Author response to comments from the Editor to the revised version of manuscript No. tc-2020-353, “PISM-LakeCC: Implementing an adaptive proglacial lake boundary into an ice sheet model”

submitted to The Cryosphere by Sebastian Hinck et al.

As requested by the editorial office, we provide

- the updated manuscript,
- a marked-up manuscript version showing the changes made, and
- the point-to-point response to the comments (this document).

The original comments are indented, while our responses aligned to the left of the page.

> Dear Hinck et all,
> thanks for your detailed reply to the comments by the two reviewers on your revisions of the manuscript submitted to the Cryosphere. The revisions where major and you have answered most of these.
>
> However, the reviewers had a number of concerns which you should answer in more detail in the final revised manuscript. In particular, this relates to the second review by Tijn Berends.
>
> You have written out answers to each comment in the reply to the reviewers. However, I expect that you also make these points in the reply letter clear to the readers, as it is likely they will have similar questions when reading your paper.
>
> In particular, please add details to the manuscript making the following key points from the reviewers more clear:

We want to thank the Editor for his thoughtful comments and for giving us the opportunity to add further details that help improving our manuscript. In the revised manuscript, we tried to respond to all of the concerns.

In the following, we reply to all of your comments and highlight, where applicable, the changes made in the manuscript.

> 1. the relative impact of surface runoff on the shelf mass (as opposed to sub-shelf melt or calving);

This is a good point, that was really not made clear enough in the previous manuscript. To show the relative impact of surface runoff, we added an additional figure, showing the runoff side-by-side with sub-shelf melt and calving rates. This plot is discussed in the Results section:

l. 342ff: "At the southern ice margin and especially at the ice shelves, where the surface elevation is low, the surface runoff is greatly increased (see Fig. 10a). Figure 10b shows the modeled mass flux due to sub-shelf melting and calving. In this region, surface runoff contributes the most to mass loss."

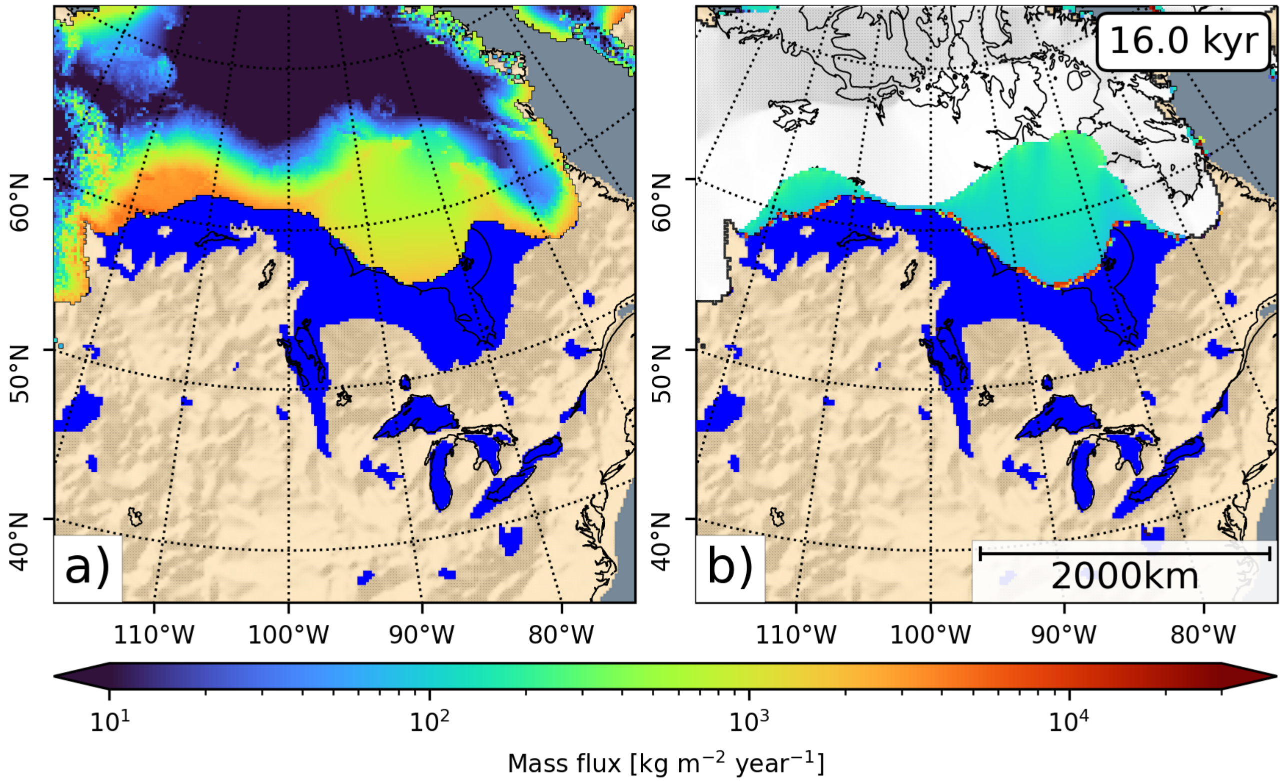

Figure 10. Comparison of the modelled mass loss due to a) surface runoff and b) sub-shelf melting and calving, shown here at 16 kyr. At the shelf regions, the surface runoff is about an order of magnitude larger than sub-shelf melting. Locally, at the shelf margin, the mass loss may be greatly increased due to calving events. The fields shown here are averaged over the ice model's reporting interval (here: 5 years).

We further expand on this in the Discussion section:

l. 387ff: "Contrary to MISI, where the ice loss is generally driven by calving and sub-shelf melt processes at the ice shelf, we observe a dominance in ice loss via surface runoff (see Fig. 10), due to the strong surface-elevation feedback in the warm climate. At the ice-shelves, the surface runoff is so large that when comparing with an experiment that has a reduced calving threshold, the shelf geometry hardly differs. The ice that is not calved off is subject to strong melting (see sensitivity run *RedCalv* in the supplementary material)."

> 2. expand on the impact of crustal deformation relative to gravitational effects;

As previously stated, due to lack of an appropriate model that includes gravitational effects we can not give an estimate of the relative strength of this process compared to crustal deformation. We do, however, expand on this by describing the potential impact on the lake surface.

l. 484ff: "Another feature missing in the GIA model is self-gravitational effects of the ice sheet. The ice sheet's mass impacts the geoid, along which the free water surfaces align. As a result, the lake water is attracted towards the ice sheet and the water depth at the grounding line would potentially increase. Due to lack of an appropriate model of gravitational change, we can not estimate the potential magnitude of this effect. However, according to James et al. (2000) the effect is secondary compared to the crustal deformation."

> 3. clarify the main focus of the paper (see note from Berents);

In the Introduction we do describe the potential importance of the proglacial lake boundary for model simulations of palaeo ice sheets, such as the Laurentide or the Fennoscandian ice sheet. In previous modelling studies this aspect was mostly ignored. Our main intention is to fill this gap by proposing a new type of model, which, as we demonstrate using a simple test scenario, drastically impacts the glacial retreat. We think that this sufficiently sets the context for our study.

To highlight the study's focus, we reworded parts of the Abstract:

During the Late Pleistocene and Holocene retreat of palaeo ice sheets in North America and Europe, vast proglacial lakes existed along the land terminating margins. These proglacial lakes impacted ice sheet dynamics by imposing boundary conditions analogous to a marine terminating margin. These lacustrine boundary conditions cause changes in the ice sheet's geometry, stress balance and frontal ablation and therefore affect the entire ice sheet's mass balance. Despite this, dynamically evolving proglacial lakes have rarely been considered in detail in ice sheet modelling endeavors. In this study, we describe the implementation of an adaptive lake boundary into the Parallel Ice Sheet Model (PISM), which we call the PISM-LakeCC model. We test our model with a simplified glacial retreat setup of the Laurentide Ice Sheet (LIS). By comparing the experiments with lakes with control runs with no lakes, we show that the presence of proglacial lakes locally enhances the ice flow, which leads to a lowering of the ice sheet surface. In some cases, this also results in an advance of the ice margin that causes the emergence of ice lobes. In the warming climate, increased melting on the lowered ice surface drives the glacial retreat. For the LIS, the presence of lakes triggers a process similar to the marine ice sheet instability, which causes the collapse of the ice saddle over Hudson Bay. In the control experiments without lakes, Hudson Bay is still glaciated when the climate reaches present day conditions. The results of our study demonstrate that glacio-lacustrine interactions play a significant role of the retreat of land terminating ice sheet margins.

In the revised manuscript, we expanded the discussion on the results: We now provide an extended table giving an overview about all experiments (including the sensitivity runs).

Table 1. Overview of all experiments done for this study. The first three experiments are discussed in the text, details about the other experiments can be found in the supplementary material.

Name	Description	Results
LAKE$^{*)}$	standard lake experiment, as described in the text	accelerated glacial retreat; occurrence of PLISI; Hudson Bay fully ice free at the end of the experiment
CTRL$^{*)}$	standard no-lake experiment, land-sea mask corrected by the SL2DCC model	Hudson Bay remains mostly glaciated at the end of the run
DEF$^{*)}$	PISM default no-lake setup, occurrence of inner-continental ocean basins	slightly faster glacial retreat than *CTRL*; Hudson Bay glaciated north of $\sim 58°$ N at the end of the run
IncCalv	increased calving; lacustrine thickness calving threshold set to 500m	almost immediate removal of shelf ice, which leads to a more rapid glacial retreat than in *LAKE*
RedCalv	reduced calving; lacustrine thickness calving threshold set to 20m	apart from slightly larger ice shelves, similar to *LAKE*
MR	tuning parameter for sub-shelf melting adapted to account for differences between marine and lacustrine environment	as above
nSG	slippery grounding line model disabled	strongly reduced grounding line flux leads to smaller ice shelves; no PLISI; Hudson Bay still glaciated north of $\sim 59°$ N
TWO	use of grounding line treatment proposed in Albrecht et al. (2020) (tillwater ocean) instead of slippery grounding line model	no qualitative difference to *LAKE*
GIA	adapted Earth model parameters for the Lingle-Clark bed deformation model	no qualitative difference to *LAKE*; only the timing is slightly different
FR5	lake fill rate set to 5m year^{-1}	no qualitative difference to *LAKE*
FR10	lake fill rate set to 10m year^{-1}	as above
FR50	lake fill rate set to 50m year^{-1}	as above

$^{*)}$ default experiments

Furthermore, we have improved the structure of the manuscript by collecting and expanding on the shortcomings of the experimental setup into an own section. This section also includes the content from former section "2.4.3 - Further lacustrine interactions". As these issues all deal with issues of other sub-models of the ice sheet model, and thus only indirectly concern the LakeCC model, this section was moved into the **Appendix A - Experiments**:

l. 469ff:
"A2 Limitations
In the following, we will mention and shortly discuss some limitations of the experimental setup.

A2.1 Climate model
The climate forcing is relatively simple in our setup. Using a glacial index leads to increased mass accumulation in cold regions and on top of the ice sheet. The experiments therefore suffer from excessive ice sheet growth after model initialization. Furthermore, the presence of vast proglacial lakes would impact the local climate by reducing temperatures and increasing precipitation patterns (Krinner et al., 2004; Peyaud et al., 2007). This could locally increase the ice sheet's SMB and counteract the accelerated mass loss observed in this study. Also, the potential impact on ocean circulation and global climate due to redistribution of freshwater (Broecker et al., 1989; Teller et al., 2002; Condron and Winsor, 2012) is ignored here.

A2.2 GIA model
PISM's default GIA model (Lingle–Clark; Bueler et al., 2007) is based on a simple two-layered Earth model and therefore lacks viscosity variations between the upper and lower mantle. This variation significantly contributes to the GIA signal in central Canada (Wu, 2006). In combination with the excessive mass accumulation due to the simple climate forcing, our results show a strongly depressed topography, with deep lake basins that only slowly relax. For a realistic simulation of the LIS deglaciation, with a proper representation of proglacial lakes, a more advanced model to calculate GIA signal would be needed.
Another feature missing in the GIA model is self-gravitational effects of the ice sheet. The ice sheet's mass impacts the geoid, along which the free water surfaces align. As a result, the lake water is attracted towards the ice sheet and the water depth at the grounding line would potentially increase. Due to lack of an appropriate model of gravitational change, we can not estimate the potential magnitude of this effect. However, according to James et al. (2000) the effect is secondary compared to the crustal deformation.
Furthermore, in the calculation of the GIA signal we do not include the mass held by the lakes. We would expect the water mass to have a significant impact on the GIA and thus also on the lake basins.

A2.3 Model initialization
Initialization of the Lingle–Clark model from a glaciated state is problematic here. For the model to calculate a relief topography, to which bed deformation is applied, it should ideally be initialized from an interglacial state when the residual GIA from previous glaciations is limited. Test runs, comparable to those in Niu et al. (2019), however, suffered from the fact that the bed deformation along the southern ice margin was so deep, that the basin was connected to the Atlantic Ocean. This consequently inhibited the formation of lakes. We therefore chose to initiate the experiments from NAICE LGM reconstructions. The mismatch in calculated relief topography, results in ice free regions to over-relax compared to the modern topography. Hudson Bay, for example, is elevated above sea level at PD (see Fig. 8f)."

> 4. expand on the potential impact of sub-glacial drainage.

In the revised manuscript, we expand on this topic.

l. 226ff: "One process that can limit the maximum fill height of a lake is sub-glacial drainage. In the LakeCC model it is only crudely included via the flotation criterion: when an ice dam becomes buoyant and opens a new drainage route. In reality, however, sub-glacial drainage also can happen on much smaller scales through channels underneath the ice. This process could also lead to repeated lake drainage and refilling events. Even though sub-glacial drainage through channels might be an important aspect of glacio-lacustrine interactions, its parameterization is not trivial and is not included in our model."

> For most of these issues you have answered the reviewers concerns in the reply letter, but not added sufficient detail in the revised manuscript. When resubmitting your final paper, keep in mind that you are writing for a reader in TC and not GMD - as such, the article should focus on the scientific results, their importance and context (in addition to the detailed description of the proglacial lake module).
>
> These additional revisions should not take too long. Please include a version with tracked changes when submitting the final version.

We hope that our revised manuscript could resolve all issues! The manuscript and a version with all marked changes is uploaded.