Detailed response to Reviewer #2's comment

The study uses coupled-climate ice sheet modeling to assess the interactions between ocean subsurface warming and ice sheet dynamics during the last glacial period (Northern Hemisphere ice), with a particular focus on basal melt rates and freshwater release. The authors describe the impact of the basal melt of coastal ice on ice sheet geometry, and explain how the response of regional sea-ice to freshwater reduces local oceanic convection, with consequences for AMOC. The overall effect of the freshwater is a negative feedback to ice mass loss in Greenland and Eurasia, although the authors find the North American ice sheet to be stable anyway.
The language used is clear to follow as, for the most part, are the figures. I enjoyed reading it. However, there are some parts of the framing that need tightening up before publication, to properly situate the work, making sure its relevance/importance can be appropriately contextualized by the reader and thus built on, by future work in the community. There is a bit too much assumed contextual knowledge/perspective. I think with some improvements in the presentation of the work (as suggested more fully below), the work will add some value to the field.
Thank you for the time you spent reading the manuscript and your detailed analysis.

In the whole framing of the study, the relation between the experiment design (and results) and the past glacial cycle is somewhat vague; it is not very clear specifically what, beyond a thought experiment for understanding this coupled-models behavior, is being tested. The final paragraph on page 2 explains the specific aims, but this needs relating back to the real world. Discussion section 4.3 has some relation to real past events, but it is short, and vague, and comes only at this late stage in the manuscript.
Thank you for this comment. We will clarify the sequence of ideas, the scientific questions we are addressing, as well as their connections with the real world, in the following response as well as in the main text's introduction and description of the experiments.

The motivation of this study is understanding the cause of the massive iceberg discharges that occurred during the Last Glacial Period. As it was not very clear, we will add the two following paragraphs at the beginning of the introduction :

"The Last Glacial Period began around 75 kyr before present (BP) and ended with the Last Glacial Maximum (LGM) around 21 kyr BP. An intriguing feature of the last glacial period is its millennial-scale variability, first revealed in Greenland ice cores, known as the Dansgaard-Oeschger (DO) cycles (Dansgaard et al., 1984, 1993). These are transitions between relatively cold (stadial) and warm (interstadial) periods in the Northern Hemisphere (Johnsen et al., 1992). The rapid warming (or DO event) generally takes place over a period of several decades and is of the order of 10oC at the North Greenland Ice Core Project (NGRIP) site (Kindler et al., 2014). These events occurred at a frequency of around 1,500 yr (Schulz, 2002), although this frequency is debated (Ditlevsen et al., 2007). They are followed by a slower cooling of the order of a hundred to a thousand years, and the cycle ends with a sudden cooling (Kindler et al., 2014).

Some of the stadials are accompanied by massive iceberg discharges from the Northern Hemisphere ice sheets in the North Atlantic Ocean, at a frequency of several thousand years (Heinrich, 1988; Bond and Lotti, 1995). The iceberg discharges are identified in marine sediment cores by one or several layers of ice rafted debris, the materials entrapped and transported by drifting ice (Bond et al., 1992; Bond and Lotti, 1995; Elliot et al., 1998). The iceberg discharges are referred to as Heinrich Events (HE) when the continental ice is originating from the Laurentide ice *sheet, the eastern part of the North American ice sheet. The Heinrich events mostly occur after several DO cycles and are followed by a DO event (Bond et al., 1993). Barker et al. (2015), through the examination of a site southwest of Iceland, suggested that massive iceberg discharges were a consequence of prolonged stadial conditions. It was suggested that massive iceberg discharges occur after an initial reduction of the Atlantic Meridional Overturning Circulation (AMOC) and the build up of a heat reservoir at the subsurface in the North Atlantic from both observations and modeling studies (e.g., Jonkers et al., 2010; Max et al., 2022; Mignot et al., 2007).”*

To date, there is no scientific consensus on the ultimate cause behind massive iceberg discharges. For instance, some studies suggest self-sustained ice sheet oscillations, while others propose a perturbation triggered by changes in ocean conditions. The focus of our study is to test the latter hypothesis, using a coupled ice-climate model, namely iLOVECLIM-GRISLI. We will add the three following sentences in the introduction to clarify this :

“Nonetheless, there is no scientific consensus on the ultimate cause behind the massive iceberg discharges to date. For instance, some studies have suggested that self-sustained ice sheet oscillations are at play (MacAyeal, 1993), while others propose that the discharges were triggered by an external forcing such as a change in ocean conditions (Alvarez-Solas et al., 2010). The focus of our study is to test the latter hypothesis, using a coupled climate-ice sheet model, namely iLOVECLIM-GRISLI.”

As explained in the introduction of the article (lines 26 to 42), it was suggested that a rise in subsurface ocean temperature during a stadial could have led to the ice discharges. However, previous modeling studies focusing on ice-ocean interactions in the context of massive iceberg discharges have relied either on an ice sheet model with oceanic forcing or on a climate model forced by a freshwater flux (hosing experiments). The novelty of our study lies in the use of a coupled model.

Previous studies using iLOVECLIM alone (Friedriech et al,2010) or GRISLI alone (Álvarez-Solas, 2011) have shown abrupt variations in ocean circulation or ice sheet discharges. However, in our setup, the iLOVECLIM-GRISLI coupling does not exhibit abrupt variations, neither in the ice sheets nor in the ocean circulation, under 40 kyr BP constant or transient forcings. This is why we conducted perturbation experiments at the interface. With the fully-coupled model, we can examine whether a perturbation at the interface is being amplified or dampened. We will add the following paragraph in the introduction to explain why we designed perturbation experiments.

“In our setup, the iLOVECLIM-GRISLI coupled model, under constant or transient forcings corresponding to the Last Glacial Period, does not exhibit abrupt internal oscillations, neither in the ice sheets nor in the ocean circulation. Therefore, in this study we chose to conduct perturbation experiments at the ice-ocean interface. With the fully-coupled model, we can examine whether a perturbation at the interface is being amplified or dampened.”

In this vein, I find the final sentence in the abstract hard to understand: what is it specifically that the presented results show, and what here is new, or how precisely does the study feed into an existing body of evidence? What is meant by ‘more accurately constrained mode results’? Constrained how and by what? And how/what would more accurate model constraints help with? Which ‘past changes’ or ‘future ice sheet behavior’ specifically are being referenced here? I’m not questioning the value of the study, but the framing needs clearer precision so that I understand precisely what message(s) to take away. That ice-ocean interactions are complex are reasonably well established with a very wide body of precise literature already.

The main point to take away is that, at the ocean-ice sheet interface, the feedback of freshwater release on ice sheet discharge is overall negative. This feedback sign was not obvious when we designed the experiments; in fact, we initially expected it to be positive. This would have implied that the ocean, through the activation of a positive feedback loop following an initial perturbation, would warm at the shelf drafts, leading to increased ice discharge – a mechanism that might have led to massive iceberg discharges of the Last Glacial Period.

As explained above, this study is motivated by our will to understand how the massive iceberg discharges during the Last Glacial Period could have been triggered by oceanic processes. More broadly, the study aims to explore interactions between ice sheets and ocean, regardless of the time period, such as a process study. In this context, the last phrase of the abstract (*"to enhance our understanding of past changes and the predictions of future ice sheet behavior and sea level rise"*) reflects the traditional goal of "understanding the past to better anticipate the future". However, we agree that this phrasing is too vague, we have removed this portion of the sentence to clarify the paper's focus and primary motivation.

By *"more accurately constrained model results"*, we were referring specifically to the last sentence of the conclusion (*"Lastly, our model can simulate ocean carbon isotopes (Bouttes et al., 2015), allowing for direct comparison with observational data from marine sediment cores and providing additional constraints."*). There were no specific constraints on the ocean to calibrate the coupled model. So, another idea for future model development is to focus on ocean conditions and calibrate the ocean with carbon isotopes.

To clarify this, we will replace the final sentence of the abstract by : *"This study highlights that the ocean-ice sheet interactions following an episode of subsurface warming may be characterized by negative feedbacks, thus dampening iceberg discharges. This emphasizes the need for further research using fully coupled models to explore the triggering mechanisms of massive iceberg discharges and to clarify the role of the ocean in these events."*

Specific points:

Introduction:

Is too short. It lacks detailed information on what is known about the processes of ice-ocean interactions, and at different scales, or what debates/known-unknowns/limitations exist within that topic. What is included is at a very large macro-level, but what are the important dynamics in grounding line-processes, and what about ice sheet cavity-scale processes in the ocean?

Thank you for this comment. We will add more information on the marine ice sheet instability to the introduction section describing ice-ocean interactions (lines 43 to 49) :

"Another positive feedback is the marine ice sheet instability, which is linked to the dynamics of the grounding line. The mathematical formulation of the ice flux at the grounding line suggests that this flux increases with the ice thickness (Schoof, 2007). When a marine-terminating ice sheet sits on an upward-sloping bed toward the ocean, an initial retreat of the grounding line causes ice thickening and acceleration of the ice flow at the grounding line, which in turn drives further retreat.

This process may have played a role in Heinrich events given the bedrock's shape at the Hudson strait mouth (Schoof, 2007).”

Feedback mechanisms arising from ice sheet-cavity scale processes are not represented in our model. In fact global cavity-enabled ocean models that include an interactive ice sheet model are currently being developed in the community but their applications are still limited to present-day climate (e.g. Mathiot et al., 2017). Cavities clearly play a role in the global ocean, but it is difficult at present to have a good picture of their related feedbacks. Nonetheless, following your advice, we have added the following in the introduction :

"Additional feedback mechanisms could emerge from ice sheet-cavity scale processes, such as tidal forcing or buoyancy-driven circulation beneath ice shelves (e.g., Makinson et al., 2011; Gwyther et al., 2016). For example, a rise in ocean temperature at the base of the ice shelves could enhance the meltwater production, thereby strengthening the circulation within a cavity, leading to an increased heat supply and further melting (Gwyther et al., 2016). However, uncertainties related to these processes remain large since very few cavity-enabled ocean models can operate at the global scale. For this reason and given our coarse resolution ocean model, we do not discuss the cavity recirculation feedbacks any further in this paper.”

Methods:

Is GRISLI an appropriate tool for addressing marine ice sheet interactions? From my background knowledge, I believe it is, but this is not clear from the manuscript. Further justification/evidence of this is needed.
Yes, GRISLI is an appropriate tool, we will add the following sentence to the Model and Methods :
“GRISLI is an appropriate tool to address ice sheet dynamics and interactions with the oceanic component as it explicitly calculates ice stream velocities, the position of the grounding line and the the behavior of ice shelves. For instance, GRISLI has shown a good ability to reproduce grounding line migrations and ice volume changes in Antarctica during the last 400 kyr BP (Quiquet et al., 2018,Crotti et al.,2022).”

Experiment design needs more justification/explanation, e.g.:

- Initial Condition section:

(a) Why 40 ka BP? Not enough to say it is relatively stable and precedes HS4 when no background is given on why this is important. There are other stable periods. What is HS4? Is LGM bathymetry appropriate? What is meant by ‘sea level forcing’?
Thank you for these questions. Heinrich stadials are now defined in the Introduction section (see above) and we will add the following sentences to the Initial condition section :

”We conduct a long coupled ice sheet-climate simulation under constant external forcing to derive the initial state. This approach assumes climate equilibrium, which is not realistic. However, the relatively small variations in greenhouse gas concentrations (GHG) and insolation at 65 °N around 40 kyr BP support the use of an equilibrium simulation for this specific time slice. Furthermore, this period aligns with Heinrich Stadial 4 (HS4), which extends from 39.85 to 38.17 kyr B.P. (Waelbroeck et al., 2019). ”

See **Figure R1** below for the evolution of the forcings. Thus, our 1000 yr long simulations following 500 yr long perturbations applied at 40 kyr BP may be compared to HS4 observations.

We will also add the following in the same section about the sea level forcing :

“The ice sheet model is forced with sea level reconstruction (-64 m at 40 kyr BP; Waelbroeck et al., 2002). The latter is only used in the GRISLI model to determine which areas of land are located above the sea level (i.e. where the continental ice can grow).”

As well as this consideration about the LGM bathymetry :

“However, since sea level and bathymetry at 40 kyr BP have intermediate value between the LGM and the Pre-Industrial (PI) values, we also test the sensitivity of the results to the Pre-Industrial bathymetry in the discussion section. Thus, two extreme bathymetry possibilities are investigated.”

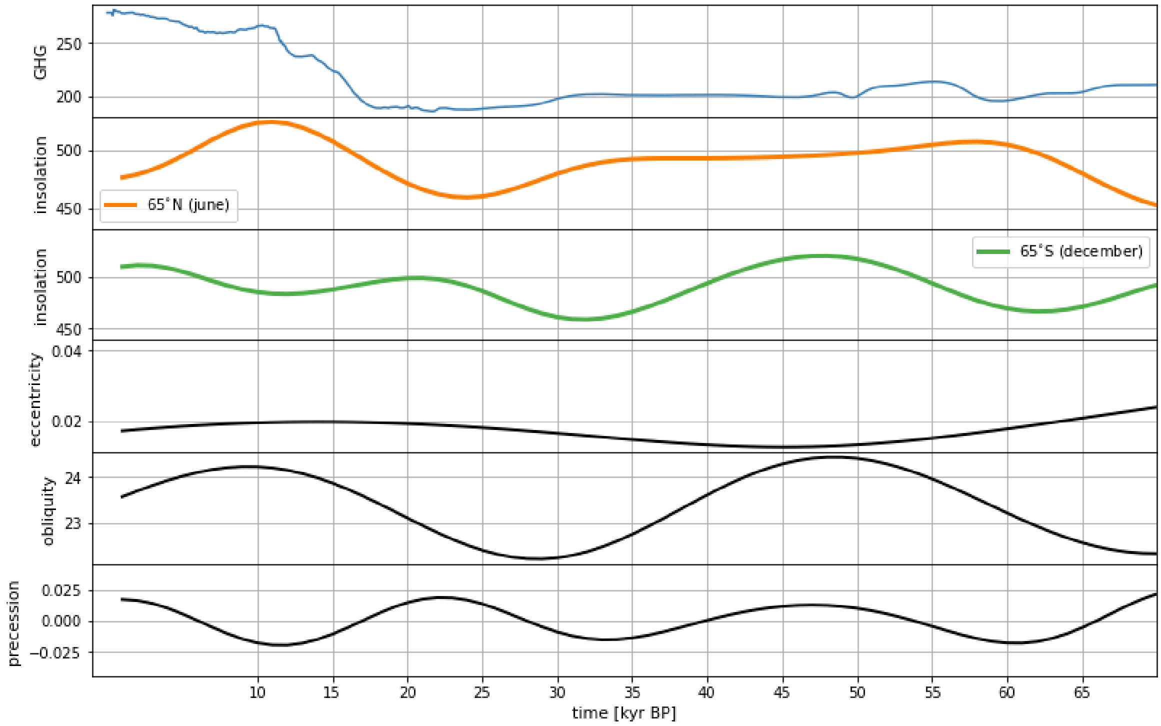

Figure R1 : GHG concentration (Lüthi et al., 2008), as well as insolation and orbital configuration forcings (Berger et al., 1978).

(b) Figure 1: shades of gray are hard to see

Thank you, we removed the shades of gray (**Figure R2**). We will also add shelf drafts and basal melt rates, following a comment of reviewer #1, so the new Figure 1 will be :

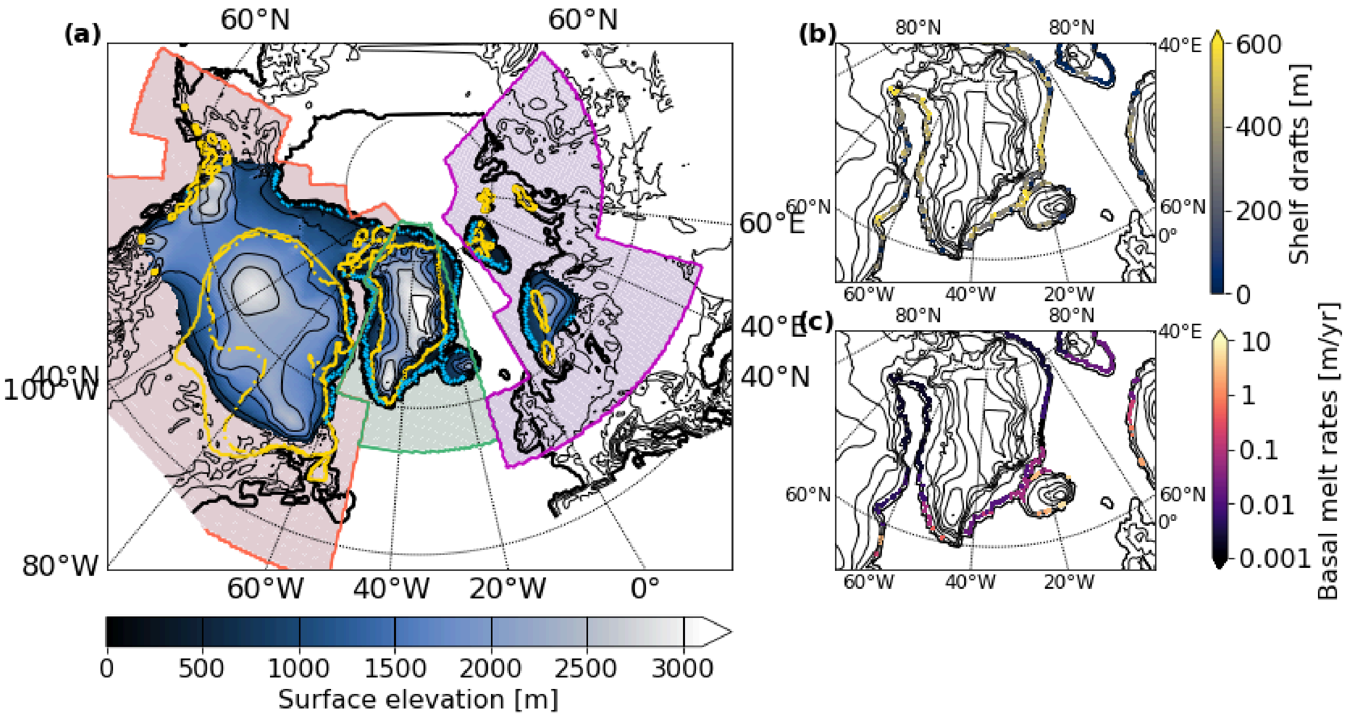

Figure R2 : 40 kyr equilibrium. Ice sheet elevation (shades of blue) [m] at the end of the equilibrium simulation. Light blue contour is the mean position of the grounding line at the same time. Yellow contours are the minimal and maximal ice sheets extent in the reconstruction from Gowan et al. (2021), these differ only over the central North American ice sheet. Areas used to derive regional ice volumes on Figure 2 are shaded in red, green and magenta for the North American, Greenland-Iceland and Eurasian ice sheets respectively. The black lines represent topographic contours at intervals of 500 meters. (b) Ice shelf drafts [m] and (c) basal melt rates beneath the shelves [m/yr] at the end of the equilibrium simulation.

(c) Line 117: ‘corresponds rather well to the extent of the reconstructed ice sheet.’ Not in my opinion, not for North American or Eurasia. Greenland also looks too large. I see big differences, and your total ice volume is (at most) almost twice as large as the reconstructed estimate. A more thorough and transparent assessment of agreement is needed here, AND a thorough and transparent discussion of what the reconstruction actually is – how certain/uncertain is that (where, when and why).
Thank you for this comment. We will replace the paragraph of the Initial condition section by the following :

“*We obtain a total volume of 24 million* km^3 *for the Northern Hemisphere ice sheets, which corresponds to 48 mSLE. In comparison, the reconstruction from Gowan et al. (2021) presents volumes of around 12 and 16 million* km^3 *for minimal and maximal scenarios, corresponding to 28 and 37 mSLE respectively. However, Gowan et al. (2021) acknowledge that their total ice sheet reconstructions for the period between 57 and 29 kyr BP (MIS3) do not align with proxy-based sea level reconstructions. Specifically, they estimate a global sea level that is 20 m higher (maximum scenario) than the reconstructed value of approximately −60 to -90 m at 40 kyr BP (Waelbroeck et al., 2002; Arz et al., 2007; Siddall et al.,2008).*
Also, the evolution of the Northern Hemisphere ice sheets remains uncertain prior to the Last Glacial Maximum. Reconstructions often rely on inverse methods that use observational data and estimates of global mean sea level, sometimes supported by numerical ice sheet modeling (e.g.;

Marshall et al., 2000; Kleman et al., 2010; Gowan et al., 2021; Pico et al., 2018; Dalton et al., 2022b). Significant discrepancies exist between the different reconstructions. For example, the question of whether the Hudson Bay area was glaciated around 40 kyr BP and to what extent remains debated (e.g.; Batchelor et al., 2019; Miller and Andrews, 2019). Given these uncertainties, we conclude that our simulated ice sheet volume falls within an acceptable range for the 40 kyr BP time slice."

- Perturbation experiment:

(a) why did you drop the acceleration and move to 1:1 run speed for both models?
The acceleration is only used for the spin up simulation, in order to equilibrate ice sheets with the climate, as the ice sheets take a long time to adjust, which is too computationally expensive in real time. For example, the 8,000-year simulation would have run for around 20 days with the 1:1 speed.

(b) What does the applied range in basal melt amplification factor correspond to in a non-technical (model) sense, i.e. in the real world? How was the range determined? How is it justified?
We agree that the experiment design should be better explained. Thank you for pointing this out. We will add the following paragraphs in the Perturbation experiment section :

"*This scaling (X) of the basal melt is equivalent to imposing a temperature anomaly, that depends on the water masses and background state of the ocean, at the shelf drafts. Specifically, we apply a perturbation whose intensity is proportional to the local temperature anomaly with respect to the freezing temperature, T_f.*

Indeed, when $T > T_f$, adding a perturbation term δT to T, defined by $\delta T = \mathcal{E}(T-T_f)$ (with $\mathcal{E}>0$) leads to the following oceanic basal melt rate : $OBM=\gamma_T A(T+\mathcal{E}(T-T_f)-T_f)^2 = \alpha(1+\mathcal{E})^2(T-T_f)^2$. And we rewrite $X=(1+\mathcal{E})^2$. So there is a direct correspondence between X and the temperature anomaly intensity $\mathcal{E}$ seen by the ice shelves. For example, a doubling of the temperature anomaly to the freezing point corresponds to $\mathcal{E} = 1$ and $X = 4$. A 10 time increase of the temperature anomaly corresponds to $\mathcal{E} = 9$ and $X = 100$.

This way, the perturbation experiments aim to represent an increased heat flux to the ice shelf drafts, reflecting subsurface ocean warming in the North Atlantic during a Dansgaard-Oeschger stadial (e.g., Rasmussen et al., 2004). The perturbation experiments were designed to be spatially consistent with the physics of the water masses. For instance, our design allows us to account for the fact that an abrupt change in AMOC likely leads to temperature changes in the AMOC's main areas of influence, rather than a uniform temperature change over the North Atlantic and Nordic Seas."

The range for X was determined empirically when we applied this method to perturb the ice sheet dynamics.

(c) Are there implications for applying the subsurface warming perturbation as a basal melt amplification factor for the response of the ocean to the resultant freshwater flux? i.e. the thermal profile of the ocean does not have subsurface warming, initially, so what does this mean for the ocean structure/stability (in terms of buoyancy profile and perturbation), both in terms of the initial ocean condition (including convection) and the response of the ocean to ice sheet freshwater fluxes? This also needs revisiting in the results/discussion.

The ocean model simply adjusts its temperatures and salinity in response to the freshwater input, with associated impacts on the density profile, vertical convection and hence ocean circulation.

Initially the thermal profile of the ocean does not have subsurface warming, the ocean structure at year (before the perturbation is triggered) is the same in the control simulation and in the perturbation experiment, as both simulations are branched on the same spin-up simulation (**Figure R3**a,b).
When the perturbation is triggered, the ocean temperatures and salinities vary, which can modulate the perturbation in the vicinity of the ice shelves.

For instance, the Labrador Sea is a convective area. The initial scaling of the basal melt leads to freshening and cooling of the near surface, while the subsurface (~300 m) warms. The vertical density gradient increases, so does the stratification. After some time, convection resumes (See for instance Figure S6 from the Supplementary Materials).

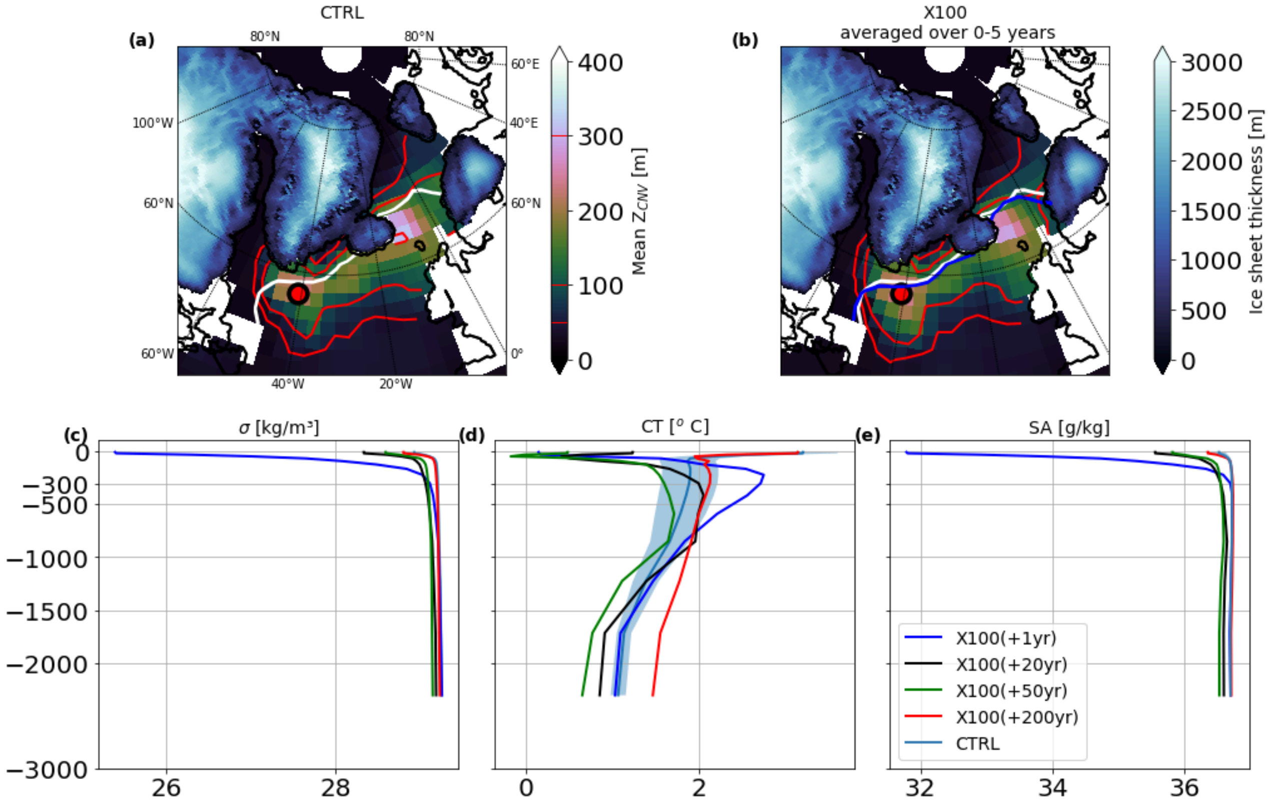

Figure R3 : Convection depth [m] (a) averaged along the CTRL simulation and (b) averaged over 0-5 years in the perturbation experiment with X = 100. (c,d,e) Profiles of density [kg/m³], ocean temperature [°C] and absolute salinity [g/kg] in the CTRL and in the perturbation experiment with factor X = 100 at different times after the perturbation is triggered. Blue shading corresponds to one standard deviation of the CTRL simulation. The location of the profiles is the red dot on (a,b). On (a,b) red contours are 100 and 300 m isocontours of mean convection depth, white and blue are the 30% sea ice extent for the CTRL and for the first 5 years of the perturbation experiment with X = 100.

We will add the three following italicized sentences to the last paragraph of the Perturbation experiments section (lines 130 to 132) in order to clarify these aspects :

From the ice sheets point of view, increasing the oceanic basal melt rates is equivalent to imposing a subsurface warming yet this has no effect on initial ocean temperatures. *“Initially, the ocean structure is the same for the control and perturbed experiments, as the simulations are branched on the same spin-up simulation.”* Since we use a coupled model setup, the ice sheet retreat induced by the perturbation impacts the ocean through the resulting freshwater flux. *“The ocean model simply adjusts its temperatures and salinity in response to the freshwater input, with associated impacts on the density profile, vertical convection and hence ocean circulation. Thus, the ocean model response can modulate the perturbation in the vicinity of the ice shelves.”*

Results:

- How well are the ice streams depicted in the model? This may also be a question about model ability, or resolution. The ice velocity maps show a wide splurge of acceleration in ice velocity, but I’m struggling to pick out many streams (with the few exceptions mentioned at the bottom of page 6). Please assess and comment (critically) on this in the revised manuscript.

Thank you for this comment. The velocities are smoothed over the topography in comparison with higher resolution models, yet GRISLI does a reasonably good job in depicting the main streams. The smoothed patch for velocities might come from the colormap we are using, see **Figure R4** below, with a different colormap and a linear colorbar.

At the LGM, the modeled ice sheet reproduces the major features of the ice streams of the North American ice sheet. Following the nomenclature from Margold et al., (2015) around the Baffin Bay the Hudson Strait ice stream at 60°N, some minor streams at the location of the current Baffin Island, the Lancaster Sound ice stream and the Nares Strait ice stream are depicted. To the north, the Kennedy-Robenson Channel at 50°W, the Nansen Sound (between 80-100°W) are also represented. Further west, there is a sluggysher patch corresponding to the Massey Sound and Prince Gustaf Adolf Sea ice streams. Between 120 and 140 °W, the M’Clure Strait and Amundsen Gulf ice streams are depicted (**Figure R4**a,b,c). To the south of the North American ice sheet, on the contrary, there are no well-identified ice streams.
The representation of the ice streams is quite similar at 40 kyr BP in our model (**Figure R4**d,e,f).

We will add the following sentences to the main text :

“Despite its low resolution (40 km), GRISLI is capable of representing large-scale features such as major ice streams at the LGM (e.g., Quiquet et al., 2021). The major ice streams remain present at 40 kyr BP. These include the Hudson Strait, the Lancaster Sound and Amundsen Gulf ice streams for example (nomenclature follows Margold et al., 2015). To the south of the North American ice sheet, on the contrary, there are no well-identified ice streams.”

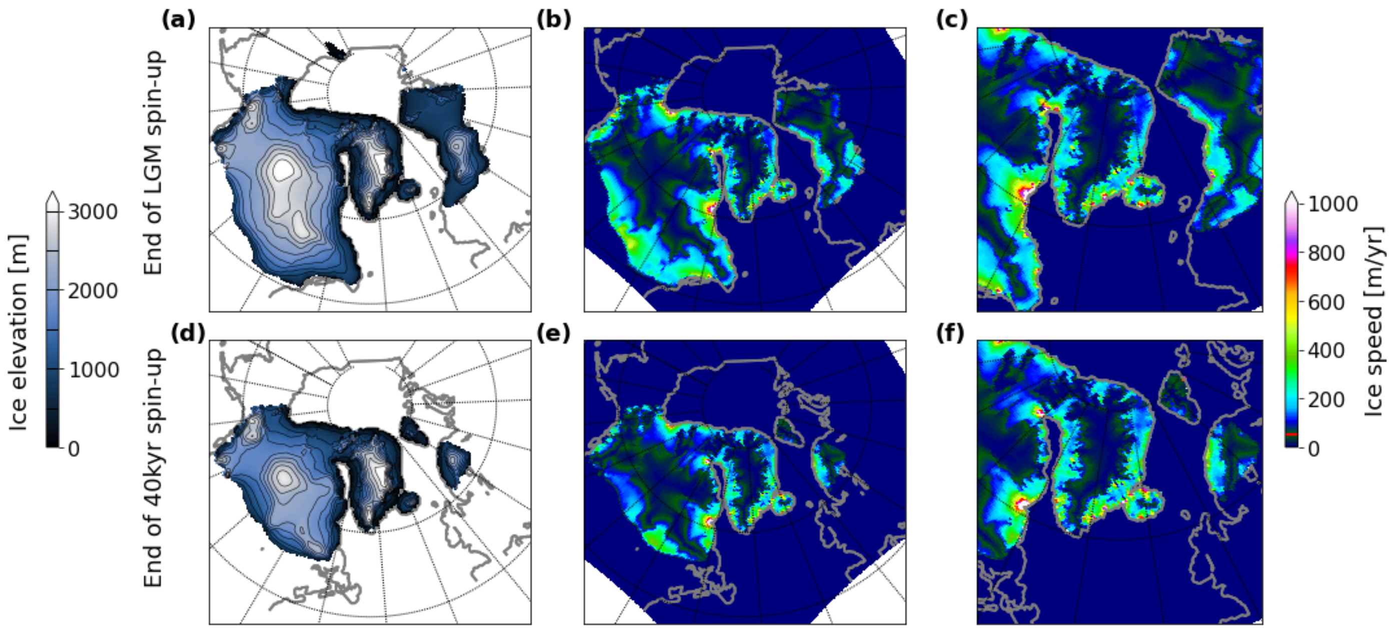

Figure R4: Ice sheet elevation above sea-level [m] modeled (a) at the LGM and (b) at 40 kyr BP. Ice speed [m/yr] (b) at the LGM and (e) at 40 kyr BP. (c,f) are zooms of (b,d).

- page 8 (around line 175) – yes, but we come back to the question of what 'X >= 100' actually means in real-world terms. What does this equate to in terms of subsurface warming/ocean structure change to drive the ice sheet change? This needs relating back to real conditions, rather than simply technical model components, to offer genuine insight for understanding the ocean-ice interaction.

Thank you for pointing this out. Please see our response above to your first comment on this subject. This sentence will be modified into :

"Together with positive anomalies of the surface mass balance to the south, this contributes to the small thickening of the North American ice sheet for experiments with at least a 10 time increase of the temperature anomaly, with respect to the freezing temperature, at the shelf drafts (i.e. X ≥ 100 ; Figure 2)."

- Line 181: ice sheet stabilizing mechanisms such as…? Please diagnose and include these, and then relate them to the real world.

Thank you for your comment, we will replace this sentence by the following ones :

This results in a freshwater flux that decreases with time (but remains significant). *"This decrease is partly attributed to the reduced ice volume exposed to basal melting as ice shelves thin or vanish in certain regions, such as Svalbard and Iceland. It also suggests the presence of ice sheet stabilizing mechanisms within the model, that is, a negative feedback that mitigates ice volume loss. Here, this feedback involves a decrease of the temperature at shelf drafts, which in turn reduces the basal melt rates."*

- Figure 5: sparks the question, what should the conditions be for these depicted metrics (based on the real, past world)? Needs showing/discussing as part of analysis.

Also, can differences in timings/temporal evolution of the different variables plotted be highlighted and explained.

Thank you for this question. We will comment on this in the revised manuscript :

“For most of these metrics, there are no past estimates available. Greenland temperatures at the NGRIP sites is the only exception (Kindler et al., 2014). At this location, the authors obtain around -40 to -45 °C around 40 kyr BP, while we simulate warmer temperatures around -35 to -40 °C. Paleoproxy records show that the AMOC was in a much lower regime during stadials than interstadials but do not provide quantitative estimates in Sv (Gottschalk et al., 2015; Henry et al., 2016, Waelbroeck et al., 2018).”

Following your comment, we went a bit further in the temporal evolution/timings analysis between the different variables.

Considering times series with 21 years centered running mean, the maximum changes for the sea ice extent ($+10^{12}$ km^2 in comparison with the control), the AMOC (−5 Sv), the NGRIP (−0.53 oC) and Northern Hemisphere (−0.49 °C) temperatures are reached after 14, 18, 21 and 33 years for the experiment with perturbation factor of 100, for instance. Differences in timings of the different variables are difficult to establish as the times series are noisy.

Considering the smoothing of 21 years and normalized time series, the maximum lagged correlation between the AMOC and sea-ice extent is $r = -0.91$ ($p < 0.05$), with the AMOC reduction lagging behind the sea ice extent increase by 4 years. The AMOC change lags behind Northern Hemisphere temperature change by 3 years ($r = 0.92$) and behind NGRIP temperature by 5 years ($r = 0.70$; both with $p < 0.05$). Northern Hemisphere temperatures lag behind NGRIP temperatures by 3 years ($r = 0.84, p < 0.05$). See **Figure R5** below.

However, the lagged correlations may not be relevant here as the time series are still noisy even with the running mean of 21 years. Lags are all zero when applying a larger smoothing of 51 years (before normalizing), or when restricting the calculation to the first 200 years after the perturbation is triggered.

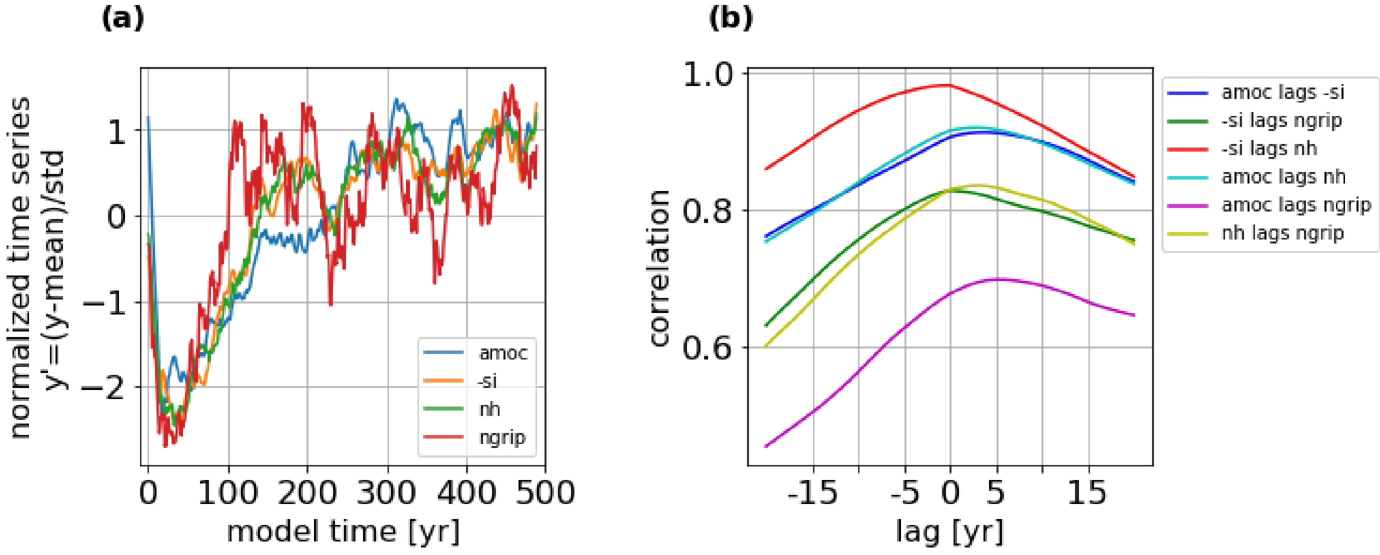

Figure R5 : (a) Normalized time series of the smoothed (blue) amoc, (orange) sea-ice extent, (green) Northern Hemisphere and (red) NGRIP temperatures with 21 years running mean (centered). (b) Correlations between time series for different lags [yr] (see figure legend). Lags are positive and leads are negative.

We will also replace lines 192 to 194 by the following :

“*The maximum changes for the sea ice extent (+10^{12} km² in comparison with the control), the AMOC (−5 Sv), the NGRIP (−0.53 °C) and Northern Hemisphere (−0.49 °C) temperatures are reached after 14, 18, 21 and 33 years respectively for the experiment associated with a 10 times increase of the temperature anomaly at shelf drafts (i.e. X=100 ; Figure 5).*“

Line 204-206: can this be tested? What would you need to do to verify?
For simplicity, here is our detailed answer to reviewer #1 on this point.

More freshwater is added locally in the perturbed experiment than in the ctrl run at the end of the simulations (**Figure R6**), so our suggestion was wrong.

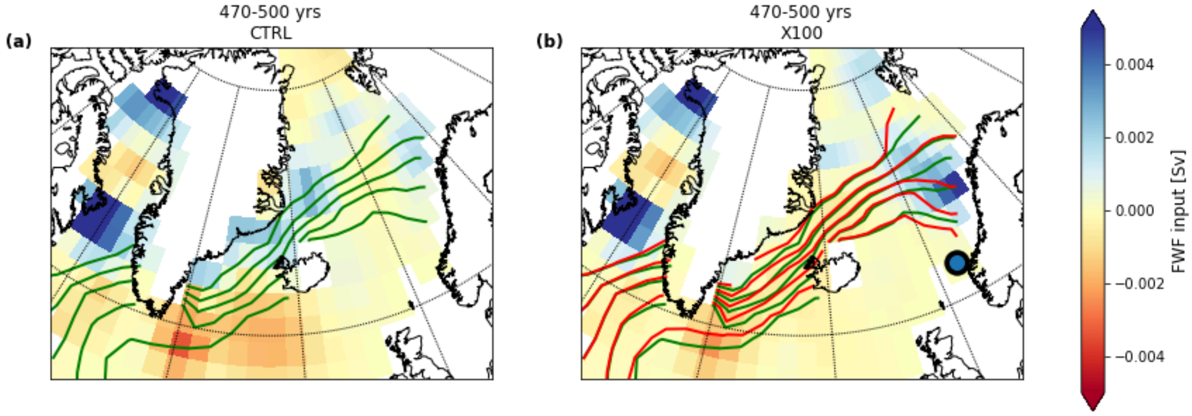

Figure R6 : Freshwater input [Sv] to the ocean model and annual sea-ice contour corresponding to 5,20,40,60 and 80% averaged over 470-500 years for (a) the control experiment and (b) the perturbation experiment with factor X=100.

We see that along the perturbation period, the yearly sea ice cover remains 0 after ~100 years. We also see that the temperature and salinity differences with the control occur over the whole water column at the chosen location (not only near the surface ; **Figure R7**).

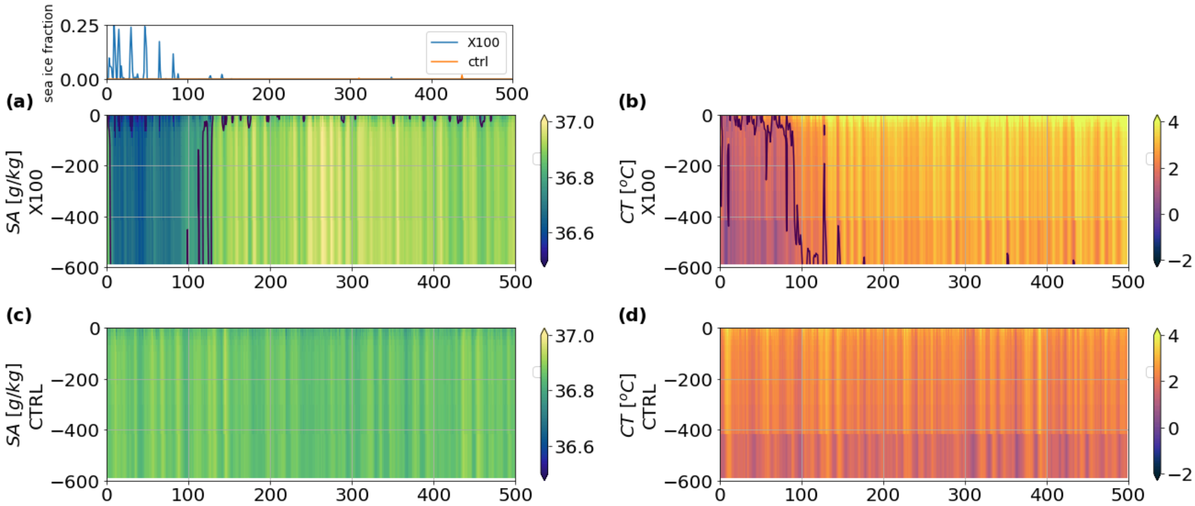

Figure R7 : Hovmoller diagrams for the profile whose location is the blue dot in Figure R6b. Absolute salinity [g/kg] and conservative temperature [°C] (a,b) for the perturbation experiment with factor X=100 and (c,d) the control simulation.

This led us to realize that the positive salinity and temperature anomalies, described lines 204-206, actually result from a resumption of the AMOC and renewed influx of heat and salt of Atlantic origin following the period of maximum AMOC slowdown. As we can see on the **Figure R8** below (that is the same as Figure 7 of the main text but with salinity anomalies included), the area of positive salinity anomaly at the end of the experiment is located not only at the surface but also at the subsurface along the Atlantic Water pathway.

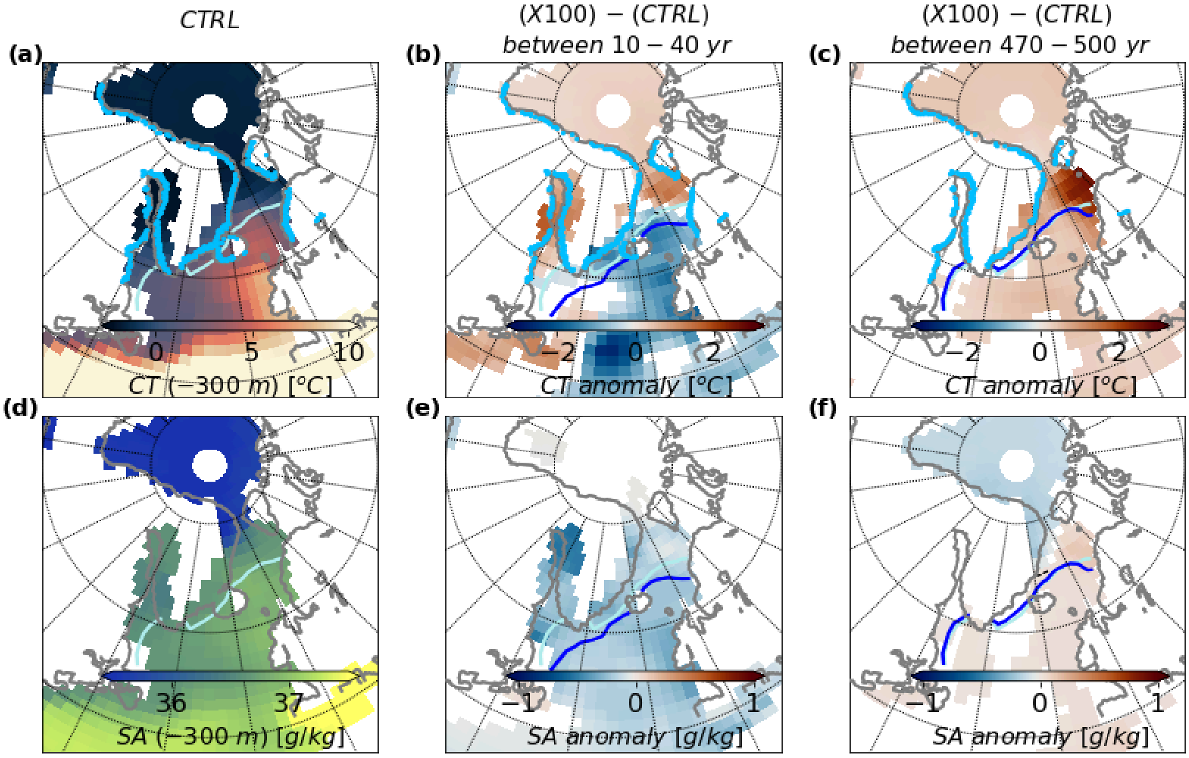

Figure R8 : Conservative temperature [°C] at 300 m depth horizon, (a) averaged over the control experiment, and associated anomaly between the perturbation experiment with X=100 (b) over 10-40 yrs and (c) over 470-500 yrs and the control. (d,e,f) Same for the absolute salinity [g/kg].

This will be corrected in the revised manuscript, thank you for your comment. The revised sentence reads :

"*The positive anomalies therefore suggest a resumption of the AMOC and renewed influx of heat and salt of Atlantic origin following the period of maximum AMOC slowdown.*"

Discussion:

- Section 4.1: is your model too stable? Or is your model correct? How do you make this assessment? How might inaccuracies in your simulation affect this result? Is It limitations with dynamical ice sheet process simulation that make the model too stable, biases in simulated climate (atmosphere or ocean), uncertainty in other boundary conditions/forcings, differences in palaeogeographies, issues of resolution, or are the palaeo data simply misinterpreted or overly generalised?

Thank you for these comments. We have evidence suggesting that the Hudson ice stream might have been very dynamic during the LGP, producing episodic large iceberg releases. Since our model does not reproduce this, even under large oceanic perturbations, we can assume that our model is too stable. This can come from ice sheet dynamical parameters and spatial resolution and/or climate biases (atmosphere and ocean). In particular, iLOVECLIM presents a warm atmospheric bias in North America that produces homogeneous temperate basal conditions (weak horizontal stresses). There is also a cold bias in the ocean in the Baffin Bay (**Figure R9**) that induces low thermal forcing in this area.

We will rephrase the beginning of this Section 4.1 as follows :

"On the one hand, the ice sheets in the fully coupled model may be too stable. This could stem from the basal drag formulation, parameter values and spatial resolution. But it could also come from biases in the climate model, in the atmosphere (warm bias producing homogeneous temperate basal conditions) or in the ocean (low thermal forcing in the Baffin Bay).

On the other hand, we have pointed out that background temperatures are rather cold at the shelf drafts and salinity is low in the Baffin Bay and adjacent Labrador Sea in comparison with the same latitudes in the eastern part of the North Atlantic. Background oceanic basal melt rates are thus lower (around 0.003 m/yr) at the mouth of the Hudson ice stream in the control simulation than around the Fennoscandian ice sheet (around 0.3 m/yr). Therefore, in our simulations, the oceanic perturbation imposed by subsurface temperature amplification at the shelf drafts is not able to destabilize the North American ice sheet/streams even with the highest multiplicative factor.

Inaccurate representations of the ocean circulation or hydrography may contribute to underestimated ocean temperatures in the Baffin Bay area at 40 kyr BP. Such inaccuracies might come from the model low resolution (resulting in the misrepresentation of recirculation patterns for example) or from underestimated processes, such as the sinking of brines in the Southern Ocean, which could alter the meridional overturning circulation in the Atlantic (Bouttes et al., 2010). Improving the ocean representation is a key objective for future works. Indeed, our model can simulate carbon isotopes (Bouttes et al., 2015), allowing for direct comparison with observational *data from marine sediment cores. This could serve as a constraint to improve ocean representation in subsequent studies."*

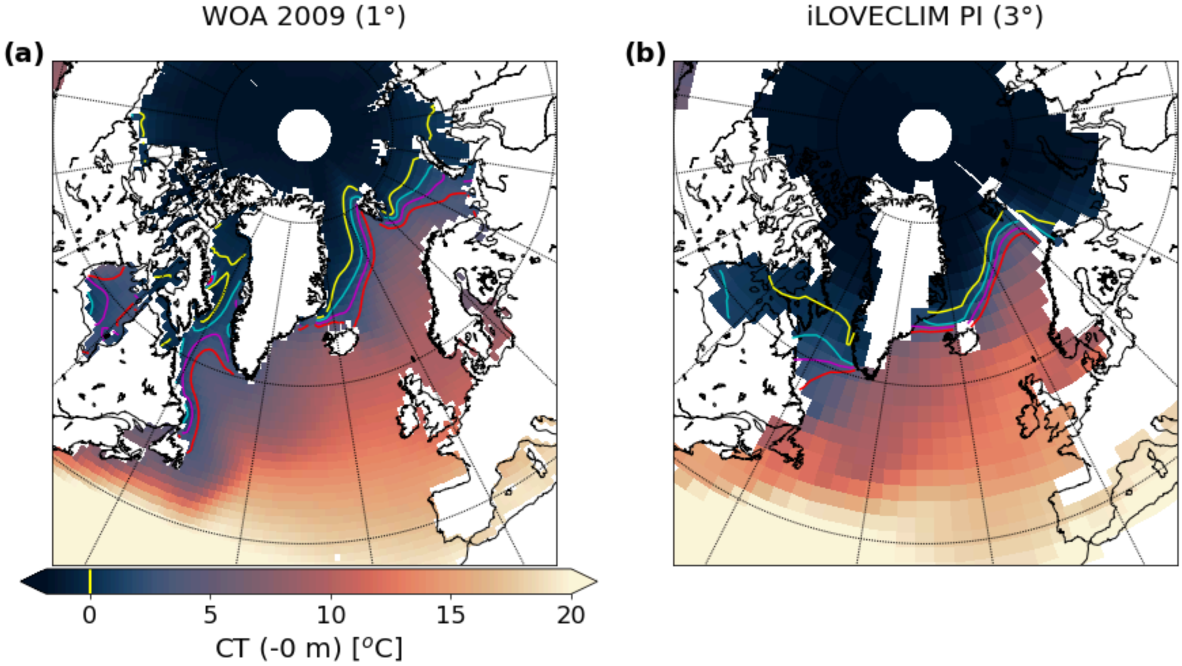

Figure R9 : Surface (a) conservative temperature from the World Ocean Atlas 2009 (1° x 1° spatial resolution), and for (b) iLOVECLIM Pre-industrial set-up (3° x 3° spatial resolution). Yellow, cyan, magenta and red contours are respectively 0, 1, 2 and 3 °C isocontours.

- Line 302: 'sensibly', how and why (i.e. caused by what)?

Since all other parameters remain constant, the differences between the two ice sheets arise from variations in bathymetry. Different bathymetries produce different ocean currents and advection patterns of heat and salt, resulting in different distributions of water masses (**Figure R10**). Furthermore, with the PI bathymetry, salinity is reduced because the salt content, that is the same as in the LGM, is more diluted due to the larger number of oceanic grid points. For instance, Barents and Kara Seas are present in the PI bathymetry (dark purple on **Figure R10**).

The primary differences between the two simulated ice sheets are observed around the Nordic Seas. With the PI bathymetry, the Fennoscandian ice sheet is smaller, while the Svalbard region shows a larger ice extent compared to the LGM bathymetry. Additionally, the southern extent of the Greenland ice sheet is reduced and the North American ice sheet reaches lower latitudes on its eastern side under the PI bathymetry.

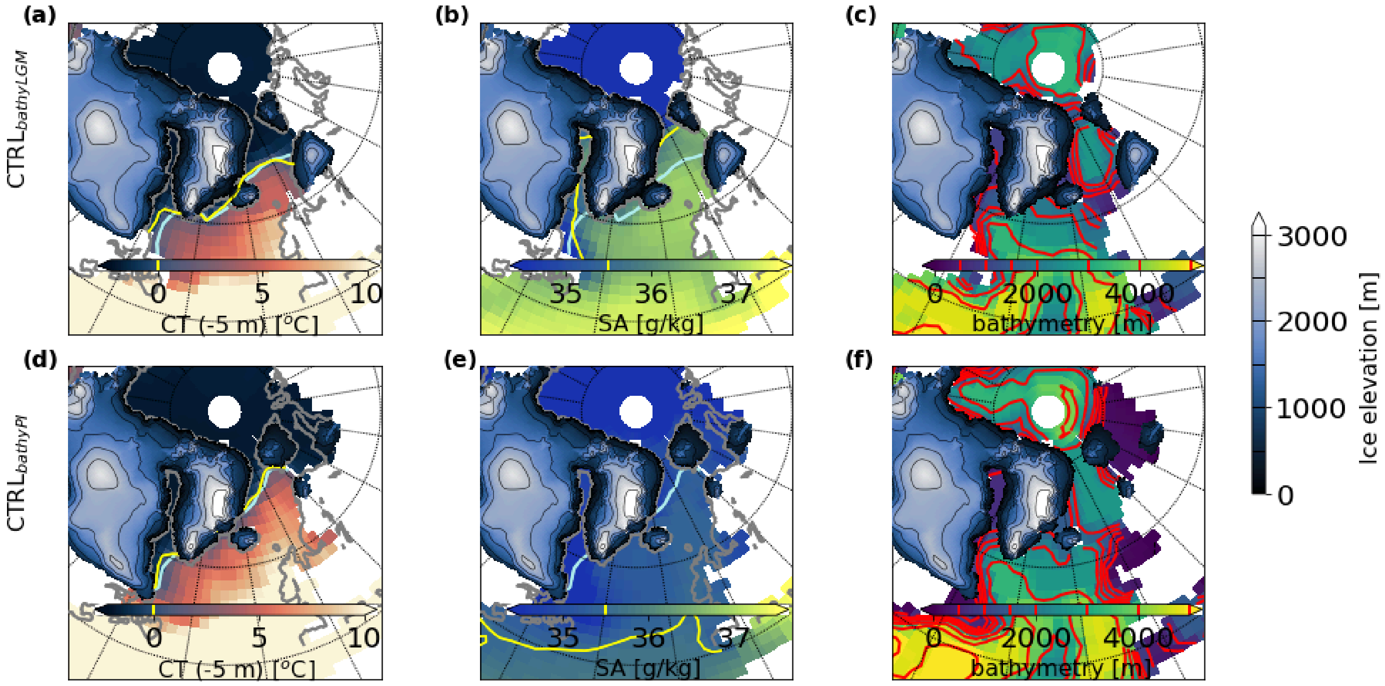

Figure R10: Maps of (a) conservative temperature [°C] and (b) absolute salinity [g/kg] near the surface, (c) bathymetry [m] together with ice sheet elevation [m] (shades of blue) for the control experiment with LGM bathymetry. (d,e,f) Same with the PI bathymetry.

Thank you for your comment. We will add the following sentence to comment on that :

"The LGM and PI bathymetries produce different ocean currents and advection patterns of heat and salt, resulting in different distributions of water masses. Therefore, changing the bathymetry also produces a change in the ice sheet's geometry, leading here to a reduced volume of about 22 million km^3 (44 mSLE). Differences in continental ice distribution include a North American ice sheet that reaches lower latitudes on its eastern side and a Fennoscandian ice sheet of smaller extent. Additionally, the PI bathymetry also leads to a reduction of the southern-east extent of the Greenland ice sheet."

- Line 310: doesn't quite follow. What results in the greater anomaly? Simply that the model started with a smaller ice sheet? But that doesn't mean it will lose the same amount, it might lose less because less ice is in a vulnerable state with respect to your forcing. Line 311 doesn't make sense (in terms of English) – how can you compare LGM bathymetry with AMOC change? This all needs expanding, explicitly, the whole paragraph; too much is brushed over.

Thank you for your comment. We realize that this paragraph was not very clear. In this subsection, we have tried to refine the analysis using a different bathymetry. We did the same diagnosis but with a Pre-industrial bathymetry, as the 40 kyr BP bathymetry lies somewhere between LGM and PI bathymetries.

As explained above, different bathymetries produce different distributions of water masses as well as different ice sheet's geometries (**Figure R10**). Both these changes could lead to a different response of the coupled model to the oceanic perturbation experiment.

Due to the differing geometries and ice exposure to warmer waters in the Nordic Seas and in the Labrador Sea, the regions experiencing volume losses are not identical when we amplify the basal melt rates. This produces a difference in the amount of freshwater input to the ocean following the onset of the perturbation, though the difference with respect to the previous bathymetry is relatively small. The key climate variables (sea-ice extent, AMOC, Northern Hemisphere and NGRIP temperatures) follow similar trajectories to those obtained with the LGM bathymetry (Figure 5 of the main text and **Figure R11**).

Although we could expect a change in the fully coupled model response to the oceanic perturbation, following the change in bathymetry and distribution of the water masses, this is not the case here. The evolution of the feedback factor is also similar to what we obtained with the LGM bathymetry.

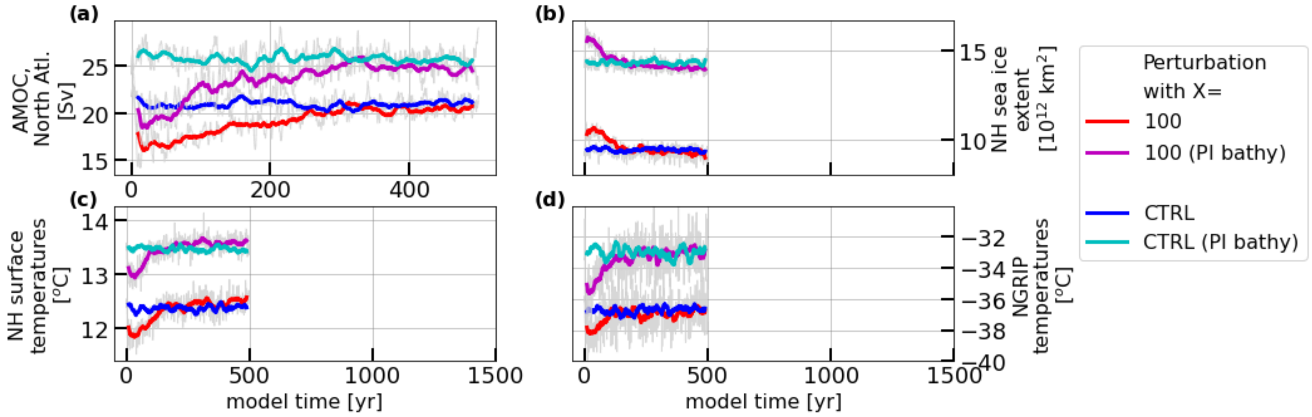

Figure R11: Same as Figure 5 in the main text but with the addition of the PI configuration.

We will rephrase the three final paragraphs (from line 305 to 320) as follows :

"Due to the differing geometries and ice exposure to warmer waters in the Nordic Seas and in the Labrador Sea, the regions experiencing volume losses are not identical when we amplify the basal melt rates. The Greenland ice sheet loses significant volume along its southeastern coast, particularly at the beginning of the experiment with a large perturbation factor (X=100). The Eurasian ice sheet still experiences substantial losses in its northern regions. The Laurentide ice sheet undergoes dynamical thinning with this geometry, but these losses are mostly confined to its southeastern region, where it is exposed to warmer waters. This produces a relatively small difference in the amount of freshwater input to the ocean following the onset of the perturbation, with respect to the experiment performed with the LGM bathymetry. The key climate variables (sea-ice extent, AMOC, Northern Hemisphere and NGRIP temperatures) follow similar trajectories to those obtained with the LGM bathymetry.

Although we could expect a change in the fully coupled model response to the oceanic perturbation following the change in bathymetry and distribution of the water masses, this is not the case here. The evolution of the feedback factor is also similar to what we obtained with the LGM bathymetry."

- Section 4.3: what about atmospheric dynamics? What are the model limitations? What is shown in the existing literature? How might your model representation affect your results? Is any of this relevant (and if not, why not)? We also come back to the comment above on model performance

(point c on experiment design) – is that a relevant feature for this discussion section?
We thank you for this remark. We will add the following paragraphs at the end of Section 4.3 :

"The atmospheric circulation was not a primary focus of this study, yet biases in the atmosphere model could also influence the ice sheet's volume variability and could be invoked to explain the absence of a DO-like event following the release of the perturbation. Climate biases have been assessed for the pre-industrial climate by Quiquet et al., (2021) : there is an overall cold bias around the Nordic Seas sector, Greenland and Fennoscandian ice sheets, with underestimated precipitation. In contrast, there is a relatively warm bias over North America, with underestimated precipitation except in mountainous areas where it tends to be overestimated (Quiquet et al., 2021). While it is unclear how these biases are translated at 40 kyr BP, they could affect the ice sheet's ability for regrowth and modulate the rate of its volume decay.

In addition, previous studies using the iLOVECLIM model have shown its ability to simulate abrupt temperature increases at the NGRIP site (~ +5 °C) associated with a significant rise in AMOC strength (~ +15 Sv) (Quiquet et al., 2021b, Figures 3 and 6). This suggests that, in our study, it is rather a lack of AMOC variability that prevents sudden warming after the perturbation is halted."

Conclusion:

I very much like this section, tight and punchy. You may want to revise/add to it following revisions in response to some of the comments above.
Thank you, we have not modified it.

Grammatical points/typos:

Line 93: 'Were' -> 'Where'
Line 106: 'present' -> 'presents'
Line 124 'experiment' -> 'experiments'
Line 144: 'Eurasian ice sheet …' or 'Eurasia and Greenland…regain ice mass'.
Line 144: 'North American ice volume'
Line 153: 'Upstream from the'
Line 163: 'thickness decrease' -> 'thinning'?
Figure 6: update units on panels to match caption

Line 202: 'subsists' -> not sure this is the correct term to use here.
Line 213: remove first three 'the's (leave the fourth)
Line 229: 'allows us to highlight'
Line 252: 'there is less loss' or 'there are fewer losses'
Line 273: 'pointed out'
Line 292: needs rewording to improve the English
Line 298: 'terminating'
Line 314: 'at the beginning'
Thank you for pointing out these typos, they will be corrected.

Figure 10: Is there a problem with the rendering of the LGM line? I can't see it before ~250 yrs in the plot.
No, as indicated in the figure caption, the values are plotted only when the ice volume variation is

above a critical value of 0.25 10^{14} m^3 to avoid ‘division by 0’ in Equation (3) as the grounded ice volume variations are not significant in the beginning of the simulations.

Thank you for all the comments and questions,

Louise Abot, on behalf of all co-authors.

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