Response to reviewer 2

We found both reviewer‘s comments very constructive and helpful. Thank you very much for helping to improve the manuscript! In particular, we have now extended our discussion and improved all figures. In this document we have compiled our replies to all raised issues and comments. The referee‘s texts are in black print, while our responses to each item are in blue and changed text passages are given in green. This pdf file contains our responses in the order of the reviewer‘s comments. New figures for the manuscript and supporting figures are included at the end of this response.

General comments:

Since the main novelty of the study lies in estimating SMB changes with and without PLs which might partially counteract the positive feedback from ice dynamics, it would be useful to compare these estimates with the increase in ice discharge found by Quiquet et al. under similar conditions for the Laurentide Ice Sheet, as well as with the GLAC1D mass loss rates for this period. This would possibly stress the need that coupled lake–ice–atmosphere modeling is required to properly assess the importance of PLs during deglaciation.

We thank the reviewer for this helpful suggestion. We have expanded the discussion in two ways:

(i) A direct comparison with Quiquet et al. 2021 is not straightforward as the ice sheet is substantially flatter with a much larger ablation zone during the peak PLISI period. Our climate response would result in a stronger absolute SMB effect for this topography.

(ii) We have substantially modified the “Balance between dynamical ice loss and climatic SMB feedbacks” paragraph of the discussion and now discuss our results in the context of other modelling experiments and evidence from reconstructions.

For (i) we have modified the paragraph “Surface mass balance response to proglacial lakes under deglacial conditions”:

The relative sensitivity of surface melt to the presence of proglacial lakes is comparable to that reported for peak glacial conditions (Colleoni et al., 2009) and also ice-dammed lakes developing during the early inception of the Eurasian Ice Sheet Complex are found to exert a similar effect (Krinner et al., 2004, Peyaud et al., 2007). However, the resulting impact on total surface mass balance differs markedly during deglaciation, because the ratio of ablation to accumulation is substantially higher. In the present experiments, the lowered ice-surface and reduced slope of the southward facing part of the Fennoscandian Ice Sheet leads to a widening of the ablation zone while the Laurentide Ice Sheet is less advanced and does not yet show advanced downwasting. As a result, total ablation exceeds accumulation by more than a factor of two and is likely to become more dominant as deglaciation progresses. This contrasts with conditions during the peak of the penultimate glacial period (around 140ka BP), when accumulation was the dominant component of the surface mass balance (Colleoni et al., 2009).

and for (ii) in: Balance between dynamical ice loss and climatic SMB feedbacks: Proglacial lakes exert a dual influence on ice-sheet evolution through opposing climatic and dynamic feedbacks, potentially decoupling deglacial ice-sheet behavior from global climate forcing. We find that explicitly coupling proglacial lakes to the climate system increases the surface mass balance of neighbouring ice sheets by suppressing summer melt and reducing mass loss by roughly 20–30%. The simulated absolute increase in surface mass balance of both ice sheets combined corresponds to a sea-level equivalent of more than 30 cm per 100 year, opposing deglacial sea level rise which by comparison was in the order of 1m per 100 years over the main deglaciation (Lambeck et al., 2014).
For the Laurentide Ice Sheet proglacial lakes increase surface mass balance and reduce mass loss by ~600 Gt for the geometry considered here. In a simulation with a fast retreating interactive ice sheet, this negative feedback would become even larger through the melt–elevation feedback under progressive downwasting of the ice sheet. Complementary to this negative feedback, recent modeling studies have studied the positive dynamic feedback, while neglecting the climate response. Proglacial lake-induced ice-sheet instabilities (PLISI) may increase Laurentide Ice Sheet mass loss by more than 3000 Gt yr^{-1} (Quiquet et al., 2021). Our results suggest that the deglaciation of Northern Hemisphere ice sheets may have been modulated by the balance between opposing dynamical and climatic effects. A conceptual picture emerges in which lake-induced instabilities initially promote rapid mass loss and margin retreat, followed by a phase in which sufficiently large proglacial lakes exert a stabilizing climatic influence by cooling the regional atmosphere and reducing ablation. Indeed Austermann et al. (2022) find that between 14.2 and 11.5 ka, retreat rates inferred from geological reconstructions were significantly higher at lake-terminating than at land-terminating margins, whereas this contrast was less pronounced before and after this interval. However sensitivity studies also reveal that the strength of the dynamic feedback strongly depends on complex processes and poorly constrained basal boundary conditions, including basal friction, ice–lake interactions, glacial isostatic adjustment, and changing lake levels or drainage events (Scherrenberg et al., 2024, Austermann et al., 2022, Hu et al., 2025), which may be another reason why geological reconstructions exhibit a more heterogeneous retreat history than represented in the above simulations with ice-only models or models of intermediate complexity: The southern Laurentide Ice Sheet exhibits highly variable ice-stream configurations and periods of stagnation and readvance (e.g. Dyke et al., 2003, Margold et al., 2018, Dalton et al., 2020, Norris et al., 2024) and contrasting retreat patterns of the Fennoscandian Ice Sheet between Bølling–Allerød and Younger Dryas despite a continuous presence of the Baltic Ice Lake (Stroeven et al., 2016).

I understand that the boundary conditions at 13 ka represent climatic conditions characteristic of deglaciation, resulting in a negative SMB for the Fennoscandian Ice Sheet and a positive SMB for the Laurentide Ice Sheet. However, the PLs clearly modulate the SMB regardless of whether the ice sheet is actively deglaciating. Here,

this effect is presented as a negative feedback on ice-sheet retreat and deglaciation, but the same mechanism may also influence ice-sheet advance and could therefore be important in the broader context of glacial cycles. I think emphasizing this point would strengthen the discussion section.
We agree that this feedback is not limited to deglaciation and the similar effect during inception is now also included in the discussion, paragraph "Surface mass balance response to proglacial lakes under deglacial conditions" as above.

Specific comments:

Units should be separated from numerical values by a space. OK

L7: There are two climatic effects, correct? Reduced precipitation and increased temperatures. Yes, the abstract has been restructured and reformulated.

L25–26: Does this refer to the additional ice loss caused by including PLs, or to the total ice loss with PLs included? Providing the increase relative to the control case would be useful for comparison.
Yes, the reviewer is correct. We have clarified the text as follows. We have reformulated this sentence:
For the deglaciation of the Laurentide Ice Sheet the coupled simulations with an Earth system model of intermediate complexity from Quiquet et al. (2021) suggest that proglacial lakes cause additional mass loss of 3000Gt per year.

L28: "Subglacial" rather than "subaqueous"? "Subaqueous" would imply beneath the water body. Correct- we have changed this accordingly.
L60–67: Are the boundary conditions kept constant throughout the simulations? The simulation setup is somewhat unclear, although using climate conditions representative of ~13 ka seems reasonable.
We have changed this:
These conditions include 13ka orography and land ice cover according to the GLAC1D reconstruction (Tarasov et al., 2012) (Fig. S1 in the Supplement), and constant orbital parameters (Berger, 1978) and atmospheric greenhouse gas concentration (Köhler et al., 2017)

L71: Are the lakes removed from REF13ka reintroduced in PL13ka, or are only the lakes identified by lakeCC included? The PL13ka experiment uses the same lake mask as experiment REF13ka + the proglacial lakes
L84: Are the boundary conditions kept constant throughout the simulation? I assume they are. Yes. We have included this: These conditions include 13\,ka orography and land ice cover according to the GLAC1D reconstruction (Tarasov et al., 2012, Fig. S1 in the Supplement), constant 13\,ka orbital parameters (Berger, 1978) and atmospheric greenhouse gas concentration Koehler et al. (2017).
Are the ocean surface conditions from 15 ka obtained by averaging years 14.1–14.0 ka from the simulation initialized at 15 ka, after running for 100 years and averaging over the final century?
This was not clear enough in the method part. We have modified line 63-65:
However, ocean surface conditions and land sea mask, not available for 13ka , are

taken from a simulation with the global coupled climate model AWI-ESM2 (Sidorenko et al., 2019)
that has been integrated for 1000 years under constant 15ka boundary conditions, orbital parameters and atmospheric greenhouse gas concentration

L91: "…for the present-day Greenland Ice Sheet". We have added this.
L97–100: The paragraph beginning "The additional cooling … Supplement Material" may fit better in the Materials and Methods section.
We appreciate this suggestion. We considered moving this paragraph to the Methods section, but decided to retain it in the Results because it presents an analysis of the simulation output rather than a part of the experimental setup.
L127: Please refer to Figure 1. OK
L132: Please refer to Figure 2. OK
L139: At what rate does this occur, and from which source? Could the rate from GLAC1D be provided? Yes, we can do so.
L144: SMB → "our modeled SMB". OK
L198: "lakes" → "lakes under deglacial conditions". OK.
L201: Please remind the reader when the Saalian glaciation occurred.
We will now use penultimate glacial period and specify the time as 140ka.

Figures Figure 1

- "test" → "t-test"? Yes.
- The upper-center panel label "PL_1kawarm" should presumably be "PL13ka_warm".

We have corrected this.
Figure 2

- "test" → "t-test"?

We have corrected this.

Figures 1–3

- Consider using a shared color bar and shared column titles to reduce whitespace and improve readability.
- The SMB estimates are useful for comparison with the positive feedback from ice dynamics.

Figure 4

- The units do not appear to be correct. Should they be mm ice equivalent, water equivalent, or snow equivalent? Since this is a flux, units of mm m-2 do not make physical sense. It should likely be expressed simply as mm or perhaps mm yr-1, if representing annual melt or melt rate.
- Why do the left and right panels not contain the same circles? The caption says they represent the same experiments and grid points, only with different color coding.
- The font size is somewhat small.

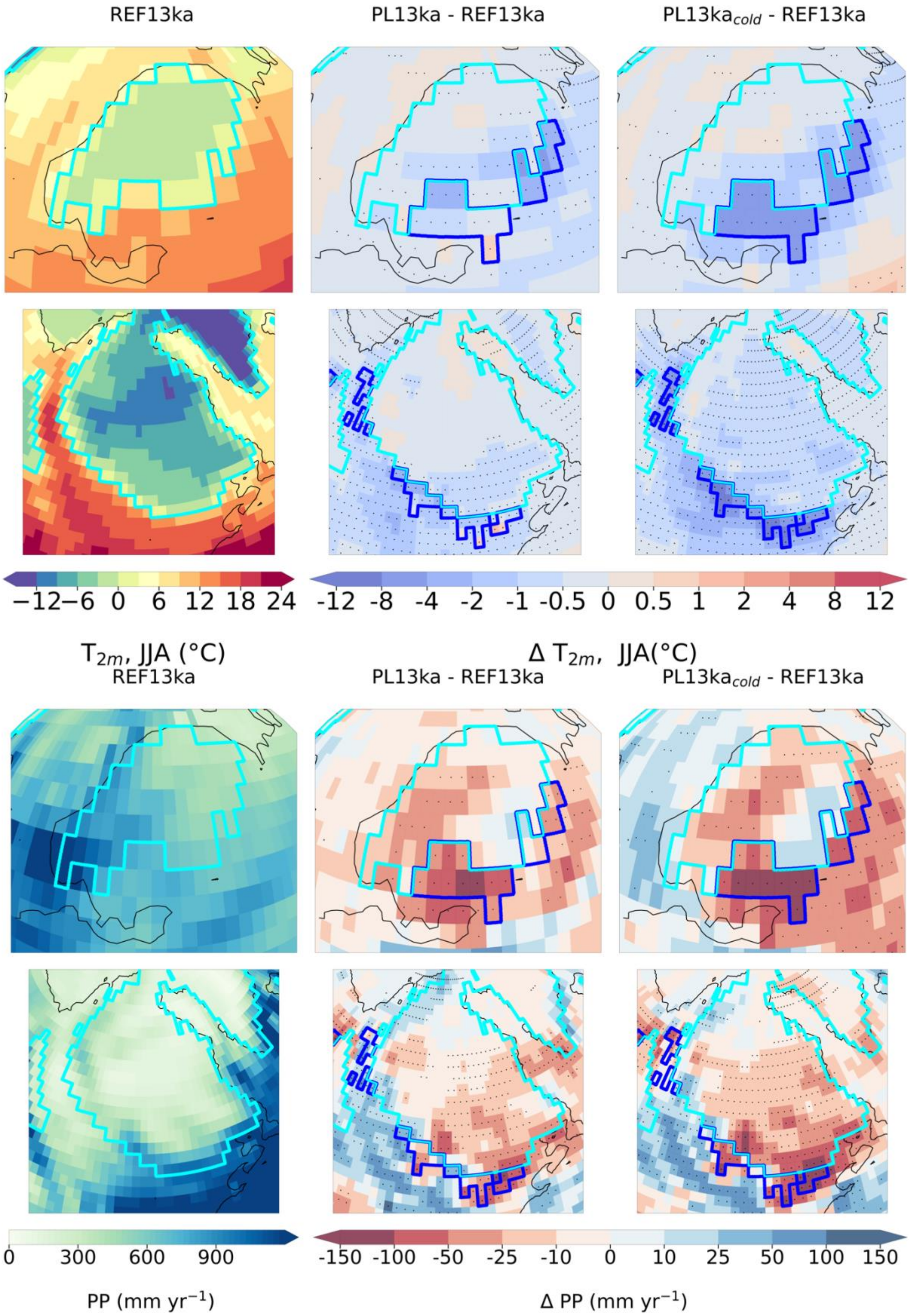
The left panel includes values from the Cordillearen and Greenland Ice Sheet- this is now explicitly stated in the caption. The unit should have been kg/year. We have updated and improved all figures accordingly.

References:

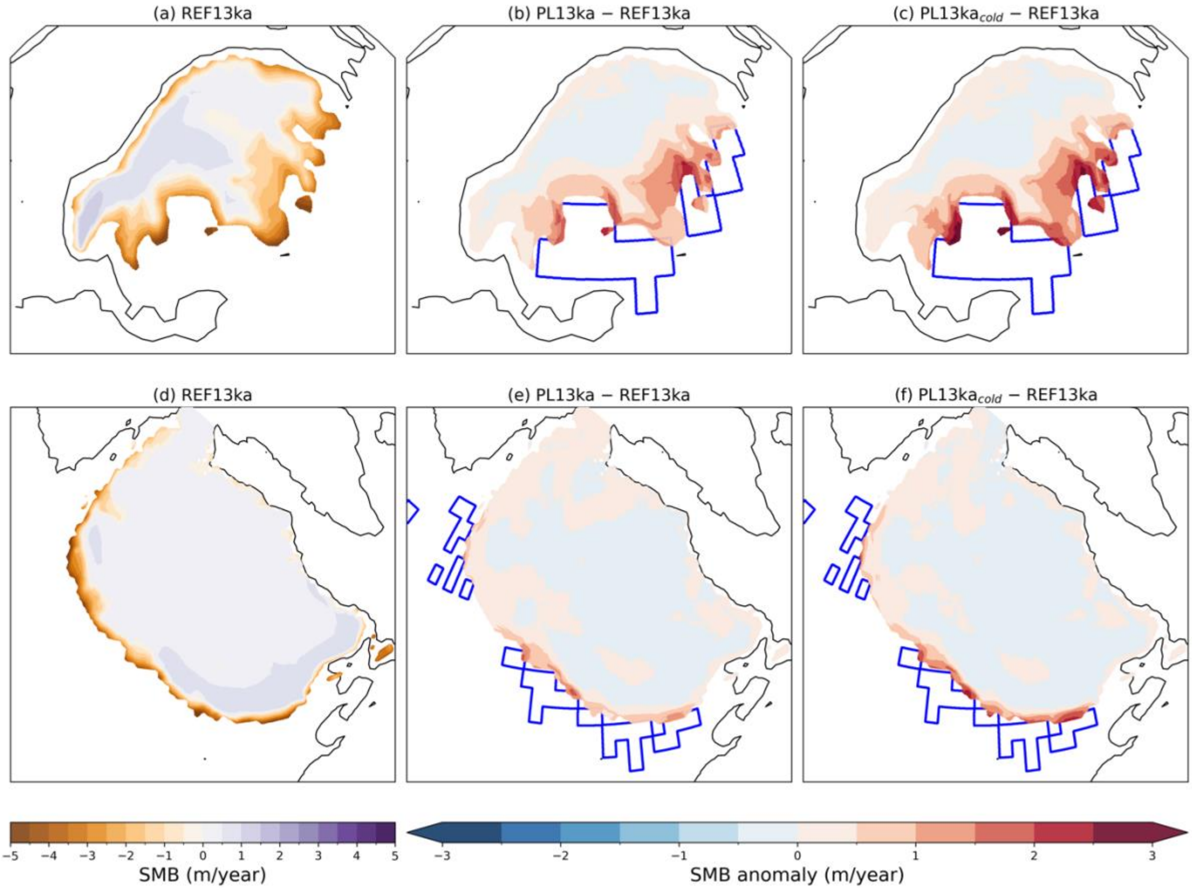
Lambeck, K., Rouby, H., Purcell, A., Sun, Y. & Sambridge, M. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. Proc. Nat. Acad. Sci. ***111****, 15296–15303 (2014).*

Margold, M., Stokes, C. R., and Clark, C. D.: Reconciling records of ice streaming and ice margin retreat to produce a palaeogeographic reconstruction of the deglaciation of the Laurentide Ice Sheet, Quaternary Sci. Rev., 189, 1–30, https://doi.org/10.1016/j.quascirev.2018.03.013, 2018.

Norris, S. L., Margold, M., Evans, D. J. A., Atkinson, N., and Froese, D. G.: Dynamical response of the southwestern Laurentide Ice Sheet to rapid Bølling–Allerød warming, The Cryosphere, 18, 1533–1559, https://doi.org/10.5194/tc-18-1533-2024, 2024.



REF13ka
PL13ka - REF13ka
PL13ka$_{cold}$ - REF13ka
−12 −6 0 6 12 18 24
-12 -8 -4 -2 -1 -0.5 0 0.5 1 2 4 8 12
T$_{2m}$, JJA (°C)
Δ T$_{2m}$, JJA(°C)
REF13ka
PL13ka - REF13ka
PL13ka$_{cold}$ - REF13ka
0 300 600 900
-150 -100 -50 -25 -10 0 10 25 50 100 150
PP (mm yr^{-1})
Δ PP (mm yr^{-1})



(a) REF13ka
(b) PL13ka − REF13ka
(c) PL13ka$_{cold}$ − REF13ka
(d) REF13ka
(e) PL13ka − REF13ka
(f) PL13ka$_{cold}$ − REF13ka
−5 −4 −3 −2 −1 0 1 2 3 4 5
SMB (m/year)
−3 −2 −1 0 1 2 3
SMB anomaly (m/year)