Author's response to reviewers

March 30, 2026

Response to Anonymous Referee 1

This is a well written and timely paper that uses numerical modelling constrained by palaeo-glaciological and geochronological data to produce a set of ice sheet histories for the Icelandic Ice Sheet through the last glacial cycle. I think the subject of the paper is suitable for Climate of the Past and could be published subject to some minor-moderate revision that address the following points:

Dear reviewer #1,

Thank you for your thoughtful and constructive comments. We provide a point-by-point response below. The reviewer comments are shown in blue and our replies in black.

Specific comments

1. The interpretation that hydrofracturing drove ice shelf disintegration and thus collapse, clearly relies upon the presence of ice shelves fringing the ice sheet during deglaciation. But what is the direct geological evidence that ice shelves did indeed fringe the IIS during retreat? Rather than an ice shelf could the retreating ice sheet margin have been in the form of a grounded tidewater margin? Can the authors rule out the latter scenario and, if not, would this have an impact on their interpretation of the role of hydrofracturing? There needs to be a more explicit justification for the existence of ice shelves based on marine geological data. I am not saying I disagree with the authors but rather that this is important to their study and they need to provide a more convincing justification for ice shelves presumably from published geological data. This could be included within #2 below.

   This is a good question and points to a limitation in our original analysis in our failure to isolate ice shelf and tidewater margins. We have expanded the discussion on ice shelf evidence and tidewater margins in the revised manuscript.

   To our knowledge, direct geological evidence for ice shelves dating from the last deglaciation does not currently exist, though this study motivates future coring in locations where our model simulates ice shelves at the onset of MWP-1A. Conversely, we know of no unambiguous evidence refuting local ice shelf presence for our NROY ensemble.

Interpretation based on Figure 7 in the manuscript may overrepresent the actual ice shelf area, as it shows the ensemble mean (although grid cells for which mean ice thickness was < 25 m were excluded). Individual ensemble members exhibit a mix of ice shelves and grounded tidewater margins. Overall, the northern margin is mostly bounded by extensive ice shelves, while the southern margin is tidewater at 15 ka for the majority of NROY simulations. A new supplementary figure (Fig. A10) shows the density distribution of floating ice within the $\mathrm{NROY}_{\mathrm{tier1}}$ sub-ensemble at 15 ka.

Hydrofracturing is also a key component of tidewater calving in the GSM [c.f. equations 31 and 32 in Tarasov et al., 2025, , as well as newly added details to the GSM description in our revised submission], so its role is not just confined to ice shelves. To disentangle the relative contributions of tidewater versus ice shelf hydrofracturing, we performed sensitivity experiments isolating each mechanism. We find that they both contribute comparably to total hydrofracturing. Thus, regardless of whether margins terminate in ice shelves or grounded tidewater glaciers, hydrofracturing remains critical in deglaciation.

Throughout the deglaciation subsection (Sect. 3.2.3) and conclusion, we updated the text to explicitly consider both ice shelf disintegration and tidewater calving as mechanisms driven by hydrofracturing, e.g.:

... surface runoff on the ice shelf increases calving via hydrofracturing, leading to both ice shelf disintegration and tidewater glacier front retreat.

The resulting elimination of ice shelf buttressing and reduced backstress at tidewater margins trigger ice stream acceleration and thereby increased ice discharge into the ocean.

Furthermore, in the sensitivity experiments subsection (Sect. 3.2.4), we added :

The experiments with hydrofracturing only for tidewater margins, and with hydrofracturing only for ice shelves indicate that both mechanisms contribute comparably to total hydrofracturing (Fig. 11). Thus, regardless of whether margins terminate in ice shelves or grounded tidewater glaciers, hydrofracturing remains critical in deglaciation.

2. I think it would be helpful if the authors included a summary of the key points from the geological data of the ice sheet history – perhaps summarised by different sector and noting in particular the geochronology on retreat timing and rate. This could be an additional section or included in the Introduction. It does not have to be very long

but it would be helpful. At the moment there is only a section on 'Palaeo-constraints' which appears as section 2.2 in Methods.

We included a summary of the empirically-inferred full last glacial cycle ice sheet evolution at the end of section 2.2 in Methods :

The spatial distribution of the geological constraints is uneven. As shown in Fig. 4, data are scarce over the southern and eastern regions of the Icelandic continental shelf. Providing a best-estimate age and age uncertainties for the LGM extent of the IIS is thus challenging and somewhat subject to interpretation of chronological and stratigraphic data [Benediktsson et al., 2022, 2023a]. However, based on the existing empirical data from different sites on the western, northwestern, and northern continental shelf, the LGM peak extent can be securely bracketed between maximum ages of 45.1 and 39.8 ka and minimum ages of 22.3, 16.2, and 15.3 ka (median probability ages based on calibrated age ranges at the 95.4% $\pm 2\sigma$ level), with a best-estimate age of 23–28 ka [Benediktsson et al., 2022, 2023a].

The peak extent during the Younger Dryas is comparably well constrained both spatially and chronologically. The empirical data suggest that it was asynchronous across the ice sheet, most probably owing to internal glacier dynamics, topographic control, and local or regional climate conditions. However, where the age of the Younger Dryas ice margin is well constrained, it broadly falls between 12.8 and 12.1 ka [Benediktsson et al., 2023b]. In other areas, the relative age of the Younger Dryas ice margin can be established from cross-cutting relationships with Preboreal deposits that are typically dated between 11.1 and 11.6 ka, yielding a wider range of 12.5 ± 3.0 ka.

3. At the very end of the paper (lines 424-428) sea level rise is mentioned as a potential driver of marine ice sheet collapse. The authors state that to address the impact of sea level they carried out a sensitivity experiment with sea level held constant at its 15 ka value. This had little impact. How realistic is holding sea level constant given that the sea level jump associated with Meltwater-Pulse 1A occurred shortly after this time and was broadly coincident with the timing of the rapid deglaciation and collapse of marine-based ice at 14.6-14.0 ka?

The point of a sensitivity experiment is to isolate a physical process, in this case, the relative role of deglacial sea-level rise in driving ice sheet collapse by exclusion of such a rise. Such isolation will generally entail imposition of idealized (i.e., contrary to paleo records) boundary conditions or forcings.

In the revised manuscript, we expanded the description of this experiment in Sect. 3.2.4:

Another potential driver of marine ice sheet collapse is sea level rise due to increasing ocean volume during deglaciation as well as associated changes in the gravitational field. To isolate the relative impact of this, we carried out a sensitivity experiment repeating the 15 ka to 0 ka deglacial interval of the simulations with the geoid held constant at its 15 ka value (≈ -100 m around Iceland relative to the Earth's center of mass). This was applied to the whole $\mathrm{NROY}_{\mathrm{tier1}}$ set of simulations. This change in forcing had minimal impact on the ensemble. A few simulations had slightly reduced mass loss rates (maximum difference at any time of ~ 0.02 mESL), while the rest had almost no visually discernible response (Fig. A14).

4. Line 27 – presumably reconstructing IIS evolution is also challenging due to the absence or sparsity of geochronological control?

   The subsequent paragraph addressed the limited constraint from proxies, but your point makes clear the current statement is misleading. As such, we have revised the beginning of the offending paragraph to:

   Reconstructing IIS evolution is challenging due to limited empirical constraints and large physical uncertainties. The latter includes: ...

Response to Anonymous Referee 2

An overall well-written and interesting manuscript on an important aspect of ice-shelf hydrofracturing and its impact on ice decay, but several aspects listed below would benefit from clarification and expansion to strengthen the interpretation of the results presented in the current version. Presentation of results (i.e., figures) could also be enhanced to support the key points.

Dear Reviewer #2,

Thank you for your review. A point-by-point response is provided below, with the reviewer comments shown in blue and our responses in black.

1 Ice dynamics, deglaciation drivers, and isostacy

The statement "We then disentangle the drivers and controls of its subsequent deglaciation" would benefit from a broader discussion of glacial isostatic adjustment. In particular, consideration of its sensitivity to heterogeneous mantle viscosity and the resultant impact on regional sea level would strengthen the interpretation of deglaciation processes, as well as their rates.

We have now carried out a sensitivity suite of subensembles to the approximate inferred range of upper mantle Earth viscosities for the region for a deglacial timescale (5×10^{18} Pa s to 5×10^{19} Pa s, [Le Breton et al., 2010, Auriac et al., 2013]), along with a subensemble with stiffer rheology appropriate for parts of Greenland (5×10^{20} Pa s). The difference in half-space timescale for the inferred rheology range (@ 1050 yr) is not much larger than the nominal ice sheet dynamical timescale during early to mid deglaciation (average grounded ice thickness/average accumulation = about 850 years). We included a summary of results in the revised manuscript (Sect. 3.2.4) :

The GSM visco-elastic GIA solver is restricted to a spherically symmetric earth rheology. However, there are likely significant lateral variations in the visco-elastic earth structure under Iceland. To bound potential uncertainties due to such variations, we reran the $\mathrm{NROY}_{\mathrm{tier1}}$ set with nominal stiff and soft bound earth rheology values. These rheologies were respectively assigned upper mantle viscosities of 5×10^{19} and 5×10^{18} Pa s along with respective lithospheric thicknesses of 96 and 46 km in accord with the previously inferred range of values for a deglacial timescale [Le Breton et al., 2010, Auriac et al., 2013]. Simulations with the stiffer earth rheology tended to have a bit more 20 ka ice volume (ranging to 14% larger, Fig. A15). In contrast, the stiff bound earth rheology gave less 15 ka grounded ice area (ranging to 10% smaller) as well as larger "iceTot" ice thickness misfits against cosmogenic age constraints. The latter is also indicative of insufficient regional ice. The difference in half-space timescale for this rheology range (approximately 1050 yr) is not much larger than the nominal ice sheet dynamical timescale during early to mid deglaciation (average grounded ice thickness/average accumulation ≈ 850 years). As such, a non-negligible impact is not unexpected.

Then, the discussion of ice stream behaviour could be expanded. In the statement "Most of these ice streams activate and deactivate independently…", basal velocities periodically drop to zero, implying complete shutdowns. How is subglacial meltwater involved in these shutdowns? A more detailed discussion of basal melting, geothermal heat flux, and meltwater production would be useful here.

The only way to get complete ice stream shutdown with 0 basal velocity is for the bed to freeze. Even if there were no basal water, there would still be (albeit strongly reduced) basal sliding. So we do not understand what specifically about the role of basal water the reviewer wants more details on, especially since basal meltwater production depends on basal thermal energy balance. The latter is quite non-trivial, e.g., increased basal water pressure reduces basal drag, which in turn increases basal velocities. These two effects have opposing impacts on basal heating. Basal energy balance also depends on ice velocities, basal geothermal heat flux (from the bedthermal module), ice thickness, upstream ice temperature, as well as surface temperature and precipitation histories. As such, we are skeptical that any simple conclusions can be drawn about the exact controls on ice stream activation/shutdown beyond that inferred from the physics of the system.

We reran the reference ensemble with the maximum basal water thickness limit increased from 2 to 10 m to isolate the impact of this limit. Though the GSM has a full distributed subglacial drainage module, previous work for the context of Hudson Strait ice stream cycle [Drew and Tarasov, 2023] has shown that the differences between simplified local drainage and full complexity subglacial drainage modelling are largely within that due to parametric uncertainties. As such, we restrict our analysis to the GSM configuration with the much cheaper local drainage module. The results of this experiment are now included in Sect. 3.2.4:

Finally, to partly address uncertainties due to the impact of a simplified "leaky bucket" local sub-glacial hydrology model, the $\text{NROY}_{\text{tier1}}$ set was rerun with a 10 m (as opposed to the default 2 m) limit on subglacial water thickness. In comparison to the reference ensemble, differences in 15 ka grounded ice area, 20 ka ice volume, and IceTot score were all less than 5% for all but a handful of ensemble members (Fig. A17). The paleoExt marine misfit score again showed the largest impact, but differences in individual scores were still less than 10% for all but two of the $\text{NROY}_{\text{tier1}}$ parameter vectors. A much more detailed assessment of the impact of basal hydrology model complexity in the context of Hudson Strait scale ice stream surge cycling [Drew and Tarasov, 2023] found that most of the differences were within the range of what was already covered by parametric uncertainties for the simplistic basal hydrology model employed herein.

2 Representation of hydrofracturing and ice shelves

The paper would benefit from a clearer discussion of the limitations associated with representing hydrofracturing at a 5° (∼7 × 6 km) grid resolution. How well can hydrofracturing processes be captured at this scale? Furthermore, ice shelves appear to occupy relatively limited areas in the northern sector (Fig. 8), whereas southern part lacks floating ice. Quantification of ice-shelf area relative to the total ice-sheet area would be helpful as this is central part of the study and heterogeneous variability would add nuance to the results. In addition, further discussion is needed on how much hydrofracturing occurs in the southern ice-sheet sector and how this compares with the north.

It is generally the case that representing a subgrid process at a resolution significantly coarser than the process scale is less challenging than representing that process at a grid scale near the process scale (a scale that fully resolves the process is ideal but often not attainable). The coarse resolution effectively allows the process to be smoothed out as a semi-random process (invoking the law of large numbers). So we don't see the resolution as a major issue, especially compared to all the other sources of uncertainty in paleo ice sheet modelling (with climate forcing generally standing out as the largest source). The appropriate representation of ice calving (both tidewater and shelf) is not well constrained, and we at least partly address this by including 3 relevant ensemble parameters. We have added in Sect. 2.1 :

As for any subgrid process, the large scale difference between the GSM grid resolution and actual terminal crevasse size reduces the need for accurate process representation as long as critical dependencies are captured within associated ensemble parameters.

In terms of addressing structural uncertainties (i.e. model uncertainties not captured by ensemble parameters) of the parametrized calving and hydrofracturing, we carried out an additional sensitivity ensemble with linear (as opposed to the current quadratic) capture of surface melt flux into the crevasses. The results of this experiment are now included in Sect. 3.2.4 :

To partly address structural uncertainties in the representation of hydrofracturing (i.e. uncertainties not covered by ensemble parameters), the $\mathrm{NROY}_{\mathrm{tier1}}$ parameter vector set was re-run with linear (as opposed to quadratic) dependence of hydro-fracturing on surface runoff for the whole glacial cycle. The linear coefficient was scale matched to that of the default quadratic dependence for a $0.5 m/yr$ surface runoff. ... The impact of this structural change is nearly unbiased on the ensemble (Fig. A16), with less than 5% impact on 15 ka grounded ice area for most simulations. The impact for three other metrics (20 ka ice volume, ice thickness misfit score, and marine ice extent misfit score) is larger over the ensemble, but in each case it is still less than 5% for the majority of simulations.

The distinction between ice shelf and tidewater margins, and their respective roles during deglaciation, was also raised by Reviewer 1. Instead of the suggested analysis against relative shelf area, we find it more elucidating to consider heat maps of NROY ice shelf distribution. We now explicitly show via a new supplementary heat map (Fig. A10) that the northern margin is mostly bounded by ice shelves, while the southern margin is predominantly tidewater at 15 ka. Hydrofracturing is also a key component of tidewater calving in the GSM, and sensitivity experiments isolating each mechanism show that both contribute comparably to deglaciation. Thus, regardless of whether margins terminate in ice shelves or grounded tidewater glaciers, hydrofracturing remains critical, with ice shelf hydrofracturing dominating over the northern margin and tidewater hydrofracturing dominating over the south.

To further elucidate the impact of hydrofracturing on ice shelf distribution, two new additional ice-shelf area heat maps for the 14 ka timeslice (just after the marine deglaciation interval in the reference ensemble) compare the reference and no hydrofracturing ensembles (Fig. A12 in the revised manuscript).

3 Geological constraints and model–data comparison

I think that perhaps a more explicit figure showing empirically reconstructed ice margins, including dating uncertainties, is needed to allow a clearer visual comparison between geological reconstructions and the model runs. Finally, heat-flux reconstructions and borehole locations from Flóvenz and Sæmundsson (1993) and Hjartarson (2015) should be shown on one of the maps to better contextualise the geothermal forcing used in the model.

We modified the current Fig. 6 in the manuscript to explicitly compare our NROY minimum and maximum bounds to the empirical reconstructions for key time periods. In particular, we added white contours on the 25, and 12 ka panels that show empirical ice-margin reconstructions for 25.5 ± 2.5 ka [Benediktsson et al., 2022, 2023a], and 12.5 ± 3.0 [Benediktsson et al., 2023b], respectively. We also provided further discussion about dating uncertainties at the end of section 2.2 in Methods :

The spatial distribution of the geological constraints is uneven. As shown in Fig. 4, data are scarce over the southern and eastern regions of the Icelandic continental shelf. Providing a best-estimate age and age uncertainties for the LGM extent of the IIS is thus challenging and somewhat subject to interpretation of chronological and stratigraphic data [Benediktsson et al., 2022, 2023a]. However, based on the existing empirical data from different sites on the western, northwestern, and northern continental shelf, the LGM peak extent can be securely bracketed between maximum ages of 45.1 and 39.8 ka and minimum ages of 22.3, 16.2, and 15.3 ka (median probability ages based on calibrated age ranges at the 95.4% $\pm 2\sigma$ level), with a best-estimate age of 23–28 ka [Benediktsson et al., 2022, 2023a].

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We also included in the supplement (Fig. A1) two maps displaying the geothermal heat-flux field distributions. However, borehole locations are only shown for the Flóvenz and Saemundsson [1993] field, as the field from Hjartarson [2015] was directly provided by the author without access to the borehole data and was extrapolated to our grid extent.

4 Minor comments

1. Line 20: Robel et al. (2019) is cited twice.
   Thanks for noticing: one has been removed.
2. Line 270: Section heading "3.2.1 pre-LGM" should be capitalised.
   Done.
3. Figure 7: Ensure that minimum and maximum extent labels are clearly identified and, if possible, differentiated by colour.
   This was addressed by differentiating the linestyle of the minimum and maximum ice extent contours.

References

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