Answer to Interactive comment on "Submarine melt as a potential trigger of the NEGIS margin retreat during MIS-3" by Ilaria Tabone et al.

Anonymous Referee #1

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This paper addresses an interesting question about the past behaviour of the NEGIS system in Greenland. Its is relevant to the readership of TC and is a useful investigation of paleo-retreat controls in this area. The conclusions reached are reasonable based on the relatively simple experimental design (although see problem below). The work is linked to the appropriate existing literature in the region, and is mostly well written. In a few places the language used needs rephrased (see below) for clarity.

The main problematic issue I found with this paper is that it is very unclear whether the advance condition fits well with the geological evidence for LGM extent and therefore it is further unclear whether the retreat is to any degree preconditioned by this lack of fit. Thus the magnitudes and rates of retreat are harder to trust when we don't see the fit between the model and the data in a clear way. This could be solved by a more rigourous discussion of fit, and with figures enabling the fit to be visualised and quantified. That said, most of the sensitivity tests show advance to a fairly similar distance from the GL and therefore the comparative nature of the sensitivity tests is useful. In addition, the fact that sustained melt could have driven the retreat seems like a conclusion that wouldn't change if there were a different fit with the model extents and geological data.

Overall, with this issue addressed above, and the general comments addressed below, then this should be a useful contribution to the understanding of the NEGIS system.

We thank the reviewer for their valuable comments and suggestions. We agree that a clear description of how our model is able to reproduce the expected LGM extent was missing in the old version of the manuscript (MS). This concern has been principally addressed by adding a figure that clearly shows the fit between our simulations and the data (new Fig. 7). Also, we improved the description of how our ice-sheet-shelf model simulates the paleo and present state of the GrIS. Knowing the general behavior of the model and its performance in comparison with reconstructions will help to evaluate our results.

An exhaustive point-by-point answer to the comments is shown below.

Note that some changes we made in the experimental setup (described in this document) may have quantitatively affected the evolution of the grounding-line position throughout the last glacial. Thus, some details in the description of the results may have changed. Please refer to the figures of the new version of the MS when reading the answers below.

General Comments:

Page 1:

L5 'important conundrum' – please indicate more clearly what the conundrum actually is. I.e. you outline that the ice stream is losing mass and retreating over the last decades and that it retreated further inland at MIS3. Why is this a conundrum?

L6: 'a modelling approach is pending' – you mean a modelling approach has never been used to test the hypotheses?

The two points above imply that this paragraph needs clarification. We changed it to: "*Alongside, a recent study suggests that the NEGIS grounding line was 20-40 km behind its present-day location for 15 ka during Marine Isotope Stage (MIS) 3. This is in contrast with Greenland temperature records indicating cold atmospheric conditions at that time, expected to favor ice-sheet expansion. To explain* *this anomalous retreat a combination of atmospheric and external forcings has been invoked. However, the ocean was not brought into play. Here we investigate the sensitivity of the NEGIS to the oceanic forcing during the Last Glacial Period (LGP) using a three-dimensional hybrid ice-sheet-shelf model. We find that a sufficiently high oceanic forcing could account for a NEGIS ice-margin retreat of several tens of km, potentially explaining the recently proposed NEGIS grounding-line retreat during MIS-3."*

L14: I would like to see a good location map with the detail of the glaciers (and names) picked out and the overall setting shown clearly.

We added a new figure zoomed on the analysed sector showing the location and names of the outlet glaciers, the observed present grounding-line position, the LGM reconstructed grounding-line positions (max and min), PD observed surface velocities, offshore bathymetry and the onshore ice cover (new Fig. 2), as suggested by the reviewer herein and below.

L16: 'almost lost' – can this actually be quantitatively described because otherwise this is quite a vague statement.

This sentence has been changed to: *"In less than 15 years the ZI floating tongue has lost the 95% of its size as a result of an enhanced mass loss (Mouginot et al., 2015)."*

L17: 'due to its bed configuration' – please describe the differences in bed configuration – add detail and explain what you mean.

L18: 'lost mass' – can the mode of mass loss be described? E.g. thinning? Retreat? Both?

The two points above have been addressed by changing this sentence to: *"In less than 15 years the ZI floating tongue has lost the 95% of its size as a result of an enhanced mass loss (Mouginot et al., 2015). Concurrently, since 1999 the 79N ice shelf has lost the 30% of its thickness at the grounding line (Mouginot et al., 2015), contributing to its inland retreat by 2 km (Mayer et al., 2018). However, since 79N is retreating over an upward-sloping bed (Mouginot et al., 2015), it may be less prone than ZI to an unstable retreat. This has been recently examined through an ice-flow model pointing out that its floating tongue has to lose several tens of km of ice before the glacier becomes unstable (Rathmann et al., 2017). A larger stability of 79N has been recently tested under various future warming scenarios by another modelling study (Choi et al., 2017), suggesting that it may be related to the presence of pinning points (such as ice rises) near the calving front. "*

Page 2:

L5: delete 'even'.

Done.

L10: delete 'further back in time'. Also, what is meant by 'largely'? E.g. the fluctuations were large in magnitude? Or most of the ice margin fluctuated?

This sentence has been changed to: "*The paleo records emerging from this study, combined with a collection of geological data assembled in the last 20 years (Weidick et al., 1996; Bennike and Weidick, 2001; Evans et al, 2009; Winkelmann et al., 2010; Arndt et al., 2015, 2017), suggest that the ice margin considerably fluctuated in magnitude throughout this period.*"

L11: delete 'even'.

This sentence has been modified to answer the next two points raised by the reviewer.

L10-12: You don't mention that there must have been readvance since MIS3. Perhaps indicate what is known about this too?

L12-13: 'The Holocene retreat. . .. Etc.' – this sentence conflates the past and the future. It would be good to separate out the past bit and then say why it is important to look at this - e.g. because conditions may have been similar to what is expected in the future. In other words, this is the justification for why the paper is a useful piece of work.

The two points raised above indicate that this paragraph needs clarification. Thus, it has been changed to: "*Although the age of these LGM reconstructions is still poorly constrained, the combination of cosmogenic exposure and radiocarbon dating has recently facilitated the reconstruction of the position of the NEGIS over the last 45 ka (Larsen et al., 2018). The paleo records emerging from this study, combined with a collection of geological data assembled in the last 20 years (Weidick et al., 1996; Bennike and Weidick, 2001; Evans et al, 2009; Winkelmann et al., 2010; Arndt et al., 2015, 2017), suggest that the ice margin considerably fluctuated in magnitude throughout this period. Around 41-26 ka BP during Marine Isotope Stage 3 (MIS-3, c. 60-25 ka) the NEGIS front was ca. 20-40 km farther inland than today, then advanced by more than 250 km toward the shelf break at the Last Glacial Maximum (LGM) and retreated again during the last deglaciation, at ca. 70 km behind its present-day position, where it stopped most of the mid-and late Holocene (7.8-1.2 ka BP). The Holocene retreat was likely due to an increase in both atmospheric and oceanic temperatures, whilst the retreat during MIS-3 was attributed to a combination of atmospheric and external forcings. However, the potential role of oceanic forcing in this retreat has not been explicitly investigated from a modelling perspective. In the light of the ongoing changes in the GrIS attributed to ice-ocean interactions, this appears as a plausible mechanism that needs to be investigated. Moreover, since it is expected that warmer Atlantic waters entering the fjords will strongly affect the NEGIS margin in the future, assessing its response to similar past warm oceanic conditions will provide new insights into the future stability of its glaciers front.*"

L13-14: delete 'On the other hand' as it is superfluous text.

Done (see the paragraph above).

L15: 'was undertaken yet' should be 'has yet been undertaken'.

This sentence has been modified (see the paragraph above).

L30-31: The friction law is mentioned, but not quantitatively described. Can it be described more quantitatively?

We agree this aspect was lacking in the old version of the MS, thus we added a more detailed description of our friction law.

This paragraph has been changed to:

"*The SSA boundary condition is provided by basal sliding below the ice streams following a linear friction law, in which the basal shear stress τ_b is proportional to the basal velocity u_b and to a friction coefficient β dependent on the effective pressure of the water at the base of the ice sheet N_{eff}, as:*

$\tau_b = - \beta * u_b$ *(Eq.1)*
where

$\beta = c_f * N_{eff}$. *(Eq. 2)*

The term c_f depends on the different features of the bedrock topography (e.g. presence of sediments); N_{eff} is calculated as $N_{eff} = \rho g H - p_w$, where ρ is the ice density, g the gravitational acceleration and H the ice thickness. The sub-glacial water pressure p_w comes from a simple basal hydrological model based on a Darcy-type law, for which water flows at the base of temperate ice as driven by a gradient of hydraulic pressure. Despite the simplicity of this hydrology scheme, it provides a fair description of the outflow systems at the base of the ice sheet (Peyaud et al., 2007)."

Page 3:

L1: Can a comment be made about whether the flotation criterion and calving model has implications for any particular behavioural characteristics of the model. E.g. will this still produce good overall responses in terms of space? Will the rates of retreat (or readvance) be expected to be robust (or too fast or too slow?). Does it deal with retreat vs. readvance hysteresis well?

Since other calving and grounding-line treatments other than the flotation criterion and the two-conditions calving law have not been implemented in our model, it is difficult to judge the behaviour of these laws compared to others. However we can make some considerations.

The same calving law has already been tested in previous work (e.g. Peyaud et al., 2007, Colleoni et al., 2014, Alvarez et al., 2018) and appears to reasonably reproduce the advance and retreat of the ice sheet throughout the time. It is suitable for hybrid coarse-resolution ice-sheet models used with paleo purposes since it is able to describe the calving processes in a simple way without demanding too high computational effort. Its satisfactory performance can be seen for example in Tabone et al., 2018, where with the same treatment of the margin front, it is shown how well the model is able to simulate the advance and retreat throughout the last two glacial cycles. However, this calving law is a function of the imposed critical ice thickness below which the ice block is calved and depending on its value, it may be more or less conservative. Here, we imposed a threshold of 200 m, and both 79N and ZI floating tongues are lost during the Holocene. This is also documented in Peano et al. (2017) for the present state of the ice sheet. It could be that by increasing the ice thickness threshold (below which the ice block is calved) in the calving law the model would show slightly more resistance to calve. Although this cannot be completely assessed without a sensitivity test on that parameter, it is likely that an increase in this critical thickness would allow for longer and rather more stable ice shelves. However, the impact of the calving is limited to the grid cells at the ice front, while the retreat caused by the submarine melt involves fluctuation in the margin of hundreds of km. In a different context, Alvarez Solas et al. (2019, under review) have assessed the sensitivity of the ice-sheet dynamics to the value of the thickness threshold below which the ice is calved through an ensemble exploring a wide value range of this parameter's values, from 10 to 800 meters. Their results showed that the overall effect of this parameter is to modulate the amplitude of the response to the oceanic perturbations but its value did not qualitatively affect their main results. Thus we expect that such a change in the calving law may cause only second-order effects on the retreat.

This point has been reported by adding the sentence in the Discussion section: *"The model behaves sufficiently well in simulating the advance and retreat of the GrIS margins throughout the last 120 kyr (see also Tabone et al (2018)). Part of this performance is related to the two-condition calving law, that is a function of the critical ice thickness Hf below which the ice edge is calved. Thus, depending on its value, this law may be more or less conservative. Here, with an imposed threshold of 200 m, both 79N and ZI floating tongues are lost at the present. It could be that by increasing the value for Hf the model would show slightly more resistance to calve. However, the impact of the calving law is limited to the grid cells at the ice front, while the retreat caused by the submarine melt involves fluctuations in the margin of hundreds of km. Alvarez-Solas et al. (2019, under review) assessed this issue in a different context (the sensitivity of the Eurasian ice sheet to the oceanic forcing during the last glacial period). Their results showed that the overall effect of this parameter is to modulate the amplitude of the response to the oceanic perturbations but its value did not qualitatively affect their main results. Thus, we expect that changes in the calving critical thickness may cause only second-order effects on the retreat."*

The flotation criterion establishes whether the ice at a given grid cell is able to float or must ground. If it floats, the point located immediately inland is assumed to contain the grounding line. Thus, in circumstances of deep bedrock (such as along the 79N and ZI fjords) and high sea level elevation (warmer state), the ice advance could be inhibited if the ice thickness at the front is too low (for dynamical or climatic reasons). This point has also been discussed a few lines below in response to another comment. However, this is more related to the bedrock itself than to the grounding line treatment itself. It would be interesting to perform this study with a more complex grounding-line treatment to see its effects on the retreat combined with the impact of submarine melt rates. However, again, we expect only second-order effects on the results.

Perhaps a general paragraph on what we know this model is good at in general would therefore be useful.

A paragraph that describes the performance on the model in fitting the present day observations (surface elevation and velocity) has been added in the Discussion to give the reader more detailed information on the model behavior: "*The comparison of our results with observations is a good strategy to assess the model performance and to comprehensively evaluate the robustness of our results. At large spatial scales our simulations fairly represent the present state of the GrIS (Fig. S1). The maximum differences in surface elevations are found in the southwest and in the east due to a mismatch in ice cover. There, the ice sheet ends in many steep and narrow fiords which are not properly represented by the 10km-resolution model. Also, the NEGIS front is located farther inland than as observed. The velocity field shows a pretty good agreement in the interior of the ice sheet, where ice speeds are expected to be lower than 50 m a^{-1} (Joughin et al., 2018). However, the simulated ice flow of outlet glaciers and ice streams shows more discrepancies. The speed of the inland flow is generally overestimated, whilst the velocities of streams as they extend far inland is underestimated. By zooming into our domain of interest we see that this pattern is also shared by the NEGIS (Fig. S2 and left panel of Fig. S3). The stream geometry is not properly recognized, although the spatial distribution of the velocities is somewhat consistent with observations (faster flow at the margins and reduced speed in the interior, as seen in Fig. S2). However, the tributary fast flows that feed the 79N are not reproduced; the SG is faster than expected and, instead of the long penetrating tongue of ice that characterises the NEGIS, the model simulates a stream catching a wider area.*
Properly modelling the NEGIS is a well-known problem of ice-sheet models that investigate the evolution of the GrIS at large spatial scales. Most of these models underestimate the stream velocity and do not properly capture its outline (Seddik et al., 2012; Greve and Herzfeld, 2013; Aschwanden et al., 2016; Calov et al., 2018; Golledge et al., 2019). Greve and Otzu (2007) succeed in reproducing a correct magnitude of its speed by increasing the basal sliding under the NEGIS by three orders of magnitude relative to the rest of the ice sheet, but they fail in reproducing its geometry. A good agreement between model and data is found in Price et al. (2011) and Peano et al. (2017), who use a spatially variable basal friction coefficient derived from an iterative inverse method to match the observed velocities.
Our imperfect reproduction of the NEGIS stream is probably related to a combination of still low spatial resolution (10 km) and problems in capturing the dynamics at the base of the ice sheet. Our basal friction coefficient β is a function of the effective water pressure at the base of the ice sheet, which is a significant degree of freedom in ice-sheet models. A better representation of basal hydrology and sliding could help to improve the simulation of the ice stream. In parallel, new studies on the origin of the stream (following Roghozina et al., (2016)), its basal characteristics (following e.g. Keisling et al., (2014), Christianson et al. (2014) and Rivermann et al., (2019)) and new data from the EGRIP ice core (following e.g. Vallelonga et al., 2014) will bring new insights in this direction."

L14: I was surprised to see that there was no sensitivity testing of the climatic controls on the model experiments. Can you comment somewhere in the text as to whether you think the results would be significantly different if the climate control was altered within a certain range of uncertainty?

The reviewer is right noting that we did not perform sensitivity tests on the climate control. We are aware that this precludes the possibility of assessing the relative role between the atmospheric and oceanic forcings. However, the impact of different climates on the NEGIS margin needs to be evaluated in the future to comprehensively understand the causes of this retreat.

To clarify this point we added this caveat in the results: "*The absence of an equal sensitivity test on the atmospheric forcing, and/or further experiments with another melt scheme, preclude the possibility to assess the relative role between atmospheric and oceanic forcings in the evolution of the NEGIS margin.*"

Also the following paragraph has been added in the Discussion: *"Further experiments accounting for changes in the atmospheric temperatures and precipitation or variations in the external forcing (i.e.*

insolation) should be carried out for a full understanding of the mechanisms involved in this retreat, here explained by considering the sole impact of the ocean. Particularly, a sensitivity study on climatic variations performed with a prescribed ocean could help constraining the effect of the atmosphere in this phenomenon to eventually evaluate the relative role between the forcings in driving the NEGIS margin."

Page 4:

L18: Can you justify why basal melt rate is not parameterised in a depth-dependent manner? Or in other words, why is a 10% Bm on all floating grid cells an appropriate decision to make?

To make the experiment as simple as possible and within the scope of a sensitivity study, we impose a spatially homogeneous temperature anomaly at the base of the ice shelf that is the 10% of that at the grounding line. This of course is a simplification of reality since submarine metl rates vary at regional and local spatial scales. However, this assumption is in line with present-day estimates of submarine melt rates at the margins of the GrIS (e.g. Münchow et al., 2014; Rignot and Jacobs, 2002; Wilson et al., 2017).

A similar approach has been also used in previous work (Alvarez-Solas et al., 2019, Blasco et al., 2019, Tabone et al., 2018) investigating the past role of the ocean on the GrIS evolution during the last two glacial cycles. A more realistic approach considering depth-dependent submarine melt rates also that spatially vary across the Greenland coasts is beyond the scope of our simple sensitivity study. However, these features should be taken into account in the scope of future work.

L25 or thereabouts: Do you make any assessment of whether the pre MIS3 state is realistic? I.e. how good is the spin-up, can it be assessed, and how does it fit to the geological/field data from the region. In addition, can you confirm you are you allowing the grounding line to evolve through time? And does the ice shelf characteristics evolve through time during spin-up?
L30: I think a map of the fit between the pre MIS-3 state and the geological evidence would be an important figure to show. This will allow better discussion of whether the system is appropriately setup for the retreat experiments. I.e. if the extent or thickness is not correct, then how can we trust the degree or rates of retreat?

The two issues above are addressed together. The spin-up covers the penultimate glacial cycle (between 250 kyr and 120 kyr ago); it includes a variable topography, variable climatology, the grounding line migration is enabled, and the submarine melting is defined through the same equation as the variable climatology (i.e. follows the orbital-driven temperature evolution, extrapolated from Kindler et al., 2014 up to 300 kyr ago). There is actually no difference in the experimental design between the spin-up and the rest of the simulation, but that interval of time is not analysed but only used to allow the model to stabilise after the initialisation. Results for the GrIS at the LIG are well within the range of other reconstructions, as results are very similar to those of Tabone et al. (2018).

However, it is hard to discuss in detail these spin-up results since, besides the model reconstructions available for the LIG, there is a huge uncertainty about the GrIS configuration before the LIG and between the LIG and the LGM. Specifically, as far as we know there is no such geological evidence for the NEGIS margin configuration before the time period showed in Larsen et al. (2018) (ca. 41 ka BP). Although temperature reconstructions, accumulation changes, insolation changes, etc. suggest that the GrIS between the LIG and MIS-3 was in a glacial state (e.g. Dahl-Jensen et al. (1998), Andersen et al. (2004), NEEM community members (2013)) and many Greenland marine-terminating glaciers advanced over the shelf reaching at least the inner part of it (e.g. Funder et al., 2011), we do not know if the NEGIS margin was actually expanded toward the continental shelf during that time, and if yes, to what extent.

Since we don't know the state of the NEGIS before MIS-3 due to the lack of data, we cannot actually corroborate that there had been a retreat from a pre-MIS-3 to a MIS-3 state. On the contrary, we want to emphasize that we can simulate a margin that *was located* farther inland during part of MIS-3 and advanced toward the shelf break during the LGM, as suggested by reconstructions. More generally, our results are in agreement with those from Larsen et al. (2018), suggesting that the

NEGIS margin strongly fluctuated during the last glacial period, but we provide a different explanation which we think is more realistic.

However a similar assessment can be made by comparing our results with the geological records for the LGM. Since our results are well in agreement with the available reconstructions (between 41 kyr BP and the present, as seen in new Fig 3) and the spin up for the first glacial cycle reproduces ranges of advance/retreat in the range of the uncertainties (not shown), we are pretty confident in the reliability of our results. However, this is discussed in more detail below, in a response to a related comment.

L32: delete 'already'.

Done.

Page 5:

L1: What is meant by 'substantially steady' – describe the margin stability pattern in clearer detail.

This sentence has been changed to: "*During MIS-3, the ice-margin position gradually advances towards its maximum glacial extent, which is reached at about 20 kyr BP (LGM), when the ice sheet becomes grounded at about 30 km far from the shelf break, reducing the area of the floating ice shelf in the region (Fig 4 a-e).*"

Note that old Fig. 1 has been changed with new Fig. 3, and old Fig.3 with new Fig. 4.

L21: 'stationing' isn't a good word to use. Do you mean 'stopping', or 'retreating to'?

Yes, we agree with the reviewer that using the word "stopping" is more appropriate. Changed accordingly.

L27: you mention that there is no melt imposed at the LGM. You could discuss somewhere later about whether you think this is a realistic condition.

This point has been addressed adding this sentence in the Methods: "*Imposing a submarine melting rate equal to zero at the LGM is probably a simplification of reality, leading to the absence of refreezing below the ice shelves. These processes may vary strongly at local scales, as we know from present observations in Antarctica (e.g. Rignot et al., 2013) and Greenland (e.g. Wilson et al., 2017). However due to the lack of data for the basal melt along the NEGIS margins for the last glacial and the coarse resolution of our model (10 km), this assumption may be considered as a fair compromise for the scope of our sensitivity test.*"

Page 6:

L1 'saturates for high values' – can the high values be stated quantitatively?

This sentence has been changed to: *"This feature then saturates for Bref higher than 3 m a^{-1}, as a further retreat inland is constrained by the bathymetry."*

L14-19: As mentioned before – I would like to see a better exploration, and a figure, showing the fit of the LGM expansion and the field data. I think the weakness of this paper lies in both a lack of description of this, but also the fact that the fit is not as good as it could be. We really need to see how good the fit is so we can better judge the results. In addition, were there no modifications, for example to the climate, or the the Bm during the advance phase, that would help enable a better fit to the data? Some more sensitivity tests on this would have been good to see.

In the new version of the manuscript we compare our simulated maximum glacial extent to previous reconstructions based on geological records (Evans et al., 2009; Arndt et al., 2015, 2017; Winkelmann et al., 2010, Funder et al., 2011) and the results are fairly good, specifically if compared to previous model reconstructions (new Fig. 7). However, there are still some discrepancies between model and data, specifically we cannot advance the grounding line up to the continental shelf break. Here we discuss what we think might be responsible for the limited extent and the consequent constrained ice volume at the LGM.

We changed the paragraph of Pag. 6 lines 14-19 (old MS) to:

"*Second, our simulated grounding-line advance during the LGM is smaller that the maximum extension suggested by reconstructions from geological records (Fig. 7). This bias furthermore increases with increasing oceanic forcing. Even in the unperturbed experiment, which allows the largest ice-sheet expansion due to the absence of melting at the marine margins, the grounding-line does not reach the continental shelf break either. Nevertheless, our simulated extent is still one of the best reconstructions of the northeast Greenland at the LGM obtained with an ice sheet model (Tabone et al., 2018, Simpson et al., 2009, Lecavalier et al., 2014, Bradley et al., 2018). This discrepancy in the LGM extents is reflected in the transient GrIS sea level contribution from the LGM to the present (Fig. S4), that is underestimated as compared to other recent modelling work (Lecavalier et al., 2014, Tabone et al., 2018). Nevertheless, our estimation is not far from others (Simpson et al., 2009, Huybrechts 2002) and well within the range proposed by Buizert et al. (2018). Note that although the LGM extent simulated by Lecavalier et al (2014) is smaller than ours in the northeast, their ice volume contribution at the glacial maximum is about 1 m SLE higher. This could be partly due to their larger grounding-line advance in the northwest, but it might be also related to a more active dynamics in our simulations. The volume discrepancy between our two studies performed using the same ice-sheet-shelf model are likely due to differences in the dynamics. The main reason seems to be related to the fact that SIA and SSA velocities are here simply summed up instead of mixed through a weighting function as in Tabone et al., 2018. This increases the velocities in the transition zones, promoting discharge of ice from the interior and consequently limiting the ice volume accretion. Second, Tabone et al. (2018) accounted for refreezing processes at the base of the ice shelves, which allowed the grounding line to advance easily, leading to a glacial state in which almost all the GrIS margins were able to reach the shelf break. It is clear that this larger extent could account for a substantial part of the ice volume discrepancy. Another possible reason could be that here we increased the basal drag at the base of grounded temperate ice (by increasing its coefficient c_f of Eq. 2). More friction at the base may foster the production of water at the ice-bed interface through heat release, making the bed more slippery and the ice flow to accelerate. However, we expect that this process is responsible for only a small fraction of the ice volume discrepancy, since it is counteracted by the increase in basal friction itself. Increasing the total ice volume during the glacial (and its extent) would probably require a substantial tuning effort, that is beyond the scope of this study. Our goal is not to provide a perfect match with the LGM but to illustrate a plausible mechanism behind the retreated ice margin at MIS-3 and its subsequent advance.*"

L17: 'insufficient basal drag' . Please tell us why the imperfect drag imposition would alter the result in this way?

Please, see the paragraph above.

Page 7:

L1: can you describe the pattern of saturation in more quantitative detail?

The paragraph has been changed to: *"The grounding-line retreat at the PD is proportional to the magnitude of the submarine melt rate imposed at the NEGIS ice margins during the mid-late Holocene, which is related to the value of Bref used. However, this correspondence is very weak and the retreat quickly saturates at about 70 km away from the PD position along the glacier flowing direction for κ higher than 3 m a-1 K-1, where it is stopped by the presence of a bedrock above the sea level (Schaffer et al., 2016; Morlighem et al., 2017). Although this retreat is supported by proxies for the mid-Holocene (Bennike and Weidick, 2001; Larsen et al., 2018), its persistence until the present day is unrealistic. "*

L9: 'it is unlikely that this could have happened for a long period of time and in such a persistent way.' Can you justify why this is the case? Explain in more detail – link to any knowledge in ocean circulation change etc.

This sentence has been added in the discussion: *"Peaks of up to 50 m a−1 occur at the NEGIS margin, however it is unlikely that this could have happened for a long period of time and in such a persistent way. Several records inferred from sediment cores in the Arctic Ocean and in Fram Strait indicate that temperatures of surface and subsurface waters strongly fluctuated during the Holocene due to the variability of the oceanic currents. The inflow of Atlantic warming waters in the early Holocene determined warmer oceanic conditions recorded at the surface (Sztybor and Rasmussen 2017) and at the subsurface (Werner et al., 2016, 2013), where temperatures increased by 3-4 °C since the beginning of the Holocene. After 9-8 kyr however, these records report a drop in temperatures, gradually (Falardeau et al., 2018.; Werner et al., 2016) or interrupted by some peaks of warming (Consolaro et al. 2018). These different oceanic conditions between the early and mid-late Holocene suggest that such a durable high melting rate during the whole Holocene is likely overestimated. "*

Page 8:

L4: 'helps to constrain' – so you mean 'helps to limit'? Constrain could be interpreted in a number of ways – e.g. to limit or to provide evidence to help understand.

Changed to "helps to limit".

L7: It would be useful to know whether the 'prolonged presence of submarine melt' is something that is a realistic prospect based on any other evidence.

This concern has been addressed in the discussion by adding this paragraph: *"Paleoceanographic records inferred from marine sediments in the Arctic Sea and Fram Strait that provide information on the oceanic state during MIS-3 at high temporal resolution are scarce. However, they all suggest rapid temperature fluctuations as a result of large changes in water masses at different depths. Warmer SST may last for 3-4 kyr before cooling (Muller et al., 2014). Generally, strong variations in the oceanic conditions are found between glacial-interglacial, but also between larger stadial-interstadial transitions (Poirer et al., 2012). A sediment record between the Nordic seas and the Arctic Ocean suggest that high SST and low intermediate water temperatures are typical of interstadials, while the opposite is found during stadials due to intrusion of warmer Atlantic subsurface water (Rasmussen et al., 2014). This strong oceanic temperature variability during the last 50 kyr is also documented by another record based on a stack of sediment records of the Arctic Ocean and the Fram Strait, suggesting the occurrence of several peaks of warmings during MIS-3 reaching temperatures 1-3 °C higher than those recorded for the Holocene (Cronin et al., 2012). However, a qualitative analysis of this temperature record at long (orbital) timescales indicate that its evolution agrees well with that of the melting rate signal used in this work: high melting during MIS-3, prolonged cooling during the LGM and high melting again during the Holocene. Thus, even though we remove some degree of realism by not considering the millennial-scale variability in the ocean, our experimental design could fairly represent the evolution of northern Greenland oceanic conditions at long timescales."*

Figures:

Fig1: I would separate the inset map to a separate new figure 1 which should be a location map showing the NEGIS area in much more detail, including the key outlets, the location of the profiles, the offshore bathymetry, the onshore ice cover etc. In addition, either on that map or on an additional new figure, all the evidence for past ice extent should be shown so that we can then use it to judge how well the model fits with
the geological dataset.

As already said at the beginning of this document, we added in the MS a map addressing all these points (new Fig. 2) in substitution of the inset map of old Fig. 1.

In addition, in this figure the growth and retreat steps are rapid. Can you say much about whether these are purely a function of the forcing provided, or whether the bed topography or fjord width is having any particular control on the 'stepped' nature of advance or retreat?

The "stepped" nature of advance and retreat, as the reviewer calls it, is primarily due to the oceanic forcing applied. This is pretty well visible comparing the submarine melting rate signal with the curve of old Fig. 1 (new Fig. 3). The large advance and retreat well follow the decreasing/increasing in melt. However, others factor may also play a role. First, the area connecting the ZI and 79N to the inland topography shows a bedrock that is 100-200 m deep (Schaffer et al., 2017; Morlighem et al., 2017). In periods of relatively high sea level, such as the first thousand years after the last interglacial, this deep bathymetry may be crucial in driving the grounding line evolution (through the flotation criterion), since it hampers the ice to ground and so the ice sheet to advance. Another reason for this "stepped" nature is the fact that in the old version of the MS we calculated the grounding-line position in time over one transect only, thus per each grid point "conquered" by ice the grounding line would advance of 10 km in a row.

To smooth the results, we now calculate the grounding-line distance on 48 transects intersecting the ZI and the continental shelf break. The final result is the average of the grounding-line position between all of them (new Fig. 3). This improvement in the experimental setup allows for a better characterisation of the results, since 1) the big uncertainty in the LGM grounding-line position of Larsen et al. (2018) (+- 50 km) accounts for the broad range of distances between the shelf break and the PD margin of the outlet glaciers and 2) the retreated position during MIS-3 is documented only for ZI (Larsen et al., 2018) and SG (Weidick et al., 1996).
This helps to smooth the grounding-line distance, however the "stepped" nature related to the other two sources explained above is of course still visible.

To make these aspects clear this sentence has been added to the results: *"We calculate the grounding-line distance from the PD position on 48 transects intersecting the ZI and the continental shelf break (Fig. 2). Then we average the results to create one transient evolution for the grounding line for each oceanic forcing."*

Also: *"Grounding-line advance and retreat is often very rapid, especially during the first advance after the LIG or during the MIS-3. This is primarily due to the oceanic forcing applied, since the large advance and retreat well follow submarine melt rate evolution. Part of this stepped nature may be due to the bathymetry too. The area connecting the ZI and 79N to the inland topography shows a bedrock 100-200 m deep (Morlighem et al., 2017). In periods of relatively high sea level, such as the first kyr after the last interglacial, this deep bathymetry may be crucial in driving the grounding line evolution (in our model through the flotation criterion), since it hampers the ice to ground and so the ice sheet to advance. This is in line with recent work suggesting that deep bathymetry combined with warmer waters entering the fjord may have important consequences in the destabilisation of the 79N (Schaffer et al., 2017)."*

Given that you mention that there was a retreat to a position inland of the present day grounding line position, can you also show a horizontal dotted line to represent the knowledge of where this inland retreat reached?

We do not understand to what position the reviewer is referring. The position of the grounding line during MIS-3 as reconstructed by Larsen et al., (2018) is represented by the dashed black line between 41-26 kyr BP in new Fig. 3 (old Fig. 1). The position reached by our simulated grounding line during the Holocene is shown by the curves representing different oceanic forcings.

Fig3: These figures are a little hard to follow because of their size. Can they be made bigger? The arrows pointing to the PG grounding line positions aren't terribly useful – surely a line on the map would be more appropriate. Finally, you mention these are snapshots at different times along MIS3 and the LGM. Please state which times these actually represent.

New Fig. 4 (old Fig. 3) is now bigger; the arrows indicating the PD grounding line have been substituted with a thin black curve and the snapshots have been named by the time they represent. Also, the reconstructed LGM extent is added to each snapshot for comparison.

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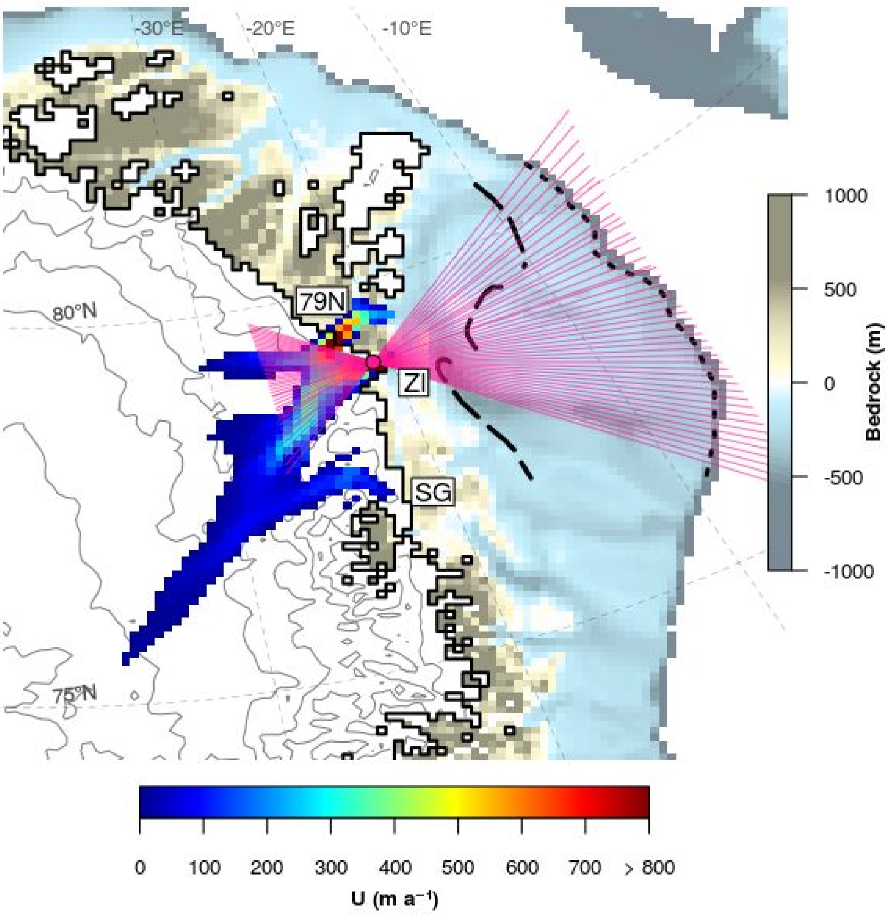
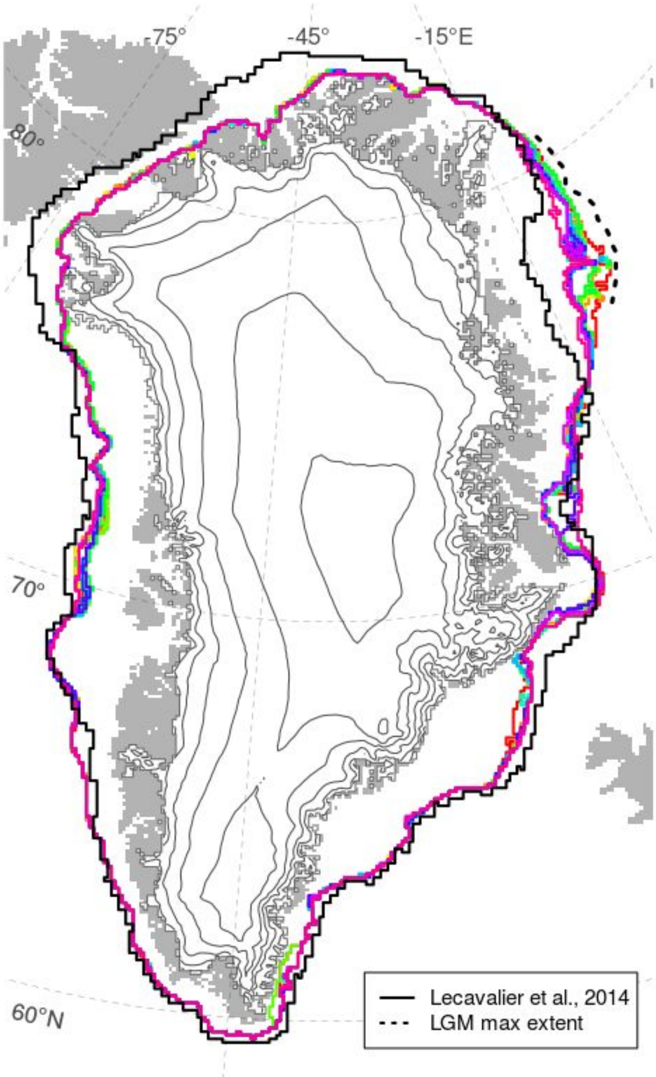
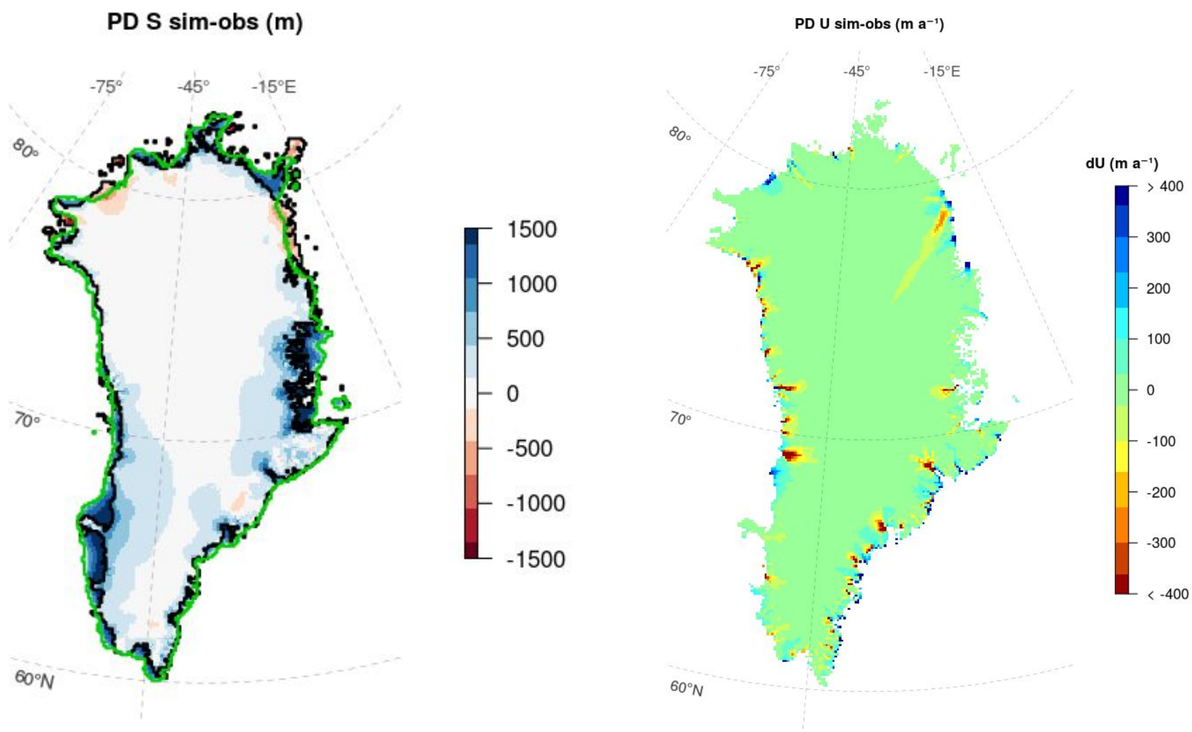
FIGURES



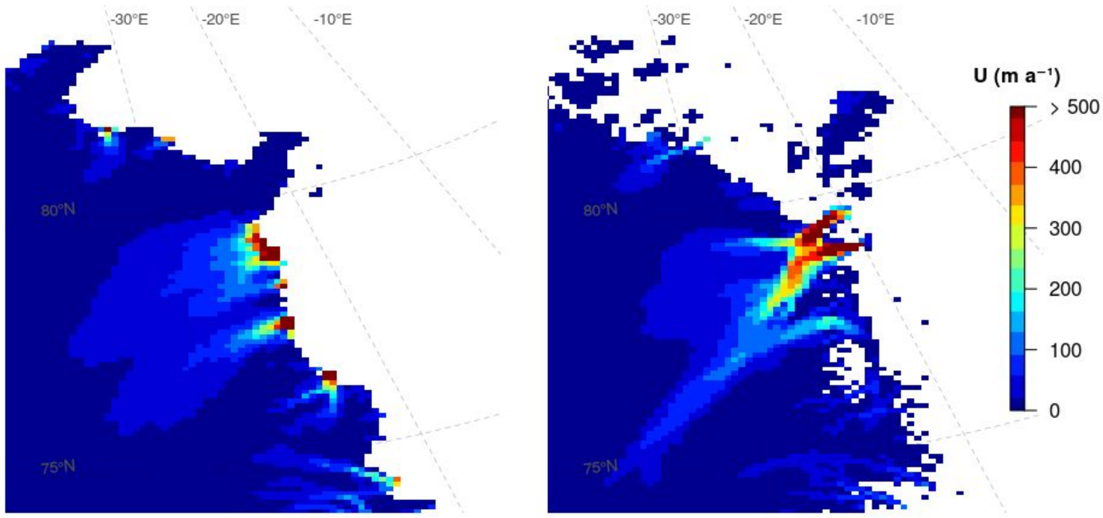
New Fig. 2. Map of the NEGIS sector showing the location of its three outlet glaciers (79N, ZI and SG), the observed present grounding-line position (solid black line), the observed present surface velocities (from Joughin et al., 2018), the offshore bathymetry and the onshore ice cover (both from Schaffer et al., 2016) and the maximum (dotted black line) and minimum (dashed black line) grounding-line positions reconstructed for the LGM (Funder et al., 2011). The 48 transects used to calculate the evolution of the grounding-line position are shown in purple.



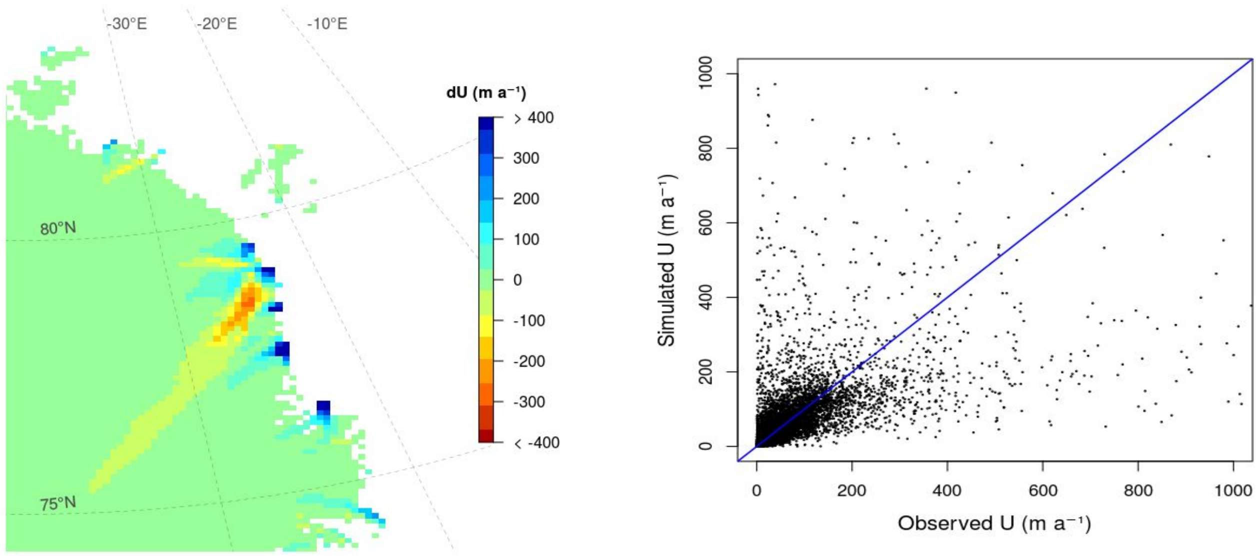
New Fig. 7. Simulated GrIS extent at the LGM for different oceanic forcings compared to other glacial reconstructions. Colored lines follow the color scale of new Fig. 3 in the MS (old Fig. 1). The solid black line refers to the maximum glacial extent simulated by Lecavalier et al. (2014), calibrated to match the minimum LGM configuration (Funder et al., 2011) in the northeast. The dashed black line represents the expected maximum glacial extent at the northeast sector as inferred from various geological data (Evans et al., 2009; Arndt et al., 2015, 2017; Winkelmann et al., 2010).



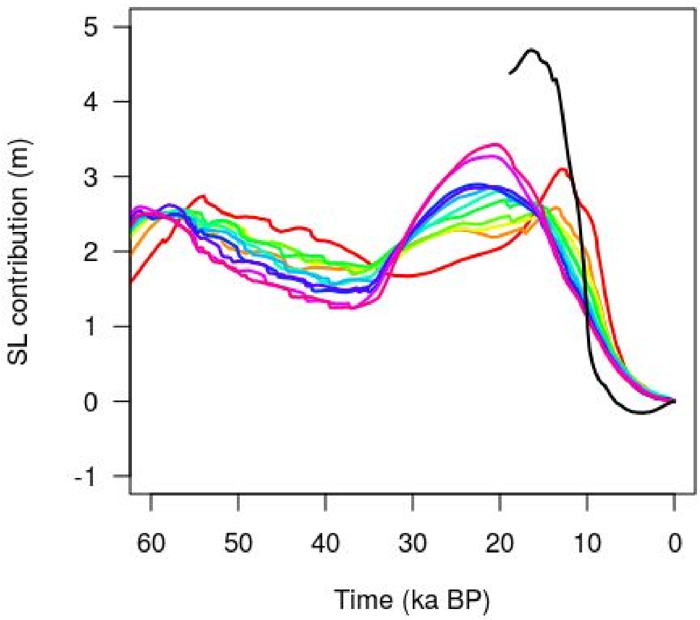
New Fig. S1 in the MS. Simulated minus observed GrIS surface elevation (left panel) and GrIS ice velocity (right panel) for the PD. Green and black lines on the left represent simulated and observed GrIS extents, respectively. Surface elevation data are taken from Schaffer et al. (2016); ice velocity observations from Joughin et al. (2018). Both maps are produced for the $\kappa = 8$ m a^{-1} K^{-1} experiment. However, the choice of another oceanic sensitivity κ would have little effect on the simulated-observed discrepancy.



New Fig. S2 in the MS. Present-day simulated (left panel) and observed (right panel) velocities for the NEGIS sector. Observed data are taken from Joughin et al. (2018).



New Fig. S3 in the MS. Simulated-observed present-day velocities for the NEGIS sector (left panel) and its scatterplot (right panel). Blue line refers to the perfect match between model and data.



New Fig. S4 in the MS. Evolution of the GrIS sea-level contribution for the last 60 kyr. Colored curves refer to the color scale of new Fig. 3 in the MS (old Fig. 1). The black curve refers to the GrIS sea level contribution for the last deglaciation modelled by Lecavalier et al. (2014).