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Climate of the Past Discussions

Interactive comment on "Repeated temperature logs from the sites of the Czech, Slovenian and Portuguese borehole climate stations" *by* J. Šafanda et al.

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We are thankful to R.Harris, D.Demezhko and Anonymous Referee 3 for their valuable comments. We also appreciate a care with which the Anonymous Referee 3 corrected and improved the language of the paper. We have accepted most of referees' recommendations and made extensive changes that are mentioned below in italics. .

Comments to the interactive comment of D.Demezhko

Ad 1) The reason, which justifies joint considering of the three sites is the existence of the borehole climate observatories at these sites. The authors do not have neither data from nor information about others similar stations in Europe. Discussion of the environmental conditions, the climate history and the geological structure on the observed data has been broadened.

Ad 2) Sensitivity of the ground surface temperature histories to a priori SDs of conductivity and temperature data obtained by the functional space inversion was tested. The values used for the Czech and Portuguese boreholes, 0.5 W/(m.K) and 0.05 K, are small enough to allow the inversion to account for the past temperature changes if the signal is there. The a priori conductivity SD for the Slovenian borehole is higher, 0.1 W/(m.K), because the conductivity data are not so well constrained by measurements here, but still within the usually used range of the a priori SD values.

Source of the disagreement between the SAT and the reconstructed GST for the shortest inverted profile of 140 m at the Czech station is not connected with the profile's length, as explained now in the revised text. The rather poor coincidence of the SAT and GST obtained by inversion of the longest profile of 260 m at the Slovenian station and the quite good coincidence in the case of the 188 m deep Portuguese profile demonstrate that the length of the profile is not an important source of the disagreement in the cases studied.

Ad 3) After the paper submission, we have succeeded to prove our hypothesis of the anthropogenic influence on the subsurface temperature at the site of the Czech station. We compiled a 3-D geothermal model of the borehole and solve numerically the heat conduction equation considering history of the anthropogenic changes and the SAT series as the surface boundary condition. The calculated warming trends within the borehole agree very well with the observed ones. Therefore, the recent warming rate of the GST yielded by the temperature log inversion is higher than the SAT trend, because of the additional, anthropogenic warming of the surface. .

Comments to the interactive comment of Reviewer #3

The objections raised in the general comment are common with those raised by

R.Harris and are answered in our comments to his review.

Ad “Abstract” - the abstract was extensively modified and reads

Two borehole climate observatories were established in Slovenia and Portugal within a joint Czech-Slovenian-Portuguese project in the years 2003-2005. Together with the older Czech observatory, which has been operating since the year 1994, they monitor air, soil and bedrock temperatures with the aim to study their coupling and the downward propagation of the surface temperature changes. We report here on the repeated temperature logs carried out within 6 boreholes at the sites of the observatories and their surroundings within a time span of 8 - 20 years (1985 - 2005). The repeated logs revealed subsurface warming in all the boreholes amounting to 0.2 - 0.6 °C below 20 m depth. The compatibility of the observed temporal changes of subsurface temperature with surface air temperature (SAT) series measured in Prague (since 1771), Ljubljana (since 1851) and Lisbon (since 1856) was checked by comparing differences of the repeated temperature logs with the synthetic ones, calculated by using the SAT series as a forcing function. A degree of agreement varies from well for two of the Slovenian boreholes, via partially well for the Czech and Portuguese boreholes to rather poor for the two remaining Slovenian boreholes located in an alluvial plain. As a source of the disagreement for the Czech borehole, anthropogenic changes in its surroundings were clearly identified. For the Portuguese borehole it might be a higher rate of the last two decade warming inland than on the coast caused by a moderating effect of the Atlantic Ocean. The weaker-than-predicted subsurface temperature response at the two Slovenian sites could be connected with a horizontal groundwater flow. The depth of the Czech borehole (140 m) and the Portuguese borehole (180 m) was sufficient enough for a reconstruction of the ground surface temperature (GST) history of the last 150 - 200 years. GSTs were compared with the SAT series measured in Prague and Lisbon, respectively. The reconstructed histories reproduce reasonably well the amplitude of the recent warming inferred from the meteorological data, 1 - 1.5 °C above the long-term mean. The depth (100 m) of the four repeatedly logged Slove-

nian boreholes was too shallow for inversion, but climatic reconstruction was carried out for a deeper borehole, logged in 2006 and located within 5 km from the Slovenian observatory. The obtained GST history was compared with SAT series from Ljubljana.

Linear fit was added to all Slovenian profiles - now in Fig.3 and 5 - in order to homogenize them with the presentation of the Czech and Portuguese profiles.

Caption of Fig.9 (the old Fig.5) changed to

Fig.9. Ground surface temperature histories reconstructed by functional space inversion for the Czech (a), Slovenian (b) and Portuguese (c) borehole climate observatories. Variations of the ground temperature are shown together with variations of the surface air temperatures and their 11-year running averages from meteorological stations in Prague, Ljubljana and Lisbon, respectively. For the Czech and Portuguese boreholes both individual and simultaneous inversions of the repeated logs were done. Three histories shown for the Slovenian borehole corresponds to three different hypothesis of thermal diffusivity assumed in the inversion. .

Comments to the interactive comment of R.Harris

The term "borehole climate station" has been changed to "borehole climate observatory" - also in the title of the paper

According to the recommendation, the term pre-observational mean (POM) was changed to the initializing temperature (IT).

References Bartlett et al.2006 a Chapman and Harris, 1993 were added

We do not think that putting the data on thermal conductivity into a table would be helpful. Structure of the data differs for the individual boreholes and we consider their description in the text sufficient.

We recognize the reviewer's recommendation to mention the role of the repeated logs in removing steady-state sources of the temperature profile curvature, e.g. (unrecognized) variations in thermal conductivities. This point was added to chapter 1. Introduction

One of important features of the repeated logs differences is an elimination of steady-state sources of curvature. (Chapman and Harris, 1993; Majorowicz et al., 2006).

and also in chapter 3.2. Ground surface temperature history

Considering repeated logs in a simultaneous inversion helps to constrain better the steady-state part of the temperature profile, which is determined in a decisive manner by possible conductivity variations with depth.

We agree with the reviewer that showing a location map for each borehole would be helpful. But on the other hand it would increase number of figures perhaps above the reasonable limit. In addition to it, we provide geographical coordinates of the boreholes at the sites of all three borehole climate observatories. We have chosen a compromise solution and add a location map for Slovenia, where, beside the borehole climate observatory and the meteorological station in Ljubljana, there are four additional boreholes strewn over the Slovenian territory.

We recognize the objection that using the term “equilibrium temperature” for the temperature logs, which are not disturbed by drilling, is - in the context of the paper dealing with transient temperature profiles - misleading. That is why we have changed the corresponding sentence in chapter 2.2. , which reads

All logs discussed in the paper were done sufficiently long after the borehole drilling for disturbances of temperature induced by the drilling to fade out. Therefore they show the true bedrock temperature.

We have changed layout of Fig.3 (originally Fig.2) in order to be consistent with Fig.1 and Fig.4 (originally Fig.3), which improved also its legibility

The reviewer pointed out a role of the initializing temperature (IT) on the synthetic

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temperature profiles and their differences. We discussed this problem in the original version. In order to demonstrate a low sensitivity of the synthetic differences to the chosen value of the IT, we considered in all cases IT values varying by ±0.5 °C around the mean of the first 50 years of the observations. The results are shown in figures and discussed in the text

Solution of the equation - the subsurface transient response to the SAT forcing function - depends on the initial temperature versus depth profile, which was considered constant. This temperature value is referred to as the initializing temperature (IT) in order to distinguish it from the so called pre-observational mean, which is the initializing temperature optimized with respect to the fit between the simulated and measured transient profiles. This parameter influences strongly the shape of the transient profile (Safanda et al., 1997; Harris and Chapman, 1997; Majorowicz et al., 1999, 2004), but not so much a difference of the transient profiles corresponding to different times. The synthetic differences for the Czech, Slovenian and Portuguese boreholes were calculated using the SAT series from meteorological stations in Prague, Ljubljana and Lisbon, respectively. A distance between a borehole and a corresponding meteorological station is not more than 100 km in all cases. The ITs used for these SAT series were equal to the mean of the first 50 years of the observations, i.e. 9,8 °C (1771 - 1820) for Prague, 9.0 °C (1851 - 1900) for Ljubljana and 15.6 °C (1856 - 1905) for Lisbon. In order to demonstrate a low sensitivity of the synthetic differences to the chosen IT, we considered in all cases also IT values varying by ±0.5 °C around the first-50-year-mean and the calculated curves are plotted together with the observed differences in Figs.6-8. As expected, the sensitivity of the synthetic difference to the chosen IT is very small. It does not exceed 0.013 °C for the Czech and Portuguese boreholes and 0.034 °C for the Slovenian boreholes, and is comparable with the noise level in the temperature logs.

We have followed recommendation of reviewers and reorganized the paper:

Original chapter 2.2 was merged with original chapter 2.1. However, original chapter

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2.1 was divided into two chapters, 2.1. Geothermal climate change observatories and 2.2. Further subsurface temperature data.

We have also changed order of chapters 3.1 and 3.2, which are now 3.1 Observed and simulated temporal subsurface temperature changes 3.2 Ground surface temperature history

We have added Table 1, summarizing amplitudes of the warming and its rate in the individual boreholes.

We have expanded chapter 3.2. “Ground surface temperature history” in order to explain use of three different diffusivity values in the Slovenian borehole, to react to the remarks on the decreasing resolution of the GST reconstructions with time in the past, and also to discuss in greater detail differences in the SAT and GST variations.

*Whereas resolution of SAT series does not change in time, resolution of the GST reconstruction decreases with time in the past. The reconstructed GST at a given moment τ in the past is a weighted average of temperature over a certain period of time, which increases linearly with τ like 0.5 - 0.7 * τ (Clow, 1992). It means that the GST value reconstructed, e.g. for the year 1850 from the temperature - depth profile measured in the year 2000, represents weighted average over the time interval 1812 - 1887 (for the rate 0.5 * τ) up to 1797 - 1902 (for the rate 0.7 * τ) This loss of resolution explains a smoothness of the reconstructed GST histories and their incapability to resolve decadal and multidecadal variations seen in the SAT series prior last few decades. The SAT series were shifted tentatively to the level of the reconstructed GST variations in the interval 1961-1990, because the long-term values of their differences are not known yet and should be determined on the established borehole climate observatories. The used SAT series represents the longest one in each of the three countries. Observations in Prague began in the year 1771, in Ljubljana in 1851 and in Lisbon in 1856. The distance of the corresponding meteorological stations from the borehole sites is about 8 km in Prague, 80 km in Slovenia and 100 km in Portugal. Each of the me-*

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teorological stations is located in a large city, with Lisbon and Prague having about 1 million inhabitants each and Ljubljana about 0.3 million. Therefore, the amplitude of the recent warming which started at the end of the 19th century may have been enhanced by the anthropogenic effect caused by the growing city (Safanda et al., 1997). This could explain different amplitudes of the warming between SAT and GST observed at Prague and in Slovenia. The amplitude of the SAT warming since the end of the 19th century is about 2 °C both at Prague and Ljubljana, whereas the amplitudes of the GST warming at corresponding borehole sites are by 0.5 - 1 °C smaller. In Portugal, nevertheless, both amplitude and course of the Lisbon SAT warming is quite well reproduced by inversion of the Portuguese profile, where it amounts to about 1.5 °C. This means that the effect of the growing city might be not so strong in Lisbon. Another explanation of this difference between Portugal and the Central Europe could be a different relative level of long-term means prior to 1840 with respect to the levels typical for the period 1840-1900. As the Prague's SAT series indicates, temperatures prior to 1840 were higher than in the period 1840-1900 in the Central Europe and that could be why the GST reconstructions yield there a long-term means higher than the 1840 - 1900 SATs. Maybe in Portugal it was not the case and the long-term mean prior to 1840 is comparable there with the 1840-1900 level.

We have expanded the discussion on a comparison of the observed and calculated differences of the repeated logs. In the case of borehole GFU-1 Prague, where the largest discrepancy between the observed and calculated differences appeared, we managed to identify a source of the discrepancy by quantifying the thermal effects of the site infrastructure on the temperature field in the borehole.

We carried out a quantitative analysis of these effects in the spring 2007 (Dedecek et al., 2007b) by solving numerically the heat conduction equation in a three dimensional geothermal model of the borehole site. In compiling the model, we used results of our ground temperature monitoring below grass, sand and asphalt (Dedecek et al., 2007a). It turned out that the above mentioned anthropogenic structures influence the

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temperature in the borehole quite strongly. Their warming effect in the uppermost 40 m is nearly as large as the warming due to increasing SAT. This fact explains very well the discrepancy between the GST and SAT warming rates in the last decades. It also means that the coupling between the air and ground temperatures is quite tight at this site.

We have reformulated one paragraph in the Conclusions

The revealed discrepancies do not mean necessarily an imperfect air - ground surface temperature tracking, because they could stem at least partially from a bias in the SAT series due to the growing city effects and/or from site specific factors. In the case of the Czech observatory, we were able to show that after taking into consideration the effect of anthropogenic structures in the borehole surroundings, the SAT series reproduces the warming trend observed in the borehole very well.

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