interpretation of the results for the reasons discussed in the comments to Introduction section. In contrast to the first sentence of the second paragraph stating that the obtained results are surprising, in my view they are not. This is because the mentioned studies use very different forcings compared to those used in your study, and also their experiments were very different from yours. Rosier et al. (2021) used forcing which is equivalent to extremely large submarine meltrates. Though you are right that conclusions of other studies that current retreat of the Pine Island Glacier is an indication of the MISI are incorrect, this is not a direct conclusion of your study.

For simplicity we have removed the last sentence of the first paragraph of the Discussion.

The second paragraph has been reformulated to remove the statement “it is perhaps surprising” and the sentence “...no indication of ongoing retreat in this sector of the ice sheet” as we agree this cannot be a direct conclusion of our study, but only something we can infer from our experiments. It now reads “Our results instead suggest that the ASE sector of West Antarctica has reversible grounding-lines in response to a small deviation from their current position”.

Line 429: the first sentence of this paragraph is not correct. The use of three models does not eliminate structural uncertainties of the individual models. Because you have created steady state or initial conditions that are very specific to these models. The only common procedure is application of submarine melt perturbations. Considering that all the models use the same vertically integrated momentum balance, solve the same set of equations (more or less) and use the same perturbations, it is not surprising that they produce fairly similar behaviour. But once again, that does not imply that their structural uncertainties are eliminated.

Changed the first sentence to “While our experiments, performed with three different ice sheet models, have shown consistent results, in the following paragraphs we note several caveats and potential sources of uncertainty.”

Lines 448-452: The comparison with idealized simulations of Robel et al (2022) is not relevant for many reasons, including their experiment design and a specific choice of the bed topography.

It was a suggestion in the previous rounds of review to add this reference. We are happy to remove it and have done so.

Lines 453-470: Your assessment that the dynamic calving front would not change your results (I paraphrase) is most likely overstatement. Acknowledging that your results are valid in this particular configuration with a fixed calving front and that simulations with a moving calving front might produce different results would be better.

We have changed one of the sentences to read “We acknowledge that an evolving calving front may produce different results, especially as recent work has shown that (in the presence of buttressing) iceberg calving could impact the stability regime of grounding lines (Haseloff and Sergienko, 2022)”

An additional limitation of your study that you do not consider any feedbacks between the ice- sheet geometry, e.g., surface elevation, the ice-shelf draft) and the climate forcing,e.g., surface accumulation and submarine melting (Sergienko, 2022; https://doi.org/10.1038/s41467-022-29892-3).

Added a sentence to the end of the discussion stating we do not account for the surface melt elevation feedback. We include the negative feedback related to melting causing the ice shelf to thin, which increases the in-situ pressure melting point and thereby reduces melting as this is covered in the PICO melt calculation. However, we do not consider feedbacks on ocean circulation that would require a coupled ice-ocean model configuration.

Conclusions: The first sentence is absolutely correct. The following sentences unfortunately not so for the reasons already mentioned above – a state of an ice sheet (its geometry and surface velocity) and its forcing cannot be considered separately. As you demonstrated, it is possible to have almost identical steady-state configurations of the Antarctic Ice Sheet with slightly different climate forcings (one for Elmer/Ice and Ua), and a transient state, which is close to the observed one with PISM. However, your results do not tell what is the cause of the present-day grounding line migration. They tell that it is not the MISI that caused them, which is a slightly different conclusion. Lines 480-481 state "Here, we have argued that the currently observed changes of the Antarctic Ice Sheet are not a manifestation of an ongoing positive-feedback related to MISI." However, the manuscript does not have a clear description of this positive feedback and, consequently a clear demonstration that this feedback does not operate in both your simulations and the real ice sheet. Here is a suggestion of Conclusions based on the results of your study:

"In this study, we have investigated the existence of a steady-state configuration of the Antarctic Ice Sheet which closely resembles the observed present-day configuration and the climate conditions that can maintain this steady state if kept constant in time. Our results show that it is indeed possible to construct such climate conditions for two different ice-sheet models Elmer/Ice and Ua that produce the geometry and surface velocities that are very close to those of the present-day Antarctic Ice Sheet. A transient state, which is close to the present- day ice sheet was obtained with PISM model. We find that the in all models the grounding line retreat caused by increasing sub-ice-shelf melting for a short period of time of twenty years is reversible. These results indicate that if the climate conditions would be the same as we have constructed and remain constant in time, the present-day Antarctic Ice Sheet would be in steady state, and this steady state would be stable. They also suggest that the grounding-line retreat obtained in simulations with drastically different climate conditions are not indications of the marine ice-sheet instability, and is externally forced retreat."

We have modified the second sentences of the conclusions to remove "(its geometry and surface velocity)". With regards to your second point, nowhere in the conclusions do we state what the cause of present-day grounding line migration is (in the previous versions of the manuscript we said "externally forced" but this is no longer in there now). Instead we have the sentence "we have argued that the currently observed changes of the Antarctic Ice Sheet are not a manifestation of an ongoing positive-feedback related to MISI", which is exactly as you state "...that MISI has not caused them". So we are not sure where this refers to. We have made the description of the positive feedback clearer above and our reversibility experiments show that it does not operate. We have revised the conclusions. See below for the new version:

"Our key finding is that the grounding lines of Antarctica, including Pine Island and Thwaites glaciers, show no indication of marine ice sheet instability (MISI) in their current state. We arrive at this conclusion by showing the existence of stable steady-state model configurations of the Antarctic Ice Sheet which closely resemble the observed present-day configuration as well as by showing reversibility of transient model configurations of the Antarctic Ice Sheet, under steady climate conditions. Our results indicate that MISI is not causing the present-day grounding line migration.

There is a general consensus within the ice-sheet modelling community that the West Antarctic Ice Sheet is susceptible to MISI. Here, we have argued that the currently observed changes of the Antarctic Ice Sheet are not a manifestation of an ongoing positive-feedback related to MISI. While our experiments suggest that an internal instability threshold has not yet been crossed in Antarctica, future retreat driven by changes in climate conditions could force the grounding lines to cross a tipping point, after which retreat becomes driven by MISI. Further work is needed to quantify the amplitude and duration of forcing required for the Antarctic Ice Sheet to enter a phase of a large-scale irreversible collapse involving grounding-line retreat over hundreds of kilometers and a concomitant sea-level rise of potentially several meters."