Clim. Past Discuss.,
https://doi.org/10.5194/cp-2019-49-AC2, 2019

Climate of the Past
Discussions

Interactive comment on "Late Weichselian thermal state at the base of the Scandinavian Ice Sheet" *by* Dmitry Y. Demezhko et al.

Dmitry Y. Demezhko et al.

ddem54@inbox.ru

Received and published: 1 November 2019

Referee #2

AC: We are grateful to Referee #2 for his response to our paper and helpful suggestions. We appreciate the constructive feedback. We have tried to answer your questions in detail and incorporate most of your suggestions into our revised paper. Referee #2 brought up an important issue concerning not only our paper but also the overall problem of paleoclimate reconstruction from borehole temperature data. Indeed, there are some factors disturbing paleoclimate signal in temperature-depth profiles such as drilling process, ground-water movements, subsurface heterogeneities etc. It is not always possible to take into account all these factors properly. The most widely used

way to suppress the influence of non-climatic factors is the regularization of the inversion procedure. It allows suppressing spurious non-climatic anomalies but leads to the decrease of climate signal amplitude. The choice of an inversion procedure and a regularization measure are unique in each individual case. Authors of the cited papers commonly analyze different approaches and discuss in details the obtained results. However, the use of different inversion techniques makes it difficult the comparing and integrating of the reconstructed GST histories. Under the circumstances, we have accepted the following methodology. 1. If the cited paper deals with several versions of the GST reconstruction obtained by different techniques and regularization approaches we choose that one which demonstrates the minimal suppression and maximal amplitude of the reconstructed GST history. A large difference of the obtained LW temperatures and their apparent spatial correlation suggest a slight impact of non-climatic factors. 2. We did not consider an entire reconstructed temperature history, but only the Late Weichselian temperatures. The last glaciation left the most noticeable trace in the present subsurface thermal field. This trace has not been affected by the previous climate history. Temperature anomaly caused by the last glaciation extends from a depth of approximately 500 m to 1.5 – 2 km. The GST reconstructions of the last glacial period are disturbed less (versus the reconstructions of more recent climate events) by local subsurface heterogeneities and ground-water movements. Therefore, the LW temperature estimates we consider seem to be quite reliable.

Author's changes: We will significantly extend the Data section and rename it as Data and Methodology. In addition, we will add LW temperature values obtained by different techniques as well as error bars and limits of the temperature history's averaging intervals in Table 1.

Specific comments

RC#2: Still, the main problem here is the quality of the applied GST histories. The data from Kukkonen et al. (2011) from the Outokumpu . . . seem of good quality. Most other results are of far less quality. This is apparent from Fig. 2, which shows the applied

GST reconstructions. Starting from the top, with SG-3, we see an almost linear trend of increasing temperature (from c. -3_C to positive) from between 10 and 5 kyr BP and up to 1 kyr BP (present GST is +1.5_C). Similar unrealistic long trends of temperature increase up to recent times are seen also in the data from Forsmark, Laxemar and Ullrik. These 'reconstructions' are clearly inconsistent with the general knowledge of past climate in these areas as well as inconsistent with the applied data from boreholes of better quality.

AC: All the applied GST reconstructions and other estimates were published in peer-reviewed journals. The applied inversion methods were described in detail and the validity of the obtained results was discussed in these papers. Six of eleven reconstructions were obtained by V. Rath who nowadays is an acknowledge leader in the field of paleoclimate interpretation of borehole temperature data. The Technical Report was published after the publication of the discussion version of our paper. It details paleoclimate interpretation of the data obtained from the Forsmark and Laxemar boreholes on 63 pages - Rath V, Sundberg J, Näslund JO, Liljedahl LC. Paleoclimatic inversion of temperature profiles from deep boreholes at Forsmark and Laxemar. Technical Report TR-18-06, April 2019 (https://www.skb.com/publication/ 2493035/).

Author's changes: We will add the reference on this Report to the revised paper.

AC: Referee #2 means "consistence with the general knowledge of past climate in these areas" by an "apparent" quality criterion of the reconstructions. We cannot completely agree with such view point. Ground surface temperature history might be significantly more complex than surface air temperature history. It is caused not only by climate change but also by the characteristics of vegetation, snow cover as well as the presence of water at the surface and ice sheets. Thus, the GST reconstructions from the Forsmark and Laxemar boreholes show long history of flooding and draining of the region after deglaciation (see the Technical Report mentioned above). Perhaps, the SG-3 and Ullrigg location areas were also influenced by flooding and following draining due to the isostatic uplift. However, our plans did not include the analysis of postglacial

history of the region. Perhaps, the applied reconstructions do not have the required quality for such an analysis. We set a goal to estimate the thermal regime in the Late Weichselian and to analyze spatial distribution of the reconstructed LW temperatures by the way of their comparing with independent evidences including geological and seismological ones. RC#2: Among the sites with very low LW GST estimates are the Kola (C-1), Krl and Onega boreholes. For Onega, we see an 'unexpected' drop in temperatures by more than 5_C from c. 5 to 2.5 kyr BP. Looking into details of original borehole temperature data (in Demezhko et al. 2013), we observe too high near surface temperatures (c. 11_C significantly above present day GST of c. 5.5_C). The applied borehole temperature data are clearly disturbed by the drilling process. A correction is attempted resulting in an unrealistic 'warming period' and the above 'unrealistic' temperature drop. This results in too large amplitude of the temperature rise from c. 20 to 10 kyr BP and significant uncertainty on the Late Weichselian temperature estimate of - 14.5_C. AC: Perhaps, 'unexpected drop' from 5 to 2.5 kyr BP for the reconstruction from the Onega borehole might be associated with unaccounted influence of non-climatic factors. However, we are interested in much earlier times that is the Late Weichselian. The GST estimate of -14.5 C is proved by the results of mathematical simulations for Karelia (Forsström P.-L. Through a glacial cycle: simulation of the Eurasian ice sheet dynamics during the last glaciation. Annales Academiae Scientiarum Fennicae, Geologica-Geographica. 2005, 168, 94 pp.). The reference to (Forsström, 2005) is given in the cited paper (Demezhko et al., 2013).

Author's changes: We will include the corresponding clarification in the revised text.

RC#2: For the Kola (C-1) site, a LW GST estimate of -18_C is indicated. The problem here is a 'deep narrow cooling' between c. 35 and 20 kyr BP.

Author's changes: We have defined more exactly this LW temperature value. Now it is a mean temperature at the GST minimum over the period 30-20 kyr BP equal to -16.8 °C.

RC#2: For borehole Krl, no GST history is given, and the low LW value of -15°C is obtain by 'selecting' an estimated 'unperturbed' heat flow of 40 mW/m2 without any mention of modelling procedure, nor information on deep background heat flow (why 40?).

AC: The paper (Kukkonen et al., 1998) does not provide a direct estimate of LW temperature value. The forward modelling suggests that the very low temperature gradients measured in this area "could be attributed to very low ground temperatures (-10 to -15°C) during the glaciation". LW temperature of -10 °C corresponds to a heat flow value of 19 to 32 mW/m2 while a heat flow value of 26 to 40 mW/m2 could be attributed to LW GST value of -15 °C. Later heat flow estimates for this region made using a large number of boreholes taking into account paleoclimate impact (Majorowicz, J., & Wybraniec, S. 2011. New terrestrial heat flow map of Europe after regional paleoclimatic correction application. International Journal of Earth Sciences, 100(4), 881-887) are equal to 40-50 mW/m2. Against this background we have chosen lower LW temperature value (-15 °C).

Author's changes: We will clarify our choice in the revised paper.

RC#2: The 'mathematical/numerical' contouring of data in Fig. 3 and the extrapolation into the Scandinavian region (with "a center of warming" located in the North Atlantic) has so large uncertainties in the region of study, that it should not be used for a detailed treatment as in Table 2 and Fig. 4 and associated discussion.

AC: The mentioned 'mathematical/numerical' model was widely discussed during the publication process in "Climate of the Past". Its statistical robustness was proved by the bootstrap analysis method. The model provides the least reliable estimates for the northwest parts of Norway and Sweden because there is no reference reconstructions here. However, the applied GST reconstructions are located outside of this region. The modelled GST estimates are in a good agreement with the obtained LW temperatures for the regions where the ice sheet existed not long and contrast strongly with those

obtained in the regions covered by the ice sheet most of the Late Weichselian.

Author's changes: We will limit the isoanomalies to the value of ΔT=20ĐŽ in the corrected text of the paper. To illustrate how the GST estimation uncertainties affect our conclusions we will add the GST values obtained using different methods as well as uncertainty envelopes in Table 1 and figures.

RC#2: The notion of a potential correlation between the region of very low modern seismicity (Fig. 6) and very low LW temperatures seems highly speculative. Most of Finland has very little seismicity, also in areas of significant ice thickness towards Gulf of Bothnia. The highest current seismicity is in southwester Norway in areas along the ice sheet margin.

AC: In Fig. 6 the territory of Finland is marked as the area with the moderate seismicity while there is no seismicity at all on the eastern and southern margins of the studied region with the lowest LW temperatures (blue circles). We mentioned in the paper that one can expect the existence of correlation (a weak one in general) between LW temperatures and seismicity caused by isostatic uplift and not by tectonics.

Interactive comment on Clim. Past Discuss., https://doi.org/10.5194/cp-2019-49, 2019.