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Solid Earth Discussions

Interactive comment on "Heat-flow and subsurface temperature history at the site of Saraya (eastern Senegal)" *by* F. Lucazeau and F. Rolandone

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We thank the referees for their positive comments and criticisms on our paper. We answer here the questions addressed by V. Rath:

1 Influence of the temperature warming following the Last Glacial Maximum

1. The borehole measurements are very shallow ($\leq$ 250 m). However, there is a paleoclimatic effect of earlier temperature changes (mainly related to the last glacial-interglacial temperature rise) even at these depths (see, e.g., Rath et al., 2012). I'm not acquainted with African paleotemperatures, but if this can be ne-

glected (see, e.g., Clark et al., 2012), it should be mentioned, and if not, the possible effect should be estimated. At these shallow depths this fortunately mainly concerns the estimate of the local basal heat flow, and thus does not influence the conclusions about the ground surface temperature histories. There might be an influence on the heat flow estimates.

We agree that such a temperature change could be recorded and affect the value of the basal heat-flow. As far as we know, the main change that affected West Africa was an abrupt transition from a wet to a dry period 5500 years ago. The so-called African Humid Period (AHP) lasted from 14800 to 5500 BP (deMenocal et al., 2000), and resulted in the formation of lakes and wetlands in the Sahara and Sahel regions (Lézine et al., 2011). According to Patricola and Cook (2007), the surface temperatures were lower during the AHP despite the increased solar forcing because of an increase of cloudiness, and the difference with the present day surface temperatures in Senegal is estimated to less than 1 C. The expected perturbation on the thermal gradient is therefore less than 0.4 mK/m, i.e. less than $\sim$ 1 mW m^{-2}.

2 Methodology

1. I think there is some important information missing regarding the inversion procedure. Even if known to many, a few lines of theory might be helpful to the reader.

   This will be added in the revised version.

2. How is the ground surface temperature history parametrized - constant time steps or logarithmically decreasing? Can a change in parametrization reduce or even eliminate the mentioned inversion artifacts (Figure 4)?

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We have evaluated the parametrization values in order to minimize the misfit with temperature measurements (defined here as the RMS) in the borehole and secondly to reproduce the increasing trend of surface temperature at Tambacounda meteorological station. Linear steps give systematically better results than logarithmic steps (Fig. 1). Optimal results are obtained with linear time steps between 1 and 3 years.

3. Explain the cutoff f : is this referred to raw or normalized singular values? How is this value chosen?

   The method provides the options of keeping only the largest singular values ("hard" option) or to add them a damping parameter f ("soft" option). In the first case, the optimal value is obtained for a cutoff = 0.1 and in the second case for f=0.01. In all cases, values higher than the optimum provide large misfits with the observations and lower values improve the fit with borehole data but create unacceptable oscillations (Fig. 1). Therefore, our method is similar to yours (Hartmann and Rath, 2005) for the optimisation of the damping parameter (we used the RMS instead of the L2 norm). We consider the ground surface temperature decrease after year 2000 as an "artefact" of the inversion process when there is no data above 30 m (in boreholes where we logged from 10 m depth, this does not happen). It appears systematically (Fig. 1) whatever the cutoff value.

4. What about the uncertainties?

   Uncertainties are usually estimated in similar studies with a sensitivity analysis of the thermal parameters. These studies conclude usually that the GST inversion is robust to the uncertainties on the thermal parameters. However, the main cause of uncertainties is more likely related to the heterogeneities and mostly to the fluid processes. In our study, we had the chance to log 8 boreholes, all in the same area, the same geological context and with the same surface conditions. Holes 1050 and 1057, which show the most important differences of curvature in the upper part of the temperature log, have almost the same GST history from the SVD method, but have very different amplitudes (0.7 and 1.4 respectively) in year 2000. We cannot exclude that fluid circulation can remove the climatic signal completely: only 25 % increase of the fluid velocity assumed for hole 1050 (Fig. 7 of our paper) would do that!

5. Which MC procedure is used, e.g., how many samples, and which prior distributions were assumed?

   The Monte-Carlo procedure is based on a forward resolution of the 1D heat equation with advection of fluids and heat production:

   $$\rho_b\, c_b\, \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\,(\lambda_b\, \frac{\partial T}{\partial z}) + A_b + A_w + \rho_w\, c_w\, V_w\, \frac{\partial T}{\partial z}$$

   where λ_b, ρ_b, c_b and A_b are respectively the bulk thermal conductivity, density, specific heat and heat production of the host rock.

   ρ_w and c_w are respectively the bulk density and specific heat of water. V_w is the vertical circulation of the fluid. A_w is a heat sink accounting for the horizontal fluid circulation.

   The equation is solved by an implicit finite differences method. The mesh is divided into 2500 cells of 0.1 m and the time step is 0.0833 year. The upper boundary condition is fixed as $T_s + \Delta T_s(t)$ where $\Delta T_s(t)$ is the temperature anomaly recorded at the Tambacounda station extrapolated to 1920 (the SVD analysis shows that GST variations are not important before). The lower boundary condition is the background heat-flow q_0.

   The five parameters in the alteration zone (λ_b, A_w, V_w, T_s and q_0) are randomly and independently chosen assuming a Normal distribution through an iterative process, but some of them can also be fixed. The number of iterations is 10000. An example of the 1000 best solutions (less than a RMS threshold) is given in Fig. 2. In table 2 of the paper, we have only reported the best solution.

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3 Water circulations

1. The treatment of the effects of fluid flow is very interesting,and critical to the estimates of past ground temperature changes. If flow is included, you need a conceptual model for the system. A sketch might help the understanding. You included the additional assumptions on the influx temperature (set to Ts), and its vertical extension (20 m to 20 m). This seems to me reasonable to me. Though there are of course a lot of equivalencies involved, it might be interesting to include the influx temperature independently into the MC procedure.

   A conceptual model is given in Fig. 3 and can be added to the revised version of our paper. The idea is that the recharge of meteoric water is fast enough that the temperature does not have time to warm up. We also thought to include the temperature of water as a free parameter in the Monte Carlo procedure, but this would mainly affect the fluid velocity for which we have no constraint.

2. In Table 2 you show the vertical velocities between 30 m and 50 m depth. What is assumed below 50 m? Is Vz the same? If not, where does the water come from or go to?

   Actually, there is a mistake in the table: the vertical flow is considered only in the aquifer ($\sim$ 20-30 m). The origin of such circulations could be local discharge or recharge, free convection in the aquifer or a change in the topography of the aquifer.

3. How can you differentiate between positive and negative values for the horizontal velocity?

   We are not sure to understand the question: the temperature of water is always less than the rock temperature such that the effect is always negative (heat sink).

4. Are there any estimate estimates of porosity or permeability available?

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Some porosity values are published for the Saraya aquifers in a PhD thesis (Diouf, 1999). Porosities are inferred from electrical resistivity and range between 18 to 54 %.

4 Particular comments

1. Equation 2 and Figure 2: From my understanding the common RMS should have the 1/n term below the square root. However in inverse literature some other measures of deviation are used (Aster et al., 2005), sometimes under the same name. Depending on what you can assume on the structure of your observation errors, the choice of the RMS may be reasonable for the misfit measure.

   That's a mistake and it will be corrected in the final version. The 1/n term is actually below the square root.

2. Figure 4: The inverse procedure parametrizes the ground surface temperature history as a series of step functions. I think it should be shown in this form, and not as a smooth curve. This would also make the character of the inversion artifact clearer.

   This will be changed in the final version and shown in the same way as for Fig. 1 of this comment.

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