

Response to reviewers

We are pleased to resubmit this manuscript after recommended revisions. We have systematically addressed all the comments made by the reviewers, and have followed their constructive suggestions.

- 5 We would like to thank both reviewers for their thoughtful and constructive comments. We trust we have adequately addressed the issues raised by the reviewers, and that the revised manuscript is significantly improved as a result.

- 10 The major changes to the manuscript are a broader discussion of the simplifications made in the experimental design (sections 3.3 and 4.4), moving the majority of the supplementary information into the main text, and a new code and data availability section. Minor revisions suggested by the reviewers have also been made. A limited number of other changes have been made, to remove typos or improve sentence clarity. All changes are highlighted in a “tracked changes” version of the manuscript.

15

Reviewer comments are in black

Author responses are in blue

- 20 A “tracked changes” version of the manuscript is attached below. Referenced page and line numbers refer to the attached tracked changes version of the manuscript.

Review #1

- 25 **Interactive comment on “Marine Ice Sheet Instability and Ice Shelf Buttressing Influenced Deglaciation of the Minch Ice Stream, Northwest Scotland” by Niall Gandy et al.**

J. Seguinot (Referee)

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- 35 N. Gandy et al. present an application of the higher-order ice sheet model BISICLES to early deglaciation dynamics of a marine-based sector of the British-Irish Ice Sheet in northwest Scotland. The Minch, a submarine trough located between mainland Scotland and the Isle of Lewis, is presented as one of the best documented marine sectors of the former ice sheet, much suited for this exercise.

The numerical experiment is divided in three stages. First, a “spin-up” run is initiated upon a previously published perfect-plastic ice geometry and brings the model to a steady state. Second, “retreat” simulations triggered by an instant increase in air temperature and sub-shelf melt are used to analyse deglaciation patterns and sensitivity to ice-shelf buttressing. Third, “readvance” simulations started at different stages of deglaciation with instant return to “spin-up” conditions are used to investigate the reversibility of marine ice “retreat”. The simulations evidence the potential for ice retreat in two stages separated by a phase of thinning but near stagnation of the ice margin, and a point-of-no-return after which deglaciation becomes irreversible.

Strongly simplifying assumptions are made (and acknowledged), but the novelty of this study lies in its regional and marine focus. In fact, the authors should be credited for making one of very few (if any other) attempts to date to use the rich, newly available submarine glacial geomorphologic record to validate marine ice sheet modelling, a topic full of physical uncertainties and numerical difficulties. The manuscript is very well written and clearly illustrated.

I strongly support publication of these results, but I would encourage the authors to increase the transparency of their methods and clear a few inconsistencies in the interpretation before publication.

1 General comments

Code availability and reproducibility

As of now, the description of the methods lacks important detail and parameter values (see also specific comments below), which hinders the reproducibility and the traceability of the model results. Since a detailed sensitivity is not (and probably need not) be included, this means that readers have to trust the authors for having made reasonable model choices and used error-proof tools. This is not reasonable given the multiple uncertainties that affect ice sheet modelling.

The statement that “Cornford et al. (2013) provides a full description of BISICLES” (p. 3, l. 20–21) is not entirely correct as that paper primarily describes the numerical treatment of ice flow and grounding line migration but not boundary model components, and the code has presumably evolved since 2013. Ice sheet models such as BISICLES are complex programs containing numerous uncertain ice physical parameters, multiple numerical approximations and configurable regularizations schemes. Most importantly, they are not exempt from coding errors.

I am certainly not advocating to clutter the article with a full model description here, which would be both disruptive and inefficient. Instead, I think that model code should be made available and the version used clearly stated in the manuscript. The required section on “code and data availability” is

missing. I also suggest that authors include a referenced list of the most important ice-physical parameters used in their set-up.

5 We have now included the required code and data availability section. It provides a link to the version of the BISICLES model code used. It also includes a DOI for the deposited data described in the manuscript. This comprises all input data needed to run the experiments, plus our outputs for each experiment. A link to the PyPDD model is also included.

A list of the most important model parameters is now included in table 1.

10

Supplementary material

15 Related to the previous point, parts of the methods, and results from two sensitivity tests are given in the supplementary. I don't really understand the authors' choice to store this important information in a supplementary file (using a proprietary format with no guarantee of long-term readability). I found it a bit difficult to follow the main text without looking at supplementary figures.

20 I suggest that Table S1, Figs. S1 and S2, and the description of the basal friction map (with added values and for the friction coefficient, and possibly a reference to the basal sliding equation) are incorporated in the main text. Perhaps Fig. S1 could be merged with Fig. 3, and Fig. S2 with Fig. 4. References are already in place where needed. Fig. S3 does not add much to Fig. 7 and could probably be omitted.

25 To make the manuscript easier to follow we have moved Table S1, and Figure S1 and S2 to the main text as suggested. A description of the basal friction map is now included in section 3.2 (Initial conditions and spin-up). Figure S3 has been removed from the Supplementary Information, as recommended.

Fast retreat and irreversible retreat

30

35 Some of the sentences in the abstract and conclusions (see specific comments) appear to amalgamate rapid retreat and irreversibility. However, it is worth noticing that the area of slow retreat at the strait's mouth (best visible in the supplementary animation) is distinct from the point of irreversibility in shallow waters further upstream. This interesting result indicates a different role of lateral and vertical confinement on marginal retreat. I find this result particularly interesting in the context of the variety of currently observed patterns of tidewater glacier retreat in Greenland and Antarctica, and believe that it should be emphasized in the abstract and conclusions.

We have edited the text to separate the discussion of fast and irreversible retreat from the abstract and conclusion. We have also added sentences (p1,l21)(p8,l7)(p14,l18) to mention the important comparison between later stages of retreat and tidewater glaciers of Greenland and Antarctica.

5 2 Specific comments

p. 1, l. 17: the ice stream becomes laterally confined at a “pinning-point”

The phrase “pinning-point” is often used to describe ice rises and other contact points stabilizing an ice shelf, which may be confusing. In line with my general comment above, I suggest replacing with a more descriptive term, e.g. the “straight’s mouth” or “the end of the trough”

The phrase “pinning-point” has been changed to “the Minch Strait’s mouth” throughout the manuscript to avoid potential confusion.

15 p. 1, l. 18: the presence of ice shelves became a major control on deglaciation

This statement does not really reflect the model results and argumentations in the main text (also see other comment below). Actually I was surprised to find how little effect ice shelves have on the pace of deglaciation, for which authors provide a very satisfactory explanation. I think this sentence should be reworked.

The sentence has been reworded to better reflect the model results (p1,l21);

25 “At this stage of the simulation, the presence of an ice shelf becomes a more important control on grounded ice volume”

p. 2, l. 1–3: The previous generation of ice sheet models do not accurately simulate the position of the grounding line, due to the use of the Shallow Ice Approximation (van der Veen, 2013).

30 It would make sense to mention possible subgrid parametrization of shallow approximations here (Feldmann et al., 2014).

Done (p2,l8)

35 p. 3, l. 21–22: we set up the model domain to cover the majority of the British-Irish Ice Sheet

No mention is made of model results outside of the Minch domain. Does the model perform reasonably well there too?

The experiments described in this manuscript were set up specifically to model the MnIS. Deglaciation is generally poorly represented outside the Minch catchment for a handful of reasons. Primarily, proximity to the domain edge causes over-stability of the ice sheet along the eastern margin. The bed friction map (figure 2c) is also likely missing a number of ice stream paths, the map is potentially most complete in the northwest of the domain. The model resolution is also much coarser outside the Minch catchment (4 km at the grounding line rather than 500 m). Overall the Barra Fan Ice Streams catchment (Hughes et al., 2014) (<https://doi.org/10.1016/j.quascirev.2014.02.002>) is the closest to also being well represented (it is located far from a domain edge and is in the bed friction map), but is still modelled at only 4 km resolution. We have not referenced model results outside the Minch domain to keep the focus on the single catchment and resulting experimental design.

p. 4, l. 3–4: we initialise ice thickness in the domain from a perfectly plastic ice sheet model

How were other variables, especially ice temperature, initialized?

We have included a new table (Table 1) that documents key model parameters, including ice temperature.

p. 4, l. 5–6: the 27ka BP margin of Clark et al. (2012) was used for the remainder of the BIIS.

Was the 27 ka BP margin used as a boundary for the plastic model? If so, in which sense is it fortunate that the plastic ice sheet matches it well? If not, how was ice extent converted to ice thickness?

Yes, the 27 ka BP margin was used in the plastic model (figure 2a). The match between the 27 ka margin the Bradwell et al., (2008) maximum extent was described as fortunate because 27 ka BP is not the global LGM, nor the maximum extent of the BIIS, but it does reasonably represent MnIS maximum extent. However, the word fortunate is removed as it doesn't convey any useful meaning.

p. 4, l. 8–10: Positive Degree Day (PDD) mass balance model, as described by Seguinot (2013) and Gregoire et al. (2016, 2015).

None of the given references contain a full PDD model description. Actually Gregoire et al. (2016) do not even mention PDD models. Does the model resolve the subannual evolution of snow cover? Does it account for meltwater refreezing? Most importantly, which PDD factors are used? Does the reference to (Seguinot, 2013) imply that the authors incorporate daily temperature variability from HadCAM3, or perhaps use the code I wrote for this publication (<https://github.com/juseg/pyppdd>)? Or is the PDD model part of BISICLES? I think a new paragraph is needed here to address these questions.

We used the PyPDD script here and have amended the text to specify this. A more explicit reference to the code is now made, and referenced to Seguinot (2013) as requested on the PyPDD GitHub page. The PDD factors, refreeze ratio, and snow/rain threshold is now summarized in table 1.

- 5 Gregoire et al. (2016, 2015) references examples of using palaeo-gcm results to drive ice sheet SMB. We have clarified this in the text.

p. 4, l. 18: To remove the effect of a SMB feedback

- 10 This is an important simplification. Although it may be justifiable under Antarctic like settings, in a warmer climate the surface elevation-mass balance feedback could strongly affect the pace of margin retreat and hysteresis effects discussed further in the manuscript. In this context, introducing a few details about input climate would help. I wonder which parts of the model domain are affected by seasonal melt, and to which extent dynamic thinning due to ice surface lowering would affect the the
15 aforementioned conclusions.

- The potential for interaction between MISI and SMB-elevation feedback (or other simplifications made) was also mentioned by reviewer #2 (please see below). We have edited the manuscript to better highlight and justify the simplifications made, primarily in the form of an extended section 4.4
20 (Comparison to empirical reconstructions).

p. 4, l. 23: sub-shelf melt (m/y) is $10\times$ the annual average SST (K)

- 25 Melt rate and temperature are distinct physical quantities. For mathematical rigour I suggest to rework the sentence and introduce an equation and a unit to the factor 10.

Done (p5,l4)

p. 4, l. 27–28: We correct the SST to permit for ice shelf formation

- 30 Presumably both modelled SST and the aforementioned factor 10 suffer from uncertainties. However, what is the justification for applying a correction on input data rather than a model parameter? Does this correction replaces or supplement the model bias correction mentioned earlier in the manuscript?
- 35 Both the modelled SST and sub-shelf melt/SST relationship do indeed have very large uncertainties. In fact, Holland et al., (2008) (<https://doi.org/10.1175/2007JCLI1909.1>) compared 9 relationships between ice shelf melting and ocean temperature. The Rignot and Jacobs (2002) rate we use is broadly representative of these relationships, but there is a large spread. We corrected the input data instead of the parameter because the modelled SST also has large uncertainties, and is a simple linear

correction. Maintaining the linear parameterization allows for easier comparison to Antarctic and Greenland ice shelves. The sub-shelf melt rates are supplementary to the frontal ablation rates discussed in section 3.1 (Model description and set-up).

- 5 Please note that the reference to Iyengar et al. (2001) was an error caused by the referencing software used, and has been manually corrected to Rignot and Jacobs (2002).

p. 4, l. 32: studies of present day ice streams using the same friction law

- 10 On which modern ice streams were these studies conducted?

Pine Island Glacier, and Basin 3 (Austfonna). Clarification added (p6,l3).

- 15 p. 5, l. 2–3: the extent of ice after a 6,000 year spin-up remains comparable even with different magnitudes of basal friction.

- Is this because the bedrock topography drops abruptly at the continental shelf edge? Thus changes in basal friction affect ice thickness but not its extent? Besides, Fig. S1 shows a significant drop in ice volume (and presumably ice thickness) for all runs. Does this decrease concerns the entire BIIS domain, or only the marine influenced sector of the Minch?
- 20

- For the Minch catchment the extent of the ice sheet is strongly controlled by the position of the shelf edge, the increase in water depth is sudden and dramatic. However, in other sectors of the ice sheet the extent is also controlled by the SMB map (Figure 2). We have now highlighted this in the text (p6,l7).
- 25

p. 5, l. 6: Isostatic adjustment was simulated using the EUST3 GIA model

- I think that a short model description and list of parameters used is needed here. Is the GIA model ran at equilibrium or transiently? Is the value of mantle viscosity below the Minch well constrained?
- 30

- The GIA model simulations with the best fit to sea level index points used a thin lithosphere (71 km), an upper mantle viscosity of $4-6 \times 10^{20}$ Pa s, and a lower mantle viscosity $\geq 3 \times 10^{20}$ Pa s. The model was run transiently by Bradley et al., (2011) and we used their results as input for the topographic adjustment. The text has been edited to clarify this (p6,l10).
- 35

p. 5, l. 14: Experiment set-up is summarised in the supplement (Table S1).

I think this table should be part of the main text, and supplemented by a second table listing other, constant model parameters (see general comment above).

Done

5

p. 5, l. 24: We keep bed topography and sea level constant

10 Similarly to the assumption on surface elevation-mass balance feedback, I think that this second assumption needs to be put in context of the regional bedrock properties. Is the bedrock response expected to be instantaneous or delayed? What is the expected rate of relative sea-level drop and how could this affect the model results?

15 The relative sea level (RSL) change is expected to be small, around 15 m sea level fall, causing a minimal change in marine/terrestrial areal extent. This is because of the counteracting effects of the expanding BIIS (depressing the bedrock) and a concurrent drop in global sea level due to increased terrestrial glaciation. This has been placed into context in the text (p7,l6), along with an expanded section 4.4 (Comparison to empirical reconstructions) justifying the simplifying assumptions more clearly.

20 Fig. 4 y-label: Ice volume (104 km²)

Dividing volume by area yields an ice thickness of ca. 20 km. There must be an orderof-magnitude error here.

25 Yes, a conversion error was occurring in a script used in Figures 3, 4, 5, and 7. All plots have been updated accordingly.

p. 6, l. 17: halving the domain's ice volume in the first 2,000 model years

30 This contradicts Fig. 4 where ice volume appears to drop from ca. 83 to ca. 62 axes units, corresponding to only around a quarter of the initial ice thickness.

This has been corrected in the text (p8,l3).

35 p. 7, l. 21: the volume change caused by removing an ice shelf is significant.

In the context of earlier simplifications on surface mass balance and bedrock topography, I am not convinced that a 10% change of volume is significant. I suspect that a few sensitivity tests on input climate, basal sliding parameters and uncertain bedrock properties would yield much larger changes in

ice volumes (cf. e.g., Seguinot et al., 2016). I would simply remove this statement, and correct the corresponding sentence in the abstract (see previous comment).

5 We have corrected the corresponding sentence in the abstract and have removed this sentence as advised.

p. 8, l. 15–16: the ice stream does not recover to ILGM extent [...] (Figure 7a,b)

I suggest to refer to Fig. 7 here.

10

Done (p9,l32)

p. 8, l. 16–17: a volume 25% smaller, and an area 50% smaller [...] state (Figure 7d).

15 I think Fig. 7a and b would be more appropriate.

Done (p9,l33)

p. 8, l. 18–19: a full shelf-edge glaciation

20

One could refer to Fig. 7c here...

Done (p10,l2)

25 p. 8, l. 19: a small Hebrides Ice Cap with glaciation in the Minch limited to the east trough (Figure 7)

And Fig. 7d here.

Done (p10,l2)

30

p. 8, l. 21–23: Hysteresis of ice sheet evolution is evidence for an instability during the advance of retreat of an ice sheet (Schoof, 2007). Ice sheets can experience a variety of instabilities (Calov et al., 2002; Gregoire et al., 2016, 2012; Schoof, 2007) which could influence the ice sheet evolution.

35 I do not really understand how these two sentences relate to the surrounding discussion. Without formal analysis of all intermediate stable states it would be more correct to write that the model results hint at an hysteresis (formally identified by Schoof, 2007). Studies by (Gregoire et al., 2012, 2016) concern a surface elevation-mass balance icesheet instability which is not only unrelated but

precisely missing in the current study, so I would just remove the second sentence, or move it to a discussion of potential weaknesses.

5 The second sentence has been removed as advised, the interaction between MISI and other ignored factors is now discussed in more length in section 4.4 (Comparison to empirical reconstructions). The wording of the first sentence has been altered (p10,l4).

p. 9, l. 5–6: east of the trough [...] west of the trough

10 If I am not mistaken, on Fig. 1 these are labelled “east trough” and “west trough”.

We have corrected this to give consistent names between map and reference in the text (p10,l22).

15 p. 9, l. 1–3: the east trough contains a small ice stream whilst the west trough has fully deglaciated and formed a calving bay.

A reference to geological observations is needed here.

Reference added (p11,l31).

20

p. 9, l. 32–33: Due to the idealised climate forcing, only the pattern, and not the timing, of the retreat can be compared to empirical reconstructions.

25 After the Mynch has been announced as well-documented by geology, and since the main model results concerns the (at least relative) timing of deglaciation, this sentence comes very disenchanting! I think it could be reworked to something more positive.

30 We think it is important to highlight that the nature of the forcing means the modelled retreat timing cannot be compared to the empirical data, but the style and comparative rate of retreat can. The dating evidence here is strong and growing, but it should be compared to these model results only considering these caveats. The sentence has been reworded to change the focus (p11,l27).

p. 10, l. 9–10: Here, we define the reconstructed retreat [...] as the “observed retreat”.

35 I think this definition is oversimplifying and potentially misleading. The discussion could become more constructive if it instead made clear what are geomorphological evidence, what are sedimentological evidence, and what are geological reconstructions containing a part of interpretation.

The definition of observed retreat was an attempt to make the comparisons between the modelled data and the empirically reconstructed data more clear. The definition has been removed, and references to the observed retreat have been replaced with comparisons to “empirical reconstructions”, including in the section header.

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p. 10, l. 19: GZW6

I assume this means “Grounding zone wedge 6”. Could this be added somewhere on a map?

10 GZW6 mistakenly refers to an unpublished map (Bradwell et al., in review). This reference has been removed from the text. References to grounding zone wedges have been replaced with “large seabed moraines”, as they have been referred to in previous literature (Clark et al., 2018; Stoker and Bradwell, 2015) (p12,l11).

15 p. 11, l. 3: However, the observed retreat began at 30ka BP, when the NGRIP $\delta^{18}O$ record suggests a cooling climate globally

The connection between numerous arguments against interpreting Greenland $\delta^{18}O$ records as proxies for global climate.

20

This has been corrected to suggest only a cooling climate of Greenland (p13,l1). Model results instead suggest a generally cooling climate, and have been referenced in the text (p13,l2).

25 p. 11, l. 8–10: There are two likely possibilities that could explain the MnIS retreating in a cooling climate (explained below); i) internal mechanisms caused by the expansion of the rest of the BIIS, or ii) a local SMB change of this sector of the ice sheet at 30ka BP.

30 I think that a third possibility should be considered here. The assumption of initial steady-state during maximum extent does not necessarily hold true. Although the authors discuss ice piracy from neighbouring ice sheet sectors, the possibility that the maximum extent of Minch ice stream is itself the result of a thermodynamic destabilisation (a surge) following build-up of stiff colder ice during the advance phase exists. This explanation should probably be included in the list.

35 The possibility of thermodynamic destabilization as a possible internal mechanism has been added to the discussion (p13,l26). This is an important point. Dating the advance of an ice sheet is inherently more uncertain than dating retreat, so it is perfectly possible given the empirical reconstructions that the advance of the MnIS was a rapid surge type event.

p. 12, l. 13: This result is evidence for a rapid retreat of the MnIS caused by marine ice sheet instability.

This sentence confuses rapid retreat with instability (see general comment above).

The reference to rapid retreat has been removed.

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Finally, I would like to congratulate the authors again for their effort to bring palaeoglaciologic data-model comparison at sea, and hope they will find my comments useful in bringing their manuscript to final form.

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Review #2

Interactive Comment on “Marine Ice Sheet Instability and Ice Shelf Buttressing Influenced Deglaciation of the Minch Ice Stream, Northwest Scotland” by Gandy et al.

15 **Anonymous Referee #2**

Received and published: 7 September 2018

20 This manuscript describes a series of simulations of the deglaciation of the Minch Ice Stream (MnIS) region within the British-Irish Ice Sheet. Using BISCICLES, the authors determine that a region of reverse-sloping bed causes rapid deglaciation of the MnIS through the marine ice sheet instability. They also determine that MnIS begins in an unconfined state during the LGM wherein the development of an ice shelf has little influence on the ice stream, but then transitions to a confined state as the ice stream retreats into a region of pinning.

25

30 Overall, the paper is well written, besides a few awkward and confusing explanations (pointed out below). The simulations that are conducted are clever and effectively show that the marine ice sheet instability and (maybe) buttressing may play a role in deglaciation of MnIS. I think the most general issues that need to be addressed in this study are: (1) To what extent are these simulations supposed to represent actual deglaciation vs. numerical experiments on the role of some ice dynamical feedbacks in this region? (2) Can you be sure that some of the other feedbacks which have been omitted purposefully (to focus on MISI/buttressing alone) do not play a role in modifying the importance of MISI/buttressing? (3) How important is buttressing, actually?

35 I think that what is needed to address these issues is either: (a) providing a stronger argument why these processes can be excluded and the conclusions of the study remain intact, (b) additional simulations which explore the role of these other feedbacks and buttressing more carefully. I think that if these issues are addressed (in addition to the more minor issues listed below), this paper would

be a valuable contribution to understanding the deglaciation of the British-Irish Ice Sheet and ice sheet dynamics more broadly.

Major Points

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1. I think it needs to be made clear that the uncertainties associated with the climate and glaciology of the MnIS during deglaciations are large enough that the simulations presented here are not necessarily representative of the actual time-dependent deglaciation, but rather investigate mechanisms that may have played a role during a generic deglaciation of MnIS. That is, you make the following assumptions in the RETREAT simulation (that I suppose is the most like actual deglaciation): climate forcing was step-like, there was an ice shelf (i.e. calving and basal melt were low enough to allow for ice shelf formation), basal friction was fixed in time, and SMB does not evolve with changing elevation. You say that you make these simplifications so that you can isolate internal instabilities. This point is important to make more clearly and upfront as the purpose of this study, since making these simplifications takes you away somewhat from reality

10

15

These simplifying assumptions are now made more explicitly in the abstract, and the first sentence of the methods sections. An increased initial discussion of the caveats in section 4.4 (Comparison to empirical reconstructions) allows for the purpose and effect of the simplifications to be put more clearly and extensively in the manuscript. Further discussion on the effects of the simplifications, and the likely differences between the simulations and reality remain in section 4.4 (Comparison to observed retreat).

20

The purpose of the simplifying assumptions is to test if the bathymetric set-up of the Minch means that the ice stream could have been vulnerable to marine influence. In reality, the numerous other factors idealised here could exaggerate or dampen the impact of MISI, but our experiments neatly demonstrate that MISI is a possible factor given the bathymetry of the Minch. This is important because hitherto, the marine nature of the BIIS has only been assumed because the ice sheet was marine grounded in significant catchments, like the Minch, and it was not known whether MISI was active here (for example, the bathymetry is so considerably less extreme than in west Antarctica that it was not obvious that conditions were right for MISI). These simulations are required to demonstrate the potential effect of MISI on the BIIS, and therefore the potential role of MISI in less extreme conditions than have so far been demonstrated.

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30

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The original intended purpose of the experiments, to test the possibility of marine ice sheet dynamics mechanisms for the MnIS, is best preserved with this now extended discussion of the justification and effects of simplifications. To truly comment on the relative importance of MISI, for the MnIS would instead require a transient simulation of evolving bed friction, hydrology, sea level, climate, and

thermodynamics. This would represent a major and challenging project in its own right and is beyond the scope of this study.

2. You have wisely decided to perform some of your numerical simulations while omitting certain
5 feedbacks, in order to test whether MISI and buttressing may occur given certain bed topography and climate forcing. This does not answer the question of whether MISI/buttressing are the most important feedbacks, or whether they might be significantly amplified or reduced by cooperating feedbacks. In particular: rebound of the bed and the elevation-SMB feedback may also play an important role in the deglaciation of ice streams. Gomez et al (Nature Geo, 2010) have shown that
10 local sea level changes may have an influence on grounding line stability during deglaciation. Robel & Tziperman (JGR, 2016) have shown that curvature of the elevation-SMB feedback may cause acceleration of ice stream during the initial stages of deglaciation. It may be worth addressing these issues by making an argument for why these other feedbacks are not important, and also potentially performing additional simulations that test the influence of these feedbacks to some extent.

15 As stated above, we do not make an argument for these other factors not being important. In reality, these factors may have been very important. We have extended the discussion (p11,ln13) to highlight the influence and interaction of other factors. The manuscript changes (section 3.3, section 4.4) aim to make clearer that the purpose of the simplifying assumptions is to test if the bathymetric set-up of the
20 Minch means that the ice stream could have been vulnerable to MISI, not to determine the relative importance of MISI. We have chosen to clarify the purpose and effects of the simplifying assumptions rather than perform additional simulations, as explained in our response to the previous point and also partly because it is not clear that additional simulations could truly reveal the relative importance of MISI with the current tools available.

25 3. Page 4, Line 22 (and page 5, line 12 and page 10, line 7-9): The elevation-SMB interaction may be considered to be an “internal instability” considering that it mostly has to do with the climate at the ice sheet surface. Another way to think about this, why do we only care about “internal” instabilities? Are these the only instabilities that are important? To what extent can we disentangle feedbacks
30 having to do with the ice sheet from those having to do with the ice sheet surface climate?

This is an important point that primarily has been tackled in the expanded section 4.4 (Comparison to empirical reconstructions). We agree with the reviewer’s implication that the difference between
35 internal and external instabilities doesn’t provide much meaning, so reference to it has been removed from the manuscript. The process of disentangling various functions of ice sheet change is also now discussed in more length in section 4.4 (Comparison to empirical reconstructions).

4. Page 5, Line 26: I can see that “the purpose of this study is to test for a retreat instability of the MnlS with a given topography” However, why is this the correct purpose for the study to have? What

does this tell us about the actual deglaciation or about the process of MISI? I think you need to go a bit further than stating that the purpose is to do some clever simulations to the purpose is to answer some particular science question.

5 This line has been replaced with a clearer description of the motivation for a constant sea level in the experiments (p7,l6). One purpose of the study was to understand if MISI was a possible mechanism given the bathymetric set-up of the Minch because this could not yet be otherwise determined without our new numerical experiments. The motivation for this approach is now discussed at more length in section 4.4 (Comparison to empirical reconstructions).

10

5. How important is buttressing, actually? (Page 7, Line 18-20) You've said that the influence of the ice shelf on the grounding line position is very small, so how much influence does the ice shelf actually have on grounding line stability? If you include floating ice in your calculation of ice volume, then it is not clear to me how much of your 10% volume difference is just the ice shelf itself. I think you need to be a little more careful in order to make a strong argument that there is any buttressing actually happening here. Especially since this is a much wider ice stream than what you typically find in Greenland (see argument p.7, line 32), it is not obvious that the buttressing will be significant.

15

The cited 10% volume divergence between RETREAT and RETREAT_NOSHELF is for grounded ice. This has been clarified in section 4.2 (Role of ice shelf buttressing), and in Figure 5 description. A 10% difference is important, but perhaps not as large as could be expected. What we find particularly interesting is the relationship between the ice shelf and the topographic setting, discussed in section 4.2 (Role of ice shelf buttressing).

20

25 **Minor Points**

page 1

Line 11: "A valuable case to examine these processes is - awkward phrasing

30 The order of the sentence has been changed to read more clearly (p1,l12).

Line 13: what is well constrained? the ice stream or a measurement about the ice stream?

35 Both – but here we meant that there is rich empirical data for the MnIS. The sentence has been reworded to avoid confusion with being topographically constrained (p1,l14).

Line 15: continental shelf

Done (p1,l18)

Line 16: sub-ice shelf melt

Changed – and changed for all other occurrences in the manuscript.

5

Line 21: We conclude that geological data. . .the future of contemporary ice sheets.

Done (p1,l27)

10 Line 29: Consequently, any change in ice thickness at the grounding line can cause an irreversible grounding line migration with no change in external forcing. [The point is that the term “instability in grounding line migration” is unclear.]

Done (p2,l3)

15

page 2

Line 1: which can stabilize

Done (p2,l5)

20

Line 3: Higher-order models have more success in accurately simulation the grounding line

Done (p2,l9)

25 Line 5: Cite Tsai et al. 2015, JGlac

Done (p2,l11)

Line 8: episodic retreat

30

Done (p2,l15)

Line 8-9: how is retreat controlled by retreat history?

35 The delayed upstream response of ice streams means that long-term projections of ice sheets “should carefully integrate long-term ice-stream history” (Jamieson et al., 2012). We think the important point here is upstream response, and the text has been updated accordingly (p2,l16).

Line 12: proxy observations (no hyphen)

Done (p2,l19)

page 3

5 Line 17: with L1L2 physics retained from the full Stokes flow equations (Schoof and Hindmarsh 2010).

Done (p3,l25)

Line 18: BISICLES uses adaptive. . .

10

Done (p3,l27)

Line 26: Is there reasons to think that a linear Weertman exponent represents ice stream dynamics effectively? Is there a good citation?

15

A linear Weertman exponent was used for other ice stream modelling studies using BISICLES (Favier et al., 2014; Gong et al., 2017), from which the bed friction coefficient map values were based. This has now been added to the manuscript (p4,l4). The ice stream velocity is primarily controlled by the prescribed bed friction map (figure 2c). Using an alternative Weertman exponent would alter the velocity magnitude and volume of the ice stream, as was the case for variations in the bed friction coefficient (figure 3a).

20

Line 28-30: This would be a good place to explain first that you pick these values specifically in order to produce large ice shelves. Otherwise, it just seems like you just replace calving with a constant parameter (not much of a “calving model”).

25

Done (p4,l9)

page 4

30 Line 2: We set the simulations initial conditions to the ice sheet state when the MnIS was at its. . .

Done (p4,l12)

Line 5: The 27 ka BP margin. . .of the BIIS, which matches well with the reconstructed. . . [In general, you don't need to use the phrase “for the purpose of this study”, which doesn't convey any information]

35

“for the purpose of this study” has been removed.

Line 14: Do the climate model simulations used to force your model take into account ice sheet topography? If so, say here. If not, you need to justify why this is reasonable.

5 Ice sheet orography was updated in the simulations used here since the simulations reported by Singarayer et al., (2011). This has been included in the text (p4,l26). More information on the climate simulations used as input has been included in this section of the manuscript.

10 Lines 23-28: If you are eventually just going to strongly adjust the sub-shelf basal melt rate to retain ice shelves, why introduce the linear parameterization in the first place? Why not just simplify this whole part by setting some arbitrary sub-shelf melt rate that either permits or removes ice shelves?

15 The linear parameterization is used because it aids interpretation of the results by putting them into the context of current ice streams in Greenland and Antarctica. Although setting the values arbitrarily is possible, it could be mechanistically different to what is observed. It therefore remains best practice to base the values (as we have done) on observed melt rates in order to preserve the mechanisms of reality.

page 5

Line 1: in what sense do you mean magnitude here?

20

Magnitude was the incorrect term to use here, replaced with morphology (p6,l4)

25 Line 13: I'm a bit confused. . .you initialize with a plastic thickness approximation, but experiments are then begun with a stable ILGM volume. Does the SPINUP run get you from the plastic thickness initial condition to the stable ILGM configuration? The initialization procedure should be explained a bit more clearly.

30 Table 2 now shows a summary of experimental design without the reader needing to refer to the supplementary information. A new first sentence added to section 3.3.1 (Deglaciation) also clarifies how ice thickness is initialized for the experiment.

35 We initialize ice thickness of the *SPIN-UP* experiment with the plastic thickness approximation, which then evolves during the simulation (Figure 3c). The end of the *SPIN-UP* experiment is used as the start of all other experiments (apart from *READVANCE* experiments).

Line 17: How were the magnitudes of the climate perturbations chosen? Are they backed up by modeling evidence for the deglacial change in climate here?

The magnitudes of change were based on the magnitude of change between 26 and 18 ka BP from the equilibrium climate modelling data we used. This has been clarified in the text (p6,l28).

page 6

- 5 Line 14-15: Why would you expect the rate of volume and area change to be constant throughout the simulation? If anything, the initial phase of retreat looks something like exponential decay, which is approximately what one would expect from a fairly simple linear response model (i.e. $dV/dt = -a*V$). Classical work on the ice sheet response time scale under forcing (Nye 1960, 1963, 1965; Jóhannesson et al., 1989; Harrison et al., 2003) finds such an exponential decay response.

10

We have changed the wording to instead focus on the fluctuation in area and volume response, and to properly acknowledge prior work (as suggested by the reviewer) that indicates an exponential decay in ice volume would be expected (p7,l30).

- 15 Line 27: As the thinning continues, the ice area begins to retreat. . .

Done (p8,l14)

page 7

- 20 Line 2: period after hindmarsh citation.

Done (p8,l17)

Line 3: Ice stream acceleration in response to the sudden collapse. . .

25

Done (p8,l19)

- 30 Line 14: how much of the 10% difference in ice volume in the NOSHELF simulation is accounted for by the volume of the ice shelf itself (assuming this isn't volume above flotation, and if so, you should indicate that).

The 10% difference in ice volume is for the grounded ice volumes of *RETREAT* and *RETREAT_NOSHELF*. This has now been clarified in section 4.2 (Role of ice shelf buttressing), and in the figure 5 heading.

- 35 Line 20: If you turned the calving rate way down and got a much larger ice shelf, could you stabilize on the retrograde slope?

Running the deglaciation without an increase in the calving rate does not prompt full deglaciation (figure 4a). A decreased calving rate therefore cannot stabilize the grounding line on a retrograde

slope, because without the increased calving rate the grounding line does not reach the retrograde slope.

page 8

5 Line 26-31: These lines include a lot of redundant information. Could be cleaned up.

A significant amount of repetition has been removed here.

Line 32: marine or shear margin?

10

Marine – clarified in the text. (p10,l16)

page 10

15 Line 19-20: You start talking about GZW6 suddenly here. Bears more explanation and/or pointing to figures.

Please see the response to a comment from reviewer #1;

20 GZW6 mistakenly refers to an unpublished map (Bradwell et al., in review). This reference has been removed from the text.

Line 34: It is also the case that a change in ice stream velocity might cause a significant change in ice sheet volume (i.e. through acceleration-induced thinning), but not much change in area. This has a lot to do with local bed topography.

25

We have added this important example of the effect of ice stream dynamics to the text (p12,l29). The importance of ice stream velocity is evident from the variations in bed friction tested during the *SPIN-UP* experiment, which produced different ice volumes but the same ice area, controlled by the position of the continental shelf.

30

page 11

Line 4-6: As mentioned above, it may be the case that triggering of ice stream acceleration by appropriately-structured climate forcing may cause a larger retreat (see Robel & Tziperman 2016).

35 This mechanism is indeed a candidate to prompt rapid deglaciation of the MnIS, though an initial climate trigger is required to increase the surface slopes at the ice sheet margin. An acknowledgement of the mechanism has been added to the text (p13,l3).

page 12

Line 1: provide citations for why hydrology may or may not be important

Done (p14,l8)

- 5 Figure 3, Panel b: colormap could use more constant, very difficult to see any difference

Done

- 10 Figures 3, 4, 5, 6, 7: The axis labels and tick labels are far too small and illegible. Also the lines in all plots could have greater thickness to increase legibility. It also looks like the text is grainy because the resolution of the figures is low. Please include higher resolution figures.

The axis labels, tick labels, and plot curves have all been increased in size. All plots are now saved at 1000dpi.

15

20

25

Marine Ice Sheet Instability and Ice Shelf Buttressing Influenced Deglaciation of the Minch Ice Stream, Northwest Scotland

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10 **Abstract.** Uncertainties in future sea level projections are dominated by our limited understanding of the dynamical processes that control instabilities of marine ice sheets. [The last deglaciation of the British-Irish Ice Sheet offers a valuable example to examine these processes.](#)~~A valuable case to examine these processes is the last deglaciation of the British-Irish Ice Sheet.~~ The Minch Ice Stream, which drained a large proportion of ice from the northwest sector of the British-Irish Ice Sheet during the last deglaciation, ~~is constrained within well constrained, with~~ abundant empirical data which ~~cannot~~ be used to inform, validate and analyse numerical ice sheet simulations. We use BISICLES, a higher-order ice sheet model, to examine the dynamical processes that controlled the retreat of the Minch Ice Stream. [We perform simplified experiments of the retreat of the Minch Ice Stream this ice stream under an idealised climate forcing to isolate the effect of marine ice sheet processes.](#)~~We simulate~~ ~~ing~~ retreat from the ~~continental shelf edge~~ under constant “warm” surface mass balance and sub-ice shelf melt, ~~to isolate the role of internal ice dynamics from external forcings.~~ The model simulates a slowdown of retreat as the ice stream becomes laterally confined at [the mouth of the Minch Strait “pinning point”](#)² between mainland Scotland and the Isle of Lewis, ~~resulting in a similar marine setting to many large tidewater glaciers in Greenland and Antarctica.~~ At this stage ~~of the simulation,~~ the presence of ~~an ice shelf ice shelves~~ becomes ~~a~~ [a more important control on grounded ice volume major control on deglaciation,](#) providing buttressing to upstream ice. Subsequently, the presence of a reverse slope inside the Minch Strait produces an acceleration in retreat, leading to a ‘collapsed’ state, even when the climate returns to the initial ‘cold’ conditions.

20 [Our simulations demonstrate the importance of the Marine Ice Sheet Instability and ice shelf buttressing during the deglaciation of parts of the British-Irish Ice Sheet.](#) ~~Thus, We conclude that~~ geological data could be [applied to further](#) constrain these processes in ice sheet models used for projecting the future of ~~our~~ contemporary ice sheets.

1 Introduction

30 Attempts to model the future evolution of the West Antarctic Ice Sheet reveal large uncertainty in the extent of future mass loss (Feldmann and Levermann, 2015; Ritz et al., 2015). This is partly because many contemporary Antarctic Ice Streams are marine based (Jenkins et al., 2010; Joughin et al., 2014; Ross et al., 2012), and are therefore vulnerable to Marine Ice Sheet

Instability (MISI). Schoof (2007) demonstrated that no stable grounding line position is possible in areas of reversed bed slope. ~~This means that any change in ice thickness at the grounding line can cause an instability in grounding line migration. Consequently, any change in ice thickness at the grounding line can cause an irreversible grounding line migration with no change in external forcing.~~ However, it has been shown that simulations of grounding line migration require not only
5 consideration of bed topography, but also ice shelf buttressing (Gudmundsson, 2013), ~~as this mechanism which~~ can stabilise grounding lines on reverse sloping beds. The previous generation of ice sheet models do not accurately simulate the position of the grounding line, due to the use of the Shallow Ice Approximation (van der Veen, 2013), ~~although significant improvements have been made using subgrid parameterization at the Grounding Line~~ (Feldmann et al., 2014). Higher-order models ~~have more success in accurately simulating the grounding line, such as used here, have various numerical approaches~~
10 ~~to solving ice flow, and have more success~~ (Favier et al., 2014; Pattyn et al., 2012), but are still sensitive to model resolution (Cornford et al., 2016) and the representation of basal sliding processes (Gladstone et al., 2017; Nias et al., 2016; Tsai et al., 2015) ~~(Gladstone et al., 2017; Nias et al., 2016).~~

It is essential for improved future predictions of ice sheet change to better understand the dynamics of marine ice sheets over millennial timescales. A numerical simulation of the palaeo Marguerite Bay Ice Stream since the Last Glacial
15 Maximum shows that the ~~non-linear episodic~~ retreat was controlled by a combination of bed topography, ice stream width, and ~~upstream response~~ ~~retreat history~~, and that these controls are crucial to understanding centennial ice sheet evolution (Jamieson et al., 2012). A valuable case to examine these processes is the last deglaciation of the British-Irish Ice Sheet (BIIS), which had a number of marine-grounded sectors (Clark et al., 2012). While contemporary ice sheets offer a decadal scale observational record, the palaeo record of the BIIS provides detailed proxy ~~observations~~ observations of ice sheet retreat over millennia.
20 The behaviour of the BIIS has been studied for over a century, resulting in much information on flow patterns and margin positions against which ice-sheet models can be compared (Clark et al., 2018). Information on the timing and pace of retreat has been considerably enhanced through the recent work of the BRITICE-CHRONO project, a multi-organization consortium, which has collected data to better constrain the timing of retreat of the BIIS, particularly in marine sectors. The data-rich environment that the empirical record now holds makes it an attractive test bed for numerical ice sheet modelling experiments
25 (e.g. Boulton et al., 2003; Boulton and Hagdorn, 2006; Hubbard et al., 2009; Patton et al., 2016, 2017). The modelling investigations of Boulton et al. (2003) and Hubbard et al. (2009) specifically highlighted the importance of ice stream dynamics in the evolution of the ice sheet. However, simulations of marine ice sheets, like the West Antarctic Ice Sheet or the BIIS, ideally require models that are able to simulate grounding line migration (Pattyn et al., 2012). The BISICLES ice sheet model was developed to efficiently and accurately model marine ice sheets (Cornford et al., 2013), allowing for new simulations of
30 the BIIS which explore marine influence on the ice sheet.

We investigate the marine influence on one very well constrained ice stream of the BIIS, the Minch Ice Stream (MnIS), using the BISICLES ice sheet model. Here, we perform and analyse numerical modelling simulations to test two hypotheses of MnIS retreat; (1) that the ice stream experienced MISI, and (2) that an ice shelf had an influential buttressing effect on the pace of retreat.

2 The Minch Ice Stream

The Minch Ice Stream (MnIS) flowed northward from the northwest Scottish Highlands through the Minch Strait (Figure 1). It reached its maximum extent, the edge of the continental shelf, at ~~~2730~~ [~2730](#) ka BP (Bradwell et al., 2008), which we here refer to as the local Last Glacial Maximum (ILGM). The ice stream's flow was topographically constrained by the Outer Hebrides, and there is no geological evidence onshore or offshore that the ice stream migrated in position during the glacial cycle (Bradwell et al., 2007). Empirical (Bradwell et al., 2008; Clark et al., 2012) and numerical-model based (Boulton and Hagdorn, 2006; Hubbard et al., 2009) studies show that this wide (~50 km) ice stream drained a large proportion of ice that accumulated over the Scottish Highlands. The MnIS trough can be divided into the outer trough, which is predominantly smooth, with low-strength sediments, and the inner trough with an undulating bed and reduced Early Quaternary sediment cover (Figure 1). The inner trough contains a Neoproterozoic bedrock high, here referred to as [thea](#) Mid-Trough Bedrock High (MTBH) (Figure 1). Either side of the MTBH, the Minch branches into east and west troughs (Figure 1).

There has been extensive onshore ([e.g.](#) Ballantyne and Stone, 2009; Bradwell, 2013) and offshore ([e.g.](#) Bradwell and Stoker, 2015; Bradwell et al., 2008; Stoker and Bradwell, 2005) studies of the MnIS catchment. Improved bathymetry data allow the identification of a reverse slope southward of the MTBH. This topography could facilitate MISI, potentially causing rapid retreat south of the MTBH, and would explain the relative sparsity of the landform record between the MTBH and the terrestrial transition (Bradwell et al., 2008; Clark et al., 2018). Numerical modelling also allows for ice sheet processes to be tested that may be less evident in the empirical record, such as the influence of ice shelves. The detailed reconstructions of the MnIS provide an excellent opportunity to test whether ice-sheet models reproduce behaviour ~~expected from recorded by~~ [the](#) empirical data.

3 Methods

3.1 Model description and set-up

[We perform numerical simulations with an idealised climate forcing to isolate the effect of marine ice sheet dynamics on the MnIS in order to determine whether the bathymetric set-up of the MnIS could have facilitated MISI.](#) We use the BISICLES ice sheet model (Cornford et al., 2013) to simulate the MnIS. BISICLES is a higher-order ice sheet model with ~~Schoof-Hindmarsh L1L2 physics~~ [L1L2 physics retained from the full Stokes flow equations](#) (Schoof and Hindmarsh, 2010), which was developed to efficiently and accurately model the dynamics of marine-grounded ice sheets. ~~BISICLES#~~ uses adaptive mesh refinement to automatically increase resolution at high velocities and the grounding line, allowing ice stream dynamics and grounding line migration to be well represented, while having a lower resolution in the rest of the ice sheet ensures efficient model speed. Cornford et al. (2013) provides a full description of BISICLES. Although our focus for analysis is the MnIS, we set up the model domain to cover the majority of the British-Irish Ice Sheet (BIIS) at 4 km x 4 km resolution, excluding the central North Sea (Figure 2). Simulating a large portion of the BIIS prevents artefacts caused by domain

boundary effects, and allows for migration of ice catchments during deglaciation. For the set-up of the study, we set a 4 km x 4 km grid refined 3 times around the grounding line in the Minch Sector to produce a maximum horizontal resolution of 500 m x 500 m. The simulations have 10 vertical levels. [The friction law uses a linear \(\$m = 1\$ \) Weertman exponent in accordance with previous BISICLES experiments \(Favier et al., 2014; Gong et al., 2017\) that were used as the basis for bed friction coefficient map values.](#) ~~The friction law uses a linear ($m = 1$) Weertman exponent.~~ We use a calving model that simulates frontal ablation by advecting the calving front with a relative velocity equal to the modelled ice velocity at the front minus an ablation rate acting in a direction normal to the front. We prescribe a frontal ablation rate of 250 m/y for all ILGM simulations, and 350 m/y for all simulations which prompt deglaciation. These frontal ablation values are prescribed as it allows for [ice shelf formation during retreat](#), a stable extent at the continental shelf edge, and causes only limited deglaciation if Surface Mass Balance (SMB) changes are not included (Figure [4aS2](#)).

3.2 Initial conditions and spin-up

~~We set the initial conditions to the ice sheet state when the MnIS was as its~~ [For the purpose of this study, we set the starting point of our simulations as when the MnIS reached its](#) maximum extent. To avoid the computational costs and uncertainties associated with simulating the full build-up of the ice sheet, we initialise ice thickness in the domain from a perfectly plastic ice sheet model (Gowan et al., 2016) fixed to the ILGM extent at the continental shelf break. ~~For the purposes of this study,~~ [The 27ka BP margin of Clark et al. \(2012\) was used for the remainder of the BIIS.](#) ~~The 27 ka BP margins of the perfectly plastic ice sheet model output match well with the reconstructed maximum extent of the MnIS (Bradwell et al., 2008).~~

To calculate SMB we use monthly mean surface air temperatures and monthly mean total precipitation from climate model simulations to drive a Positive Degree Day (PDD) mass balance model ~~as in (Gregoire et al., (2016, 2015),~~ [Gregoire et al. \(2016, 2015\).](#) ~~We use the PDD model PyPDD as described by (Seguinot, 2013), which accounts for the subannual evolution of snow cover, and meltwater refreezing. The PDD factors, and refreezing ratio is summarised in Table 1.~~ The PDD model is driven by mean temperature and precipitation data calculated from the final 50-years of the 26 ka BP bias-corrected equilibrium climate simulation described by Morris et al. (2018), run with the HadCM3 coupled atmosphere-ocean-vegetation general circulation model (Gordon et al., 2000; Pope et al., 2000; Valdes et al., 2017). This simulation is part of a series of “snapshot” equilibrium simulations covering the last deglaciation that are a refinement of those previously reported by Singarayer et al. (2011) with updated boundary conditions [including ice mask, ice sheet orography, bathymetry, and land-sea mask](#) (Ivanovic et al., 2016). It belongs to the same set of simulations used by Swindles et al. (2017) ~~and (Morris et al., (2018)~~ to recently derive ~~Holocene climate~~ [the climate of the Holocene and since the Last Glacial Maximum, respectively](#). We downscale surface air temperatures onto the pre-spin up initial ice sheet surface using a lapse rate of 5.1 K/km, which has been identified as a suitable lapse rate for modelling the Eurasian Ice Sheet (Siegert and Dowdeswell, 2004).

To remove the effect of a SMB feedback, where surface elevation change causes a positive feedback to SMB due to atmospheric lapse rate, the SMB is decoupled from elevation feedback. In practice, this means that once surface air temperatures are downscaled onto the initial ice sheet surface elevation to create the SMB map for the domain, SMB does not

evolve as the ice sheet surface elevation evolves; there is no lapse rate feedback. This removes the possibility for a SMB instability of retreat, allowing for ~~the internal instabilities of any MISI during~~ the ice sheet ~~retreat~~ to be isolated.

We prescribe a sub-~~ice~~ shelf melt rate using a linear relationship with Sea Surface Temperature (SST);

$$mM = -10Tt$$

5 ~~Where m is melt (metres of melt water equivalent) and T is the temperature (K) above the freezing point of the ocean, assumed to be -1.8 °C. Where sub-shelf melt (M) is a function of SST (t) above the freezing point of seawater, taken to be -1.8 °C. This relationship between SST and sub-ice shelf melt rate is based on measurements from Pine Island Glacier, Antarctica (Rignot and Jacobs, 2002). SST values are taken from the same climate simulation that is used to calculate SMB. However, initial SST~~
10 temperatures are corrected by -2 °C as exploratory sensitivity tests show that the uncorrected SST does not allow for ice shelves to form at the ILGM. We correct the SST to permit for ice shelf formation, allowing the influence of the presence or removal of an ice shelf to be tested.

15 We assume that contemporary land properties ~~were~~ like the bed properties beneath the MIS, ~~and we use a bed friction map reconstruction which parcelled together areas of similar bed friction using a combination of sediment thickness, palaeo-ice stream location, and subglacial bedforms (Supplementary Information 3). The basal friction coefficient map was produced by grouping regions of similar bed friction, then prescribing values to those regions based on bed friction coefficient values from other studies. Regions of similar basal friction were classified into the following five groups based on observable surface morphological features in satellite imagery and DEMs, and from the glacial map of Britain (Clark et al., 2018) as well as reference to superficial geology maps:~~

- 20 1. ~~Palaeo-ice streams, based upon the presence of mega-scale lineations, convergent flow-patterns from subglacial bedforms and previous reporting in the literature (Margold et al., 2015; Stokes and Clark, 1999). As the main outlets for ice-flow and fastest flow regions, these regions were assigned the lowest basal friction coefficients (β); 100.~~
- 25 2. ~~Marine-sediments, defined based upon geological maps and the presence of characteristic marine bedforms. These are highly deformable, and were therefore assigned a value of 1,000, the second lowest basal friction coefficient (β).~~
- 30 3. ~~Subglacial lineations or drumlins, identified on the glacial map and elevation models. Lineations are thought to represent reasonably fast ice flow and be the product of subglacial bed deformation (Ely et al., 2016). These were assigned an intermediate basal friction coefficient (β) of 2,000.~~
4. ~~Subglacial ribs or ribbed moraines, identified from previous mapping and elevation models. These are thought to be characteristic of slower ice flow than that of subglacial lineations, and were thus assigned a higher basal friction coefficient. A bed friction coefficient (β) of 3,000 was prescribed here.~~
5. ~~Exposed bedrock was assigned the highest basal friction coefficient. These high roughness areas were defined by their characteristic surface morphology and from geological maps, and were prescribed the highest value bed friction coefficient (β), 4,000.~~

The values for bed friction coefficients used as input into BISICLES (Figure 2c) were based on studies of present day ice streams using the same friction law Weertman exponent ($m = 1$), which calculated coefficients by inverting observed surface [velocities of Pine Island Glacier and Austfonna Basin 3-velocity](#) (Favier et al., 2014; Gong et al., 2017). This approach simulates an ice stream of a similar [morphology/magnitude](#) as reconstructed using empirical data (Bradwell et al., 2007).
5 Sensitivity tests reveal that the ice sheet volume is sensitive to changes in bed friction coefficient map (Figure [3aS1](#)), but the extent of ice after a 6,000 year spin-up remains comparable even with different magnitudes of basal friction [as ice extent in our experiments is primarily controlled by the continental shelf edge and surface mass balance \(Figure 2b\)](#).

To recreate isostatically adjusted bed topography, we adjust modern topography using [results from](#) a Glacio-Isostatic Adjustment (GIA) model (Figure 2d). GEBCO (Becker et al., 2009) provides modern offshore bathymetry, and SRTM (Farr et al., 2007) provides onshore topography. Isostatic adjustment ~~was simulated using~~ [uses results from](#) the EUST3 GIA model (Bradley et al., 2011). EUST3 accounts for near-field and far-field isostatic adjustment due to ice loading. The Relative Sea Level (RSL) change from EUST3 at 30ka BP is used to deform contemporary topography, maintaining a high resolution ice sheet bed whilst also accounting for RSL change.

3.3 Experimental design

15 We designed our experiments to use an idealised representation of the external forcings of ice sheet retreat (surface mass balance and sub-shelf melt) in order to isolate the internal ice sheet mechanisms and instabilities of retreat. All experiments begin at a stable ILGM volume, with continental shelf edge glaciation and a small ice shelf (<4 km from shelf front to the grounding line) (Figure 3). Experiment set-up is summarised in [Table 2, the supplement \(Table S1\), is \(Bradley et al., 2011; Clark et al., 2012; Seourse et al., 2018\)](#) ~~These experiments are designed to test the applicability of MISI to the MnIS.~~
20 [In reality, ice sheet evolution is a function of climate fluctuations, ice surface evolution, and sea level change as well as MISI. However, to isolate the effects of MISI, sea level is held constant throughout the experiments, there is no elevation-SMB feedback, and the climate change is a simple step-change.](#)

~~in the experimental design were made to investigate the mechanism of in the MnIS, and as such, approach [LG1][DH2]~~

3.3.1 Deglaciation

25 [The end of the SPIN-UP simulation is used as the start point for the RETREAT experiment.](#) In the simulation *RETREAT*, we use an idealised climate perturbation approach to trigger deglaciation, which consists of applying an instantaneous uniform warming of the surface air temperature by 1.5 K and SST by 2 K each month, without changing precipitation. [The magnitude of these perturbations are based on changes between the 26 and 18 ka BP equilibrium climate simulations.](#) The resulting surface mass balance and sub-ice shelf melt are then kept constant throughout the run. As for the
30 *SPINUP* simulation, SMB is decoupled from an ice elevation-SMB feedback. Therefore, any change in the rate of ice sheet retreat is caused by internal ice sheet dynamics.

To test the relative role of ocean and atmospheric warming in driving the retreat, we ran *RETREAT_ATMOS* and *RETREAT_OCN* where only SMB or sub-ice shelf melt rate are perturbed respectively. Both of these simulations only lead to partial deglaciation (Figure 4aS2), while the combination of both forcings (*RETREAT*) cause deglaciation to the northwest Scottish Highlands. We keep bed topography and sea level constant for the duration of the deglaciation simulations as [an evolving sea level could interact with the process of MISI. Therefore, a constant sea level is necessary to understand the potential for MISI during the retreat of the MnIS. In reality, only a small RSL change \(~15 m sea level fall\) would be expected because of the competing effects of BIIS expansion and global sea levels fall \(Bradley et al., 2011\).](#) ~~the purpose of the study is to test for a retreat instability of the MnIS with a given topography. This prevents RSL change exaggerating or dampening any simulated instabilities as it would have done during the last deglaciation.~~

10 3.3.2 Reversibility of ice stream retreat

We test whether retreat is irreversible once it is initiated, or whether ice volume and area recovers to ILGM levels given a return to ILGM climate. In experiment *READVANCE*, we test for the reversibility of ice stream retreat by reverting the climate perturbations during the deglaciation. A set of simulations were started from points at 800 years intervals through the *RETREAT* simulation with the boundary conditions returned to ILGM and run for 10,000 model years to allow the ice sheet to reach a new stable state (constant volume and extent). Here, ice sheet collapse is defined as an ice sheet not returning to its ILGM extent given ILGM boundary conditions following retreat.

3.3.3 Ice shelf influence

We tested whether an ice shelf is important in influencing the dynamics of the MnIS retreat, by providing a buttressing force to reduce ice stream flux over the grounding line. To test this hypothesis, we ran a simulation (*RETREAT_NOSHELF*) where the sub-ice shelf melt rate was increased to 100 m/y (52.9 m/y higher than during the *RETREAT* simulation) in order to force the removal of the ice shelf during deglaciation. Note that, in this experiment, we kept the frontal ablation rates identical to *RETREAT* in order to isolate the effects of ice shelf buttressing, removing the influence of any increased ocean ice mass loss.

4 Results and Discussion

25 4.1 Pattern of retreat

Imposing a constant SMB and sub-ice shelf melt perturbation (simulation *RETREAT*) causes a retreat of the MnIS from the continental shelf edge to the highlands within 8,000 model years (Figure 4; Video S4). Although the SMB and sub-ice shelf melt are constant through the simulation, with SMB decoupled from the change in surface elevation, the rate of volume and area change ~~fluctuates is not constant~~ through the simulation (Figure 4a), [whilst an exponential decay in ice volume would be expected given a simple climate forcing](#) (Harrison et al., 2003; Johannesson et al., 1989; Nye, 1963, 1960). The

evolution of the ice stream during the *RETREAT* simulation can be divided into three stages; an initial retreat phase, a stagnation phase, and a late retreat phase. Volume loss is most rapid at the initial retreat phase (Figure 4b-d), [reducing the domain's ice volume in the first 2,000 model years by ~25%. halving the domain's ice volume in the first 2,000 model years of the simulation.](#) In the stagnation phase, between 2,000 and 6,300 model years of the simulation (Figure 4d-e), volume loss slows. Finally, during the late retreat phase volume loss slightly increases from 6,300 model years onwards (Figure 4e-f). The slower rate of volume loss in the stagnation phase occurs as the margin retreats beyond marine influence onto the Outer Hebrides for the majority of the domain. [At this stage the ice stream is in a similar marine setting to many tidewater glaciers in Greenland and Antarctica](#) (Joughin et al., 2008), and the re-acceleration of the late retreat phase only begins once the grounding line has retreated further south towards the inner trough of the Minch ~~Strait~~ (Figure 4e).

The ice area loss produces a broadly similar trend to volume loss, although in the stagnation phase (3,500 to 6,300 model years) there is negligible area loss despite continuing volume loss (Figure 4a). This is associated with a near-stagnation of the grounding line when the margin of the ice sheet has mostly retreated onshore and the marine-terminating ice stream becomes confined between the Scottish mainland and the Outer Hebrides (Figure 4d-e). During the stagnation phase ice loss occurs through thinning with limited change in margin position. As the thinning continues, the ice area begins to retreat more rapidly just after 6,300 model years, which coincides with the start of a rapid margin retreat in the Minch (figure 4e).

4.2 Role of ice shelf buttressing

Ice shelves provide a buttressing membrane stress to the ice streams flowing upstream of them (Hindmarsh, 2006), [and the result of the sudden collapse of ice shelves](#) Ice stream acceleration in response to the sudden collapse of ice shelves has been observed in the contemporary Antarctic Peninsula (Scambos et al., 2004). The buttressing effect of ice shelves can also allow a stable grounding line position given a reverse sloping bed (Gudmundsson, 2013), meaning it is important to consider the impact of ice shelves when examining MISI. The ice shelf that forms during the simulations of the MnIS is initially unconstrained by topography or surrounding ice until the grounding line retreats during the stagnation phase of retreat at 6,300 years (Figure 4e). It is therefore expected that removing the ice shelf from the simulations whilst triggering deglaciation will initially have negligible impact on the retreat of the ice stream, before having greater impact once the ice shelf is constrained by surrounding grounded ice.

For the first 5,000 model years the simulated [grounded](#) ice volumes diverge by less than 1% in the simulations with (*RETREAT*) and without (*RETREAT_NOSHELF*) an ice shelf (Figure 5). After 5,000 model years there is a notable divergence in the evolution of [grounded](#) ice volume of the two simulations, where the simulation without an ice shelf has higher rates of mass loss compared to the simulation with ice shelves (Figure 5a). At the time of maximum volume difference between the simulations (7,000 model years), the simulation *RETREAT_NOSHELF* has a [grounded](#) volume ~2,000 km³ (10%) smaller than the simulation *RETREAT*. However, the acceleration of mass loss during the late retreat phase occurs in both simulations, suggesting the presence or removal of an ice shelf cannot prevent continued ice volume loss. Although the presence of an ice shelf affects the ice volume, it has almost no impact on the location of the grounding line and its chronology of retreat (e.g.

Figure 5b-c), with the difference in the grounding line location mostly within the finest resolution of the model (500 m). The removal of the ice shelf also means that the grounding line has no mechanism for stability on the reverse sloping bed retreat southward of the MTBH (Gudmundsson, 2013). These results suggest that ~~although~~ the presence or absence of an ice shelf has only a limited influence on the spatial pattern and timing of MnIS retreat, ~~the volume change caused by removing an ice shelf is significant~~. A significant difference in ice volume is not reflected in grounding line position, showing that ice flux across the grounding line is important, not just the position of the grounding line. The significance of the ice shelf influence demonstrates that in order to be confident of the future evolution of our contemporary ice sheets, we need to be confident of the future evolution of ice shelves over centennial timescales.

The unconstrained nature of the Minch Ice Shelf at the start of the deglaciation makes the mechanics of ice shelf buttressing different from many areas of the contemporary West Antarctic Ice Sheet, where large ice shelves are buttressed laterally by surrounding ice or bedrock (Pritchard et al., 2012). In a number of prominent places in Antarctica, ice shelves are also pinned from underneath by bedrock rises (Matsuoka et al., 2015). This may suggest that the dynamics of the Minch Ice Shelf during the first stage of retreat are more analogous to East Antarctic Ice Shelves. The Minch Ice Shelf is not constrained laterally until the later stages of the deglaciation where the shelf is supported by surrounding ice (Figure 5), where the topographic setting is similar to examples of fjord-like confined glaciers in Greenland (Joughin et al., 2008). Whilst the MnIS and many Greenland ice streams can retreat beyond direct marine influence (Funder et al., 2011), this is not possible for Antarctic ice streams grounded in deeper troughs. Empirical evidence of the last Eurasian ice sheet has the western ice margin constrained by the continental shelf edge across the majority of the Atlantic margin (Hughes et al., 2016). This suggests that ice shelves at maximum ice extent across the Atlantic margin would be similar to the Minch Ice Shelf in the early stages of deglaciation, limited in size by the continental shelf break, and unconstrained. It is likely, therefore, that ice shelves along this Atlantic margin were not influential in the retreat of the ice sheet until the grounding line retreated to areas laterally constrained by topography or surrounding ice.

4.3 Testing ice stream instability with readvance experiments

Given the bathymetric profile of the ice stream path (Figure 6), it would be expected that the MnIS would experience MISI ~180 km along the AB transect (Figure 6b). This is because of the reverse slope (downhill retreat) that the ice stream path would encounter in the later stages of the deglaciation after retreating beyond the MTBH. The experiment *READVANCE* returns the ice stream to the ILGM climate at 800 year intervals during the *RETREAT* experiment, in an attempt to recover the ice stream to ILGM extent.

For the first 5,600 model years of the recovery experiment (*READVANCE*) ice volume returns to ILGM extent given a return to ILGM forcings. All simulations started from *RETREAT* at model year 800 to 5,600 readvance to the ILGM extent. However, in simulations with a point of recovery (initial conditions) beyond 5,600 model years, the ice stream does not recover to ILGM extent given ILGM boundary conditions (Figure 7a,b); instead it evolves towards a reduced stable state with a volume ~25% smaller, and an area ~50% smaller than the stable ILGM state (Figure 7a,bd).

We identify two stable ice conditions in these *READVANCE* simulations given our initial ILGM forcings; a full shelf-edge glaciation (Figure 7c), and a small Hebrides Ice Cap with glaciation in the Minch limited to the east trough (Figure 7d). The resulting stable extent of the ice stream is dependent on the evolution history of the ice stream; there is hysteresis in the MnIS evolution. Hysteresis of ice sheet evolution ~~is evidence for~~ suggests an instability during the advance or retreat of an ice sheet (Schoof, 2007). ~~Ice sheets can experience a variety of instabilities (Calov et al., 2002; Gregoire et al., 2016, 2012; Schoof, 2007) which could influence the ice sheet evolution.~~

The zone of collapse is defined here as the point of divergence of recovery states; the position of the grounding line at which returning to ILGM forcing no longer allows recovery to initial ILGM extent, and only allows recovery to the new stable condition of limited Minch glaciation (Figure 7d). The zone of collapse occurs 5,600-6,400 model years into the retreat, ~180 km along the mapped AB transect, as the margin retreats onto a retrograde bed slope (Figure 6). ~~The AB transect shows that for the majority of the deglaciation the ice stream is retreating “uphill” from the continental shelf edge. A reverse slope is present from ~180 km along the AB transect (Figure 6).~~ The point of collapse is simulated to occur after the margin has retreated back from the MTBH, ~~The results of the *READVANCE* simulations suggesting~~ that the MnIS transitions through a zone of instability when its grounding line retreated past the MTBH on a reverse slope at this point, thus indicating that the observed hysteresis is caused by MISI.

As well as the influence of MISI, the morphology of the ice stream marine margin may also cause an instability during the retreat of the ice stream. For the majority of the retreat, the ice stream is buttressed to the east and west by surrounding ice (Figure 4). However, in the smaller stable state (Figure 7d), the ice stream is not buttressed on the western margin, due to the bay forming in the west trough of the Minch. This removal of the lateral buttressing of the ice stream to the west may also contribute to the inability of the ice stream to recover the ILGM extent in this experiment.

The difference between the grounding line position at the zone of transition and at the collapse state, i.e. the magnitude of collapse, varied across the ice stream (Figure 8a). In the East-of-the Trough the magnitude of collapse was limited, and a bathymetric transect shows only a limited reverse slope to facilitate MISI (Figure 8b). However, in the West-of-the Trough the magnitude of collapse was more significant, and the bathymetric transects shows a more sustained reverse slope to facilitate MISI (Figure 8c).

With ice unable to advance beyond the MTBH in the recovery simulations, a mechanism is required to allow ice to first advance towards the shelf edge prior to the ILGM, but then be unable to advance after retreat from ILGM extent. Although this study started with an ice extent already at the ILGM extent, other studies such as Patton et al. (2016) successfully simulated the build-up of the entire Eurasian ice sheet, with ice overcoming the MTBH and reaching the shelf edge given an ILGM climate. The variability and uncertainty in the climate forcing could allow readvance back to the continental shelf edge. In particular, in our model, if the ILGM climate is uniformly cooled by 0.5 K across the entire domain ice readvances from a “collapsed” position to an ILGM position. It is reasonable that this small correction falls within the error of the climate simulations or variability in the climate during the build-up phase. Nonetheless, even with the cooled climate, recovery back

to ILGM extent is considerably slower beyond 5,600 model years. Despite cooling the climate to force a recovery to ILGM extent, a behavioural change in the ice stream readvance beyond 5,600 model years remains.

Topographic changes over the course of the glacial cycle may also explain why the simulations did not readvance over the MTBH given ILGM conditions. These topographic changes would be present in two ways; changes in isostasy during the glacial cycle, and bed erosion and deposition. The simulations run on an ice sheet bed adjusted for isostasy at 30ka BP, which exaggerates the reverse slope causing MISI. The original advance of the ice stream would likely be on a bed where the slope was reduced. Bed erosion could also increase the prominence of the hard bedrock topographic high after initial glaciation. According to the modelling of Patton et al. (2016), the MnIS is an area with high potential cumulative erosion 37-19ka BP. Both these mechanisms could exaggerate the reverse slope subsequent to glaciation, potentially allowing initial glacial advance, but not readvance from a retreated state. Therefore, this demonstrates the importance of understanding future topography evolution in understanding the long-term evolution of out contemporary ice sheets.

4.4 Comparison to ~~observed retreat~~ empirical reconstructions

To investigate the mechanism of marine influence on the MnIS, and simplify the experimental design, several assumptions were made which take the experiments away from “reality”. In reality, the various controlling factors of ice sheet change would interact together to exaggerate or dampen the effect of MISI. For example, rebound of the ice sheet bed during deglaciation could dampen or eliminate the observed effect of MISI. Similarly, an elevation-SMB feedback could exaggerate any observed MISI as the ice sheet thins and retreats. Removing the experiments from a set-up akin to reality is justified to investigate the possibility of marine influence on the BIIS. The simulations test the applicability of MISI to such a bathymetric setting, but do not imply a relative importance of MISI. To consider relative importance, the simulations would also need to consider evolving sea level, elevation-SMB feedback, evolving climate, thermodynamics, and bed friction, amongst others. This approach remains beyond current ice sheet models.

The resulting pattern of retreat from the *RETREAT* simulation has a number of similarities with previous retreat reconstructions (Bradwell et al., 2008; Clark et al., 2012; Hughes et al., 2016) despite the idealised nature of the climate forcing. For example, the margin appears to “hinge” on the northern point of the Isle of Lewis (Bradwell et al., 2007; Bradwell and Stoker, 2015) (Bradwell et al., 2007). The margin also recesses into the Minch, with a small ice cap on the Outer Hebrides persisting during deglaciation. The idealised nature of the climate forcing means that pattern and relative rate of retreat can be compared to empirical reconstructions, but the absolute timing cannot. Due to the idealised climate forcing, only the pattern, and not the timing, of the retreat can be compared to empirical reconstructions. There are close similarities between the simulated retreat and reconstructed retreat in the later stages of the deglaciation. In the later stages of retreat, both in the reconstructed and simulated retreat, the east trough contains a small ice stream whilst the west trough has fully deglaciated and formed a calving bay (Bradwell and Stoker, 2015). We take the key similarities of retreat pattern and margin morphology between the simulated deglaciation and empirical deglaciation reconstructions as an indication that the main mechanisms that controlled the deglaciation of MnIS are replicated in our simulations.

All simulations in this study use constant climate forcing which do not account for the evolution of climate during the deglaciation of the BIIS. The fluctuations in volume and area change in the simulations are the signal of internal dynamical ice sheet processes, which do not include the feedback between SMB and elevation or any transient evolution of external forcing in climate and sea level. ~~Here, we define the reconstructed retreat from the geomorphological and sedimentological evidence as the “observed retreat”.~~

The ~~observed retreat~~empirically reconstructed retreat history of the MnIS is the result of both the ice sheet internal and external forcing signal. Therefore, the signals simulated in these experiments could be exaggerated or dampened by external forcing; the climate signal. This style of retreat is evident from the moraine record (Figure 1), which shows a series of back stepping moraines across the continental shelf (Bradwell and Stoker, 2015; Bradwell et al., 2008; Clark et al., 2018)(~~Bradwell et al., 2008; Clark et al., 2018~~). It is inferred that these moraines form during a period of relative stability of the margin. These ~~Grounding Zone Wedges~~large seabed moraines occur in several places across the shelf edge, but there is only one period during the *RETREAT* simulation when the margin is stable, when the margin passes the northernmost tip of Lewis and enters the Minch (Figure 4 a and d). The surface expressions of the ~~Grounding Zone Wedges~~large seabed moraines are present in the bed topography used in the simulations. However, the ice margin retreats over other areas with a greater surface expression than ~~Grounding Zone Wedges~~these morainic wedges with no stabilisation of the margin. ~~Based on our results, we suggest that GZW6 could have been caused by topographic influence, while the other GZWs are expressions of the climate signal.~~ [LG3]

The area and volume loss acceleration during the late retreat phase, which we interpret as the beginning of MIS1, in reality would also be influenced by the climate fluctuations ~~during the observed retreat~~. The magnitude of this area and volume loss would be exaggerated or dampened depending on the increasing or decreasing SMB of the ice sheet at any given period. Overall, the simulated volume and area change in these simulations is relatively smooth, whilst ~~during the observed retreat in reality~~ climate fluctuations will have caused annual or even decadal dynamic margin fluctuations, more akin to the Hubbard et al. (2009) simulation of the ice sheet evolution which was driven by a transient climate.

Geomorphological studies of palaeo ice sheets are able to reconstruct the area of ice sheets. Reconstructing ice thickness, and therefore volume, requires the introduction of further uncertainties, like bed friction and SMB, and therefore it is sometimes assumed that area change can directly inform volume change of the ice sheet (Hughes et al., 2016). However, model simulations of palaeo ice sheets can consider both area and volume changes. In these simulations although volume and area evolution showed a similar trend, the area evolution during *RETREAT* had more obvious pauses and accelerations in area loss than the pattern of volume loss. A change in ice stream velocity could also alter ice sheet volume without altering the ice sheet area, as shown by variations in the bed friction for the varying the bed friction in the SPIN-UP experiment (Figure 3a). In this example, understanding the area change through geomorphic empirical evidence may overstate the magnitude of changes expected in volume loss.

An idealised climate warming perturbation was used to trigger deglaciation in the simulations (e.g. *RETREAT*) in order to isolate the internal mechanisms of retreat. However, the ~~observed~~ retreat began before ~~at~~ ~2730ka BP, when the NGRIP

$\delta^{18}O$ record suggests a cooling ~~climate globally rather than a warming climate~~ rather than a warming climate over Greenland (Andersen et al., 2004). Whilst rapid deglaciation can be achieved in ice sheets with significant ice streaming due to ice stream acceleration (Robel and Tziperman, 2016), a climate trigger is required to increase the surface slopes at the ice sheet margin. Model results also suggest a generally cooling global climate at ~2730ka BP (Singarayer and Valdes, 2010). The warming mechanism we used to trigger deglaciation in our simulations is not apparent in the climate record. The results of the *RETREAT* simulations also indicate that internal dynamical mechanisms alone would not have been sufficient to continue retreat until the triggering of MISI when the ice stream retreats past the MTBH. It seems that the MnIS was retreating in a cooling climate, but these simulations idealised climate forcing to isolate internal ice sheet instabilities, and therefore do not reveal a mechanism that explains MnIS retreat in a cooling climate. There are two likely possibilities that could explain the MnIS retreating in a cooling climate (explained below); i) internal mechanisms ~~caused by the expansion of the rest~~ of the BIIS, or ii) a local SMB change of this sector of the ice sheet ~~prior to~~ at ~2730ka BP.

A local SMB change could be caused by atmospheric warming or a reduction in precipitation. Local warming of the northern British Isles, whilst the rest of the BIIS and other northern hemisphere ice sheets expanded, could be a mechanism to explain early MnIS retreat. The NGRIP ice core is more than the synoptic scale away from the Minch, and there could reasonably be local warming during global cooling. Given the uncertainty in palaeo climate modelling, particularly at high latitude due to sensitivity to ice-sheet forcing (Singarayer and Valdes, 2010), it is a reasonable possibility that a local warming would not be included in the HadCM3 last glacial simulations used to force the ice sheet model. However, it seems unlikely that climate could be warming in the Minch whilst allowing rapid expansion for the remainder of the BIIS. Additionally, a local reduction in precipitation could be caused by a change in the position of the polar front, which would have been affected by the advance and retreat of the northern hemisphere ice sheets during the last glacial cycle (Oster et al., 2015). A migration in the polar front would likely affect the entire western margin of the BIIS, potentially causing the start of deglaciation to be asynchronous with the rest of the northern hemisphere (Scourse et al., 2009). However, as the forcing in these experiments remains idealised, this is only a speculative driver of early BIIS retreat.

Alternatively, internal mechanisms of the BIIS that were not simulated as part of this study could explain a retreating MnIS in a cooling climate. Two candidates for this mechanism are ice piracy from other catchments of the BIIS, or the initial advance of the MnIS being the result of a surge-type advance. The simulations presented here did not feature a lapse rate effect on SMB as the ice sheet surface lowered into a warmer climate. This process could help facilitate rapid retreat in a cooling climate, but could not be a trigger for retreat. During the retreat of the MnIS, ice was extending over Northern Ireland out to the shelf edge (Clark et al., 2012; Dunlop et al., 2010). It is theorised that a significant proportion of the ice feeding this advance came from the Hebrides Ice Stream, evidenced by large moraines northward of Donegal Bay. The source ~~of the areas of the Hebrides Barra Fan~~ Ice Stream will have significantly overlapped with the MnIS, and the advance of the Hebrides Barra Fan Ice Stream could have initiated ice piracy from the MnIS, causing retreat in a cooling climate. The initial advance of the MnIS could also have been caused by a surge-type advance, which subsequently retreated as the remainder of the ice sheet advanced. These experiments assumed an initial steady state at ILGM extent. Dating the advance of ice sheets is inherently more uncertain

than retreat (Hughes et al., 2016), and although the significant Trough Mouth Fan could be taken as evidence for a relatively stable MnIS, it almost certainly ~~have~~ formed over multiple glacial advance and retreat cycles (Bradwell and Stoker, 2015). ~~This mechanism is~~ These mechanisms are speculative, and would require experiments with transient forcings to test. These internal instabilities would not have been represented in these simulations because a warming climate was used to trigger deglaciation, forcing the ~~Barra Fan~~ Hebrides Ice Stream to retreat rather than advance. Bed friction and topography also do not evolve during the simulation, meaning ice streams in the simulations cannot activate or shutdown due to sediment exhaustion, or bed hydrology changes. Bed hydrology evolution has been identified as a key control of ice streams, but this process remains challenging to incorporate into ice sheet models (Hewitt, 2013). These simulations therefore provide evidence for internal processes during the retreat of the MnIS, but the initial trigger ~~of~~ for deglaciation of the MnIS in a cooling climate remains elusive.

5 Conclusions

We simulated the retreat of the MnIS from a position of maximum extent, using an idealised climate perturbation in order to identify the role of the internal dynamical mechanisms ~~on~~ ice sheet retreat. This simulation showed a retreat in three phases, an initial retreat (0-3,500 model years), stagnation (3,500-6,300 model years), and a late retreat (after 6,300 model years). The stagnation phase occurred as the ice stream retreated past the northernmost tip of the Isle of Lewis. This slowing of volume and area loss coincides with a significant proportion of the ice sheet margin retreating onto the Outer Hebrides, beyond marine influence. At this point in the simulation, the MnIS is in a similar marine setting to many retreating tidewater glaciers in Greenland and Antarctica. During this phase, a laterally constrained ice shelf provided buttressing to the ice stream. In the late retreat phase, the area and volume loss rate re-accelerated as the grounding line retreated on a reverse bed slope. We reversed the idealised climate perturbation regularly during this simulated deglaciation to test for instabilities of retreat. After the re-acceleration of volume and area loss at 6,300 model years, the ice sheet did not recover to ILGM volume and area given ILGM conditions. ~~This~~ We suggest this result is evidence for a ~~rapid~~ retreat of the MnIS caused by marine ice sheet instability.

We compared the simulated retreat to a simulation with the ice shelves removed, which was otherwise identical. The simulations show that ice shelves were not influential to the magnitude and pattern of retreat for the first 5,000 model years of the simulated deglaciation, when the ice shelf was unconstrained. Once the margin had retreated into a trough geometry that constrained the ice shelf, the removal of the ice shelf caused higher ice stream velocities and a more rapid ice volume loss. We therefore find evidence for an influential ice shelf buttressing effect during ~~the~~ MnIS deglaciation. Our simulations demonstrate the importance of ~~the~~ MISI and ice shelf buttressing during ~~the~~ retreat of the Minch ice stream. These processes currently represent the largest source of uncertainty in projecting the future evolution of the Antarctic ice sheet. We suggest that the detailed chronology of BIIS retreat currently being produced ~~of retreat of the British and Irish ice sheet currently produced~~ by

the BRITICE-CHRONO project has the potential to constrain important processes controlling MISI in models used for future sea level projections.

Code and data availability. We used a branch of the BISICLES ice sheet model, revision 3635 (<https://anag-repo.lbl.gov/svn/BISICLES/public/branches/smb/>). Output files and required input files to reproduce the described experiments can be found at (<https://doi.org/10/cvv7>). Code for the PDD model used is available at (<https://github.com/juseg/pypdd>).

Competing interests. The authors declare that they have no conflict of interest.

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Parameter	Value	Units
Flow law	Power Law	-
Weertman exponent	1	-
Ice temperature	268	K
Ice density	918	kg m ⁻³
PDD _{ice} factor	0.008	m °K ⁻¹ d ⁻¹
PDD _{snow} factor	0.003	m °K ⁻¹ d ⁻¹
Re-freeze ratio	0.07	-
Snow-rain threshold	275.15	K
Lapse rate	5.1	K/km

Table 1: Key model variables and parameters.

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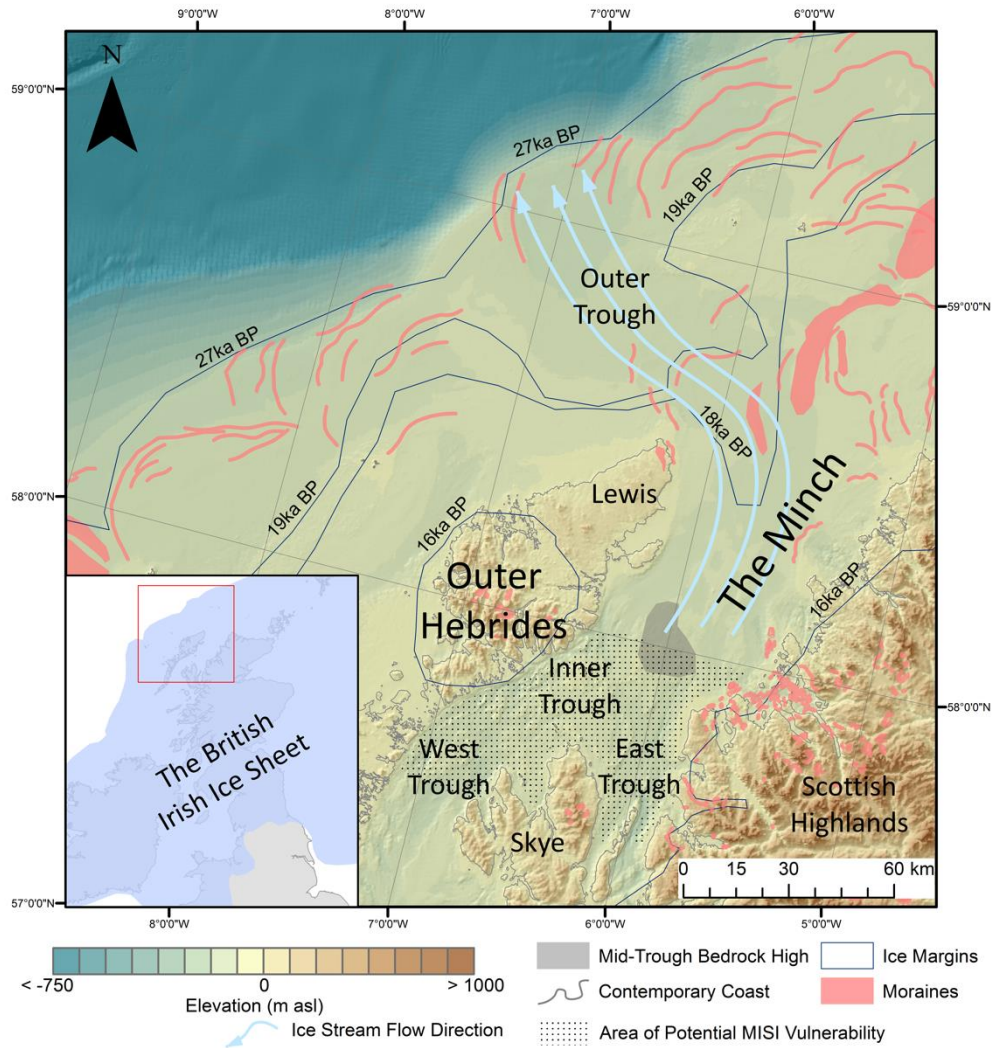
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Name	Initial ice Thickness	Surface mass balance	Sub-shelf melt	Basal Friction
<i>SPINUP</i>	Plastic thickness	26 ka BP	26.3 m/y	Standard (Fig. 4a)
<i>RETREAT</i>	<i>SPINUP</i>	26 ka BP + 1.5 K	47.1 m/y	Standard
<i>RETREAT_ATMOS</i>	<i>SPINUP</i>	26 ka BP + 1.5 K	26.3 m/y	Standard
<i>RETREAT_OCN</i>	<i>SPINUP</i>	26 ka BP	47.1 m/y	Standard
<i>READVANCE_xxxxyr</i>	Retreat at model x yr (800 yr intervals)	26 ka BP	26.3 m/y	Standard
<i>RETREAT_NOSHELF</i>	<i>SPINUP</i>	26 ka BP + 1.5 K	100 m/y	Standard
<i>READVANCE_COOLING</i>	Stable <i>READVANCE_8000yr</i>	26 ka BP – 1.5 K	26.3 m/y	Standard
<i>SPINUP_MAXFRICT</i>	Plastic thickness	26 ka BP	26.3 m/y	Standard x 1.5
<i>SPINUP_MINFRICT</i>	Plastic thickness	26 ka BP	26.3 m/y	Standard x 0.5

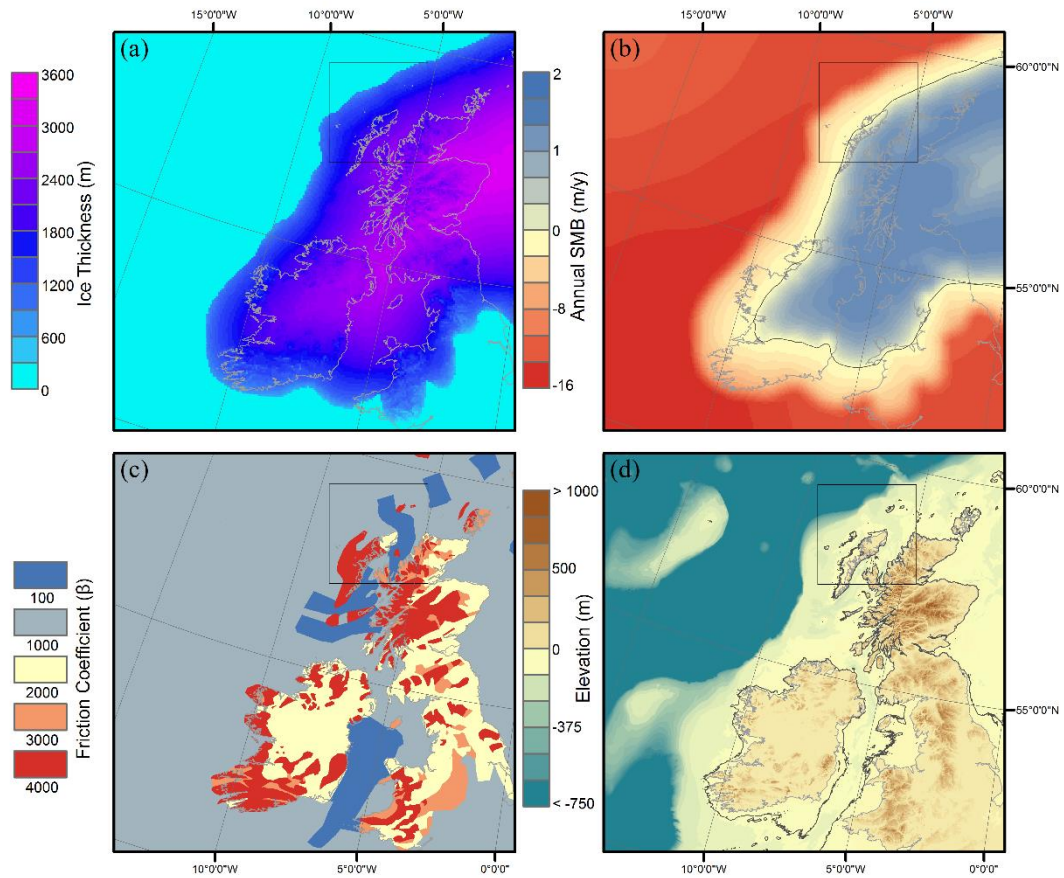
Table 2: Summary of experiment set-up and forcing

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5 **Figure 1: Location and geographical setting of the Minch Ice Stream.** The inset shows the maximum extent of the British-Irish Ice Sheet from Clark et al. (2012). The red box indicates the Minch ice stream region shown in the larger map. Ice margins and dates are from Clark et al. (2012). Moraines are from the BRITICE glacial landform map, version 2 (Clark et al., 2018). Area of potential MISI vulnerability is inferred from the presence of marine retrograde slopes. Key locations mentioned in the text are labelled.



5 **Figure 2: Initial conditions and boundary conditions for the equilibrium spin-up ILGM ice sheet simulation, showing the full domain of the simulations. (a) Initial ice thickness (m), (b) Annual Surface Mass Balance (m/y), with black contour line representing the Equilibrium Line (SMB = 0 m/y). (c) Bed Friction Coefficient (β), (d) Isostatically adjusted topography (m) corresponding to 30 ka BP. The maps show the full ice sheet domain and the black boxes indicate the area of model grid refinement referred to as the Minch sector.**

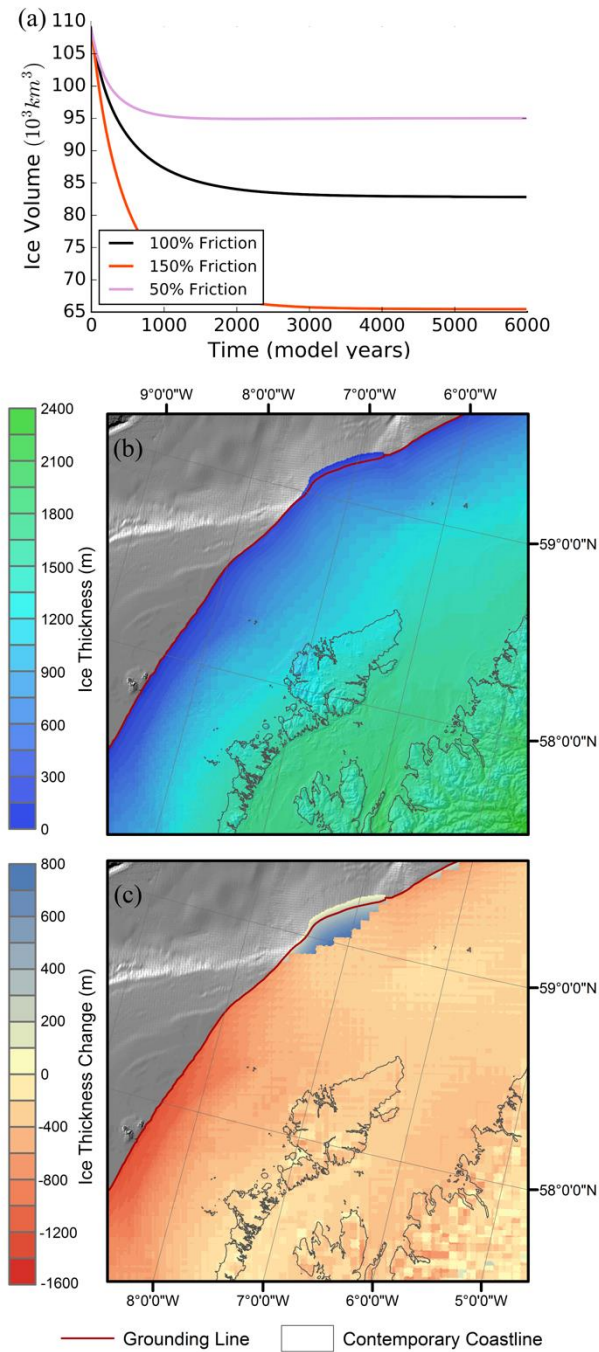


Figure 3: a) Evolution of the ice sheet volume over the Minch sector during spin-up. b) Simulated ice sheet thickness after 6,000 model years of spin-up, c) Ice thickness change between the start and end (year 6000) of the spin-up simulation (i.e. difference between Figure 2a and Figure 3b.)

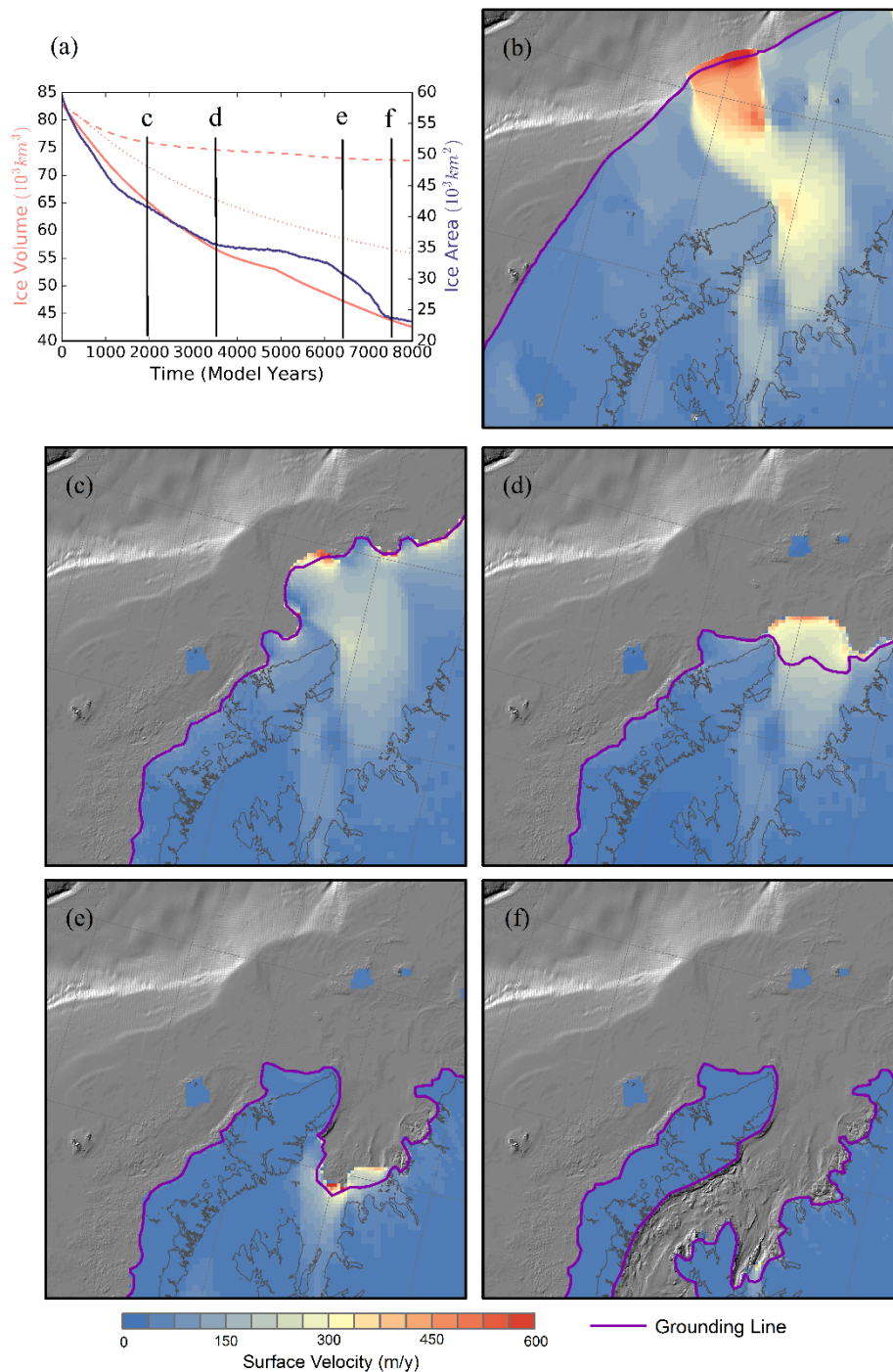


Figure 4: Evolution of the ice sheet in the Minch sector in the *RETREAT* simulation. a) Timeseries of ice volume and area over the Minch sector. The dashed curve shows the volume response to *RETREAT OCN*. The dotted curve shows the response to *RETREAT ATMOS*. Ice surface velocity (b, c, d, e, and f) at 0, 2000, 3500, 6300, and 7500 model years respectively with grounding line shown in purple.

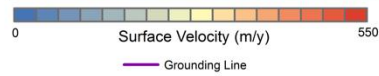
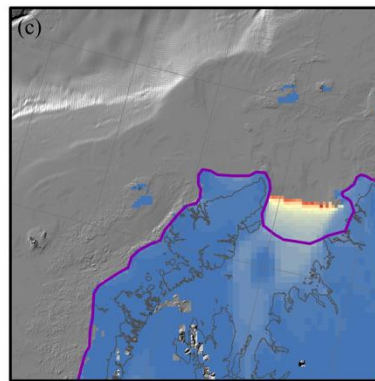
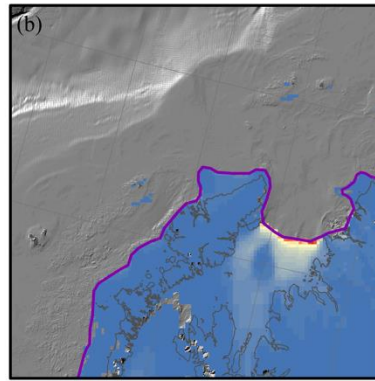
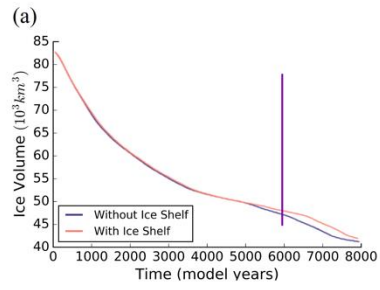


Figure 5: Effect of ice shelves. (a) Evolution of [grounded](#) ice sheet volume over the Minch sector in simulation *RETREAT* with ice shelves (red line) and *RETREAT_NOSHELF* in which ice shelves are forcibly removed (blue line). (b,c) Surface velocity and grounding line location (purple line) in *RETREAT_NOSHELF* (b) and *RETREAT* (c).

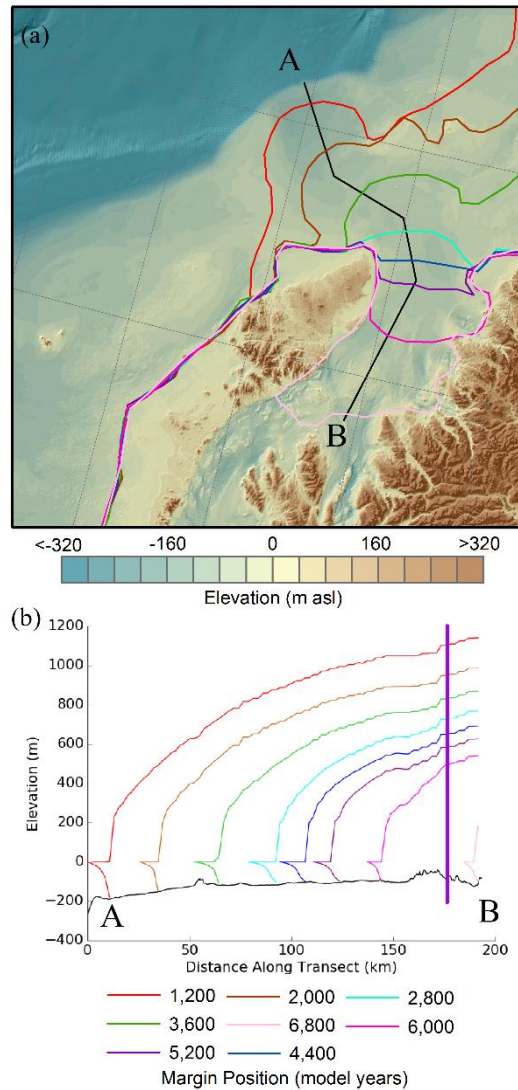
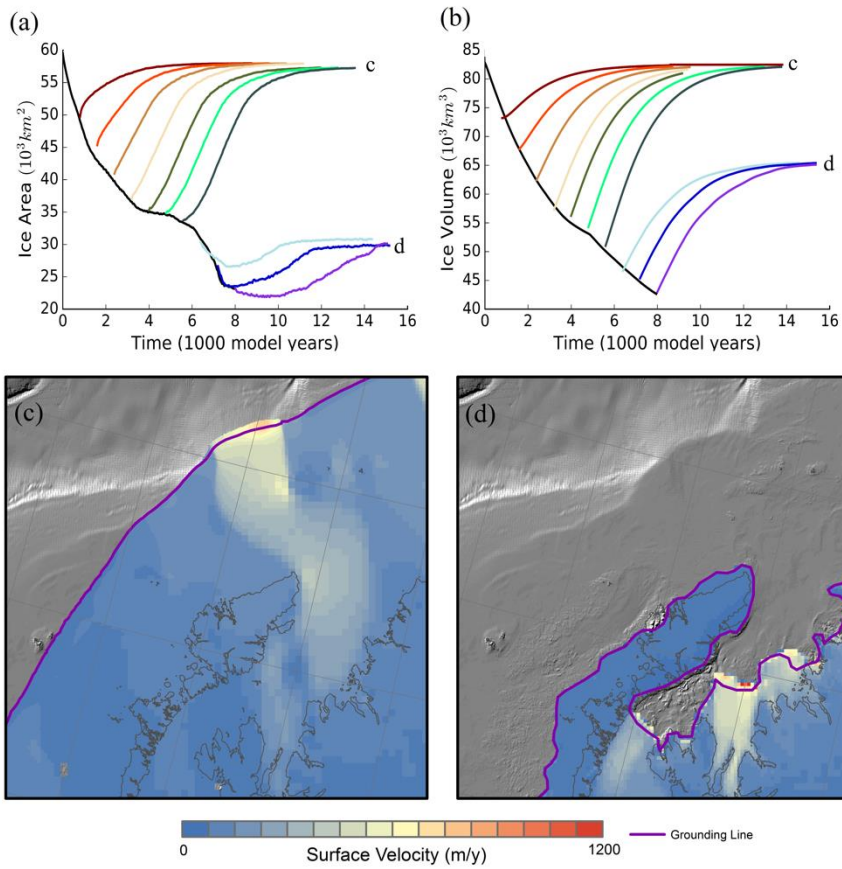


Figure 6: a) The grounding line position of the ice sheet at 800 year intervals during the *RETREAT* simulation. b) Transect through the ice stream showing the ice sheet elevation at the same intervals. The purple line marks the grounding line position in the stable “collapsed” ice sheet state from the *READVANCE* simulations (Figure 7d).



5 **Figure 7: Results of the ensemble of *READVANCE* simulations testing instability in the Minch Ice Stream. (a,b) Evolution of the ice sheet area (a) and volume (b) over the Minch sector in the *RETREAT* (black) and *READVANCE* simulations (coloured lines). Labels c and d indicate the “maximum” (c) and “collapsed” (d) stable states with corresponding panels showing the respective surface ice sheet velocity (m/y) and grounding line locations (purple line).**

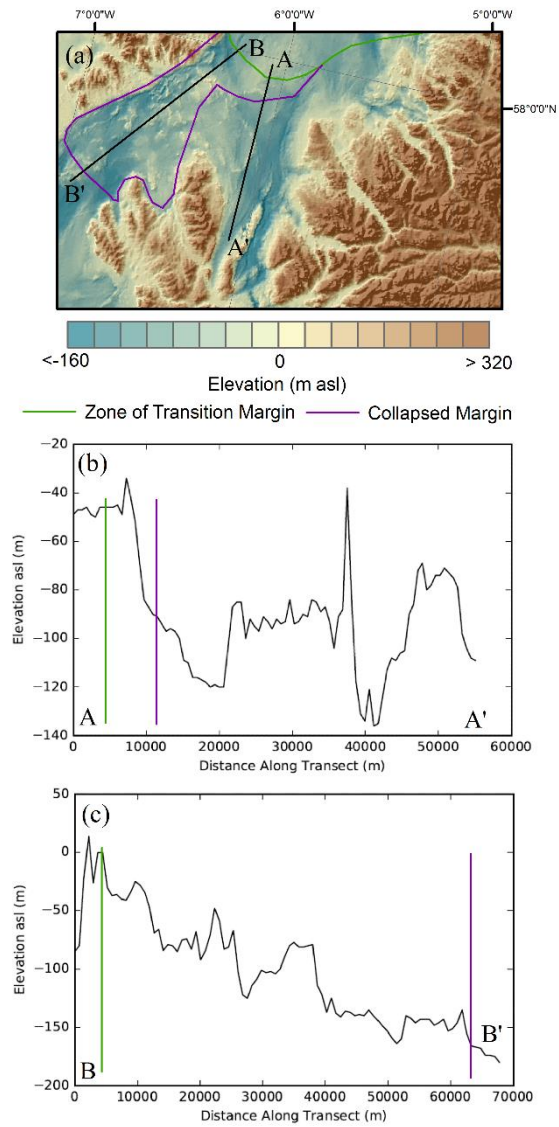


Figure 8: The difference in the effects of MIS1 between the East Trough and the West Trough. a) 6,400 model year *RETREAT* margin (green) and the stable “collapsed” extent margin (purple). b) A-A’ transect of bathymetry and collapse extent in the East Trough. c) B-B’ transect of bathymetry and collapse extent in the West Trough.