Reviewer #1

Overall, I find the manuscript to be a very well written and clearly presented investigation into the impact of using one of five different calving on the future behaviour of the calving front of three Greenlandic ice shelves. This is a very topical and impactful area of research, as our ability to simulate ice shelf calving is a known area of uncertainty when making predictions for how ice sheets will respond to a warming climate. I am happy to recommend publication, provided my comments can be addressed.

Thanks for taking the time to review our manuscript and providing valuable constructive feedback. We have responded to all comments below in blue.

Firstly, we would like to point out that the calving calibrations figures 2 (Petermann) and 3 (Ryder) in the original manuscript submission were missing results of the PD parametrisation. This was due to a mistake when compiling the file in overleaf. We have included the correct figures at the bottom of this response and apologise for the mistake.

My first comment is that the calibration exercise does not currently show the impact of calving front shape on ice discharge (although this can be inferred from time 0 on Fig7). It might be good to have a figure showing this.

Currently you are tuning to minimise the misfit in total shelf area. Potentially, this could result in a shelf front being greatly advanced on one side of the domain whilst retreated by the same amount on the other. This is likely to have a quite different amount of buttressing when compared to a shelf position that is everywhere on the observed position, despite similar misfits. It can also potentially ignore an ice shelf that has detached from a lateral boundary. For example, the observed position of Petermann in Fig 2(i) compared to the MT law on the left hand boundary. Perhaps incorporating a comparison to observed discharge rates in combination with the area match might be a better metric for calibration?

Thank you for raising the topic of velocities. You are correct that when evaluating the performance of a calving law it is useful to consider changes in both ice dynamics and terminus positions. That said, we only find subtle differences in ice velocities and grounding line discharge between the different calving laws tested at the three ice shelves (Figures 1, 2 and 3 below). As discussed in the manuscript, this is because most of the buttressing from Greenlandic ice shelves occurs closer to the grounding line, so fluctuations around the contemporary terminus positions don't result in pronounced ice velocity changes. While it is possible for our misfit metric to be *confused* by a shelf front that greatly advances on one side and retreats on the other, we do not observe such behaviour from our calving calibration tests.

Furthermore, changes in shelf velocities and discharge rates may be influenced by factors other than calving. For example, both Petermann and 79N have seen a rise in discharge rates over recent decades linked to an increase in submarine melt under the shelf and near the grounding line (Ehrenfeucht et al., 2024; Wekerle et al., 2024). As climatic forcings are kept stable during our calibration simulations, adding a velocity component to the misfit metric may bias towards greater calving of the ice shelf.

As such we are inclined to stick with our current misfit metric that focuses on terminus position which also includes a qualitative discussion on terminus shape. This is in-line with other calving comparison papers (Amaral et al., 2020; Choi et al., 2018; Wilner et al., 2023), and plan to include the figures of velocity difference in the supplementary material.

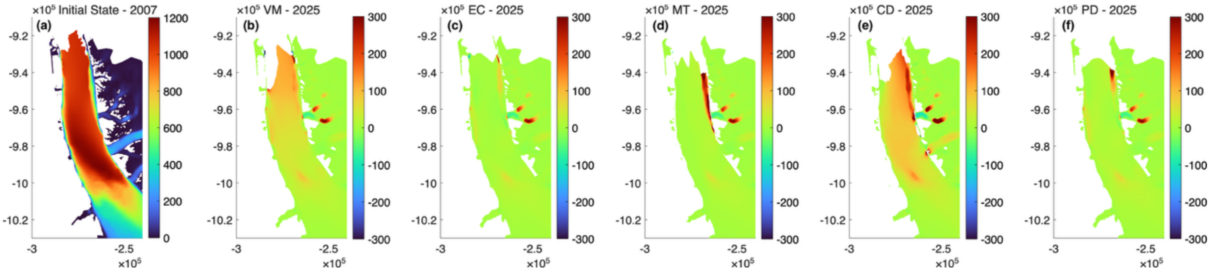

Figure 1 - Comparison of ice velocities (in m/a) between the different calving laws at Petermann Glacier. (a) Initial velocities after model relaxation. Change in ice velocities during the calibration simulation for (b) VM, (c) EC, (d) MT, (e) CD and (f) PD.

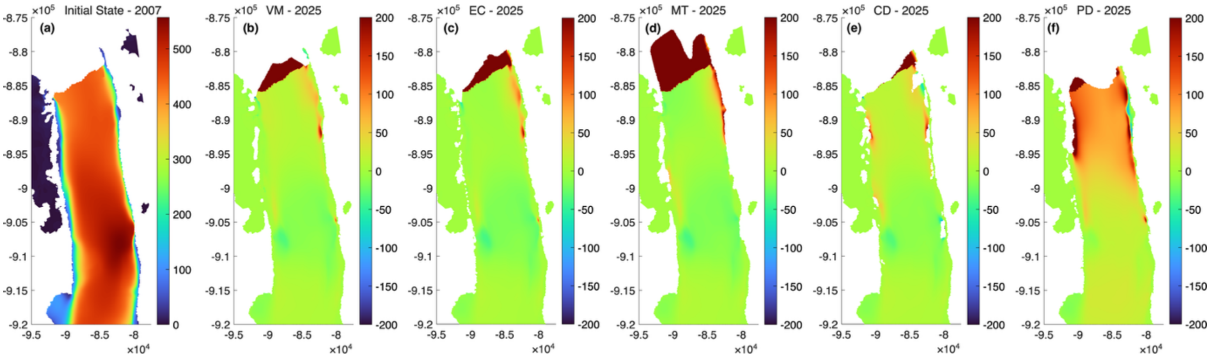

Figure 2 - Comparison of ice velocities (in m/a) between the different calving laws at Ryder Glacier. (a) Initial velocities after model relaxation. Change in ice velocities during the calibration simulation for (b) VM, (c) EC, (d) MT, (e) CD and (f) PD.

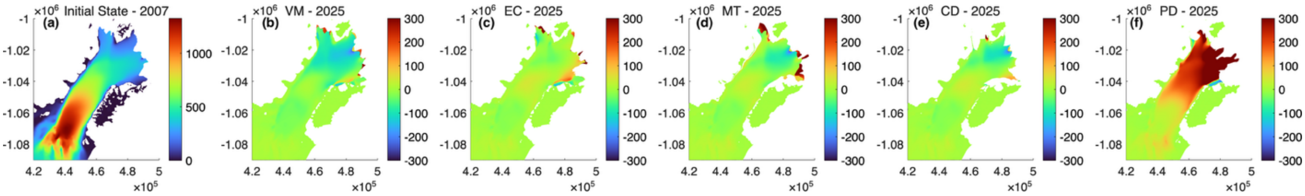

Figure 3 - Comparison of ice velocities (in m/a) between the different calving laws at 79N. (a) Initial velocities after model relaxation. Change in ice velocities during the calibration simulation for (b) VM, (c) EC, (d) MT, (e) CD and (f) PD.

My second comment is in regard to the melt profiles used for forcing. My understanding is that all simulations have a minimum melt layer that never experiences any melting near the surface. Whilst I gather this is a good match to present day observations, can you comment on how likely this is to continue in a warming climate? Do you see any evidence of ice thickness at the calving front being strongly linked to your choice of this minimum melt layer (is it ~110m at Ryder to match the minimum melt depth, for example)? Perhaps a figure showing flow line profiles of ice thickness could help here. Do you results appear unduly influenced by the choice of the size of this melt layer?

Thanks for highlighting some of the confusion around the applied melt rate profiles; similar comments were given by reviewer #2. We confirm that the minimum melt layer at the surface of our profile does increase with melt in the *ocean*Full scenario and apologise this was not clear in the original manuscript. In our revised manuscript, we will include a new figure that describes the initial melt profiles at the three ice shelves as well as the effect of scenarios *ocean*GL and *ocean*Full on the melt rates at 79N (Figure 4). Furthermore, we have re-writen the description of melt profiles in our methodology section as follows:

"We apply this increase linearly but through two different experiments. Firstly, to isolate the effects of increased melt near the grounding line, the highest melt rates in the linear depth profile are increased while maintaining zero melt in shallow waters. Secondly, the entire melt profile beneath the shelf is increased uniformly. These scenarios are referred to as oceanGL and oceanFull, respectively (Fig. 2d-e)."

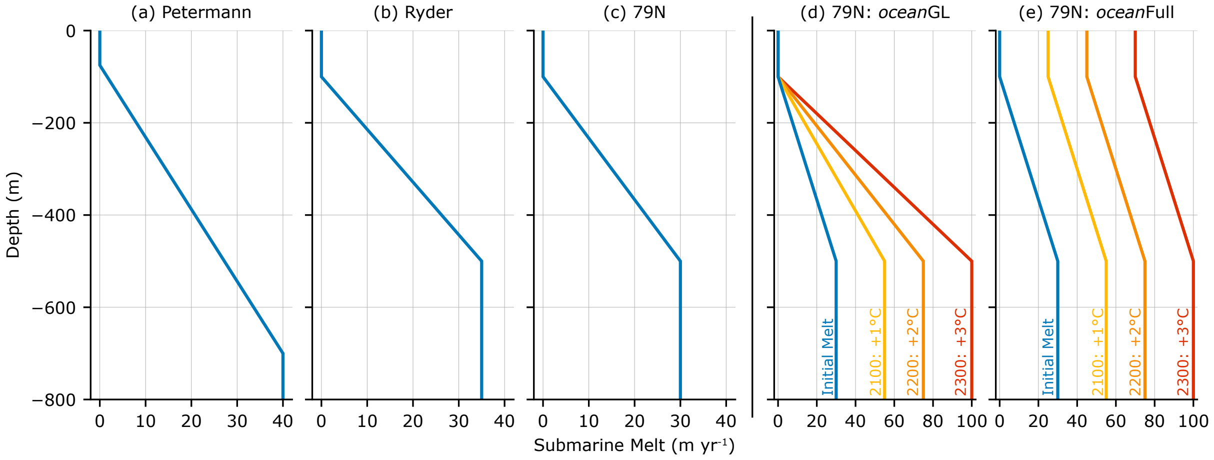

Figure 4- Initial ocean melt profiles for (a) Petermann, (b) Ryder, & (c) 79N ice shelves. Perturbed ocean melt rates for the (d) oceanGL and (e) oceanFull scenarios are shown for 79N.

Line comments/typos below.

L103: Can you comment on the different melt profiles used for Petermann and Ryder, despite them being so geographically close to each other? Are the different profiles assumed to be a result of differences in ocean forcing or due to the shape of each ice shelves cavity?

Yes of course. We agree, it's interesting that the melt profiles differ despite their proximity. This is likely because of both ocean forcing and cavity geometry. At Ryder Glacier, a bathymetric sill in Sherard Osborn Fjord shields the glacier from the influence of warm deep Atlantic Waters. This is not the case in Petermann Fjord which may explain the higher maximum melt rates (Jakobsson et al., 2020). At Ryder, the ice shelf cavity is smaller in both length and width than Petermann and the grounding line is ~150 m deeper, this may contribute to the slightly steeper melt rate profile. While these are interesting points, we feel like they are outside the scope of the paper and prefer not to include them in the manuscript.

L111: How often is this limiting maximum migration rate used in the simulations? For an example, is there an approximate percentage of time for the run where this maximum is reached?

Unfortunately, we don’t have a metric that records the percentage of time where the maximum migration rate is enforced but it appears to be rarely used, if at all. We included this restraint in all simulations as a precaution against unrealistic large terminus retreats, but, as our results show, the ice shelves are quite stable, and excessive retreats are very uncommon.

L115: For clarity, define whether a positive calving rate advances or retreat the front position.

A positive calving rate retreats the ice front. This will be added for clarity.

L115: In which direction is this calving rate applied? Perpendicular to ice geometry at the calving front, or antiparallel to ice velocity at the calving front?

The calving rate is applied perpendicular to the calving front (following level-set gradients). This will also be added to manuscript.

L130: For the Crevasse Depth and Minimum thickness laws. Are these applied at every model time step or some longer interval? (Monthly, Yearly, etc)

Both the CD and MT laws are evaluated at every time step.

L189: "kept fixed in our"

Fixed. Thanks for noticing.

L200: To clarify, does this mean that all simulations still maintain their minimum melt sections of 0 melting during these warming scenarios? If so, the term oceanFull may be a little misleading.

We hope we have clarified the melt rate scenarios in the above comments, and shown that the minimum melt section of 0 does increase with *ocean*Full.

L209: Are there any cases where you chose a parameter that gave you a qualitatively better match to ice front position even if the quantitative misfit value was worse?

This is a good question. There aren’t any cases where a qualitative misfit appears better than our quantitative misfit. We attribute this to a consistent style/mode of calving across the different calibration values used for each calving law. Take, for example, VM at Ryder Glacier, where different calibration values result in an advance or retreat of the central ice shelf but maintain similar shelf edge positions. Or PD at 79N, where the extent of retreat is impacted by the calibration value, but the shape of the ice shelf remains very consistent. Therefore, as the calving style remains generally consistent across the different calibration values our quantitative misfit does well in capturing the *best* calibration value.

L295: In the static case for Petermann, VM has a greater front retreat rate than CD during the 2100s, and yet CD has a greater retreat of the grounding line. Can you comment on this?

Thanks for raising this; it is an interesting result of two different calving behaviours. For CD, there is greater calving on the eastern side of the shelf, which causes it to detach from the fjord walls while the centre and western side of the shelf remain extended. This is not captured in the figure, where a central flowline tracks ice front and GL position movement, but is instead in the 2D aerial view of front position changes (Fig. 6d, S2d & S3d in the manuscript). This uneven calving reduces lateral friction and promotes ice acceleration which in turn leads to grounding line retreat. In contrast, VM retreats the shelf in a uniform manner, where both sides remain attached to the fjord walls and buttressing is upheld. This was briefly touched on with Lines 291 – 294 in the original manuscript and we plan to add that VM (and EC) retreat with a maintained connection to both fjord walls.

L328: Should velocities be ice discharge here?

Yes, this has been corrected. Thanks for highlighting.

L331: VM and EC appear the best on average, but do noticeable worse on Petermann. Can you comment on this?

Yes, they do appear to do relatively worse at Petermann compared to the other laws. For EC, we attribute this to a decrease in lateral strain rates as Petermann Glacier currently terminates in a narrowing section of the Fjord. As the law has a first-order dependency on the strain rate tensor, it performs badly when a glacier does not terminate in an unconfined embayment, unlike at Ryder and 79N ice shelves. This is why we caution against using the law for the future ice shelf retreat at Ryder and 79N, as it is unable to retreat Petermann's front to match observations (Lines 345-355 in the original manuscript).

Regarding VM, there is a tendency for greater calving on the western side of Petermann's ice shelf. We attribute this to high velocities at the fjord walls that cause particularly high strain rates. In contrast, the eastern side of the shelf has a much more gradual velocity change towards the margin, and relatively slow-moving ice at the shelf edge (Figure 5). As the VM law relates the calving rate to velocity this likely explains why greater retreat occurs at the western-side of Petermann.

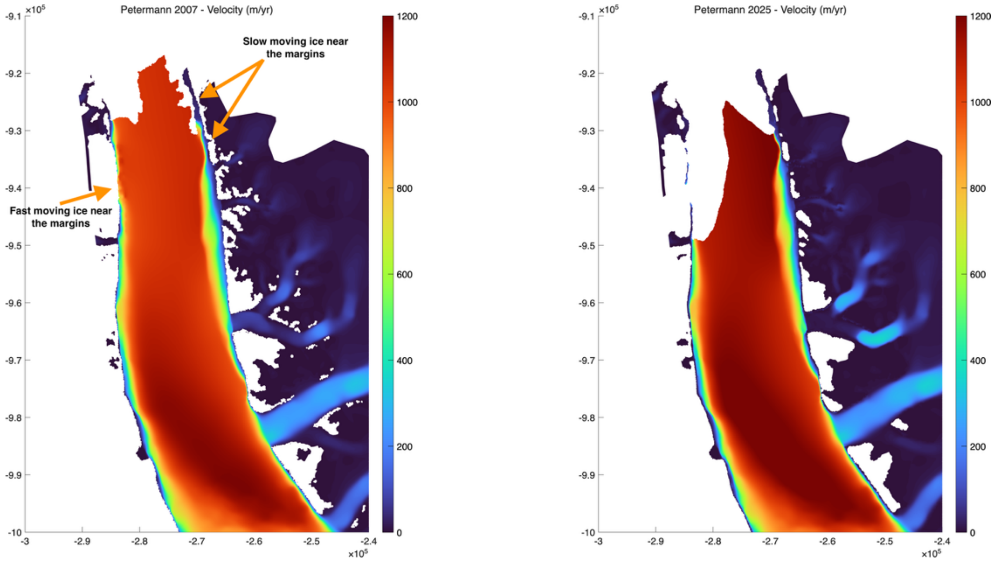

Figure 5 – Ice velocities at the beginning (2007) and end (2025) of the calibration simulation for the Von Mises calving law.

L395: Is it unreasonable to calibrate for individual Glaciers in large scale ice sheet simulations? It will certainly be more work, and will require some technical challenges around the boundaries between different glaciers, but I don't foresee any absolute barriers to doing so. Your results from just three glaciers already imply differences in how each law performs at different glaciers.

Thanks for raising this. It is correct that it is certainly possible to tune a calving law to every Greenlandic Glacier. While it might be cumbersome and time consuming there are no technical barriers that prohibit it. The idea of this paragraph was to highlight how it is much more advantageous if a calving law functions well with the same calibration value across different glaciers. We have therefore re-written the paragraph to show this:

While it is possible to tune a calving law on a glacier-by-glacier basis for large ice sheet simulations (e.g Choi et al., 2021), it is preferable to use a parameterisation that performs well across different glacial settings with a single, consistent calibration value. For this reason, we would recommend either the VM or the CD calving law. Both performed well in our calibration simulations and can utilise similar tuning values across three remaining Greenlandic ice shelves, assuming that the ice sheet model is able to discriminate between floating and grounded ice.

L448 able to parameterise

Thanks, will be corrected.

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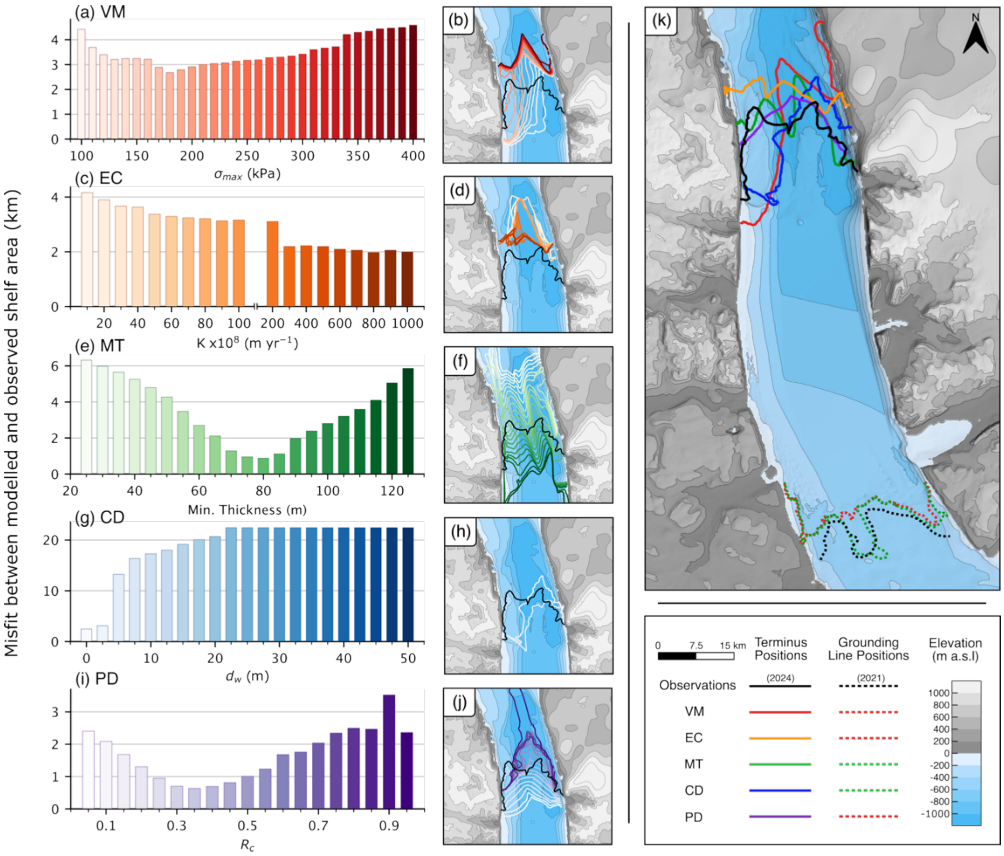

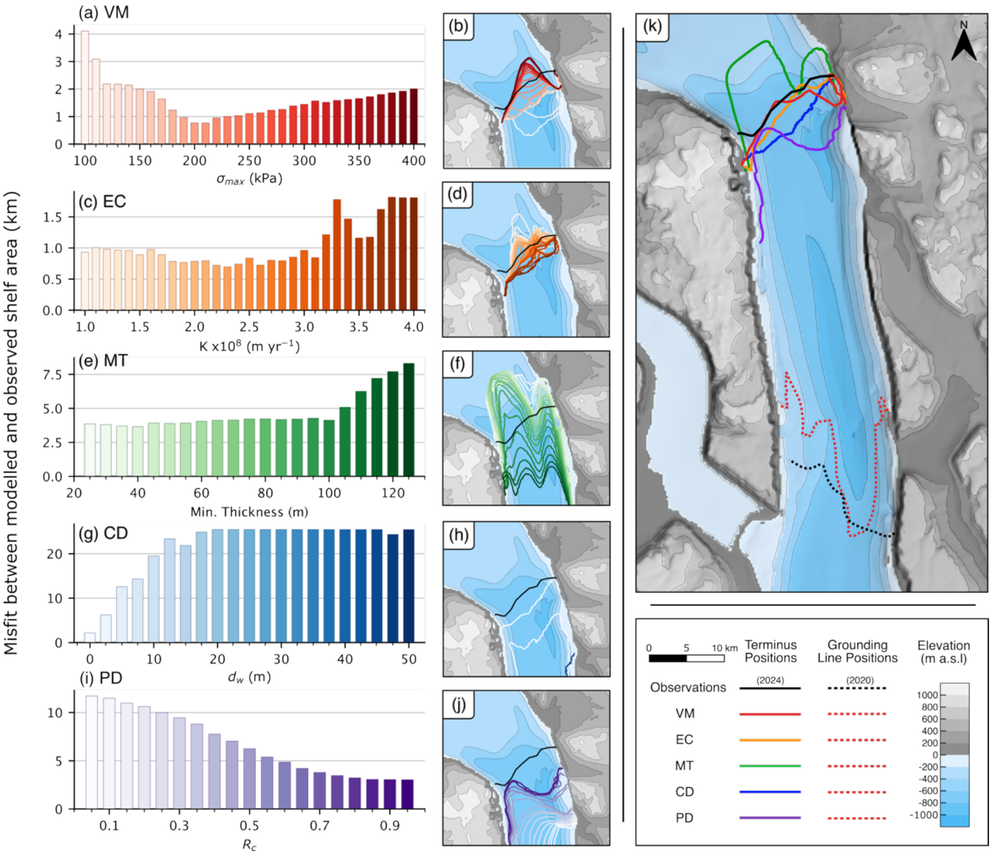
Misfit between modelled and observed shelf area (km)
(a) VM
σ_{max} (kPa)
(c) EC
K x10^8 (m yr^{-1})
(e) MT
Min. Thickness (m)
(g) CD
d_w (m)
(i) PD
R_c
(b)
(d)
(f)
(h)
(j)
(k)
N
0
5
10 km
Terminus Positions
Grounding Line Positions
Elevation (m a.s.l)
Observations
(2024)
(2020)
VM
EC
MT
CD
PD
1000
800
600
400
200
0
-200
-400
-600
-800
-1000