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UNCERTAINTIES OF APPARENT THERMAL DIFFUSIVITY OF ALLUVIAL-MEADOW SOIL ESTIMATED BY DIFFERENT NUMERIC METHODS

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Abstract

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The apparent thermal diffusivity (***a***) of Fluvisol was estimated by applying the Amplitude, Phase, Arctangent, Logarithmic and Harmonic methods on soil temperature data measured at 0.10 and 0.20 m depth with automatic meteorological station in 92 clear sky days under different soil moisture conditions. The uncertainty between these method was high (Cv = 31% in average). Our results showed that there was not significant difference between the apparent thermal diffusivity obtained by the Amplitude, Logarithmic and Harmonic methods. The Phase and Arctangent methods produced higher values of the apparent thermal diffusivity and with a higher coefficient of variation. The lowest variation of ***a*** was obtained by the Harmonic method (C_v = 15%), which can be recommended for estimation of thermal diffusivity on a daily basis. The obtained results were compared with direct measurement in laboratory conditions with KD2-Pro device, and with estimation by de Vries model (de Vries, 1963), and by the annual soil temperature wave method based on 10 years records (Marinova et al., 1990). The minimum values of ***a*** obtained on a daily basis coincided with the highest values predicted by de Vries model for high soil moisture content. It was not found dependence of the apparent thermal diffusivity from soil moisture content. The prediction of ***a*** by the annual soil temperature wave method was close to the average values obtained on a daily basis. This study demonstrate the possibility of using soil temperature data registered by automatic weather station to produce reliable estimates of soil thermal diffusivity for relatively shorter time period.

Key words: soil thermal diffusivity; thermal properties; numeric methods

Introduction

Thermal diffusivity (***a***) of soil determines the rate of propagation of temperature fluctuation in the soil profile and is expressed as (eq. 1):

$$a = \frac{\lambda}{C_v} \quad (1),$$

where λ is the thermal conductivity and C_v is the volumetric heat capacity of soil.

Data from direct measurements of soil thermal diffusivity ***a*** were obtained for different soil varieties in Bulgaria using the laboratory method of Kondratiev based on the theory of regular regime (Shein et al., 2001). The reported values varied between ≈ 1.10^{-7} $m^2.s^{-1}$ for dry soils to $2\text{-}3.10^{-7}$ $m^2.s^{-1}$ for moist fine texture soils and $5\text{-}7.10^{-7}$ $m^2.s^{-1}$ for moist coarse texture soils (Ilieva and Krasteva, 1973; Dilkova and Ilieva, 1974). Due to the limited size of soil sample, the radial moisture transfer and respectively the transfer of heat with moisture did not realize fully. That is why the value of the apparent thermal diffusivity received by Kondratiev method was underestimated (Shein et al., 2001).

The measured soil thermal diffusivity in laboratory conditions coincides well with the calculated *a* (Eq. 1) with

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values of λ and C_v estimated via the models of de Vries (de Vries, 1963; Ochsner et al., 2001) and Usowicz (1992) (Doneva, 2007).

Other indirect methods for estimation of the apparent soil thermal diffusivity are based on solution of heat transfer equation and the variation of soil temperature measured at two or more soil depths. The diurnal course of soil temperature is used for describing damping of the amplitude and shifting the temperature phase in depth, which is reflected in several methods – Amplitude, Phase, Logarithmic, Arctangent, Numeric and Harmonic methods (de Vries, 1963; Horton, 2002). The attractiveness of these methods is relatively easy way of collecting soil temperature data sets, especially using automatic weather station for the estimation of the apparent thermal diffusivity. It should be noted that the successful implementation of these methods depends on fulfilment of the requirements stemmed from the theory of one-dimensional heat conduction transfer in homogeneous soil profile. Such are constant average temperature within the soil profile, constant moisture content during the day, weather condition ensuring sinusoidal form of surface soil temperature wave (clear sky radiation, low wind velocity) (Horton et al., 1983; Shein et al., 2001; Heusinkveld et al., 2004).

The inter-comparison of these methods was investigated by lot of studies (Wierenga et al., 1969; Horton et al., 1983; Horton, 2002; Verhoef et al., 1996; Ochsner, 2001; Heusinkveld et al., 2004; Gao et al., 2009; Gnatowski, 2009; Adeniyi et al., 2012) etc. Wierenga et al. (1969) obtained realistic values of the soil apparent thermal diffusivity by applying Amplitude and Phase methods. The authors used diurnal temperature data and the results referred to the case when the fluctuations were not too large: successive numbers of clear days, rather uniform water content distribution (irrigated plot) and the surface temperature wave was a periodic function. For the non irrigated plot the values were less reliable. It's pointed out (Wierenga et al., 1969; Horton et al., 1983) that Numerical and Harmonic methods are more reliable in comparison with the Amplitude, Phase, Arctangent and Logarithmic methods for estimation of thermal diffusivity. Verhoef et al. (1996) received best results for thermal diffusivity in the upper soil layer using Amplitude and Harmonic methods. Gao et al. (2009) pointed out that Phase and Amplitude methods overestimate the phase and the amplitude of soil temperature, respectively and also that the choice of the time of four temperature measurements considerably influenced the values of soil thermal diffusivity in case of Arctangent and Logarithmic methods. Gnatowski (2009) found that the estimated values of *a* with the Phase equation were significantly lower and highly variable compared to the other methods and concluded that this method should not be considered as appropriate method for thermal diffusivity determination for organic soils. Most of the investigations evaluate the performance of different methods by predicting soil temperature using the estimated thermal diffusivity with measured soil temperature data (Horton et al., 1983; Gao, 2009). Others compare the results of temperature wave methods with those obtained by de Vries model (Adeniyi et al., 2012). Evstatiev (2013) proposed a method for calculation the thermal diffusivities of the inhomogeneous soil layer using soil temperature data from three depths and claimed that the new method gives more accurate results than the harmonics one for days with low temperature amplitudes and for days with changing weather conditions.

Temperature wave approach can be applied also with annual soil temperature data for determining mean values for soil thermal diffusivity. The procedure for determining the thermal diffusivity was described in details in Marinova et al. (1990) and Marinova (1993). The long-term average daily temperature data were approximated with 5th-order polynomial curve in order to determine the position of maximums. The estimated mean thermal diffusivities of soils of 17 meteorological stations of the National Institute of Meteorology and Hydrology varied between $2.4 \cdot 10^{-7} \div 6.5 \cdot 10^{-7}$ $m^2.s^{-1}$ (Marinova, 1993) and $2.3 \cdot 10^{-7} \div 5.3 \cdot 10^{-7}$ $m^2.s^{-1}$ (Doneva, 2007) using soil temperature data averaged correspondingly for the periods 1980-1985 and 1993-2002.

The aim of current study was to estimate the uncertainty of the apparent thermal diffusivity of Alluvial-meadow soil in the experimental field Tsalapitsa calculated by different numeric methods using selected diurnal records of soil temperature data.

Materials and Methods

The apparent thermal diffusivity was estimated using soil temperature data measured at two depths – 0.10 and 0.20 m in A horizon of the grassed Alluvial-meadow soil (Fluvisol) in the meteorological polygon at the experimental field Tsalapitsa, Plovdiv region. The main physical and chemical properties of this horizon are presented in Table 1. Particle-size distribution was determined by sieving for the sand fraction and by the pipette method for the silt and clay fractions. The soil texture was classified as Loam according to USDA (Soil Survey Division Staff, 1993).

Soil temperatures were measured with two temperature probes (thermistor, #6470, connected to the Wireless Soil Moisture/Temperature Station, Davis Instruments) installed at 0.10 and 0.20 m soil depths. Data was recorded every hour by the Vantage Pro2 Plus console station (DAVIS Instruments). The accuracy of the measurements is ±0.5°C.

Table 1

Physical and chemical properties of A horizon of Fluvisol. Particle size distribution and texture class according to USDA; SOC – soil organic carbon content; BD – bulk density, PD – particle density, P – porosity, FC – field capacity (at -33 kPa suction); WP – wilting point (at -1500 kPa).

Depth, cm	Sand, %	Silt, %	Clay, %	Texture class	SOC, %	BD, $g.cm^{-3}$	PD, $g.cm^{-3}$	P, $cm^3.cm^{-3}$	FC, $cm^3.cm^{-3}$	WP, $cm^3.cm^{-3}$
5-20	44.0	35.8	20.2	Loam	0.51	1.49	2.64	0.44	0.29	0.13

The soil moisture is evaluated indirectly with measurement of soil water potential by the Watermark® Soil Moisture Sensor (#6440) which registers the soil water suction with a range from 0 (wettest) to 200 (driest) centibars. In order to estimate the water content at the recorded suctions a pF curve was constructed using laboratory measurements by suction type apparatus (for pF < 2.5) and membrane apparatus (for pF 4.2) (Figure 1). Additionally 4 points were determined in the field by gravimetric measurements of soil water content, which lay below the laboratory data (Figure 1). There are different reasons accounting for the well-known difference between laboratory and field methods for determination of soil water retention curves – sample size, measurement scale, assumptions in the theory, measurement procedure (hysteresis) (Basile et al., 2003). As it was found by Popova et al. (2001) the laboratory WRCs overestimated water content by about 0.13-0.18 $cm^3.cm^{-3}$ in Vertisols and 0.07-0.12 $cm^3.cm^{-3}$ in Chromic Luvisols conditions.

The apparent thermal diffusivity was calculated using 92 series of 24-hours soil temperature readings at days with different soil moisture content. The solar radiation measured in the selected days was more than 80% of the clear sky radiation. This requirement assures the periodicity of temperature wave near to the soil surface.

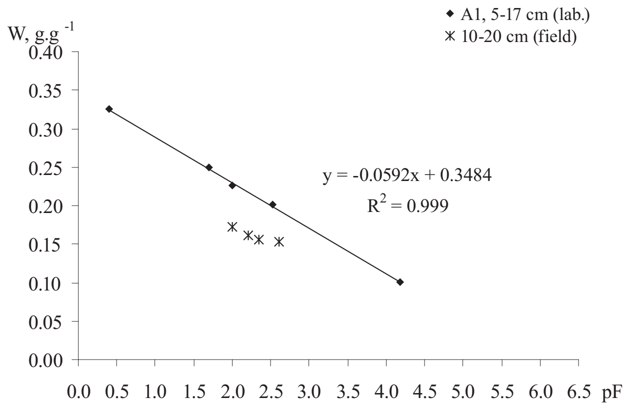

Fig. 1. Water retention at different suctions (pF curve) determined in laboratory conditions by suction type apparatus (for pF < 2.5) and membrane apparatus (for pF 4.2) and in field gravimetrically at potentials recorded by Watermark® Soil Moisture Sensor (Davis Instruments)

The equation which describes conductive heat transfer in a one-dimensional isotropic medium is:

$$C_v \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right), \tag{2}$$

where T is the soil temperature, t is the time, z is the depth, Cv is the volumetric heat capacity and λ is the apparent thermal conductivity. In the case when it is accepted that C_v and λ are independent of depth and time, Eq. (2) becomes:

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial z^2}, \tag{3}$$

where a is the apparent thermal diffusivity (as defined in eq. 1), which is constant for the investigated time interval and depth.

The following five methods based upon the solution of the Eq. (3) were used to calculate a as described in detailed in Horton et al. (1983), Heusinkveld et al. (2004), Gao et al. (2009). These methods estimated the so called apparent thermal diffusivity. The term "apparent" means that both processes – conduction and convection – are performed in heat transfer in moist soil and in the presence of a temperature gradient.

Method 1 (Amplitude)

The Amplitude method is based upon the first Fourier's law which describes the damping of the soil temperature amplitude with depth.

With boundary conditions:

$$T(0,t) = \overline{T} + A\sin(wt), \tag{4}$$

$$T(\infty,t) = \overline{T}. \tag{5}$$

The solution of Eq. (3) is:

$$T(z,t) = \overline{T} + A\exp(-z\sqrt{w/2a})\sin(\omega t - z\sqrt{w/2a}), \tag{6}$$

where $\overline{T}$ is the average soil temperature, assumed to be the same at all depths, A is the amplitude of the surface temperature wave and ω ($rads^{-1}$) the radial frequency equal to $2\pi/P$, with P being the period of the diurnal cycle (P = 864 000 s).

The apparent thermal diffusivity can be solved as the amplitude equation:

$$a = \frac{\omega}{2}\left[\frac{z_2 - z_1}{\ln A_1 / A_2}\right]^2, \tag{7}$$

where A_1 is the amplitude at depth z_1, A_2 is the amplitude at depth z_2.

Method 2 (Phase)

If the time interval between measured occurrences of maximum soil temperature at depths z_1 and z_2 is $\Delta t = (t_2 - t_1)$, the phase equation stemming from Eq. 6 is:

$$a = \frac{1}{2\omega}\left[\frac{z_2 - z_1}{\Delta t}\right]^2. \tag{8}$$

Frequent observations of T are necessary to ensure accurate estimates of t_1 and t_2. As it was discussed in several studies the thermal diffusivity a calculated by Phase method is most prone to the errors of times of occurrence of temperature maximums (Horton et al., 1983; Gao et al., 2009; Gnatowski, 2009) etc. In order to determine Δt more accurately a regression polynom of 6th was fit ($R^2 > 0.9$) to each of selected diurnal data series. The times of maximums were determined using nonlinear optimization tool of Excel – *Solver*.

Method 3 (Arctangent)

Soil temperature near the surface can be described by a series of sine terms. Measured values of temperature at a specific depth can be fitted to Fourier's series using standard linear least square regression techniques. Hence:

$$T(t) = \overline{T} + \sum_{n=1}^{M}[A_n\cos(nwt) + B_n\sin(nwt)], \tag{9}$$

where $\overline{T}$ is the mean value of the temperature in the time interval considered, M the number of harmonics, A_n and B_n are the amplitudes.

If the first four terms ($M = 2$) of the above series are assumed to describe an upper boundary condition at $z = z_1$, where z may be zero (i.e., at the soil surface) or greater, the apparent thermal diffusivity can be calculated from:

$$a = \frac{w(z_2 - z_1)^2}{2\left\{\arctan\left[\frac{(T_1 - T_3)(T_2' - T_4') - (T_2 - T_4)(T_1' - T_3')}{(T_1 - T_3)(T_1' - T_3') + (T_2 - T_4)(T_2' - T_4')}\right]\right\}^2}, \tag{10}$$

where temperatures T_i and T'_i are recorded each 6 h at two depths, z_1 and z_2, respectively (Nerpin and Chudnovskii, 1967).

Method 4 (Logarithmic)

Using the assumption made above for Method 3, Seemann (1979) showed that the apparent thermal diffusivity can be calculated from:

$$a = \left[\frac{0.0121(z_2 - z_1)^2}{\ln\left[\frac{(T_1 - T_3)^2 + (T_2 - T_4)^2}{(T'_1 - T'_3)^2 + (T'_2 - T'_4)^2}\right]}\right]^2, \tag{11}$$

Methods 3 and 4 are analogous to Methods 1 and 2 but take advantage of a greater number of temperature observations to approximate a potentially nonsinusoidal behavior.

As it was pointed by Horton et al. (1983), the timing of the four pairs of temperature measurements greatly affected the calculated values of a by the Arctangent and Logarithmic methods. The authors suggested that the estimated a should be based on not less than three calculations per day. In the current study five calculations per day were performed.

Method 5 (Harmonic)

An equivalent representation of Eq. (9) is:

$$T(t) = \overline{T} + \sum_{n=1}^{M}[C_n\sin(nwt + \phi_n)], \tag{12}$$

where C_n is the amplitude of the n^{th} harmonic equal to $(A_n^2 + B_n^2)^{1/2}$ and ϕ_n is a phase angle equal to arctan (A_n/B_n) as well as arcsin (A_n/C_n) (Conrad and Pollak, 1950). The amplitudes and phase spectrum of each data series in our study were obtained using the routine of Numpy Fast Fourier Transformation (FFT) (Python 3.2.2 release for Windows).

For the following boundary conditions, where variation in the surface temperature of a homogeneous soil is described by M harmonics:

$$T(0,t) = \overline{T} + \sum_{n=1}^{M} C_{on}\sin(nwt + \phi_{on}), \tag{13}$$

$$T(\infty,t) = \overline{T}, \tag{14}$$

the solution of Eq. (2) developed from Eq. (5) using superposition is (Van Wijk, 1963):

$$T(z,t) = \overline{T} + \sum_{n=1}^{M}[C_{on}\exp(-z\sqrt{nw/2a})\sin(n\omega t + \phi_{on} - z\sqrt{n\omega/2a})], \tag{15}$$

where C_{on} and ϕ_{on} are the amplitude and phase angles of the n^{th} harmonic for the upper boundary (z_1 = 0.10 m), respectively. The apparent thermal diffusivity was solved implicitly from Eq. (15). The value of a is selected to minimize the sum of squared differences between the calculated (Eq. (15)) and measured temperature values at depth z_2 (in our case z_2 = 0.20 m) via nonlinear optimization tool of Excel – *Solver*.

The five methods were compared among them by applying the analysis of variance (ANOVA) of the Statgraphics Plus software.

The data were also compared with the soil thermal diffusivity calculated by Eq.1 with soil thermal conductivity and volumetric heat capacity estimated by de Vries model (Van Wijk and De Vries, 1963; Hopmans and Dane 1986; Ochsner, 2001) and with measured data for soil thermal conductivity received in laboratory conditions with KD2-Pro device with SH-1 sensor.

De Vries model (de Vries, 1963) for soil thermal conductivity is calculated as the weighted average of the conductivities of water (*w*), solid (*s*) and air (*a*), depending on volumetric water content θ, which defines the continuous fluid surrounding the solid particles – air for dry soil and water for moist soil:

$$\lambda_{sat} = \frac{x_w \lambda_w + k_{sw} x_s \lambda_s}{x_w + k_{sw} x_s} \qquad \theta = \theta_{sat} \tag{16}$$

$$\lambda = \frac{x_w \lambda_w + k_{sw} x_s \lambda_s + k_{aw} x_a \lambda_{app}}{x_w + k_{sw} x_s + k_{aw} x_a} \qquad 0 < \theta < \theta_{sat} \tag{17}$$

$$\lambda_{dry} = 1.25 \frac{x_a \lambda_a + k_{sa} x_s \lambda_s}{x_a + k_{sa} x_s} \qquad \theta = 0 \tag{18}$$

where $x_{w,s,a}$ are the volume fractions of soil constituents (*w* – water, *s* – solids, *a* – air), $\lambda_{w,s,a}$ are the thermal conductivities of each constituents, k_{sw}, k_{aw}, k_{sa} are weighting factors, which depend on the shape and the orientation of the granules of the soil constituents and on the ratio of the conductivities of the constituents. Detailed description of the calculation of k-factors can be found in De Vries (1963), Hopmans and Dane (1986), Ochsner et al. (2001) and in Doneva (2007). The calculation procedure of de Vries model was realized using Visual Basic as user defined function in Excel. As it was recommended by Ochsner et al. (2001), the thermal conductivity of soil solids λ_s should be chosen to fit the modeled with the measured data at water saturation of soil samples.

The volumetric heat capacity C_v was calculated according to de Vries formula (1963):

$$C_v = (2.0x_m + 2.51x_0 + 4.19x_w).10^6, \text{ J.m}^{-3}\text{K}^{-1}, \tag{19}$$

where x_m is the volume fraction of the soil minerals, x_o the volume fraction of organic mater, x_w volumetric water content ($x \equiv \theta_w$).

Results and Discussion

The data of soil thermal diffusivity of A horizon obtained by direct measurements (in the ASCAMM center, Barcelona) and estimated with de Vries model (eq. 16÷19) and with the annual temperature wave method (Marinova et al., 1990) are presented on Figure 2. The estimated values by de Vries model were obtained by setting the thermal conductivity of soil solids λ_s =2.5 W.m^{-1}.K^{-1} which lead to better fit with the laboratory measurements at high soil moisture content. The model predicted three ranges of the relationship: the lower-range values of thermal diffusivity (***a*** = 2.0÷2.4.10^{-7} m^2.s^{-1}) at soil water content less than 0.15 cm^3.cm^{-3}, the higher-range values (***a*** = 4.7÷5.2.10^{-7} m^2.s^{-1}) at soil water content above 0.25 cm^3.cm^{-3}, and the intermediate range when *a* increases with water content from lower to higher range.

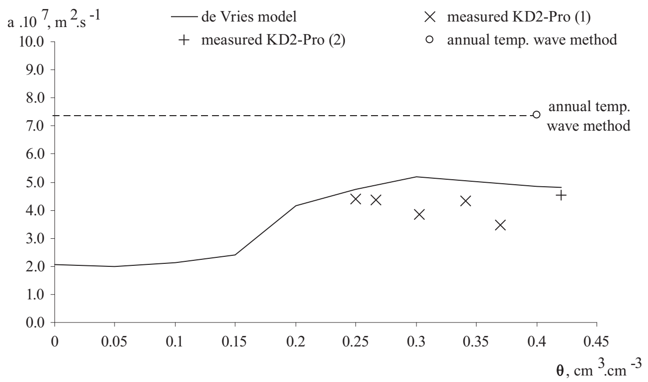

Fig. 2. Thermal diffusivity of A horizon of Fluvisol measured in laboratory conditions with KD2-Pro (1 – in the Institute of Agrophysics, Lublin; 2 – in the ASCAMM center, Barcelona), estimated by the model of de Vries, and by the annual temperature wave method (Marinova et al., 1990, Doneva, 2011)

The values of soil thermal diffusivity, estimated by the Amplitude, Phase, Arctangent, Logarithmic and Harmonic methods with diurnal soil temperature data varied in a wide range (Table 2). The highest variability of the values (C_v = 47%) was obtained when using the Phase method for calculation of ***a*** at soil moisture > 0.23 cm^3.cm^{-3}. This is the only one method with lower average values at high soil moisture than at low soil moisture. This uncertainty usually is explained with difficulties in exact determination of phase shift and is the reason to consider this method as not appropriate for determination of thermal diffusivity (Gnatowski, 2009). The variability between the methods was high (*CV*** = 31% in average). The analysis of variance performed on the whole data set (*n* = 92), showed that there was no significant difference between the Amplitude, Logarithmic and Harmonic methods, while this group of methods considerably differed from Phase and Arctangent method.

Table 2
Statistical parameters of the apparent thermal diffusivity of Alluvial-meadow soil calculated by 5 different methods using field-measured diurnal soil temperature at 0.10 and 0.20 m soil depth

Parameter	Amplitude	Phase	Arctangent	Logarithmic	Harmonic	CV**,%
Soil water content ≤0.23 $cm^3.cm^{-3}$, n = 36						
Average, $m^2.s^{-1}$	6.55×10^{-7}	10.04×10^{-7}	11.29×10^{-7}	6.75×10^{-7}	7.86×10^{-7}	31
Maximum, $m^2.s^{-1}$	10.81×10^{-7}	19.86×10^{-7}	20.64×10^{-7}	8.85×10^{-7}	11.02×10^{-7}	
Minimum, $m^2.s^{-1}$	3.40×10^{-7}	5.24×10^{-7}	5.41×10^{-7}	4.63×10^{-7}	5.67×10^{-7}	
Standard deviation, $m^2.s^{-1}$	2.03×10^{-7}	3.26×10^{-7}	3.59×10^{-7}	0.98×10^{-7}	1.22×10^{-7}	
Cv*, %	31	32	32	15	15	
Soil water content >0.23 $cm^3.cm^{-3}$, n = 56						
Average, $m^2.s^{-1}$	8.20×10^{-7}	8.16×10^{-7}	12.3×10^{-7}	8.02×10^{-7}	8.01×10^{-7}	31
Maximum, $m^2.s^{-1}$	16.98×10^{-7}	18.88×10^{-7}	24.61×10^{-7}	17.82×10^{-7}	11.01×10^{-7}	
Minimum, $m^2.s^{-1}$	3.01×10^{-7}	1.22×10^{-7}	5.09×10^{-7}	4.71×10^{-7}	4.98×10^{-7}	
Standard deviation, $m^2.s^{-1}$	2.70×10^{-7}	3.69×10^{-7}	4.60×10^{-7}	2.65×10^{-7}	1.43×10^{-7}	
Cv*, %	33	45	37	33	18	

Cv* – coefficient of variation between days, CV** – average coefficient of variation between methods

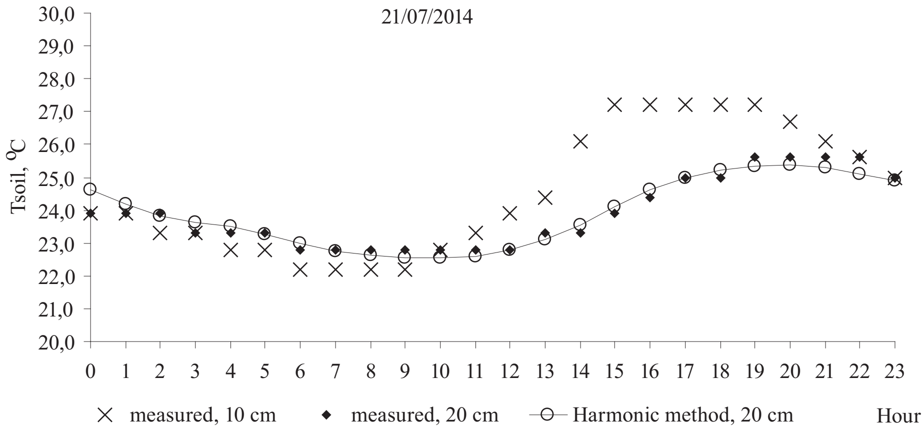

Fig. 3. Measured and predicted (Eq. 14) soil temperature at 20 cm soil depth

As it is shown in Table 2 the variability of the apparent thermal diffusivity within the two ranges of soil moisture (below and above 0.23 $cm^3.cm^{-3}$) and relatively low difference between the average values didn't outline the relation between ***a*** and soil moisture content, similar to that described by de Vries model (Figure 2). Such findings were reported by Gnatowski (2009) for organic soils. Ochsner et al. (2001) found stronger relationship between ***a*** and air-filled pores volume in case of laboratory experiment. The data in our study which stemmed from the field measurements did not show such relationship.

The Harmonic method is characterized with lowest variability (C_v = 15 and 18%, respectively for $\theta \leq 0.23$ $cm^3.cm^{-3}$ and $\theta > 0.23$ $cm^3.cm^{-3}$). This method is usually recommended as most appropriate for calculation of the apparent thermal diffusivity (Horton et al., 1983; Heusinkveld et al., 2004, etc.) and gives best fit with soil temperature data in case of small changes of mean soil temperature in depth as demonstrated on Figure 3.

The minimum values of ***a*** obtained on a daily basis coincided with the highest values predicted by de Vries model for high soil moisture content. The prediction of ***a*** by the annual soil temperature wave method $a = 7.41 \times 10^{-7}$ $m^2.s^{-1}$ based on the long-term field measured daily soil temperature data (1983-1992) (Doneva, 2011) was close to the average values obtained on a daily basis.

Conclusion

Our results showed that there was not significant difference between the apparent thermal diffusivity obtained by the Amplitude, Logarithmic and Harmonic methods. The Phase and Arctangent method produced higher values of the apparent thermal diffusivity and with a higher uncertainty. The lowest variation of ***a*** was obtained by the Harmonic method (C_v = 15-18%), which can be recommended for estimation of thermal diffusivity on a daily basis. The minimum values of ***a*** obtained on a daily basis coincided with the highest values predicted by de Vries model for high soil moisture content. It was not found dependence of the apparent thermal diffusivity on soil moisture content, as described by de Vries model. The prediction of ***a*** by the annual soil temperature wave method was close to the average values obtained on a daily basis. This study demonstrate the possibility of using soil temperature data registered by automatic weather station to produce reliable estimates of soil thermal diffusivity for relatively shorter time period.

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