Modeling the response of Northwest Greenland to enhanced ocean thermal forcing and subglacial discharge – Response to reviewers –

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We thank Andy Aschwanden and an anonymous reviewer for their very constructive and insightful comments. We address their remarks below point by point.

1 Reviewer #1: Andy Aschwanden

This is an important and relevant paper as it extends previous efforts by the same group from a single outlet glacier to a regional view. It certainly deserves publication after some polishing of the text. While the science is sound, the writing is relatively poor and sloppy, with many typos and grammatical errors. It seems the manuscript was put together in a haste and would have benefited significantly from a round of proof reading before submission (see all my technical comments).

We thank the reviewer for his comment, and apologize about the typos that were in the manuscript, despite the proofreading from all authors before the initial submission.

The methods and data section need polishing and clarification: Please explain more carefully how subglacial discharge and thermal forcing are applied, are these daily or monthly forcing, or annually averaged? Is the subglacial discharge averaged over a certain time period like the surface mass balance?

They are both monthly averaged, we added this to the main text.

What is the resolution and the time step of the model? Since it's an unstructured grid, please inform the reader of the minimum and maximum cell size.

Done (between 100 m and 1 km and 7-day time step)

Equation 2 uses ambiguous notation. First, TF should not be used as a variable because it could mean TxF, how about something like T_h? I realize that this kind of sloppy notation has become more widespread in the glaciological literature over the past few years, and that the authors want to use the same notation as previous publications.

We indeed tried to use existing notations. We replated TF by $\tilde{T}$.

Second, it took me several readings to understand that $q_{sg} \times 1$ and TF +1°C is a shorthand for anomalies. The problem with this is that it is unclear when the authors talk about the initial (present day) forcing, and when anomalies are meant. I think what the authors are doing is something like this:

$$\dot{M} = (Ah(q_{sg}(x,y)q_a)^{\alpha}(t) + B)(T_h(x,y) + T_a(t))^{\beta}, \tag{1}$$

where $q_a(t)$ and $T_a(t)$ are multiplicative and additive time-dependent scalar anomalies, respectively. Use of a notation like this would improve clarity.

This is an excellent point, we added this equation to the manuscript in the "Experiments" section and discuss anomalies accordingly.

Regarding climate (surface mass balance) forcing: Why do you use the 1960-1991 average surface mass balance? This could possibly effect both the calibration and the projections. The 1960-1991 average was longer than today, thus to match the observed frontal retreat, your calibration procedure for the ocean forcing will have to compensate. Furthermore, use of the 1960-1991 average SMB for projections is questionable and as a consequence, one has little confidence in the sea-level contribution (Figure 5). As the focus of this paper is on glacier front retreat, I wonder if I'd be best to remove Figure 5 (and related text)? I do not think the manuscript would lose anything.

We decided to use the 1960-1991 average surface mass balance as this was a period for which the Greenland ice sheet was approximately in equilibrium and we wanted to conduct here a sensitivity study with respect to ice front dynamics. We therefore want to isolate the frontal forcing. The simulations shown here are not projections, but compare the effect of an increase in TF or q_{sg} on ice front dynamics, and how this translates to mass loss. We tried to calibrate the models with different SMB fields and the rate of retreat was not significantly sensitive to the surface mass balance used over the hindcast period. We decided to keep Figure 5, to highlight the fact that ice front dynamics can account for large mass losses, but revised the text slightly to highlight the fact that with projected SMBs, the mass loss would be even greater.

Detailed comments

p 1, l 8: Northwest → northwest

Done

p 1, l 13-14: "While these parametrizations are approximations..." this statement is almost universally true and I thus suggest to remove it from the abstract with any loss. How about "These parametrizations have shown to provide reliable estimates..."

We removed the sentence based on reviewer #2's comments.

p 1, l 17: include the year. The 50km retreat occurs from present day until year 2100, otherwise the reader might think the glacier retreats 50 km over the course of 15 years.

Done

p 2, l 9: remove comma. "...the rate of undercutting at the calving face..."

Done

p 2, l 11-12. Rephrase "We don't...", this sentence does not make much sense to. Or leave the sentence out?

We removed the sentence.

p 2, l 20-21: It remains unclear, however, to which extent glaciers of the...

Rephrased.

p 2, l 30-31: "While a lot of progress has been made in terms of capturing ice flow through the development of new, higher-order stress balance solvers, ..." I respectfully disagree with this statement; significant progress was due to the availability of more accurate ice thickness instead. I'm not aware of a publication that demonstrates that higher-order stress balance solvers have greatly improved our ability to capture ice flow on a continental scale.

We agree with the reviewer that the improvement in bed topography (and higher mesh/grid resolution) was undoubtebly critical in improving models, as shown by *Aschwanden et al.* [2016]. We used the term "higher-order" a bit loosely here, meaning "non-shallow-ice models". It is known that SIA does not include membrane stresses and therefore does not capture the effect of ice shelf buttressing, or ice shelf collapse, among other important processes. We rephrased the sentence to avoid any ambiguity.

p 3, l 25: insert comma after equation

Done

p 3, l 27-28: A lot of research is currently being dedicated to derive parametrizations for c and $\dot{M}$; here we chose to recent parametrizations described below

Done

p 5, l 4: insert comma after equation

Done

p 6, l 1 simplification,but $\rightarrow$ simplification, but

Done

p 6-7: "As we do not run a coupled model, we rely on the last year of constrained rate of undercutting (year 2016) and repeat it" This sentence does not make sense. As I understand it, you calculate undercutting from thermal forcing and subglacial discharge, what do you mean with "repeating"?

We repeat the 2016 time series from 2017 onwards for all years until 2100. We clarified the text.

p 8, l 13: overestimates the retreat on the southern...

Done

p 8, l 31: Kjer Gletscher exhibits almost the same...

Done

p 8, l 33-34: I think it should read "up to 70 km upstream to where the bed..." (not sure though)

Done

p 8, l 34: add year: but continue to retreat another 17km by 2100 to reach...

Done

p. 9, l 1: the northern branch retreats 45km...

Done

p. 9, l 9: "has" is very colloquial. Use "shows" or "exhibits" instead.

Done

p. 9-10: "In our simulations, Cornell Gletscher shows some of the most stable behavior of all investigated glaciers: under all scenarios, it retreats roughly another kilometer upstream." Remove the "or so", this is too colloquial.

Done

p. 10, l 4: the model projects that...

Done

p. 10, l 6: ...no additional increase in TF

Done

p. 10, l 8: I think it should read "..., on the other hand, has retreated more..."

Done

p. 10, l 10: Our simulations suggest that the glacier may reach..."

Done

p. 10, l 11: clarify "by 4km or 11km", on what does this depend?

Done

p. 11, l 2: is multiplied by a factor of six

Done

p. 11, l 5: in the control experiment, in which we kept the ice front fixed.

Done

p. 11, l 11: Under these conditions, ...

Done

p. 12, l 12: "(not shown here) → this results is highlighted in the abstract, I thus think it needs to be shown here.

This is also something that was requested by reviewer #2. We added an additional figure (Figure 5) that shows velocity profiles for all scenarios in 2030, as well as the ice front position and bed topography. This figure also helps understand the behavior of the glaciers. To be consistent with the figure (that shows the state of the glaciers in year 2030), we changed the acceleration factor to 3 over 23 years.

p. 12, l 24: move towards coupled ice-ocean-climate models

Done

p. 12, l 33: "Among other limitations...". Clarify and rewrite. "the thermal forcing is dictated by the undercutting" ? Isn't it the other way around?

Yes, this sentence was confusing and has been rephrased.

p 5, l 13-14 and 22: is there a contradiction? First you say you are using ECCO from 1992-2015 and further down it's 2007 until 2015? I understand that the simulations start in 2007, so what is the ECCO data prior to 2007 used for?

This is a good point. We actually only use the data from 2007 to 2015, we corrected the manuscript.

Figures: the figures are beautiful.

Thank you!

Figure 1: ..., and white crosses indicate the locations of CTD data from NASA's Oceans Melting Greenland campaign that were used to calibrate thermal forcing

Done

Figure 3: add units to colorbars.

Done

2 Reviewer #2

General comments:

The authors explore the sensitivity of Northwest Greenland's marine-terminating glaciers to decadal-scale increases in thermal forcing and subglacial discharge. Using the Ice Sheet System Model (ISSM), they run an ensemble of 21st century experiments with thermal forcing increasing by up to 3 deg C, and subglacial discharge increasing up to a factor of 10. The model uses two parameterizations that determine the terminus location: one for calving, driven by tensile stresses, and the other for undercutting, driven by thermal forcing and subglacial discharge. It makes innovative use of ECCO ocean output, along with new bed topography data from NASA. The authors find a wide range of glacier responses, with some glaciers sensitive to small increases in thermal forcing, and others quite stable. They argue that bed topography controls the rate and magnitude of retreat. The paper is clearly structured. It places the problem in scientific context, lays out methods and parameterizations, quantifies the results, draws general conclusions, and discusses model limitations. The experiments are a significant step toward Greenland-wide projections of the evolution of Greenland's marine outlet glaciers. However, some sections are written in a cursory way without enough details and justification. In particular, the paper seems to rely on some implicit assumptions that are not fully explained and defended, thus casting doubt on the validity of the model calibration. Although the study is timely and important, the methodology and description should be improved, as described below.

We thank the reviewer for his general assessment and hope that the new version of the manuscript addresses all of the concerns.

Specific Comments:

First, I will restate what seems to be the underlying assumptions in Section 2: The terminus location of marine-terminating glaciers (at least in Northwest Greenland) is determined mainly by (1) mass transport; (2) undercutting driven by thermal forcing (TF) and subglacial discharge, as quantified by Eq. 2; and (3) calving proportional to ice velocity and tensile stress, as described by Eq. 3. The steady-state terminus location is determined by a balance between (1), which advances the front, and (2) and (3), which drive frontal retreat. Processes (2) and (3) are largely independent of each other. Marine glacier retreat of the past decade can be attributed primarily to increased thermal forcing and undercutting.

One way to test the validity of these assumptions would be to calibrate the model by fitting simulated termini to observed locations prior to retreat. The model could be initialized using observed or model-derived values of velocity, tensile stress, runoff-derived discharge, and ocean thermal forcing, appropriate for a period before the recent retreat (say, late 20th century) when the termini were relatively stable. Of these fields, TF might be the least certain (as suggested on p. 7, l. 2), so *one approach to initialization would be to invert for TF based on pre-retreat terminus locations. This would give a baseline TF to which anomalies would be added. In this study, however, there is no calibration based on pre-retreat termini. If I understand Section 2 correctly, the model is initialized to 2007 geometry and then run forward with a linear sliding law and RACMO-derived runoff, along with the undercutting and calving parameterizations of eq. 2 and 3. The calving parameter sigma_max is adjusted in each basin to match the observed retreat of the past decade. This approach left me wondering how much of the simulated decadal-scale retreat is associated with recent increases in TF (as shown in Fig. 2b for ECCO). Part of the retreat could be a model transient that would occur without increasing TF, because of biases in SMB, basal friction, or other factors. Based on information given in the paper, I don't know how to make this judgment, and to be confident that eq. 2 and 3 capture the essential physics (albeit with uncertainty in empirical parameters). If it is not feasible to calibrate the model based on pre-retreat terminus locations, I would ask the modelers to describe the difficulties and explain why their approach is preferred.*

We actually had a similar idea initially to calibrate the model. There are a few reasons why we ended up not doing it. First, it is virtually impossible to find a surface DEM at the scale of northwest Greenland prior to 2007. There are some regions where we have decent DEMs based on photogrammetry, but their spatial extent is too limited. Another reason is that stable glaciers generally have their terminus on a distinct feature (ledge, ridge, etc) in the bed topography and the numerical model is also stable for a wide range of σ_{max}. Constraining the calving threshold, σ_{max}, is easier to do for retreating calving front as we constrain the *rate of retreat* as opposed to just the *stability* of the glacier. This is something that we noticed in *Morlighem et al.* [2016] and *Choi et al.* [2018]. It is also difficult to invert for TF because of its natural variability, while we can assume that σ_{max} does not change over short time scales. Ultimately, we agree with the reviewer that the situation is not satisfying given that the projections rely heavily on 2 parameterizations that need further validation, which is what we mention in the discussion and conclusion.

Comments with page and line references follow below.

p. 1: The abstract is longer than necessary. Some of the details and elaborations could be left out (for example, the sentence beginning "While these parameterizations remain approximations. . .").

We removed this sentence.

p. 2, l. 11: The last sentence of this paragraph might fit better at the end of the Introduction section.

We removed this sentence based on reviewer #1's suggestion.

p. 3, l. 10: In this paragraph, please state the ISSM grid resolution (or range of resolutions).

Done

p. 3, l. 17: It would be helpful to see an equation for the Budd sliding parameterization, along with the chosen parameter values (such as a sliding proportionality constant C). Using this parameterization, how close is the fit of simulated glacier velocities to observed velocities?

Done

p. 3, l. 23: Since undercutting is closely related to processes that might be classified as calving, it would be helpful to state that calving and undercutting are considered to be independent processes for purposes of the paper.

This is a good point but we think this is already mentioned in the text (Section *Calving parameterization*: " It is also assumed here that c and $\dot{M}$ are independent, which is a simplification").

p. 3, l. 29: For readers not familiar with the Rignot et al. paper, please describe the motivation for choosing this particular functional form for undercutting, and these parameter values. For example, why is the B term needed? Are there theoretical reasons to expect alpha and beta to have roughly these values, or are they strictly empirical? Why the dependence on h?

The coefficients α and β are close to that expected from the plume theory [*Jenkins et al.*, 2010; *Jenkins*, 2011], but were determined from a a high-resolution ocean model study. B is necessary because there is still melt for zero q_{sg}. The dependence on h was determined from model experiment with different depths and seems to reflect an acceleration of the melt plume when it rises from greater depths. This is now mentioned in the manuscript.

p. 4, Fig. 1: This is a very useful and visually attractive figure.

Thank you!

p. 5, l. 1: Please give equations showing how TF is computed.

Done

p. 5, l. 9: This is a helpful explanation of the interplay between bed topography and thermal forcing.

Thanks!

p. 5, Fig. 2: This is another useful figure, which helped me visualize the model forcing, but the caption is not very informative. For instance, the caption for Fig 2a could state that the initial calving front is at x = 0 km and the fjord mouth is at x = 80 km (if I'm interpreting it correctly). For Fig. 2b, please give the source of the data.

Done

p. 5, l. 17: "repeat TF of year 2016 until the end of the simulation." I found this confusing. Do you mean that TF from 2016 is the baseline to which the TF anomaly is added?

This is also something that was mentioned by reviewer #1, we rephrased the sentence as follows: "For 2017 to 2100, as we do not run a coupled model, we repeat the thermal forcing and subglacial discharge of year 2016 until the end of the century, with the anomalies described above."

p. 6, l. 9: Please see the above comments on model calibration. There is no explanation here of why σ_{max} is the specific parameter chosen for calibration, or of why calibration to the observed retreat is preferable to calibration to pre-retreat terminus location.

Hopefully this is addressed above.

p. 6, l. 10: Landsat-derived ice front retreat is mentioned here for the first time. I suggest describing the observed retreat, perhaps with a reference to the left column of numbers in Table 1, as part of the background discussion.

Done

p. 6, l. 16: Can you say approximately how many CMIP5 models were used to compute this average anomaly, and what is the spread among models?

We now refer to *Yin et al.* [2011]. They used an ensemble of 19 climate models to quantify this ocean warming in the next two centuries. They found that West Greenland's subsurface ocean temperature would warm by 1.5 degrees on average by 2100, with 5-25-50-75-95th percentiles of 0.5-1-1.5-2.5-4°C. This is now in the text.

p. 6, l. 17: I'm not sure the 2-degree Paris target is entirely relevant here, given that the target might be exceeded, and we want to know the consequences of missing the target. It would be more appropriate to choose an upper limit based on the CMIP5 spread.

The Paris agreement is for global air temperature and the ocean is generally slow to respond to an increase in atmospheric temperature. We therefore see a +2°C increase in TF as a high-end scenario (even though we go up to $+3°C$). We added the spread from *Yin et al.* [2011], keeping in mind that the reported warming is for 2100, and not instantaneous.

p. 6, l. 24: Can you say why you increase the TF anomaly instantly, instead of phasing it in linearly as might be more realistic? Similarly for SMB/discharge.

We agree that for projection purposes, it would be more realistic to have a linear increase but we wanted here to do a sensitivity analysis in order to determine the glaciers that are more at risk. In future projection studies based on this work, the forcings will be related to RCP scenarios.

p. 6, l. 26: It is unclear exactly what is being repeated here.

Rephrased the sentence.

p. 7, ll. 3-5: Referring again to the comments above, I'm wondering if a bias correction to the ECCO data would be more defensible than adjusting σ_{max}. Then you would more likely be capturing the recent retreat for the right reason.

This is a very good point that was also mentioned by the editor during the initial review. The reason why we do not tune the thermal forcing is that it is a complex time series and we do not know whether we should just optimize for a bias, or if there is a missing trend. Optimizing the threshold was simpler, but we agree that there is no unique solution. We added a sentence in the results section about that.

p. 8, l. 2: How informative is it that ice front retreat is in good agreement with observations when σ_{max} is tuned? Does this suggest that there is something fundamentally "right" about the parameterizations, or does it simply reflect high sensitivity to modest changes in σ_{max}?

It is a bit of both, but we would like to highlight the fact that we are comparing here a time series of 2-dimensional ice front positions and, while the terminus position may be on target along a flow line, the model does a surprizingly good job at capturing the pattern of retreat as well. We refer to the study by *Choi et al.* [2018], which compares different calving laws and finds that the one we use here does a reasonable job compared to other existing laws.

p. 8, l. 9: The text states that the model overestimates the recent retreat of Kakivfaat Sermiat, but Table 1 shows a small underestimate.

This is a good point. If we look at the figure, we see that on average, the model overestimates the retreat. But for the central flowline that was chosen to make the table, we have a slight underestimation. This is one of the reasons why we have both a table and a figure, as it makes it easier to compare the retreat qualitatively (figure) and quantitatively (table), but there may be disagreement depending on where the flowline lies. We agree that this may be confusing but did not change the table since this is what is calculated along the flow line.

p. 10, Fig. 5: This figure nicely illustrates that the TF anomaly is the primary driver of retreat. However, I wondering how the shape of the figure would be different if anomalies were ramped up gradually. Also, I suggest that the caption briefly state what is left out of the fixed-front simulation, such as SMB changes.

We hopefully addressed the first point above. We added the note in the caption about the SMB that is held constant in all scenarios (including the fixed front one)

p. 11, l. 17: I couldn't find a description of the control experiment in which the ice front is held fixed.

We added a description in the Experiment section.

p. 12, l. 3: The paper makes a strong case for the importance of calving dynamics. At the same time, it does not quantify mass changes due to a more negative SMB, or discuss possible feedbacks of SMB on dynamics. For instance, could a decreasing SMB potentially cause much more mass loss than dynamic retreat? Could SMB-driven thinning significantly modify the calving dynamics (e.g., through reduced tensile stresses)? I realize that SMB changes are beyond the scope of the modeling study, but it would be helpful to talk about them in Section 4.

This is correct. We keep the SMB constant here, as we want to evaluate the effect of ice/ocean interactions only. The possibility of feedbacks between changes in SMB (primarily surface melt) and calving is indeed interesting to mention. We added a sentence in the discussion about possible feedbacks between SMB and calving.

p. 12, l. 7: This statement about models with fixed calving fronts seems too general. For example, consider a model without a physically based calving law, in which calving is simply prescribed at the present-day CF. Suppose the model is forced with increasingly negative SMB. This could result in significant thinning, and perhaps ungrounding, of ice all the way to the CF, without necessarily moving the CF. This isn't to say that moving boundaries aren't an improvement, but just to acknowledge that models without moving boundaries may still be able to make useful projections, which might not be overly conservative (especially if SMB dominates the mass balance).

We agree with the reviewer that models with a fixed ice front will capture some mass loss with an increasingly negative SMB, but these estimates will still be underestimates because of the additional resistive stresses (e.g. basal friction, buttressing, etc). Now, depending on the forcings, the changes in mass due to SMB may outweigh the changes due to calving front migration. We now limit this statement to the case of ocean warming.

p. 12, l. 15: I agree that this is an interesting result, which might not have been guessed ahead of time. Given the result, it would be helpful to comment (either here or in Section 2) on the robustness or theoretical justification of alpha and beta.

We now provide more details as to where the undercutting rate is coming from.

Technical corrections:

p. 2, l. 1: Please be consistent in capitalization of "Northwest" vs. "northwest"

We now use "Northwest Greenland" and "the northwest coast".

p. 2, l. 11: don't → do not

Done

p. 2, l. 19: Maybe "on the edge" → "on the verge"

Done

p. 2, l. 27: To me, "plan-view" suggests 2D in the xy plane. Maybe "3D"?

It is actually an xy plane, we use a 2d depth-averaged model. We kept "plan-view".

p. 2, l. 28: "a lot of" → "much". Also p. 3, l. 24.

Done

P. 2, l. 33: Define RCP

Done

Fig. 1 caption: "are used to calibrate the thermal forcing." Also, capitalize "south" in the figure.

Done

p. 5, l. 6: Maybe reword as ". . .the assumption of uniformly distributed melt generates only. . ."

Done

p. 5, l. 11: As worded, the subject of "decreases" is "calculation", which isn't intended. Maybe change to "The calculated effective depth"

Good point! Done

p. 5, l. 17: "future simulation" $\rightarrow$ "simulations of future climate"

Done

p. 6, l. 7: Hyphenate "real-world"

Done

p. 7, Fig. 3 caption: undercutting rate should be m/day instead of m/yr?

Yes, good catch!

p. 7,l. 7: 4-¿four

Done

p. 9, l. 6: "about 8, 13 and 23 km upstream are distances we find. . ."; awkward wording.

Rephrased

p. 9, l. 9: position $\rightarrow$ positions

Done

p. 9, l. 11: "under no warming condition" $\rightarrow$ "without further ocean warming"

Done

p. 10, l. 5: Run-on sentence

Restructured.

p. 11,l. 2: “10 km or so”-¿“$\sim$10 km”

Done

p. 11, l. 3: project $\rightarrow$ projects

Done

p. 11, l. 23: advances $\rightarrow$ advance

Done

p. 11, l. 25: retrograde (no hyphen)

Done

p. 12, l. 17: sensitive $\rightarrow$ more sensitive

Done

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Modeling the response of Northwest Greenland to enhanced ocean thermal forcing and subglacial discharge

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Abstract. Calving front dynamics is an important control on Greenland's ice mass balance. Ice front retreat of marine-terminating glaciers may, for example, lead to a loss in resistive stress, which ultimately results in glacier acceleration and thinning. Over the past decade, it has been suggested that such retreats may be triggered by warm and salty Atlantic water, which is typically found at a depth below 200-300 m. An increase in subglacial water discharge at glacier ice fronts due to enhanced surface runoff may also be responsible for an intensification of undercutting and calving. An increase in ocean thermal forcing or subglacial discharge therefore has the potential to destabilize marine terminating glaciers along the coast of Greenland. It remains unclear which glaciers are currently stable but may retreat in the future, and how far inland and how fast they will retreat. Here, we quantify the sensitivity and vulnerability of marine-terminating glaciers along the ~~Northwest~~ northwest coast of Greenland (from 72.5° to 76°N) to the ocean forcing and subglacial discharge using the Ice Sheet System Model (ISSM). We rely on the undercutting parameterization based on ocean thermal forcing and subglacial discharge, and use ocean temperature and salinity from high-resolution ECCO2 (Estimating the Circulation & Climate of the Ocean, Phase II) simulations at the fjords mouth to constrain the ocean thermal forcing. The ice flow model includes a calving law based on a tensile Von Mises criterion. ~~While these parameterizations remain approximations and do not include all the physical processes at play, they have been shown to provide reliable estimates of undercutting and calving rates, respectively, on a number of glaciers along the coast of Greenland.~~ We find that some glaciers, such as Dietrichson Gletscher or Alison Gletscher, are sensitive to small increases in ocean thermal forcing, while others, such as Illullip Sermia or Cornell Gletscher, are remarkably stable and remain stable, even in a 3-degree ocean warming scenario. Under the most intense experiment, we find that Hayes Gletscher retreats by more than 50 km inland by 2100, into a deep trough, and its velocity increases by a factor of ~~10 over only 15~~ 3 over only 23 years. The model confirms that ice-ocean interactions can trigger extensive and rapid glacier retreat, but the bed controls the rate and magnitude of the retreat. Under current oceanic and atmospheric condition, we find that this sector alone will contribute more than 1 cm to sea level, and up to 3 cm under the most extreme scenario.

1 Introduction

Over the past two decades, many glaciers along the northwest coast of Greenland have been retreating and accelerating, sometimes dramatically (e.g., Moon et al., 2012; Wood et al., 2018). It has been suggested that the retreat of these glaciers is initiated by the presence of warm, salty, subsurface Atlantic Water (AW) in the fjords (e.g., Straneo et al., 2010; Straneo and Heimbach, 2013; Rignot et al., 2012; Holland et al., 2008). This water is typically found 200 to 300 m below the surface (e.g., Rignot et al., 2016a; Holland et al., 2008). Surface runoff has also been increasing over the past decades (van den Broeke et al., 2009; Fettweis et al., 2013b; Tedesco et al., 2013), which enhances subglacial water discharge at the base of calving fronts. This freshwater flux enhances the circulation of the ocean in the fjord (Xu et al., 2012), which in turn further increases the melting rate, and therefore the rate of undercutting ~~,~~ at the calving face of marine terminating glaciers. While we expect both surface runoff and the ocean heat content to continue to increase over the next century, it remains unclear how they are going to affect ice dynamics and the ice discharge into the ocean. ~~We don't focus here on all of the feedback mechanisms that may be involved, but focus solely on their effect on ice front dynamics.~~

While geographically close, individual outlet glaciers along the coast respond differently to frontal forcing. It has been proposed (e.g., Wood et al., 2018; Catania et al., 2018) that this heterogeneity in glacier behavior may be due to differences in bed topography and fjord bathymetry, which may prevent the access of AW to interact with calving fronts due to the presence of sills in the fjord. It has also been suggested that many glaciers are currently resting on pronounced ridges, or in regions of lateral constrictions, which stabilizes the glaciers' calving fronts, and prevents warm water from dislodging them from their current position (Catania et al., 2018). The idea that ice front dynamics is, to a large extent, controlled by subglacial topography has been first investigated in Alaska (Mercer, 1961; Meier and Post, 1987) and has more recently been extended to Greenland (e.g., Warren, 1991; Warren and Glasser, 1992; Carr et al., 2015; Lüthi et al., 2016). It ~~remains unclear, however, the extent to which~~ is not certain to which degree the glaciers of the northwest coast ~~are~~ remain sensitive to enhanced ~~oceanic forcing~~ thermal forcing from the ocean: some glaciers ~~could be on the edge~~ are on the verge of a fast and extensive retreat, ~~some may continue to retreat~~ others may continue retreating at the same rate, ~~while some others will~~ and some may remain stable. Numerical modeling can help us assess the sensitivity of these individual glaciers to ocean temperature along the coast, and their potential for fast retreat and mass loss, affecting sea level rise.

While many model-based studies have been focusing on the response of Greenland to climate change, they either did not include moving calving fronts (e.g., Bindschadler et al., 2013; Gillet-Chaulet et al., 2012), or were based on flow-line models (e.g. Nick et al., 2013) that do not capture changes in lateral drag well (since lateral drag is parameterized) or the complex three-dimensional shape of the bed that affects the retreat rate (Choi et al., 2017; Bondzio et al., 2017), and did not consider undercutting. Here, we want to overcome these limitations by using a plan-view model with a moving boundary. The calving front position is allowed to move and depends on the ice speed, the calving rate and rate of undercutting. While ~~a lot of~~ much progress has been made in terms of capturing ice flow through improved datasets (Aschwanden et al., 2016) and through the development of new ~~, higher-order~~ stress balance solvers not based on the Shallow Ice Approximation, calving and undercutting remain areas of active research. We use two existing parameterizations of ocean undercutting (Rignot et al., 2016b) and calving

(Morlighem et al., 2016). While these parameterizations are approximations and do not include all the physics involved in ice/ocean interactions, they have been tested with reasonable success on several glaciers of Greenland (e.g. Morlighem et al., 2016; Choi et al., 2017; Rignot et al., 2016b). The objective of this study is not to make projections, as we are not forcing the model with given ~~RCP~~ Representative Concentration Pathway (RCP) scenarios, but to assess the sensitivity of Northwest Greenland using existing parameterizations for iceberg calving and undercutting.

We focus here on the northwest coast of Greenland between 72.5° and 76°N: from Upernavik Isstrøm to Sverdrup Gletscher (figure 1). This is one of the regions of Greenland where the bed is remarkably well constrained by ice thickness measurements from NASA's Operation IceBridge mission (Morlighem et al., 2017), and where NASA's Oceans Melting Greenland mission has been collecting multibeam bathymetry data.

We first describe the numerical model and then run the model to 2100 under different scenarios of increase in ocean thermal forcing and subglacial discharge. We then discuss the implications of these experiments, the model limitations, and make recommendations for future model studies.

2 Method and data

2.1 Ice flow model setup

We use the Ice Sheet System Model (ISSM, Larour et al., 2012) and initialize the model with conditions similar to 2007, which is the nominal year of the surface digital elevation map used here (gimpdem, Howat et al., 2014). The ice surface elevation and bed topography are from BedMachine v3 (Morlighem et al., 2017), and we use satellite derived surface velocities from Joughin et al. (2010) to invert for basal friction, following Morlighem et al. (2010). We use a Shelfy-Stream Approximation (SSA, MacAyeal, 1989) for the ice stress balance. While not accurate in slow moving regions, this model is an excellent approximation for the fast outlet glaciers (i.e. $>$ 200 m/yr) that we are focusing on here, where sliding velocities are significantly larger than deformational velocities (e.g., Rignot and Mouginot, 2012). We assume a depth-averaged viscosity equivalent to a temperature of -8°C, which is consistent with Seroussi et al. (2013), and we use a linear viscous basal friction law following Budd et al. (1979)~~, where the basal effective pressure is assumed to be~~ :

$$\boldsymbol{\tau}_b = -C^2 N \mathbf{v}_b, \tag{1}$$

where $\boldsymbol{\tau}_b$ is the basal friction, $\mathbf{v}_b$ is the ice basal velocity, C is a friction coeficient that is inverted for using surface velocities, and N is the effective pressure. For simplicity, we assume that N is equal to the ice pressure above hydrostatic equilibrium, as if the subglacial hydrological system was forming a sheet connected to the ocean. The model's mesh comprises 380,000 elements, and its resolution varies between 100 m near the coast and 1 km inland. The model time step is one week.

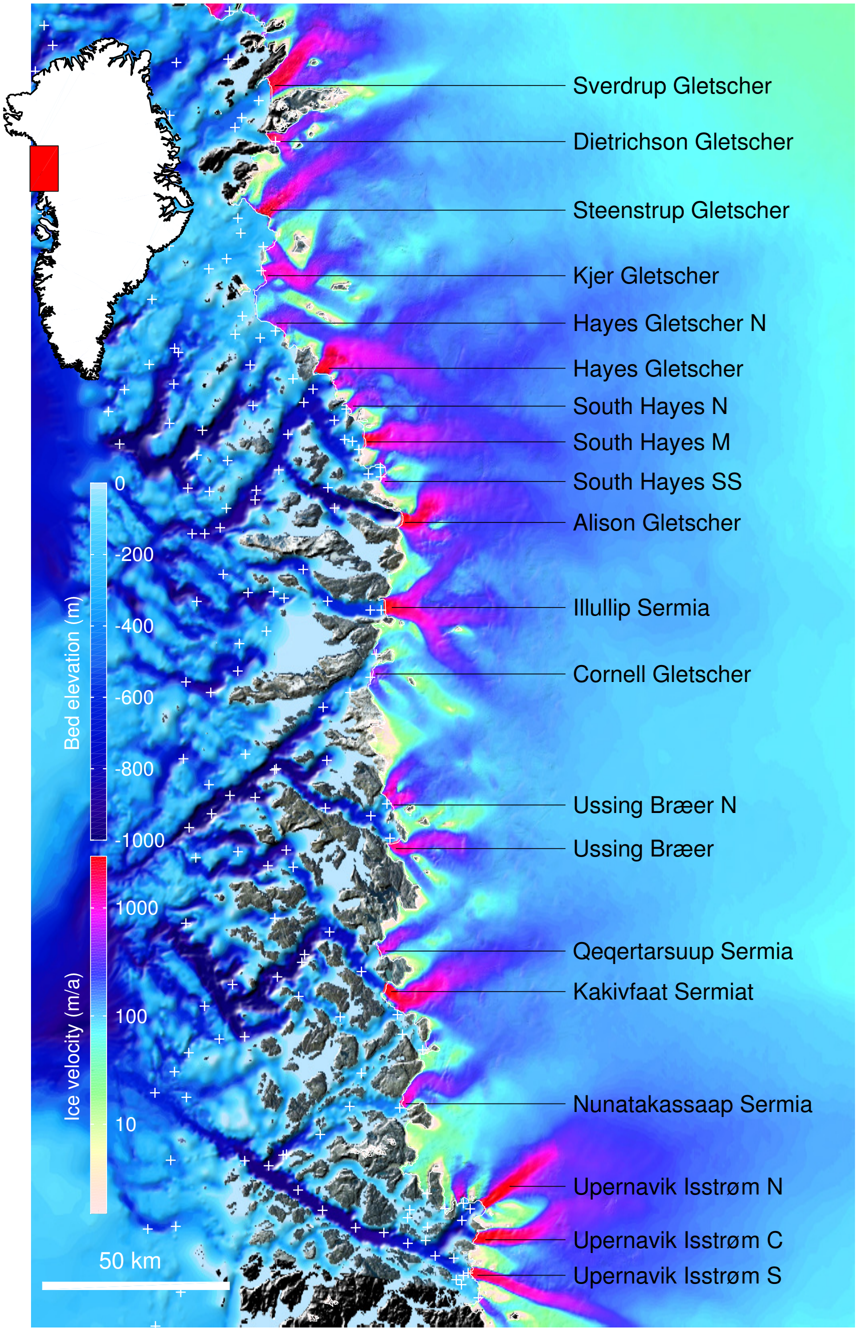

Figure 1. Ocean bathymetry (m, blue color scale) and ice velocity (m/a Joughin et al., 2010) of Northwest Greenland. The white line shows the 2007 ice sheet extent, and white crosses indicate the locations ~~where~~ of CTD data from NASA's Oceans Melting Greenland campaign that are used to calibrate the thermal forcing.

In order to capture the dynamic motion of the calving front, we rely on the level set method (Osher and Sethian, 1988; Bondzio et al., 2016), where the velocity at which the calving front moves is defined as:

$$\mathbf{v}_{\text{front}} = \mathbf{v} - \left(c + \dot{M}\right)\mathbf{n}, \tag{2}$$

where $\mathbf{v}$ is the ice horizontal velocity vector, c is the calving rate, $\dot{M}$ is the rate of undercutting at the calving face, and $\mathbf{n}$ is a unit normal vector that points outward from the ice domain. ~~A lot of~~ Much research is currently being dedicated to derive parameterizations for c and $\dot{M}$~~. We choose here~~; here we chose to use two recent parameterizations described below.

2.2 Undercutting parameterization

We rely on the undercutting parameterization from Rignot et al. (2016b), where the rate of undercutting (in m/day) at the calving face is assumed to follow:

$$\dot{M} = \left(A\,h\,q_{sg}^{\alpha} + B\right)\cancel{\mathrm{TF}}\tilde{T}^{\beta}, \tag{3}$$

where h is the water depth at the calving front (in m), $A = 3 \times 10^{-4}$ m$^{-\alpha}$ day $^{\alpha-1}$ °C$^{-\beta}$, α = 0.39, B = 0.15 m day^{-1} °C$^{-\beta}$, and β = 1.18. ~~TF~~ $\tilde{T}$ is the ocean thermal forcing (in °C), defined as the difference in temperature between the potential temperature of the ocean and the depth dependent freezing point of sea water:

$$\tilde{T} = T - T_F \tag{4}$$

where T is the ocean temperature at a given depth, and T_F is the temperature of local freezing point, which is assumed to be a linear function of salinity and pressure, following equation (1) of Xu et al. (2012). q_{sg} is the subglacial discharge at the glacier terminus (Rignot et al., 2016b) (in m/day)~~resulting in un undercutting rate in m/day.~~. Both $\tilde{T}$ and q_{sg} are monthly averaged. The coefficients α and β are close to the ones expected from the plume theory (Jenkins et al., 2010; Jenkins, 2011), but were determined from a a high-resolution ocean model study. The introduction of B is necessary to account for the presence of melt in the case where there is no subglacial discharge. The dependence on h was determined from model experiment with different depths and seems to reflect an acceleration of the melt plume when it rises from greater depths (Rignot et al., 2016b).

To estimate the subglacial discharge of melt water, $\cancel{q_{sq}}q_{sg}$, we use the results from the downscaled 1 km RACMO runoff field (Noël et al., 2016) with the subglacial melt rates from Seroussi et al. (2013), and assume for simplicity that the discharge is uniformly distributed across the calving face. Xu et al. (2013) showed that ~~assuming melt uniformly distributed~~ the assumption of uniformly distributed melt generates only a 15% uncertainty in melt compared to a distributed source of $\cancel{q_{sq}}q_{sg}$.

The ocean thermal forcing, ~~TF~~$\tilde{T}$, is derived from the Estimating the Circulation and Climate of the Ocean, Phase 2 (ECCO2, ~~1992-2011~~2007-2011) and Phase 4 (~~2001-2015~~2007-2015), following the procedure described in Wood et al. (2018). To account for the presence of sills in the fjord, ~~TF~~ $\tilde{T}$ is depth averaged between the sea level, and the deepest point for which there is a direct horizontal connection to the fjord mouth. The ~~calculation of this~~ calculated effective depth assumes an ocean perfectly stratified, and decreases as we get closer to the calving front since ocean currents are potentially blocked by the bathymetry. Figure 2 illustrates the effective depth for the case of Sverdrup Gletscher. Note that we define the effective depth over the entire model domain, even under currently ice-covered regions. If the modeled ice front retreats past a high bump, it will be accounted for in the calculation of the thermal forcing and the rate of undercutting will be reduced (See figures 3b and 3c). Note that this undercutting parameterization facilitates the definition of the rate of undercutting everywhere in the model domain, and its magnitude depends on the ice front location. ~~The time series provided by ECCO2 goes from 2007 until 2015.~~

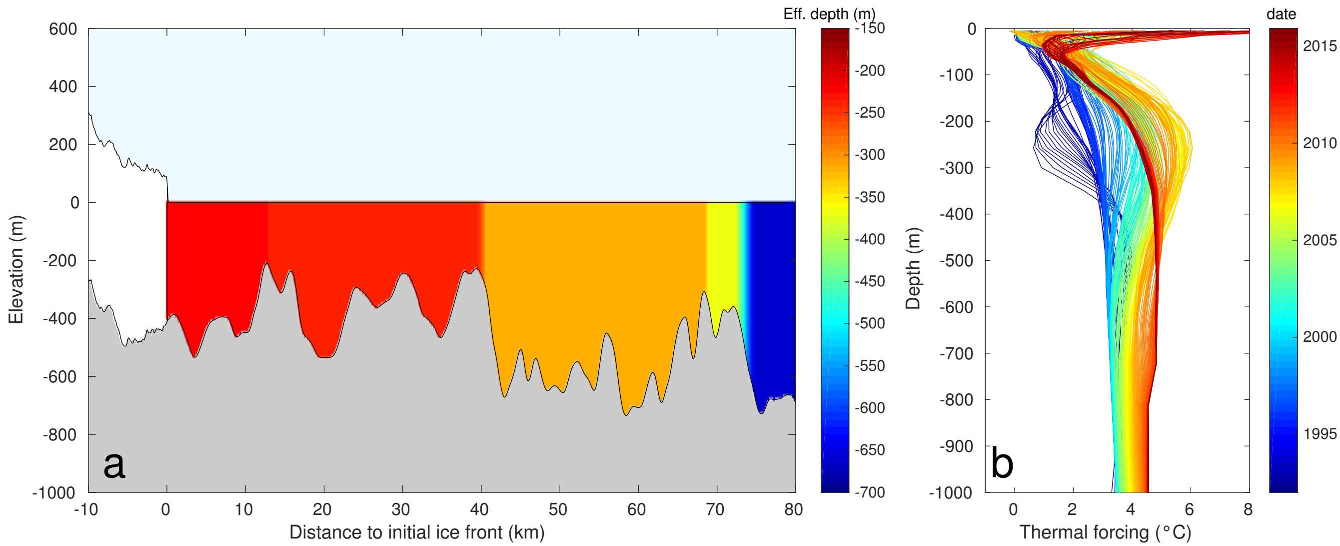

Figure 2. (a) Effective depth (m) ~~and~~ of the fjord of Sverdrup Gletscher. The effective depth decreases as we go from the fjord mouth (x = 80 km) to the glacier terminus (x = 0 km). (b) Thermal forcing at the fjord's mouth (°C) for Sverdrup Gletscher from ECCO2.

~~In future simulation, we repeat TF of year 2016 until the end of the simulation. The~~ The ice sheet model is forced by the surface mass balance of RACMO 2.3 averaged between 1961 and 1990: the increase in runoff (due to the anomaly applied) is assumed to not affect the surface mass balance, but only undercutting through the parameterization provided by equation 3.

2.3 Calving parameterization

We assume that the calving rate follows the parameterization proposed by Morlighem et al. (2016), for which the calving rate is proportional to the tensile von Mises stress:

$$c = \|\mathbf{v}\| \frac{\tilde{\sigma}}{\sigma_{\max}} \tag{5}$$

where $\tilde{\sigma}$ is the tensile von Mises stress, as defined in Morlighem et al. (2016), and $\sigma_{\max}$ is a threshold that needs to be calibrated for each basin. This calving law is obviously a simplification that may not capture all modes of calving as it only relies on tensile stresses. It is also assumed here that c and $\dot{M}$ are independent, which is a simplification, but has shown some promising results on ~~real world applications (e.g., Morlighem et al., 2016; Choi et al., 2017)~~real-world applications (e.g., Morlighem et al., 2016; Choi et al., To calibrate the calving threshold, we run the model for 10 years: from 2007 to 2017, using the thermal forcing from ECCO2, and adjust $\sigma_{\max}$ in order to match the extent of Landsat-derived ice front retreat: we try to match the observed retreat from 2007 to 2017 along a central flow line for each glacier, not the retreat rate. This calving threshold is uniform by basin and held constant through time in all runs.

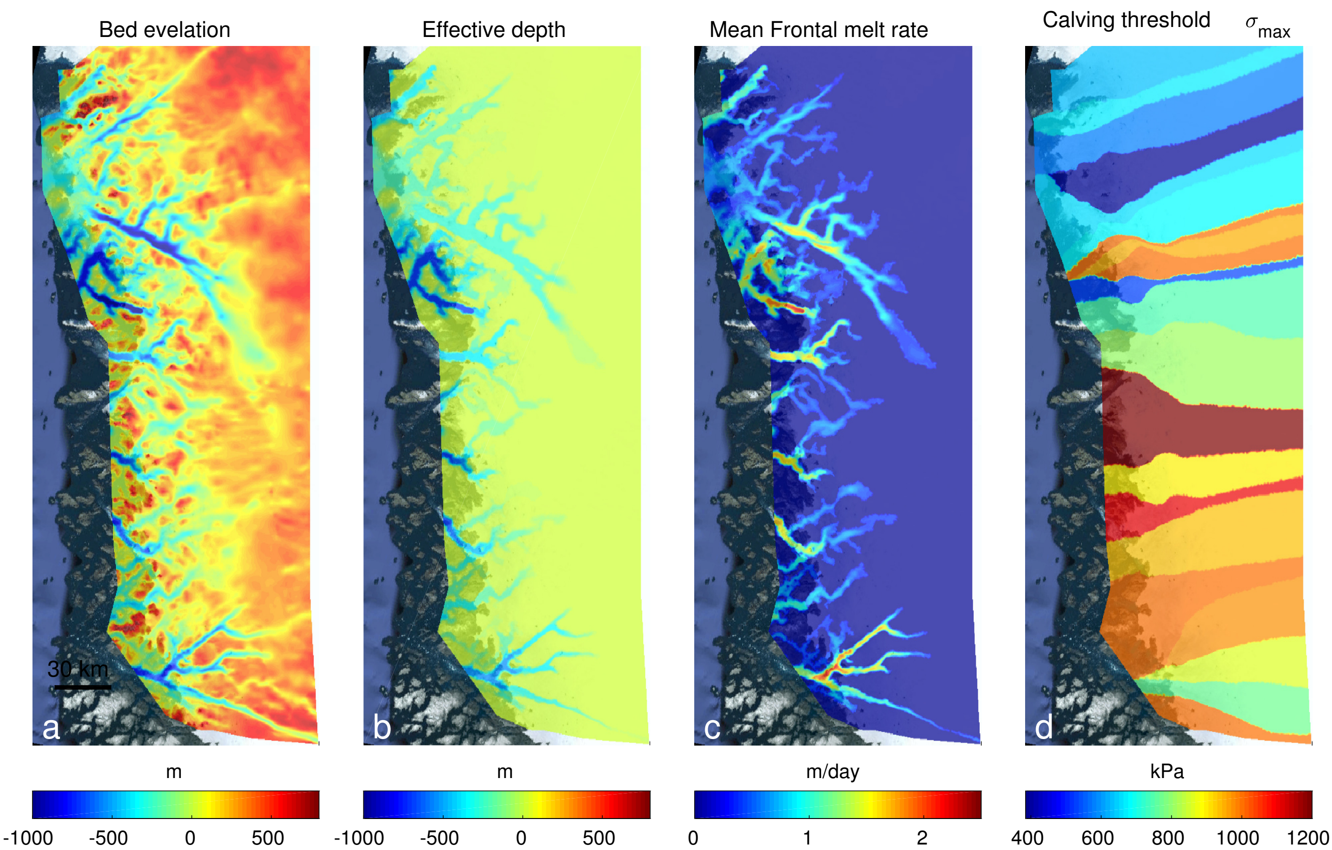

Figure 3. (a) bed topography (m), (b) effective depth (m), (c) calculated mean rate of undercutting from 2007 to 2017 (m/~~yr~~day), (d) calibrated $\sigma_{\max}$ (kPa)

2.4 Experiments

After this calibration phase, we run the model forward, from ~~2007~~ 2017 to 2100, under different scenarios of ocean forcings and different scenarios of increase in subglacial discharge. Yin et al. (2011) analyzed the results of 19 climate models to quantify ocean warming around the coast of Greenland over the coming centuries. They found that West Greenland's subsurface ocean temperature between 0.5 and 4°C, with a mean of 1.5°C by 2100. CMIP5 ~~results suggest that, on average, the ocean temperature anomaly along the northwest coast will reach +2°Cby~~ results suggest similar rates of warming by the end of the century under RCP8.5 (D. Slater, pers. comm.). A +2°C is also in line with the global atmospheric temperature rise target of the Paris

Agreement. Even though there will be a lag in the response of the ocean to atmospheric warming, we do expect that polar amplification could increase ocean temperature further at high latitudes. We therefore consider here a range in ~~TF~~ $\tilde{T}$ increase from 0 to +3°C.

In terms of subglacial discharge, observations over the past decade have shown that surface melting has increased over the entire Greenland ice sheet (van den Broeke et al., 2009; Fettweis et al., 2013b; Tedesco et al., 2013). Fettweis et al. (2013a) showed that meltwater runoff could be multiplied by a factor of 10 by the end of the century. We therefore multiply the subglacial discharge by a factor of up to 10, starting at year 2017.

Overall, we perform here 40 experiments: we increase the ocean thermal forcing, ~~TF~~$\tilde{T}$, instantly from 2017 to 2100 by increments of 1°C up to 3°C, and multiply the ocean subglacial discharge by up to a factor of 10. ~~As we~~ The rate of undercutting (Equation 3) is therefore modified as follows:

$$\dot{M} = (A\,h\,(q_{sg} \times q_a)^{\alpha} + B)\left(\tilde{T} + \tilde{T}_a\right)^{\beta}, \tag{6}$$

where the subglacial discharge anomaly factor q_a varies from 1 to 10, and the thermal forcing anomaly, $\tilde{T}_a$, varies from 0 to 3°C. From 2007 to 2016, we rely on the thermal forcing ($\tilde{T}$) and subglacial discharge (q_{sg}) from ECCO2 and RACMO. For 2017 to 2100, as we do not run a coupled model, we ~~rely on the last year of constrained rate of undercutting (~~repeat the thermal forcing and subglacial discharge of year 2016 ~~) and repeat it~~ until the end of the century~~under the scenarios of enhanced TF and q_{sg}~~, with the anomalies described above.

Additionally, we perform a *Control Experiment* where the ice front is kept fixed. We apply the same surface forcing as all other experiments. This control experiment is designed to quantify the impact of including moving boundaries in future simulations.

3 Results

Figure 3d shows the chosen value of the stress threshold over the model domain. For the southern half, we find a stress threshold within 20% of 1 MPa, which is consistent with what was found in other studies (Petrovic, 2003; Morlighem et al., 2016). Over the northern side of the domain, however, the stress threshold has to be decreased to ∼650 kPa in order to match the pattern of retreat. This would suggest that the ice is less resistant to tensile stresses, but this is more likely to be an artifact that is due to the fact that our rate of undercutting is underestimated in this region. Wood et al. (2018) noted that the north-south temperature gradient in the ocean model was poorly-represented in this region, and that the resulting thermal forcing was too cold. The model therefore requires a decrease in the stress threshold, thereby increasing the calving rate, c, in order to capture the correct amount of ice retreat over the past 10 years. We could have kept ~~c~~ σ_{max} constant, equal to 1 MPa, and optimize for the ocean thermal forcing instead, but the spatial and temporal variability in ~~TF~~ $\tilde{T}$ makes its calibration difficult, and optimizing a single scalar parameter per glacier was more practical.

Figure 4 shows the ice front positions manually digitized from Level 1 Landsat imagery, and the modeled ice front position between 2007 and 2017 for ~~4~~ four glaciers along the coast. The first two columns of table 1 list the observed and modeled retreat for the same time period along a central flow line for the chosen value of the stress threshold. By manually tuning the stress threshold, σ_{max} for each basin, we are able to match the retreat of the past 10 years for all 17 glaciers for which a change has been documented, except for Ussing Bræer N (Table 1) for which we model a retreat of almost 3 km instead of an advance of 300 m. This inconsistency may be due to errors in the bed topography near the front. We note, however, that under all scenarios, this glacier remains remarkably stable at its 3 km retreated position, due to the presence of a large bump in the bed topography. Overall, we find that with a unique scalar parameter constant in time for each glacier, the modeled ice front retreat is in very good agreement with observations, which is consistent with (Choi et al., 2018). The retreat rate of Dietrichson Gletscher is well captured (figure 4a vs 4b). While the model overestimates the retreat ~~in~~ on the southern side of the fjord, there is nonetheless an overall good agreement between the modeled and observed retreat between 2007 and 2017. The front of Illullip Sermia is remarkably stable in both observations and in the model (figure 4c and 4d), as it is currently located on a pronounced sill in the bed topography. The modeled ice front of Upernavik Isstrøm retreats more in the southern half of the fjord than the northern half compared to the observations, but the increase in ice retreat over the past 2 years is captured (figure 4e and 4f). The complex pattern of ice front retreat of Kakivfaat Sermiat is also reproduced with a slight difference in timing (figure 4g and 4h). The 2017 modeled front position is also more retreated than what has been observed, but we find the same strong control of the bed topography in the pattern of retreat.

If we now look at projections~~until 2100~~, table 1 and the supplementary table list the modeled retreated distance compared to the 2007 position for all 40 experiments along a central flow line~~.~~, and figure 5 shows velocity profiles for the different experiments in 2030. Under today's oceanic conditions (~~TF~~ $\tilde{T}$ $+0°$C and $q_{sg} \times 1$), Sverdrup Gletscher is predicted to continue to retreat for another 5 km (i.e., 8 km upstream of its 2007 position) by 2030 and another 5 km by 2100. Under the strongest scenario (i.e. ~~TF~~ $\tilde{T}$ $+3°$C and $q_{sg} \times 10$), Sverdrup Gletscher retreats by 23 km compared to 2007 by 2030 and remains there until the end of the century. We find that Sverdrup Gletscher has three distinct stable positions: ~~about~~ $\sim$8, 13 and 23 km upstream of the 2007 ~~are distances~~ terminus are ice front positions that we find for a majority of simulations, and they coincide with clear features in the bed topography. Further south, Dietrichson Gletscher will retreat another 1–3 km under the current thermal forcing, and may retreat by up to 55 km by 2100 compared to 2007 if ~~TF~~ $\tilde{T}$ increases by 1°C or more, or if the subglacial discharge increases by a factor 8 or more. Again, we find clear common retreated ~~position~~positions, 5, 8, 30, 38 and 55 km upstream of 2007, which coincide with topographic features in the bed. Steenstrup Gletscher remains somewhat stable ~~under no warmingcondition~~without further ocean warming, but retreats by more than 30 km upstream, where the bed rises above sea level, if the ocean temperature warms by a degree or more or if the subglacial discharge is doubled. Kjer Gletscher ~~has~~ exhibits almost the same behavior for all scenarios: it will continue to retreat another $\sim$40 km upstream over the coming two decades in a region of prograde bed slope, and remain stable there. Hayes Gletscher N slightly readvanced over the past 10 years but the model suggests that it will retreat by up to 70 km upstream, to where the bed is higher than sea level. Hayes Gletscher would retreat 13 km by 2030~~but continue~~, in a marked overdeepening of the bed, and continues to retreat another 17 km to reach a position 30 km upstream of its 2007 position by the end of the simulation. If the thermal forcing increases by 2 or 3°C, the glacier retreats 20 km further inland. The different branches of Unnamed south Hayes also retreat, the Northern branch ~~retreat~~ retreats 45 km by 2100 in all scenarios, to reach a position where the bed rises above sea level. The middle branch (M) retreats

Table 1. Observed and modeled ice front retreat (in km) between 2007 and 2017 under current forcing (first two columns), modeled retreat between 2007 and 2030 and between 2007 and 2100, under different scenarios of ocean forcing with today's q_{sg} for individual glaciers along the ~~Northwest~~ northwest coast. A more complete table is provided in supplementary material.

	2017 Retreat (km)		2030 Modeled retreat (km)				2100 Modeled retreat (km)			
Glacier name	Observed	Modeled	+0°C	+1°C	+2°C	+3°C	+0°C	+1°C	+2°C	+3°C
Sverdrup Gletscher	2.89	2.89	8.0	12.9	13.3	14.8	13	13.9	23.4	23.4
Dietrichson Gletscher	3.56	3.74	4.9	7.0	8.1	13.4	6.2	54.7	54.7	54.7
Steenstrup Gletscher	1.79	1.68	1.5	29.5	33.4	36.7	4.2	37.4	37.4	37.4
Kjer Gletscher	6.08	6.03	28.9	32	34.5	36.3	38.7	38.7	39.4	40.5
Hayes Gletscher N	-0.266	-0.533	27.5	30.4	30.7	37.9	53.9	54.3	54.3	77.1
Hayes Gletscher	0.475	0.104	12.9	25.4	30	30.1	30.1	31.2	41.9	53.3
Unnamed south Hayes N	0.06	0.06	0.6	3.3	4.4	25.2	45.3	45.3	45.4	46.8
Unnamed south Hayes M	-0.28	0.13	0.2	2.1	12.1	12.1	39.9	40.3	42	63.6
Unnamed south Hayes SS	1.12	1.12	3.1	4.0	5.3	7.3	3.5	6.5	14	65.4
Alison Gletscher	2.36	2.64	9.5	9.8	10.5	10.6	10.5	10.5	14.5	18.3
Illullip Sermia	0.12	0.12	0	0.9	4.6	9.5	0	1.4	17.1	16.9
Cornell Gletscher	0.807	1.43	2.3	2.3	2.5	2.6	2.3	2.4	2.8	6.5
Ussing Bræer N	-0.282	2.91	2.9	3.1	3.4	3.4	3.3	3.4	3.4	3.5
Ussing Bræer	0	0	0	0.1	2.3	4.54	0	2.2	8.4	15.1
Qeqertarsuup Sermia	0.162	0.162	0.2	0.3	1.1	2.2	0.2	0.9	4.1	9.6
Kakivfaat Sermiat	4.8	4.27	12.8	19.1	19.3	19.5	19.4	19.4	19.5	19.5
Upernavik Isstrøm N	0.813	0.603	4.5	4.5	5.6	10.4	4.3	4.5	5.0	11.2
Upernavik Isstrøm C	2.93	2.93	4.5	6.3	8.4	8.4	6.3	7.7	8.8	15.1
Upernavik Isstrøm S	0.105	0.105	0.1	5.0	10.1	13.8	0.1	17.6	27.2	29.1

by about 40 km by the end of the century in all cases except if the thermal forcing increases by +3°C, in which case its ice front retreats by 64 km by 2100. The southern branch ~~has~~ shows a more binary behavior: it retreats another 3–7 km, depending on the warming scenario, but for enhanced thermal forcing simulations, it may retreat 43 km upstream or even 65 km upstream in the case of a +3°C warming in ~~TF~~ $\tilde{T}$. Alison Gletscher has been retreating by 2.5 km over the past 10 years, and the model projects that by 2030, in all cases, it will retreat another 7–8 km upstream due to the lack of features in the bed topography that may stop the retreat. By 2100, the glacier may retreat another 5 km if the thermal forcing increases by +2°C or more.

Illullip Sermia also has a binary behavior. For the strongest forcing, it retreats by 17–18 km, but in the more conservative scenarios, it stays at its current position that coincides with a large bump in the bed topography. Cornell Gletscher is one of the most remarkably stable glaciers of the model: under all scenarios, it retreats another kilometer ~~or so~~ upstream of its 2017

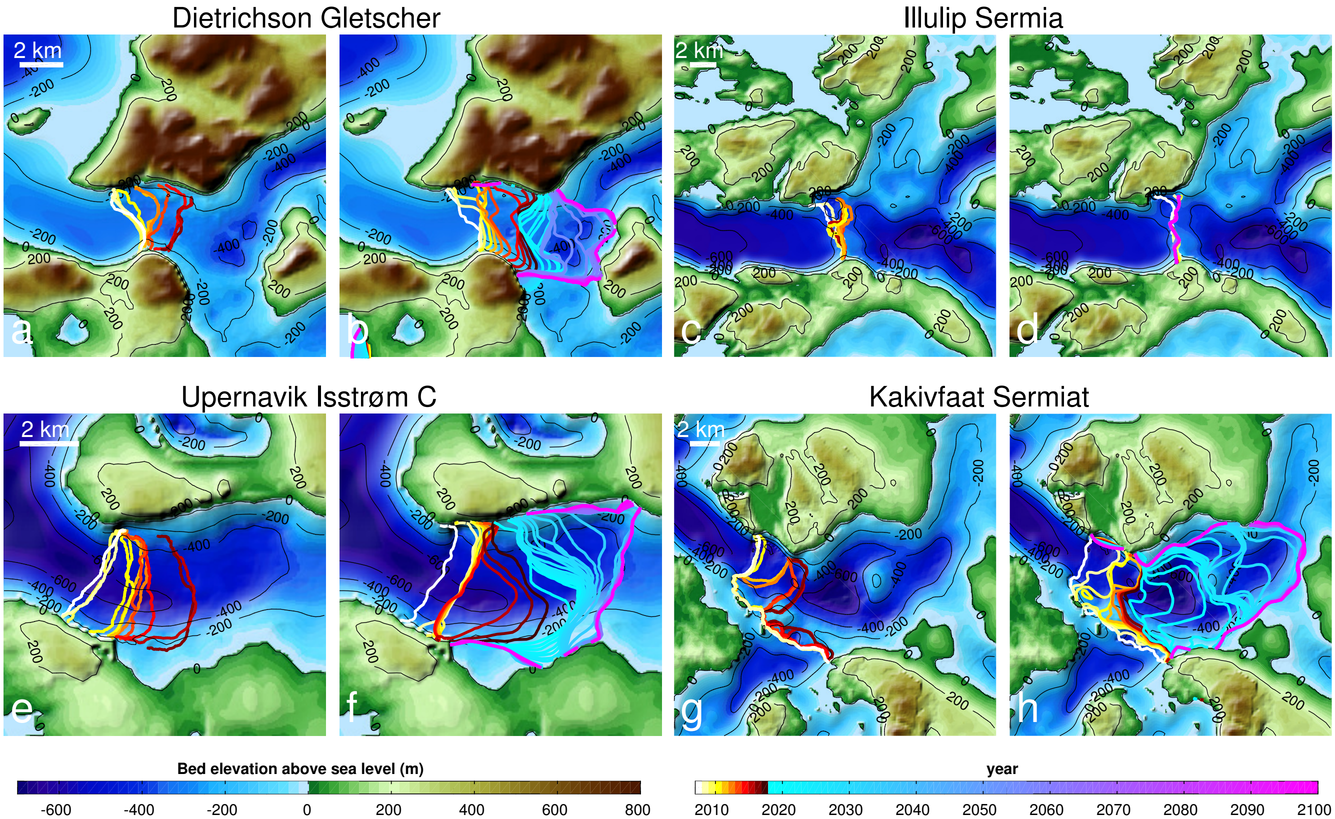

Figure 4. Observed (left) and Modeled (right) ice front position for Dietrichson Gletscher (a and b), Illulip Sermia (c and d), Upernavik Isstrøm C (e and f), Kakivfaat Sermiat (g and h). under current conditions (~~TF~~ $\tilde{T}$ +0°C, $q_{sg} \times 1$). Warm colors are for 2007 to 2017 and cold colors are the model projections for 2017 to 2100.

position and remains stable there, except in the case of +3°C increase in ~~TF~~$\tilde{T}$, for which it could retreat by another ~10 km~~or so.~~ .

Ussing Bræer N is the glacier for which we do not capture the advance, but under all scenarios, the model ~~project~~ projects that it will remain stable 3 km upstream of its current position, where the bed is very shallow. Ussing Bræer has been stable over the past 10 years, and the model suggests that it may retreat by 9 to 15 km if the ocean thermal forcing increases by 2 to 3°C, but the glacier does not retreat even when the subglacial discharge is multiplied by 10 in the case of no additional ~~warming in TF~~increase in $\tilde{T}$. Qeqertarsuup Sermia is also one of the stable glaciers of this region: the model marginally retreats, and under the strongest forcing (+3°C) retreats by about 10 km. Kakivfaat Sermiat, on the other hand, has ~~been retreating~~ retreated more than 4 km since ~~2007, and the~~ 2007. The model suggests that, in all cases, it will retreat another 15 km, where a pronounced feature in the bed topography keeps the ice front stable ~~. According to the model, the~~ (figure 5). Our simulations suggest that the glacier may reach this position by 2030 and remain stable there. Upernavik Isstrøm N retreats by 4 km or 11 km ~~for the stronger~~ depending on the forcing, by 2100. Upernavik Isstrøm C continues to retreat about 3–6 km upstream of its 2007

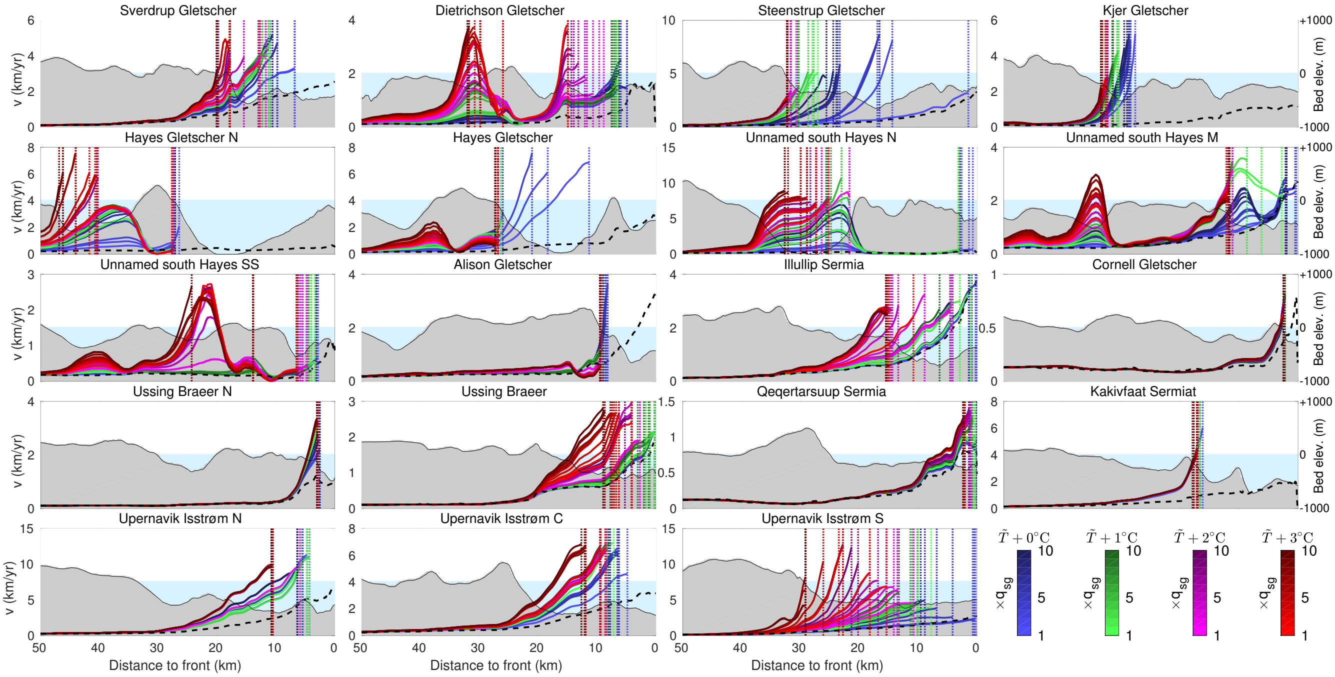

Figure 5. Modeled ice velocity (solid line) and ice front position (dashed vertical line) in 2030 for all 40 scenarios. The black dashed line is the current ice velocity (m) and the x axis shows the distance to the current calving front position

position, except in the case of a +3°C ocean warming under which it would retreat by 23 km. Finally, Upernavik Isstrøm S would remain stable if the current conditions of q_{sg} and ~~TF~~ $\tilde{T}$ are maintained, but may retreat between 17 and 29 km if the subglacial discharge is multiplied by ~~6~~ a factor of six or if the thermal forcing increases.

Figure 6 shows the contribution to sea level rise of the entire domain for the 40 different scenarios. In all cases, even under current conditions, our simulations suggest that this region will continue to lose mass. The mass loss is significantly stronger than in the control experiment~~that~~, in which we kept the ice front fixed. We also notice that the spread in mass loss due to temperature change (with a fixed q_{sg}) is significantly larger than the spread in mass loss due to an increase in subglacial discharge (with fixed ~~TF).~~ $\tilde{T}$). Note that we rely here on a 1960-1991 average surface mass balance, and the projections of ice loss do not account for the increase in surface melt. Our simulations are therefore conservative and should not be used as actual projections.

4 Discussion

Our simulations suggest that all glaciers of the ~~Northwest~~ northwest coast, except for four (Illullip Sermia, Ussing Bræer, Qeqertarsuup Sermia and Upernavik Isstrøm S) will continue to retreat several kilometers inland under today's thermal forcing and subglacial discharge. Under these ~~simulations~~conditions, we do not find any glacier which ~~advances~~advance.

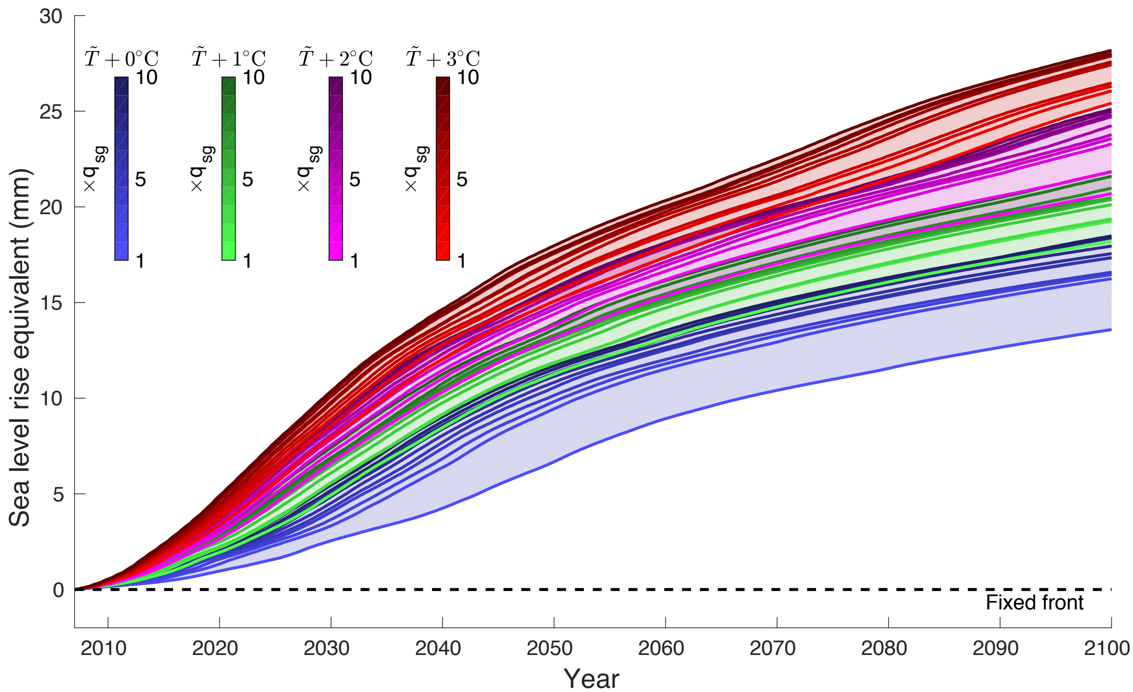

Figure 6. Contribution to sea level rise (mm) for all 40 scenarios. The black dashed line is the modeled contribution to sea level with a fixed calving front. All simulations rely on a constant surface mass balance.

In all scenarios, we find that the rate and extent of ice front retreat is strongly dependent on the bed topography: ice fronts are stable on topographic bumps and pro-grade bed slopes, and unstable on ~~retro-grade~~ retrograde bed slope, which is consistent with previous studies (e.g. Warren, 1991; Bassis, 2013; Carr et al., 2015; Catania et al., 2018; Wood et al., 2018). This is for example illustrated in figure 4h, where the ice front jumps from basal bump to basal bump and retreats rapidly in over-deepenings. We find this behavior common to all glaciers in the model domain. There is, however, no “intuitive” way to predict where the glaciers will stabilize without running a model. In most cases, the fjords are not symmetrical or ridges do not go all the way across the fjord walls, which makes it difficult to determine whether the ice front will stabilize or not.

We find that some glaciers, such as Alison Gletscher or Upernavik Isstrøm S, are more sensitive to small increases in ocean thermal forcing, while others, such as Cornell Gletscher or Qeqertarsuup Sermia, are very difficult to destabilize, even under a +3°C increase in ocean thermal forcing. On the other hand, we find that Hayes Gletscher retreats more than 30 km inland into a deep trough once it goes past a ridge, and its velocity increases by a factor of ~~10 over only 15 years(not shown here)~~3 over only 23 years, before restabilizing, under all warming scenarios.

We show here that calving dynamics is an important control on the ice sheet mass balance that should not be ignored. It has been driving the recent dynamic thinning of several Greenland outlet glaciers (e.g. Nick et al., 2009, 2013; Khan et al., 2014;

Felikson et al., 2017; Bondzio et al., 2017), and our model study shows that it may continue to control the mass balance of Greenland. Figure 6 shows, for example, that in all cases the system loses a significant amount of mass, and this mass loss is not captured by the model that keeps a fixed calving front. Models keeping ice boundary fixed (e.g., Gillet-Chaulet et al., 2012; Seroussi et al., 2013; Bindschadler et al., 2013) will consistently provide under-estimates of ice sheet mass loss as they do not capture the effect of ocean warming. These conservative projections should therefore be taken with caution and efforts should be made to include moving boundaries in continental scale simulations of the Greenland ice sheet in order to account for ice-ocean interactions, despite the complexity and high mesh/grid resolution needed to resolve moving boundaries (∼1 km, Bondzio et al. (2016)) of such simulations. It is also important to note that the future evolution of Greenland is strongly influenced by the ocean (through the ocean thermal forcing). It is important to not only force predictive ice sheet models with projections of surface mass balance, but also to include projections of ocean thermal forcing at the fjord mouth. There may also be some positive or negative feedbacks between changes in surface mass balance and calving. More surface melt, for example, could enhance calving through hydrofracture, while at the same time reducing the ice thickness at the calving front, hence reducing the stress. Ideally, the community should move towards ~~ice/ocean/climate~~ ice-ocean-climate coupled model to fully understand the processes that control the stability of the ice sheet (Nowicki and Seroussi, 2018).

Another interesting aspect of this analysis is that glaciers are more sensitive to an increase of one to two degrees in ocean thermal forcing than in a 5 to 10-fold increase in subglacial discharge. This is actually a result of the parameterization of undercutting used here (eq. 3), which is itself sensitive to ~~TF~~ $\tilde{T}$ than q_{sg}: the parameterization is sub-linearly dependent on q_{sg} and above-linear in ~~TF~~$\tilde{T}$. The effect of surface runoff is also limited to summer months, while the ocean thermal forcing affects the glacier year-round. That being said, we do not account for other effects that surface runoff may have on ice dynamics, such as enhanced damage due to hydrofracture, which may lead to a decrease in the stress threshold σ_{max}. Glaciers might therefore be more prone to retreat as q_{sg} increases than what is captured by the current model.

Among other limitations in this study, no ocean numerical model is included: the thermal forcing ~~of the ocean is entirely dictated by the parameterization~~ is prescribed and dictates the rate of undercutting. Similarly, the calving law is not capturing all the modes of calving and requires more validation. This study is indeed relying on two parameterizations that drive the response of the model to ocean forcings. It is therefore critical to further validate these parameterizations, or develop new ones that include more physics and better capture the transfer of heat from the fjord mouth to the calving face, and iceberg calving. We also assumed that the subglacial discharge was distributed uniformly across the calving front but observations show that the majority of discharge is routed to one or more large channel outlets (e.g., Fried et al., 2015). Frontal undercutting is therefore not distributed uniformly either, even though numerical experiments suggest that the uncertainty in melt is on the order of 15% (Xu et al., 2013). We have also shown how our results were strongly influenced by the bed topography. While the bed is pretty well constrained in this region (Morlighem et al., 2017), it is not free of error, and we have shown again here how important features in the bed topography are for calving front stability.

More importantly, this study paves the way for a Greenland-wide projection that includes realistic parameterizations of moving boundaries, which will provide more reliable estimates than current models that do not include calving. This work also suggests that development of more accurate parameterization of undercutting and calving should be developed as they control the response of the model, and its stability in future scenarios. While this work is a first step in this direction, more validation should be performed on these parameterizations, and future parameterizations of undercutting and calving will make models more reliable.

5 Conclusions

In this study, we modeled the response of the northwest coast of Greenland to enhanced oceanic forcing and subglacial discharge and found that this sector will continue to lose mass over the coming decades, regardless of the scenario adopted. The model confirms that ice-ocean interactions have the potential to trigger extensive glacier retreat over a short amount of time (i.e. decades), but the bed topography controls the magnitude and rate of retreat. Overall, the model showed greater sensitivity to enhanced thermal forcing compared to subglacial discharge, but did not account for other effects that runoff may have on ice flow. While ~~these results are promising in terms of our ability to capture current changes and make projections using numerical modeling,~~ more work on validating this parameterization of undercutting and ~~calving laws is neededto determine the degree to which we capture accurately the response of this sector~~the calving law employed here is needed, we showed that accounting for ice front dynamics can lead to significantly more ice loss than with a fixed calving front. Under the current oceanic and atmospheric conditions, this sector alone will contribute more than 1 cm to sea level rise by the end of this century, and up to 3 cm in the worst case scenario.

Code and data availability. The data used in this study are freely available on the National Snow and Ice Data Center, or upon request to the authors. ISSM is open source and freely available at http://issm.jpl.nasa.gov.

Author contributions. MM set up the model, designed the experiments, ran the simulations and wrote the manuscript. MW provided the data required to compute the rate of undercutting, HS and YC assisted in conducting the numerical experiments. All authors participated in the writing of the manuscript.

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