Detailed response to Reviewer #1's comment

General comments

In the paper the authors present results from simulations of a coupled climate-ice sheet model exploring the interaction between ice sheets and the ocean during glacial times. In particular they apply different scaling factors to the basal melt rate and investigate the resulting ice sheet model response. The coupled climate model further allows them to explore the subsequent impact of the ice sheet meltwater input on the ocean state and its feedback on ice sheets. They show that scaling the basal melt rate generally results in a decrease in ice sheet volume, which is more pronounced for the Fennoscandian and Greenland/Iceland ice sheets than for the Laurentide ice sheet. The freshwater input results in an AMOC weakening, sea ice expansion and cooling and provides a negative feedback on ice sheet retreat.

The paper is generally well written and clearly organized. However, I have some comments that should be addressed before the paper is suitable for publication.
Thank you for your careful reading and the time you have spent reading and commenting on the manuscript.

Major comments

I'm missing some more guidance in the interpretation of the experimental setup and how the experiments are related to the real world. What are the simulations trying to represent? Is it trying to explain the climate-ice sheet response to something like DO or Heinrich events?
Thank you for these questions. Indeed, in the literature of the last decade, it has been suggested that oceanic temperature variability in the Atlantic (driven by oceanic circulation change for instance) may be a trigger for massive iceberg discharges and Heinrich events (e.g. ; Alvarez-Solas et al., 2010, 2013, Barker et al., 2015). So, the perturbation we apply aims to mimic changes in the heat supply to the ice shelves and how it could have led to massive iceberg discharges during the last glacial period (here at 40 kyr BP).

This theory has not been verified with fully coupled models that include an ice sheet component, while there could be potentially large feedbacks on ice loss arising at the interface that are due to the release of freshwater. Fully coupled models are useful to capture the feedbacks between components and the iLOVECLIM climate model coupled with the ice sheet model GRISLI is such a model.

The ocean-driven ice sheet changes might come from internal oceanic oscillations (e.g. salt oscillator). However, in our setup, we do not have self-generated oceanic oscillations in our simulations, under constant 40 kyr external forcings but also under transient 40-20 kyr forcings. This is why we designed experiments with amplified sub-shelf melt perturbations. We wanted to test how the ice sheet dynamic, in the fully coupled model, can be perturbed by the ocean, as well as the signs of the feedbacks at the ice sheet-ocean interface within the model.

We agree that the context was not well highlighted. We will emphasize the massive iceberg discharges framework in the revised manuscript by adding the two following paragraphs in the Introduction section :

"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)."

We will also explain with more details the experimental setup and how experiments are related to the real world by adding the following explanations to the corresponding 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 with respect 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. "

What is the increase in basal melt intended to represent? Subsurface warming during DO stadials? Why is basal melt increased instantaneously?
Thank you for these comments. We will complement the Perturbation experiment section by adding the following sentence :

"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 (DO) stadial (e.g., Rasmussen and Thomsen, 2004)."

We have chosen to increase the basal melt instantaneously, as this seemed to be the most direct way to evaluate the sign of the feedback and to maximize the ice sheet response to the perturbation. Proceeding differently did not seem to serve the purpose any better at this stage of the study. We will also add a sentence to comment on that :

“Here, we amplify the basal melt rates instantaneously as this seems to be the most direct way to maximize the ice sheet response to the perturbation and to evaluate the sign of the feedbacks at the ice-ocean interface.”

However, we took good notice of this question and ran another set of experiments, with a gradual increase in basal melt rates rather than an instantaneous increase (**Figure R1**b). This way, the ice volume decrease is delayed and smoothed at the beginning (see for example the time derivatives around yr = 0 on **Figure R1**a, Greenland-Iceland or Eurasian) in comparison with the previous experiment (grey versus orange lines on **Figure R1**). Thus, less freshwater is brought from the continent toward the ocean and in a less abrupt manner. Therefore AMOC response to such a perturbation is also dampened (**Figure R1**c).

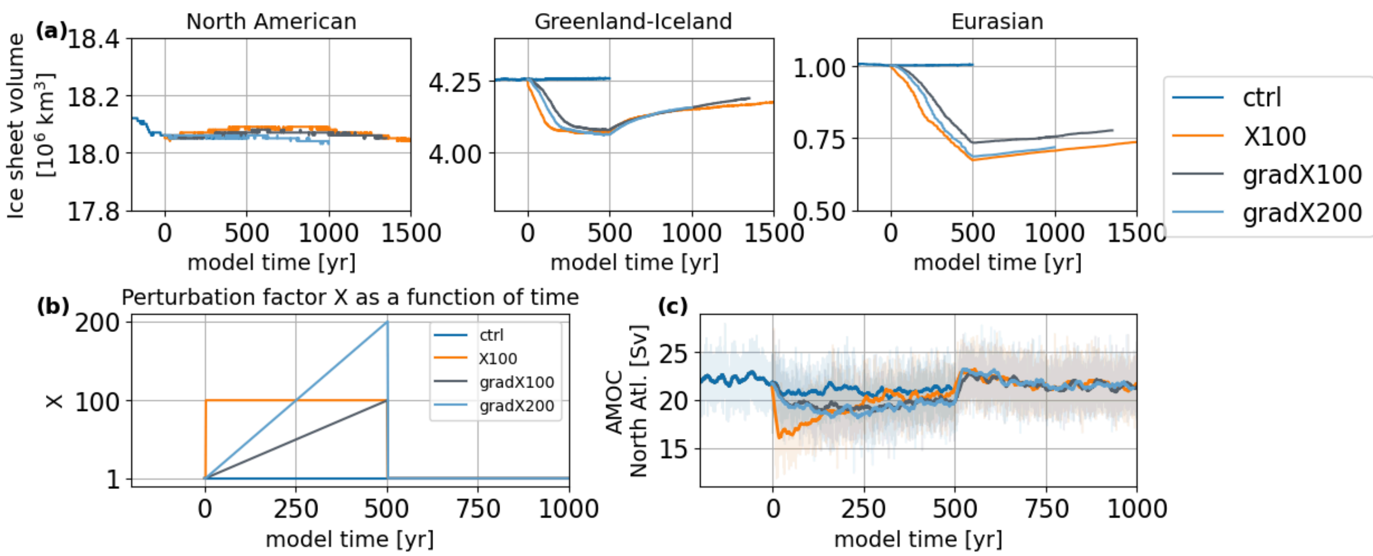


Figure R1 : Time series of (a) grounded ice volume [10^6 km³] for the North American, Greenland-Iceland and Eurasian ice sheets in perturbation experiments, with the (b) perturbation factor X [-] as a function of time, and (c) AMOC [Sv] for the same experiments.

Thank you for mentioning it. We will add this to the Supplementary Material and add the following sentence to the main text:

“Note that the impact of a gradual increase in basal melt rates on ice loss is similar to that of an instantaneous increase (Supplementary Material S3)."

A map showing more clearly the ice shelf thickness in the control run would be useful to interpret the results. Similarly, the 2D field of basal melt rate would provide useful information about the spatial distribution of reference melt rate. Both ice shelf thickness and basal melt could be conveniently integrated as additional panels into Fig. 1.
That is a good idea. Thank you for this recommendation. We will change the Figure 1 of the main text for the **Figure R2** below.

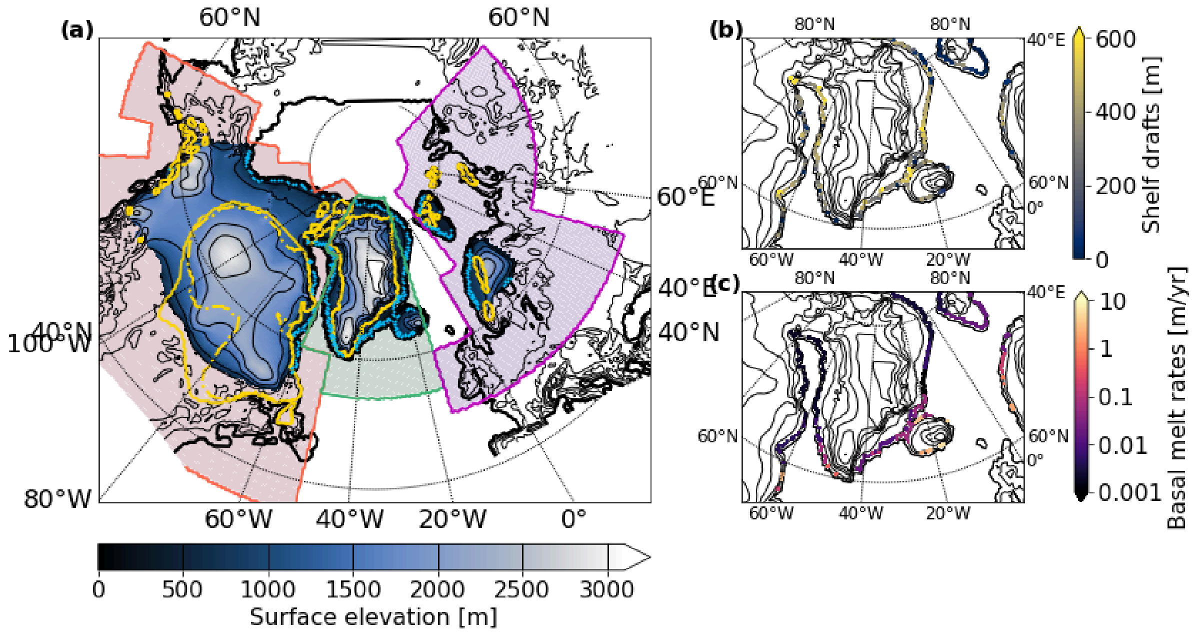


Figure R2 : 40 kyr equilibrium. Ice sheet elevation (shades of blue) [m] at the end of the equilibrium simulation. Light blue contour is the mean position of the grounding line at the same time. Yellow contours are the minimal and maximal ice sheets extent in the reconstruction from Gowan et al. (2021), 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.

Why is the freshwater flux increase after the application of the basal melt scaling so large initially and decrease so quickly? Is the shelf ice generally so thin that it melts away in a few years? Or is the calving process responsible for this behavior?
Thank you for these comments. Lines 176 to 182 will be replaced by the following paragraphs :

"*The overall volume loss experienced by the ice sheets is equivalent to a freshwater release toward the ocean (Figure 4a). This freshwater flux is particularly large during the first few years in all experiments and results from both abrupt increased basal melt and calving fluxes in the first few years (Figure 4b,c). The initial amplification of the melt rates leads to large losses at the beginning as a basal melt flux (Figure 4b). The initial amplification of the melt rates also leads to an abrupt increase of the calving flux (Figure 4c). Indeed, some of the shelves are rather thin before the perturbation is triggered (Figure 1b), so the perturbation causes the shelves' thickness to fall below the calving threshold (Supplementary Text S2).*

Then, the calving flux drops toward the control value after 10 years while the basal melt flux slowly decreases toward the control value. 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."

Following your comment the Figure 4 of the main text will be replaced by the following **Figure R3**:

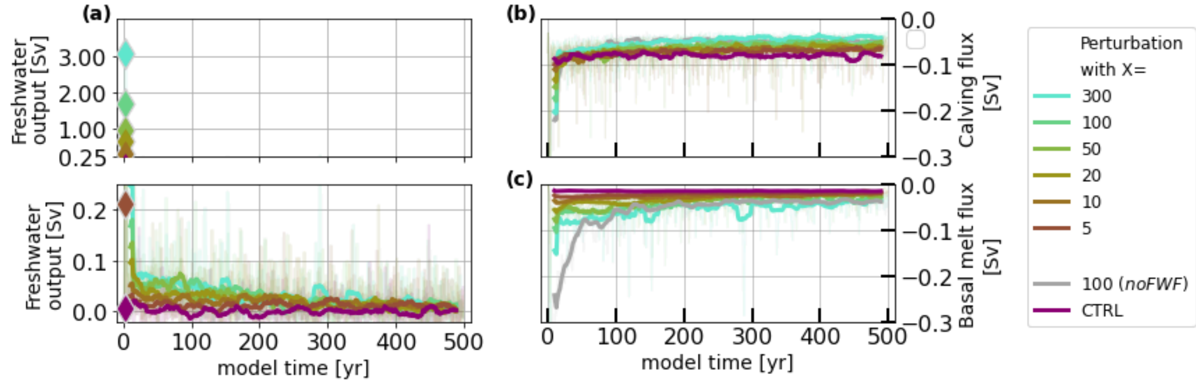


Figure R3 : Time series of (a) freshwater output from GRISLI to iLOVECLIM [Sv] (as a total ice volume change) in experiments with different perturbation factors. Diamonds are the freshwater release for the first year of perturbation, light colors are the yearly outputs and saturated colors are smoothed time series (running mean over 21 years, centered). Times series of (b) calving flux [Sv] and (c) basal melt flux [Sv], also smoothed (running mean over 21 years, centered)

We will also change units for the basal melt and calving flux to Sverdrups following one of your comments below.

On 2D maps, we can also see the effect of the perturbation once it is activated (here at yr=+1, middle column on **Figure R4**), the basal melt increases and the thinnest shelves disappear, eventually reappearing later (last column).

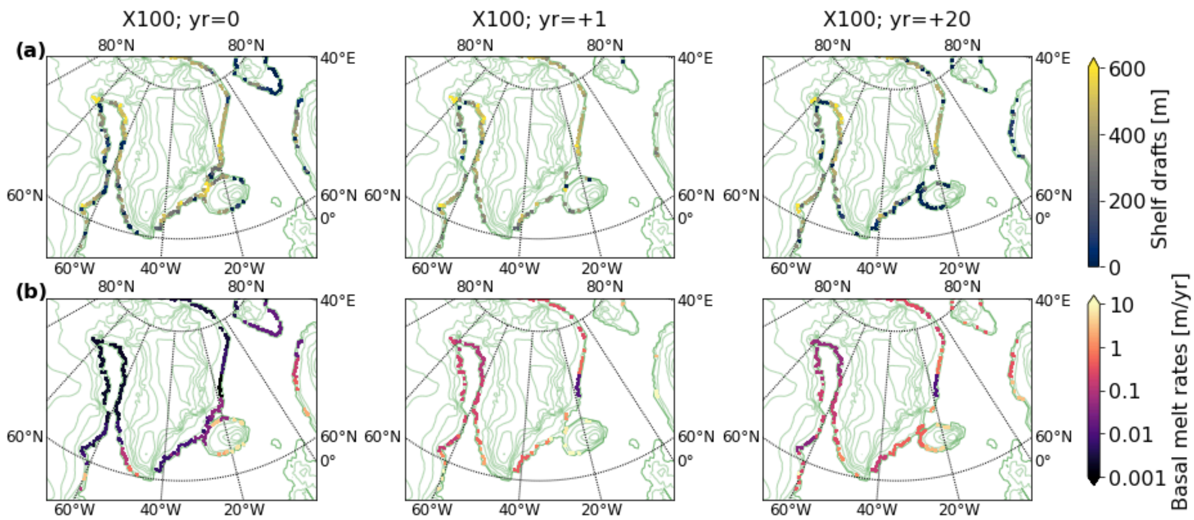


Figure R4 : (a) Ice shelf drafts [m] and (b) basal melt rates [m/yr] for perturbation experiment with factor 100 at three different times : (left column) before the perturbation is triggered, (middle) one year after (right) and after 20 years.

To what extent are the results expected to depend on the ice shelf area in the control run?
The results are expected to depend on the model configuration and the associated ice shelf area

as a larger ice shelf area would produce more melt fluxes to the ocean. We will detail this further below.

And what determines how far the floating ice extends into the ocean in the model? Is it mainly controlled by calving? This should be discussed, as the initial ice shelf area is probably relevant for the strength of the response of the model to the applied basal melt perturbation.
Yes, the extent of the ice shelves are controlled by calving and we provide in the following a detailed explanation of how this flux is calculated. This will be added to the Supplementary Material :

"*In the ice sheet model, the floating ice shelves are cut and calved according to the following procedure. The cutting thickness **hcut** is a function of the bathymetry **d** and four parameters : **dpla** ('depth of the plateau'), **daby** ('depth of the abysses'), **hcutpla** (criterion for the ice shelf thickness above the plateau), **hcutdab** (criterion for the ice shelf thickness above the plateau).*

For every grid point :
    *If there is an ice shelf with thickness **H** and the bathymetry is **d** :*
        ***dH** := the elevation change due to the upstream flow, local surface mass balance and basal melt.*
        *if **H**+**dH** < **hcut(d)** then the ice shelf is calved.*

Between, dpla and daby, hcut is a linear function such as hcut(dpla)=hcutpla and hcut(daby)=hcutdab."

```
!
!  hcut(d)
!    ^                          ______ hcutaby
!    |                         ./
!    |                       ../
!    |                     ../
!    |                   ../
!    | hcutpla ______/
!    ------------------^---------^------------------------- > section running from the coast to the open
!                    dpla     daby                          ocean with bathymetry d
!
```

A critical region in our experiment is the Baffin Bay where ice shelves can easily develop due to positive surface mass balance, low sub-shelf melt rate due to low oceanic temperatures and ice convergence fed by Greenland and North American ice streams. In this region the model tends to build-up thick ice shelves that finally end up grounded at the seafloor. Once grounded the ice there becomes insensitive to oceanic temperatures and remains present for all the simulations. Since this configuration is unlikely to have happened in the past, we prevent this in our reference configuration. To do so, we choose dpla = 250 m and daby = 1500 m, hcutpla = 250 m and hcutaby = 2000 m.

Nonetheless, we made new experiments that favour larger ice shelves (but still ensuring a non-grounded Baffin Bay) by setting **dpla** to 1000 m and **daby** to 2500 m (**Figure R5**) in order to assess the impact of the shelf area.

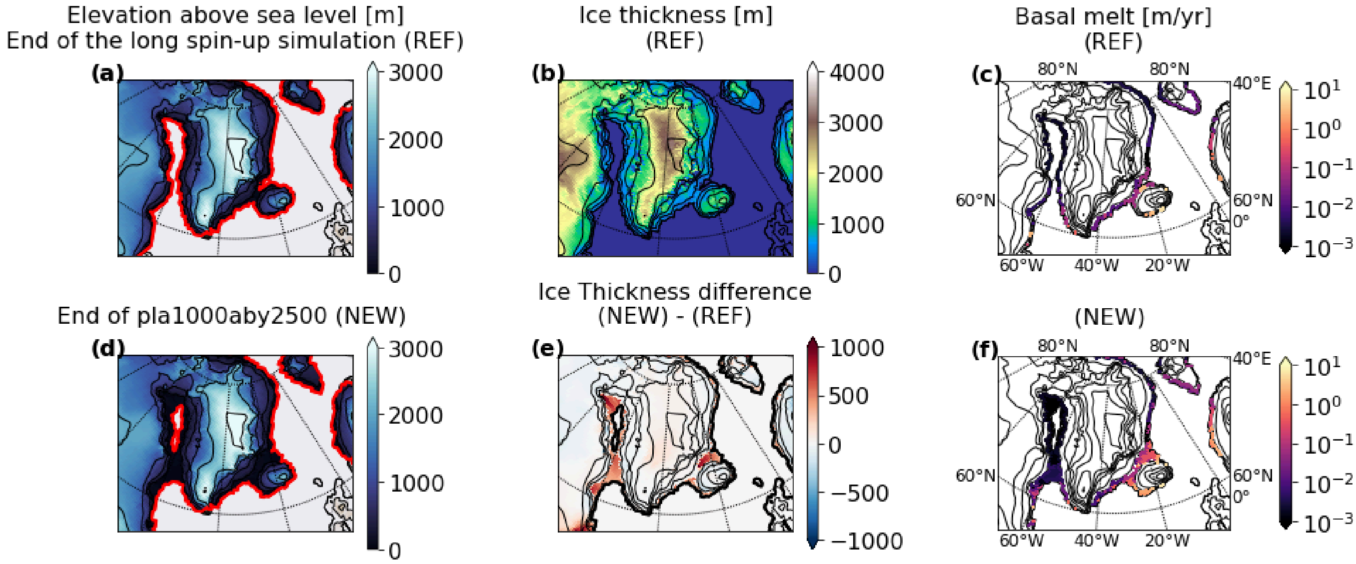


Figure R5 : Comparison of the last hundred years of two long spin up configurations : the one from the manuscript (REF) and a second configuration with larger shelves (NEW).

Applying the perturbation with X=100 on this configuration with larger shelves leads to similar results as before. Larger shelves melting lead to more freshwater input from the ice sheet model to the climate model, especially in the beginning of the simulations (**Figure R6**e). This is associated with a bit more reduction of the AMOC and NGRIP temperatures in comparison with the previous experiment.

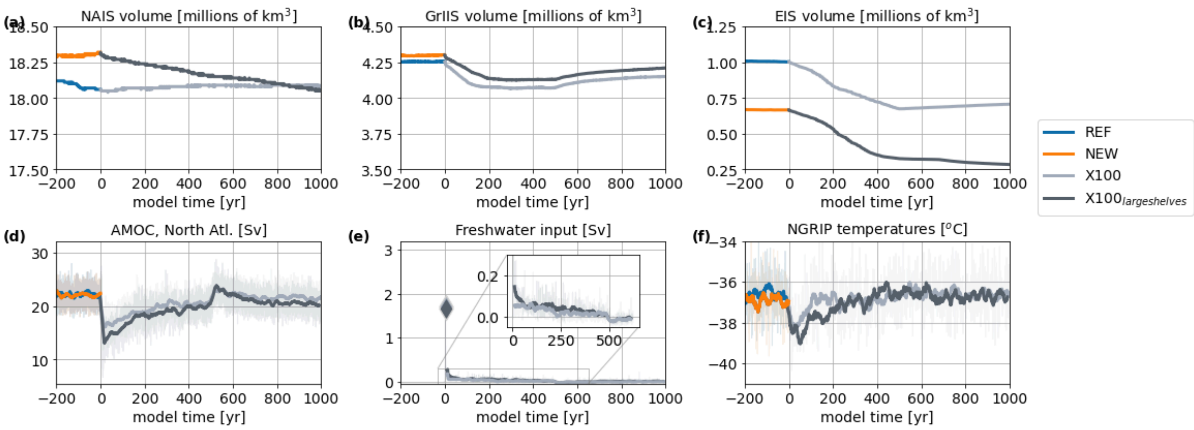


Figure R6 : Comparison between the same perturbation experiments with factor X=100 branched on the long spin up configuration (REF) and on a new configuration with larger shelves (NEW).

The North American ice sheet seems to be more sensitive to the perturbation in the large shelves case (**Figure R6**a). However, the latter is mainly driven by climatic effects (**Figure R7**c). Although we could expect some inland ice dynamics change related to larger ice shelves due to a change in buttressing, this is not happening here since there is no drastic change in elevation that are due to ice divergence anomalies over the North American ice sheet (**Figure R7**f) with respect to our reference experiment (Figure 3 from the main text). The differences with the previous setup are mainly restricted to coastal areas.

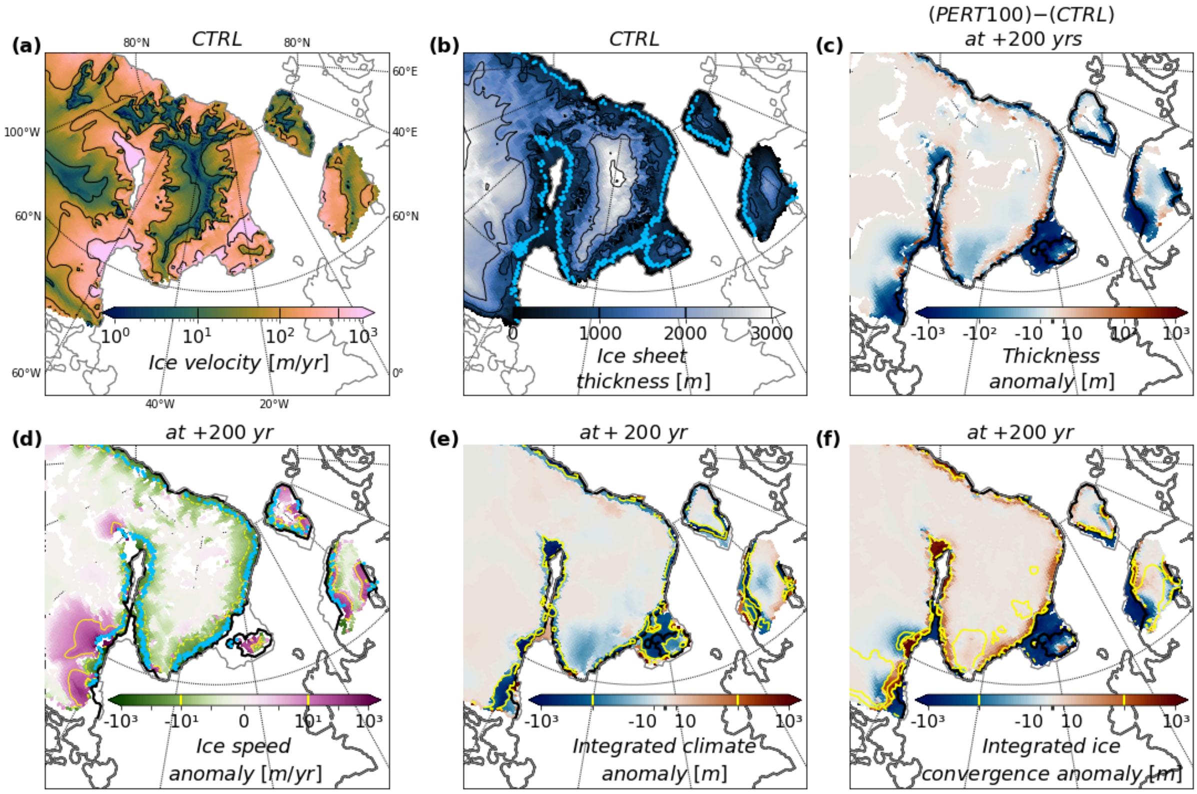


Figure R7 : Same as Figure 3 from the main text but for the configuration with larger shelves.

The rationale behind the basal melt scaling approach is not very clear to me. If the intention is to investigate the response to subsurface warming, from a physical point of view it would make more sense to apply different temperature offsets instead and then derive basal melt from eq. (1). I guess that results would be quite different if a uniform temperature increase would be applied instead of the melt scaling.

The main reason why the melt scaling approach is not very appropriate is because where basal melt is very small in the control run, due to e.g. low water temperatures, even a scaling by a factor 100 or more will not necessarily result in a substantial increase of melt. In other words, a given scaling factor will result in a very different change in basal melt for different water conditions. This probably explains much of the differences seen in the response of the different ice shelfs to the perturbation experiments presented in the paper. This is acknowledged in section 4.1, but it remains unclear why the authors opted for the scaling approach in the first place.

Thank you for all of your comments. We will add the following explanation in the revised Perturbation experiments section :

“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.“

Also, we wanted to be sure that it was possible for the system to amplify/dampen the perturbation away/toward the control state, to evaluate the sign of the feedback. To this end, we have chosen not to impose constant values either of basal melt rates nor oceanic temperatures.

A limitation of doing so is that the experiment results are dependent on the initial representation of the temperature in the ocean and model biases.

We agree that applying a constant temperature offset might overcome the model biases and is as such an interesting experiment to run. For this reason, we performed additional experiments, applying $T'=T+T_{offset}$ with T_{offset}=2,6,8,10 °C (**Figure R8**).

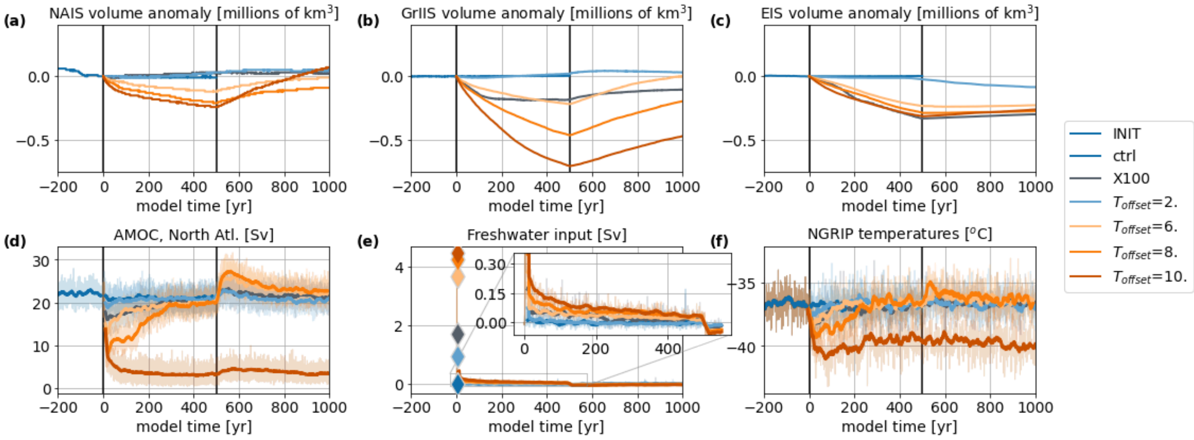


Figure R8 : Ice sheet volume anomaly [10^6 km³] for (a) the North American, (b) the Greenland-Iceland and (c) the Eurasian ice sheets. Time series of (d) AMOC [Sv], (e) Freshwater input to the ocean model [Sv] and (f) NGRIP temperatures [°C] in perturbation experiments with T_{offset}=2,6,8,10 °C as well as the experiment with X=100.

These experiments are interesting as this way we force the North American ice sheet volume to decrease (yet not only from the Baffin Bay but also to its northern part). Discrepancies with the previous experimental setup also includes overshoots of the AMOC and NGRIP temperatures when the perturbation is halted. In the extreme case of +10 °C, the AMOC eventually shuts down, with no recovery after the perturbation ends. In this case, surface cooling and freshening is so large that convection stops in the North Atlantic Ocean yet develops in the North Pacific Ocean (**Figure R9**).

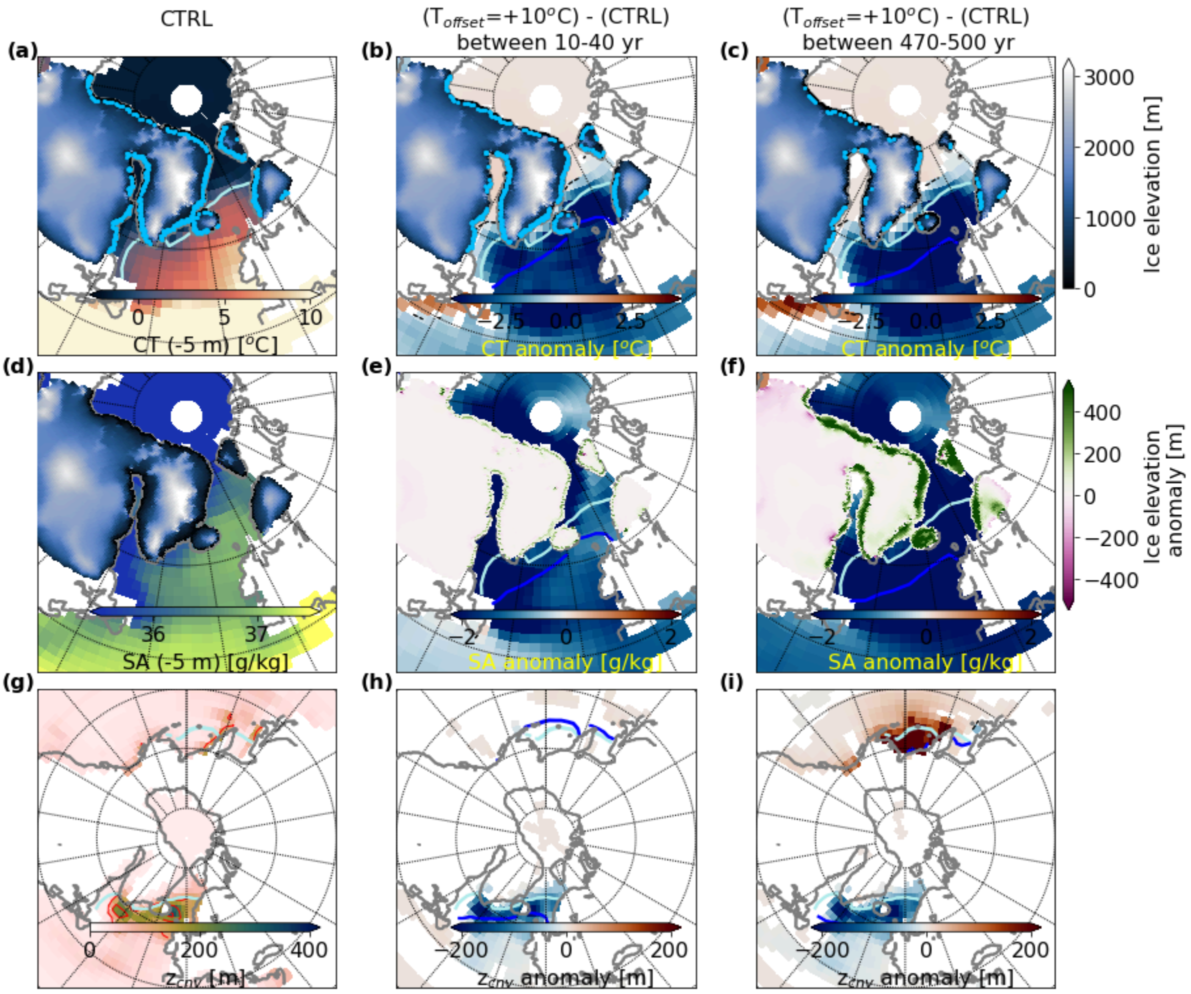


Figure R9 : Same as Figure 6 from the main text but for the experiment with T_{offset}=10 °C. Ice elevation is also depicted on (a),(d) for the control simulation and on (b) and (c), between 10-40 yr and between 470-500 yr after the perturbation starts. Ice elevation anomalies with respect to the control are depicted on (e) and (f).

These experiments with constant temperature offsets will be added to the revised article by replacing the experiments with constant melt rates (Figure 9 from the main text), as these are easier to connect to the real world. We will also add the following line to the Perturbation experiments section :

"A limitation of the basal melt scaling approach is that the experiment results are dependent on the initial representation of the temperature in the ocean and model biases. To overcome this limitation, we perform additional experiments by applying a constant temperature offset (Section 4.1)."

Some more details on the freshwater balance of the climate-ice sheet system are needed. Some additional information is provided in the SI, but I don't quite understand how the freshwater flux from the ice sheet can be ignored without resulting in a drift in ocean salinity. Water that is evaporating from the ocean will fall as precipitation over the ice sheets and, if ice sheets are in steady state, the same amount of water that is precipitating over the ice sheets has to reach the ocean as surface runoff, basal melt or calving in order to conserve water. If these freshwater fluxes to the ocean are ignored, this will lead to a drift in ocean volume and salinity. How is this prevented

in the noFWF experiments, including the spinup?
We acknowledge that the latter is not very clear in the main text and thank you for pointing this out.

It is to be noted that iLOVECLIM, the climate model, has its own hydrological cycle. This implies that surface runoffs are decomposed in two components : surface runoffs from iLOVECLIM and surface runoffs from GRISLI.

When there is no ice sheet coupling, or when the ice sheets are maintained constant, with V the ice sheet volume, then dV/dt = 0. Nevertheless, precipitation over land is still routed toward the ocean, such as an exchange between the atmosphere model and the ocean model to maintain a closed water budget in the climate model.

When the ice sheet coupling is activated, the iLOVECLIM hydrological cycle remains activated, ensuring that precipitations that fall over the ice sheet are routed toward the ocean. However, this time V can vary so we can use dV/dt as an additional freshwater flux. When dV is negative then freshwater is routed toward the ocean, such as an exchange between the ice sheet and the ocean model. dV is the sum of basal melt, calving and surface melt/accumulation. In the noFWF experiments, we ignore the transfer of dV (as a freshwater flux) from the ice sheets to the ocean but the iLOVECLIM hydrological cycle is still working.

This explanation will be added to the Supplementary Material.

Lines 228 to 230 will be rephrased as :

“We perform another set of simulations, maintaining the oceanic perturbation and cutting off freshwater fluxes from the ice sheet model to the ocean model while the hydrological cycle of the climate model remains activated and precipitation that falls over land is still routed toward the ocean. In other words, here the ocean does not respond to the continental ice melt water and the associated oceanic feedback on the ice sheets is suppressed.”

Minor comments

L. 2: Please clarify that the forcing that is applied is actually not ‘subsurface warming’ but scaling of basal melt, which can produce very different results.
Thanks for your comment, this will be changed so there is no misconfusion.

L. 5: ‘destabilisation’ of what?
Thanks, we will remove this remnant of a previous version.

L. 26-27: should be kyr BP and not years BP.
Thank you, we will change it.

L. 53: again, this can be misleading and doesn’t reflect what is done in the experiments.
Thanks, we will modify the sentence.

L. 72-73: Does this imply that ice shelves can not grow back after their thickness falls below 250 m?
It does not, the ice shelves can still expand as a result of upstream flow and surface accumulation. Thank you for pointing this out, we will add the following sentence to make this clearer :

"It is to be noted, that after calving, the ice shelves are allowed to grow back, as a result of upstream ice flow and surface accumulation."

L. 82: Does the model resolve the diurnal cycle?
No, the four hour timestep in the atmospheric model is related to numerical stability.

L. 86-87: And what about the latent heat associated with basal melt? Is that not accounted for?
The latent heat associated with the basal melt is not taken into account in the model. It could be included in a future version. Still, according to the results of this study, we suppose that including it would affect the results by leading to a larger negative freshwater feedback on the continental ice volume losses.

Thank you, we will add this consideration after line 262 ("In addition, the local latent heat flux due to oceanic melting of the calved ice also helps to cool the upper part of the water column and to maintain a cold water layer that extend from the surface to the ice shelf drafts.") by adding the following sentence :

"The latent heat flux associated with sub-shelf melt is not taken into account in the model, yet including it would lead to a larger cooling of the upper water column in this case."

L. 93: Is the depth dependence of the freezing temperature not considered? As mentioned also in the introduction, this dependence can be important.
Indeed, it is not considered, the Millero formulation is a function of the local salinity and the depth z, but in the model z was set to a constant that is equal to 200 meters depth for every grid point in the freezing temperature formulation.

We have tested to what extent the depth dependance could change the results by taking the real model depth for each grid point rather than the 200 m constant. It appears that the results are not modified in this case (gray curves on **Figure R10**).

Yet, following your comment, we will keep the z dependance for the freezing temperature in future versions of the coupling. Thank you for pointing this out.

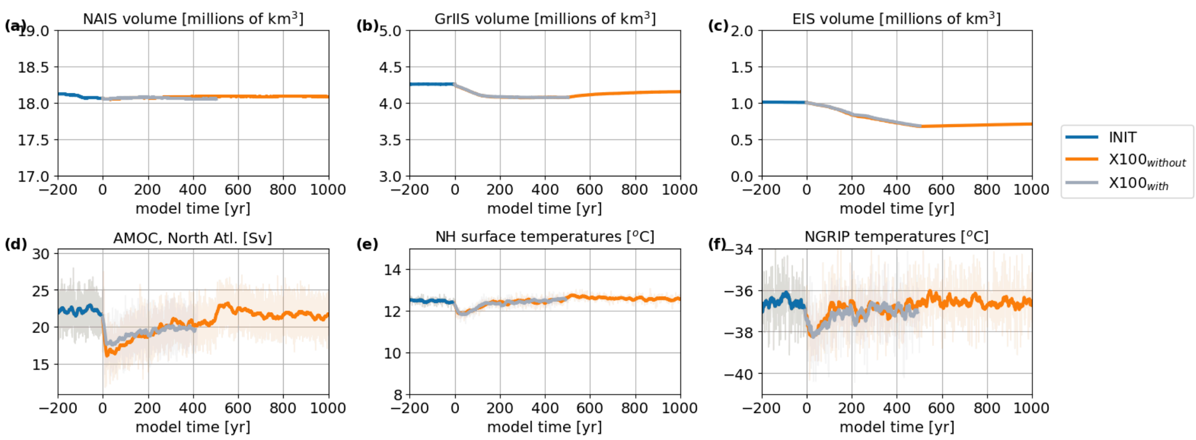


Figure R10 : Ice volume evolution for (a) the North American, (b) the Greenland-Iceland and (c) the Eurasian ice sheets. Times series of (d) AMOC in the North Atlantic, (e) Northern Hemisphere surface temperatures and (f) NGRIP surface temperatures for two experiments : X100$_{without}$ (ie.

without depth dependance of the freezing temperature, same as in the main text) and $X100_{with}$ (ie. with depth dependance of the freezing temperature).

L. 96: What is the target of the calibration procedure?
Thank you for the question. We have tested different values for the parameter γ_T during the calibration phase (as well as other parameters related to the coupling). In the fully coupled model, in a large number of cases, ice sheets disintegrate (towards the pre-industrial ice sheets) or expand (towards the LGM ice sheets and beyond).

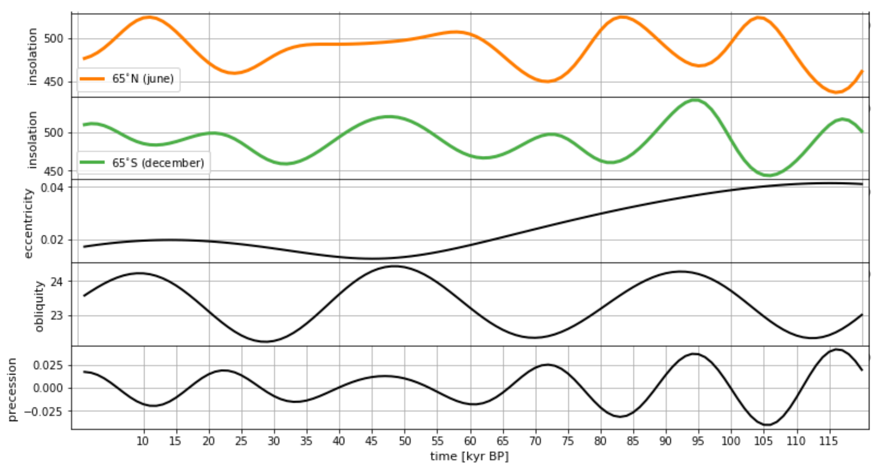
Consequently, at this stage of the model development, here we want to maintain the volume of the ice sheets at a level between these extreme states (PI or LGM-like ice sheets), this is the target. This may seem to be a wide range of possibilities for a target, but in the end, it has been quite difficult to achieve.

L. 101-102: How is that done in the free-surface ocean model?
The CLIO model is said to be free-surface as the sea-surface elevation is solved. The reference level for the sea-surface elevation is chosen such that the average of the surface elevation anomalies over the globe is zero. Thus, the total volume of the ocean does not vary over time. The procedure is well described in Goosse , et al. (2001)., "Description of the CLIO model version 3.0.", sections 2.4 to 2.5.

L. 106: 'relatively stable conditions regarding June insolation at 65°N.'. What does that mean in the context of constant 40 ka orbital configuration?
Thank you for this question. We will clarify this sentence by adding the following paragraph :

"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."

See **Figure R11** below for the forcings.



<u>Figure R11 :</u> Insolation and orbital configuration forcings from Berger et al., (1978).

ky, k.y., k.y. B.P., ky B.P. are used interchangeably, causing some confusion. Please consistently use the same throughout the paper.
Thanks for this remark, we will change that.

L. 107-108: What does 'The ice sheet model is forced with sea level reconstruction' practically mean? Does sea level affect the bathymetry and land-sea mask? But the bathymetry in the climate model is set to LGM, so how are the two approaches combined?
The sea-level reconstructions are used by the ice sheet model to determine which areas of land are above water (ie. where the continental ice can possibly grow). These are not used by the iLOVECLIM model so it does not impact the bathymetry and land-sea mask.

We will add the following sentence to clarify this point :

"The latter is only used by GRISLI to determine which areas of land are located above the sea level (i.e. where the continental ice can grow)."

L. 107-108: Since constant values are used for GHGs and sea level, it would be clearer to state those values in the text.
You are right, thank you. We will add the values in the main text. The value for the GHG is set to 200 ppm and for the one for the sea level to minus 64 m. Thank you.

L. 125-127: This needs some clarification. Does that mean that during the spin-up phase the freshwater fluxes (runoff, basal melt and calving) from the ice sheet are ignored? I understand that the total ice volume change is small at equilibrium, but that doesn't imply that the freshwater fluxes are zero, just that total ice accumulation and ablation balance each other. I would think that it is important that the ocean 'sees' the freshwater fluxes from the ice sheets in the equilibrium initial model state.
Thank you for this comment. During the spin-up phase the freshwater fluxes from the ice sheet model to the ocean are indeed ignored. iLOVECLIM freshwater cycle is style activated, as described in a previous answer.

You are right that the freshwater fluxes (from the ice sheets to the ocean) are non zero at equilibrium (locally and over the total ice sheet), yet we have ignored them for the spin-up phase, the latter reason is detailed below.

The long spin-up is an accelerated experiment. We have chosen to do it this way as we initialize the spin-up with an LGM ice sheet and climate. It would have taken a long (real) time to equilibrate the fully coupled model to 40 kyr BP conditions without the acceleration since ice sheets have a slow dynamic, in comparison with ocean and atmosphere. Indeed, when the full coupling is activated and with no acceleration, we are able to run ~400 years per day.

However, when using an acceleration factor (here of 10 years), we cannot conserve both total ice mass change and the rate of mass change, as explained in Supplementary Text S2. If we conserve the total mass change, then the ocean model would receive the equivalent of 10 consecutive years of melting (and the freshwater fluxes would be 10 times larger than the annual mean flux). This could lead to AMOC shutdown, especially in the beginning of the spin-up simulation as we start from an LGM ice sheet. Conversely, if we provide CLIO with the mean freshwater flux, we only account for one-tenth of the total mass change and it could still be a large flux (again as we start from an LGM ice sheet).

The best we could do in a future version, could be either to perform the spin-up feeding CLIO with an annual mean flux from GRISLI or extend the spin-up simulation with synchronous coupling and freshwater exchange between the ice sheet and the ocean for several hundreds of years.

Nevertheless, here, when we extend the spin-up simulation with synchronous coupling and including the freshwater fluxes from the ice sheets to the ocean, the drift is quite small (see the **Figure R12** below or for instance the mean difference in global mean salinity between CTRLfwf and CTRLnofwf on Figure S2 from the Supplementary Material).

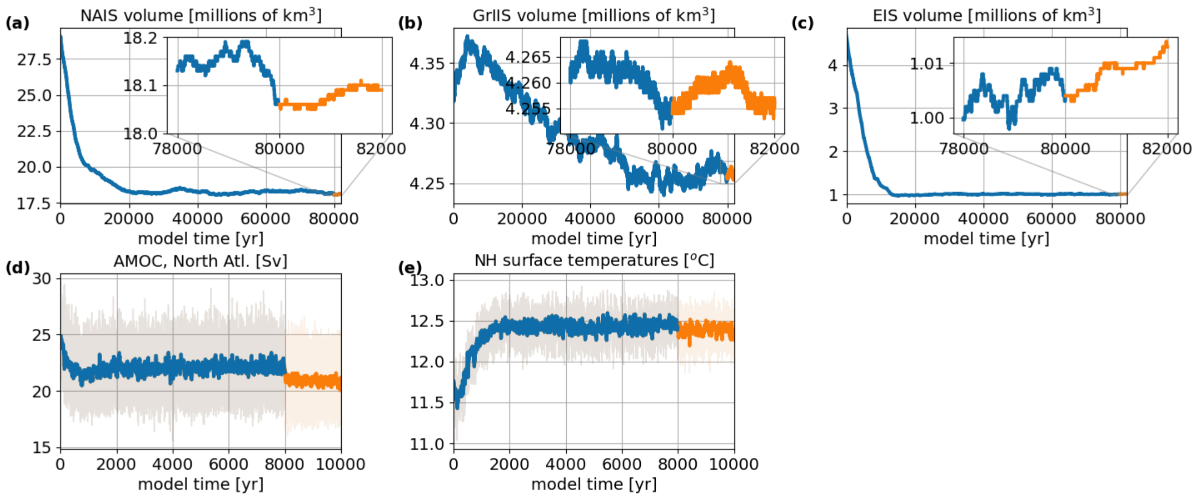


Figure R12 : Ice volume evolution for (a) the North American, (b) the Greenland-Iceland and (c) the Eurasian ice sheets. Times series of (d) AMOC in the North Atlantic, (e) Northern Hemisphere surface temperatures for two simulations. In **blue** : the long spin-up simulation (asynchronous, so 8,000 years for the climate and 80,000 for the ice sheets, with no freshwater fluxes from the ice sheet to the ocean) ; in **orange** : an extended simulation of 2,000 years that is synchronous and includes freshwater fluxes from the ice sheet to the ocean.

Comparing the last thousand years of the spin-up and for the first hundred years of the extended run that includes freshwater fluxes from the ice sheet to the ocean, the North American ice sheet's volume goes from 18.14 to 18.06 millions of km^3 (-0.5%) ; the Greenland-Iceland volume goes from 4.259 to 4.258 millions of km^3 (-0.02%) ; the Eurasian volume from 1.006 to 1.007 millions of km^3 (+0.06%) ; AMOC reduction is of 5%, from 22.15 Sv to 21.09 Sv and Northern Hemisphere temperature decrease is of 0.2%, from 12.45 °C to 12.39 °C.

Thank you for pointing this out. This will be further detailed in the Supplementary Material.

We will also add the following sentence to the description of the spin-up simulation.

"During the spin-up phase the freshwater fluxes from the ice sheet model to the ocean are ignored. This approach is necessary because we cannot conserve both total ice mass change and the rate of mass change when using an acceleration factor (Supplementary Text S3). However, at the end of the spin-up phase the ice sheet is in equilibrium with the rest of the climate system. Therefore the ice sheet volume is quasi stable and produces a net zero freshwater flux to the ocean. There is thus no significant discontinuity in our control experiment with ice sheet freshwater flux included when branched from the spin-up simulation."

L. 141-142: Not fully clear what is meant here. I don't think that a new equilibrium can be reached in only 500 years.
We will modify this sentence by *"before reaching a new state with minimal ice volume change for the Greenland-Iceland ice sheet"*, thank you for noticing it.

L. 177-178: Would be interesting to see the separate contributions of basal melt and calving. This should also be discussed in some more detail in relation with the calving law that is applied in the ice sheet model, which I guess could result in thick shelf ice being cut instantaneously if basal melt lowers the ice thickness below 250 m. How realistic is that?
L. 178: The equivalent number in Sv units would be useful, as that is more commonly used when it comes to freshwater forcing of the ocean. Moreover, this number should depend on the magnitude of the basal melt scaling factor, no?
We will change the number to Sv units, thank you. You are right that this number depends on the intensity of the scaling factor, the numbers were given for the experiment with X=100. The sentence will be corrected.

250 m is a common magnitude order for ice shelves thickness at the terminus, when they are thinner, they are more likely to break-up as a result of processes such as hydrofracturing.

L. 204-206: This sounds very speculative. Is it not more likely that the warming is a result of the transition from perennial ice shelf to seasonal sea ice cover?
Following your comment we have checked this a little bit further, thank you for noticing it.

More freshwater is added locally in the perturbed experiment than in the ctrl run at the end of the simulations (**Figure R13**), so our suggestion was wrong.

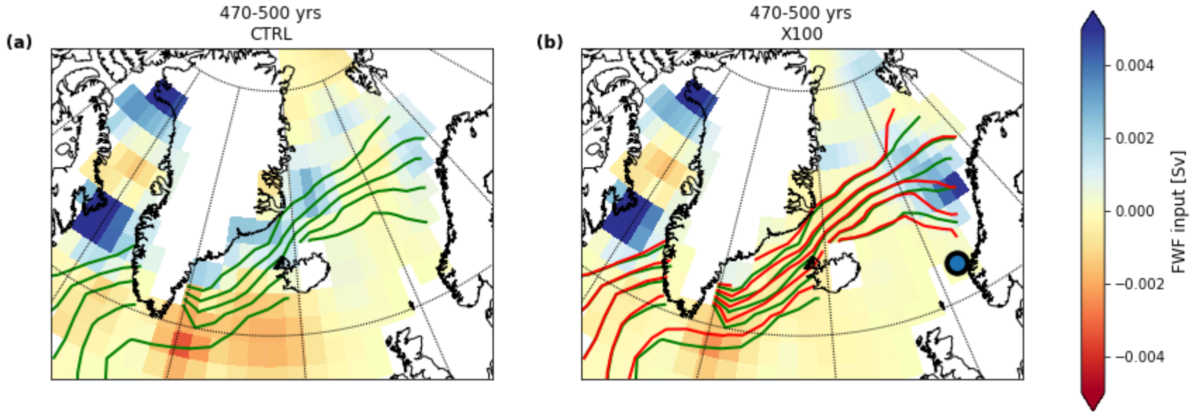


Figure R13 : Freshwater input [Sv] to the ocean model and annual sea-ice contour corresponding to 5,20,40,60 and 80% averaged over 470-500 years for (a) the control experiment and (b) the perturbation experiment with factor X=100.

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 R14**).

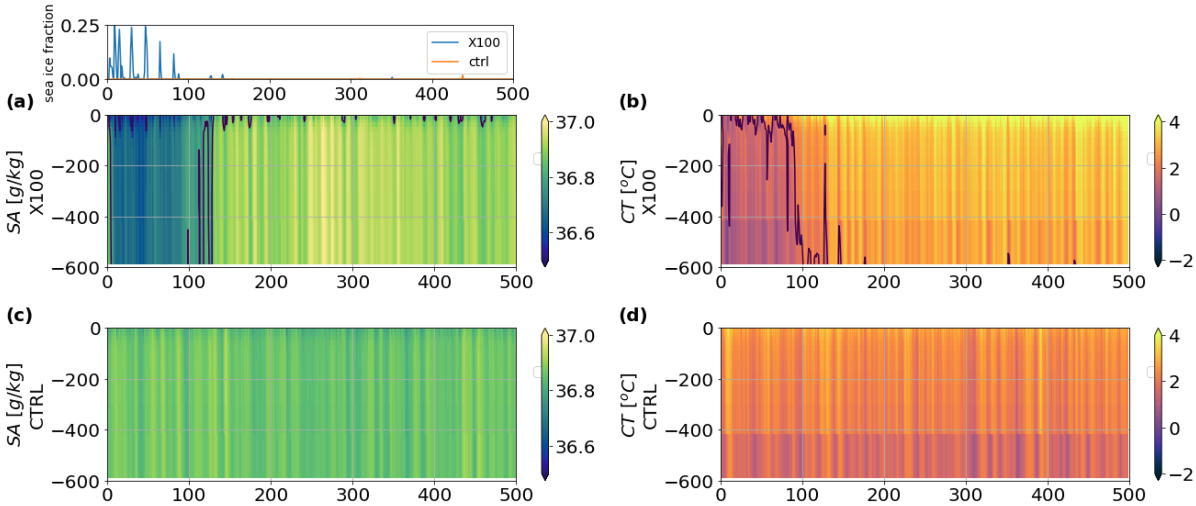


Figure R14 : Hovmoller diagrams for the profile whose location is the blue dot in Figure R13b. For the perturbation experiment with factor X=100 (resp. the control experiment), (a) (resp. (c)) absolute salinity [g/kg] and (b) (resp. (d)) conservative temperature [°C].

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 R15** 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.

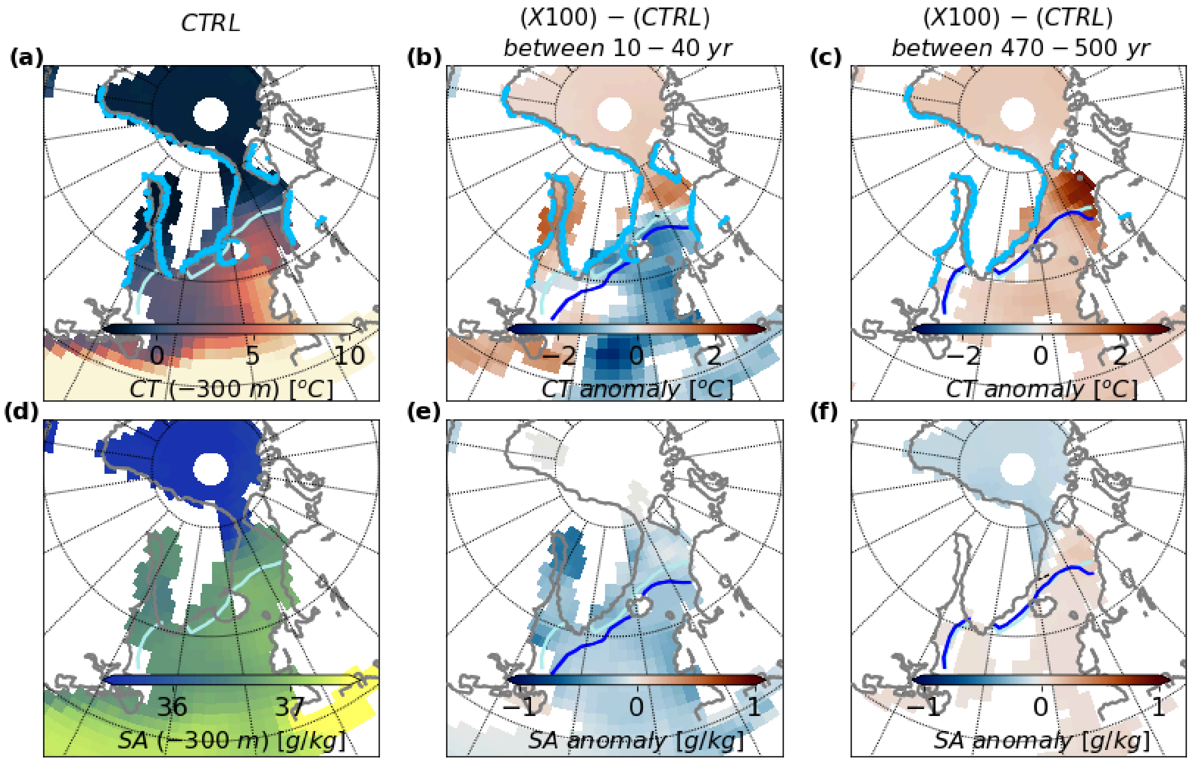


Figure R15 : Conservative temperature [°C] at 300 m depth horizon, (a) averaged over the control experiment, and associated anomaly between the perturbation experiment with X=100 (b) over 10-40 yrs and (c) over 470-500 yrs and the control. (d,e,f) Same for the absolute salinity [g/kg].

This sentence will be replaced by the following :

"*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.*"

L. 260-262: Do you really account for the difference in temperature of the meltwater relative to the ocean water temperature? Or is the described cooling due to the latent heat extracted from the ocean to melt the ice?
No we don't, freshwater is added at the temperature of the surrounding waters. We agree that this was not clear in the manuscript. In this sentence the cooling was referring to the cooling in the ocean following the freshwater addition (Figure 6e,7c).

Thank you for noticing it, the sentence will be replaced by the following :

"Meltwater fluxes into the ocean bring water that is fresher than the surrounding ocean and favor sea-ice expansion."

L. 334: Why 'contradiction'?
We used 'contradiction' in the sense that our Laurentide ice sheet doesn't display any significant volume variations although paleo-data have shown that it was the case for this time period. We will replace the sentence by : *"There are several possible reasons for this discrepancy between the simulated behavior and the observations :"*

Fig. 6: I guess that 5 m depth is equivalent to the surface? Or how thick is the top ocean model layer? Panels g-i seem to show depth of convection rather than density, as stated in the caption.
Yes it is, the first layer is centered at 5 m depth and is 10 m thick.
Panels g-i are indeed the depth of convection, sorry for the mistake in the caption.

Specific comments
L. 48: increases -> increase
L. 284: others -> other
Thanks, these mistakes will be corrected.

Thank you for all the comments and questions,

Louise Abot, on behalf of all co-authors.

References

Alvarez-Solas, Jorge, et al. "Links between ocean temperature and iceberg discharge during Heinrich events." *Nature Geoscience* 3.2 (2010): 122-126.

Alvarez-Solas, Jorge, et al. "Iceberg discharges of the last glacial period driven by oceanic circulation changes." *Proceedings of the National Academy of Sciences* 110.41 (2013): 16350-16354.

Barker, Stephen, et al. "Icebergs not the trigger for North Atlantic cold events." *Nature* 520.7547 (2015): 333-336.

Bond, Gerard, et al. "Evidence for massive discharges of icebergs into the North Atlantic ocean during the last glacial period." *Nature* 360.6401 (1992): 245-249.

Bond, Gerard, et al. "Correlations between climate records from North Atlantic sediments and Greenland ice." *Nature* 365.6442 (1993): 143-147.

Bond, Gerard C., and Rusty Lotti. "Iceberg discharges into the North Atlantic on millennial time scales during the last glaciation." *science* 267.5200 (1995): 1005-1010.

Berger, André. "Long-term variations of caloric insolation resulting from the Earth's orbital elements." *Quaternary research* 9.2 (1978): 139-167.

Dansgaard, Willi, et al. "North Atlantic climatic oscillations revealed by deep Greenland ice cores." *Climate processes and climate sensitivity* 29 (1984): 288-298.

Dansgaard, Willi, et al. "Evidence for general instability of past climate from a 250-kyr ice-core record." *nature* 364.6434 (1993): 218-220.

Ditlevsen, Peter D., Katrine Krogh Andersen, and Anders Svensson. "The DO-climate events are probably noise induced: statistical investigation of the claimed 1470 years cycle." *Climate of the Past* 3.1 (2007): 129-134.

Elliot, Mary, et al. "Millennial‐scale iceberg discharges in the Irminger Basin during the last glacial period: Relationship with the Heinrich events and environmental settings." *Paleoceanography* 13.5 (1998): 433-446.

Goosse, Hugues, et al. "Description of the Earth system model of intermediate complexity LOVECLIM version 1.2." *Geoscientific Model Development* 3.2 (2010): 603-633.

Gowan, Evan J., et al. "A new global ice sheet reconstruction for the past 80 000 years." *Nature communications* 12.1 (2021): 1199.

Heinrich, Hartmut. "Origin and consequences of cyclic ice rafting in the northeast Atlantic Ocean during the past 130,000 years." *Quaternary research* 29.2 (1988): 142-152.

Johnsen, S. J., et al. "Irregular glacial interstadials recorded in a new Greenland ice core." *Nature* 359.6393 (1992): 311-313.

Jonkers, Lukas, et al. "A reconstruction of sea surface warming in the northern North Atlantic during MIS 3 ice-rafting events." *Quaternary Science Reviews* 29.15-16 (2010): 1791-1800.

Kindler, Philippe, et al. "Temperature reconstruction from 10 to 120 kyr b2k from the NGRIP ice core." *Climate of the Past* 10.2 (2014): 887-902.

Max, Lars, et al. "Subsurface ocean warming preceded Heinrich Events." *Nature Communications* 13.1 (2022): 4217.

Mignot, Juliette, Andrey Ganopolski, and Anders Levermann. "Atlantic subsurface temperatures: Response to a shutdown of the overturning circulation and consequences for its recovery." *Journal of Climate* 20.19 (2007): 4884-4898.

Rasmussen, Tine L., and Erik Thomsen. "The role of the North Atlantic Drift in the millennial timescale glacial climate fluctuations." *Palaeogeography, Palaeoclimatology, Palaeoecology* 210.1 (2004): 101-116.

Schulz, Michael. "On the 1470-year pacing of Dansgaard-Oeschger warm events." *Paleoceanography* 17.2 (2002): 4-1.