Charles University, Faculty of Science
Institute of Hydrogeology, Engineering Geology and Applied Geophysics

Doctoral study programme: Applied geology

Summary of the Doctoral thesis

Transient temperature field of the shallow subsurface and its sources

Nestacionární teplotní pole pod zemským povrchem a jeho zdroje

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Abstrakt

Z důvodu rozlišení a popisu možných zdrojů nestacionární složky teplotního pole pod zemským povrchem byly zpracovány dlouhodobé teplotní řady a opakované teplotní karotáže zaznamenané v několika vrtech v České republice, Slovinsku a Portugalsku. Z dlouhodobých teplotních záznamů byl pak pomocí dvou různých metod proveden výpočet tepelné difuzivity půdy a skalního podloží. Na základě těchto výpočtů byl prokázán zanedbatelný vliv konvektivního přenosu tepla v půdě a horninovém masivu do hloubky 10 m a také, že vliv změny půdní vlhkosti na teplotní pole je významný pouze ve svrchních 5 cm půdního horizontu. Využitím 3D numerického modelování byl prokázán přímý vliv činnosti člověka na nárůst teploty pod zemským povrchem a byly rozlišeny příspěvky jednotlivých antropogenních struktur k tomuto oteplování. Díky tomu bylo možné rozdělit a popsat vliv změny klimatu a vliv člověka na nestacionární složku teplotního pole.

Abstract

Long-term air and ground temperature series and repeated temperature logs from several boreholes in Czech Republic, Slovenia and Portugal were processed to distinguish and describe possible sources of transient signals in subsurface temperature field. Two methods for estimation of the soil and bedrock thermal diffusivity from long-term temperature records are presented and compared. Results proved that on the annual time scale the convective heat transfer did not contribute significantly to the temperature-time variations monitored in the uppermost 10-m depth zone and that the influence of moisture changes on subsurface temperature field noticeably appears only in the upper 5 cm of soil. Using 3D numerical modelling a direct human impact on the subsurface temperature warming was proved and contributions of individual anthropogenic structures to this change were evaluated. It made it possible to split the transient component of the present-day temperature depth profiles into the climatic and anthropogenic signals.

1. Introduction

The information stored in the transient component of the temperature-depth profiles can be used as a valuable archive of the past climatic changes (Harris and Chapman 1997; Beltrami 2002; Šafanda et al. 1994). The steady-state part of the subsurface temperature corresponds to the long-term annual mean of the ground surface temperature. The seasonal and inter-annual surface temperature variations propagate downward and disappear at the depth of 15–25 m. In case of a climatic change, however, the long-term annual mean of the surface temperature changes and this transient signal propagates much deeper— to hundreds of meters for the centennial and millennial climatic changes and to first kilometers for the glacial—interglacial cycles.

Apart from the climate change, the transient component of subsurface temperature field can be affected by the ground isolation that can be formed for instance by a vegetation or snow cover (Lewis and Wang 1992; Majorowicz and Skinner 1997a, b; Smerdon et al. 2003; Majorowicz and Safanda 2005), by moisture changes or latent heat released or consumed during phase changes of water within the active layer of soil (Beltrami and Kellman 2003; Smerdon et al. 2003; Woodbury et al. 2009)

Beside the natural sources of disturbances, the human activities like deforestation and urbanization can have crucial influence on transient component of subsurface temperature field (Bense and Beltrami 2007, Ferguson and Woodbury 2004, 2007, Taniguchi et al. 2005, 2007)

2. Aims of the study

The aim of my thesis was to find mechanisms affecting the transient component of subsurface temperature field and specially to separate the influence of climate and "disturbing" signals caused by human activities or water movement in vadose zone.

3. Material and methods

In my work I process the long-term temperature series recorded at observatories located in the Czech Republic, Slovenia and Portugal. The air temperature at 2 m and 0.05 m above the ground level and soil and bedrock temperatures up to depth of 40 m are recorded at all stations. Beside the long-term temperature series the repeated temperature logs of borehole Še-1 in Šempeter, Slovenia were used to describe the evolution of subsurface temperature field.

Thesis can be divided into three parts, which are connected to each other. The first part deals with the evaluation of long-term temperature measurements in relation to regional climate changes and in the second part two methods for the estimation of thermal diffusivity from temperature series are developed. The algorithms used also allow to evaluate the influence of precipitation and conductive heat transfer in the vadose zone. In the third part, the results obtained in the first two parts are utilized and 3D numerical models are compiled to evaluate the effect of anthropogenic structures on the subsurface temperature field at two localities in the Czech Republic and Slovenia.

4. Results and discussion

4.1. Transient temperature signal in shallow subsurface

Different warming rates were found in temperature series measured at a similar depth in two places in the Czech Republic. Figure 1 shows 15-year long (1994-2008) temperature record from Prague divided into periods of approximately constant warming rate. The warming trend of the whole observational period 1994 – 2008 is 0.034 °C per year. On the other hand, the temperature series measured in a borehole in a meadow near the Kocelovice meteorological station shows by about 0.013 ° C less warming at the same time (Figure 2). The reason is the different location of both stations, where the GFU borehole is located in the built-up area of Prague Sporilov and Kocelovice borehole is located in the rural area without urbanization. There is a clear evidence, that higher warming rate in Prague is done by “Urban Heat Island” effect.

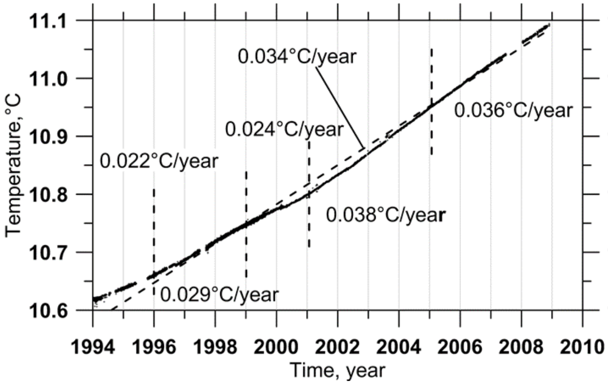

Figure 1. The observed time – temperature series at 38.3 m in the GFU-2 borehole.

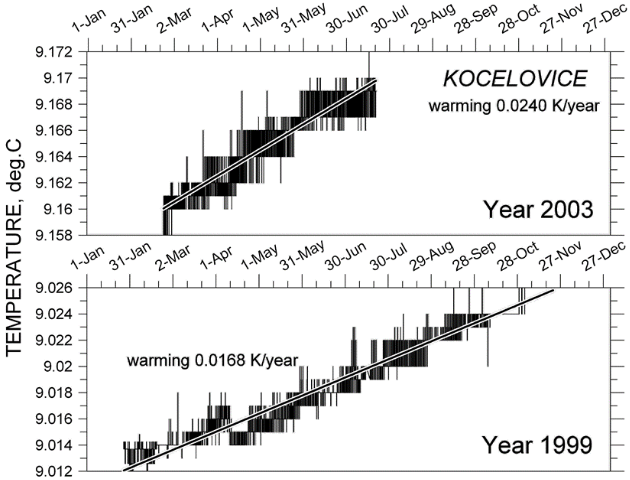

Figure 2. Results of temperature monitoring at depth of 40 m (Kocelovice hole). Two records correspond to 1999 and 2003 monitoring series.

4.2. Thermal diffusivity from subsurface temperature series

I have used two methods of calculating thermal diffusivity (TD) from long-term temperature series in the thesis. The first method, based on the solution of the heat conduction equation by the error function, allows detailed analysis of TD changes in the surface layer of soil. The second method is based on the downward propagation of the annual surface temperature wave and uses its amplitude attenuation and phase shift to calculate the average TD within the zone of the annual wave penetration. Beside the TD estimation, both methods allow to evaluate influence of the soil moisture changes or convective heat transport in vadose zone.

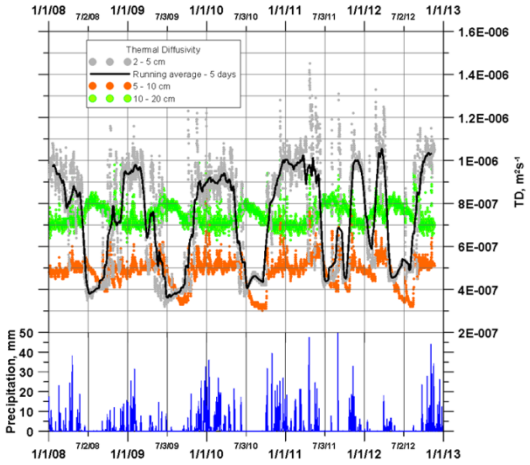

Figure 3. Seasonal changes of thermal diffusivity of soil in Evora connected with daily sums of precipitations.

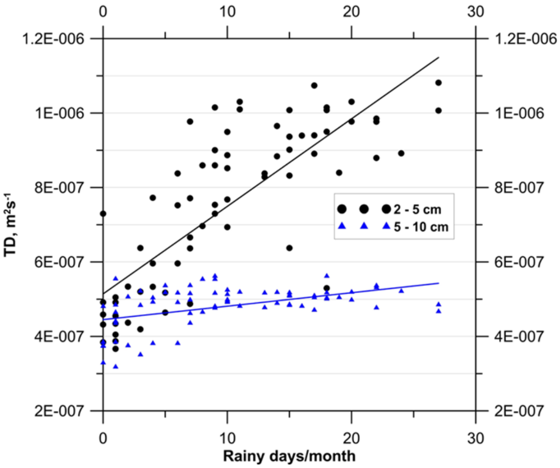

Figure 4. Dependence of the monthly TD averages on the number of rainy days per month in Evora in years 2008 – 2013.

Figures 3 and 4 present results obtained by application of the “error function” method to data from Evora observatory in Portugal. The climate in southern Portugal is characterized by alternating hot dry summer and rainy winter periods. There are clearly visible seasonal variations in the 2-5 cm layer related to the change of moisture, when the TD increases more than twice during the wet period (Figure 3). However, this dependence decreases significantly at a depth of 5-10 cm. It is also evident in Figure 4 depicting a dependence of monthly averages of TD on the number of rainy days in the individual months.

The data series from Malenece observatory (Slovenia) were processed by the second method based on 1-D solution of the heat conduction equation in a semi-infinite homogeneous medium with a periodic surface boundary condition.

Interval	k_{AA}[a]	k_{PA}[a]	k_{CCA}[a]	W (m/s)
0.02-0.05	0.187	0.198	0.198	0.81×10^{-8}
0.05-0.10	0.350	0.316	0.316	-1.77×10^{-8}
0.10-0.20	0.533	0.469	0.468	-2.74×10^{-8}
0.20-0.50	0.487	0.440	0.440	-2.11×10^{-8}
0.50-1.00	0.546	0.496	0.496	-2.12×10^{-8}
1.00-2.50	0.502	0.592	0.590	4.00×10^{-8}
2.50-5.00	0.547	0.699	0.694	6.50×10^{-8}
5.00-10.0	0.490	0.485	0.456	-0.19×10^{-8}

***Table 1**. TD and parameter W calculated for different depth intervals ([a] k_{AA}, k_{PA} and k_{CCA} were calculated by the AA, PA and CCA methods, respectively, and are given in 10^{-6} m^2/s).*

Two conductive (AA - Amplitude algorithm, PA – Phase algorithm) and one Conduction-Convection (CCA) algorithm were developed to estimate TD and specially to evaluate influence of convective heat transport in vadose zone. Table 1 presents the values of TD (*k*) obtained by individual algorithms and parameter W, which characterizes the fluid flux density (Gao et al., 2008) and W=0 means purely conductive heat transfer. As seen, all three algorithms gave reasonably similar results. TD values obtained by the CCA that specifies on a presence of the subsurface fluid flow, revealed a good agreement with the results given by only conduction solution and together with very low values of W parameter suggest that heat conduction dominates in the entire domain.

4.3. Impact of anthropogenic structures on subsurface temperature field

Discrepancy between the regional climate change and observed temperature response in subsurface was studied in two urban areas - in Prague and in Šempeter (Slovenia). Three-dimensional transient geothermal models (cube, length of the sides 1000 m) of the boreholes' sites were compiled with the aim to distinguish in the observed transient component of the temperature logs the part caused by construction of new buildings and other anthropogenic structures in surroundings of the boreholes, and the part generated by the ground surface temperature warming due to the surface air temperature rise.

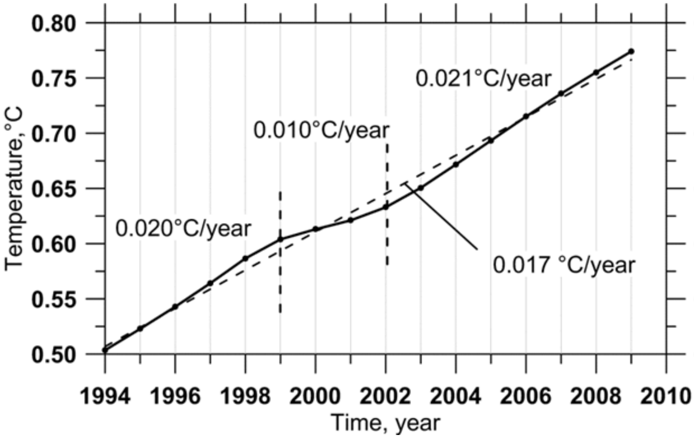

Figure 5. Time – temperature variations at 38.3 m of the GFU-2 borehole calculated as a subsurface temperature response to the surface air temperature variations only.

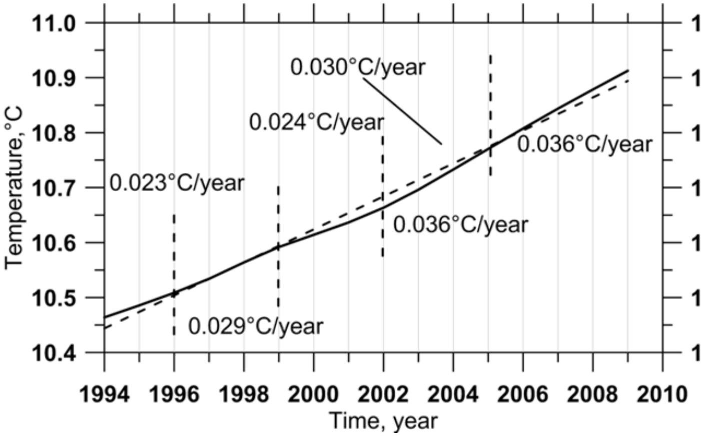

Figure 6. Time – temperature variations at 38.3 m in the GFU-2 borehole calculated by the final model as a subsurface temperature response to the surface air temperature

variations together with the effect of the anthropogenic structures.

The results from the first studied locality at the campus of Institute of Geophysics in Prague are presented in Figures 1, 5 and 6. Comparing the calculated (synthetic) warming rate (Figure 5) yielded by the SAT variations from Klementinum meteorological station with the rate of the observed curve (Figure 1), we see appreciable quantitative difference. Namely, the mean annual warming rate for the whole period of observation is 0.034 °C per year instead of the calculated rate of 0.017 °C per year.

Taking into account also the effects of individual anthropogenic structures as well as the effect of the intensity of solar radiation on the asphalt temperature in individual years, we get warming rate, which is very close to the observed values (Figure 6).

The second studied locality is within the industrial zone of the town Šempeter. A large sporting hall is situated in the borehole's close vicinity with adjacent asphalt areas together with a small playing field and industrial halls and asphalt roads further away. The temperature logs of Šempeter borehole display a U-shape with a minimum at the depth of 65 – 70 m migrating downwards at the rate of about 1 m per year, and a gradual warming at the rate of 0.01 – 0.02 K per year (Figure 7). The individual effects of the regional climatic and local anthropogenic forcing together with their composite effect on the subsurface temperature field in the borehole Še-1 are shown in Figure 8 in comparison with the observed transient component (meteorological station Ljubljana)

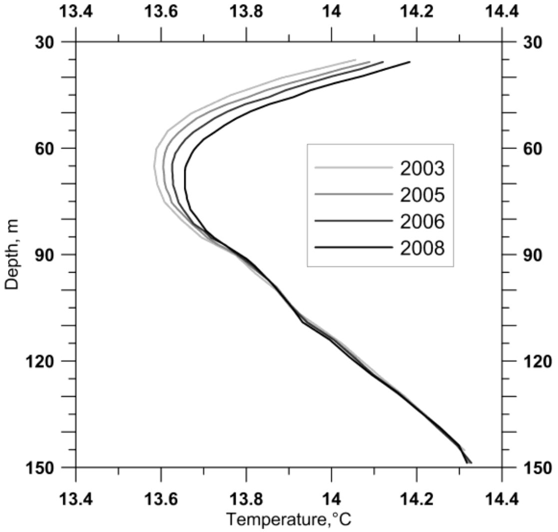

Figure 7. Temperature logs in the borehole Še-1, Šempeter, Slovenia, measured in the years 2003, 2005, 2006 and 2008 (from left to right) at the depth section 40 m – 150 m.

The warming effect of the anthropogenic structures is about 50 % of that caused by the SAT warming at the depth of 50 m and becomes negligible below 100 m. The impact of climatic signal attenuates more slowly with depth than the anthropogenic one and becomes smaller than one hundredth of degree below 160 m. The sum of the two signals approximates fairly well the observed transient component of the Še-1 temperature logs.

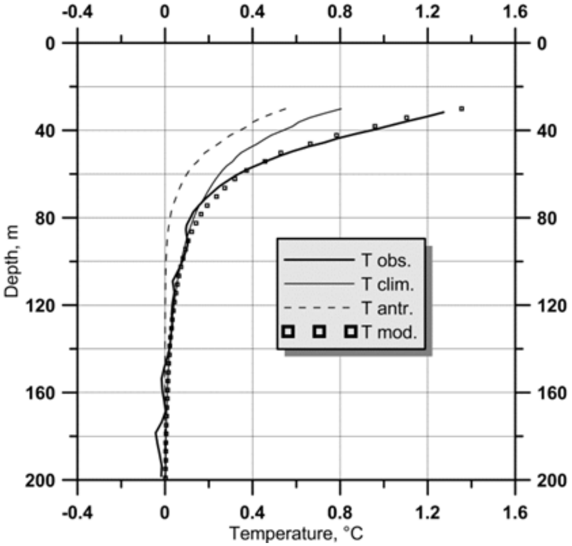

Figure 8. Transient components of the temperature – depth profiles in the borehole Še-1 in 2008 generated (i) by the individual effects of the regional climatic (Tclim) and local anthropogenic (Tantr) forcings and (ii) by their composite effect (Tmod) compared with the observed transient component (Tobs).

5. Conclusions

The thesis has shown that the present subsurface temperature field can be strongly influenced both by the recent regional climatic changes and by thermal effects of local anthropogenic structures. On the other side the influence of water movement on subsurface temperature field caused by a meteoric water infiltration is negligible and heat conduction dominates in vadose zone. Only the thinnest layer of soil to a depth of 5 cm is affected by changes in moisture and the induced seasonal variations of thermal diffusivity can affect heat transfer in the shallow subsurface, especially in places where the significant alternation of hot dry and cooler wet periods occurs.

The results of the study indicate that the factor of “thermal pollution” due to local anthropogenic effects in precise temperature logs must be taken into account seriously both in the terrestrial heat flow studies and in the ground surface temperature history reconstructions. Especially for the climatic studies based on the temperature logs, selection of boreholes or borehole sites should always consider this possible problem.

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Curriculum vitae

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H-index (Web of Science): **6**

Research results summary: Author or co-author of 13 scientific research papers indexed in WOS, more than 30 conference contributions

Research interests

- Thermal properties of rocks and soils, heat production of rocks
- Energy balance of Earth´s surface
- Temporal and spatial changes of the heat flow and temperature gradient
- Time dependent numerical models of the Earth´s crust temperature field, temperature prediction to the depth
- Geothermal energy

Research skills

- Temperature logging and long-term monitoring
- Numerical modelling (COMSOL code), programming (Pascal, Matlab)
- Laboratory measurement and estimation of thermal properties of rocks and soils

Selected publications

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