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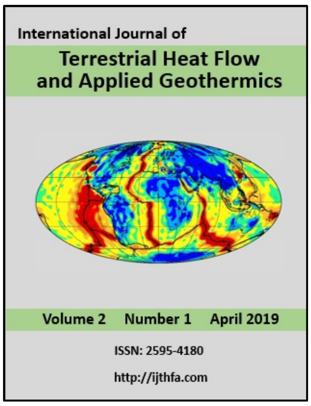

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About the penetration of the diurnal and annual temperature variation into the subsurface

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Abstract

In order to evaluate the effect of the penetration of diurnal and annual wave temperature into the subsurface, the temperature has been monitored at an hourly recording frequency at depths of 40, 60 and 78 m between summer 2016 and summer 2018, at the geothermal experimental test site "Neutra" of the Georg-August-University of Göttingen, Germany. It has been asserted that the mean temperature gradient between 40 and 78 m continuously increases, because the temperature decreases at 40 m. The decrease can be explained by an increase in vegetation cover (trees, shrubs, etc.) in the perimeter of the test area, increasing the absorption of solar energy by the leaves. During the phenological growth season the diurnal temperature variation at the surface can be recorded in phase with opposite sign, even at a depth of 40 m, and the drop of the temperature at 40 m, when surface temperature reaches a value of nearly 9 °C, can be observed during small events of eco-dormancy during winter. The annual surface temperature variation of ±10 K induce the same effect with an amplitude of ±2mK at 40 m. It is stated that the dormant state of the vegetation cells is the reason of the annual variation of the residual temperature. At greater depths groundwater flows prevail and influence the temperature according to the structural properties of the encountered lithologies and the precipitation. The vegetation can transfer the daily and seasonal temperature variation to larger depths than expected based on the theory of heat conduction. This timely variation of the temperature gradient demonstrates that the determination of the terrestrial heat flow density is subject to several impacts induced from the surface as well as from the Earth's interior. As a conclusion, temperature gradients determined at shallow depths may be influenced by changes in surface coverage.

1. Introduction

Heat conduction into the ground has been investigated for several years. 200 years ago, Jean Baptiste Joseph Fourier (1768-1830) formulated the theory of heat, compiling his papers into a book in 1822. His theoretical background to all heat conduction problems stimulated Georg Wilhelm Muncke (1772-1847), a physicist at the Georg-August-University of Göttingen/Germany, to present an analytical solution of the heat conduction equation for penetrating temperature waves into the subsurface (Muncke 1827). During the 1830s, Siméon-Denis Poisson (1781-1840) reported the exponential attenuation of the amplitude with depth in his work, entitled "Théorie Mathematique de la Chaleur" (1835) and Lambert-Adolphe-Jacques Quetelet (1796-1874) considered the diurnal and annual temperature variations as sine waves in 1837 (Buntebarth, 2002).

The penetration of temperature variations at the Earth's surface became meaningful with the context of discussions on climate warming (e.g. Cermak et al. 1999), and ever since this debate has started, more attention has been paid to temperature changes at the Earth's surface, its penetration in the subsurface, and its consequence for the environment (e.g. Shen et al. 1995; Cermak et al. 2000; Majorowicz, 2002; Hamza and Vieira, 2011). This contribution demonstrates that the diurnal and annual surface temperature variation can change the temperature field in the subsurface more deeply than the theory yields, in addition to the changes at the surface such as, the phenology and, more specifically, the growing season variation (Guiot et al. 2010; Kaspar et al. 2015; Koerner, 2016).

Microtemperature variations are monitored for some decades (Shimamura, 1980; van Ruymbeke and Somerhausen, 1999). Special attention has been paid to provide arguments for earthquake prediction (e.g. Buntebarth et al. 1997; Demetrescu and Shimamura, 1999; Middleton, 1999), volcanic activity (e.g. Shimamura and Furuya, 1999) and in most of the studies for groundwater flows (e.g. Drury et al. 1984; Hamza, 1999).

2. Methodology

In order to evaluate the penetration of diurnal and annual wave temperature into the subsurface, the temperature has been monitored at a reading frequency of one per hour at depths of 40, 60 and 78 m from summer 2016 to summer 2018 at the geothermal experimental test site “Neutra” of the Georg-August-University of Göttingen.

The city of Göttingen is located in the Leinetal graben, part the West European rift zones. The base of the Leinetal valley is formed by folded Variscan units overlain by a discordant Permian Zechstein, the Triassic (Buntsandstein, Muschelkalk and Keuper), and finally Jurassic formation (Lias) (Wunderlich, 1959). Its structural geological formation is highly complex due to polyphase tectonic development under various tension forces and pronounced tectonics in the layers. These processes, also termed as “Saxonian folding”, produced a number of folds, faults and fractures.

In this area, a five-spot groundwater well arrangement is surrounded by high scrubland and approx. 20 m high maple and birch trees, which grow at a distance between 15 and 25 m to the boreholes (Figure 1A). The five wells of the arrangement, one of which was drilled in 2008, and the other four, including the used North well (Figure 1B), drilled in 2012 reach to a depth of 78 m and has diameter of 6’’. They are equally configured with alternating permeable and impermeable screens. The permeable screens consist of 3m slotted PE pipe sections that are filled up with filter gravel overlapping 1m. The impermeable screens consist of fully cased PE pipes filled up with high density clay. This configuration achieves hydraulic connection to separated, individual geological strata. The surface construction (Figure 1) consists of concrete rings with hydraulic top covers providing room for experimental equipment and easy access to the wells.

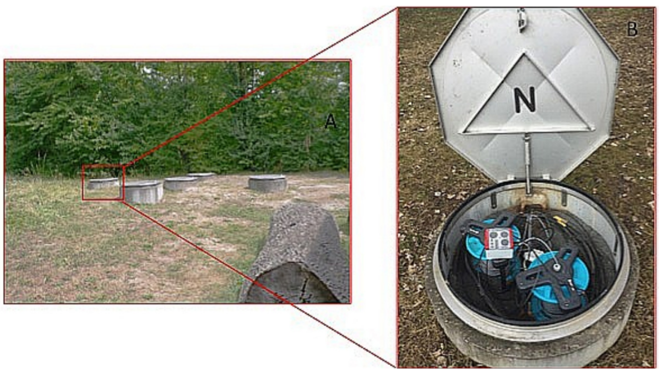

Figure 1 - Geothermal experimental test site “Neutra” at the Campus of the Georg-August-University of Göttingen (A) and North well (B).

The Northern (N) well encountered in the upper 12 m of the profile a mixture of limestone, claystone, quartz and feldspars. From 14 m until the bottom, follow predominantly different shades of claystone mixed, in some layers, with siltstones and sandstones in different proportions. Special attention is given at depth of 64 to 68 meters, where there is a layer of gray-colored mudstone, a number of mineralized fractures and is loosely layered, followed by a beige fine sand breccia, possibly indicating mechanical weathering. The matrix of this breccia consists of gray clayey siltstone with fine dark gray mudstone fragments (Werner, 2013).

For the temperature measurement the LogBox microT thermometer of geotec-instruments company was employed, a high precision thermometer with a resolution of 0,0002 degrees. The instrument is protected by a weatherproof casing and is directly located at the borehole in the metallic borehole head (Figure 1B). The 3 individually calibrated temperature sensors are protected in a waterproof stainless-steel capsule.

The solution of the heat conduction equation subjected to the boundary condition at the surface with T(z,0) = 0 and T (0, t) = $\pm T_0$ exp (iωt) is given by e.g. Tautz (1971) in dependence on depth z and the elapsed time t after the onset with:

$$T(z,t) = 0.5T_0 \exp(i\omega t)\left[\exp(z\sqrt{i\omega/\kappa})\, erfc\left(\frac{z}{2\sqrt{\kappa t}} + \sqrt{i\omega t}\right) + \exp\left(-z\sqrt{i\omega/\kappa}\right) erfc\left(\frac{z}{2\sqrt{\kappa t}} - \sqrt{i\omega t}\right)\right] \quad (1)$$

in which κ is the temperature diffusivity and ω is the circular frequency of the temperature wave.

After a very long time, i.e. after many cycles, the start-up period passes over into a steady state condition which simplifies eq. (1) to:

$$T(z,t) = T_0 exp\left(-z\sqrt{\omega/2\kappa}\right) cos\left(\omega t - z\sqrt{\omega/2\kappa}\right) \quad (2)$$

Eq. (2) accounts for a maximum value at a given depth z when the cosine function has its maximum with unity. For a mean temperature diffusivity of 10^{-6} m²/s of the sub-ground and a temperature amplitude of ±10 degrees, a variation of T of 10^{-3} °C is estimated at a depth of 1.5 m. The same variation is calculated at a depth of 29 m for an annual variation.

3. Results

Based on the calculated penetration of diurnal and annual wave temperatures into the subsurface, eight graphs are plotted. The daily mean values are shown together with the temperature of the recording device at Figure 2. The temperature of the device is close to the surface temperature. Fast variations, however, can be dampened, so that the diurnal surface variations might differ slightly.

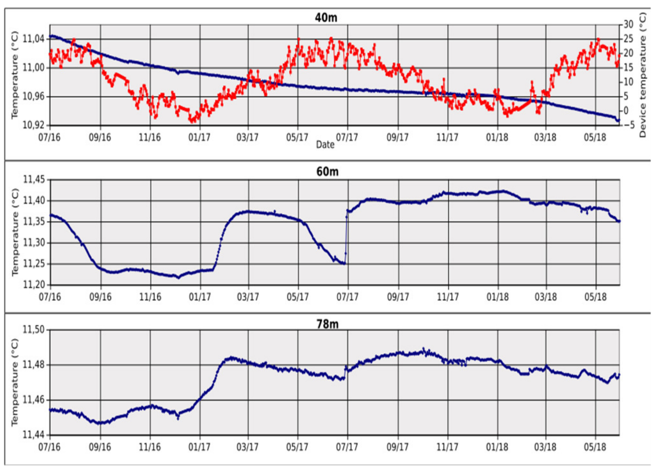

Figure 2 - Borehole temperatures at depths of 40, 60, and 78 m and the device temperature at the geothermal test field site of the Georg-August-University of Göttingen from July 2016 to June 2018.

The temperature continuously decreases, at the depth of 40 m by 0.12 K during the record of 2 years while the temperature at 78 m increases from 2016 to 2017 by 0.004 K and it decreases from 2017 to 2018 by 0.002 K. The temperature at 60 m depth is influenced by precipitation, since this depth is close to a lithological change, with mineralized fractures and layers present, followed by a fine sand breccia, which may create a preferential flow of meteoric water.

The temperature gradient can be calculated as mean for depths between 40 and 78 m. Figure 3 shows this gradient during the 2 years of recording. A continuous increase in gradient is apparent which can be explained by a decrease in temperature at the depth of 40 m. A short-term climate change exhibiting a decline in surface temperature is not known. Another possible reason may be an increase in density of the vegetation cover in the test area, i.e. an increase in absorption of solar energy by the leave canopy. This demonstrates the sensitivity of the assessment of the temperature gradient with time. During the recorded 2 years, it increases significantly from 0.010 to 0.014 K/m. This temporal variation of the temperature gradient demonstrates that the determination of the terrestrial heat flow density is subject to several impacts induced from the surface as well as from the Earth's interior.

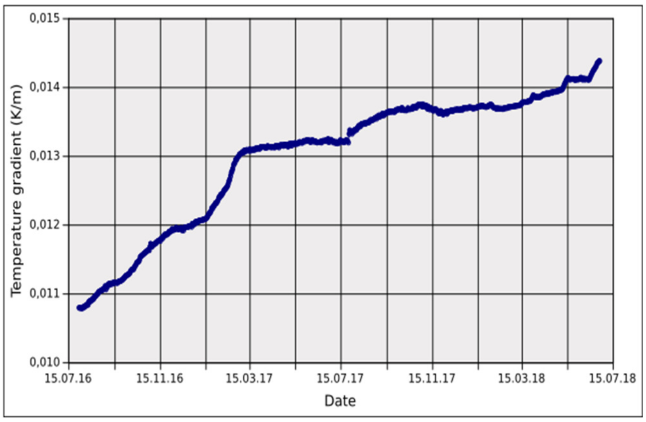

Figure 3 - Variation of the mean temperature gradient between 40 and 78 m of depth during the period July 2016 to June 2018.

The penetration of the annual surface temperature variation could not be recorded, if eq. (2) is applied. The amplitude would be less than 1mK at the depth of 40 m applying a temperature diffusivity (κ) of 10^{-6} m²/s and a surface temperature amplitude of 10.5 K. The data series, which are shown at Figure 2 for the depth of 40m, is analyzed by calculating a polynomial trend of the 3rd degree. The difference between the recorded values and the trend yields a residual temperature. This residual temperature is illustrated together with the device temperature, as the surface temperature in Figure 4. The amplitude is twice as high compared to that expected from theory. Figure 4 illustrates the case of applying eq. (2) with an assumed phase shift of 1.5 years, which imply a temperature diffusivity of $2*10^{-6}$ m²/s. This value is also reached, if it is calculated based on the attenuation of the temperature amplitude. However, such high values of temperature diffusivity are not feasible for sedimentary rocks.

The anticyclic behavior displayed in Figure 4 seems to be caused by another mechanism. For this purpose, the temperature records are investigated with respect to their daily variation during the extreme values of the residual temperatures. Figure 5 shows the temperature sequence during November 2017. There is a scatter ranging within 1mK and when the surface temperature (T) reaches a value of nearly 9 °C, the temperature at the depth (z) of 40 m drops.

During late spring and summer, the diurnal surface temperature continuously ranges above the threshold (Figure 7). As a consequence, the surface temperature with opposite sign coincides in phase with the temperature at the depth of 40 m.

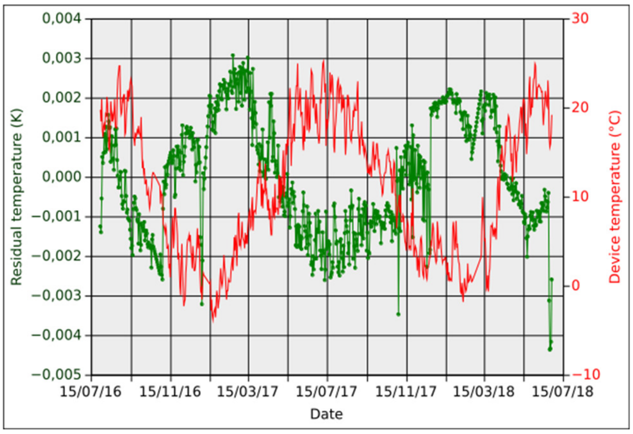

Figure 4 - Phase shift and amplitude attenuation of the recorded temperature and the trend at 40m.

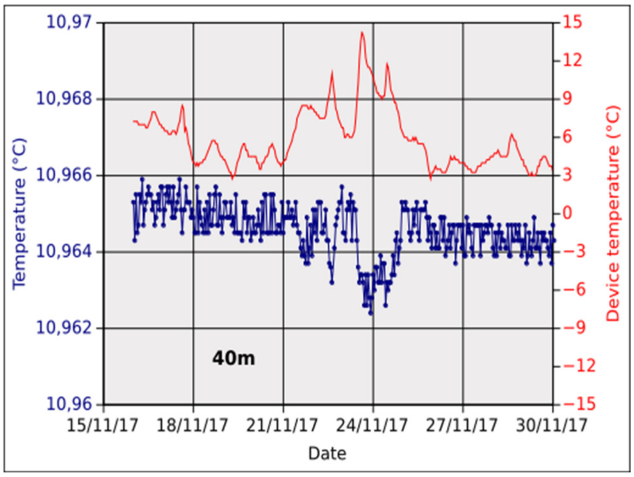

Figure 5 - Temperature sequence at the surface and at the depth of 40m during November 2017.

A few months later, i.e. during spring, the surface temperature is mirrored whenever a threshold value of about 9°C is exceeded, demonstrated in Figure 6.

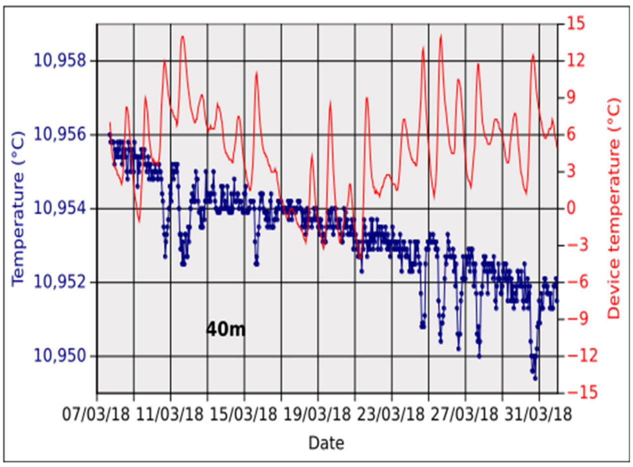

Figure 6 - Temperature sequence at the surface and at the depth of 40m during March 2018.

It can be concluded that a diurnal temperature variation of approximately 2mK occurs during the phenological growth season (Figure 4 and 7), and that the drop of the temperature at 40 m, when surface temperature reaches a value of about 9 °C, can be observed during small events of eco-dormancy during winter (Figure 5 and 6). The roots of the trees take up water and this effect causes a migration of water from the adjacent porous rocks, producing a diurnal variation in phase with surface temperature. It is stated that the dormant state of the vegetation cells is the reason of the annual variation in residual temperature, obtained from Figure 4.

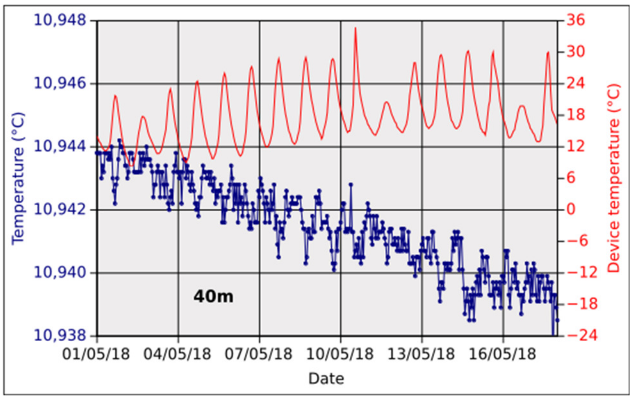

Figure 7 - Temperature sequence at the surface and at the depth of 40 m during May 2018.

The temperature variation at the depth of 60 m is strongly influenced by water migration along the near fractured zone intercepting the borehole. The temperature changes following several impacts such as precipitation, air pressure variation and earth tides. Figure 8 shows periodical variations, which are not related to the surface temperature. During the middle of December, it was snowing, and the snow melted some days later, associated with an increase in temperature by a few Millikelvin. The complex relations between the different mechanisms, their relative impacts as well as their interaction however cannot be analyzed within the context of this study.

At the depth of 78 m, the temperature variations are smaller than that at 60 m as demonstrated in Figure 9. A continuous scatter with a range of 2mK is recorded as well as some influence of groundwater flow in the fractured horizon. The temporal resolution of the records is not fine enough to resolve the question of whether the scatter is caused by periodical impacts, gas bubbles or by sensor properties.

4. Discussion and Conclusion

Many studies are based on repeated temperature records. Each temperature record is, however, an instantaneous and unique record that cannot be interpolated to shallow depths, because variations in vegetation cover can affect the temperature of the subsurface to a large extent demonstrated in this study. A subsurface temperature drop of up to several degrees centigrade can for example be caused by the shading effect of a growing forest. The impact of vegetation can also be considered as a sudden increase in surface temperature resulting from a change in surface condition such as deforestation or urbanization. In addition, it is important to include the phenological variations and, more specifically, the variation of the growing season, caused by climatic variations (Guiot et al. 2010; Kaspar et al. 2015; Körner, 2016).

All activities that alter the surface albedo result in temperature variations at depth. These long-term variations hide the relatively small periodic annual and diurnal variation. This case study may demonstrate that in addition to structurally caused water migration, which can occur at any depth, vegetation can transfer the daily and seasonal temperature variation to a depth larger than that predicted by the theory of heat conduction. Furthermore, high-resolution temperature can be applied to identify a dormant state in plant cover, even without any phenotypic changes. It is surprising that the daytime temperature range, which is attenuated below detection within the top two meters, has an in-phase amplitude of 2mK at a depth of 40 m. As a conclusion, temperature gradients determined at shallow depths may be influenced by changes in surface coverage.

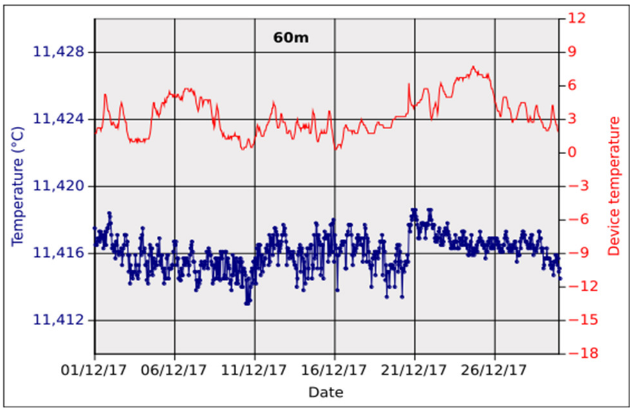

Figure 8 - Temperature sequence at the surface and at the depth of 60m during December 2017.

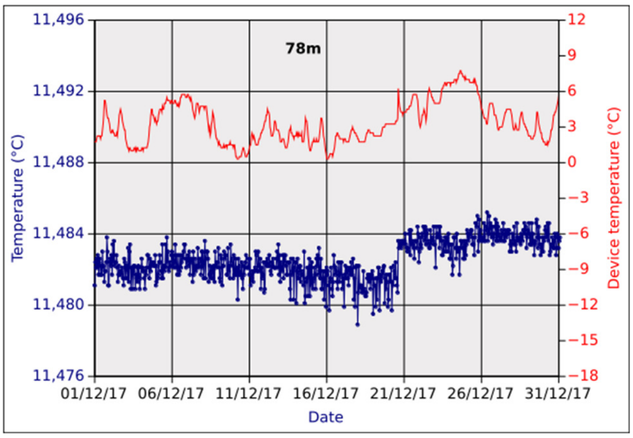

Figure 9 - Temperature sequence at the surface and at the depth of 78m during December 2017.

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