Interactive comment on “Hypersensitivity of glacial temperatures in Siberia” by Pepijn Bakker et al.
Anonymous Referee #2

Review of "Hypersensitivity of glacial temperatures in Siberia” by Bakker et al.
Geological evidence has shown that Siberia was partially glaciated during some glacial states while it kept mostly ice-free during others. Different previous studies have explored several potential explanations for these differences but a consensus is still lacking. Bakker et al. show that the ensemble of climate model experiments from PMIP2 and PMIP3 shows a very large spread in their simulated glacial summer (JJA) temperatures for the last glacial maximum (LGM) over Siberia. Bakker et al. argue that the large model spread could be an indication for a real “hypersensitivity” of glacial summer temperatures over Siberia, and hence regional glaciation itself. To explore some of the possible factors which may result in climatic differences over Siberia, they conduct several sensitivity simulations with CESM and show that the spread in simulations resulting from different ice sheet heights, vegetation feedback or changes in atmospheric physics of CAM4/5 can cause an equally large spread (∼20 K) as the PMIP model ensemble (∼24 K).

Overall, the manuscript is very well written and provides interesting insights into the problem of glacial summer temperature hypersensitivity and how it might explain the absence or presence of glaciation in Siberia during different glacials. However, the potential reasons for what may cause the large simulated temperature spread over Siberia could be explored in a bit more detail. I generally recommend publication in Climate of the Past after adding some more analysis to explain the summer temperature discrepancies.
**We thank the reviewer for the kind words and for having a critical look at the manuscript.**

General comments:
The study is very well written and presents very interesting and important aspects to better understand the possibly real “hypersensitivity” of the Siberian climate during glacials as well as the behaviour of models. Regarding the analysed variables in the manuscript, it is a bit difficult to understand whether local radiative processes (e.g. what about albedo, spring snow cover and lagged warming?) or large-scale temperature advection play a major role for the temperature spread – or both. Because Siberia builds up a spatially widespread thermal low during summer, the correlation between summer temperature and SLP can be expected to be mainly temperature driven. Increasing temperature will hence cause lower SLP which then can increase horizontal advection into Siberia. Consequently, changes in SLP would be rather a feedback to the warming (or cooling) and not the mechanism which causes the effect.
**We agree with the reviewer that it is difficult to disentangle local versus large-scale effects on Siberian temperatures. This is especially true when doing so through the analysis of sea-level pressure fields. Fortunately we have found out that for all but one PMIP2/3 LGM simulation also geopotential height fields are available, and this makes for a more direct line of arguments and, in our opinion, a more convincing analysis to showe that changes in the large-scale, circumarctic atmospheric circulation are indeed the cause of the spread in simulated Siberian JJA temperatures.**
**In the updated manuscript we will show PMIP results for geopotential height anomalies at 500hPa (with the zonal mean removed), and together with the existing CESM geopotential height results we argue that both clearly show large-scale anomaly patterns that resemble a classical stationary wave pattern and therefor indicate changes in the large-scale atmospheric circulation. Based on CESM results we already showed that as a result of these circulation changes, meridional heat transport into the region under discussion increases. These circumarctic patterns are unlikely to be caused by local Siberian temperature changes, but rather are the cause of the Siberian temperature changes to which in turn local sea-level pressure changes provide a feedback.**

I also wonder whether the correlation in Fig. 3 is really statistically significant in terms of field significance given the low spatial degrees of freedom of SLP and that the relatively small regions with statistically significant correlations might be just those which are allowed to be significant by chance. In general, I would rather expect that the large-scale gradients in the pressure and temperature field e.g. relative to the Arctic and Tropics are important for temperature advection into Siberia. It would be interesting to see some analysis of the large-scale wind fields or pressure gradients and how different they are with respect to the model spread e.g. of the warmest vs. coldest PMIP member. I was also wondering if large-scale teleconnections might be very different for very warm vs. very cold simulations of Siberian summer temperatures (e.g. a one-point-correlation map of the averaged Siberian SLP and temperature with the northern hemisphere SLP and temperature).
**We thank the reviewer for these interesting suggestions.**
**Likely as a consequence of the many differences within the PMIP ensemble, strong relationships such as the ones suggested by the reviewer have not been found. The strongest pattern we could find is a linear correlation between local (Siberian) JJA temperature anomalies and the large-scale stationary wave pattern anomalies (described by 500hPa geopotential height anomalies with the zonal means removed). The fact that this correlation map resembles a classical stationary wave pattern to us is a strong indication of the importance of this mechanism to explain our findings.**
**We agree with the reviewer that the calculations of the significance provide only limited additional information and we have therefore removed them.**

Regarding the large temperature spread over Eurasia, I was also wondering whether there is a potential link between warm and cold model experiments and the used atmospheric resolution (see below). In any case, the paper would strongly gain from a bit more detailed analysis and discussion of these aspects while the rest of the paper is very well written and does not require notable changes with exception of clarifying the sections about the role of the thermal low.

Specific comments:
Title of the paper: Maybe be more specific and write “glacial summer temperatures”?
**Thanks for the suggestion. We have changed the title accordingly.**

Page 2, line 2: Due to the quite shallow Arctic shelf, sea-level changes during the glacial lead to quite large changes in additionally exposed land during low level stands along the Arctic and Siberian coast. During summer, the additional landmass clearly increases the area which can heat up strongly during boreal summers with 24 hours of daylight. I could imagine that such an effect would be higher in models with a high horizontal resolution. It would be very interesting if you could add some information in the manuscript about individual ensemble members if there are indications that their differences in atmospheric resolution lead to systematic differences in Siberian temperatures.
In this context, there is one recent example where a very coarse resolution simulation has been repeated with the same ocean state and external forcing but using a 4x higher atmospheric resolution with CESM1 (Schenk et al. 2018) for the late glacial. In their supplementary figure 4, they show that a much higher atmospheric resolution with CESM1 predicts considerably warmer summers during the Younger Dryas stadial over Eurasia and Siberia compared to the coarse resolution simulation with CCSM3 despite using the same ocean state. They argue that atmospheric blocking in response to the Fennoscandian Ice Sheet (among other reasons) leads to warmer Eurasian summers. They show that the blocking and hence warmer summers are only captured at high resolution. Is this also the case for the warmest vs. coldest PMIP members?
Given the very strong difference in simulated summer temperatures at a different model resolution by Schenk et al. (2018) and the very important results of other studies concerning the atmospheric flow disturbance by ice sheets (as already cited by the authors on page 3), I would suggest to add a

paragraph about whether atmospheric resolution differences in the presence of large continental ice sheets can partly explain the spread of warming or cooling over Siberia.

**The notion of a resolution dependency of the Siberian LGM temperatures is an interesting one. We have now added the LGM JJA temperature anomalies for the Siberian target region in a table to ease such an analysis. However, when comparing these temperature anomalies with the spatial resolution of the atmospheric models (ranking both and plotting them against each other) we do not find any relationship, not even a hint of it. We have added some text to the concluding section of the manuscript to discuss the matter "Recently, Schenk et al. (2018) showed that the spatial resolution of the atmospheric model is key to obtaining realistic glacial temperature anomalies. However, we do not find any correlation between atmospheric model resolution and Siberian JJA LGM temperature anomalies (Table 1), despite having some models with a resolution very similar to one used by Schenk et al. (2018). We note, however, that we did not perform a dedicated experiment changing only the spatial resolution while keeping all other factors the same."**

Regarding the exposed Arctic shelf during stadials: Is there any geological evidence that glaciations in Siberia might correlate with periods of higher sea-level stands (less exposed Arctic shelf and possibly cooler summers with a weaker thermal low and less advection)?

**We have not been able to find any such information in the geological record.**

Page 2, line 20: Can you give an example which one is good and possibly why?

**This is not easy to do. First of all, some of these studies specifically included new mechanisms in order to obtain a good match (be it for the right reasons or not), and other studies show results of ice sheets models driven by multiple climate models and as a result they obtain very different configurations of the Siberian ice cover. For the introduction part of the current manuscript we don't think it is needed to go into the specifics of all these studies.**

Page 5, line 1: Components of GLAC-1D have been published in different papers. Please add here the reference of the complete version which is Ivanovic et al. (2016).

**Thank you for pointing this out. We have updated the text accordingly.**

Page 5, line 3: Figure 5A is too small to see the important differences in ice sheet heights.

**The details of the differences between these two LGM ice sheet reconstructions are not the focus of this study. In some regions one is higher, in other regions the other reconstruction, a complex picture (as shortly described in the method section) and as such one cannot easily make a connection with large-scale circulation changes. In previous publications on the topic this was often possible because they performed sensitivity studies in which they altered the height of the ice sheets in a controlled maner, or removed one of the ice sheets completely. We have added a comment to the method section referring the readers to the work by Kageyama et al. (2017) for more details.**

Page 5, line 27: The green contour line is not visible. Please add in addition the coordinates for the target region in the manuscript (for the analysed 1 ◦ x1 ◦ grid). Version

**We have improved the readability of the green contour. Giving the coordinates is not feasible since the region is not a rectangle.**

Page 6, lines 13-14: Regarding ". . .could be a consequence of local temperature changes. . .": This is quite certain as the low pressure over Siberia during summer is a thermal low and not a dynamic low. The sentence should be modified accordingly.

**Indeed in this region warm summer temperatures lead to a low pressure system, a so-called thermal low. However, that is not our point here. Previous work has suggested that local increases in sea-level pressure, driven by large-scale atmospheric circulation changes, lead to**

**a decrease in cloud cover and a resulting increase in surface temperatures. The finding of a negative relationship in our study between local summer temperatures and sea-level pressure rather than a positive one, suggest that this mechanism can't explain the PMIP results. Rather, temperature changes lead to local changes in sea-level pressure (in line with the formation of the thermal low mention by the reviewer). However, we think it is not necessary, and indeed only complicates matters, to describe the background climate characteristics. It is the changes and the sign of possible feedbacks that we are interested in here.**

Page 6, lines 15-16: The link to the Asian monsoon region and possibly other large-scale teleconnections are very important and should be explored a bit more in the manuscript.
**Even though we agree that these are interesting topics, they are really outside of the scope of this manuscript and we have no reason to assume that they are central to the description of the mechanisms driving the large inter-model differences in Siberian summer temperatures.**

Page 6, lines 17-25: The paragraph should be clarified with respect to the low being a thermal low. It appears odd to argue here that a deepening of the low-pressure cell over central Asia (it is not really a cell but rather a diffuse area) should control the amount of warming in Siberia when the deepening of the low is driven by the warming. This might be rather a positive feedback where warming increases convection which lowers the pressure which increases horizontal advection. This implies that another process causes the warming and the change in SLP is only a feedback. Please rewrite accordingly.
**Using geopotential height anomaly maps we now show in an updated figure 3 that local Siberian summer temperatures are linearly correlated with a change in the large-scale circumarctic stationary wave pattern. Far-field surface pressure anomalies are no longer discussed.**

Page 10, lines 21-22: It would be interesting to get a number for the overall temperature change of the northern hemisphere in response to using a different ice sheet in CESM.
**Thanks for pointing this out. We have now added a line "On a large scale, using the GLAC-1D ice-sheet reconstruction leads to a smaller LGM JJA temperature anomaly in the Northern Hemisphere (-6.4◦ C) than the simulation that includes the ICE-6G ice-sheet reconstruction (-7.2◦ C)."**

Page 10, lines 24-25: This again is due to the thermal low which has to deepen with increasing temperature due to an increase in the rise of warm air.
**Since we no longer focus on far-field sea-level pressure changes we assume this issue is resolved.**

Page 10, line 31: The similarity of the spatial anomaly pattern for temperature and SLP can be expected for the behaviour of the thermal low in summer. There has to be another reason for the warming first and the SLP change cannot be the mechanism but rather a positive feedback.
**Since we no longer focus on far-field sea-level pressure changes we assume this issue is resolved.**

Page 15, line 17: Please add a concluding paragraph about which model configuration for CESM (and e.g. which ice sheet) would be plausible for the LGM (no glaciation in Siberia) and why. In this context, can you give some examples about which PMIP models would be plausible for the LGM and absence of Siberian glaciation and which not and why?
**We think this is really not the point of our manuscript, and perhaps in fact inappropriate. Indeed the simulated temperature fields over Siberia (and as a result snow cover and potential ice sheet cover) are very different between models and more in line with geological data in some of them. We show that large changes in simulated temperatures can have many causes,**

**from boundary conditions (ice sheets), to feedbacks (vegetation) to model formulation (atmospheric model). A 'good' simulation can thus result from various combinations of these factors. Moreover, there are indications that during previous glacial periods the ice sheets in northeastern Siberia were more extensive, so a 'good' model should also be able to simulate such a situation. We have added a short comment on the possible implications of our findings for the presence and absence of this ice sheet during various glacial periods.**

Figure 1: The green contour in panel B is not visible.
**Thanks for pointing this out. We have updated it.**

Figure 2: Please strongly increase the size of numbers in the figure as well as the axis description.
**Thanks for pointing this out. We have updated the axis description. However, the size of the numbers in the plots cannot be increased because they will start to overlap and make the figure more difficult to read.**

Figure 3: Are the significant areas really statistically significant globally or only by chance? Given that the correlations may rather represent the thermal low, I'm not sure how this figure helps to understand the spatial spread over Siberia. Pressure gradients and teleconnections might be more suitable as they would represent how the changes of the thermal low interact with remote regions.
**Please refer to the replies given earlier in this rebuttal.**

Figure 8: The red and blue for CAM4/5 is very difficult to see.
**Thanks for pointing this out. We have updated it.**

Table 1: It would be important to add a column here with the temperature difference LGM minus PI over Siberia for each model simulation to identify which models are unusually warm/cold. This would make it easy for others to further explore why which models differ from others. In this way, a potential dependency on the model resolution could be easily identified.
**Thanks for pointing this out. We have included the information to table 1.**

Table 2: Also here the temperature difference LGM minus PI over Siberia would be interesting.
**Thanks for pointing this out. We have included the information to table 2.**

Additional references:

Ivanovic, R. F. et al. Transient climate simulations of the deglaciation 21âĂŤ9 thousand years before present (version 1)âĂŤPMIP4 core experiment design and boundary conditions. Geosci. Model Dev. 9, 2563–2587 (2016).

Schenk, F. et al. Warm summers during the Younger Dryas cold reversal. Nature Commun. 9:1634 (2018).