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Monitoring of air-ground temperature coupling and examples of shallow subsurface warming in Slovenia

Opazovanje povezanosti zračnih in talnih temperatur ter primeri segrevanja plitvega podzemlja v Sloveniji

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Ključne besede: globalno segrevanje, temperaturni profili v vrtinah, temperature površja, temperature tal, povezanost zračnih in talnih temperatur, Slovenija
Key words: global warming, borehole temperature profiles, surface temperatures, soil temperatures, air-ground temperature coupling, Slovenia

Abstract

We have started with a long-term monitoring of the air-ground temperature coupling in three different climate provinces of Europe with the aim to explore the assumption on a long-term tracking of the mean annual surface air temperature and the ground surface temperature. Under the frame of a joint project the borehole climate stations have been established in three countries and the monitoring launched in Prague (Czech Republic) in 2002, near Kostanjevica (Slovenia) in November 2003, and near Evora (Portugal) in May 2005. The monitoring is vital for the climatic interpretation of the ground surface temperature history that is obtained from present-day temperature-depth profiles that are measured in deep boreholes. With temperature measurements every 30 minutes in the air, in the soil and in the bedrock down to 40 m depth we are able to observe a propagation of surface soil temperature changes into depth. Gathered data on the differences between mean air and soil temperatures and its inter-annual variability from the Slovene station are presented. The 2 year and 10 months long monitoring has given so far a rough estimation of the difference between mean annual soil and air temperatures to be around 1 °C. We present also examples of non-conductive features in the temperature time series both in the soil and in bedrock. Another method of checking the air-ground temperature coupling is based upon repeated temperature measurements in the boreholes. The present rate of surface warming is large enough, and therefore, allows a reliable detection of the underground temperature-time changes in the temperature-depth profiles that are acquired by repeated temperature logging with a time span of several years. We present the results of these repeated measurements in some chosen boreholes in Slovenia with the time span of measurements between 8 and 20 years.

Povzetek

Z namenom raziskati domnevo o dolgoročnem sledenju srednje letne temperature zraka ob površju in temperature tal na površju smo pričeli s projektom dolgoročnega opazovanja povezave med zračnimi in talnimi temperaturami v treh različnih podnebnih pokrajinah Evrope. V okviru skupnega projekta so postavljene t.i. merilne klimatske postaje na vrtinah v treh državah in opazovanje se je tudi že začelo leta 2002 na Češkem v Pragi, v Sloveniji novembra 2003 pri Kostanjevici in maja 2005 tudi na Portugalskem pri Evori. Opazovanje je pomembno za klimatsko interpretacijo poteka temperature tal na površju v preteklosti, ki se pridobi iz sedanjih profilov temperature z globino, izmerjenih v globokih vrtinah. Z meritvami temperature v 30 minutnih presledkih v zraku, tleh in v kamninski podlagi do globine 40 m smo sposobni opazovati širjenje sprememb temperatur tal na površju v globino. Iz postavljene postaje v Sloveniji predstavljamo pridobljene podatke o razlikah med srednjimi letnimi temperaturami zraka in tal ter njihovo medletno spremenljivost. Dve leti in 10 mesecev dolgo opazovanje je zaenkrat dalo grobo oceno razlike srednjih letnih temperatur tal in zraka, ki znaša okrog 1 °C. Predstavljamo tudi primere pojavov nekonduktivnega značaja v temperaturno-časovnih nizih, tako v površinski zemlji kot v kamnini podlage. Druga metoda preverjanja povezanosti zračnih in talnih temperatur je osnovana na ponovljenih temperaturnih meritvah v vrtinah. Sedanja stopnja segrevanja površja je dovolj velika, da se lahko zanesljivo odkrijejo podzemne časovne temperaturne spremembe v profilih temperatur z globino, katere pridobimo s ponavljanjem temperaturnih meritev vzdolž čim daljšega stolpca vrtine v časovnem razponu več let. Prikazujemo rezultate teh ponovljenih meritev v nekaterih izbranih vrtinah v Sloveniji, ko je bil časovni razpon med meritvami od 8 do 20 let.

Introduction

When the international project »Climate change inferred from borehole temperatures« was opened at the Meeting of International Union for Geodesy and Geophysics in 1991, we began with systematic temperature measurements in some carefully chosen boreholes also in Slovenia on the initiative of prof. Ravnik and an international group under the leadership of prof. H. Pollack. First results of interpretation of temperature measurements into the paleoclimatic changes of the surface in Slovenia were acquired already in 1994 (Ravnik et al., 1995), and later the interpretations were improved with data from additional boreholes (Rajver et al., 1998; Šafanda & Rajver, 2001). The climate interpretation of the ground surface temperature history (GST history) obtained from present-day temperature-depth profiles that are measured in deep boreholes is based on an assumed long-term tracking of the mean annual surface air temperature and the ground surface temperature (Majorowicz & Šafanda, 2005; Majorowicz et al., 2004; Smerdon et al., 2004). During the last decade the researchers have become aware of a certain imperfection as a consequence of a fact that heat conduction is definitely not the only heat transfer mechanism in a soil (Kane et al., 2001). Also some sudden short-term but strong climate events (rain, raising or decreasing of the water table, etc.) can influence the heat transfer mechanism. The reconstructed GST histories are therefore 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. The long-term relationship between the soil and surface air temperatures is therefore the key issue in interpreting the results in terms of the long-term climatic variability. Environmental conditions as soil moisture or type of a vegetation cover are suspected to be the most important factors influencing the air-soil temperature difference. The sensitivity of ground surface temperatures to environmental parameters applies in particular to diurnal temperature variations and, therefore, is important mainly for the temperature regime in the very shallow subsurface. Much less is known about the influence of the surface conditions on the long-term (annual) mean ground surface temperature that controls the geothermal state at greater depths. This problem has been investigated in few »geothermal–climate change« observatories as described by Putnam & Chapman (1996), Beltrami (2001) and Schmidt et al. (2001). The group from Geophysical Institute in Prague has been running two experimental test sites in Czech Republic (Čermák et al., 2000). To explore the assumption of before mentioned tracking we started a project of long-term monitoring of the air-ground temperature coupling in three different climate regions of Europe. Therefore, under the NATO scientific programme support and the initiative of the Czech geophysicists the so called borehole climate stations have been established. They were established in three countries and the monitoring has been already launched there, the first one in Prague at Geophysical Institute (Czech Republic) in 2002, then in November 2003 near Kostanjevica in Slovenia and finally in May 2005 near Evora in Portugal.

Subsurface warming, revealed from temperature measurements in boreholes

Another method of checking the air-ground temperature coupling exists that is founded on repeated temperature measurements in boreholes. Our goal has been also to ascertain the transient component of the underground temperature field and its temporal variations on several sites in

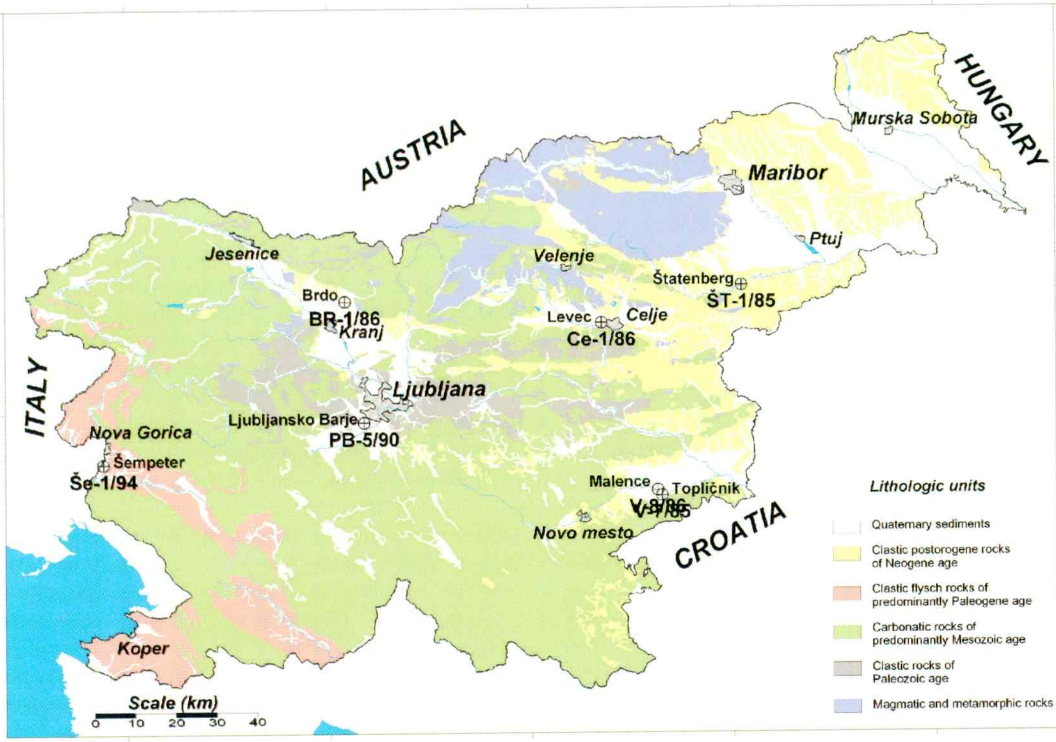


Figure 1. Sites of geothermal boreholes in Slovenia, discussed in this paper
Slika 1. Lokacije v tem članku obravnavanih geotermičnih vrtin v Sloveniji

Slovenia. Consequently we repeated temperature measurements in November 2003 in the four carefully selected boreholes along as long borehole stem as possible. The investigated boreholes were (Figure 1): Ce-1/86 (Levec near Celje), V-8/86 (Malence near Kostanjevica), PB-5/90 (Ljubljansko Barje – Ljubljana Moor, south of Ljubljana) and Še-1/94 (Šempeter near Nova Gorica). The measurements followed the first loggings in years 1986 (Celje), 1987 (Malence), 1990 (Ljubljana Moor) and 1995 (Šempeter). We carried out temperature measurements also with an objective to select the borehole with appropriate temperature-depth profile, and without any discernible disturbing influences. At one time they were a part of a task to reconstruct the past climate changes from the present-day temperature-depth profiles measured in boreholes. We present herein the results of some measurements that clearly show the effects of warming of the atmosphere. The first temperature loggings were performed by the logging team of geological Survey of Slovenia using the Pt-100 sensor with LAGOT-3 instrument, and the later loggings were done by the Geophysical Institute team (Prague) using the Antares thermistor.

The V-8/86 borehole at Malence near Kostanjevica is located in the Krško basin which is filled with Tertiary and Quaternary sediments of the Pannonian basin. The basin itself is encompassed by the Internal Dinarides. The borehole was finished in October 1986 through 16 m of Quaternary clay, sand and gravel, and down to the bottom at 100 m through Miocene marl which is probably more silty or sandy in its upper part. The first temperature logging, presented in Figure 2, was accomplished 13 months after the drilling has finished. Both logs indicate a warming by two tenths of degree at the depth of 20 m between 1987 and 2003 which is consistent with the observed surface warming. This borehole was finally chosen for establishing the borehole climate station.

The PB-5/90 borehole, 171 m deep, is located south of Ljubljana in the Ljubljansko Barje (Ljubljana Moor) area which belongs to geotectonic unit of the External Dinarides. It was drilled in September 1990, first

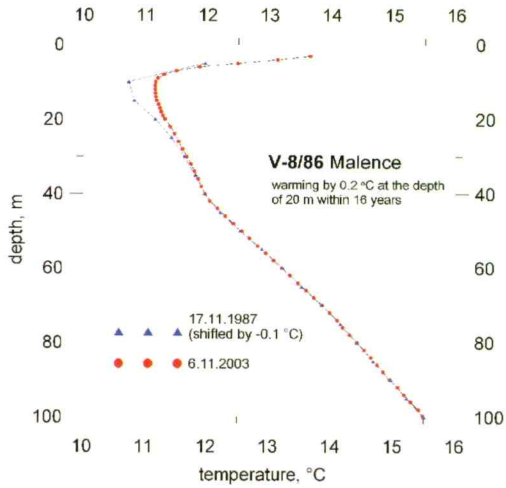


Figure 2. Temperature-depth profiles from the borehole V-8/86 at Malence

Slika 2. Profila temperature z globino iz vrtine V-8/86, Malence

through 41 m of Holocene mixture of sand, gravel, clay and silt, then to a depth of 167 m through practically the same mixture of Pleistocene age and at the bottom it finished in a dolomite of Upper Triassic age. The first temperature logging was performed 1 month after the termination of drilling and testing. Both logs reveal warming of several tenths of degree at the depth of 20 m between 1990 and 2003 (Figure 3), similar to that observed in the borehole Malence.

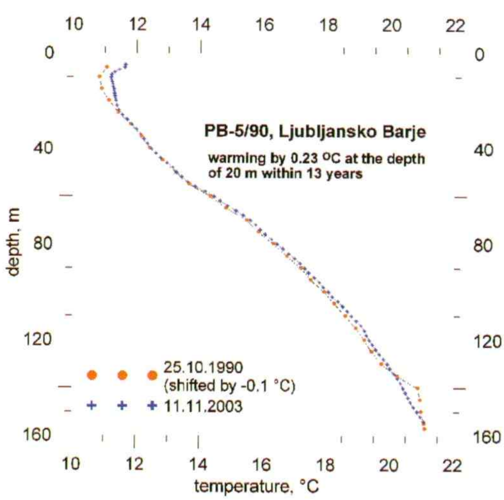


Figure 3. Temperature-depth profiles from the borehole PB-5/90, Ljubljansko barje (Ljubljana Moor)

Slika 3. Profila temperature z globino iz vrtine PB-5/90, Ljubljansko barje

The ŠE-1/94 borehole in Šempeter is 1563 m long with a true depth of 1541 m due to the borehole inclination. It is situated in the geotectonic unit of the External Dinarides. The drilling started in May and finished in October 1994, while the testing lasted until November 10th 1994. The stand-by time lasted therefore 125 days until the first logging. The borehole penetrated through 90 m of Quaternary gravel, sand and clay, down to 1381 m (true depth) through various sediments (marl, sandstone, limy breccia, conglomerate, clayey marl, siltstone) of Middle Eocene and down to 1541 m through marl, sandstone and limestone of Paleogene age.

We present here the upper part of temperature logs (Figure 4) that were measured in 1995 and 2003, and also the repeated log in 2005. The latter two high precision profiles reveal a distinct temperature minimum at the depth of 65 m. The reduced temperature calculated as a difference between the measured curve and its upward linear extrapolation indicates the transient component of 2 °C magnitude. As a source of this evidently non-climatic disturbance we have identified a construction of the factory hall, now the sports hall, some 20 m apart from the borehole in the mid 1970's. A basement of the hall and surrounding asphaltic area have higher mean annual surface temperature than it was before the construction and this surface warming propagates by heat conduction into the subsurface. The best result of a 3-D finite element simulation of this process has shown that considered surface temperature had increased by 10 °C and 5.5 °C on the sites of the hall and the asphaltic area, respectively.

In the end of June 2005 we repeated the temperature logging in another three boreholes, ŠT-1/85, BR-1/86 and V-7/85, and only some results are described here. As mentioned before, we also repeated the temperature logging in Šempeter borehole, again to a true depth of 883 m. In comparison with the 2003 temperature profile, the latest one shows small but clear signs of warming. The zone around the minimum at 65 m has warmed up since November 2003 by about 0.02 °C (Figure 4).

The ŠT-1/85 borehole at Štatenberg, 100 m deep, is situated in the slightly hilly area of the Pannonian basin's south-west border

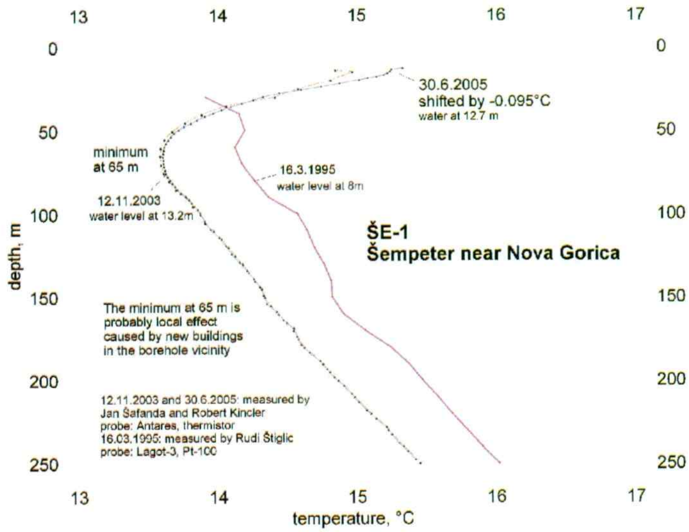


Figure 4. Temperature-depth profiles from the borehole ŠE-1/94 at Šempeter near Nova Gorica (upper part of 250 m only)

Slika 4. Profili temperature z globino iz vrtine ŠE-1/94 v Šempetru pri Novi Gorici (le zgornjih 250 m)

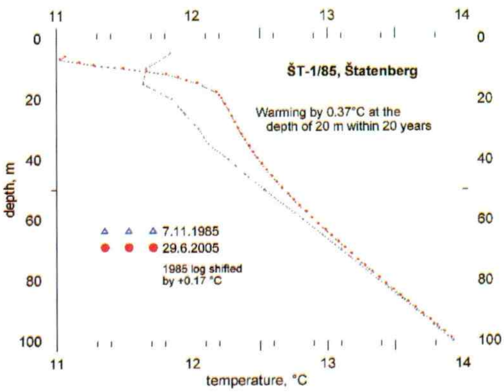


Figure 5. Temperature-depth profiles from the borehole ŠT-1/85 at Štatenberg

Slika 5. Profila temperature z globino iz vrtine ŠT-1/85 pri Štatenbergu

region. It was drilled in June 1985, through the upper 4 m of Quaternary sand, silt and gravel, then down to 60 m depth through marl and to the bottom through siltstone of Upper and Middle Miocene, respectively. The first temperature logging shown in Figure 5 was done 133 days after the termination of drilling. A strong subsurface warming by 0.37 °C at the depth of 20 m within 20 years is indicated by comparison of the old and the new temperature profiles.

In the previous figures older temperature logs are shifted for a certain temperature. It is done so with the intention of matching the lower part of both logs while leaving the real difference due to surface warming in the upper part of the borehole column.

The BR-1/86 borehole at Brdo near Kranj, 98 m deep, is located in the Ljubljana basin, and filled with sediments of the Pannonian basin within the Southern Alps. It was drilled in October 1986, through the upper 7.8 m of Quaternary gravel, sand and clay, and down to the bottom through Oligocene clay. The first temperature logging shown in Figure 6 was performed 70 days after the termination of drilling. Similar to the Štatenberg site, a strong subsurface warming by 0.45 °C at the depth of 20 m within 18 years is evident by comparison of the old and the new profiles. At both sites, Štatenberg and Brdo, the profiles are quite smooth, which indicates a conductive regime in both boreholes.

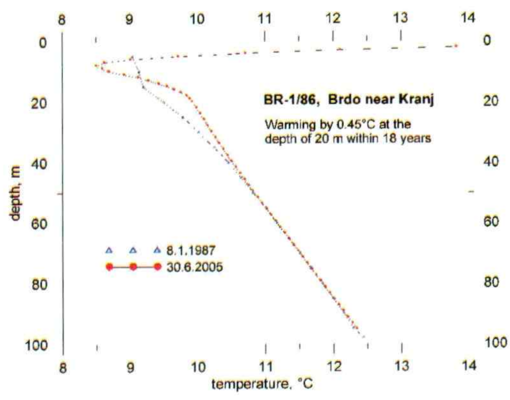


Figure 6. Temperature-depth profiles from the borehole BR-1/86 at Brdo near Kranj

Slika 6. Profila temperature z globino iz vrtine BR-1/86 na Brdu pri Kranju

In all figures, presented so far, 20 m is considered as a reference depth for comparison of the two logs because this is the depth where the annual temperature run already dies out. We may suppose that the surface temperature of the Earth varies cyclically with angular frequency ω, so that at time t it is equal to $T_0 \cos \omega t$, where T_0 is the peak temperature during a cycle (Lowrie, 1997). The solution of the heat conduction equation at depth z and time t is for a surface temperature $T = T_0 \cos \omega t$ equal to

$$T_{(z,t)} = T_0^{-z/d} \cdot \cos(\omega t - \frac{z}{d})$$

d = decay depth $(\sqrt{2\kappa/\omega})$ of the temperature

At this depth the amplitude of the temperature fluctuation is attenuated to $1/e$ (0,37) of its value on the surface. At the depth of $5d$ the amplitude is less than 1% of the surface value and is effectively zero. Therefore, d depends inversely on the frequency, so long-period fluctuations penetrate more deeply than rapid fluctuations. Comparison of the decay depths for daily and annual temperature variations in the same ground equals to

$$\frac{d_{annual}}{d_{daily}} = \sqrt{\frac{\frac{2\pi}{1}}{\frac{2\pi}{365}}} = \sqrt{365} = 19{,}1$$

i.e. the annual variation penetrates about 19-times the depth of the daily variation, which is approximately 1 m. This means that at about 20 m below surface the climatic effects die out. Therefore, we choose as a reference point this depth for the estimation of subsurface warming.

The V-7/85 borehole at Topličnik near Kostanjevica, 100 m deep, is located almost 1.7 km south-east from the V-8 borehole at Malence. It was drilled through 9 m of Quaternary sand and gravel, and through Upper Miocene marl to the bottom. The first temperature logging shown in Figure 7 was done 36 days after the termination of drilling. The temperature profiles indicate similar warming as Štatenberg profile, but its depth extent is shallower, about 30 m only, whereas in Brdo profile it is visible down to 50 m and in Štatenberg even to 75 m. These differences might be due to different thermal diffusivity. The smallest thermal diffusivity,

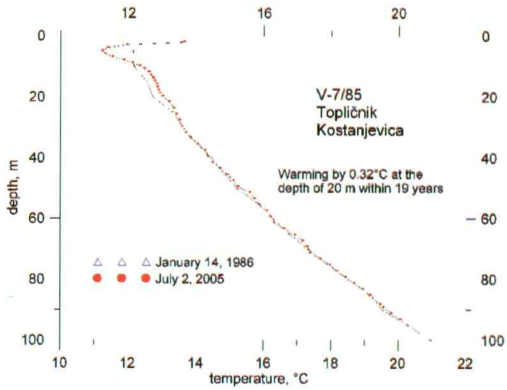


Figure 7. Temperature-depth profiles from the borehole V-7/85 at Topličnik near Kostanjevica

Slika 7. Profila temperature z globino iz vrtine V-7/85 pri Topličniku pri Kostanjevici

according to measured thermal conductivity on the cored samples from the boreholes, is from the Topličnik geological column (depth 52 m: λ=1.55 W/m·K and depth 100 m: λ=1.23 W/m·K, both marl samples), slightly higher is at Brdo site (60 m: λ=1.43 W/m·K, clay), and the largest at Štatenberg site (98 m: λ=2.01 W/m·K, siltstone). The lower diffusivity of Topličnik would correspond also with a shallow position of its annual run minimum, which is 5 m, compared to 7-8 m at the Brdo and Štatenberg sites.

The setting up of the "borehole-climate" station at Malence and some first monitoring results

In order to study a coupling between the air, soil and bedrock temperatures, we established the borehole-climate station in the borehole V-8/86 at Malence in November 2003 (Figure 8). The 16-channel monitoring unit that is connected to 15 platinum RTD probes was installed there. The data logger records in 30 minute intervals air temperatures at 2 m and 0.05 m above the ground, the soil temperatures at 2, 5, 10, 20, 50 and 100 cm below the surface and the deeper soil or bedrock temperatures in the borehole in the depths of 1, 2.5, 5, 10, 20, 30 and 40 m.

The specific borehole, searched for the borehole-climate station, had to meet some important conditions:

- Prevailing conductive regime in a borehole or small variations of the water level in the borehole

Figure 8. View of the borehole-climate station Malence

Slika 8. Pogled na klimatsko postajo na vrtini Malence

- Knowledge of the underground lithologic structure, at least in the borehole depth range
- More or less constant vegetation (irrespective of cultivated soil, field, meadow, forest,...)
- At least some warranty, that the monitoring unit will not be destroyed by children or vandals (locality in the private land or protected somehow)

When looking for the appropriate borehole it has been proved that we had to pay regard quite much to the last point.

As an example of one month data monitoring, figure 9 shows 30-minute data for December 2004 where it is evident how greater day-night air temperature variability at 2 m and 5 cm is already much smoothed at depths of 2 and 5 cm in a soil. Daily averages for the same levels (Figure 10) show that air temperature at 5 cm is in winter usually lower than that at 2 m, from spring to autumn this is less valid, and that soil temperature at 2 cm is in winter time usually lower than at 5 cm. In the summer time it is mostly the other way round. The 30 minute data in the soil at depths of 5 to 100 cm (Figure 11) very well present the smoothing and time delay effect. The results of the monitoring in the period December 2003 – Spring 2006 are presented in a few following figures.

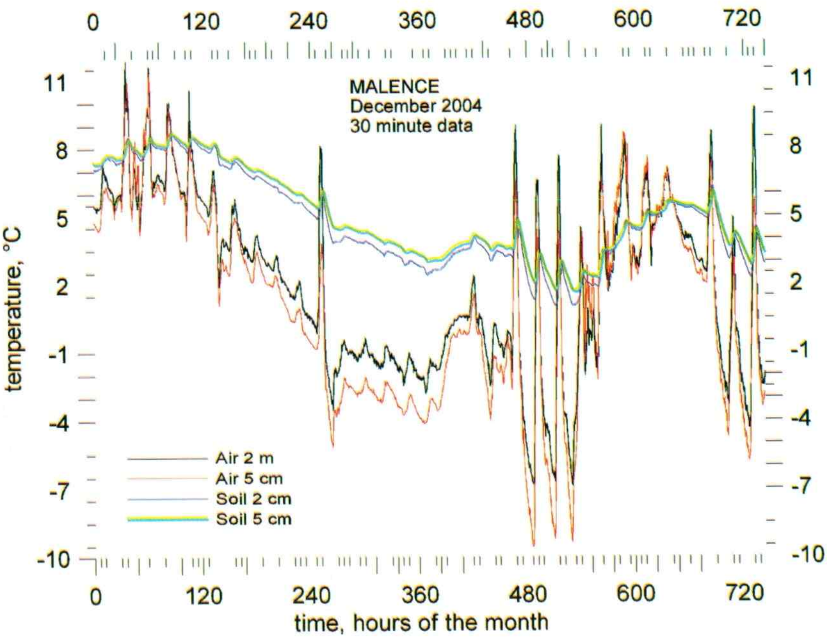


Figure 9. Station Malence: 30 minute data in December 2004 at 2 m and 5 cm in the air, and in the soil depths of 2 and 5 cm

Slika 9. Postaja Malence: 30 minutni podatki v decembru 2004 na 2 m in 5 cm v zraku ter v talnih globinah 2 in 5 cm

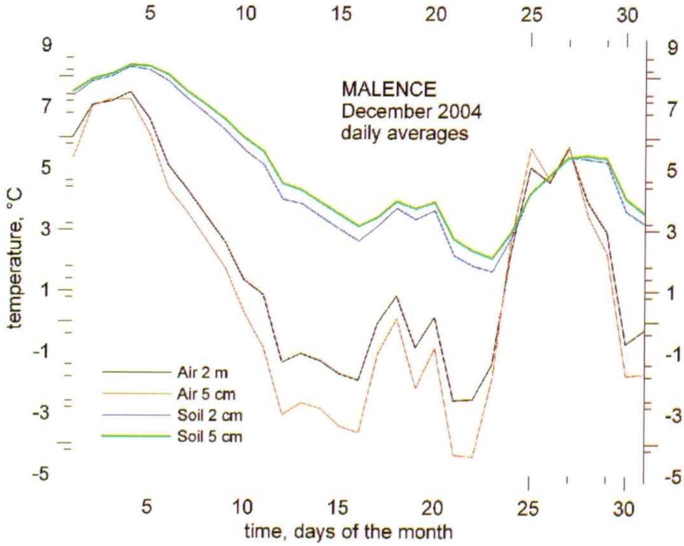


Figure 10. Station Malence: mean daily temperatures in December 2004 at 2m and 5 cm in the air, and in the soil depths of 2 and 5 cm

Slika 10. Postaja Malence: srednje dnevne temperature v decembru 2004 na 2 m in 5 cm v zraku ter v talnih globinah 2 in 5 cm

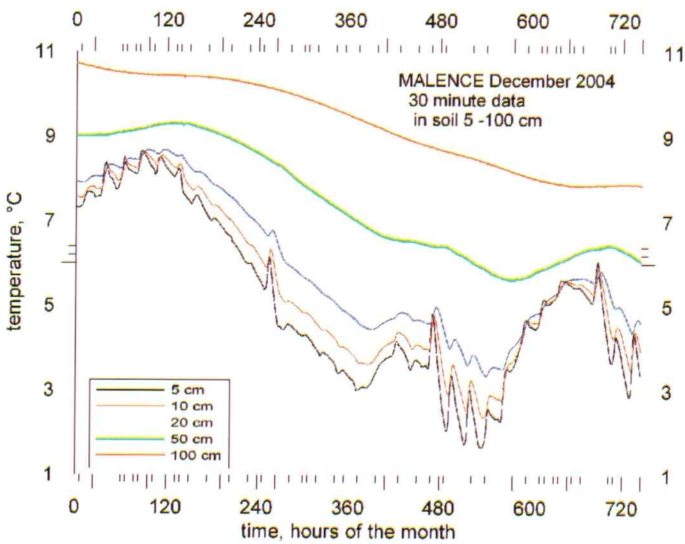


Figure 11. Station Malence: 30 minute data in December 2004 in the soil depths of 5 to 100 cm

Slika 11. Postaja Malence: 30 minutni podatki v decembru 2004 v talnih globinah od 5 do 100 cm

Daily temperature averages at 2 m in the air, at depths of 2, 20, 50 cm and 1 m in the soil (Figure 12) reveal short-term and seasonal variations, the amplitude of which decreases with depth. The decrease is more pronounced at short periods. On the contrary, the phase delay with depth is more pronounced at the annual period.

An amplitude attenuation and a phase shift are clearly evident on a plot of daily averages in depths of 1 m (both in the soil and borehole), and at depths of 2.5, 5 and 10 m in the borehole (Figure 13). Both temperature curves at the depth of 1 m track well each other, and they have greater annual variability than deeper temperature curves. However, also time delay of highs and lows and the smoothness of curves increase with depth of measurements. For instance, the maximum daily averages observed at 1 m depth roughly 268 days since December 1, 2003, were registered at the depth of 2.5 m some 32 days later, at 5 m about 102 days later, and at 10 m depth already about 212 days later. The annual runs at the depths of 2.5 and 5 m show some peculiarities. Every time on the turn December/January the gradual temperature decrease at 5 m depth is accelerated. It is exactly at the moment, when the temperature at 2.5 m depth drops

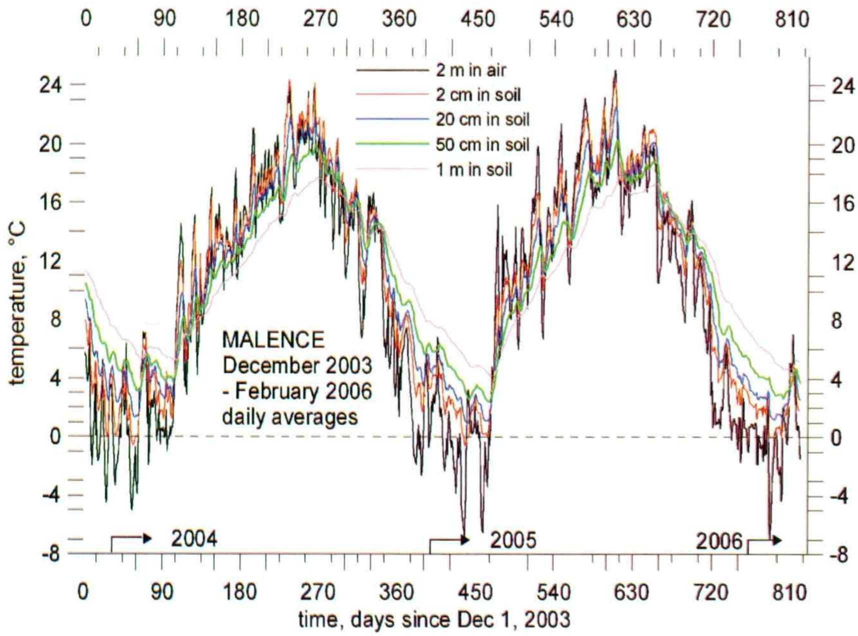


Figure 12. Station Malence: daily averages from December 1, 2003 to February 28, 2006 at 2 m in the air and in depths of 2, 20, 50 cm and 1 m in the soil

Slika 12. Postaja Malence: dnevna povprečja od 1. decembra 2003 do 28. februarja 2006 na 2 m v zraku in v globinah 2, 20, 50 cm in 1 m v tleh

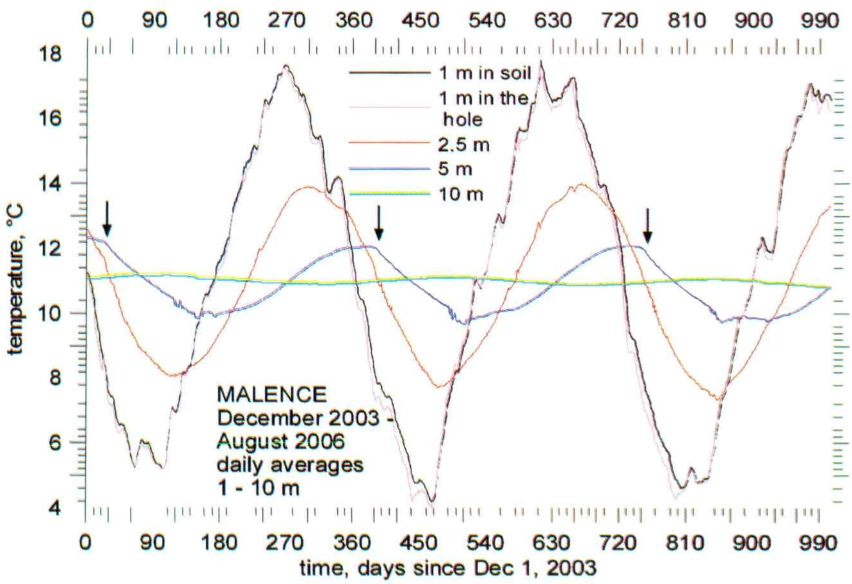


Figure 13. Station Malence: daily averages from December 1, 2003 to August 31, 2006 in depths of 1 to 10 m

Slika 13. Postaja Malence: dnevna povprečja od 1. decembra 2003 do 31. avgusta 2006 v globinah 1 do 10 m

below the temperature at 5 m by more than 0.7 °C. This temperature difference is probably large enough to launch the water convection within the upper part of the borehole.

Daily averages in depths of 10 to 30 m (Figure 14) exhibit non-periodical variations in the first 145 days since December 1, 2003, which might be connected with the installation of the temperature sensors' chain inside the borehole. At the depth of 10 m there is still some inter-annual variability, 0.2 – 0.3 °C roughly, whereas at deeper levels it is much less. It seems that we have acquired a certain long-term tendency of warming at the depth of 40 m since July 1, 2004, which amounts now to 0.016 °C/yr. At 30 m depth the rate of warming amounts to 0.019 °C/yr. Both rates change after every two months of monitoring by few thousands of degree per year.

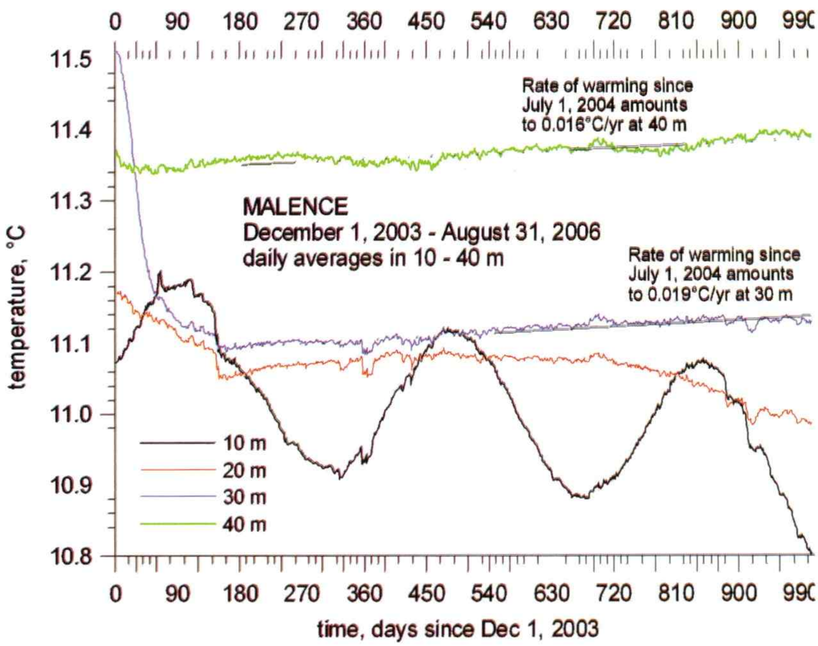


Figure 14. Station Malence: daily averages in depths of 10 to 40 m from December 1, 2003 to August 31, 2006

Slika 14. Postaja Malence: dnevna povprečja v globinah 10 do 40 m od 1. decembra 2003 do 31. avgusta 2006

Both rates of warming at 30 and 40 m depth are, however, much smaller than the multidecadal trends of the surface air temperature observed at Slovenian meteorological stations, for example, during the last 20 to 30 years (Figure 15). The meteorological record for Ljubljana shows an increase for about 2 °C in the last 20 years. Almost the same rises are recorded in Novo mesto, at Rateče and also at Lesce despite the latter record is a bit too short. It would be recorded also at Brnik but in 1994 the recording unit

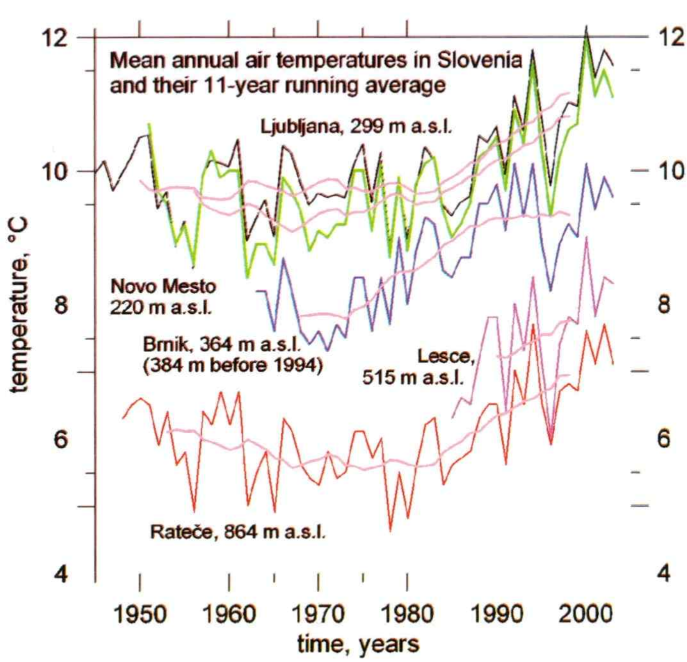


Figure 15. Mean annual air temperatures at 2 m in Slovenia for Ljubljana, Novo mesto, Brnik, Lesce, Rateče (B. Kurnik, personal com.)

Slika 15. Srednje letne temperature zraka na 2 m v Sloveniji za Ljubljano, Novo mesto, Brnik, Lesce in Rateče (B. Kurnik, osebno sporočilo)

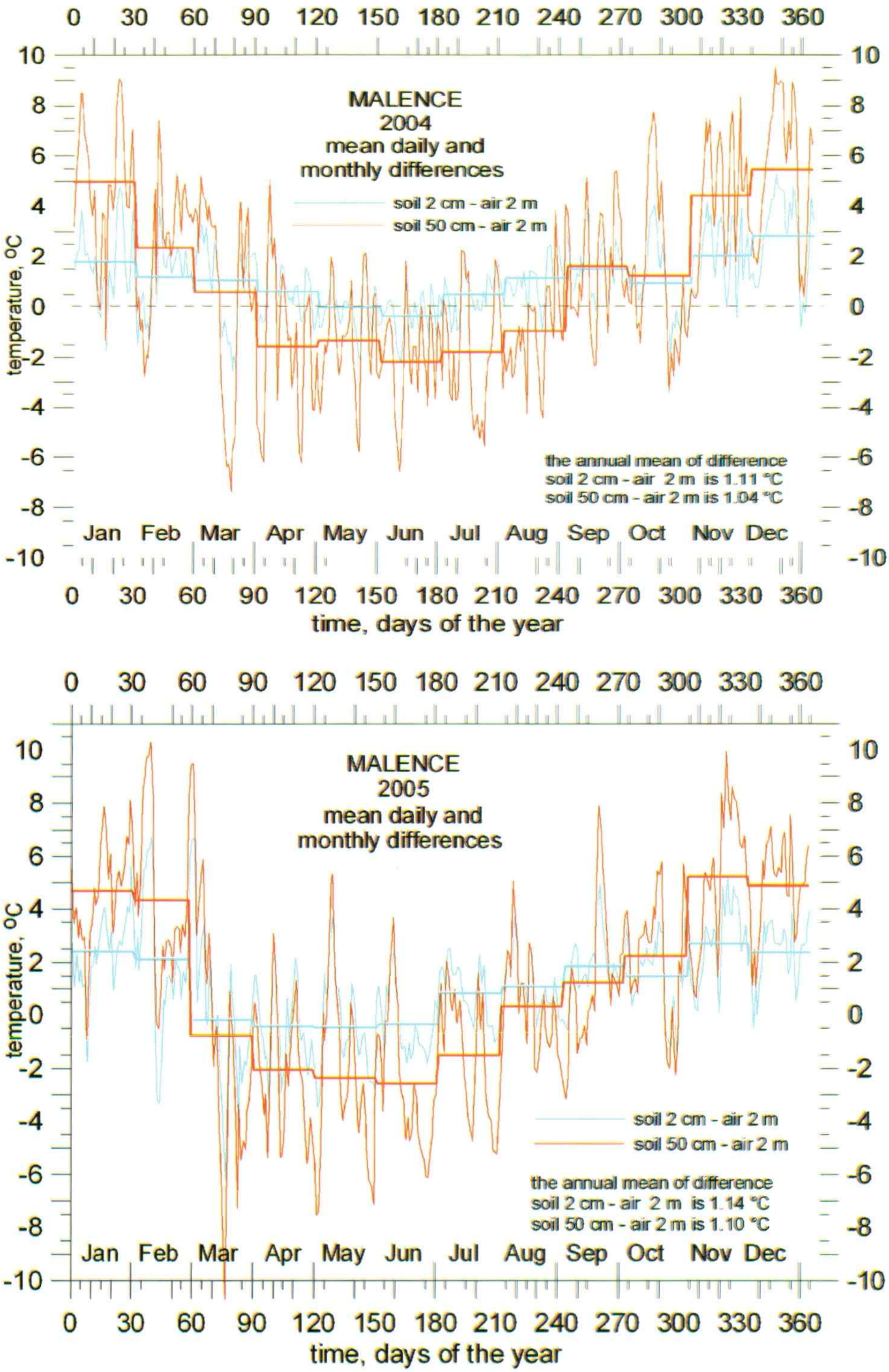


Figure 16. Station Malence: mean daily and monthly differences in a) 2004 and b) 2005.
Slika 16. Postaja Malence: srednje dnevne in mesečne razlike v letu a) 2004 in b) 2005

there was moved to another, a bit cooler site. Noticeable in Figure14 is an acceleration of cooling at the depth of 20 m, which might be a response to a 2-year cooling at 10 m depth, and also simultaneous oscillation of daily averages since the end of May 2006, the amplitude of oscillation decreases with depth. It could be somehow connected with rains in the end of May and consequent increase of Krka river level (Mesečni bilten ARSO, 2006). Well visible is deeper than usual minimum of the annual run at the depth of 10 m. We do not understand yet why the minimum is so deep, when the last winter, according to figure 12, was not cooler than the previous one. The unexplained decline at 20 m depth is maybe a possible cause.

Figure 16 (a and b) is an example showing mean daily and monthly differences between soil and air. Because annual climate changes are more pronounced at shallower soil levels, there is greater difference in winter time between temperatures of soil at 50 cm depth and air at 2 m than of soil at 2 cm depth and air at 2 m. Temperatures at 2 cm depth are closer to air temperatures at 2 m. During summer time it is usually inversely. Difference between temperatures at 50 cm depth and at 2 m in the air is also greater than the one between temperatures at 2 cm depth and 2 m in the air. This latter difference actually in the summer almost does not show, while temperature at 2 m in the air is usually higher than the one at 50 cm depth. The mean annual difference between soil (2 cm) and air (2 m) attained 1.11 °C in 2004 and 1.14 °C in 2005. Both values are very close to the results from the station in Prague (Geophysical Institute) where the annual difference of 1.04 °C in 2004 and 1.07 °C in 2005 were registered at the grassy surface.

If mean annual temperatures at all depths are compared (Figure 17) we see the air temperature at 5 cm is persistently lower than that at 2 m by about 0.5 °C. More precisely, mean annual difference of air at 2 m and 5 cm attained +0.49 °C and +0.54 °C in 2004 and 2005, respectively. Another interesting feature is a decrease of the soil temperatures with depth. The annual means between 2 and 50 cm are within 0.1 °C, and this is a very good result compared with traditional soil temperature measurements at meteorological stations, which display a scatter of several tenths of degree in this depth interval. For a decrease between 0.5 m and 1 m in the soil one can only speculate that it could

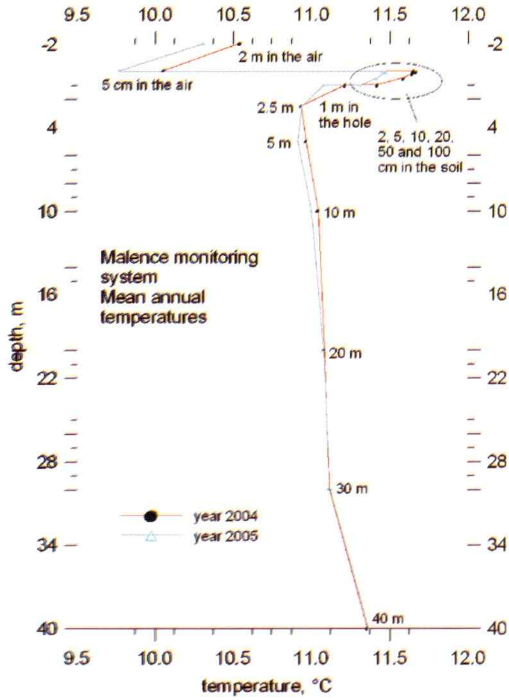
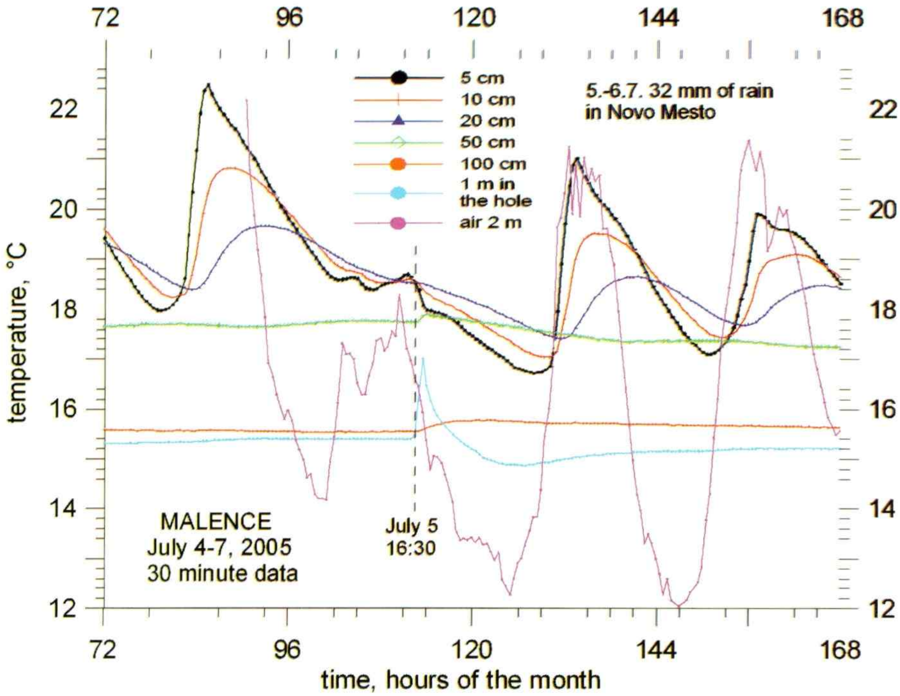


Figure 17. Station Malence: mean annual temperatures in all depths

Slika 17. Postaja Malence: srednje letne tempetarure v vseh globinah

be a result of higher thermal conductivity during the winter when the soil moisture is greater or a boundary effect of the meadow – forest interface. In a forest the soil temperature is probably by about 1 °C lower than under the meadow.

A non-conductive heat transfer in the soil can also be visible from the monitoring results. The rapid warming (Figures 18a and 18b) at depths of 50 and 100 cm on July 5, 2005 at 16:30 and on August 3, 2005 at 20:30 was preceded by heavy rains (Mesečni bilten ARSO). The infiltrating rain water cooled the uppermost 5 to 20 cm of soil, where the temperature was higher than that of the rain itself which is assumed to be close to the air temperature. At 50 and 100 cm the water has, however, an advective warming effect, because temperature is lower there than in the overlying soil layer. The temperature at 1 m depth in the borehole reacted much more intensively than the temperature at 1 m in soil because the water level in the borehole could be above 1 m depth after heavy rains. The onset of the large warming at 1 m depth in the hole precedes clearly the war-



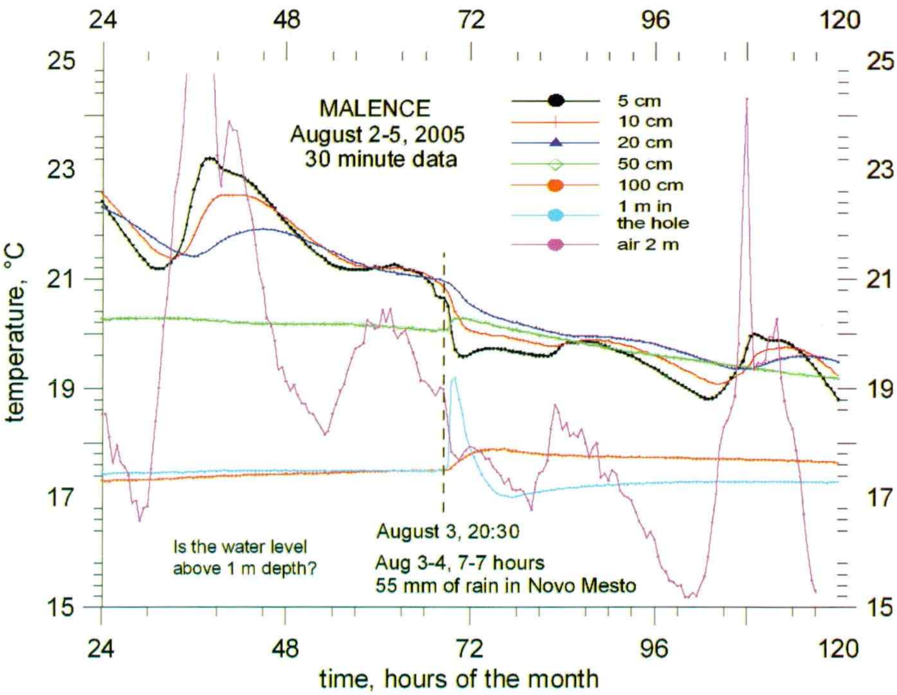


Figure 18. Station Malence: examples of a non-conductive heat transfer in the soil caused by the rain water infiltration for a) July 4-7, 2005 and b) August 2-5, 2005

Slika 18. Postaja Malence: primeri nekonduktivnega prenosa toplote v tleh zaradi pronicanja vode za a) 4-7. julij 2005 in b) 2-5. avgust 2005 ming in the 50 to 100 cm depths of soil at least by 30 minutes. The water level behind the casing of the hole can increase quickly, also above 1 m below the surface. The influence of the groundwater advection in Quaternary sediments of the Krka river alluvial plain, especially after heavy rains, can not be excluded either.

Looking at one year long monitoring in the period December 1, 2003 – November 30, 2004 (Table 1), we may see that the mean annual soil temperature in the depth range of 0.02 – 0.5 m is very stable, 11.56-11.60 °C, which is by 1.1 °C higher than the mean annual air temperature at 2 m. The mean annual temperature increase between depths 10 and 40 m attained 0.3 °C, which yields a vertical temperature gradient of 10 °C/km and, considering the thermal conductivity, a heat flow of about 20 mW/m^2, which is almost a four times smaller value than that in the deeper part of the borehole. Provided the conductive heat transfer is prevalent, it is an evidence of the recent surface warming.

Table 1.
Minimum, maximum and mean annual air, and soil temperatures and temperatures in the borehole at the borehole-station Malence, in the period Dec. 1, 2003 to Nov. 30, 2004

Tabela 1.
Najnižje, najvišje in srednje letne temperature zraka, tal in temperatur v vrtini na klimatski postaji na vrtini Malence v obdobju od 1. dec. 2003 do 30. nov. 2004

Depth (m)	Minimum Temp. (°C)	Maximum Temp. (°C)	Mean Temp. (°C)
air -2	5.02	24.16	10.48
air -0.05	-8.73	24.59	10.01
soil 0.02	-0.61	24.29	11.56
soil 0.05	-0.01	23.48	11.59
soil 0.1	0.58	22.68	11.59
soil 0.2	1.32	21.77	11.60
soil 0.5	3.06	19.91	11.58
soil 1	5.18	17.64	11.43
hole 1	5.17	17.55	11.25
hole 2.5	8.03	13.88	10.94
hole 5	9.85	12.32	10.98
hole 10	10.91	11.20	11.05
hole 20	11.05	11.17	11.09
hole 30	11.08	11.51	11.14
hole 40	11.34	11.37	11.35

Conclusions

A noticeable subsurface warming as a consequence of atmosphere warming has been detected with temperature measurements in some examined boreholes in Slovenia in the time span of measurements from 8 to 20 years. The determined warming for 0.35 to 0.45 °C in the upper 20-30 m has confirmed the transient character of these temperature-depth profiles. The present-day surface warming is large enough for reliable revealing of the subsurface (underground) temporal temperature changes in the temperature-depth profiles that are acquired with repeating the temperature measurements in the boreholes during several years or even decades. The measurements helped us to select an appropriate borehole with nice temperature profile for the establishment of the station for monitoring the air-ground temperature coupling.

The 2 year and 10 months fluently running of the monitoring unit Malence promises to acquire important information on long-term tracking of ground and air temperatures and on mechanism of depth propagation of inter annual variations of the ground surface temperature into the underground rock formation. We have discovered also that a non-conductive heat transfer is going on in the soil besides the prevailing conductive one. After some heavy rain the rapid jumps or drops occur in the temperature runs, depending on the time of season, and this happens even earlier in the borehole than in the soil at the same depth. This monitoring has so far yielded a rough estimate of the mean annual soil and air temperature difference that is now around 1 °C. But the time of monitoring is still too short to acquire a reliable long-term tendency in a depth of 40 m. This long-term warming amounts now to 0.016 °C/yr, while in 30 m depth it is now 0.019 °C/yr. Because this tendency changes in time, it has not yet stabilized, this is one of the reasons for which the monitoring is foreseen to continue for at least several next years.

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