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# **Reply to the comments on *Impact of postglacial warming on borehole reconstructions of last millennium temperatures***

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First of all we want to thank Jean-Claude Mareschal and the anonymous reviewer for their constructive comments and suggestions which will surely improve the quality of this article considerably. In the revised manuscript we have taken into account all of minor items given by both reviewers, but will only deal with the major points of the discussion here.

## Referee #1, J.-C. Mareschal

J.-C. Mareschal points out correctly, that when using field data, “*we need to use some caution and not blindly apply a correction to all the temperature profiles*”. We fully agree with this caveat. A meaningful paleoclimatic interpretation of boreholes is only possible adopting certain working hypotheses, e.g., concerning topographic effects, advective heat transport, and subsurface distribution of rock properties including porosity. However, when reducing borehole temperature profiles at a given place, we have to introduce additional assumptions.

To give an example, the dominating signal from the glacial-interglacial temperature rise is not globally homogeneous. The recent study of Clark et al. (2012) demonstrates clearly the large scale variability. On the other hand, it has to be kept in mind that subsurface temperatures record the ground surface temperatures, which is not always simply related to atmospheric temperatures. One of the problems, which is particularly important in the North American and Eurasian data sets, is the development of the Laurentide and Weichselian ice sheets. The varying conditions at the base of these ice sheets may lead to GSTHs which may not at all look similar to the ones assumed in our purely numerical study. Depending on the subglacial conditions, surface temperature may even show a temporal behavior inverse to the atmospheric temperatures above the ice. As found in our current studies of the influence of the Laurentide ice sheet on subsurface temperatures (Matharoo et al., 2012; Rath et al., 2012), new problems may arise from flooding related to isostatic effects of the ice sheets. The interpretation of field data is indeed a challenging task, and the blind use of a mistaken correction may produce even worse results due to the thus introduced artifacts. To make this clearer, we introduced a few sentences to this effect in the expanded *Conclusions* section of the revised manuscript.

The second point which J.-C. Mareschal raises concerns the “*nearly linear behavior*” of the residual effect of the postglacial warming. We agree with him that in shallow boreholes the linear assumption is an acceptable approximation because the cumulative variation is small. However, also the curvature increases with depth. In the histogram plot shown in the manuscript this is partly hidden by the wide variation of the rock thermophysical properties. It is slightly better visible in Fig. 1 of this reply, showing only the top 1000 m of a Monte Carlo (MC) simula-

tion without perturbing the thermophysical properties (thermal conductivity  $\lambda$  and volumetric heat capacity  $\rho c$ ). Of course, the domain of “linearity” depends on the particular values of these parameters.

## **Referee #2, Anonymous**

This reviewer raises mainly two questions. One concerns the sensitivity of the approach to the parametrization, which of course includes strong simplifications. The other one deals with the impact on the model-data comparison.

### **Impact of changes in the parametrization**

Before going into the details of these questions, we want to make clear that for this proof-of-concept study, the particular parametrization does not make any difference for the arguments presented. Here, the “true” GSTH is known, and the samples from the MC were chosen consistent with the general properties of the parametrization. However, the sensitivities of the responses chosen for the reduction with respect to some features of the assumed GSTH are helpful in the practical use of this approach. Therefore we have run a few additional numerical simulations relevant to the particular form of the GSTH used for MC simulation and the correction.

The reviewer’s concerns are related to: (a) the approximation of the post-glacial temperature rise by a step function; (b) the temperature history during the glacial period, and (c) the role of earlier glacial cycles. Generally, it has to be emphasized that the sensitivity of the responses with respect to short period temperature changes in intervals being as ancient as the glacial-interglacial transition 15 kyr BP is low due to the strong attenuation of these signals in the subsurface. At this time scale, merely an average temperature over a reasonable long period is resolvable. Additionally, realistic assumptions on the uncertainties present in the data and the remaining model parameters will further reduce the requirements for the accuracy of the reduction response.

Concerning the most recent features of the GSTH used for reduction, the reviewer asks “*whether it is important that the glacial-interglacial transition is represented as a step function*”. The sensitivity of the results to the duration of the post-glacial warming is demonstrated in Fig. 2. Here we vary the duration of the corresponding temperature rise as a linear increase in an interval of  $2\Delta t_2$ , where centered at 14 kyr with  $\Delta t_2$  varying between 0.1 kyr and 6 kyr. The particular form of the temperature rise of course makes some small differences in the response, but these will not play an important role in practice due to the other uncertainties in the reconstruction process. Fig. 3 shows again the residual vertical temperature for some GSTHs which could possibly represent the true temperature variation during the glacial period. In addition to the boxcar variation actually used in the MC study, we assumed a two-step model, and a linear ramp-like decrease of temperature between 100 kyr BP to 20 kyr BP, followed by a sharp increase at 14 kyrs. In this case, the maximum residual vertical temperature gradient is less than  $0.2 \text{ K km}^{-1}$ , well below the limits of detection. The differences can be made even smaller by choosing appropriate average values for the boxcar amplitude. This said, it is clear that there is no need to require a GSTH with high temporal resolution during the glacial period, resolving the short period variability identified in ice cores (see, e. g., Jouzel et al., 2007). Finally, the impact of earlier glacial cycles has been studied by Majorowicz et al. (2008). As expected, from these studies it can be concluded that while the amplitude and average temperature of earlier glacial cycles have a considerable influence, the particular form is not important. As in the case of the internal variations of the glacial temperatures, an appropriate average will suffice for the purposes pursued here.

### **Impact to model-data comparisons**

We agree with the reviewer that this part needs clarification. Mentioning the fact that AOGCMs are initialized with a subsurface temperature state that does not represent the real situation was indeed misleading: the shallow depth of the subsurface model implies loosing the memory of the initial state after some time of simulation. We have moved the model-data arguments to an expanded *Conclusions* section, clarifying the impact of the earlier GSTH on model-data comparison. We also avoid the use of the AOGCM abbreviation, as the particular type of model

does not matter here.

There are two problems with the treatment of subsurface temperatures in relation to the output of numerical climate models. From the arguments given in the manuscript it follows that under most conditions observed BTPs will contain a long-term signal. This, however, can not be represented in most numerical simulation codes due to their very limited treatment of subsurface processes. As shown earlier (Smerdon and Stieglitz, 2006; Stieglitz and Smerdon, 2007; MacDougall et al., 2010), the assumption of a no-flux bottom boundary condition at shallow depths prohibits the inclusion of long term GST changes into the model, with further implications discussed in the literature cited. Simple calculations show that to present the subsurface thermal effects on the scale of 10,000 years, the zero or fixed flux boundary condition should be imposed at a depth of more than 1000 m. Keeping in mind that subsurface processes on shorter time scales could be important for a correct representation of climate variability, it has to be concluded that the required improvements to the numerical codes are challenging. The comparisons published to date generate synthetic observations with offline subsurface models (see, Stevens et al., 2008; González-Rouco et al., 2009) not suffering this limitations, at the price off neglecting any land-atmosphere feedback from the subsurface due to its changing heat content. If these offline models take into account the earlier GSTH, this could be equivalent or even better than the approach proposed here. However, the signal originating from earlier GST changes like the postglacial warming has to be taken into account one way or the other.

### **Additional changes**

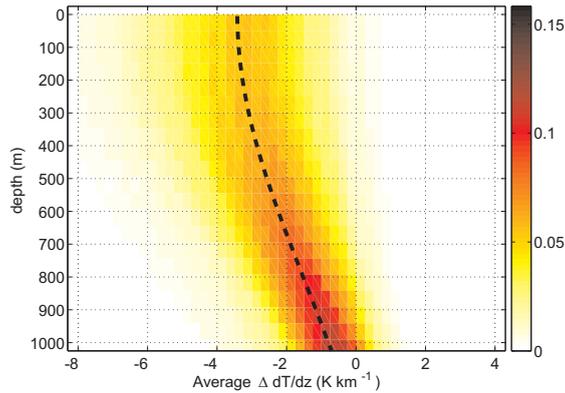
For the revised manuscript, we have moved the appendix *Sensitivity studies for the correction approach* to the main text, also improving the figures to include more information. Finally, for the revised manuscript we suggest to publishing the software as a supplement to this article, as the links to the author's web page may not have the required long-term stability. We have changed the text accordingly, moving the link information to the introduction.

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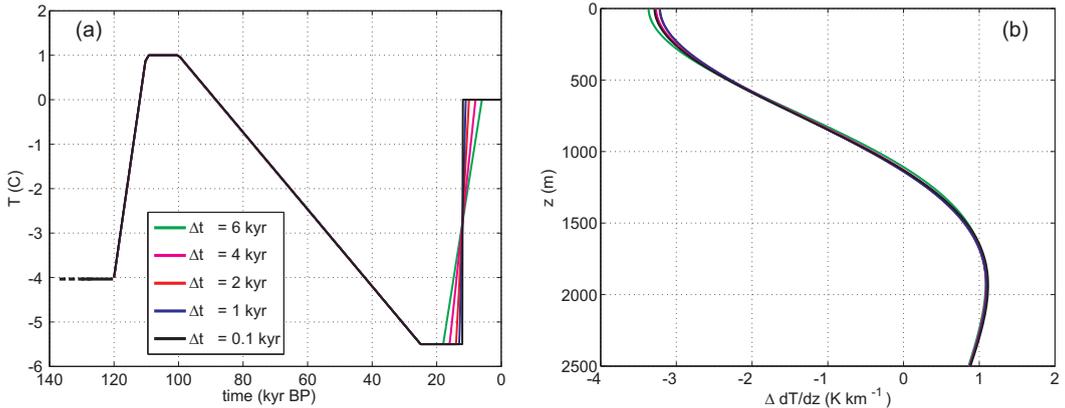
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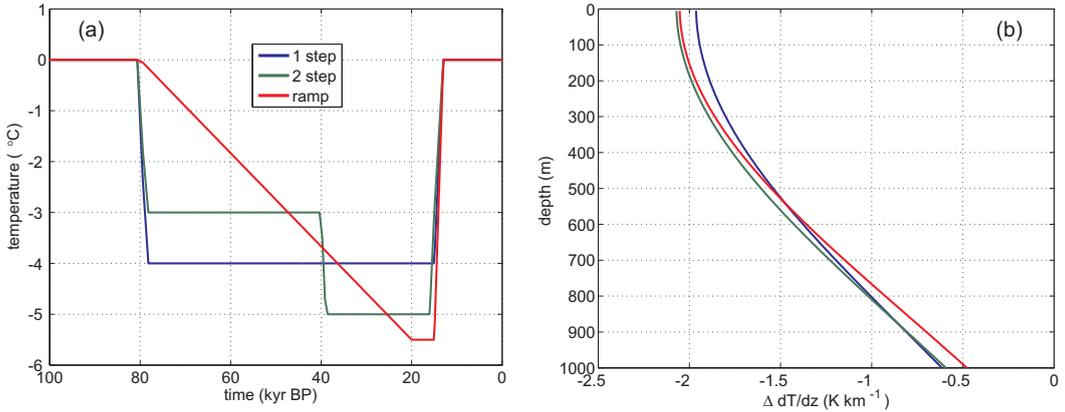
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**Fig. 1.** Results of MC simulations without varying the thermal properties. Shown are normalized histograms of the vertical derivatives of temperature deviation with respect to steady-state conditions as functions of depth. The integral along the horizontal axis is equal to 1 for all depths, as the densities are normalized by the number of runs (10 000). In this figure only the top 1000 m are shown, illustrating the “*nearly linear behavior*” in shallow boreholes. Curvature increases with depth. The black line marks the mean model on which the MC priors are based.



**Fig. 2.** Residual responses for different glacial-interglacial transition times between quasi instantaneous ( $\Delta t_2=0.2$  kyr) and a smooth temperature rise of 12 kyr. In panel (a) the GSTHs for each case are given, while panel (b) shows the responses, respectively. The vertical temperature gradients spread about  $0.2 \text{ K km}^{-1}$ . Temperature differences (not shown) are less than  $0.05 \text{ K}$ .



**Fig. 3.** Comparison of the BTP response (b) to different GSTH functions (a). In addition to the boxcar variation actually used in the MC study, we include a two-step model and a linear ramp-like decrease of temperature between 100 kyr BP to 20 kyr BP, followed by a sharp increase at 14 kyrs. The effect is visible but small, and could be further decreased by choosing an optimum value for the boxcar amplitude and/or length.