Response to reviewer1

We found the reviewers' 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:

• Time period choice – In the abstract you state that the time period choice for this experiment is 'inspired by the Allerød interstadial' but nowhere in the text do you give a full justification for the time period chosen. Is your time period choice intended to suggest that the formation of large proglacial lakes at the end of the Allerød interstadial could have caused dramatic cooling and ice margin stabilisation during the Younger Dryas? I don't think there is necessarily anything with the time period chosen, I would just like a more clear framing of why this time period was chosen and a bit of caution about the insights that can be taken from this time period.

We have chosen the Allerød because it was a period when the proglacial lakes of both the Laurentide and. Fennoscandian ice sheet were both quite extensive. We added this to the modified abstract:

Here, we quantify this atmospheric feedback for the Laurentide and Fennoscandian ice sheets using an atmospheric model coupled to an ice-sheet surface mass balance scheme in simulations representative of the Allerød (~13 ka), which was a period during which large proglacial lakes formed at the margins of both the North American and European ice sheets.

• The time period choice is also interesting because you set up your model and evaluate the influence of these lakes, but there is a considerable lake history prior to 13ka. I wonder what role considering this longer lake history would have? Suggesting lakes as a stabilising influence due to the dramatic influence they hold over climatic conditions is maybe complicated by the fact that lakes tend to grow slowly following ice sheet retreat. Is there a threshold you believe that would tip lakes over into being a stabilising influence?

Because the atmosphere has a relatively short adjustment timescale compared with lake evolution, we expect the climatic response to closely follow changes in lake extent. The strength of the response will depend on the heat capacity of the lacustrine mixed layer and consequently will grow slowly with lake area. Consequently we do not expect to see rapid climate change while lakes form and grow, but complete lake drainage events might cause abrupt shifts in regional climate.

• You state throughout that this modulates ice sheet retreat, but the approach taken doesn't directly demonstrate this since the ice sheet geometry is fixed and you aren't actually modelling dynamic retreat. I would suggest stating this more cautiously as a potential modulating influence that should be tested in coupled ice-climate models. This would frame your work better as a potential first step towards this goal, which I feel is more appropriate.
We agree that our experiments do not directly simulate changes in ice-sheet geometry through time. Our conclusions therefore concern the climatic influence of proglacial lakes on surface mass balance rather than ice-sheet evolution itself. The cooling response is nevertheless consistent with previous modelling studies. The magnitude of the temperature anomaly of ~1 K is consistently found in various studies (Hostetler et al., 2000, Krinner et al., 2004, Colleoni et al., 2000). If proglacial lakes form or vanish on millennial time scales this regional cooling may very well modulate the long-term warming trend and thereby also the surface mass balance (continental summer temperatures rise by ~10 K or less from Last Glacial Maximum to Holocene, Bartlein et al., 2010).

• Following up from that, I feel like you could be a little more confident in your conclusions if you attempted to make some comparisons to geological records to potentially highlight these results. Without any attempt to make this comparison it feels like the study should be phrased a little more conservatively as a kind of model sensitivity analysis.
We agree that comparison with geological evidence would be valuable. However, because our simulations isolate a single process under fixed boundary conditions, a direct quantitative comparison with geological reconstructions is beyond the scope of the present study. To better acknowledge this limitation, we have rewritten the entire abstract and now explicitly classify our experiments as a sensitivity study: These sensitivity experiments demonstrate that cold proglacial lakes can partially offset the positive dynamic feedbacks associated with deglacial lake formation, highlighting an important stabilizing climate feedback during ice-sheet retreat.
We have also extended the discussion (in: “Balance between dynamical ice loss and climatic SMB feedbacks”) to acknowledge the sensitivity of PLISI to various boundary conditions and the complex picture which arises from reconstructions:
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).

• As a follow on, is there any comparison of the LakeCC outputs you have generated and geologically reconstructed lake extents? Are your lakes realistic?
LakeCC as a tool to identify lakes has been evaluated in Hinck et al. (2020) and the lake mask compares qualitatively well with Dyke et al. (2004). If LakeCC was used with a different land surface reconstruction slightly different lake configurations might arise.
• Why are ocean surface conditions and a land sea mask taken from a 15ka simulation? Some of the model setup feels quite brief and could be expanded upon.
Using the 15ka simulation for the ocean boundary condition was a pragmatic choice- coupled climate models including an ocean component require a long (~1000year) spin-up and the 15ka coupled simulation was readily available. We modified the respective sentence to:
However, ocean surface conditions and land sea mask, not available for 13ka , were taken from a 15ka simulation with the global coupled climate model AWI-ESM2
We also might add the following sentences to the Method section: In any event, the drivers of the Allerød interstadial are poorly understood and the millennial-scale variations during fundamental climate transition are almost impossible to reproduce in coupled climate simulations- a more consistent model set-up would not necessarily be more realistic.
• How much does lake size matter. In North America (even in your simulation), you also have a second large glacial lake (glacial Lake McConnell). What is the influence of these smaller lakes?
Unfortunately we did not analyze the influence of individual lakes.

• How could model resolution affect your results? In your simulations Agassiz is just 11 pixels, would a higher resolution model have much of an impact? In general, it feels like there are no other sensitivity tests for other parameters that might influence the results? But, again, my direct experience of modelling is limited so I would leave this to another reviewer to hopefully comment on the appropriateness of this set up. It currently just feels like the uncertainties are not super well constrained and I do believe the results are valuable, but that this could be framed more as a first step.
In our experiments the lakes dampen the seasonal temperature amplitude due to their heat capacity. The resulting cooling in summer should be quite robust. What might be sensitive to model parameters and boundary conditions is the spatial distribution of this cooling as this depends on regional atmospheric circulation.
• On all figures, the choice of line colour to delineate lakes and ice could be slightly higher contrast, currently I find it difficult to distinguish. Perhaps using a black outline for ice and a blue outline for lakes could be a better contrast.
We have improved the figures accordingly and attach them below.
• The naming scheme of the simulations – currently you describe your reference simulation, the warm lake simulation and then the cold lake simulation. Whenever I was reading the manuscript I kept reading PL13ka and expecting it to be the warm simulation, just because that one was introduced first. Could we possibly rename PL13ka to PL13kacold. I think it would just be clearer to always state whether the lake simulations are warm or cold.
Good point, we have renamed the PL13ka experiment to $PL13ka_{cold}$ but renamed PL13ka_{warm} simply to PL13ka, which is maybe also intuitive, as these are not especially warm lakes.
• I would appreciate a greater description and comparison of the differences in lake influence between the two areas. It looks like the influence of Agassiz is greater across North America, than for the Fennoscandinavian lake. Is this true? Why? Any other comparisons of the effects would also be interesting. What are the reasons for the changing precipitation patterns between different simulations?
The Fennoscandian Ice Sheet already has a lower surface and the deglaciation is further advanced. In the discussion we have added to the paragraph "Surface mass balance response to proglacial lakes under deglacial conditions":
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.

• I am not a palaeoclimate modeller but a 250 year model spin seems a little short, is there a reason for this? Or I might just be wrong and this length is appropriate!
For a coupled climate simulation 250 years would not be sufficient, indeed. Due to the short memory of the atmosphere, this spin-up period is however sufficient.
Line-by-line comments:
Abstract – The opening line is a little confusing, you state that proglacial lakes existed and that they were cold… But why? I don't get a sense of the importance of the study or why the lakes being cold matters.

Please be explicit that large lakes developed, they were cold and that this may have influenced climate and stabilised ice sheet retreat. It might also be worth highlighting in the abstract that previously people have suggested lakes are a destabilising influence and that you are attempting to assess the opposite.You bring this in at the end, but I feel like you could have this element earlier to stress the importance of your work.

We have modified the abstract:

During the last deglaciation, large proglacial lakes formed along the margins of retreating continental ice sheets. Sustained by meltwater inflow and iceberg calving, these lakes likely remained cold throughout summer and may have modified the regional climate, potentially reducing ice-sheet melt. While proglacial lakes are commonly regarded as promoting ice-sheet retreat through dynamic interactions with the ice margin, their climatic influence may instead act to stabilize retreat. Here, we quantify this atmospheric feedback for the Laurentide and Fennoscandian ice sheets using an atmospheric model coupled to an ice-sheet surface mass balance scheme in simulations representative of the Allerød (~13 ka), which was a period during which large proglacial lakes formed at the margins of both the North American and European ice sheets. We show that cold proglacial lakes reduce summer air temperatures over a broad surrounding region, while decreasing precipitation and increasing the snow-to-rain ratio. These effects are enhanced when lake temperatures are constrained below 4 °C to represent continued cooling by meltwater inflow and iceberg calving. In our simulation, total melt decreases by 18% and 27% for the Laurentide and Fennoscandian ice sheets, respectively, and by 23% and 35% with additional lake cooling. These sensitivity experiments demonstrate that cold proglacial lakes can partially offset the positive dynamic feedbacks associated with deglacial lake formation, highlighting an important stabilizing climate feedback during ice-sheet retreat.

Line 19 – The Austermann reference is more complicated than highlighting just dynamic retreat. This approach looking at geological evidence (Figure 4) shows a complicated relationship with lakes sometimes driving fast ice margin retreat and sometimes not seeming to have much of an influence. This is a good justification for your study and I think you could make more of some of these kinds of observations. I think you could actually use the output from this study, look at the changing lake area during deglaciation and compare it to changes in ice sheet extent based on ice margin reconstructions (e.g. the Dalton reconstructions) and see whether there is a point where larges lakes relate to slower ice margin retreat as a way to support your model observations.

Scherrenberg et al. (2024) as well Austermann et al. (2022) and Hu et al. (2025) demonstrate that PLISI is very sensitive to various boundary conditions. We therefore interpret the spatial variability in reconstructed retreat as reflecting the combined influence of multiple interacting processes - a quantitative comparison between reconstructed lake extent and ice-margin retreat would be an interesting study in its own right. However, we believe it falls beyond the scope of the present manuscript, whose aim is to isolate the climatic feedback associated with proglacial lakes. We have however extended the discussion as provided above in the paragraph “Balance between dynamical ice loss and climatic SMB feedbacks.

Line 50 – When you talk about the Allerød interstadial, especially in the first mention, you should describe what it is, including defining the full time period of the interstadial (13.9-12.9ka). This is important context for readers to highlight that you are focusing on the end of a warm period.
We now introduce the Allerød as follows:
We conduct these sensitivity experiments under otherwise identical deglacial boundary conditions representative of the Allerød, the second part of the Bølling-Allerød interstadial (13.9-12.9 thousand years before present), a warm excursion from the last deglaciation associated with a strengthening of the Atlantic Meridional Overturning Circulation and increasing Northern Hemisphere summer insolation. During this interval, rapid retreat of the Laurentide and Fennoscandian ice sheets led to the widespread development of large proglacial lakes.
Line 51 – Should it not be 'atmospheric general circulation model'
Yes, we will correct this.

Line 54 –'… allows us to investigate…'
OK, we will correct this.

Line 64 – Why are ocean conditions from 15ka used for a 13ka simulation?
See answer above.
Line 85 –'appear to be sufficiently equilibrated' How did you assess this? Was this qualitative or do you have some quantification that you can use to demonstrate this?
We can add: exhibit no noticeable drift in near surface climate and appear to be sufficiently equilibrated.
Line 90 –' A model intercomparison demonstrated…' switch to active voice
We can change that accordingly
Line 160 –'We would like to note that surface melt…' OK

Line 201 – Define Saalian. When is the Saalian and what is the Saalian?
We will use penultimate glacial period and specify the time as 140ka.
Line 216 – The Austermann et al. (2022) paper would also support this point about non-uniform retreat
patterns (see their Figure 4).
We have include Austermann et al. (2022) in the modified part of the Discussion (see above).
A quick follow-up, I think your study and results do show something interesting and important, but here I think you have an opportunity to expand and attempt to validate your results by making comparisons to some geological data. Can you attempt to relate geological observations of ice margin retreat rates with changes in glacial lake extent? For example, use the Dalton et al. (2020) ice margin chronology to calculate the changes in areal extent of the Laurentide Ice Sheet through time. Calculate the lake extent change through time from Austermann et al. (2022). Compare these changes to test whether periods of large lake extent correlate with slower retreat rates?I have a general belief that model simulations without verification against geological constraints are of limited use, so this would provide independent validation of your modelled effects and strengthen your conclusions about lakes as a stabilizing influence.

You are welcome to say no to this but I don't feel like these plots would take that much time and might provide a geological comparison to back up and strengthen your conclusion.
We agree that such a comparison would be valuable. However, we expect observed retreat rates to reflect the combined influence of several processes, including background climatic warming, basal hydrology, glacial isostatic adjustment, calving, and the climatic effects of proglacial lakes. We therefore do not expect it to be possible to isolate the climatic feedback from retreat histories alone.

Figure comments – would it be possible to get a scale bar and lat/long grids for each figure?
We have updated the figures accordingly. They are attached at the end.

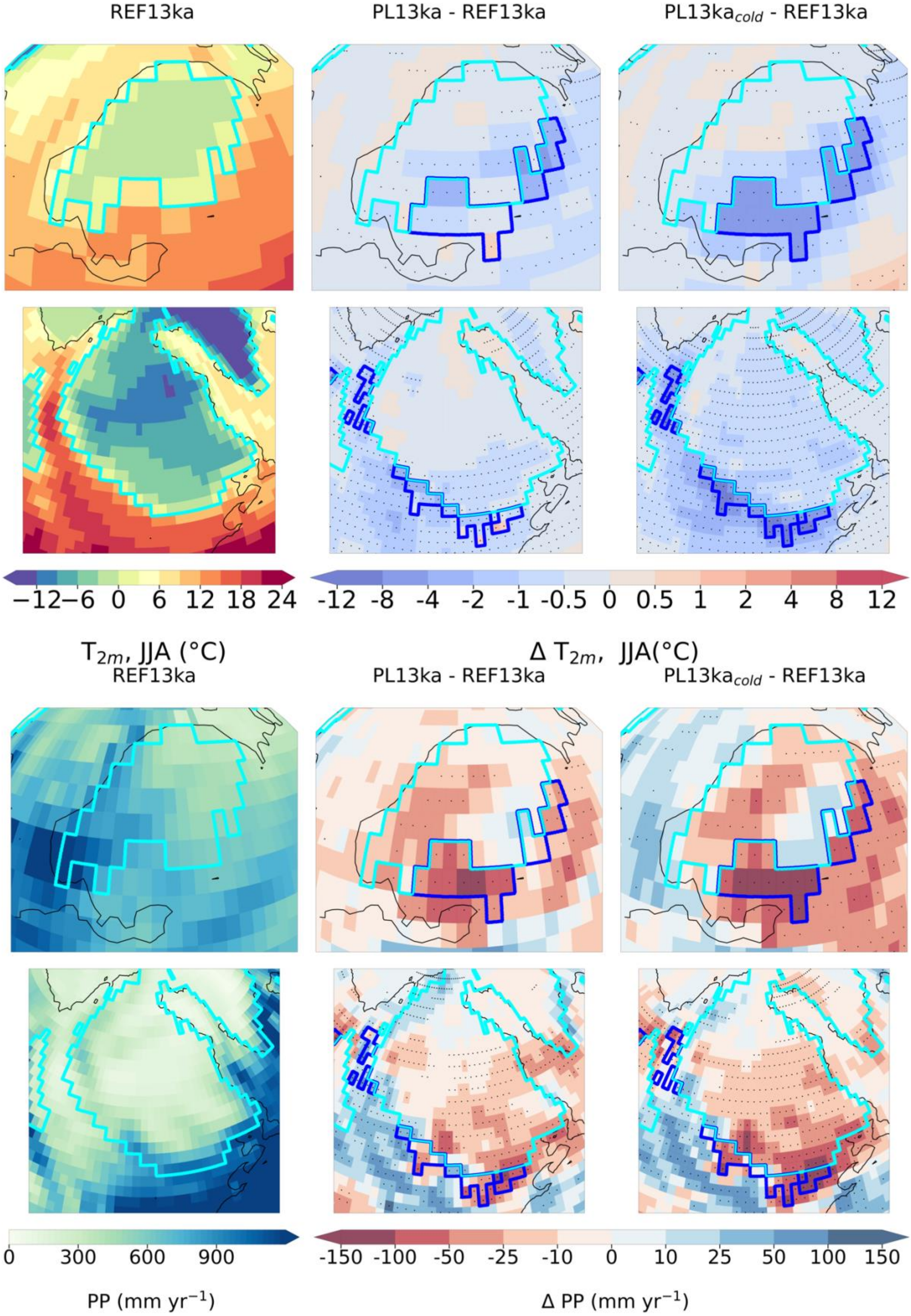
References:

*Bartlein, P.J., Harrison, S.P., Brewer, S. et al. Pollen-based continental climate reconstructions at 6 and 21 ka: a global synthesis. Clim Dyn **37**, 775–802 (2011). https://doi.org/10.1007/s00382-010-0904-1*

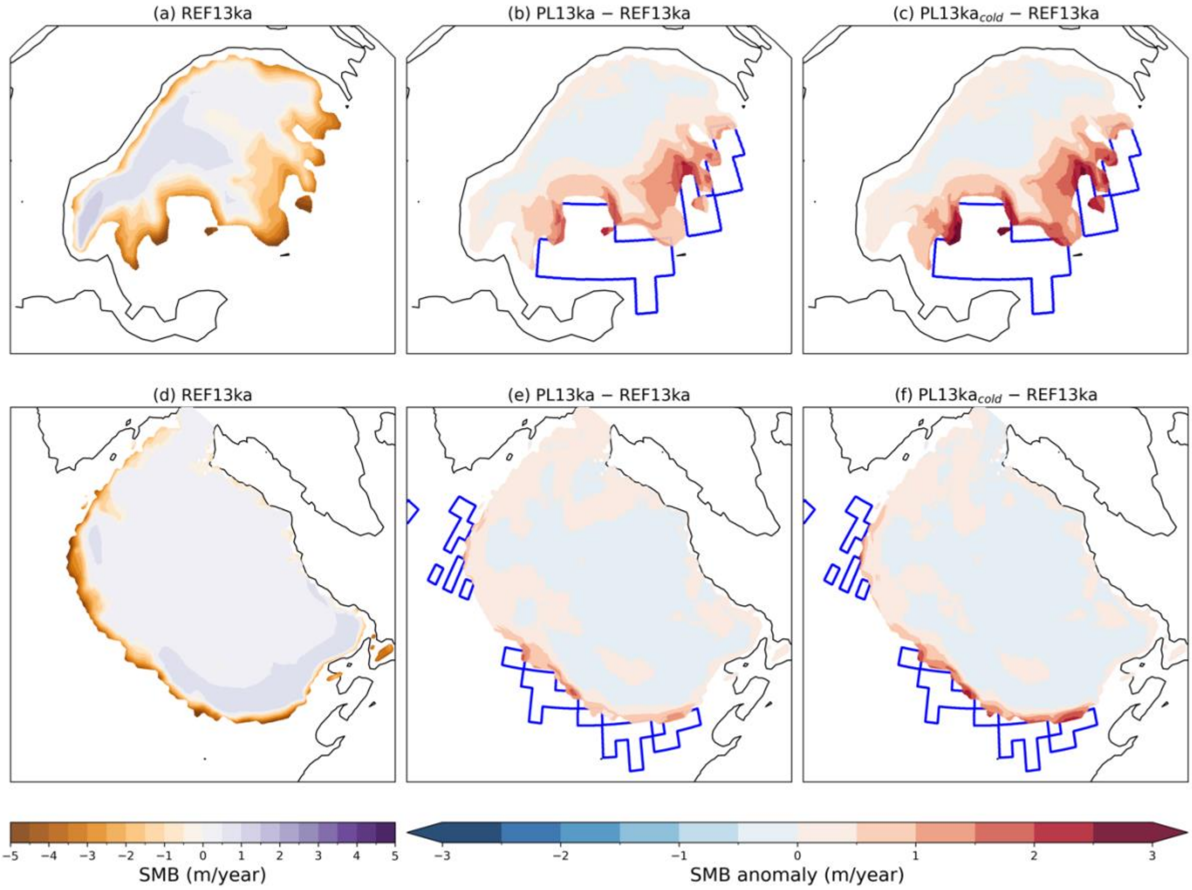
*Lambeck, K., Rouby, H., Purcell, A., Sun, Y. & Sambridge, M. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. Proc. Nat. Acad. Sci. **111**, 15296–15303 (2014).*

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)