

## Responses to comments from Reviewer Tong Zhang

### Damage intensity increases ice mass loss from Thwaites Glacier, Antarctica

We thank the editor and the two reviewers for their constructive feedback, which has helped us improve the manuscript. In response to the comments, we have thoroughly revised the manuscript. The key updates are the following:

- We have improved the writing, formulation and structure of the manuscript to enhance clarity.
- Appendix A has been removed and merged into section 2.1, where the model formulation has been extensively revised.
- To provide greater clarity on our methodology, we have introduced separate sections for the simulation protocol (Section 2.2) and the initialization (Section 2.3).
- Appendix B has been removed and integrated into the results section, which has been thoroughly revised to improve readability.
- A comparison of the modeled damage pattern and observations has been added (see Figure 5 in the revised manuscript).

Further details on these revisions are provided in our responses below. In the following, we use “**bold text**” for the reviewer’s comments, “regular” text for our responses, and “*italic*” for text extracted from the manuscript.

### General remarks:

**This manuscript aims to address an important question in ice sheet modeling studies, i.e., if and how much the ice damage affects the ice flow in some vulnerable regions like WAIS. Thus, it is no doubt a valuable study and lies perfectly in the scope of TC.**

**Despite the damage method has been used in some previous numerical studies, it is still necessary to compare the modeled damage field with observed crevasse and rift images – I think it is critical to convince us how much we can trust the damage model results.**

Response:

Thank you for your comments. As suggested, we have compared our simulated damage fields with observed crevasse distribution and added the relevant description in **Section 3.1** of the revised manuscript. We have also included a new figure (Figure 5 in the revised manuscript) showing the crevasse distribution across the ice shelf regions of the Thwaites Glacier basin, derived from Landsat-8 satellite images (December 2020), alongside our present-day simulated damage fields. Please see the following responses to specific comments and the revised manuscript for further details.

**If the authors aim to give a plausible projection of GMSL contribution from Thwaites Glacier, then it is necessary to use CMIP forcing data, from both atmosphere and ocean.**

Response:

Thank you for your comment.

We would like to emphasize that this study does not aim to produce sea-level projections. Instead, we focus on testing the influence of ice damage on the Thwaites Glacier basin under constant present-day climate conditions. Our sensitivity experiments allow us to quantify TG's mass loss response to the damage feedback mechanism.

To clarify this in the manuscript, we have revised our presentation of the results, shifting the focus away from GMSL and instead emphasizing relative mass changes. For details, please see the following responses as well as the revised manuscript.

**And more details of forcing data and model configurations are needed. See the following details:**

Response:

Thank you for your comment. We have added more details on the forcing data and model configurations, as suggested. Especially, to provide greater clarity on our methodology, we have introduced separate sections for the simulation protocol (Section 2.2) and the initialization (Section 2.3). Please see the following responses and the revised manuscript for further details.

**Details:**

**1) L10: damage is a result (or metric) of crevasses, not the reason.**

Response:

Thank you for your comment. We revised this sentence as follows:

(Line 9–10 in the revised manuscript without tracks): “...*Ice damage, which results from the formation and development of crevasses on glaciers, plays a critical role in ice-shelf stability, grounding-line retreat, and subsequent sea-level rise. ...*”.

**2) L17: GMSL instead of sea-level rise**

Response:

Thank you. As mentioned above, we have revised our presentation of the results, shifting the focus away from GMSL and instead emphasizing absolute and relative mass changes. We revised this sentence as follows:

(Line 15–17): “...*When extending simulations to the year 2300, we show that*

*accounting for ice damage results in more than twice the ice mass loss compared to simulations that neglect ice damage mechanics....”*

**3) L21: again, damage is the result of rifts and crevasses**

Response:

Thank you for your comment. We revised this sentence as follows:

(Line 20–21): “...*The weakening of ice due to the formation of large-scale crevasses and rifts, known as damage, is gaining attention due to its impact on glacier and ice sheet evolution in a warming climate....”*

**4) L29-39: the review has not included other studies, e.g., Duddu et al. (2020) and Kachuck et al. (2022), and probably many others, a big improvement of this paragraph is highly necessary.**

Response:

Thank you for your feedback. We have carefully revised the introduction and incorporated additional relevant studies (e.g., Duddu et al., 2020; Kachuck et al., 2022, Huth et al., 2021, 2023; Ranganathan et al., 2024).

Duddu, R., Jiménez, S., and Bassis, J.: A non-local continuum poro-damage mechanics model for hydrofracturing of surface crevasses in grounded glaciers, *Journal of Glaciology*, 66(257), 415-429, doi:10.1017/jog.2020.16, 2020.

Kachuck, S. B., Whitcomb, M., Bassis, J. N., Martin, D. F., and Price, S. F.: Simulating ice-shelf extent using damage mechanics, *Journal of Glaciology*, 68(271), 987-998, doi:10.1017/jog.2022.12, 2022.

Huth, A., Duddu, R., and Smith, B.: A generalized interpolation material point method for shallow ice shelves. 2: Anisotropic nonlocal damage mechanics and rift propagation, *Journal of Advances in Modeling Earth Systems*, 13(8), e2020MS002292, doi:10.1029/2020MS002292, 2021.

Huth, A., Duddu, R., Smith, B., and Sergienko, O.: Simulating the processes controlling ice-shelf rift paths using damage mechanics, *Journal of Glaciology*, 69(278), 1915 – 1928, doi: 10.1017/jog.2023.71, 2023.

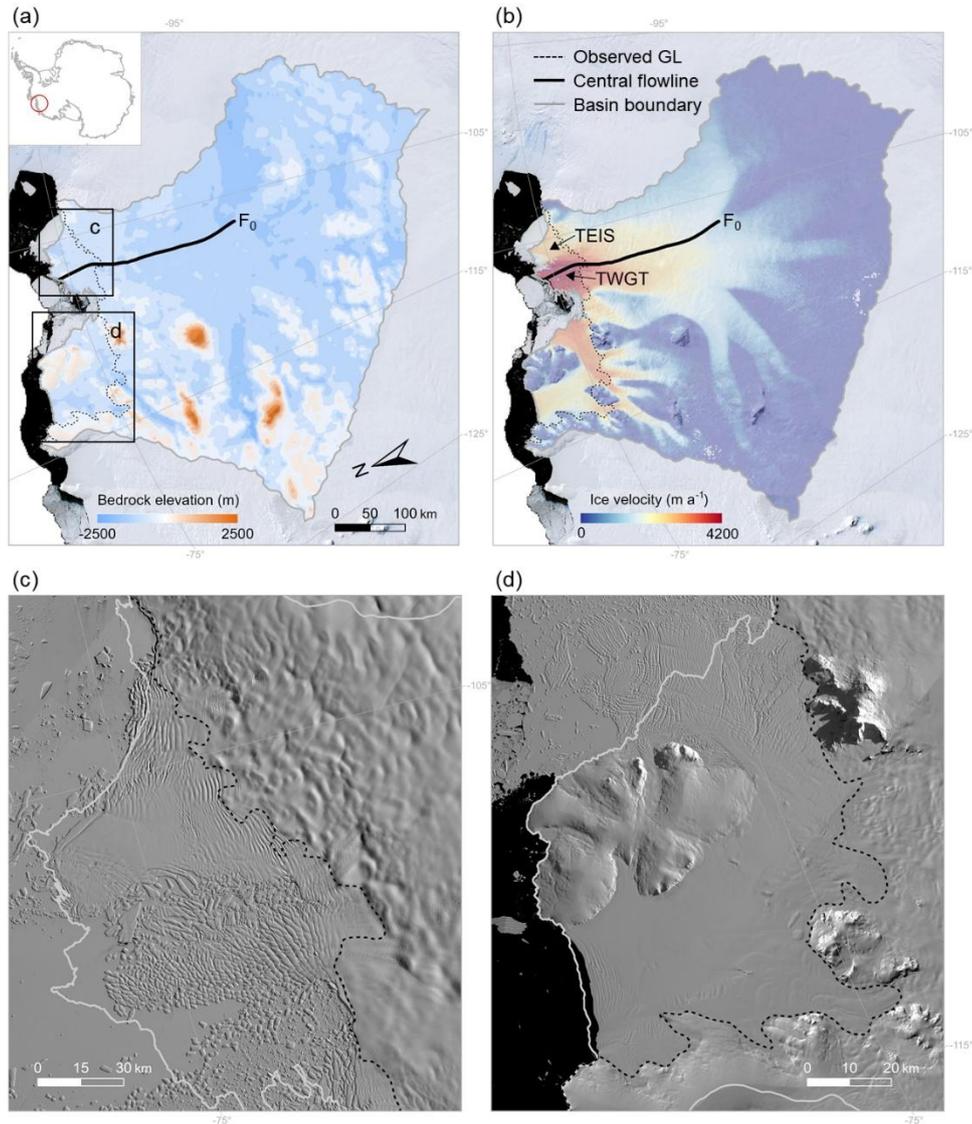
Ranganathan, M., Robel, A. A., Huth, A., and Duddu, R.: Glacier damage evolution over ice flow timescales, *EGUsphere* [preprint], <https://doi.org/10.5194/egusphere-2024-1850>, 2024.

**5) L40-54: It would be very helpful if you can provide an image showing the crevass distribution across Thwaites Glacier along with the current Fig 1.**

Response:

Thank you for the suggestion. We have revised Figure 1 by adding Figures 1c and 1d showing the crevasses distribution across the ice shelf regions of the Thwaites

Glacier basin, based on Landsat-8 satellite images derived in December, 2020.



**Figure 1.** Bedrock elevation and ice velocity in the TG basin. (a) Observed bedrock elevation of the TG basin based on BedMachine v2 data (Morlighem et al., 2020) and (b) observed ice velocity of the TG basin based on Making Earth System Data Records for Use in Research Environments (MEaSUREs) InSAR-Based Antarctica Ice Velocity Map, Version 2 (Rignot et al., 2017) overlaid on the Landsat Image Mosaic of Antarctica (LIMA; Bindschadler et al., 2008). The solid black curve is the central flowline profile stemming from the Antarctic surface flowline dataset developed by Liu et al. (2015), which spans 340 km from the inland grounded ice ( $F_0$ ) to the calving front. The dashed black line shows the position of the observed grounding line (Gardner et al., 2018). The inset in panel (a) shows the location of the TG basin in Antarctica. TEIS represents the Thwaites Eastern Ice Shelf and TWGT represents the Thwaites Western Glacier Tongue. The black rectangular insets in panel (a) are panels (c) and (d), which show the crevasse distribution across the ice shelf regions in the TG basin, based on Landsat-8 satellite images

acquired in December 2020. The gray line is the basin boundary of the TG basin derived from Zwally et al. (2015).

- 6) **L55: Here I think there probably lacks a paragraph describing what diagnostic and prognostic modeling studies we currently have, and what kind of problems in those studies have by not including the damage mechanics in their models, before you move on to this paragraph introducing your solutions.**

Response:

Thank you for your suggestion. We have revised the introduction and added separate paragraphs discussing existing diagnostic and prognostic studies.

(Line 32–59): “...Several studies have investigated the influence of damage on the behavior of the Antarctic Ice Sheet (AIS). Borstad et al. (2012) applied a large-scale ice dynamical model to invert for damage on the Larsen B Ice Shelf prior to its collapse in 2002. They concluded that calving was triggered by the loss of load-bearing surface area due to fracturing. Albrecht and Levermann (2014) investigated the role of damage in softening ice across several Antarctic ice shelves using a fracture density field derived from observations. Gerli et al. (2023) demonstrated that the vertical propagation of crevasses within ice shelves can instantaneously increase the flux of upstream glaciers. Huth et al. (2021, 2023) integrated a creep damage model into a large-scale shallow-shelf ice flow model to simulate rift propagation leading to the formation of iceberg A68 from the Larsen C Ice Shelf. Damage is facilitated through hydrofracturing, and the combined effect of non-linear viscous rheology and damage processes within ice at water-filled crevasse tips can influence calving dynamics (Duddu et al., 2020). Sun and Gudmundsson (2023) conducted a series of numerical perturbation experiments to show that damage evolution significantly affects ice-shelf velocities and must be accounted for to accurately replicate observed velocity patterns. These studies reveal the interaction between damage processes and observed ice flow dynamics. They have one critical limitation, i.e., being diagnostic, which means that they investigate the instantaneous effect of damage on ice dynamics, but not the evolution of damage when ice thickness is allowed to evolve according to the applied changes. They therefore fail to predict future ice sheet behavior or feedbacks induced by external changes, such as fracture enhancement due to atmospheric or oceanic forcing.

Prognostic modeling enables the assessment of ice sheet and ice shelf evolution in response to fracture dynamics. However, most existing studies focus on idealized ice sheet geometries. Sun et al. (2017) coupled a continuum damage mechanics (CDM) model with an ice-sheet model based on the zero-stress Nye approach (Nye, 1957). Applying this model to an idealized ice-sheet geometry (MISMIP+; Cornford et al., 2020), they found that ice damage leads to greater grounding-line retreat compared to simulations without damage. Using the same model, Lhermitte et al. (2020) showed that intensifying damage at a specific location within shear

*zones triggers widespread propagation and amplification of damage, supporting the hypothesis of a positive feedback mechanism. By integrating a continuum damage mechanics model with necking instability into an ice sheet model, Kachuck et al. (2022) simulated the evolution of the damage field and accurately predicted steady-state extents for a series of idealized, isothermal ice tongues and ice shelves. Similarly, Ranganathan et al. (2024) developed a damage evolution model coupled with a marine-terminating glacier flowline model and showed that damage can enhance mass loss from both grounded and floating ice. However, the results obtained from idealized geometries may not fully translate to the real world conditions, and studies investigating the effects of ice damage on the dynamics of actual glaciers, such as Antarctic glaciers and ice shelves, remain limited....”*

**7) L76: “zero-stress assumption” might be better**

Response:

Thank you for your suggestion, this has been modified.

**8) L79: do not understand how you get  $d_1(\tau_1)$  even after looking at Appendix 1. Intuitively, it looks like to be  $\min((d_s+d_b), C_1*h)$ , i.e., the min value between the total crevasse depth and the limit you set. Can you provide more explanations?**

Response:

Apologies for the confusion. The equation of  $d_1(\tau_1)$  should be in the following form:

$$d_1(\tau_1) = \min(d_s + d_b, C_1 * h)$$

We use the parameter  $C_1$  to impose an upper limit to  $d_1(\tau_1)$  as a fraction of the ice thickness (with  $C_1$  ranging from 0 to 1), preventing an overestimation of crevasse depth in our gridded domain.

We have also corrected the equation and revised section 2.1 accordingly.

**9) L80: remove the comma after where**

Response:

Done.

**10) L83: remove extra () for  $d(\tau_1)$**

Response:

Done.

**11) L84: I need more details of  $d1(\tau_1)$  to understand this equation**

Response:

Please see the response to **comment L79**.

**12) L85: remove the comma after where**

Response:

Done.

**13) L92: change “steady state” to “steady-state”, same for other places**

Response:

Thank you for your comment. In alignment with both this suggestion and parallel feedback from other reviewers, we have revised the relevant sentence as follows:

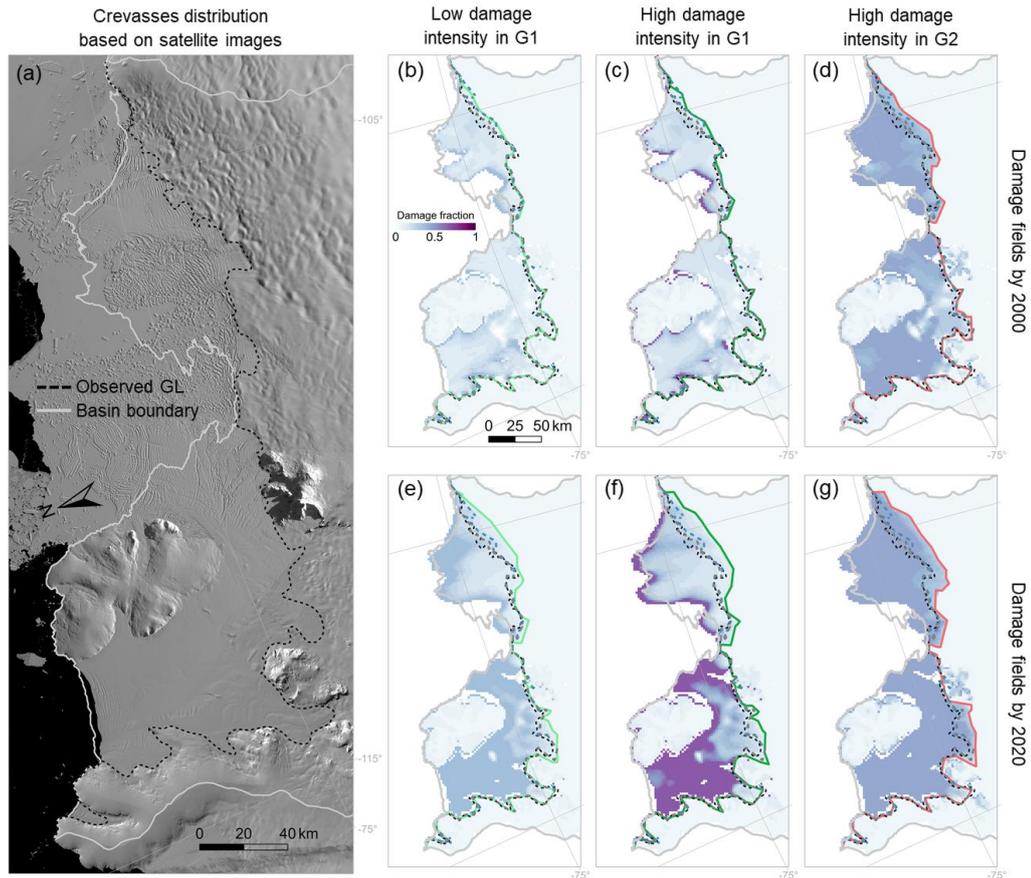
(Line 160–162): “...*In the damage sensitivity experiments, ice damage is activated from the first timestep of the historical simulation, meaning that the ice sheet is considered undamaged at the start of 1990. Given that this assumption is somewhat idealized, the simulated damage can be interpreted as relative to the initial state. ...*”

**14) L102-109: have you compared the modeled damage results to the observed crevasse distribution from satellite image? I think this is also important.**

Response:

Thank you for your suggestion. Figure 5 of the revised manuscript now allows for a comparison of observed and modeled crevasse distribution. The following statement has been included in the results section:

(Line 276–280): “...*Figure 5a presents the distribution of crevasses observed across the ice shelves of the TG basin, derived from Landsat-8 satellite images taken in December 2020. Our vertically averaged ice damage patterns tend to overestimate damage on the Dotson ice shelf, suggesting the need for a threshold stress parameter to better capture damage initiation. In contrast, ice fracture is underestimated in the Thwaites Western Glacier Tongue, likely due to the stabilizing influence of the Northwest pinning point (Surawy-Stepney et al., 2023). ...*”



**Figure 5.** Damage distribution in the TG basin. (a) Observed crevasses distribution across the ice shelves of the TG basin, based on Landsat-8 satellite images acquired in December 2020. Vertically averaged damage fields (i.e.,  $\mathbf{d}(\mathbf{x}, \mathbf{y})/\mathbf{h}(\mathbf{x}, \mathbf{y})$ ) in the year 2000 and 2020 of the low damage intensity of Group 1 (G1) are shown in (b) and (e); the high damage intensity of G1 in (c) and (f); and the high damage intensity of Group 2 (G2) in (d) and (g). The dashed black line is the observed grounding line (Gardner et al., 2018). The light gray line is the basin boundary of the TG basin derived from Zwally et al. (2015). The dashed gray and blue lines present the initial grounding-line positions of the Ctrl/damage experiments and the Ctrl<sub>dhd</sub> experiment, respectively.

The comparison with observations is also discussed in the Discussion section:

(Line 395–413): “...Our approach has the benefit of using a physical approach to infer crevasse formation. However, direct comparison with observation remains challenging, since the damage field is highly variable and corresponds to a particular time moment. Our results are highly dependent on the forcing and model uncertainties, which makes a direct comparison unfeasible. Moreover, modeled damage patterns are highly variable across ensemble members. These discrepancies may be explained by the limitations of the damage model. For example, our approach does not account for all mechanisms of damage healing, which may result in an overestimation of damage (Sun et al., 2017). In reality,

*crevasse healing can occur when shear stress along the flow path decreases notably (Wesche et al., 2013; Benn and Åström, 2018), and dense crevasses near the grounding zone may heal during their advection towards the calving front. However, studies on the process of ice healing are still scarce due to the challenges of monitoring and quantifying this process (Albrecht and Levermann, 2012). Additionally, a vertically-integrated model may not be appropriate for accurately representing crevasse formation mechanisms. The application of threshold stress for damage initiation as well as mechanisms of crevasse healing, such as the accretion of marine ice within basal crevasses, should be explored (Sun et al., 2017). The lack of representation of plastic necking (Bassis and Ma, 2015) also introduces uncertainties in our results. While the comparison of modeled, vertically integrated damage fields with snapshots of surface crevasses is not straightforward, these discrepancies underline the need for further validation and calibration of the damage model. Instead of solely relying on ice sheet mass loss data, future efforts should incorporate observational datasets of crevasse distributions. Moreover, while the simulated historical state of the TG basin is overall consistent with observations, the 1995–2014 mean boundary conditions used to initialize the model and simulate hindcasts for 1990–2020 (Kittel et al., 2021; Schimdtko et al., 2014) do not necessarily reflect the actual imbalance of the ice sheet during that period. ...”*

**15) L110-116: What are the forcings for the experiments Ctrl and Ctrl\_cal?**

Response:

All simulations in our study, including experiments Ctrl and Ctrl<sub>cal</sub> (renamed 'Ctrl<sub>dht</sub>' in the revised manuscript for clarity) are forced with constant present-day conditions, using the present-day surface mass balance and temperature obtained from the polar regional climate model MARv3.11 (Kittel et al., 2021) and present-day ocean temperature and salinity derived from data provided by Schimdtko et al. (2014).

This has been clarified in the revised manuscript.

**Do you calibrate the forcing data for Ctrl\_cal in order to reproduce the historical trend of ice mass change? If so, how do you do the calibration?**

Response:

To reproduce the dynamic disequilibrium observed during the historical period in the 'Ctrl<sub>cal</sub>' experiment (renamed 'Ctrl<sub>dht</sub>' in the revised manuscript for clarity), we apply the initialization method described in van den Akker et al. (2025). Specifically, the initial state of the Ctrl<sub>dht</sub> experiment is obtained by adding a 'correction term' - equal to minus the observed mass change rates - to the present-day surface mass balance during the transient nudging procedure. This ensures that by the time the nudging procedure has achieved a constant geometry, the model has been trained to produce ice fluxes that closely match observations. In other

words, the ice sheet model is ‘trained’ to equilibrate toward a state where observed mass change rates are implicitly accounted for.

We have also revised the related sentences to make it clearer.

(Line 163–168): “...*To reproduce the dynamic disequilibrium observed during the historical period, we apply the initialization method of van den Akker et al. (2025). Specifically, the initial state of the Ctrl<sub>dhd</sub> experiment is obtained by adding a ‘correction term’ – equal to minus the observed mass change rates (taken from Bevan et al., 2023) – to the present-day surface mass balance (Kittel et al., 2021) during the transient nudging procedure. This ensures that, by the time the nudging procedure has achieved a steady geometry, the model has been trained to produce ice fluxes that closely match observations. In other words, the ice sheet model is ‘trained’ to equilibrate toward a state that implicitly accounts for observed mass change rates. ...*”

van den Akker, T., Lipscomb, W. H., Leguy, G. R., Bernales, J., Berends, C., van de Berg, W. J., and van de Wal, R. S. W.: Present-day mass loss rates are a precursor for West Antarctic Ice Sheet collapse, *The Cryosphere*, 19, 283–301, doi:10.5194/tc-19-283-2025, 2025.

### **What is the time span for the historical runs?**

Response:

The time span of the historical simulations is 30 years from 1990 to 2020. We have clarified that in the revised manuscript.

### **16) L119: what is the RMSE for grounding line position?**

Response:

We calculated the mean distance between the modeled grounding-line positions and the observed grounding-line position based on the “open-ended box” method proposed by Moon and Joughin (2008). We have clarified this in the revised manuscript.

(Line 176–178): “...*In addition, we estimate the mean distance between the modeled and observed grounding-line position using the “open-ended box” approach of Moon and Joughin (2008). ...*”

We have also added the information about modeled grounding-line position for the Ctrl and the Ctrl<sub>dhd</sub> experiments into the revised manuscript:

(Line 181–182): “...*The modeled grounding-line position of the TG basin is in good agreement with observations (Gardner et al., 2018), with an average offset of 1.3 km. ...*”

(Line 184–185): “...*The modeled grounding-line position also closely aligns with observations, with an average offset of 2.3 km. ...*”

**17) L120: I do not follow the sentence “At the start of the historical run, the present-day SMB is reinstated without the additional mass-change term”. Can you explain it a bit more?**

Response:

As developed in the response to comment 15), the initial state of the Ctrl<sub>dhd</sub> experiment is obtained by adding a ‘correction term’ - equal to minus the observed mass change rates - to the present-day surface mass balance during the transient nudging procedure. This correction term is removed from the surface mass balance at the start of the historical run. As a result, the ice will start to thin/thicken at (almost) exactly the observed rates. That is, the model will reproduce per construct the observed mass-balance rates as a drift.

**18) L124: So no CMIP projection forcing data? Then we should be careful to conclude a GMSL contribution from this study, as it is more like a comparison (damage v.s. no damage) study.**

Response:

Indeed, it is important to underline that this study does not aim to produce sea-level projections. Instead, we focus on testing the influence of ice damage on the Thwaites Glacier basin under constant present-day climate conditions. Our sensitivity experiments thus allow us to quantify TG’s mass loss response to the damage feedback mechanism.

To clarify this, we have shifted the focus away from GMSL, instead emphasizing relative mass changes, throughout the manuscript.

**19) L129: how do you do with the basal melt rates for previously grounded the regions after they become floating as GL retreats? Do you couple the PICO model with the ice sheet model?**

Response:

Yes, the basal melting underneath the floating ice shelves is estimated at each time step using the PICO model of Reese et al. (2018).

**20) L141: 43-member?**

Response:

Correct, thank you for spotting this.

**21) Section 3.1: There are something I do not understand in this part. For Ctrl<sub>cal</sub>, you can actually calibrate the forcing and let the modeled and observed mass**

**change match each other, even you do not turn on the damage mechanism, correct? But from Fig 2a, clearly there is still some disagreement between Ctrl\_cal and the observations. Why is that?**

Response:

Thank you for your question. By integrating the observed mass change rates during the initialization procedure (Ctrl<sub>dhd</sub>t), the modeled and observed mass changes can indeed be matched, even without activating the damage mechanism.

First, it is important to clarify that the observational data used for the initializing procedure of the Ctrl<sub>dhd</sub>t experiment and those used for validation in Figure 2 are not the same. For the model initialization, we use 2D satellite-based data of present-day ice mass change rates in the TG basin (Bevan et al., 2023) to correct the present-day surface mass balance. For the validation in Figure 2, we use satellite-derived observations of the sea-level contribution between 1992 and 2017, spatially-aggregated over the basin, from Shepherd et al. (2019).

Your comment likely stems from how the observations were initially represented in the figure, which was not optimal. We now have adjusted the figure by representing the observations as an error bar on the right side of the plot. This hopefully now better shows that the Ctrl<sub>dhd</sub>t captures the observational trends well.

**For G1 and G2, basically what you do is damage parameter calibration, and you can find some parameter combinations that can give a good model output. But how can you tell the difference of model and observations is not from the bias of the forcing data you use, but is due to the damage mechanism? That is the point I am still confused.**

Response:

Thank you for your comment. To quantify the impact of the damage mechanism, we conducted two baseline experiments (Ctrl and Ctrl<sub>dhd</sub>t) excluding damage throughout both the historical and projection simulations. All experiments (with or without damage) are forced with constant present-day climate conditions.

The Ctrl experiment starts from the same initial state as the 43-member ensemble that includes damage. Comparing these simulations therefore allows us to assess the influence of damage on the evolution of the TG basin. Our historical simulation results show that when damage is considered (G1), the simulated sea-level contribution (SLC) and net mass balance align well with observations, whereas the Ctrl experiment fails to reproduce the observations accurately. This indicates that the mass balance trend of G1 is induced by the damage feedback rather than by a bias in the forcing. That said, we acknowledge that no model is perfect -- a simulation may match the observations for the wrong reason, just as it may diverge from them despite incorporating relevant physics (here, damage parameters). To account for this, we deliberately adopted a flexible calibration approach, including G1 simulations that fall within  $\pm$  twice the observational error.

Note that the Ctrl<sub>dhd</sub>t experiment does match the observations, but because its initial

state was explicitly adjusted to equilibrate toward a state that implicitly accounts for observed mass change rates.

**That is another reason that I think a comparison between modeled damage value and observed crevasse distribution is necessary.**

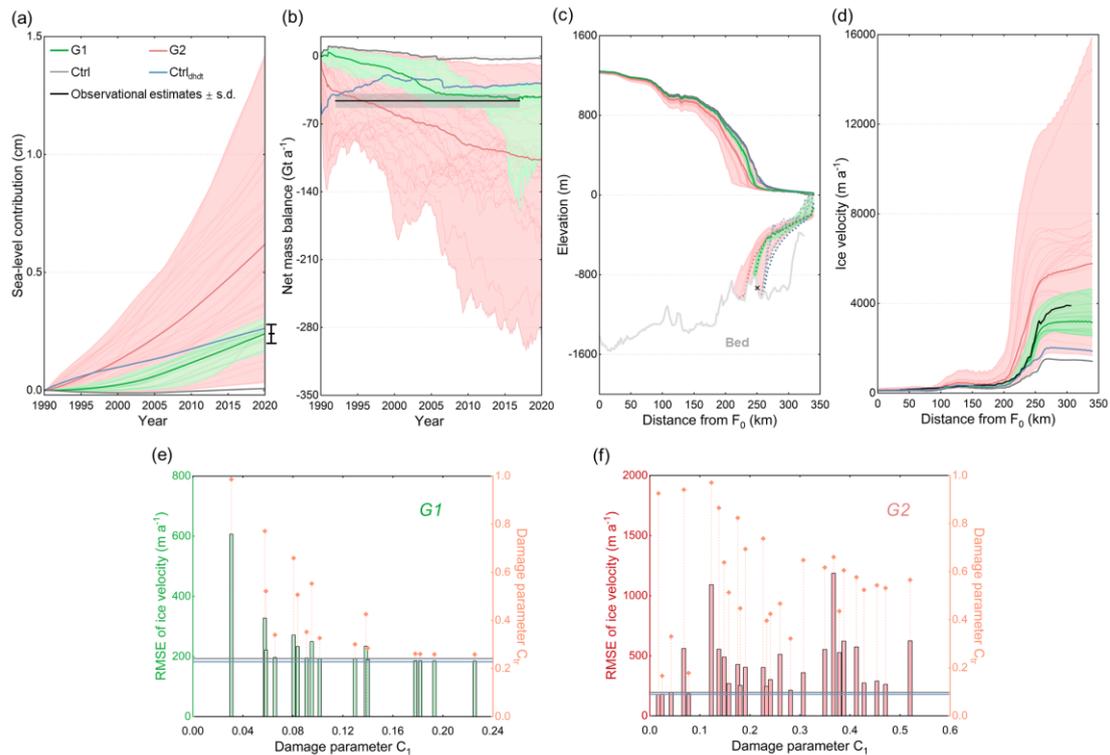
Response:

Agreed. Please see our response to **comment 14**) above.

**The current form of Fig 2 needs improvements too. It is hard to tell those curves for G1 and G2. I would suggest to keep only several curves that are close to observations, and put the whole ensemble somewhere in the Appendix.**

Response:

Thank you for your comment. To improve the clarity of Figure 2, we have added hatched areas showing the range (i.e., the spread between the minimum and maximum values) for the G1 and G2 ensembles (see below).



**Figure 2.** Simulated change trends of ice mass balance and grounding-line position in the TG basin under different damage intensities over the period 1990–2020. (a) the simulated contribution of ice mass loss in the TG basin to sea level; (b) the net mass balance (considering volume above flotation only, i.e., the rate of mass change contributing to sea-level rise) in the TG basin; (c) the geometry profiles along the central flowline profile (solid black line in Fig.1) and the simulated (dashed red and green lines) grounding-line positions; (d) the simulated ice velocity along the central flowline profile. RMSEs between the simulated and

observed ice velocity under different parameter combinations of  $C_l$  and  $C_{tr}$  in (e) Group 1 and (f) Group 2. The dark red and green lines in panels (a)–(d) represent the mean, and the hatched area represents the ensemble range, i.e., spread between maximum/minimum values. The black lines and shaded areas in panels (a) and (b) represent the observed mean value  $\pm 1$  standard deviation (Shepherd et al., 2019). The gray line represents the simulation result of the model that ignored ice damage processes and did not integrate satellite-based observations of present-day mass-change rates to constrain the model initialization (Ctrl experiment), and the blue line represents the simulation result of the model that ignored ice damage processes but integrated satellite-based observations to constrain the model initialization (Ctrl<sub>dhd</sub> experiment). In panel (c), the dashed light gray and blue lines represent the initial grounding-line positions for the Ctrl/damage experiments and the Ctrl<sub>dhd</sub> experiment, and the black cross marks the location of the observed grounding-line position (Gardner et al., 2018).

**22) L176-192 and Fig 3: So this part explains again my concern for Section 3.1. The RMSE of Ctrl\_cal is even smaller than G1-G15. Does that mean we can calibrate the forcing data, e.g., basal melt rates, to get a better hindcast modeling result than tuning the damage parameters, or can we say that forcing is more important than damage?**

Response:

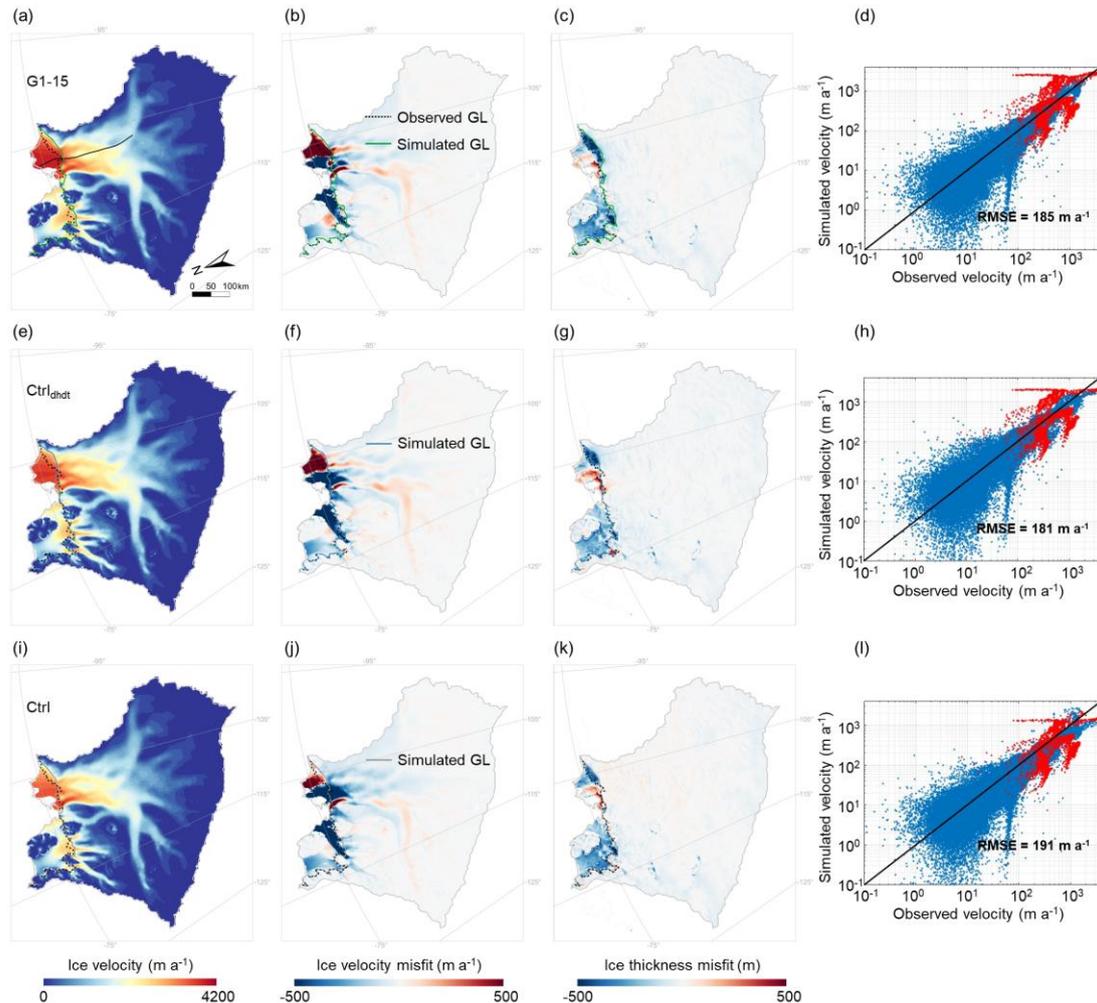
Thank you for your comment. The initial state of the Ctrl\_cal (now Ctrl<sub>dhd</sub>) was explicitly adjusted to equilibrate toward a state that implicitly accounts for observed mass change rates. Given this, it is not surprising that it results in a smaller RMSE compared to the other experiments. However, such a simulation does not capture the driving mechanisms behind the mass change. In particular, it does not account for damage feedback mechanisms which, as we show, can have a strong influence on ice dynamics. Observations from satellite remote sensing highlight the widespread distribution and dynamic evolution of crevasses and rifts in the ice shelf and shear zones of Thwaites Glacier. This suggests that while the specific initialization procedure of Ctrl<sub>dhd</sub> may improve the agreement with observations and hence better reproduce short-term mass loss, it does not necessarily remain valid on the long term given that it does not account for key processes which may have a significant influence on future ice loss.

As our results show, the long-term projections of Thwaites Glacier's evolution over 2020–2300 in the Ctrl<sub>dhd</sub> experiment differ significantly from those produced when explicitly including ice damage (Figs. 6 and 7). Specifically, simulations accounting for ice damage predict more than twice the ice mass loss than the Ctrl<sub>dhd</sub> experiment (Fig. 6).

**In Fig 3, I would also like to see the comparison of modeled and observed ice thickness data, which is a also very important information, or you might consider to add an additional figure for thickness.**

Response:

Thanks for your suggestion. We added panels (c), (g), and (k) showing the difference between the modeled and observed ice thickness in Figure 3 (now appears as Figure 4 in the revised manuscript):



**Figure 4.** Simulated ice velocity and ice thickness under different simulation experiments over the historical period 1990–2020. G1-15 denotes the simulation experiment in the ensemble of Group 1 ( $C_l=0.23$ ,  $C_{lr}=0.26$ ) that gives the most accurate (lowest RMSE) ice velocity simulation results. The Ctrl<sub>dhdt</sub> and Ctrl are the two simulation experiments of the model with deactivated damage processes (see Sect. 2 for details). (a), (e), and (i) show the spatial distribution of simulated ice velocity in the TG basin of different simulation experiments. (b), (f), and (j) show the difference between simulated and observed ice velocities. (c), (g), and (k) show the difference between simulated and observed ice thickness. (d), (h) and (l) show the comparison between simulated and observed ice velocities at each grid cell in the TG basin, with blue and red dots representing the grid cells of grounded ice and floating ice, respectively. In all maps, the dashed black lines are the observed grounding line (Gardner et al., 2018), the solid lines are the simulated grounding lines, and the light gray line is the basin boundary of the TG basin

*derived from Zwally et al. (2015). The solid black curve in (a) is the central flowline profile stemming from the Antarctic surface flowline dataset developed by Liu et al. (2015)....*”

**23) Section 3.2: I’ll hold my opinions for this section for now, as I do not see much information about SMB and basal melt forcings, e.g., if you use a coupling scheme between ice sheet and ocean model or you use a some parameterization approach. Before I have these information, I can’t tell how meanful the projection numbers are in this section.**

Response:

All the simulations in Section 3.2 are continued from the historical state in 2020, i.e., under constant present-day climate conditions. We have thoroughly revised sections 2.2 and 2.3 and hope this clarifies our methodology.

As mentioned above, we would like to underline that this study does not aim to produce sea-level projections. Instead, we focus on testing the influence of ice damage on the Thwaites Glacier basin under constant present-day climate conditions. Our sensitivity experiments thus allow us to quantify TG’s mass loss response to the damage feedback mechanism.

**24) Figure 6: you do have the current damage field. Then I think you probably want to compare them with some satellite images of crevasses. I think it is important for us to understand if the damage method you use is valid or not.**

Response:

Agreed. Please see our response to comment 14) above.