Responses to Reviewer #1’s comments

This is an interesting and generally well-written manuscript, that explores the sensitivity of a simulated Eurasian Ice Sheet (EIS) to different forcings. I agree with the general approach – use a palaeo-ice sheet to explore the impact of different processes within the framework of an ice sheet model. I also think that such approaches are much needed to help elucidate the long-term processes that operate within ice sheets. We can increase the number of ice sheets we study by using the palaeo examples. However, I have a few major concerns, outlined below, which make me question the conclusions of the manuscript. The largest concern is that the main finding that atmospheric processes dominate over ocean processes for the EIS, is model set-up specific, rather than an interpretable generalization as presented.

The authors are very grateful to Reviewer #1 for taking the time to write such helpful, thorough and constructive comments. All the comments have been taken into consideration in the revised manuscript. Our responses are written in blue, and excerpts from the manuscript are italicized. Line numbers refer to the revised manuscript.

Major concerns:

Model specific result?

My main concern is that the results presented in the manuscript are specific to the model-setup, and not a general representation of the actual processes that drove the deglaciation of the EIS. Potential reasons why the results may be model specific are highlighted below (basal sliding, MISI, sensitivity to other parameters, spin up). These model specific results are interesting enough to other ice sheet modellers, and perhaps Quaternary Scientists who study the EIS. But, the manuscript is presented as if the model were close enough to reality that the results represent what the ice sheet actually did (for which there is no current verification conducted against say proxy records). Foremost, this requires a title change, perhaps: **Relative importance of the mechanisms triggering the Eurasian ice sheet deglaciation *in the GRISLI2.0 ice sheet model***

We acknowledge that our results may be specific to the GRISLI model and that we did not sufficiently emphasize this point in the original manuscript. Therefore, as suggested, we have modified the tittle to: Relative importance of the mechanisms triggering the Eurasian ice sheet deglaciation in the GRISLI2.0 ice sheet model.

Then throughout the manuscript, it is worth highlighting that this is a model-specific result. For example, in the abstract (L19) “EIS retreat is primarily triggered by atmospheric warming,” and the similar statement on L538, should add model-specific caveats.

Throughout the manuscript, we have tried to specify that our results were those obtained with the GRISLI ice sheet model by adding expressions such as: "with the GRISLI model" "using the GRISLI ice model", "this series of experiments conducted with the GRISLI ice sheet model (e.g. Abstract, Introduction, Section 4.2.5, Conclusion). Moreover, in the Discussion and Conclusion sections, we have added the following paragraphs:

Discussion:

The ISMIP6 project (Seroussi et al., 2020) shows a significant difference in ice sheet behavior depending on the ice sheet model used (Seroussi et al., 2020). Despite the numerous sensitivity experiments presented in this study with various parameter values and different parameterizations of the ice dynamics (see section 4.4.), we cannot totally exclude the possible model-dependency of our results To reduce the uncertainties associated with the use of a single ice sheet model, we strongly encourage other ice-sheet modelers to perform the same kind of sensitivity tests with several other ice sheet models having, if possible, higher resolution so as to better capture the fine-scale structure of outlet glaciers and the ice flow dynamics at the grounding line and the marine ice sheet instability.

Conclusion:

In order to assess the robustness of our analyses, we suggest to other modelling groups to reproduce the same kind of sensitivity tests with ice sheet models of similar or higher complexity. This pluralistic approach would allow to better understand the uncertainties associated with the ice sheet model used.

Unfortunately, this model dependency of the result makes the broader conclusion that the EIS (or parts of it) cannot be analogues for the West-Antarctic Ice Sheet (WAIS) unjustified. I also think this is poorly laid out in the manuscript, appearing only in the conclusions, rather than given proper thought in the discussion. Perhaps a section on “potential comparison to the WAIS” in the discussion is required, rather than appearance in the conclusions. Note that all of the below are not criticisms of the model, but rather reasons why the results may be model dependent.

Thank you for this interesting comment. We have followed your advice and developed our arguments in the abstract and the discussion section:

Abstract:

Due to the strong sensitivity of EIS to the atmospheric forcing highlighted with the GRISLI model and the limited extent of the confined ice shelves during the LGM, we conclude by questioning the analogy between EIS and the current WAIS, However, because of the expected rise in atmospheric temperatures, risk of hydrofracturing is increasing and could ultimately put the WAIS in a configuration similar to the past Eurasian ice sheet.

Discussion:

The second round of sensitivity experiments conducted with new values of climate-related parameters and new parameterizations related to the ice dynamics also confirm the high sensitivity of the EIS to the atmospheric forcing in the GRISLI ice sheet model. This contrasts with the current situation in the West Antarctic Ice Sheet (WAIS), where ice volume loss is mainly due to melting under the ice shelves (Pritchard et al., 2012). This difference in the response of the two ice sheets raises questions about the mechanisms responsible for their respective evolution.

In addition, WAIS is characterized by large areas of confined ice shelves exerting a buttressing effect on the grounded ice, whereas most of the ice shelves in our simulated LGM EIS are unconfined (see Section 4.4.2) However, as temperatures are expected to rise in the future, larger amounts of meltwater will be produced on the surface of the ice shelves (Kittel et al., 2021), favouring potentially the ice-shelf disintegration through hydrofracturing (Banwell et al., 2013; Lai et al., 2020). Although this process differs from basal melting, it could bring WAIS into a similar configuration to the past Eurasian ice sheet.

Basal sliding:

The model setup for basal sliding is inadequately described and the choice of sliding law seems at odds with the norm within ice sheet modelling. The sliding law used is linear (L138), but most models use a non-linear sliding law (e.g. a Columb “pseudo-plastic” law or the newer Zoet and Iverson (2020) law). The method of calculating N for equation 3 is inadequately described also – does this depend on a hydrology parameterisation? The reason this leads to a model specific result is that both factors will affect the pattern of ice streaming simulated by the model, and thus the thickness of ice at the grounding line which will influence retreat rates.

To better described how the effective pressure is calculated we added the following sentence (Section 2):

The effective pressure N depends on the groundwater hydrology which is calculated according to Darcy's law (Quiquet et al., 2018)

In order to investigate the impact of physical parameterizations we conducted a new series of sensitivity experiments (see Section 4.4.2, Figure 11 and Table 4). In particular, we changed the linear friction law used in the standard version of the GRISLI ice sheet model (GRISLI2.0) and used a plastic dragging law (i.e. Coulomb’s law) in which the friction varies quadratically with the basal velocity. With this new law, we performed a new 100 kyr spin-up simulation (constant LGM climate forcing) and new sensitivity experiments to atmospheric temperatures (+1 °C and +5°C) and to oceanic conditions (Kt= 10 $m°C^{-1}yr^{-1}$ and Kt = 50 $m°C^{-1}yr^{-1}$) to the same main conclusion (i.e. the atmospheric forcing dominates the ocean forcing in the EIS retreat at the beginning of the last deglaciation). In section 4.4.2, we have added the following paragraphs and the new figure (Fig. 11f, SP12g):

Another source of huge uncertainties lies in the choice of the basal friction law (e.g. Brondex et al., 2017, Joughin et al., 2019; Akesson et al., 2021). An appropriate choice of this law is of primary importance as basal friction exerts a strong control on the dynamics of the grounding line and fast-flowing ice streams. In our previous experiments, the basal friction was parameterized using a linear dragging law (Eq. 2). In order to investigate the extent to which the choice of the friction law can influence the sensitivity of the EIS to atmospheric temperature and basal melting perturbations we used a plastic dragging law where the basal drag depends quadratically on the basal velocity (Pattyn et al., 2017).

In contrast to previous works investigating the ice sheet sensitivity to friction laws, our findings reveal that experiments using the non-linear basal friction do not exhibit significant differences compared to EXP1 and EXP3 simulations after 1,000 and 10,000 years (Fig. 11f). However, it is important to note that Joughin et al. (2019) and Akesson et al. (2021) explored the sensitivity of the Antarctic ice sheet, which differs from the EIS configuration. This may explain (at least partly) why the EIS may exhibits a different sensitivity to changes in the friction law.

MISI and grounding lines:

An improvement to the model presented here is the inclusion of an analytical treatment of the grounding line. However, the coarse resolution of the model (20 km grid size) means that the ice thickness at the grounding line is likely poorly represented. Though there is subgrid treatment of ice velocity at the grounding line, this does not incorporate different values of elevation. Likely, this means an underestimate of the ice thickness variations across the grounding line, and hence a dampening of the marine ice sheet instability. Thus, a model that resolves the bed topography at the grounding line at higher resolution (e.g. BISICLES) may produce different results. This is especially the case for narrow fjord areas of Norway and the main troughs, which will be represented by a few pixels only at the mouth of the ice stream in the model.

We fully agree with this remark. We added a comment at the end of the discussion section pointing in this direction:

To reduce the uncertainties associated with a single ice sheet model, we strongly encourage other ice-sheet modelers to perform the same kind of sensitivity tests with several other ice sheet models having, if possible, higher resolution so as to better capture the fine-scale structure of outlet glaciers and the ice flow dynamics at the grounding line and the marine ice sheet instability.

This raises another point – are the differences between this paper and previous results (Petrini et al., 2019) a consequence of including the grounding line parameterisation or spin up procedure (the latter is the focus of the authors in the discussion, but the former is a big change to the model)?

Thank you for this comment. Indeed, Petrini et al, 2018 shows that the use of the grounding line flux in the PSU ice sheet model can decrease the sensitivity of BKIS to warmer ocean temperatures. To address this issue, we removed the parameterization of the grounding line flux in the GRISLI ice sheet model and conducted a new spin-up simulation (constant LGM forcing) and the same sensitivity experiments as for our tests related to the basal friction law (Tadd = +1 °C and +5°C; Kt= 10 m°C^{-1}yr^{-1} and Kt = 50 m°C^{-1}yr^{-1}). Compared to the reference simulations (EXP1 and EXP3.1), the only significant change was observed for Tadd = + 5°C at 10,000 years, with a substantial reduction of ice volume loss (i.e. ~14%). This means that in the absence of the grounding line flux adjustment, the importance of the atmospheric warming is reduced and the relative importance of oceanic warming is enhanced. This result obtained with our model fully contradicts the conclusions drawn by Petrini et al. (2018). This point has been developed in Section 4.4.2; see also Figure 11g, Fig. SP12a and Table 4):

Besides the climate related parameters, changes in the representation of the dynamic processes may have a strong impact on the relative importance of the mechanisms responsible for the triggering of the EIS retreat. For example, using the PSU ice sheet model (Pollard and De Conto, 2012), Petrini et al. (2018) found that the implementation of a grounding line flux adjustment reduces the sensitivity of BKIS. To go a step further and compare our findings with those of Petrini et al. (2018), we removed the grounding line flux parameterization in the GRISLI model and assessed its impact on the EIS sensitivity. Without the flux adjustment, the EIS sensitivity to basal melting and atmospheric temperature perturbations is reduced (Fig. 11e). This contrasts with the findings of Petrini et al (2018). More specifically, after 10 000 years, a + 5°C atmospheric perturbation results in a reduced amount of melting of about 14% compared to the reference experiment (with parameterization of the grounding line flux). In other words, these results suggest that in the absence of the grounding line flux adjustment, higher atmospheric temperatures can potentially enhance the ice sheet's sensitivity to oceanic forcing through grounding line retreat.

The sea level lowering of 120 m is also likely an under representation – is the bed depressed by isostatic loading?

We agree that a description of the isostatic rebound is missing. We have therefore added a description in section 2

In the GRISLI model, isostatic rebound is considered by the ELRA model (Elastic-Lithosphere Relaxed-Asthenosphere, Le Meur and Huybrechts, 1996). The relaxation time of the lithosphere under the effect of the mass of an ice sheet is about 3000 years, with a radius of about 400 km over which the effect of this mass applies.

Sensitivity to other parameters:

My reading is that the authors use a single set of parameters in their model, which are then exposed to different forcings. These parameters need listing, perhaps as a table in the supplement. However, this also raises a question of whether the results are dependent upon the choice of parameters, which are presumably left at some default value. For example, if calving rates, or positive degree day parameters were different then the response of the simulated ice sheet may be different. For example, lower positive degree day melt rates might lead to less sensitivity to climate. Similar changes may happen for a wide variety of parameters. Ideally, a wider set of parameter values would be used to make an inference about the EIS behaviour. But in the absence of a perturbed parameter ensemble experiment, this limitation should at least be noted.

Thank you for this interesting comment. The standard parameters of the GRISLI ice sheet model are listed in a new table (Table 2) added in the revised manuscript. We have not performed an ensemble of simulations to examine the EIS response to a wide range of parameter values. However, we conducted several sensitivity experiments by modifying the following parameters: the degree-day factors (Csnow and Cice in the PDD formulation), the vertical temperature gradient and the precipitation-to-temperature change ratio. Our objective was to examine whether a change in the values of these parameters led to a different relative importance of atmospheric forcing compared to oceanic forcing. The sensitivity experiments performed for each modified parameter are indicated in Table 4. The results are displayed in Figure 11 and described in Section 4.4.1. The analysis of these results leads to the following conclusion:

As such, this series of perturbed experiments shows that changing climate-related model parameters results in only small changes in the EIS ice volume loss compared to the standard configuration of the GRISLI ice-sheet model, and does not question the prevailing influence of the atmospheric forcing suggested by our reference sensitivity experiments.

We have also changed the calving cut-off criterion (from 250 m to 50 m) with the objective of increasing the area covered by ice-shelves. This is described in Section 4.4.2 dedicated to changes in physical parameterizations:

Thinning of confined ice shelves through basal melting produce a weakening of the buttressing effect, implying an acceleration of the grounded ice streams and ultimately a substantial ice discharge in the ocean. This sequence of events was observed in the Antarctic Peninsula after the collapse of the Larsen B Ice Shelf in 2002 (Rignot et al., 2004; De Rydt et al., 2015). In our reference experiments, the ice shelf extent is small (Fig. 3). This likely explains why the EIS appears poorly sensitive to basal melting. In order to potentially increase the area of ice shelves, we reduced the calving criterion from 250 m to 50 m. This results in a slight increase of the ice shelf area at the LGM (Fig. SP12d) compared to the reference simulations (Fig 3). However, this increase did not result in a substantial change of the sensitivity of the EIS to basal melt and atmospheric temperature perturbations (Fig. 11g). This limitation is due to the topography, which does not allow for adequate confined ice shelf development, unlike the Antarctic, where the presence of bays (in Ross and Weddell Seas for example) allows the formation of confined ice shelves.

Spin-up:

Both the spin up in this work and the previous (Petrini et al., 2019) assume some sort of (quasi?) steady-state at the LGM. However, the LGM was likely a snapshot in time, and in many places across the EIS was not achieved synchronously (see Clark et al., 2022 for an example across the BIIS). If a transient spin-up was applied, growing the LGM ice sheet to a non-stable extent, then a model may produce different results.

Thank you for this comment. The new Section 4.3 added in the revised manuscript addresses this issue. The transient spin-up method is described as follows:

For this purpose, we reconstructed a climatology evolving from the Last Interglacial (-127 000 years) to the LGM (-21 000 years) using a multi-proxy climatic index (Quiquet et al., 2021c). In the same way as above, we used the 10 PMIP3/PMIP4 forcings shown in Table 1. As the last interglacial simulations were not available for some of the PMIP3/PMIP4 models, we made the approximation that the -127 000 climate was represented by the pre-industrial climate (i.e. piControl experiments, Eyring et al., 2016).

Starting from the LGM ice sheets obtained with the transient spin-up experiment, we performed sensitivity experiments to oceanic conditions and atmospheric temperatures (see Table 4). The results are displayed in Figure 11 and described in Section 4.3. However, in this section, we explain in detail why the results obtained with this new experimental setup are not directly comparable to those obtained in the reference simulations for time scales longer than 1000 years (see also the new figure SP13). For short time scales (~1000 years), no significant difference is observed between the two series of simulations.

Other concerns:

I think for those who study palaeo-ice sheets from evidence (i.e. not modellers) the paper needs more explanation. Perhaps explicitly say you are not aiming to get the right timing/pattern of deglaciation, but rather explore the sensitivity of this model. This should come around L89, and would help this other community engage with your work.

Following the reviewer's suggestion, we have added the following sentence in the Introduction section of revised manuscript:

Our ultimate objective is not to reproduce the exact timing of the last deglaciation of the EIS but rather to explore the sensitivity of EIS to various perturbations using the GRISLI ice model.

Minor corrections:

- L12 – only the BKIS is generally talked about as an analogue to WAIS, not the whole EIS. Modified: EIS → BKIS
- L26 – typo in "pas**t**»: Done
- L50 remove "the" from "of the marine…" Done
- None of the papers have dates in the reference list. Done
- Code availability should be listed at the end of the manuscript. Sorry for this omission. We added the following at the end of the manuscript: *Code availability. The GRISLI2.0 code is available upon request from Aurelien Quiquet (aurelien.quiquet@lsce.ipsl.fr) and Christophe Dumas (christophe.dumas@lsce.ipsl.fr) (Laboratoire des Sciences du Climat et de l'Environnement, LSCE).*

Overall

Overall, I would like to see this manuscript published, as I am sympathetic to the aims. But substantial revisions are required to improve the robustness of the results. What is really required is an inter-model comparison. I am not suggesting the authors conduct such an approach, but perhaps this is something the authors might suggest in the discussion. Instead, a refocussing towards the specifics of this model is recommended. I hope my comments help in improving the manuscript.

Thank you once again for your comments. We did our best to address all your suggestions. We hope that the changes made in the revised manuscript will greatly improve the clarity of our objectives and the robustness of the main conclusions drawn from the analysis of the GRISLI model simulations.

Responses to Reviewer #2’s comments

General comments:

This manuscript presents an interesting study of the Eurasian Ice Sheet, addressing a wide range of configurations towards the Last Glacial Maximum under different climate forcings and evaluating the mechanisms that might have triggered its deglaciation.

Overall, the manuscript presents a nice approach, using a palaeo-ice sheet to explore the impact of individual processes needed to account for the mechanisms involved in the growth and demise of EIS. My comments mainly concern the finding of the dominance of atmospheric processes over ocean processes for the EIS and its dependence on the parameters chosen. The following suggestions will contribute to strengthening the analysis and conclusions.

The authors are very grateful to Reviewer #2 for taking the time to write such helpful, thorough and constructive comments. All the comments have been taken into consideration in the revised manuscript. Our responses are written in blue, and excerpts from the manuscript are italicized. Line numbers refer to the revised manuscript.

Specific comments:

Result-dependence on the parameters chosen. The first filter to select the global circulation models that reproduce in a good manner the geometry of EIS are the positive degree day (PDD) factors, the precipitation correction with the temperature, and the lapse rate. A sensitivity analysis of those factors will clarify if the finding is robust.

Thank you for this feedback. To address this comment, we have performed new spin-up simulations (100 kyr under constant LGM climatic forcing) and new perturbation experiments of the atmospheric temperature and the oceanic conditions (Tadd = +1 °C and +5 °C; Kt= 10 $m°C^{-1}yr^{-1}$ and Kt = 50 $m°C^{-1}yr^{-1}$). We have also modified the standard values of the degree-day factors, the factor controlling the precipitation correction with temperature and the lapse rate. As the main conclusion of the paper is the prevailing effect of the atmospheric forcing over the oceanic forcing in the EIS retreat at the beginning of the last deglaciation, the new values of model parameters have been chosen as to reduce the relative importance of the atmospheric forcing. The list of the new sensitivity experiments is given in the new Table 4. These new experiments and the related conclusions are described in a new section in the revised manuscript (Section 4.4.1). The results are displayed in Figure 11. The analysis of these results leads to the following conclusion:

As such, this series of perturbed experiments shows that changing climate-related model parameters results in only small changes in the EIS ice volume loss compared to the standard configuration of the GRISLI ice-sheet model, and does not question the prevailing influence of the atmospheric forcing suggested by our reference sensitivity experiments.

A list of key parameters and the range of values that were tested should be included.

Besides Table 4 that is related to the new sensitivity experiments, we have also added two Tables (Table 2 and Table 3) that list the model parameters (and their value) and the physical parameterizations used in the GRISLI2.0 ice sheet model.

As mentioned before, the conclusions are highly dependent on the parameters. For instance, different PDD factors and calving rates might lead to a different sensitivity to the climate.

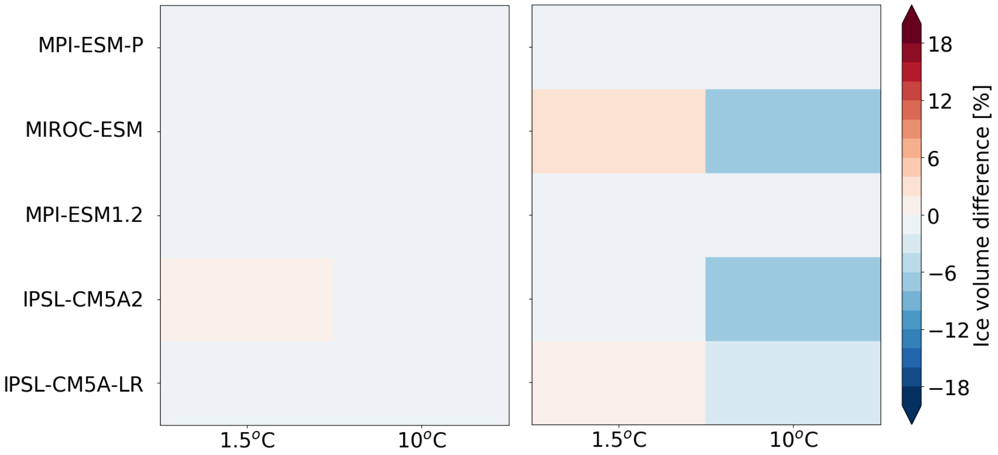
We have also changed the calving cut-on criterion (from 250 m to 50 m) with the objective of increasing the area covered by ice-shelves. This is described in Section 4.4.2 dedicated to changes in physical parameterizations:

Thinning of confined ice shelves through basal melting produce a weakening of the buttressing effect, implying an acceleration of the grounded ice streams and ultimately a substantial ice discharge in the ocean. This sequence of events was observed in the Antarctic Peninsula after the collapse of the Larsen B Ice Shelf in 2002 (Rignot et al., 2004; De Rydt et al., 2015). In our reference experiments, the ice shelf extent is small (Fig. 3). This likely explains why the EIS appears poorly sensitive to basal melting. In order to potentially increase the area of ice shelves, we reduced the calving criterion from 250 m to 50 m. This results in a slight increase of the ice shelf area at the LGM (Fig. SP12d) compared to the reference simulations (Fig 3). However, this increase did not result in a substantial change of the sensitivity of the EIS to basal melt and atmospheric temperature perturbations (Fig. 11g). This limitation is due to the topography, which does not allow for adequate confined ice shelf development, unlike the Antarctic, where the presence of bays (in Ross and Weddell Seas for example) allows the formation of confined ice shelves.

For better analysis and understanding of the reader, the multi-model mean of the ice thickness should be shown as a reference. → Done (see the new figure 3 in the revised manuscript)

Although the sensitivity experiments performed in this study cover a wide range of possible drivers (EXP1-5), experiments conducted to evaluate the impact of changing both oceanic forcing and the sea level could be performed.

This is a very interesting suggestion because sea-level rise can lead to changes in the geometry of both grounded ice sheet and ice shelves. In turn, changes in the EIS configuration could modify its sensitivity to oceanic conditions. Following this suggestion, we have performed additional experiments by combining a sea-level perturbation (+10 m with respect to -120 m) and an oceanic temperature perturbation (+1.5°C and +10°C). The results are displayed in the following figure:



Differences in ice volume loss (in %) between the experiments combining sea level and oceanic perturbations and the corresponding EXP3.2 experiments.

As shown in this figure, differences with the EXP3.2 experiments are negligible on time scales of 1000 years. On longer time scales, differences do not exceed 7% for only two GCM forcings. We commented these results in the revised manuscript at the end of Section 4.2.5 :

However, it should be noted that sea level rise can lead to changes in the geometry of the ice sheet and floating ice shelves. Therefore, these changes in the EIS configuration may influence its sensitivity to oceanic temperature perturbations. We tested this hypothesis by raising the sea level from -120 m to -110 m compared to the current level and by raising concomitantly the oceanic temperatures (+1.5°C and +10°C). Adding a sea level perturbation to the oceanic temperature perturbation does not drastically change the response of the ice sheet. Differences of 6 to 7 % in ice volume losses were only observed for the highest temperature perturbation (+10°C) after 10 000 years for only two GCM forcings (MIROC-ESM and IPSL-CM5A2), while the differences are negligible (lower than 2%) for smaller perturbations, shorter timescales and other GCM forcings (not shown).

Technical corrections:

L126: “Bmelt” instead of “bmelt” “done”

L515: “4-1” instead of “4_1” “done”