Response to Editor Review

In the following, the editor comments are in blue and our responses in black.

I have gone through your revised version of the manuscript and concluded that it still requires quite some work before publication. I would rate the required revisions as moderate rather than minor. Attached to this decision is the file with your manuscript including comments on the necessary improvements and sample markings of numerous typos and poor formulations using the new Discussion session as an example. I would like to emphasize that the manuscript needs a thorough editing for grammar and clarity, not only in the Discussion section but throughout.

Thank you for your time in reviewing thoroughly our manuscript. We have corrected the typos and formulations you pointed out in the discussion. We have also done our best to improve grammar and clarity for the rest of the paper. We apologize in advance if errors are nonetheless still present and we hope that this does not hamper the understanding. In any case we will be happy to benefit from the Copernicus editing service if our paper gets eventually accepted.

Below are major points that must be improved:
- Model and model setup descriptions (missing details and vague formulations);

Following your suggestion in the annotated pdf we now give more precision on the coupling of the ice sheet model and the the rest of the climate system. Notably, we now provide the equation for surface mass balance and we explain better how the atmospheric temperature bias is indirectly corrected with a geographical adjustment of the melt parameter c_{rad} in the melt equation.

We also corrected the imbalance between the description of the climate model and the ice sheet model, simplifying the description of the ice sheet model since we do not do any modification to it for this paper.

We have added a table in the supplement that contains the major parameters of the coupled ice sheet – climate model. We have also added a Supporting Text to explain more precisely how the alternative ice sheets were elaborated (stand-alone climate and ice sheet integrations). This reads:

“In the standard version of the model, the melt parameter c_{rad} used in the surface mass balance model is locally changed according to the annual mean temperature bias with respect to present-day reanalysis ERA-interim. The local modification is linear, using a coefficient of 0.1°C^{-1}. This has been implemented to indirectly correct for the temperature biases in the climate model. For a temperature bias of +10°C we use a c_{rad} of -80 W m^{-2} instead of the reference value of -40 W m^{-2}.

To elaborate alternative ice sheet geometries for the penultimate glacial maximum, we run 100-yr long simulations of the climate model with prescribed LGM ice sheets branched from the 142 kaBP climate equilibrium. For theses simulations we modify regionally the value of the reference temperature bias in order to impact the value of the local melt parameter value. For the two alternative ice sheet geometries, we divide by 5 the temperature bias in the region of North America (approximatively for longitudes from -140 to 0°E). Since the temperature bias is mostly positive in this region, this modification results in higher value of the c_{rad} parameter (more melt). For Eurasia (longitude lower to about 140°E), we replace the temperature bias by a value of +20°C (larger Eurasian ice sheet case) and +40°C (much larger Eurasian ice sheet case). These modifications in Eurasia produce a larger SMB. Finally, we use the climatological SMB resulting from these 100-yr long simulations to force offline the ice sheet model until equilibrium, similarly to what we did to generate the initial LGM ice sheets.”

- Justification of the initial ice sheet geometry choices;

It is true that in the original version of the paper we only referred to our previous publication on the last deglaciation. To make the manuscript self-consistent we now explain how we elaborated our initial reference ice sheet geometry for TI, which is the same as for TII, in the beginning of the experimental setup section (Sec. 2):

“The experiments discussed here for TI are the coupled ice sheet – climate model simulations covering the last 26 kaBP from Quiquet et al. (2021). For these, the initial climate conditions and ice sheet geometries were obtained using uncoupled simulations. We first run the climate model for 3,000 years with prescribed ice sheet reconstructions (GLAC-1D, Tarasov et al., 2012; Tarasov and Peltier, 2002; Briggs et al., 2014) using fixed 21 kaBP orbital configuration (Berger, 1978) and greenhouse gas forcings (Lüthi et al., 2008). The last hundred years of this climate spin-up is used to derive climatological climate forcings required by the ice sheet model. We used these forcings to run stand-alone ice sheet model simulations for 200-kyr to reach equilibrium. The spun-up ice sheet and climate states were then used as initial conditions for our coupled simulations.”

Later when we describe the different experiments performed we now provide technical details of how we elaborate the two alternative initial ice sheets that we used for TII. Since there is no evidence for a significantly different eustatic sea level for the PGM with respect to the LGM, our alternative ice sheets do not imply large changes in total ice volume. The first alternative (slightly smaller NAIS, -6%, and larger EIS, +36%) does not change the total ice volume stored on land. The second alternative (slightly smaller NAIS, -6%, and much larger EIS, +71%) corresponds to an increase of about 5~m of sea level equivalent of the total ice volume. This part now reads:

“Accelerated experiments are first used to assess the sensitivity of the simulated TII to the initial ice sheet geometry. Our initial ice sheet geometry for our TII experiment is the same as for the TI experiment. This is a modelling simplification since it is unlikely that the configuration of the Northern Hemisphere ice sheets was identical for the two previous glacial maximums. To explore this model assumption, we elaborated alternative PGM ice sheet geometries. To generate these we run new stand-alone ice sheet model simulations using different SMB forcings to the ones used to generate the LGM ice sheet spin-up. The new SMB forcings were obtained by running the climate model for 100-yr simulations with regionally modified crad parameter in the melt equation of the ITM. In the reference model, this parameter is locally adjusted to indirectly correct for the temperature bias in the model. To obtain alternative SMB we apply regional modifications to this temperature bias. More specifically, we reduce the bias correction in North America in order to generate higher surface melt rates since the temperature bias is positive in this region. In Eurasia, we impose a fixed artificial positive bias so that the crad gets reduced to produce less melt. More information on these modifications is available in the supplement (Supp. Text 1). These artificial SMB modifications are only used to produce alternative ice sheets with GRISLI stand-alone simulations but they are removed for transient coupled simulations. The alternative ice sheet geometries consist in a reduced North American ice sheet by about 6% in volume with respect to the LGM (about -2.0 10^6 km^3) and a larger (+36% volume, about +2.1 10^6 km^3) or much larger (+71%, about +4.2 10^6 km^3) Eurasian ice sheet. The first alternative (larger Eurasian ice sheet) does not change the total ice volume stored on land while the second (much larger Eurasian ice sheet) corresponds to an increase of about 5 m of sea level equivalent of this volume. The alternative Eurasian ice sheets display a larger extent towards the East more in agreement with the palaeo data

(Svendsen et al., 2004). These experiments serve to quantify the sensitivity of our simulated deglacial climate and ice sheet trajectories to the ice sheet glacial geometry.”

One point we need to mention is that it is difficult to use very different ice sheets while keeping some realism for the deglaciation. We made a lot of different tests varying ice sheet geometries but due to the strong albedo feedback in coupled simulations it is very easy to end up with very different climate trajectories for all these tests. For example, larger Eurasian ice sheets tend to easily expand to the East, generating a large Siberian ice sheet which is not present in our reference simulations. In North America it happens very often that the ice sheet expands too much over Alaska, making eventually a bridge between North America and Siberia. This feature is also found in other experiments by other groups (Willeit and Ganopolski, 2018), even with more complex models (e.g. Ziemen et al., 2014), but is known to be inconsistent with ice-sheet reconstructions. These ice sheets can become very resilient and they can survive a deglaciation due to the strong albedo feedback. We decided not to keep all these different geometries since they are too far away from our general understanding of ice sheet geometry changes through the two last glacial-interglacial cycles. Instead we have preferred to use relatively small changes with respect to the LGM configuration.

- A stronger discussion of model limitations and their implications (one of the reviewer’s comments has not been addressed sufficiently – regarding QGPV model at low resolution, review 2);

Reviewer 2 is correct in suggesting that QGPV approximations in atmospheric models is intrinsically inadequate to simulate parts of the tropical atmospheric circulation. This is a well-acknowledged limitation of QGPV model and that is why, in the early development of ECBilt (the atmospheric component of iLOVECLIM), additional ageostrophic terms have been added as potential vorticity forcings (cf. Opsteegh et al., 1998). This particularity might explain why the model has been shown able to reproduce to a first order some aspects of the tropical climate (Goosse et al., 2010), such as the East-Asian monsoon activity, even in its broad late Quaternary evolution when compared to water isotopologues proxy record (Caley et al., 2014).

This information was already added in our revised version of the manuscript. To be completely honest we do not know exactly what we should add with this respect.

If taken to face value, the comment of Reviewer 2 implies that any model that is not implementing the primitive equations to its fullest should not be used in coupled climate studies. This is both excessive and very limiting. Excessive in the sense that, at present, there are still many other models that implement various forms of the equations of the atmospheric circulation that are not the full implementation of the primitive equations. One can, for example, think about the statistical-dynamical atmospheric models class (cf. Petoukhov, 2003, POTDSAM ; Totz et al., 2018, AEOLUS1.0) or models that do implement the primitive equations in other forms (AEOLUS2.0, https://www.pik-potsdam.de/en/institute/departments/earth-system-analysis/models/aeolus-2.0) that are argued to be more pertinent for some aspects of the atmospheric variability (Rostami et al., 2022). Very limiting in the sense that even the appropriate discretization of the primitive equations can be disputed: should there be a limit on the number of vertical layers to describe the troposphere – stratosphere interaction? Are models such as simplified GCMs (Molteni, 2003, Kucharski et al., 2006, SPEEDY model ; Smith et al., 2008 & Smith, 2012, FAMOUS model) also too limited for this? Even further, one could argue that GCMs are also very inadequate to represent many aspects of the weather at fine scales, contributing to the climate potentially and that CRMs should be used (Stevens et al., 2020), while some others still argue to keep the GCM class (Balaji et al., 2022).

The latter type of reasoning is always pushing to have "more" and results in models that are way to computationally demanding to be useful at the timescales we are looking at in our manuscript, such that intermediate complexity retain its value (Kucharski et al., 2013).

Overall, the recent past record of publications in the field has shown that many aspects of the climate system, on a long-term basis, can be investigated with such models as the ones we cite here-above. Though not representing all aspects of the climate as one could wish for, they are still a valued tool to access realms that are not even accessible with GCMs.
The remark of the reviewer is an extremely general question that casts doubt on many results obtained with such kind of models over more than 40 years of scientific research. There is no study, to our knowledge, that show that the approximation made in our atmospheric model and others should dismiss the general conclusions we reach in our study. We thus do not feel that our paper should contain a dedicated paragraph on this matter since it is far beyond the target of our manuscript.

- Discussion of some earlier studies is too superficial;

We have largely rewritten the discussion section, in particular the limitations due to atmospheric model resolution. This section now reads:
"The simulated atmospheric circulation changes when using different ice sheet geometries at the PGM do not seem to impact drastically the individual ice sheet volume evolution through TII (Fig. S7). These can be caused by the low spatial resolution of our atmospheric model that can underestimate the atmospheric circulation changes. For example, Lofverstrom and Liakka (2018) used an atmospheric-only general circulation model at various spatial resolutions to generate climate forcings to run stand-alone ice sheet model simulations. They showed that the model ability to reconstruct the LGM ice sheets strongly depends on the spatial resolution of the atmospheric model, higher resolution showing generally better performance. The authors suggest in particular that the T21 spatial resolution is fundamentally inadequate to resolve numerically the baroclinic waves. Indeed, to insure stability of the numerical scheme, coarse resolution models show a larger diffusivity which dampens the waves (Magnusdottir and Haynes, 1999; Polvani et al., 2004; Lofverstrom and Liakka, 2018). However, while we use a T21 resolution, our model temperature biases are not comparable to the ones shown in Lofverstrom and Liakka (2018). For example, they show that their model at T21 is unable to reconstruct the Eurasian ice sheet, independently from the surface mass balance scheme they use. In our case, the model does build up an ice sheet in Western Eurasia and none in Siberia, even without the indirect bias correction that we use in the melt equation (Eq. 2 leads to increase crad in Eurasia, inducing more melt). This suggests that other biases (apart from numerical diffusion) can alter model performance and that the fact that our model correctly represents the LGM ice sheets might be the results of some compensating biases. More generally, using outputs from the Paleoclimate Modelling Intercomparison Project (PMIP) phase 3 and 4 LGM database to force ice sheet models, both Niu et al. (2019) and van Aalderen et al. (2023) show that most general circulation models do not provide suitable climatic forcing fields to reconstruct ice sheets in agreement with geological reconstructions. These deficiencies are generally not related to spatial resolution differences amongst participating models. However, for a given climate model, a higher spatial resolution will tend to have a more accurate representation of the topography and this will induce noticeable difference with its lower spatial resolution version (Lohmann et al., 2021). In fact, SMB is highly correlated to topography, notably due to the direct impact of elevation on surface temperature. This is why different groups have used different strategies to downscale ice-processes (Robinson et al., 2010; Fyke et al., 2011; Krebs-Kanzow et al. 2021; Crow et al., 2024). While the downscaling scheme that we use does not allow any improvement in the topographically-induced atmospheric circulation change, it nonetheless better capture the melt elevation feedback than a standard vertical lapse rate approach"

- The literature overview can be improved through citations of more studies presenting geological evidence of deglaciation modes through TI vs TII.

There are no strong evidence for the deglaciation pattern of the Northern Hemisphere ice sheets during TII (Pollard et al., 2023). This lack of constraints was already noted in the community modelling protocol of Menviel et al. (2019). The reconstructions of ice sheet during the PGM are also subject to considerable uncertainties, notably since the maximal ice sheet extension is not necessarily synchronous between the different ice sheets. Some regions of the Eurasian ice sheet show a maximal extent circa 160 kaBP, much earlier than the PGM (Hughes and Gibbard, 2018; Pollard et al., 2023).

We have added this precision in the introduction when we discuss the ice sheet geometry differences between the PGM and LGM:
“Nevertheless, the maximal expansion of the Eurasian ice sheet might have occurred significantly earlier than the PGM (Hughes and Gibbard, 2018; Pollard et al., 2023) and precise reconstruction of the PGM ice sheets is still lacking.”

More generally we have added a few additional reference for proxy data in the introduction. At the end of the paragraph discussing TII with respect to the palaeo records:

“Other types of records, such as speleothems or oceanic sediment data, display abrupt changes, concomitant with oceanic changes (Martrat et al., 2014; Govin et al., 2015; Cheng et al., 2016).”

And later, we added a new paragraph dedicated to a more direct inter-comparison of the two terminations. This paragraph reads:

“In summary, the last two glacial terminations display significant differences. In terms of ice sheet disintegration, there are some proxy data evidence for a higher rate of mass loss during TII with respect to TI (Carlson, 2008; Stoll et al., 2022; Grant et al., 2014). This higher loss rate might explain the long (~7 ka) period of weak AMOC across TII (Böhm et al., 2015; Deaney et al., 2017). A feature that significantly differs from the several shorter events during TI (McManus et al., 2004). If speleothem and oceanic records suggest that H11 share similar large scale characteristics with H1 or the Younger Dryas, these events largely differ in terms of timing of their occurrence during the termination (Martrat et al., 2014; Govin et al., 2015). In terms of ice sheet geometries, apart from the fact that they were different for the two glacial maximums (Svendsen et al., 2004; Pollard et al., 2023), the geometry changes through the terminations cannot be easily compared due to the lack of strong constraints for TII.”

With this decision, I encourage you to rework your manuscript and submit it for final decision.

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