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Borehole paleoclimatology – the effect of deep lakes and "heat islands" on temperature profiles

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Abstract

It is known that changes in ground surface temperatures could be caused by many non-climatic effects. In this study we propose a method based on utilization of Laplace equation with nonuniform boundary conditions. The proposed method makes possible to estimate the maximum effect of deep lakes and "heat islands" (areas of deforestation, urbanization, farming, mining and wetland drainage) on the borehole temperature profiles.

1 Introduction

At present many efforts are made to determine the trends in ground surface temperature history (GSTH) from geothermal surveys. In this case accurate subsurface temperature measurements are needed to solve this inverse problem – estimation of the unknown time dependent ground surface temperature (GST). The variations of the GST during the long term climate changes resulted in disturbance (anomalies) of the temperature field of formations. Thus, the GSTH can be evaluated by analyzing the present precise temperature-depth profiles. The effect of surface temperature variations in the past on the temperature field of formations is widely discussed in the literature (Cermak, 1971; Lachenbruch and Marshall, 1986; Beltrami et al., 1992; Shen and Beck, 1992; Mareschal and Beltrami, 1992; Wang, 1992; Shen et al., 1992, 1995; Bodri and Cermak, 1995, 1997; Kukkonen et al., 1994; Harris and Chapman, 1995; Huang et al., 1996; Huang and Pollack, 1998; Huang et al., 2000; Pollack and Huang, 2000; Majorowicz and Safanda, 2005; Hamza et al., 2007). Earlier the forward calculation approach (FCA) was used to the analysis and interpretation of borehole temperatures in terms of a GSTH (Eppelbaum et al., 2006). Three groups based on the geographical proximity were formed. Fifteen borehole temperature profiles from Europe (5), Asia (4) and North America (6) were selected (Huang and Pollack, 1998; www.geo.lsa.umich.edu/~climate). The objective of this study was the estimation of the warming rates in 20th century by the FCA method and comparing with those obtained by the few parameter estimation (FPE) technique (Huang et al., 1996; Huang and Pollack, 1998). It was reasonable to assume that for close spaced boreholes, the values of the warming rates obtained by the two inversion methods, should vary in narrow limits. The results of inversions (FCA) have shown that for boreholes in North America the current warming rates vary in the 0.41–2.45 K/100 a range. The wide range for the warming rate of 0.33–2.48 K/100 a was also determined for boreholes in Europe. Interesting results we obtained (Eppelbaum et al., 2006) for four boreholes in Asia (China). In this case the warming rate varies in relatively narrow limits (1.16–1.59 K/100 a). The warming rate estimated by the FPE technique (Huang and Pollack, 1998) varied in wide ranges: 0.38–2.49 K/100 a (North America); 0.21–3.75 K/100 a (Europe), and 0.30–2.53 K/100 a (Asia). Thus we can conclude that for boreholes in North America and Europe both approaches provide practically the same ranges of warming rates. For Asian boreholes the FCA approach gives a more consistent (narrow) range of warming rates (1.16–1.59 K/100 a). The results of temperature inversion by both techniques indicate that probably some of non-climatic effects (vertical and horizontal water flows, steep topography, lakes, vertical variation in heat flow, lateral thermal conductivity contrasts, thermal conductivity anisotropy, deforestation, forest fires, mining, wetland drainage, agricultural development, urbanization, etc.) may have perturbed the borehole temperature profiles (e.g., Carslaw and Jaeger, 1959; Lachenbruch, 1965; Kappelmeyer and Haenel, 1974; Blackwell et al., 1980; Lewis and Wang, 1992; Majorowicz and Skinner, 1997; Powell et al., 1988; Guillou-Frottier et al., 1998; Lewis and Wang, 1998; Kohl, 1999; Safanda, 1999; Pollack and Huang, 2000; Cermak and Bodri, 2001; Lewis and Skinner, 2003; Gosselin and Mareschal, 2003; Gruber et al., 2004; Bodri and Cermak, 2005; Mottaghy et al., 2005; Nitoiu and Beltrami, 2005; Taniguchi, 2006; Chouinard and Mareschal, 2007; Hamza et al., 2007; Safandra et al., 2007).

We should note that all climate reconstruction methods are based on one-dimensional heat conduction equation. It is assumed that a uniform boundary condition

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is applied on a plane surface, the formation is a laterally homogeneous medium, and the thermal properties can only depend on a depth. For this reasons any subsurface temperature variations arising from conditions that depart from that theoretical model have the potential to be incorrectly interpreted as a climate change signature (Pollack and Huang, 2000). As was mentioned by Nitoiu and Beltrami (2005) from over 10 000 borehole temperature logs worldwide (The International Heat Flow Commission global geothermal data set), only about 10% of these data are currently used for climate studies because a number of known non-climatic energy perturbations are superimposed on the climatic signal.

Therefore, an extreme caution should be used in selection of temperature-depth profiles for inferring the ground surface temperature histories. To demonstrate the well selection procedures we briefly present two examples. In the study conducted by Guillou-Frottier et al. (1998), only 10 from 57 temperature profiles were selected for inversion of past ground surface temperatures.

The following criteria were considered in rejecting boreholes from the study: steep topography, proximity of lakes, water circulation, instrumental problems, other identifiable terrain effects (such as heat refraction, permafrost effects), and recent changes in surface conditions (clearing of trees). For most of the boreholes that were discarded, the shallowest part of the temperature profile is perturbed. As was mentioned by co-authors these perturbations are often similar to the perturbations due to changes in surface temperature. If the terrain conditions had not been considered, warming would have been inferred for 25 boreholes. Ten boreholes show apparent cooling, and only one shows no difference. To screen out borehole temperature data from Eastern Brazil with indications of possible perturbations arising from non-climatic effects, the following quality assurance conditions were imposed (Hamza et al., 2007):

1. The borehole is sufficiently deep that the lower section of the temperature-depth profile allows a reliable determination of the geothermal gradient, presumably free of the effects of recent climate changes. Order of magnitude calculations indicate that surface temperature changes of the last centuries would penetrate

to depths of nearly 150 m,

2. The time elapsed between cessation of drilling and the temperature log is at least an order of magnitude large compared to the duration of drilling,

3. The temperature-depth profile is free from the presence of any significant non-linear features in the bottom parts of the borehole, usually indicative of advection heat transfer by fluid movements, either in the surrounding formation or in the borehole itself,

4. The elevation changes at the site and in the vicinity of the borehole are relatively small so that the topographic perturbation of the subsurface temperature field at shallow depths is not significant, and

5. The lithologic sequences encountered in the borehole, have relatively uniform thermal properties, and are of sufficiently large thickness that the gradient changes related to variations in thermal properties do not lead to systematic errors in the procedure employed for extracting the climate related signal.

Out of a total of 129 temperature logs only 17 were found to satisfy the above set of quality assurance conditions (Hamza et al., 2007). Corrections can be applied, for example, to correct borehole temperature profiles for the effect of topography (Lachenbruch, 1965; Blackwell et al., 1980; Safanda, 1994, 1999). However, this is rarely done because the amplitude of the climatic signals is often smaller than the uncertainty on these corrections (Chouinard and Mareschal, 2007). Safandra et al. (2007) presented interesting results of repeated temperature logs from Czech, Slovenian and Portuguese borehole climate observatories within a time span of 8–20 yr. The repeated logs revealed subsurface warming in all the boreholes amounting to 0.2–0.6°C below 20 m depth. The warming rate of 0.05°C/yr. at the Czech observatory (located in a park within the campus of the Geophysical Institute in Prague) was estimated. This warming rate is two times more than the simulated value (using the surface air temperature as a forcing function). It was assumed that subsurface temperature at the station is influenced by new structure built within the campus of the Geophysical Institute within the last 10–20 yr and/or by other components of infrastructure built 40–50 yr ago. The authors (Safandra et al., 2007) conducted a quantitative analysis of these effects by solving numerically the heat conduction equation in a three dimensional geothermal model of the borehole site. It was found out that the mentioned anthropogenic structures influence the temperature in the borehole quite strongly.

Nitoiu and Beltrami (2005) attempted to correct borehole temperature data for the effects of deforestation. The authors simulated the ground surface temperature changes following deforestation by using a combined power exponential function describing the organic matter decay and recovery of the forest floor after a clear-cut (Covington, 1981). The presented examples demonstrate that application of this correction could allow incorporate many borehole data into the borehole climatology database (Nitoiu and Beltrami, 2005).

In his study Taniguchi (2006) attempted to attribute the rise in ground surface temperature in Bangkok as a result of both global climate change and urbanization. As was mentioned by Taniguchi (2006) the "heat island effect" on subsurface temperature due to urbanization is one of the global environmental issues. It was determined that the magnitude of surface warming, evaluated from subsurface temperature in Bangkok, was 1.7°C which agreed with the meteorological data during the last 50 yr. The results show that the expansion of urbanization in Bangkok reaches up to 80 km from the city center (Taniguchi, 2006).

Thus by analyzing the regional temperature profiles one should be aware that changes in GST could be caused by many non-climatic effects. These effects need to be documented since they produce distortions of the borehole temperature profiles similar to those produced by climate change (Chouinard and Mareschal, 2007). In this study we make an effort to estimate the maximum effect of deep lakes and "heat islands" on the borehole temperature profiles. We will consider areas of deforestation, urbanization, farming, mining and wetland drainage as "heat islands". In all cases we will assume that surface temperature anomalies (due to lakes) and the above mentioned non-climatological factors existed for a very long time. Therefore, the Laplace differential equation can be utilized to evaluate the maximum impact of deep lakes and "thermal islands" on borehole temperature profiles.

The ultimate objective of this study is to assist in choosing drilling sites for borehole climate observatories where the effect of lakes and non-climatological factors will be minimal. A simulated example that demonstrates the effect of a deep lake on temperature profiles of wellbores located within 300 m (400 m from the center of the lake) is presented.

2 Working equations

Let us assume that the well site is located within or outside of a deep lake. In our case the term "deep lake" means that the long term mean annual temperature of bottom sediments can be considered as a constant value. We will assume that $z=0$ is the vertical coordinate of the lake's bottom.

The temperature regime of formations in this area (within and outside of the lake) is subjected to the thermal influence of the lake. The extent of this influence depends mainly on the lake's dimensions, on the current depth, the distance from the lake, and on the difference between the long term mean annual temperature of bottom sediments and the long term mean annual temperature of surrounding lake formations (at $z=0$). We will assume that the island existed for an infinitely large period of time.

The following designations will be used below:

ρ, ϕ, z are the cylindrical coordinates (ρ is the distance from the z axis, ϕ describes the angle from the positive xz-plane to the point, and z is depth); T_{is} is the long term mean annual temperature of bottom sediments; and T_{ot} is the long term mean annual temperature of surrounding lake formations at $z=0$. Firstly, let consider a lake of an arbitrary contour (Fig. 1).

The Laplace equation for the semi-infinite solid area is

$$\frac{\partial^2 T}{\partial \rho^2} + \frac{1}{r}\frac{\partial T}{\partial \rho} + \frac{1}{\rho^2}\frac{\partial^2 T}{\partial \varphi^2} + \frac{\partial^2 T}{\partial z^2} = 0 \tag{1}$$

The boundary conditions are:

$T(\rho, \phi, z = 0) = T_{is}$ within the lake area

$T(\rho, \phi, z = 0) = T_{ot}$ outside the lake area

$T(\rho = \infty, \phi, z) = T_{ot} + \Gamma z$

where Γ is the regional (outside the lake area) geothermal gradient.

The solution of Laplace equation is possible by division of an arbitrary contour lake into sectors. However, the solution is expressed through a complex Poisson integral and fairly elaborate and time-consuming computations are needed (Balobayev and Shastkevich, 1974).

Let $\rho_{\max}$ be the maximum value of the set $\rho_1, \rho_2, \ldots \rho_n$ (Fig. 1). By introducing a safety factor (the maximum thermal effect of the lake on temperature profiles) we can assume that the lake has a circular shape with a radius $R_i=\rho_{\max}$. In some cases the radius of the lake can be approximated by

$$R_i = \sqrt{\frac{S}{\pi}}$$

where S is the surface area of the lake. Now the Laplace equation and boundary conditions are

$$\frac{\partial^2 T}{\partial \rho^2} + \frac{1}{r}\frac{\partial T}{\partial \rho} + \frac{\partial^2 T}{\partial z^2} = 0, \tag{2}$$

$T(\rho, z=0) = T_{is}, \rho \le R_i,$

$T(\rho, \phi, z=0) = T_{ot}, \rho > R_i,$

$T(\rho = \infty, z) = T_{ot} + \Gamma z.$

The solution of Eq. (2) is following (Balobayev and Shastkevich, 1974):

$$T(\rho, z) = T_{ot} + \Gamma z + M(T_{is} - T_{ot}) \quad (3)$$

$$M(\rho, z) = 1 - A_1 \left[A_2 \Pi(\alpha_1^2, k) + A_3 \Pi(\alpha_2^2, k) \right] \quad (4)$$

$$A_1 = \frac{z}{\pi\sqrt{z^2 + (R_i + \rho)^2}}; \quad A_2 = \frac{\sqrt{z^2+\rho^2} - R_i}{\sqrt{z^2+\rho^2} + \rho} \quad (5)$$

$$A_3 = \frac{\sqrt{z^2+\rho^2} + R_i}{\sqrt{z^2+\rho^2} - \rho}; \quad \alpha_1^2 = \frac{2\rho}{r+\rho}; \quad \alpha_2^2 = -\frac{2\rho}{r-\rho} \quad (6)$$

$$r^2 = \rho^2 + z^2; \quad k^2 = \frac{4\rho R_i}{z^2 + (R_i + \rho)^2} \quad (7)$$

where $\Pi(\alpha_1^2, k)$ and $\Pi(\alpha_2^2, k)$ are the complete elliptical integrals of the third order (Abramowitz and Stegun, 1965).

At all climate reconstruction methods the reduced temperatures, $T_R(\rho,\ z)$, are utilized.

From Eq. (3) we obtain

$$T_R(\rho, z) = T(\rho, z) - T_{ot} - \Gamma z = M(T_{is} - T_{ot}) \quad (8)$$

It is easy to see that the Eqs. (3–8) can be also used to describe the effect of "heat islands" on borehole temperature profiles. In this case R_i is the radius of the "heat island" (for example, area of deforestation), T_{is} is its surface temperature, and T_{ot} is the land's (outside of the "heat island") surface temperature. Both values (T_{is} and T_{ot}) are temperatures at the depth with practically zero oscillation of the annual temperature.

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3 Example of calculations

Consider a 30 m deep lake with a radius of R_i=100 m and T_{is}=10°C. The regional geothermal gradient is Γ=0.0300°C/m and T_{ot}=20°C. The drilling sites of 5 wellbores (500 m deep each) are located at distances from 100 m to 400 m from the center of the lake (Table 1).

What are the magnitudes of the formation temperature perturbations (expressed through the reduced temperatures) caused by the lake? The results of calculations after Eqs. (4) and (8) are presented in Table 1 and Figs. 2 and 3. We have to note that bottom of the lake has a coordinate z=0 and because of this the actual depth is $z^*=z+30$ m. In our case $T_{is}-T_{ot}=-10$°C and the lake has a cooling effect on the temperature profiles. The values of $T_R(\rho, z)$ are decreasing with depth and practically can be neglected for radial distances of 550–600 m from the center of the lake (Figs. 2 and 3). A commercially available software, Maple 7 (Waterloo Maple 2001), was utilized to compute the function $M(\rho, z)$.

4 Conclusions

A proposed method allows to estimate the maximum effect of deep lakes and "heat islands" (areas of deforestation, urbanization, farming, mining and wetland drainage) on the borehole temperature profiles. An example of calculations is presented which shows to what extent the proximity of a deep lake affects the borehole temperature profiles.

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Table 1. Function $M(\rho, z)$ for five boreholes.

z, m	Distance from the center of the lake, m				
	100	150	200	300	400
20	0.3828	0.0525	0.0168	0.0042	0.0017
50	0.2815	0.0950	0.0370	0.0100	0.0041
70	0.2332	0.1023	0.0456	0.0134	0.0056
100	0.1787	0.0985	0.0518	0.0174	0.0076
120	0.1510	0.0919	0.0528	0.0193	0.0087
150	0.1189	0.0805	0.0512	0.0212	0.0101
200	0.0827	0.0628	0.0450	0.0222	0.0116
250	0.0598	0.0488	0.0379	0.0215	0.0122
300	0.0449	0.0384	0.0315	0.0198	0.0122
400	0.0275	0.0249	0.0219	0.0159	0.0111
500	0.0184	0.0172	0.0157	0.0125	0.0095

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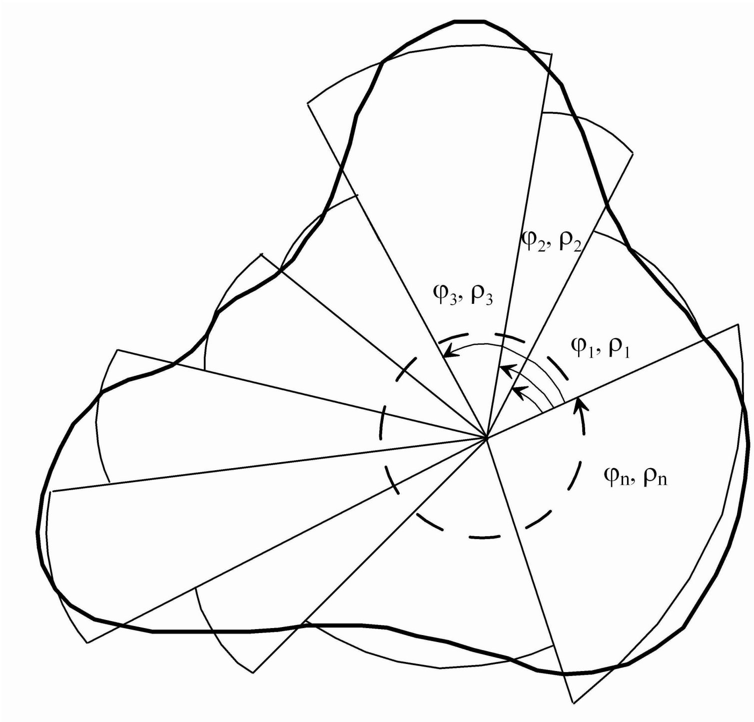

Fig. 1. Division of an arbitrary contour lake into sectors (Balobayev and Shastkevich, 1974).

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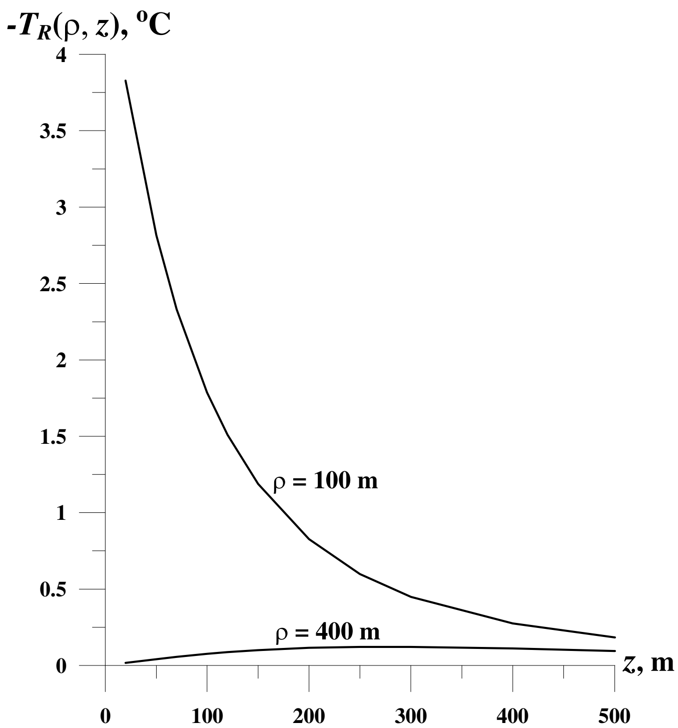

Fig. 2. The reduced temperatures for two wellbores.

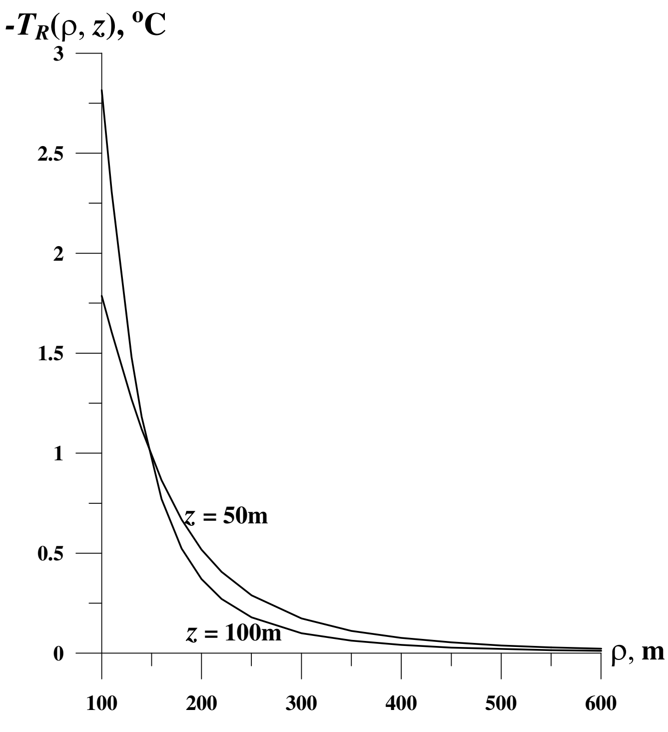

Fig. 3. The reduced temperatures versus radial distance for two depths.