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Investigations of the air – ground temperature coupling at location of the Malence borehole near Kostanjevica, SE Slovenia

Raziskave povezanosti temperatur zraka in plitvega podzemlja na lokaciji vrtine Malence pri Kostanjevici, JV Slovenija

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Abstract

In this paper we present the results of monitoring of temperatures in the air, soil and a borehole V-8/86 at Malence near Kostanjevica in the southeast Slovenia. The results include the temperatures measured in the period from year 2011 to 2015. Highlights of the paper are mainly on the influence of heavy rainfall on temperatures in the upper parts of the shallow subsurface, on understanding how the heat transfers between air and soil and in determination of the warming rate in the shallow subsurface with the assumption that conduction is the prevalent mechanism of heat transfer within the rock. The analysis has shown that heavy rainfall has a greater impact at depth of 1 m in the borehole than at 1 m in the soil, since the sensor at 1 m in the borehole is actually still in the air (inside the borehole) so the rainwater and consequently the air temperature change can reach it faster than the rainwater can infiltrate through soil to depth of 1 m. During infiltration the rainwater's temperature interact with the soil temperature and the change between the rainwater and soil temperatures is no longer evident at 1 m depth in the soil. Based on the measured temperatures from years 2014 and 2015 the rate of warming at the depth of 40 m is 0.011 °C/yr. While analysing the temperature-depth profile of daily means of temperature on the 15th day of each month, we concluded that the influence of seasons can be tracked down to depth of 20 m. At the depth of 20 m temperatures vary within 0.04 °C (2015). The assumption that the conduction is the prevalent mechanism of heat transfer is reasonable, because the theoretical values do not differ much from the measured ones (within 5 %).

Izvleček

V članku so prikazani rezultati merjenja temperatur v zraku, tleh in vrtini V-8/86 v Malencah pri Kostanjevici v jugovzhodni Sloveniji. Podatki obsegajo obdobje od leta 2011 do 2015. Osredotočili smo se predvsem na odzive temperatur v plitvem podpovršju na obilnejše padavine, na prehajanje toplote čez mejo zrak-tla in na določanje stopnje segrevanja v vrtini s predpostavljenim konduktivnim načinom prehajanja toplote znotraj kamnine. Analiza je pokazala, da obilnejše padavine bolj vplivajo na temperaturo v globini 1 m v vrtini kot v globini 1 m v tleh, saj je senzor na 1 m v vrtini dejansko še v zraku in ga deževnica in posledično sprememba zračne temperature doseže hitreje, kot pa se deževnica infiltrira do globine 1 m v tleh. Med pronicanjem se temperatura deževnice približa temperaturi tal in razlike med temperaturama na globini 1 m v tleh ne zaznamo več. Na podlagi podatkov iz leta 2014 in 2015 je trend naraščanja temperature na globini 40 m 0,011 °C/leto. Pri analizi odvisnosti povprečne dnevne temperature za vsak 15. dan v mesecu od globine, smo prišli do sklepa, da letno spreminjanje temperature zraka vpliva do globine 20 m, kjer so razlike med posameznimi meseci samo še znotraj 0,04 °C (2015). Predpostavka konduktivnega načina prehajanja toplote kot prevladujočega za izračun teoretičnega poteka temperatur v odvisnosti od časa in globine je smiselna, saj teoretične vrednosti ne odstopajo bistveno od izmerjenih (znotraj 5 %).

Introduction

Studies of the air-ground temperature coupling get more and more attention as an auxiliary insitu method in research of the long-term temperature variations and therefore climate changes in the present and in the past (Čermák, 1971; Lachenbruch & Marshall, 1986; Šafanda et al., 1997; Smerdon et al., 2004; Bodri & Čermák, 2007). The climate interpretation of the ground surface temperature (GST) history, which is obtained from present-day temperature-depth profiles, measured in deep boreholes, is based on an assumed long-term tracking of the mean annual surface air temperature and the ground surface temperature (i.e. Majorowicz et al., 2004). The reconstructed GST histories are temporal changes of the ground temperature at the upper boundary of the heat conduction domain, which begins somewhere in the soil-rock basement transition zone. Environmental conditions are suspected to be the most important factors influencing the air-soil temperature difference. In 1993 an international project under the NATO scientific programme support and initiative of the Czech Geophysical Institute (GFÚ) was lunched with an aim to explore the assumption on a long-term tracking of the mean annual surface air temperature and the ground surface temperature. Furthermore, this project was initiated also in order to determine the poorly investigated impact of environmental conditions such as soil moisture, type of vegetation cover and the amount and type of precipitation, on heat transfer in the soil and shallow subsurface. Understanding these impacts is essential for understanding how the heat transfers through different layers of shallow subsurface. This knowledge is needed for reconstruction of the past climate based on the temperatures measured along deep boreholes (Beck & Judge, 1969; Čermák, 1971; Shen & Beck, 1991; Kane et al., 2001).

Therefore, a study, based on the air-ground temperature coupling, began in year 1993 to determine how temperatures in the shallow subsurface follow the long-term variations of the air temperatures in different recent climates and how significant is their influence on heat transfer in the shallow subsurface. The main aim of the monitoring is to explore the assumption on a long-term tracking of the mean annual surface air temperature and the ground surface temperature, which is vital for the climatic interpretation of the GST history obtained from present-day temperature-depth profiles measured in deep boreholes. The project comprises permanent temperature measurements in the boreholes in Czech Republic (since 1994), Slovenia (since 2003) and Portugal (since 2005).

One of the most important parameters of heat transfer in the shallow subsurface is thermal diffusivity, which determines how much heat transfers conductively through the material (Gosar & Ravnik, 2007). Thermal diffusivity can be measured directly on the rock sample in a laboratory using e.g. a flash method (Dědeček et al., 2013). Researchers at the aforementioned project *Air-ground temperature coupling in three different climates* decided to use an auxiliary in-situ method for studying the air-ground temperature coupling. With the long-term logging of temperatures at different heights in the air and depths in the soil and borehole every 30 minutes a large database has been generated, covering interval since Nov. 12th 2003 until Dec. 31st 2015 and beyond until today. The 30-minutes interval has been chosen by Czech geophysicists (with longer experience in this matter) as the most appropriate, as it is not too rare (e.g. with regard to precipitation events) neither too dense. This database can be used for determining the effects of environmental conditions and the nature of propagation of surface temperatures into shallow subsurface. By exploring the temperature-time series in three boreholes located in different climates the results can be correlated. Boreholes are located in three experimental sites as follows: a GFÚ-1 borehole of 150 m depth (Šafanda, 1994) in Prague (Czech Republic) at the premises of Czech Geophysical Institute with monitoring down to 38 m depth, a V-8/86 borehole at Malence near Kostanjevica (Slovenia) of 100 m depth and a TGQC-1 borehole of 180 m depth in Caravelinha near Évora (Portugal) (Smerdon et al., 2004, 2006). While the borehole in Prague is in the southeast suburb Spořilov of a metropolitan city, the other two are found in rural areas, at Malence on the edge of meadow, and at Caravelinha in the sparse oak forest near Évora. Both observatories in Slovenia and Portugal monitor temperatures down to 40 m depth (Šafanda et al., 2007).

Herein we present the results of measurements from the Malence Borehole Temperature Observatory (MBTO) near Kostanjevica in the period from 2011 to 2015.

Air-ground temperature coupling

The method of inverting the measured temperatures in deep boreholes in order to reconstruct the GST history was represented by Beck and Judge (1969), who reconstructed the climate in the decade previous to the year of their study. They were soon followed by Čermák (1971), who used the temperature measurements from a borehole in Canada and, although he reconstructed the climate in the past millennium, he also stated that the method needed improvements. The method does not predict the nonconductive heat transfer (Shen & Beck, 1991; Majorowicz et al., 2004). The nonconductive heat transfer, such as infiltration of rain water and freezing or defrosting of the soil, were examined among others by Kane at al. (2001).

First studies of the past climate change in Czech Republic were conducted by Šafanda & Kubík (1992). Analysis of measurements from two boreholes (one in SW and one in NE part of the Czech Republic) has shown an increase of the average surface temperature from -6 °C to 7 °C around 12,000 years ago, a warming by 0.9 °C some 475 years ago, a cooling by 0.5 °C some 36 years ago, followed by an increase of temperature by 1.3 °C nine years ago (as regard to the time of writing the cited paper).

Survey of temperatures obtained from seven boreholes in Slovenia suggests the surface warming by 0.6 to 0.7 °C in the decade 1988-1998 (Rajver et al., 1998). The study has also shown a glacial minimum (3 °C) some 14 to 13 thousand years ago, which was followed by the post-glacial maximum (10.5 °C) around 2 to 3 thousand years ago.

The signature of the last ice age (75 to 10 thousand years ago) in the present subsurface temperatures was studied in boreholes from Slovenia and the Czech Republic by Šafanda & Rajver (2001) who have used temperature-depth (T-z) profiles from 1.5 to 2.4 km deep boreholes. They confirmed a glacial minimum extending 19 to 10 thousand years ago and a postglacial warming of 6 to 15 °C.

The first measurement results from 2003 to 2005 at MBTO were published by Rajver et al. (2006). Data from a period of 2003 to 2009 and a conductive and conductive-convective heat transfer mechanisms were studied by Dědeček et al. (2013).

Heat from surface transfers into the shallow subsurface mainly by conduction. Surface temperature is regulated largely by heat flow from the Sun. Therefore, differences in surface temperature are mostly due to daily and annual cycles. These differences can be tracked down to the depth of about 50 m. Any deeper variations of temperatures, which substantially depart from the conductive heat flow, are the result of a drastic changes in climate (e.g. ice age) (Kappelmeyer & Haenel, 1974).

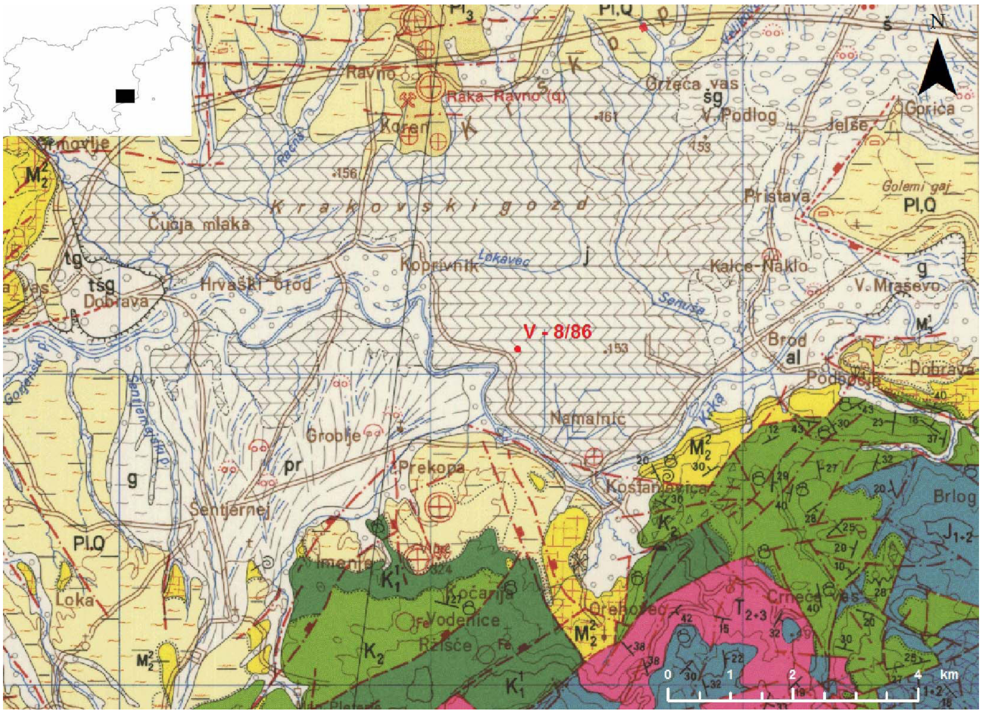

Fig. 1. Location of the V-8/86 borehole at Malence, SE Slovenia. Geology is after OGK Novo mesto (Pleničar & Premru, 1977).

Methodology of temperature measurements in the borehole V-8/86 at Malence

The borehole V-8/86 is located at Malence near Kostanjevica (45°52.1' N, 15°24.5' E, z=152 m a.s.l.) (Fig.1) in the Krško basin in southeast Slovenia. The basin is filled with Tertiary sediments of the Pannonian basin and Quaternary deposits from the Sava river (Pleničar & Premru, 1977) and is part of the Sava folds (Placer, 1998). The borehole was finished in October 1986 and is 100 m deep (Fig. 2a). It was drilled through Quaternary clay, sand and gravel in the first 16 m, below which lies Miocene marl, which gradually becomes more clayey with depth (Rajver et al., 2006; Šafanda et al., 2007; Dědeček et al., 2013). In Figure 2a the last temperature log from August 30th, 2011 is also presented. The borehole is cased with zinc-coated tube of 41.5 mm (1.6 inch) of inner diameter. Temperature was logged four times along the whole borehole depth, from October 1986 to August 2011 (Fig. 2b), using two different temperature sensors. The first two loggings in 1986 and 1987 were done using the Pt-100 sensor, connected to LAGO-T meter (Ravnik & Lakovič, 1984) with a precision of 0.01 °C and accuracy of +/- 0.1 °C, while for the other two loggings the Antares thermistor was used with a resolution of 1 mK and accuracy better than 0.1 K. The thermistor's drift is of the order of first hundredths K over the time the GFÚ team uses the probe (more than 10 years), but the probe is calibrated practically every year, so the effect of possible drift is eliminated (Šafanda, pers. com.). The Pt-100 sensor has been only occasionally calibrated, nevertheless the results are comparable with those of Antares thermistor.

There have been only two rock samples collected, from depths of 0.7 m (sandy clay) and 99 m (clayey marl). On both a thermal conductivity has been measured using different but comparable methods, TCS and transient hot wire, respectively, and results were 1.7 W/(m·K) for the one from 0.7 m and 1.45 W/(m·K) from 99 m (Rajver et al., 2006; Šafanda et al., 2007). Estimation of thermal diffusivity is based on typical density and specific heat values and can differ between 0.6 and $0.8 \cdot 10^{-6}$ m^2/s. Due to high specific heat of pore water, it could be as low as $0.4 \cdot 10^{6}$ m^2/s (for 30 % total porosity) (Šafanda et al., 2007). Dědeček et al. (2013) extracted thermal diffusivity from subsurface temperature data at Malence. They got 0.2 - $0.3 \cdot 10^{-6}$ m^2/s in the top 5 to 10 cm of soil and 0.5 - $0.7 \cdot 10^{-6}$ m^2/s within 0.1 to 10 m of the bedrock. Simple calculation using reasonable parameter values shows that with 15 % of water content in the sample and the mineral density

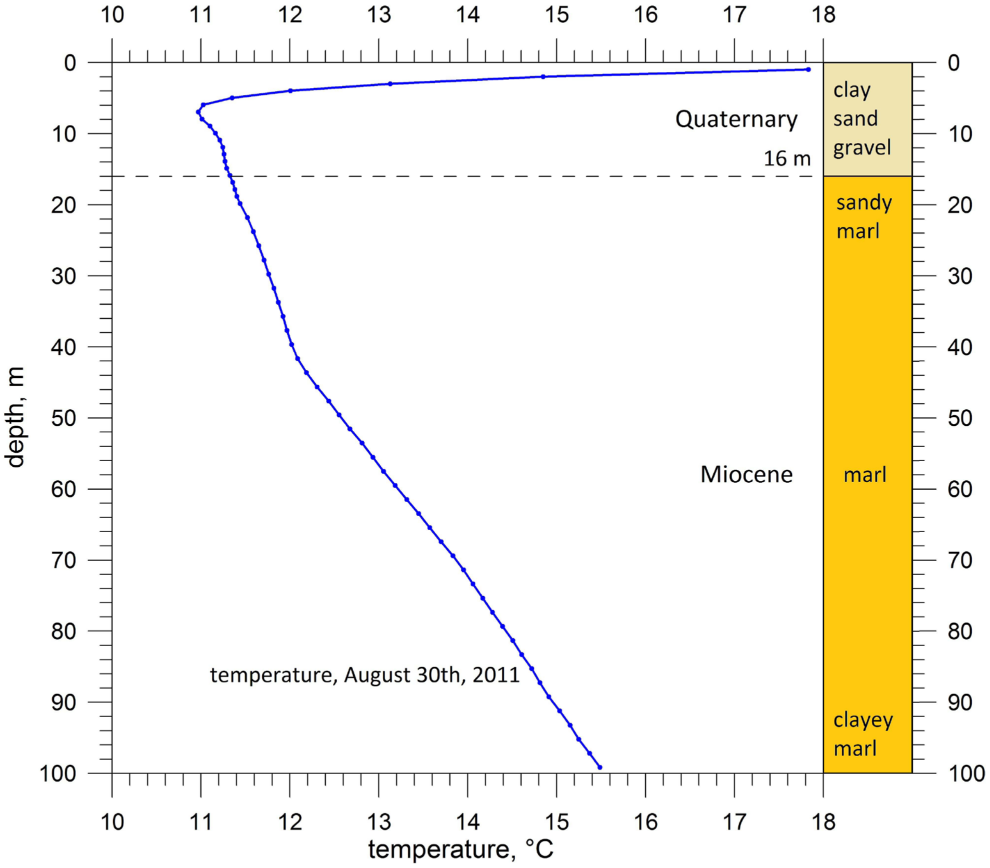

Fig. 2a. Geological column of the V-8/86 borehole with the last T-z profile of August 30th 2011. Lithological data are summarized by Rajver et al. (2006).

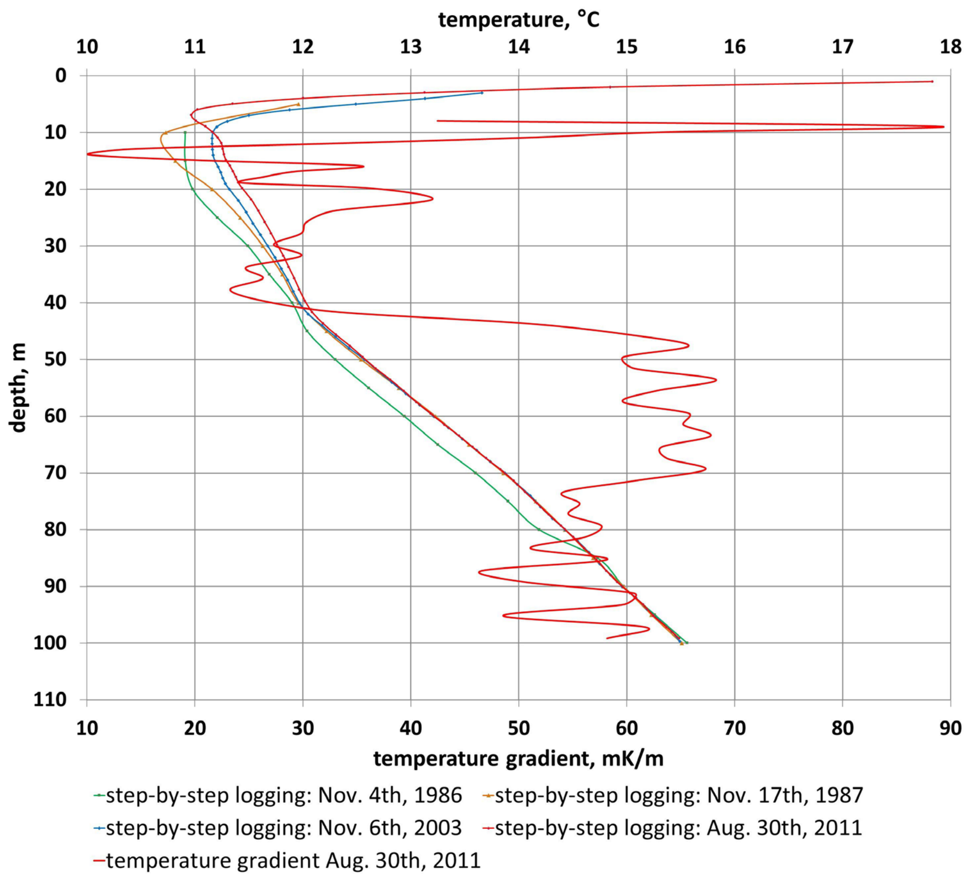

Fig. 2b. The measured temperature (T-z) profiles in the V-8/86 borehole in a period from 1986 to 2011.

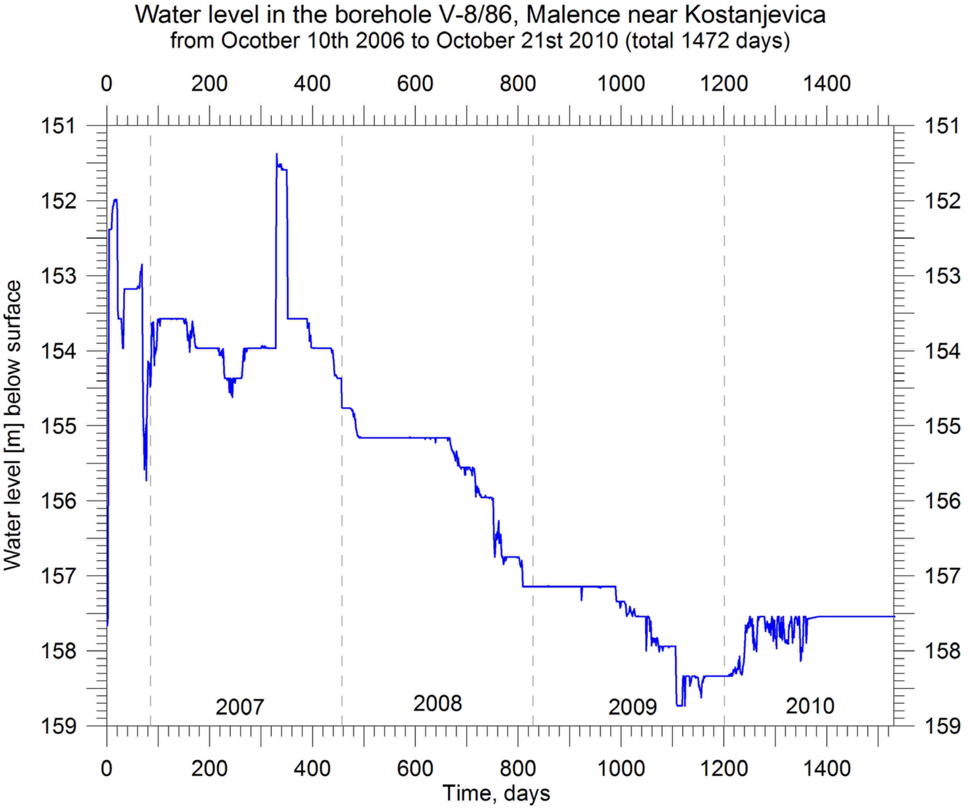

Fig. 3. Water level in the borehole V-8/86, monitored in a period of 4 years (2006 to 2010).

of 2,670 kg/m^3, the effective specific heat (ρ·c) is $2.51 \cdot 10^6$ J/(m^3·K), and thermal diffusivity $\kappa = \lambda / (\rho \cdot c)$ is $0.68 \cdot 10^{-6}$ m^2/s. The borehole has been chosen as the most suitable among available and investigated boreholes in Slovenia because of its location with an easy access, a good knowledge on lithology and relatively stable level of groundwater. The water level in the borehole was monitored only in a period from Oct. 10th 2006 to Oct. 21st 2010 (Fig. 3), using the piezometer sensor that has been connected to one of the channels instead of a temperature sensor at 1 m in the borehole. This monitoring showed only slightly water level variations between 151 and 159 cm below ground surface. Since the fluctuation is quite small and does not show any periodic characteristics, we can assume it does not respond to differences in the level of nearby Krka River. Unfortunately, this period does not match with the period of temperature analyses. The borehole is located on the edge of the meadow, which on the north side continues into the forest, so the vegetation around the borehole is more or less constant and in micro location cleaned out when necessary. We have no data on depth of saturated zone in the shallow subsurface. It is believed this zone is at least 1.5 m deep because the soil to this depth consists mostly of clay and sandy clay, and deeper to 16 m also of gravel in mixture with clay and sand. The borehole is located on a private land and data logger with battery is being kept in a locked metal box so the risk of vandalism is quite low.

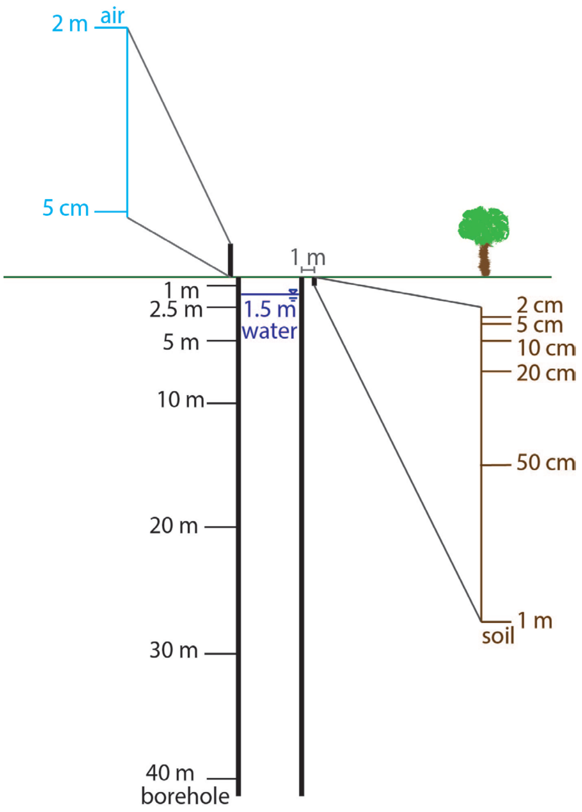

Fig. 5. Layout of the temperature sensors in the air, in the soil and in the borehole V-8/86.

In order to explore the assumptions of (i) a long-term tracking between the mean annual surface air temperature and the ground surface temperature and (ii) a conductive propagation of soil temperature changes into bedrock, the MBTO station has been established (Fig. 4). It consists of a data logger, battery and sensors for monitoring air temperatures at different heights above the ground level (2 m and 5 cm), soil temperatures at different depths below the surface (2, 5, 10, 20, 50, 100 cm) and bedrock temperatures in the borehole (1, 2.5, 5, 10, 20, 30, 40 m) (Fig. 5). The platinum sensors (Pt 1000, class A, resolution of the system is 3 mK) were installed in November 2003 for permanent measurements (Rajver et al., 2006; Dědeček et al., 2013). The accuracy < +/- 0.15 °C is

Fig. 4. Malence Borehole Temperature Observatory (in Sept. 2011). Sensors in the soil are buried within depicted trapeze.

given by producer for the users that do not calibrate the sensors. All MBTO sensors are calibrated. The absolute error of the measured temperature can be estimated at 0.01 K (Šafanda, pers. com.). Temperatures are recorded in 30-minute intervals with a data logger system (16 channels, 24 bits A/D converter, 16 bits resolution, producer Fiedler Magr s.r.o., Czech Republic). Data used in this study cover the period from September 2nd 2011 to January 1st 2016. The MBTO station faced several difficulties in monitoring due to hardware malfunctions. For example, in the period of Oct. 21st to Dec 14th, 2010, some abnormally high positive and negative peak oscillations appeared in the measured temperatures at 1 to 40 m depths, resulting also in high peaks of daily averages. We did not notice this immediately and until Aug. 30th, 2011, we couldn't transfer the measured data to computer, which was later discovered as a memory malfunction of the data logger. Consequently, the GFÚ team decided to install a new data logger unit on Aug. 30th, 2011. They also changed two sensors (the borehole's at 10 m and the air sensor at 2 m). The sensors' and data logger's functioning is occasionally but constantly controlled by the GFÚ team, and the sensors are calibrated before their installation. Contrary to thermistors, the platinum sensors are stable in time. Therefore, we are convinced there are no sensor drifts. Later on, the data were lost or are missing in the following periods: Sept. 17th to 23rd, 2011, when voltage regulator was disconnected, Oct. 15th to 17th, 2012, when all the sensors were changed with the new ones, and Sept. 13th to Oct. 22nd, 2014, when five sensors (at 2.5, 5, 10, 20 and 30 m) in the borehole were changed and the time unit was properly set. A short disruption of the borehole data occurred when on Nov. 14th, 2013, all the borehole sensors were replaced with a new set of sensors.

Results of temperature monitoring and discussion

An example of 30-minute data interval is presented for February, 2012 (Fig. 6), which shows an influence of snow on temperatures in the upper part of soil. In the beginning of the month, the temperatures at depths of 2 and 5 cm in the soil stayed roughly at 0 °C since snow acted like an insulator. Review of data from the meteorological (precipitation) station in Kostanjevica – Brod (3 km away) confirmed that there was a snow cover present from 4th – 23rd of February (Internet 1). Another example (Fig. 7) of the influence of the snow cover insulation is shown for a period January 14th – March 2nd, 2013 (Internet 1), and can be tracked down to depth of 100 cm in the soil.

An example of the influence of rain is shown in Figure 8 with 30-minute data for July 2012, where the temperatures in the air at 2 m and 5 cm

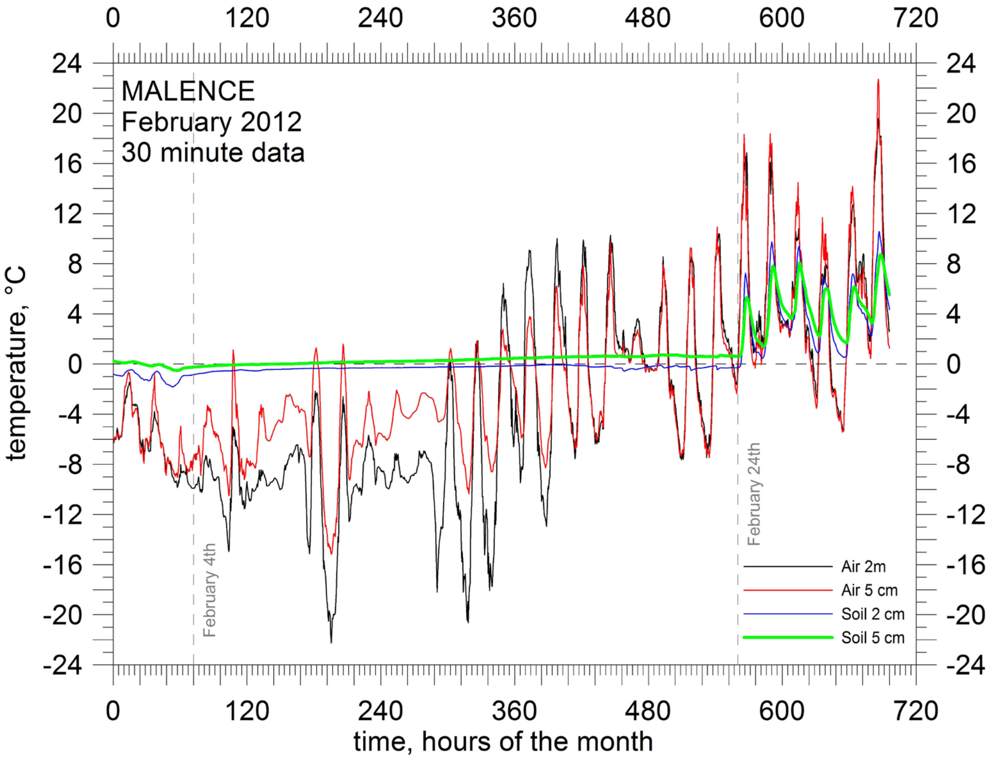

Fig. 6. 30-minute data in February 2012 at 2 and 5 cm in the air and in the soil depths of 2 and 5 cm showing influence of snow cover (February 4th to 24th).

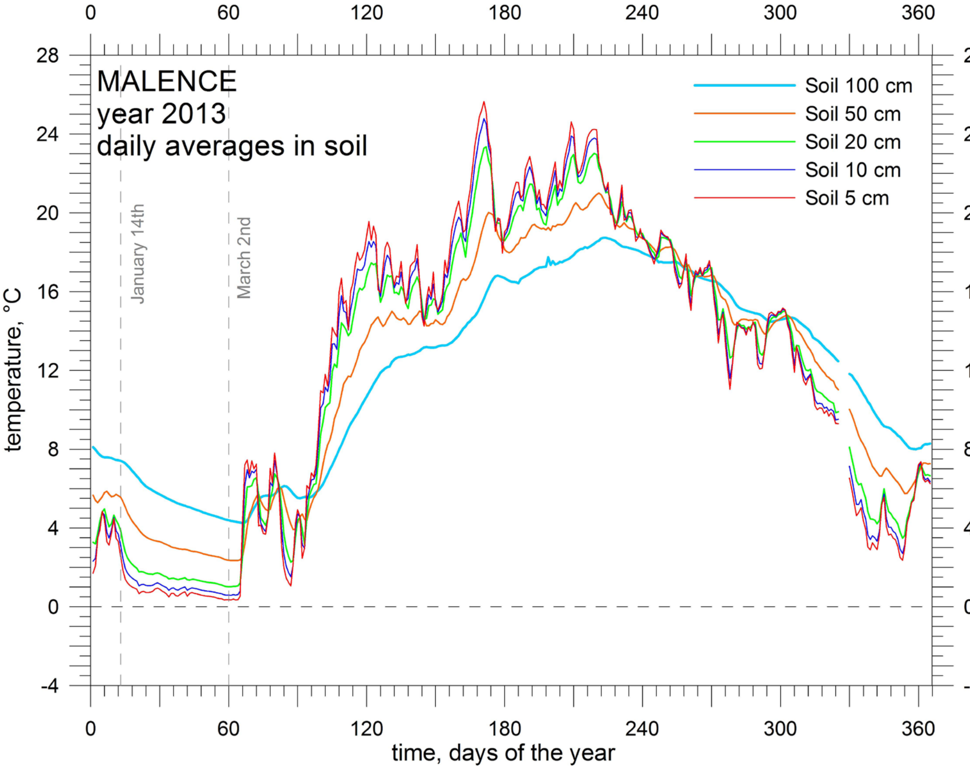

Fig. 7. The average daily temperatures in 2013 at depths from 5 cm to 1 m in the soil showing the influence of snow cover (January 14th to March 2nd) on temperatures to a depth of 1 m.

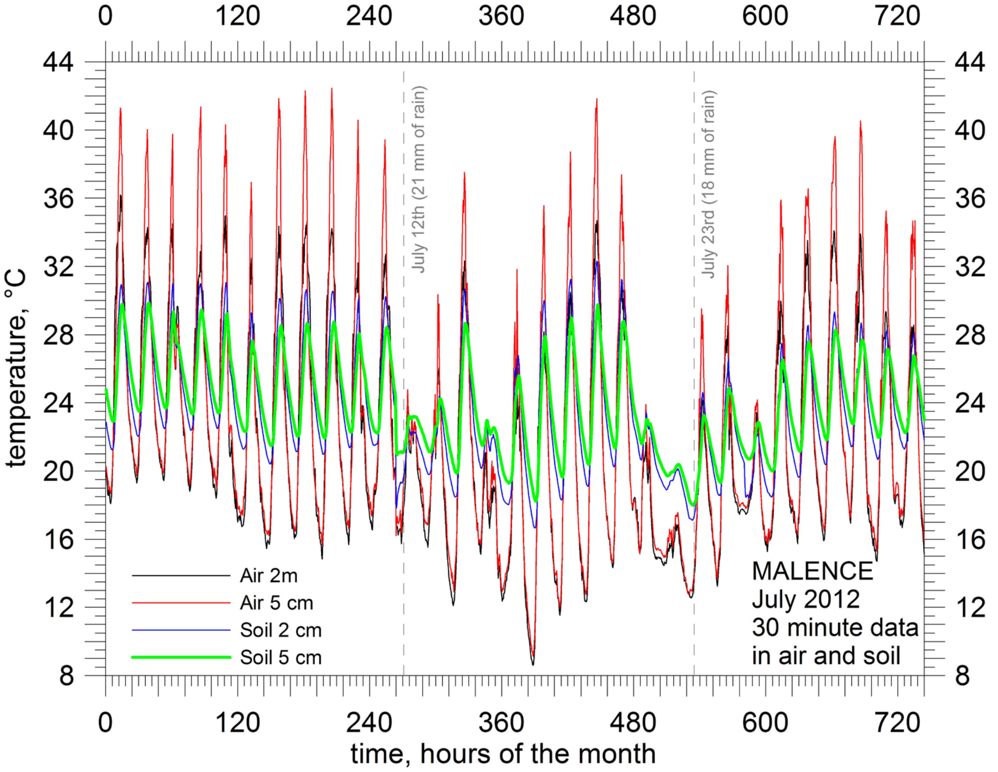

Fig. 8. 30-minute data in July 2012 at 2 m and 5 cm in the air and the soil depths of 2 and 5 cm. Impact of rainfall is evident in two events.

decreased just before the precipitation occurred (Internet 1). Consequently, the temperatures in the soil at 2 cm and 5 cm also decreased. This reaction was due to considerably lower air temperatures of the weather front with the similar precipitation temperatures. Figure 8 also shows typical greater daynight variability at 2 m and 5 cm in the air, which is gradually smoothed in the soil.

How infiltration of the rain water influences the temperature in the soil and in the borehole at depth of 1 m is shown in Figure 9. Due to some non-conductive heat transfer the temperature in the soil at depths of 5 to 20 cm slightly fell after heavy rains in the night from 13th to 14th August, 2014, recorded at Kostanjevica - Brod (Internet 1), which is the result of infiltration of relatively cooler rain water. This influ-

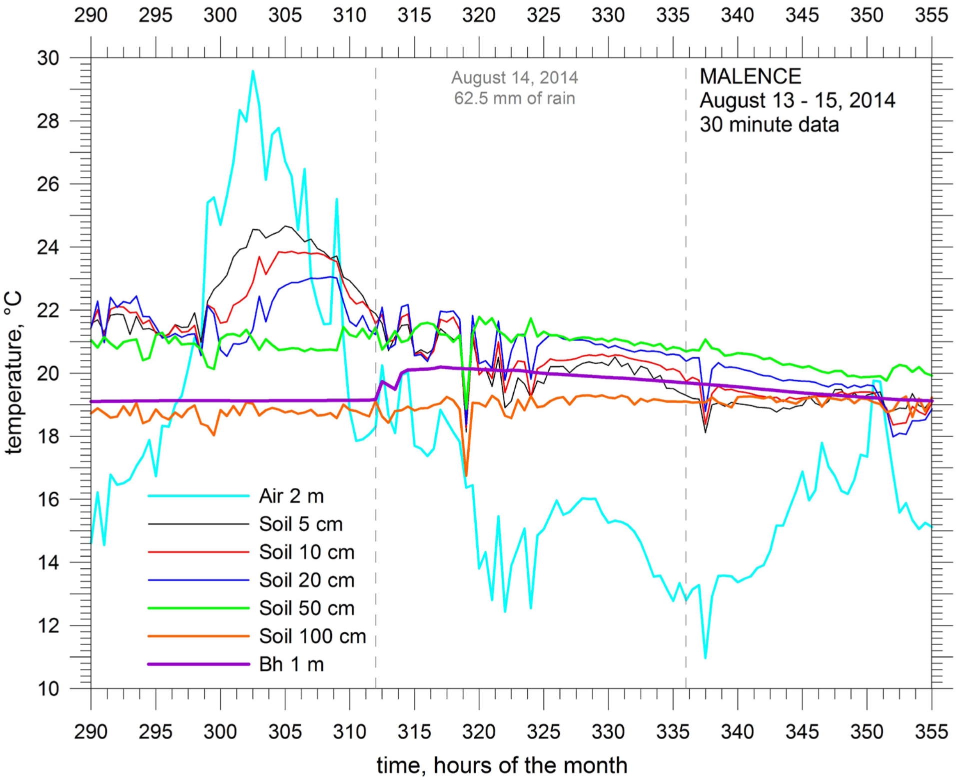

Fig. 9. Measured temperatures in the period between August 13th and 15th 2014 at a height of 2 m in the air and depths ranging from 5 cm to 1 m in the soil and in the borehole at a depth of 1 m showing the temperature response to heavier rainfall.

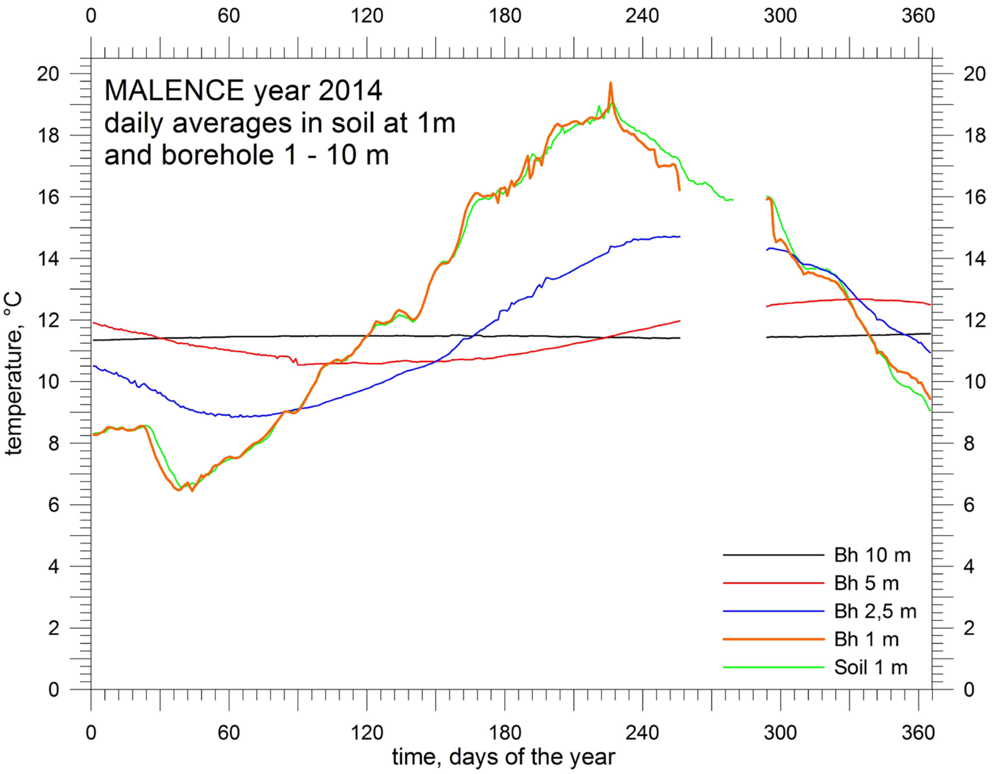

Fig. 10. The average daily temperatures in 2014 at depths of 1 m to 10 m in the borehole showing amplitude decreasing with depth and the delay of the temperature minima and maxima with depth. The sensor at 1 m depth in borehole records the temperature in the air, others record in the water.

ence is not evident any more at depths of 50 and 100 cm in the soil, but there is a sudden warming of 1 °C in ca. 2 hours at depth of 1 m in the borehole. This happened due to slightly warmer rain water temperature (and the air temperature surrounding the rainfall itself) than the air in the top part of the borehole column, but still slightly cooler than the soil down to depth of 50 cm.

Daily temperature averages at depths from 1 to 10 m in the borehole and at 1 m in the soil (Fig. 10) demonstrate the amplitude decrease with depth. Temperatures at 1 m in the soil and 1 m in the borehole nicely fit together and vary within 13 °C, and since the sensor in the borehole at 1 m is in the air, it records the variations just slightly earlier than the sensor at 1 m depth in the soil. Temperatures at a depth of 10 m vary only with-

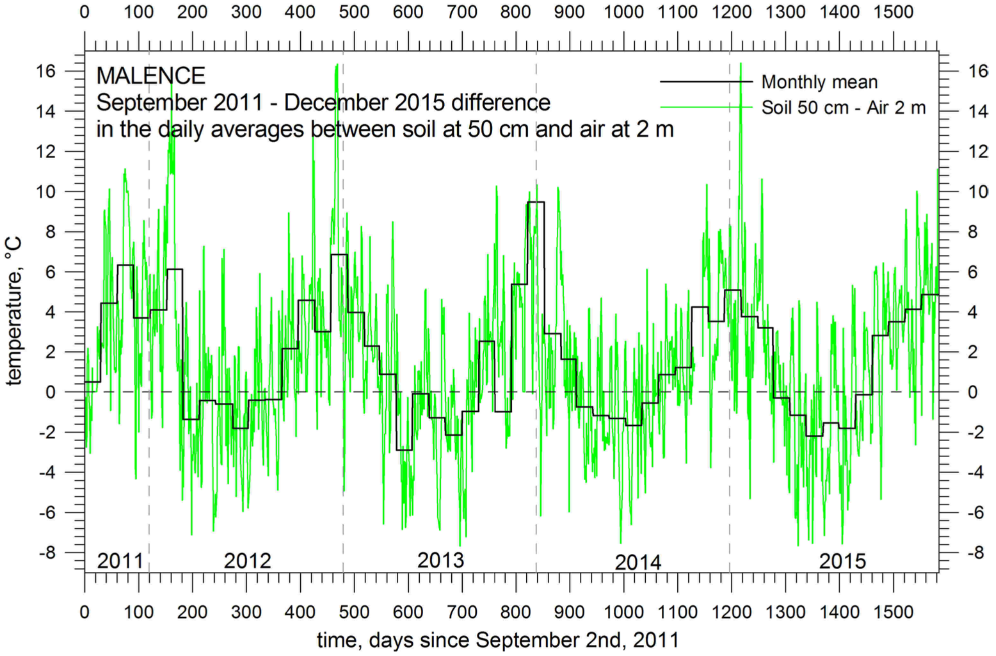

Fig. 11. The average daily and monthly differences between the soil at 50 cm and the air at 2 m from 2011 to 2015.

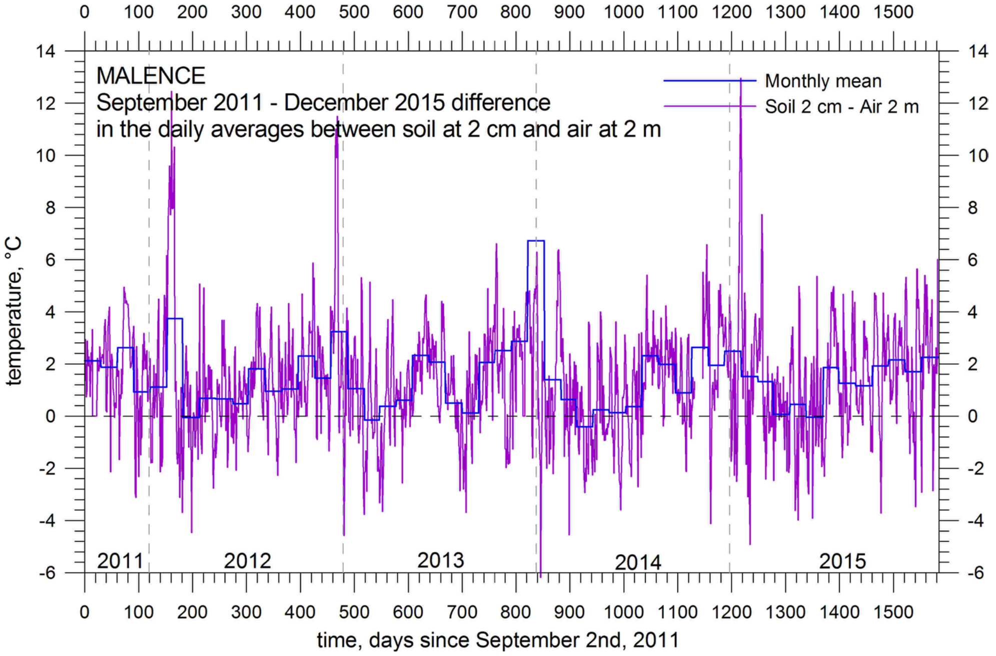

Fig. 12. The average daily and monthly differences between the soil at 2 cm and the air at 2 m from 2011 to 2015.

in 0.5 °C. The gap at the end of the year is due to unfortunate malfunctioning of the sensors in the borehole.

Appropriate differences must be examined to understand the correlation and tracking between the air and soil temperatures. Figures 11 and 12 are examples of daily and monthly differences between the air and the soil in the period from September 2011 to the end of year 2015. Both graphs are useful to show the heat transfer through the air-soil boundary. There is a larger difference in the winter time between the temperatures of soil at 50 cm depth and air at 2 m than between the temperatures of soil at 2 cm depth and air at 2 m height, just because the annual climate changes are more pronounced at shallower soil levels. During the summer time it is usually the opposite. Differences between 50 cm in the soil and 2 m in the air are smaller in the summer time, while there are much smaller variations between the seasons in differences between the soil at 2 cm and the air at 2 m. Temperature differences between 2 cm in the soil and 2 m in the air are mostly positive, which means that the soil in shallow depths is most often warmer than the air at 2 m. At 50 cm depth this is not so much evident, but the temperature differences between the soil at 50 cm and the air at 2 m exhibit that the soil is warmer in the winter time, consequently the differences are greater.

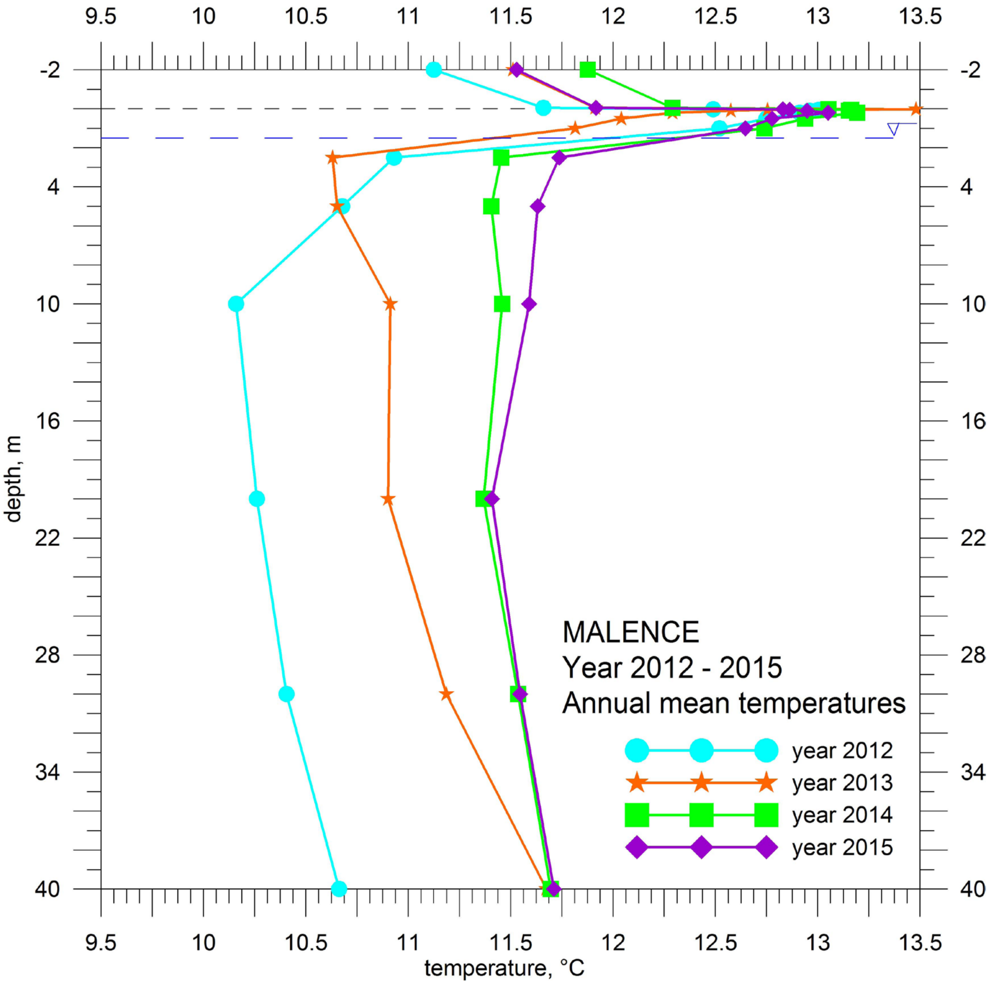

Fig. 13. The mean annual temperatures for the years 2012 to 2015 from a height of 2 m in the air to a depth of 40 m in the borehole. The average water level in the borehole is indicated.

By comparing the mean annual temperatures at all depths down to 40 m (Fig. 13) one can see that temperatures at 2 m in the air are lower than those at 5 cm in the air by about 0.7 to 1.0 °C. This is contrary to the results of the study for years 2004 and 2005 (Rajver et al., 2006). It could be due to general climate warming, which influences strongly the shallow soil levels (2 to 10 cm depth) and consequently the air temperature at 5 cm is presumably under the influence of additional shallow soil heating, therefore in such a way beating the air temperature at 2 m. In this context it is not yet clear if some cleaning of the forest (in summer 2011) just north of the borehole has any influence on air temperatures at 2 m. In the years 2004 and 2005 the mean annual temperatures at shallow soil levels (2 to 5 cm) reached ca 11.7 °C (Rajver et al., 2006), and in later years (2006 to 2009) they increased to 12 to 13.1 °C, while in the 2012 to 2015 period they reached 13 to 13.5 °C, again obviously due to global warming. The temperature is the highest at depth of 20 cm in the soil and gradually decreases with depth to 10 m in 2012, to 2.5 m in 2013 and to 20 m in 2014 and 2015. We have no direct comparison of this effect with other data in other parts of Slovenia. The observation period is too short to make some firm conclusions, as in the period 2004 to 2009 these minima were changing between 2.5 m and 20 m. It is the consequence of the surface temperature variations that propagate into the soil and bedrock and are drawn as mean annual air temperatures. Since the platinum sensors are stable in time, we are not certain about any malfunctioning except the data logger itself, which is also not likely. Below these depths temperature slowly increases due to geothermal gradient. An increase in mean annual temperatures over the years is a result of increase in surface temperature in the past decades as a result of global warming. For the years 2014 and 2015 the mean annual temperature at 20 m was 11.4 °C and at depth of 40 m it was 11.7 °C. We don’t have any comparable systematic temperature measurements so far, showing the global warming from Slovenian boreholes. However, from the repeated temperature downhole loggings in several boreholes in Slovenia (Rajver et al., 2006), the global warming is evident in the upper 20 to 30 m. Much more data on the evidence of global warming from borehole temperature loggings are found in many other countries

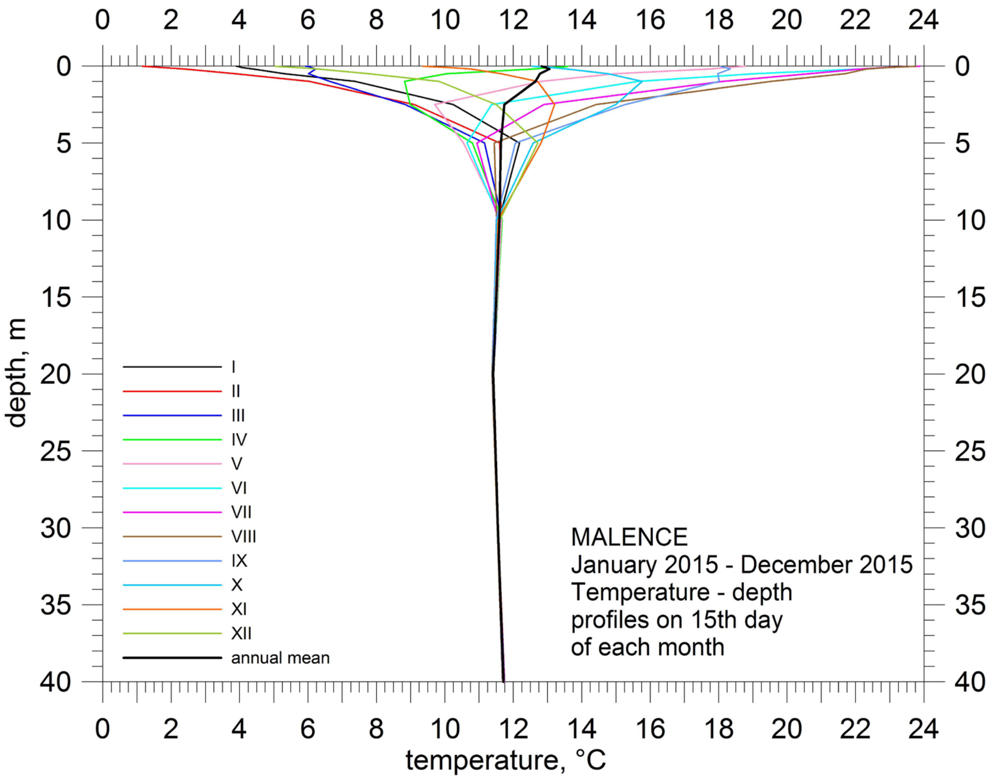

Fig. 14. The average daily temperatures on the 15th day of the month for 2015 in the depths of 0 to 40 m.

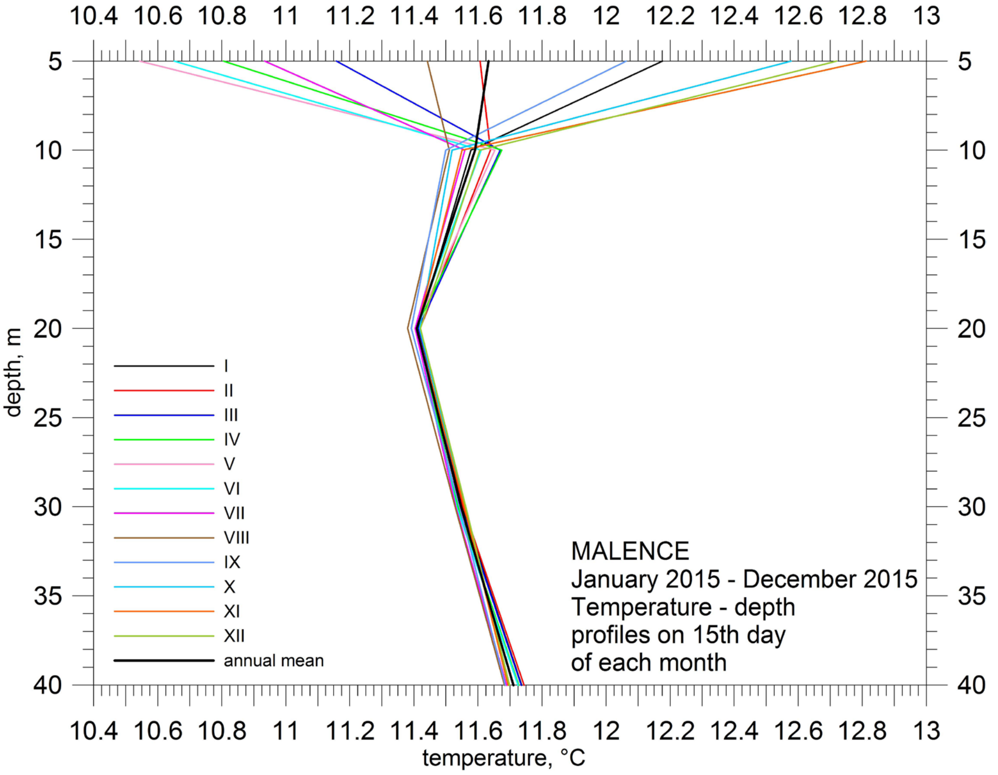

Fig. 15. The average daily temperatures on the 15th day of the month for 2015 in the depths of 5 to 40 m.

(i.e. Bodri & Čermak, 2007). The last three temperature loggings in the V-8/86 borehole clearly revealed the influence of global warming in the shallow underground, more exactly by 0.12 °C in less than eight years and by 0.28 °C in almost 24 years (Fig. 2b).

Temperatures on the 15th day of each month in 2015 are shown in Figures 14 and 15. Temperatures down to depth of 5 m vary significantly throughout the year, but the differences diminish with depth. This is a typical example of the influence of periodic air temperature variations on the subsurface temperatures down to depths of 20 m.

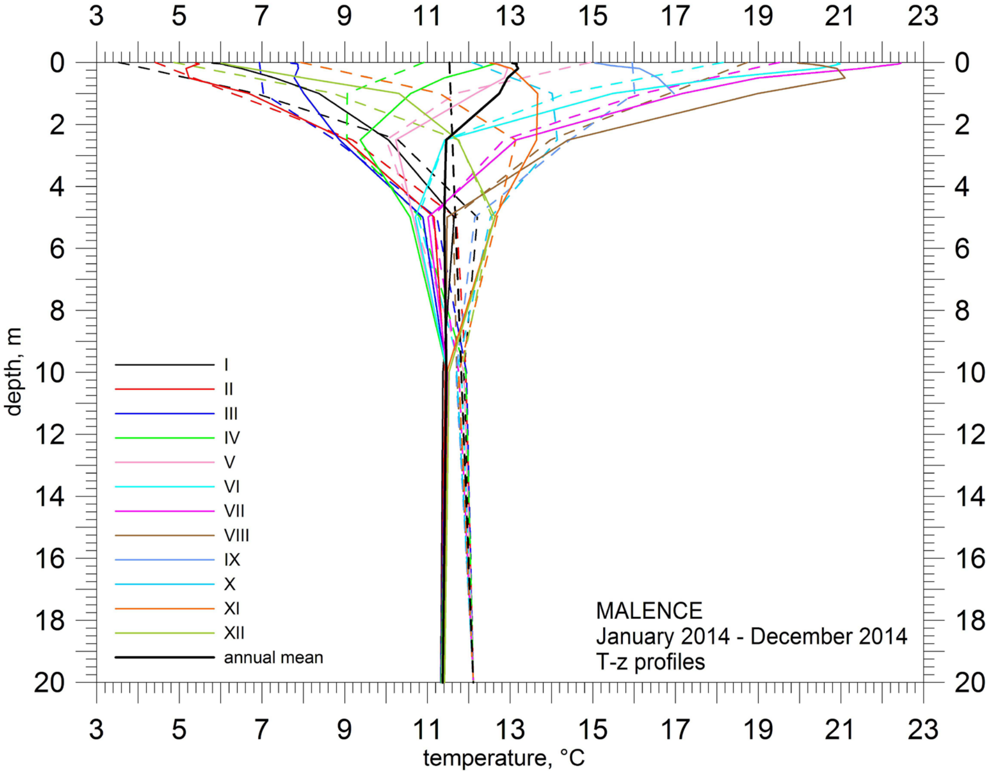

Fig. 16. Comparison of the calculated (dashed curves) and measured (solid curves) average daily temperatures on the 15th of the month for the year 2014 in the depths of 0 to 20 m.

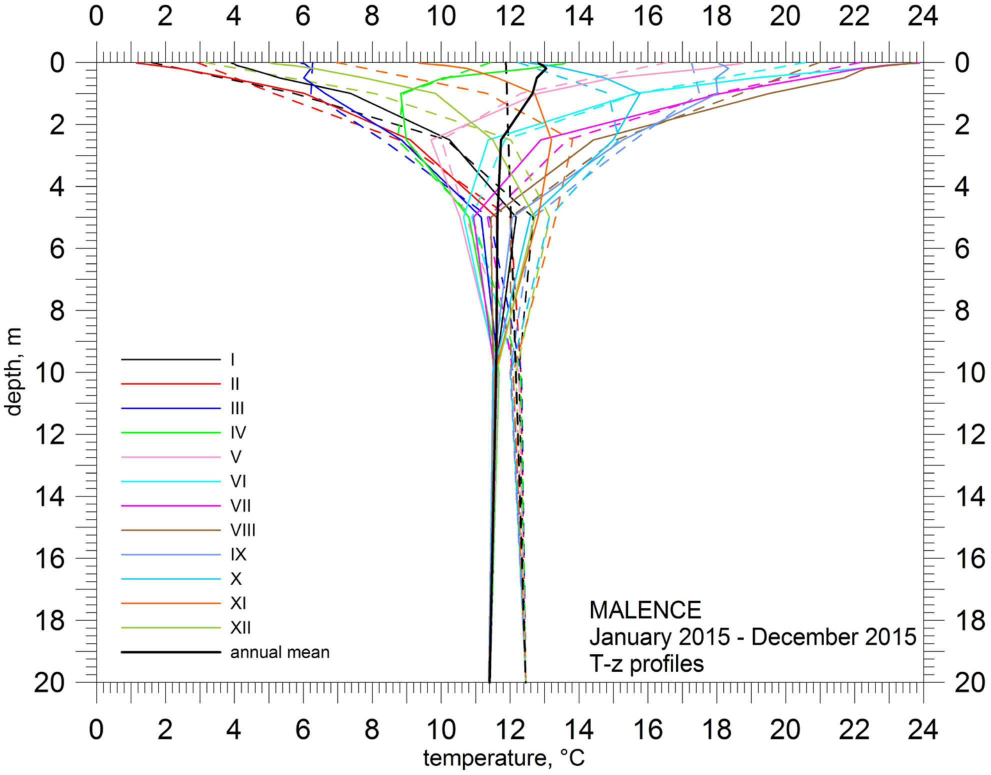

Fig. 17. Comparison of the calculated (dashed curves) and measured (solid curves) average daily temperatures on the 15th of the month for the year 2015 in the depths of 0 to 20 m.

At depth of 20 m the difference between minimum and maximum temperature is 0.04 °C (see Fig. 15 for detail). This is already out of the absolute error of the measured temperature (0.01 K). The influence of variation of surface conditions decreases with depth and loses its effect in most cases somewhere between 10 and 20 m. However, the repeated temperature downhole loggings (everywhere at least 13 years apart) in several boreholes in Slovenia (Rajver et al., 2006) show the influence of surface warming down to depths between 22 and 70 m, which is visible in the comparison of the boreholes' single T-z loggings.

To see the extent of the effect of non-conductive heat transfer we compared synthetic T-z profile, calculated with a diffusion equation (Gosar & Ravnik, 2007), with measured data for the years 2014 and 2015 (Strgar, 2016) (Figs. 16 and 17). Deviations in the upper part indicate that there is some heat transferred non-conductively but is relatively small and can be neglected. On average, the difference between the calculated and measured temperatures at depth of 5 m was -0.20 °C (-1.8 %) in 2014 and -0.39 °C (-3.3 %) in 2015. The difference between the calculated and measured temperatures deeper than 10 m is due to geothermal gradient used in calculations, which was determined by measurements of temperature down to the bottom of the borehole at 100 m in August 2011 (Fig. 2b). The difference is within 5 %, but it could be corrected with trying different input values (e.g. more accurate geothermal gradient). At 40 m the average difference between measured and calculated temperature is -8.5 % (2014) and -11.3 % (2015). Since the difference occurs mostly because of the utilized geothermal gradient, such difference is still small enough and we can confirm that effect of nonconductive heat transfer is low enough and that diffusion equation can be used for further calculations.

Conclusions

The analysis of temperature measurements at the MBTO near Kostanjevica has shown a slight presence of non-conductive heat transfer predominantly in the upper parts of the shallow subsurface. A good example is the influence of the infiltration of precipitation in the soil after heavy rainfalls. The temperature in the soil to depths of 20 cm changes, so it matches the temperature of rain water. While deeper than 20 cm temperatures in the soil stay unaffected, temperature in the borehole at 1 m raises rapidly. The effect of the snow cover, which acts like insulator, can be tracked down to depth of 1 m.

Comparison of the measured T-z profiles with synthetic profile also indicates possibility of the heat transfer mechanisms other than prevailing conductivity regime. However, differences are small enough so the diffusion equation can be used for further calculations.

There has been a slight increase of mean annual temperatures over the years due to global warming of the present climate change. This increase is more noticeable in the upper parts of the shallow subsurface due to the slow propagation of surface temperature variations into the subsurface. The changes in temperature throughout the year affect the temperature down to depths of about 20 m. It is still not possible to acquire a very reliable long-term tendency on this locality at least at 40 m depth also due to difficulties with the sensors and data logger. The long-term warming amounts to 0.011 °C/yr at 40 m depth taking into account a short period of 2014 to 2015 only. Despite it being a quite short period for deep analysis, it coincides with the absolute error of the measured temperature. The trend is comparable to some of the previous periods. For example: the period from July 2004 to January 2008 shows very similar trend at 40 m depth of 0.013 °C/yr. This is a clear evidence of the recent surface warming provided that the conductive heat transfer is the prevalent mechanism.

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