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Thermal signal propagation in soils in Romania: conductive and non-conductive processes

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Abstract

Temperature data recorded in 2002 and 2003 at 10 stations out of the 70 of the Romanian automatic weather stations network are presented and analyzed in terms of the heat transfer from air to underground. The air temperature at 2 m, the soil temperatures at 0, 5, 10, 20, 50 and 100 cm below soil surface as well as precipitation and snow thickness have been monitored. The selected locations sample various climate environments in Romania. First order modelling confirm that at certain locations and for certain time intervals soil temperatures track air temperature variations and consequently the heat transfer is by conduction, while at others, processes such as soil freezing and/or solar radiation heating play an important part in the heat flux balance at the air/soil interface. However, the propagation of the annual thermal signal in the first meter of soil is through conduction; the effective thermal diffusivity for 8 stations with continuous time series at all depth levels ranges from 3 to $10\times10^{-6}\mathrm{m}^2\mathrm{s}^{-1}$.

1 Introduction

Reconstruction of past climate changes from geothermal data has proven, in the last decade, to be an additional source of information to complement meteorological and proxy records of climatic change (Harris and Chapman, 1998; Şerban et al., 2001; Pollack and Smerdon, 2004; González-Rouco et al., 2006). The interest in this method lies in the fact that it examines a direct measure of temperature, free of problems such as variable standards found in meteorological and proxy data. Unlike proxy records, it has a very clear physical interpretation (i.e. temperature).

However, although the Earth's response to the energy transfer at the surface is related to the surface air temperature (SAT), the ground surface temperature (GST) is an integral of the effects of air temperature variation, vegetation and snow cover variations, phase changes and solar radiation changes at the soil surface (Oke, 1987).

The setting up of a new automatic weather station network in Romania in the last

few years is likely to produce from now on a homogeneous data set for a territory characterized by lateral climatic variability (Ţîştea et al., 1979; Boroneanţ et al., 2004) that can be used in clarifying some of the aspects of the heat transfer at the Earth's surface. In the present paper we analyze the soil heat transfer for 10 stations from Romania using daily air and soil temperature data recorded continuously for two years.

The role of a variety of processes, such as snow cover variation, land cover changes and precipitations, influencing the relationship between air and ground temperatures and thus the ground surface energy transfer, has been widely investigated (Barlett et al., 2004; Nitoiu and Beltrami, 2005; Trenberth and Shea, 2005). The controversy regarding the magnitude of the last century global warming revealed from borehole inversions and proxy data (Esper et al., 2002; McIntyre and McKitrick, 2005) triggered investigations of the basic assumptions (i.e. the ground is a perfectly conductive medium) underlying the theory of borehole inversions (Pollack and Smerdon, 2004; Pollack et al., 2005).

Though the process of heat transfer within soils is important for correct interpretation of the climatic signal extracted from geothermal data, there is a limited number of studies at mid-latitude, from where most of the borehole temperature logs come, on this subject (Beltrami and Kellman, 2003; Smerdon et al., 2003). At high latitudes, the role of snow cover fall rate, onset time and duration, the role of its physical properties and their variation throughout the year on the SAT signal propagation into the ground have been intensively studied, mainly because of concerns regarding the effects of global warming in melting of the permafrost (Goodrich, 1982; Ling and Zhang, 2003).

Using a one-dimensional finite difference numerical model to generate the soil temperature variations in the upper first meter of the ground, Schmidt et al. (2001) and Beltrami (2001) showed that during winter, the process of heat conduction is disturbed by the presence of snow cover and the freezing and melting of the soil water. Mainly in open field areas, processes arising from precipitation fall, water movement or infiltration influence the subsurface heat transfer regime throughout all seasons of the year, leading to a non-conductive heat transport that affects the soil temperature pro-

files (Trenberth and Shea, 2005). These processes make more difficult modelling of the near surface ground temperatures.

In this study, we examined the character of the heat transfer regime in the subsurface (1) qualitatively, by analyzing perpendicular superposition of temperature records at various depths, and (2) quantitatively, at two temporal scales, firstly by looking at the fit between the soil temperatures simulated with a simple conduction model and the measured data at the inter-daily temporal scale, and secondly, at the annual variation scale, in terms of perfect sinusoidal functions of time describing the observed variations. An effective thermal diffusivity of the upper meter of soil was obtained by the second approach.

2 Data

The National Meteorological Agency network comprises 70 automatic weather stations evenly distributed over the country. Each station is equipped with MAWS 301 Vaisala measuring systems that are designed to measure the atmospheric pressure, air temperature, relative humidity, wind speed and direction, liquid precipitations, as well as global, net and diffuse radiation. At mountain weather stations an ultrasonic device is used to measure the snow depth; at low altitude stations, the soil temperature is measured using a QMT 107 system. The accuracy of the air and soil temperature records is better than ±0.2 K. All stations are located in open field and thus exposed directly to the sun.

In this study, air (2 m) and soil temperature at six depth levels (0, 5, 10, 20, 50, 100 cm) recorded by 10 of the Romanian automatic weather station network (Fig. 1), in 2003 and 2004, have been used. The stations were chosen to uniformly cover the Romanian territory and thus to sample the main climatic areas on the Romanian territory. The mean annual SAT and GST, as well as the total annual precipitation and snow thickness for each meteorological station for 2003 and 2004 are given in Table 1. The mean daily SATs and GSTs were calculated by averaging the temperature values

measured at 01:00 am, 07:00 am, 01:00 pm and 07:00 pm., local time.

It is generally accepted that GST is higher than SAT (Beltrami and Kellman, 2003), and the Romanian stations make no exception as it can be seen from the annual averages from Table 1. This was discussed by Demetrescu et al. (2006) in greater detail. However, problems related to the definition of soil surface temperature (GST) in the measuring system, which we became aware of later and have not been clarified yet, prevent us using the corresponding data set in the present paper.

The analysis was performed for each of the ten stations, but here we show the results for only one station because of simplicity reasons. We chose to show the results for Bistriţa station because it has the most continuous records available. The daily-averaged temperatures recorded at Bistriţa are illustrated in Fig. 2 as time series. The daily-averaged temperatures recorded at all stations are illustrated in Fig. 3 and Fig. 4 as isopleths on temperature/depth/time plots. One can easily see the attenuation of the high frequency temperature fluctuations and the attenuation of the annual variation as the signal is propagated into the ground, the phase shift with depth of the temperature wave, as well as the heat valve effect (in summer the heat flows downwards, while in winter the heat flows toward the Earth surface) (Beltrami, 2001) and the zero curtain effect (negative temperatures cannot be found in the ground until the water in the soil completely freezes) (Kane et al., 2001). Massive missing data can be noticed in case of Adamclisi, Reşiţa and Roman stations. In case of Adamclisi the 1 m depth data are missing only for 2003, thus to maintain the same format as for the other stations, the 2004 data were not plotted.

3 Heat transfer regime in the subsurface: Qualitative perspective

In Fig. 5 the measured air temperatures at Bistriţa in 2003 are compared with the soil temperatures recorded at various levels as indicated and in Fig. 6 the soil temperatures at 10 cm are compared with the deeper temperature series. In ideal conductive conditions the plots should be ellipses with their long axes becoming smaller as one

goes deeper into the ground, because of the attenuation with depth of the annual signal amplitude, and with their short axes becoming larger, due to phase difference between temperatures recorded at different levels (Beltrami, 1996). This behavior is recognizable in the plots, but is strongly disturbed by shorter-term fluctuations and by nonconductive heat transfer at the air-soil interface. The latter is apparent from the flattening of the interception figures around the freezing point and from the high variability during summer (the maze from the upper part of the interception figures) due to direct solar radiation and to evapotranspiration, the station being located in open field. The short term oscillations are reduced when one analyzes the heat transfer within soil between 10 cm and 20, 50 and 100 cm respectively (Fig. 6). The extremely low thermal diffusivity of the upper part of the soil (Nitoiu, 2005) filters out the high frequency temperature variations. Figure 6 clearly shows that during winter the soil temperature below 20 cm is above the freezing point, thus non-conductive effects associated with the latent heat of melting and freezing of the liquid present within soil pores do not appear anymore to be superimposed on the process of heat transfer through conduction. However, other factors such as the water content and/or convective heat transfer might still intervene. Below 50 cm several short term temperature fluctuations are still visible, but the conduction seems to be the main mechanism of heat propagation to the underground (see Fig. 7).

4 Heat transfer regime in the subsurface: Quantitative assessment

4.1 Inter-daily variation: Analytical modelling using step functions

In an ideal conductive subsurface, variations of surface temperature are propagated into the ground according to the one-dimensional heat conduction equation (Carslaw and Jaeger, 1959)

$$\frac{\partial T(z,t)}{\partial t} = \kappa \frac{\partial^2 T(z,t)}{\partial z^2}, \tag{1}$$

where T is temperature, κ is thermal diffusivity, z is depth and t is time.

If the variations of soil surface temperature are modelled as a series of K temperature changes, then the subsurface temperature signals from each step change are superimposed, and the temperature perturbation at depth z ($T_t(z,t)$) is (Mareschal and Beltrami, 1992)

$$T_t(z,t) = \sum_{k=1}^{K} T_k \left[erfc\left(\frac{z}{2\sqrt{\kappa t_k}}\right) - erfc\left(\frac{z}{2\sqrt{\kappa t_{k-1}}}\right)\right], \quad (2)$$

where $erfc$ is the complementary error function.

Modelling temperature variations at a given depth induced by temperature variations at surface following Eq.(2) would show, when compared to actual recorded temperatures, if the transfer of heat is by conduction or other processes are present too. Taking as a forcing function the daily mean air temperature variation with respect to the first day of data (January 26th 2003), we generated the 5 cm soil temperature variation assuming different values for the soil thermal diffusivity ranging from $0.1\times10^{-6}\mathrm{m}^2\mathrm{s}^{-1}$ to $0.5\times10^{-6}\mathrm{m}^2\mathrm{s}^{-1}$ (see Fig. 8). Whatever thermal diffusivity value is used, the pure conduction model is not able to reproduce the actual temperatures recorded over an entire year interval. The discrepancy is large in winter and summer, when processes such as freezing or evaporation of the water content imply latent heat contribution and, respectively, evapotranspirative cooling and convection. The effective thermal diffusivity of the first meter of soil is varying accordingly.

At deeper levels processes mentioned above should diminish in importance. Taking as a forcing function the 50 cm soil temperature variation with respect to the measured value on 6 February 2003 (there are missing data in January between 5 cm and 50 cm depth due to recording system mal-function), we generated the soil temperature variation at 100 cm for the year 2003, using different values for thermal diffusivity, and we compared the modelled temperatures with the measured ones. The best fit (rms error of ±0.77 K) is obtained for a thermal diffusivity of $0.4\times10^{-6}\,\mathrm{m}^2\,\mathrm{s}^{-1}$ (see Fig. 9). The figure shows that heat conduction is the dominant heat-transfer mechanism in the

50–100 cm depth range only in winter and spring (days 0–150). In summer and autumn, measured temperatures at 1 m are systematically lower than the predicted ones, probably because of evapotranspirative cooling and convection. Another factor which might intervene is the soil water content, variable in the course of a year. A comparison with the recorded precipitation (Fig. 10) shows that the fit worsens precisely after a significant increase in precipitation, possibly responsible for increasing the water content of soil in the 50–100 cm depth range. Between 4 September (day 210) and 15 October (day 251) 2003, the best fit between the measured and modelled temperatures is obtained for a thermal diffusivity of $0.2\times10^{-6}\,\mathrm{m^2\,s^{-1}}$ (rms difference of ±0.50 K), while the rms difference is of ±0.91 K when using a thermal diffusivity of $0.4\times10^{-6}\,\mathrm{m^2\,s^{-1}}$. The above example shows that, at the day to day scale, the effective thermal diffusivity of the first meter of soil is variable during the course of a year.

4.2 Annual variation: Analytical modelling using sinusoidal functions

To assess the character of heat transport in the first meter of soil at the annual timescale we use the method described by Hurley and Wiltshire (1993) and previously applied on data from North America by Smerdon et al. (2003).

If, on a certain time scale, the air and soil temperature series can be assumed as sinusoidal functions of time, the soil surface temperature varies according to

$$T(0,t) = T_0 + \Delta T \cos(\omega t + \epsilon), \tag{3}$$

where T_0 is the mean temperature, ΔT is the amplitude of the sinusoidal oscillation, ω is the angular frequency, and ϵ is the initial phase of the oscillation.

The time-dependent soil temperature fluctuation at depth z is then described (Carslaw and Jaeger, 1959) by:

$$T(z,t) = T_0 + \Delta T \exp\left(-z\sqrt{\frac{\omega}{2\kappa}}\right)\cos\left(\omega t - z\sqrt{\frac{\omega}{2\kappa}} + \epsilon\right). \tag{4}$$

The amplitude of the soil temperature fluctuation at depth z is $A(z)=\Delta T \exp\left(-z\sqrt{\frac{\omega}{2\kappa}}\right)$. The amplitude of the soil temperature variation decreases to $1/e$ of its surface value at the depth $d_e = \sqrt{\frac{2\kappa}{\omega}}$. The phase difference between temperature variations at surface and any depth z is given by $\phi(z)=z\sqrt{\frac{\omega}{2\kappa}}$.

We spectrally decomposed the air and soil temperature series using Fourier analysis. The dominant signal is the one year period variation, and as expected, the power of the annual signal decreases with depth. The amplitude and phase of the annual signal were calculated fitting the signal with a cosine function:

$$y = y_0 + a\cos\left(\frac{2\pi}{b}t + c\right), \tag{5}$$

where the regression parameters are y_0, the initial temperature, a, the amplitude, b, the period of oscillation, and c, the phase. An example is illustrated in Fig. 11 for the Bistriţa station. One can easily see the attenuation with depth of the high frequency oscillations that are present in SAT (upper panel); at one meter (lower panel) the measured signal is almost perfectly ($r^2 = 0.984$) described by a sinusoidal function.

To further investigate the conductive character of heat propagation into the soil, we plotted the natural logarithm of amplitude $\left(lnA = ln(\Delta T) - z\sqrt{\frac{\omega}{2\kappa}}\right)$ (upper panel) and the phase shift as function of depth (bottom panel) for Bistriţa, in Fig. 12. The linear decrease with depth of the natural logarithm of amplitude and the linear increase with depth of the phase shift indicate conductive dominated heat transport.

The slope of the linear regression of both $lnA(z)$ and $\phi(z)$ gives an estimate of the thermal diffusivity for the first meter of soil. The results for 8 stations (because of missing data below surface, Roman and Reşiţa stations could not be used for this part of the study) are presented in Table 2. There is a good correlation between the two values of diffusivity (r^2=0.843) but a slight bias toward the diffusivities computed from lnA data can be noticed (Fig. 13). The two values differ from their mean by less than

±10% except in the case of Adamclisi and Satu Mare stations (±13% and, respectively, ±17%). The rms difference between the annual temperature signal propagating in one meter of soil with a given thermal diffusivity (κ_a) and the annual temperature signal propagating through one meter of soil with a thermal diffusivity higher or smaller than κ_a by 10% ($\kappa = \kappa_a \pm 10\%$), is less than 0.2 K, which is negligible when compared to the amplitude of the annual temperature wave (around 12 C at the surface and 7 C at one meter depth). In the Adamclisi case, the marginally larger difference between κ_A and κ_ϕ can be explained by a weaker definition of the sinusoid for the depth of 1 m, because of missing data. The Satu Mare result, however, might indicate that the mechanism of propagation in the first meter of soil of the annual temperature wave is dominated by other processes than conduction.

5 Non-conductive processes: the zero-curtain and the snow thermo-insulation effect

Throughout the year, many non-conductive processes influence the heat transfer in shallow soils. During winter, phase changes occurring at the release or absorption of heat through freezing or melting respectively, lead to a decoupling between surface and deep soil temperatures. For the winter season of 2003–2004, spanning approximately from 16 November 2003 until 15 March 2004, we plotted in the upper panel of Fig. 14 the mean daily SAT and the mean daily temperature at 5 and 20 cm in the subsurface for Bistriţa. Daily snow thickness for the same period of time is represented in the bottom panel of Fig. 14.

The zero-curtain effect is obvious in days when no or little (1–2 cm) snow cover is present on the ground. For the days 360–380, as SAT decreases below 0°C and the surface layer is freezing, latent heat is released, heat that delays the downward penetration of the freezing front (Kane et al., 2001). As long as the volume of water contained in the soil does not freeze, the temperature is kept constant near zero; the transition layer is called zero-curtain (Kane et al., 2001). The layer of soil beneath this

region is isolated from the cold temperature of the soil surface. Once the soil water is converted to ice, the freezing front propagates fast (thermal conductivity of ice is 2.25 $Wm^{-1}K^{-1}$ while the thermal conductivity of water at room temperature is 0.60 $Wm^{-1}K^{-1}$ (Carslaw and Jaeger, 1959)) through conduction to deeper levels. Thus, as the air temperature decreases below the freezing level on 3 January 2004 (day 368), because of the zero-curtain effect the freezing front penetrates at 5 cm only 2 days later, on 5 January 2004, and the soil temperature at 20 cm decreases below 0°C only on 9 January 2004. The magnitude of the cold front propagating downward decreases both because of the zero-curtain and the low thermal diffusivity of the soil.

The air and deep soil temperatures relationship is also influenced, during the winter months, by the presence of snow cover (Grundstein et al., 2005). At Bistriţa station (see Fig. 14), the ground was covered by a snow layer having a thickness of at least 5 cm for the time period spanning from 20 January 2004 (day 385) to 25 February 2004 (day 421). During this period, while SAT decreased to as much as −18.8°C, because of the thick layer of snow and because of the buffering effect of the upper layer of soil, the 5 cm soil temperature has never decreased to less than −1.5°C, and the 20 cm soil temperature has not decreased below −0.1°C. In contrast, in intervals with no snow, the temperatures at 5 cm and 20 cm decreased to −4.6°C and −1.5°C respectively, when SAT attained a minimum of only −11.4°C.

Using the measured SAT and soil temperatures at 5 cm, the daily thermal gradient was calculated for the period 16 November 2003 (day 320) and 15 March 2004 (day 440) and plotted in Fig. 15. Also, the daily thermal gradient was calculated for the layer of soil 5–10 cm and plotted in Fig. 15 with black line. The negative thermal gradient for the SAT–5 cm layer clearly shows the isolation of the shallow soil from the surface temperature variations during the presence of the snow layer and the cooling of the ground during the zero-curtain period. The strongest negative thermal gradient for the 5–10 cm layer is around day 375 and shows the net cooling of the ground after the closure of the zero-curtain period (Romanovsky and Osterkamp, 2000).

6 Conclusions

The preliminary analysis of air and soil temperature data acquired by the new automatic Romanian weather network, reported here, shows that:

- The heat transfer in shallow soils is influenced by non-conductive processes such as phase changes. The zero-curtain and the snow thermo-insulation effects are discussed, based on recorded temperatures to depths of 20 cm and on derived thermal gradients;

- At the inter-daily time-scale, qualitative assessment by means of perpendicular superposition of temperature records at various depths shows the presence of non-conductive processes disturbing an ideal conductive environment down to 1 m depth, though more pronounced in the first 50 cm of the subsurface. Simple conductive models cannot reproduce recorded soil temperatures during the freezing season or during the summer. Incorporating latent heat contribution to the heat transfer in the active layer is a necessary step;

- At the seasonal time-scale, an effective variable thermal diffusivity for the first meter could be defined. The variation of the water content of soil was identified as a source of thermal diffusivity variations, even in case of the 50–100 cm depth range;

- The annual signal in data represented by sinusoidal fit to measured values is controlled, in the first meter of soil, by heat conduction; the effective thermal diffusivities for 8 stations with continuous time series at all depth levels range from 3 to $10\times10^{-7}\,m^2s^{-1}$;

- Detailed studies on heat transfer through the upper meter of the ground at the 1 day time-scale would be possible upon changes in data acquisition protocol which, at present, retains temperatures at four terms a day.

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Table 1. Mean annual climatic conditions for 2003 and 2004 at the meteorological stations.

Station	SAT (°C)	GST (°C)	Precip. (cm)	Snow (cm)
Adamclisi	11.07	11.88	57.50	35.4
Bistriţa	8.72	9.66	60.76	95.65
Oradea	10.60	11.14	61.92	48.55
Reşiţa	10.58	10.62	77.87	30.60
Roman	9.21	10.47	46.32	34.15
Satu Mare	9.93	11.10	57.49	46.90
Slobozia	11.01	12.60	54.51	36.90
Tg. Jiu	10.91	12.15	82.80	84.90
Tg. Mureş	9.05	10.19	55.94	72.35
Vaslui	9.75	10.77	52.16	58.45

Table 2. Annual surface temperature amplitude, in C, and thermal diffusivity, in units of $10^{-7}m^2s^{-1}$, for the first meter of soil obtained from the sinusoidal treatment.

Station	Id. No.	$A_{surface}$ (fitted)	κ_A	κ_ϕ	$\overline{\kappa}$
Adamclisi	1	13.48	4.36	3.33	3.85 ± 0.52
Bistriţa	2	14.23	4.89	4.16	4.53 ± 0.37
Oradea	3	13.60	4.63	4.10	4.37 ± 0.27
Satu Mare	4	14.30	3.67	5.21	4.44 ± 0.77
Slobozia	5	14.83	9.89	8.81	9.35 ± 0.54
Tg. Jiu	6	14.57	5.41	5.28	5.35 ± 0.07
Tg. Mureş	7	14.87	2.94	2.50	2.72 ± 0.22
Vaslui	8	14.27	4.87	4.59	4.73 ± 0.14

Fig. 1. Location of the 10 stations of the Romanian automatic weather stations network used in the present study (The Romanian map was modified from www.maps.com).

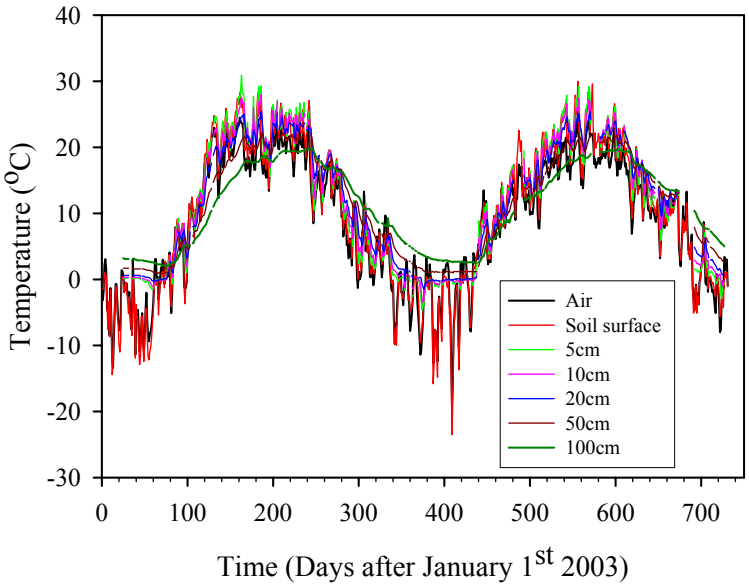

Fig. 2. Daily-averaged temperatures for Bistriţa for the years 2003 and 2004: air (black line), soil surface (red), 5 cm within soil (light green), 10 cm (yellow), 20 cm (blue), 50 cm (brown) and 100 cm (dark green).

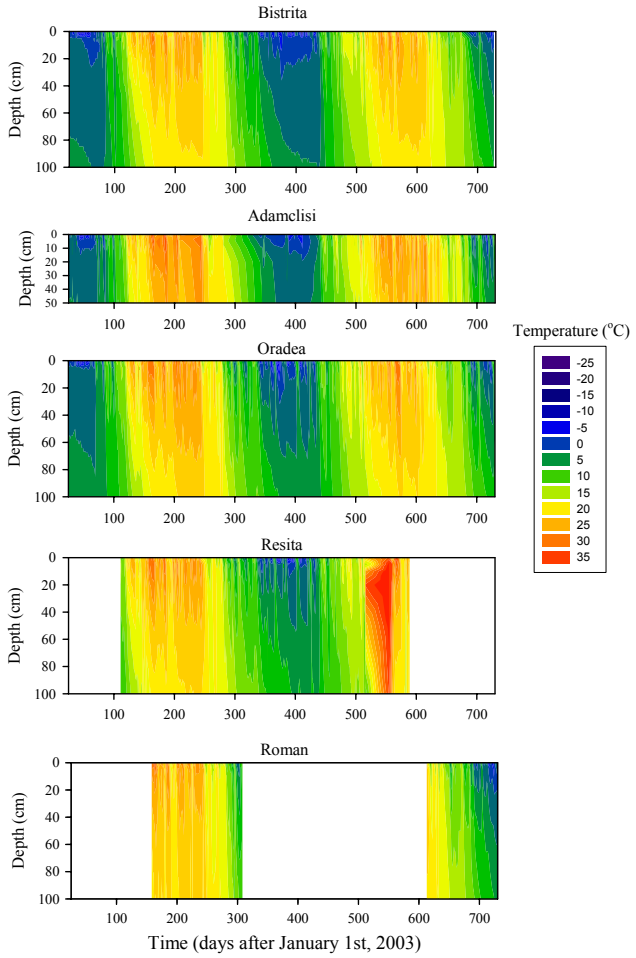

Fig. 3. Isopleths of daily-averaged temperatures for Bistriţa, Adamclisi, Oradea, Reşiţa and Roman stations, for the years 2003 and 2004.

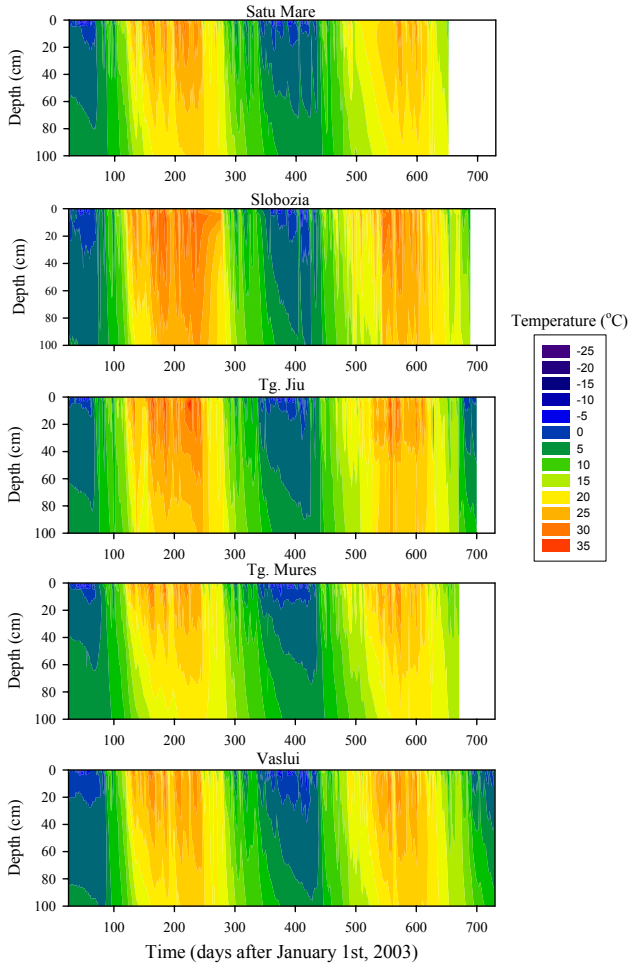

Fig. 4. Isopleths of daily-averaged temperatures for Satu Mare, Slobozia, Tg. Jiu, Tg. Mureş and Vaslui stations, for the years 2003 and 2004.

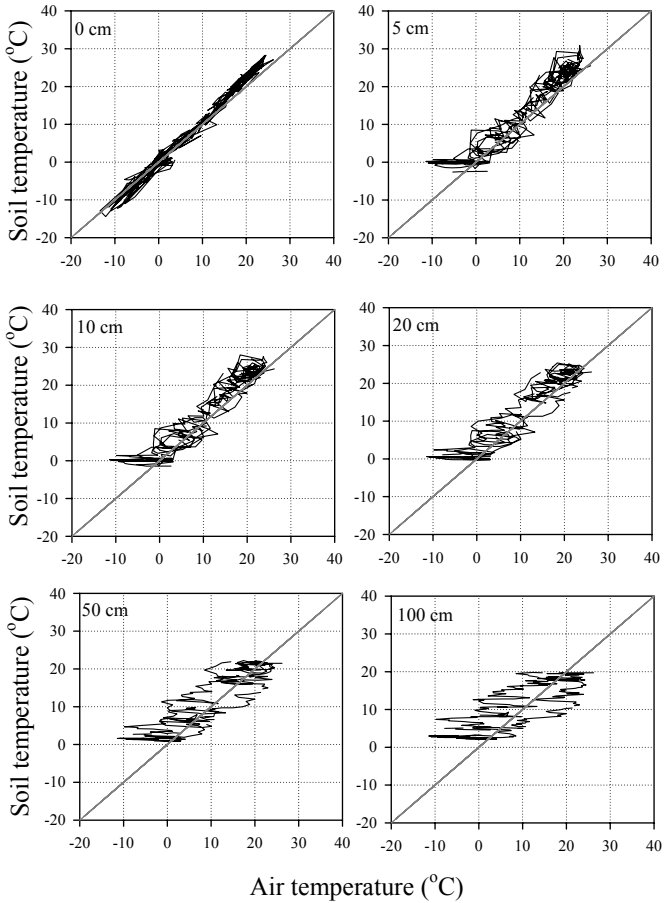

Fig. 5. Perpendicular superposition of air and soil temperatures series measured at Bistriţa station in 2003.

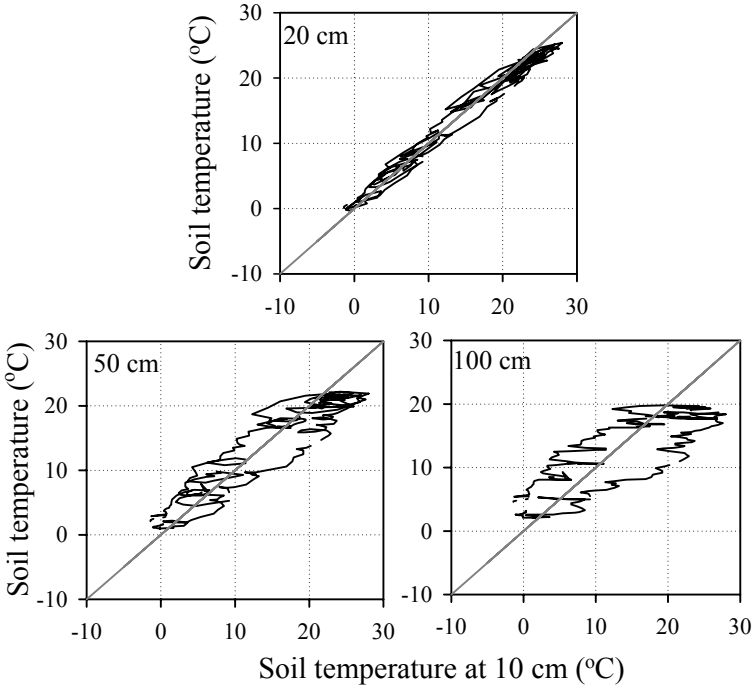

Fig. 6. Perpendicular superposition between the 10 cm soil temperature and the soil temperature measured at 20 cm, 50 cm and 100 cm, for the year 2003, Bistriţa station.

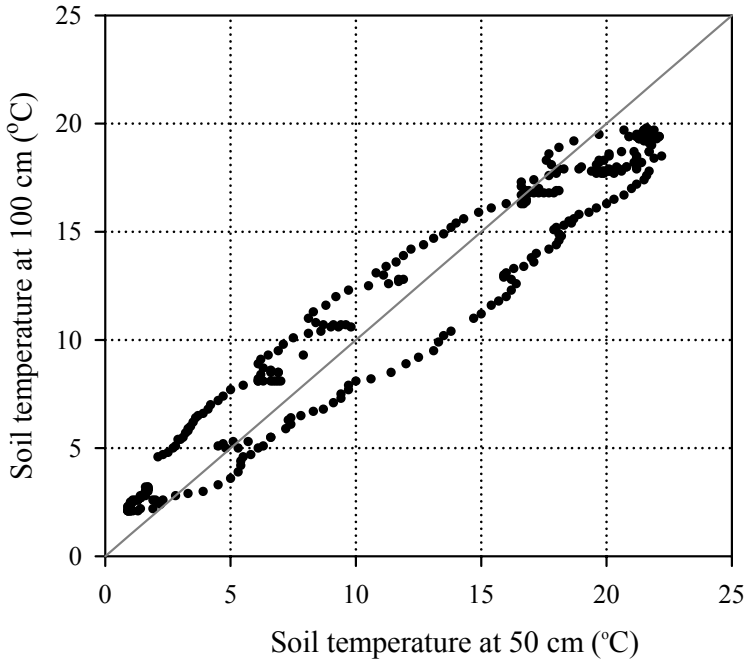

Fig. 7. Perpendicular superposition of 50 and 100 cm soil temperatures recorded at Bistriţa in 2003.

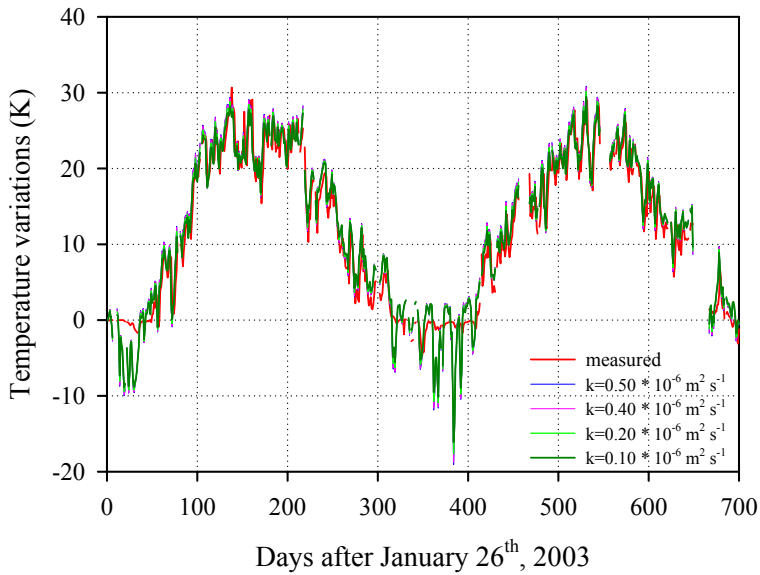

Fig. 8. Measured and modelled daily 5 cm soil temperature variations (with respect to 26 January 2003) at Bistriţa for 2003 and 2004, using different values of thermal diffusivity for the 0–5 cm layer of soil.

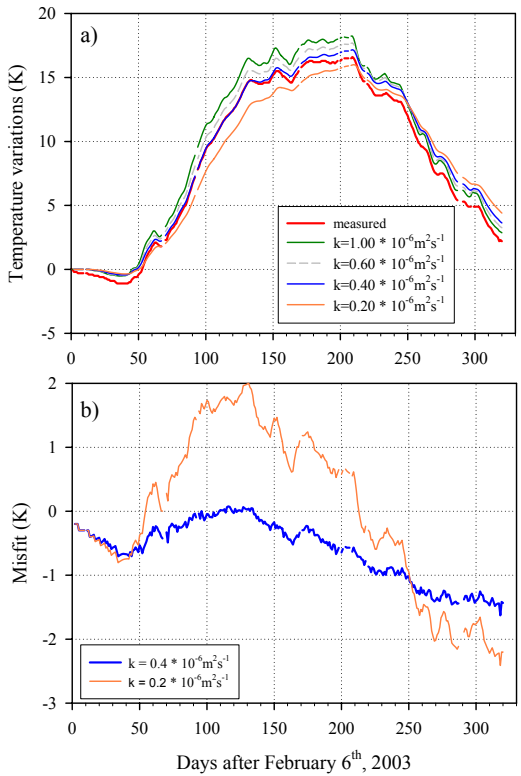

Fig. 9. **(a)** Heat transfer from 50 to 100 cm: measured and modelled daily 100 cm soil temperature variations (with respect to 6 February 2003) at Bistriţa for 2003, using different values of thermal diffusivity for the 50–100 cm layer of soil. **(b)** The misfit between the measured and modelled temperatures for two thermal diffusivities: $0.2\times10^{-6}\mathrm{m}^2\mathrm{s}^{-1}$ and $0.4\times10^{-6}\mathrm{m}^2\mathrm{s}^{-1}$.

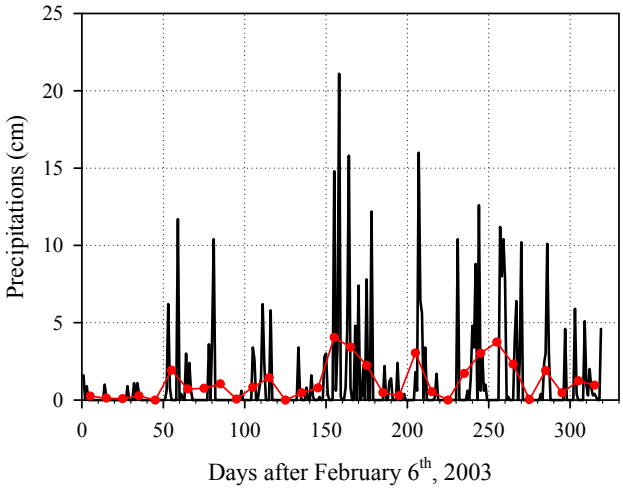

Fig. 10. Recorded precipitations at Bistriţa for 2003. With red line we represented the 10 days average precipitations.

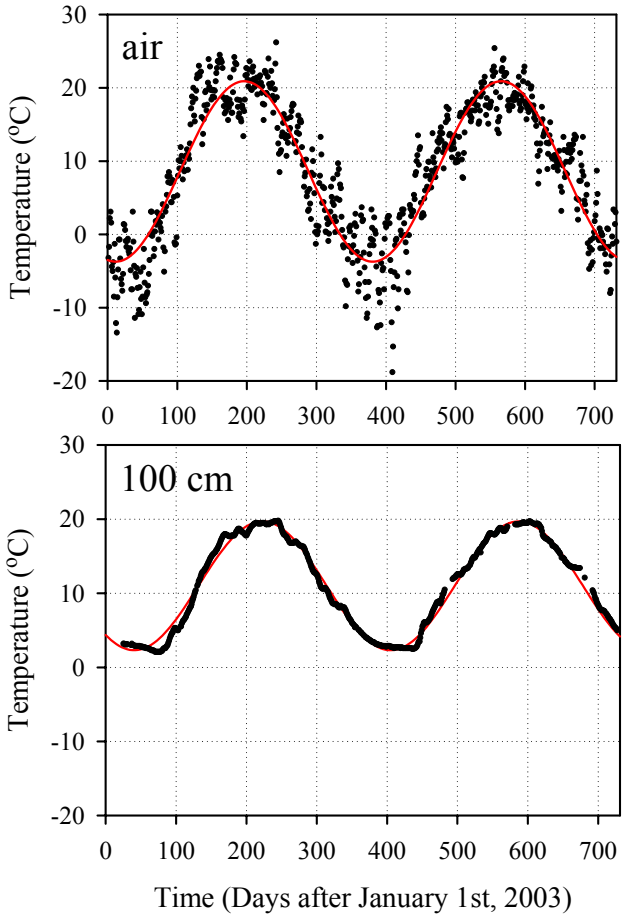

Fig. 11. Daily SAT (upper panel) and 100 cm (bottom panel) soil temperatures recorded at Bistriţa station for 2003 and 2004. The sinusoidal function fit is illustrated with red line.

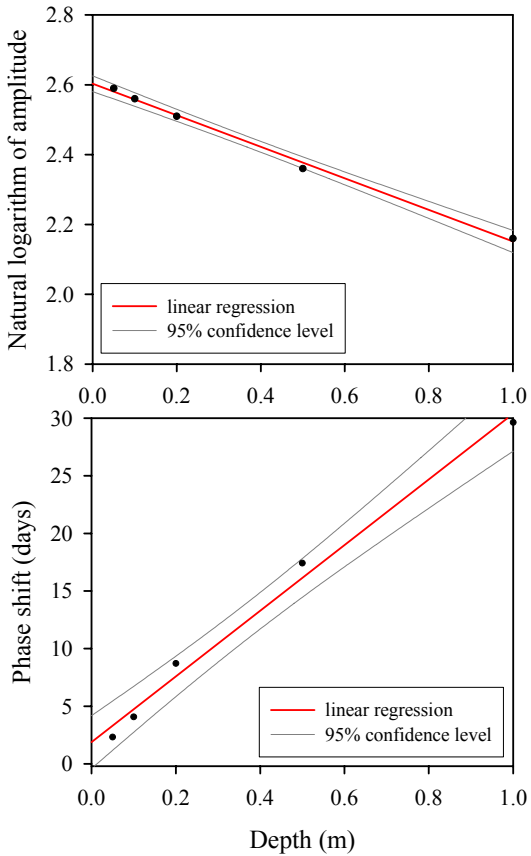

Fig. 12. Natural logarithm of amplitude (upper panel) and phase shift relative to the SAT (bottom panel) as function of depth for Bistriţa. The coefficient of determination of the regression line is r^2=0.996 and r^2=0.990 for amplitude and phase shift, respectively. The 95% confidence interval is also included.

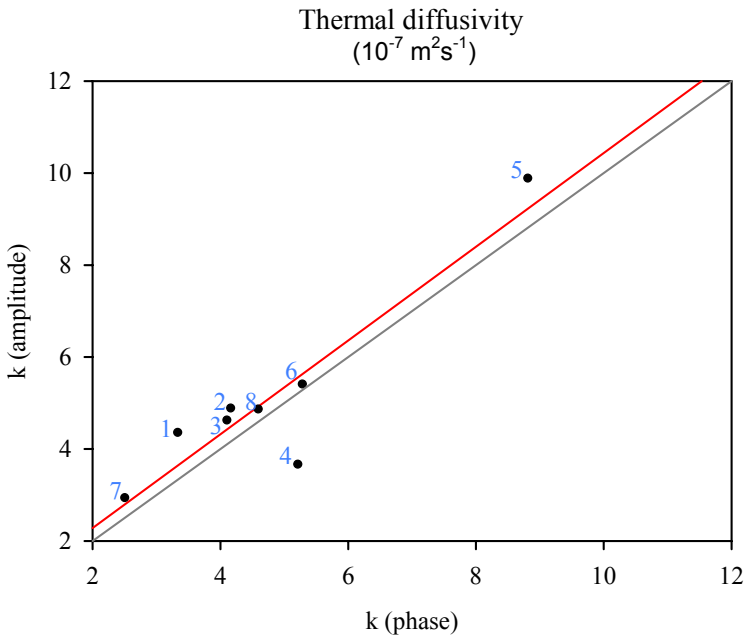

Fig. 13. Comparison of effective thermal diffusivity of the first meter of soil computed from the natural logarithm of amplitude and from phase. 1–8: identification number (Id. No.) from Table 2.

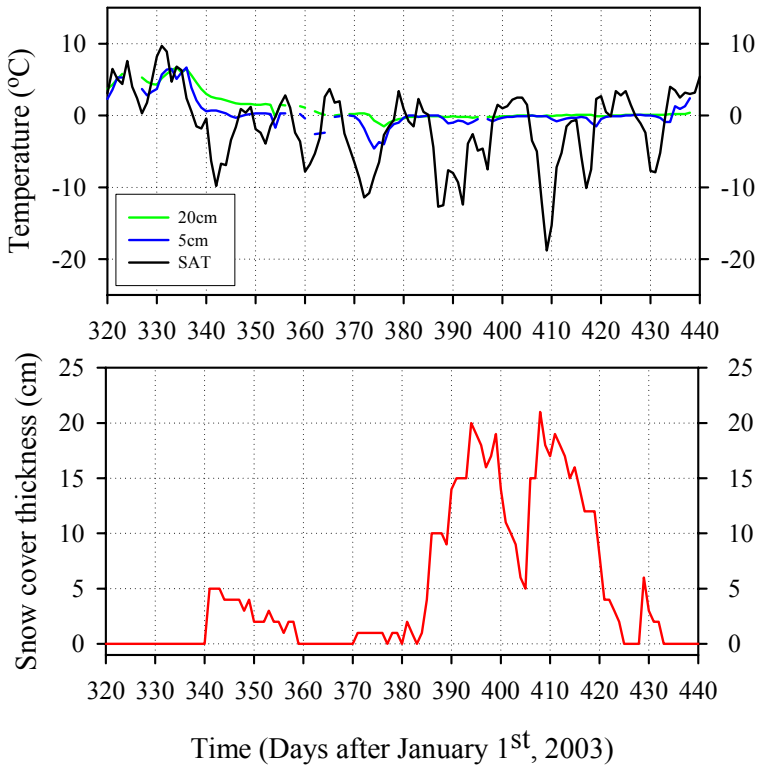

Fig. 14. Daily soil temperature records for the indicated depths at Bistriţa station for the winter season 2003–2004. The bottom panel shows the daily snow thickness (cm) for the same period of time.

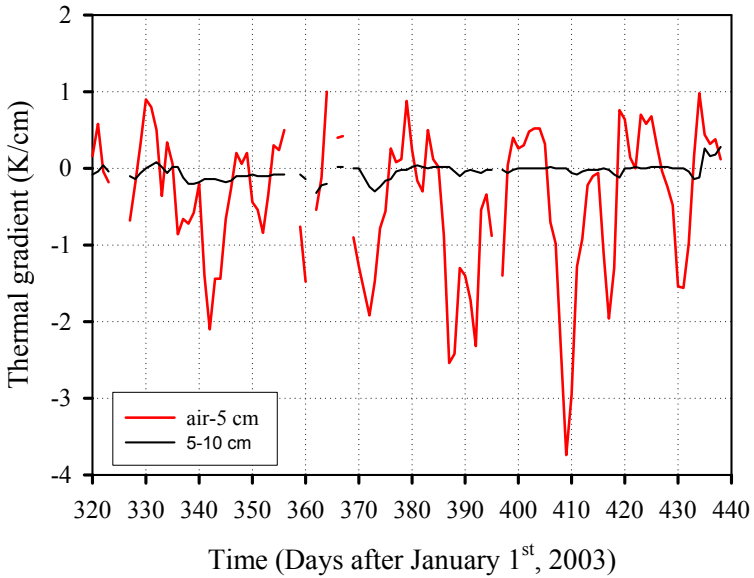

Fig. 15. Variation in time of the thermal gradient for SAT–5 cm (red line) and for 5–10 cm (black line) layers, at Bistriţa station for the winter season 2003–2004.