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EVALUATION OF THERMAL DIFFUSIVITY OF SOIL NEAR THE SURFACE: METHODS AND RESULTS

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Abstract

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In the present study has been developed a method for evaluation of the mean daily thermal diffusivity of soil, assuming it is vertically inhomogeneous. The method uses data for the temperature variation of soil at three depths. Additionally the soil surface heat flow has been defined as a function of the thermal conductivity and thermal diffusivity coefficients. The method's performance conditions have been defined and their critical value has been determined for sensors with accuracy 0.1 °C. The method performance has been validated using data for the soil temperature variation at depths 1 cm, 10cm and 20 cm, acquired experimentally on the territory of the University of Ruse. The soil thermal diffusivity has been evaluated using the developed method and the harmonics method, considered to be the most reliable one. The results showed 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.

Key words: soil temperature, thermal diffusivity, soil heat flow

Introduction

The thermal diffusivity is an important soil property, used in many areas as agriculture, climatology, engineering, etc. It greatly affects the soil temperature profile, which determines the earth's heat and mass transfer, and is an important parameter in energy balance applications such as land surface modeling, numerical weather forecasting and climate prediction (Holmes et al., 2008).

There are multiple known methods, used for evaluation of the soil thermal diffusivity. Two of the most common methods are the amplitude and the phase ones, which present the soil temperature variation as a sine wave. However, the assumption that the soil temperature could be expressed as a single sine wave leads to significant errors under certain conditions. Van Wijk (1963) suggested that this error could be reduced by using a multiple harmonic Fourier series to describe more accurately the soil temperature fluctuation. This led to the introduction of the arctangent algorithm, presenting the soil temperature with two harmonics (Nerpin and Chudnovskii, 1967).

Horton et al. (1983) further developed the sine wave amplitude and phase methods, considering higher harmonics, by approximating the thermal diffusivity for a temperature variation expressed with two harmonics. More recently, Heusinkveld et al. (2004) presented a more accurate method, which expands the soil temperature variation in Fourier series with multiple harmonics (harmonics method).

All of the above algorithms assume vertically homogenous soil; however, the thermal diffusivity can vary in depth. For this purpose Gao et al. (2003, 2008a) approximated the thermal diffusivity assuming it has a vertical gradient (conduction-convection method). If the vertical gradient is 0, the method reduces to the common phase and amplitude ones.

It has been observed that many of these methods tend to return inaccurate data under certain environmental conditions (Horton et al., 1983). Verhoef et al. (1996) examined the soil thermal diffusivity at the HAPEX-Sahel site by using five algorithms. The conclusion was that the amplitude and the harmonic methods are the most reliable. Another experimental comparison showed that the amplitude and the phase methods produce realistic estimates only for vertically homogenous dry soils (Gao et al., 2008a). It has also been determined that the water movement in soil is not negligible and can vary significantly in height (Gao et al., 2008a, b). Gao et al. (2009) also compared all of the above algorithms us-

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ing experimentally acquired data. The results showed that the conduction-convection method returns more accurate results than the other methods excluding the harmonics one. The latter returns the most reliable results in most cases with the exception of days with changing weather conditions.

A common problem for all of the above models is that they assume the soil temperature variation is a periodic function, which is a necessary condition to expand it in Fourier series. This requirement is met when the daily temperature variation of the soil surface is in a steady state condition. However, when rainy/cloudy ones follow sunny days, the assumption is incorrect and the accuracy of these methods decreases (Gao et al., 2009). Another problem is most of the methods assume vertically homogenous soil, which is applicable only for very thin soil layers.

The goal of the study is to develop a new method for evaluation of the mean daily thermal diffusivity of soil, assuming vertically inhomogeneous soils and applicable for both steady and unsteady states of the daily soil temperature variation.

Materials and Methods

Theoretical formulation and used dependencies

The heat transfer in the classical theory in a one-dimensional isotropic medium is described by:

$$C.\frac{\partial T}{\partial t} = \frac{\partial}{\partial t}\left(\lambda.\frac{\partial T}{\partial t}\right) \qquad (1)$$

where T is the soil temperature, ^{0}C;

t – the time, s;

C – the volumetric heat capacity, J.m^{-3}.K^{-1};

λ – the soil thermal conductivity coefficient, W.m^{-1}.K^{-1}.

In many cases, it can be assumed that a soil is vertically homogenous, in which case C and λ are independent of depth, which allows to present equation (1) as:

$$k.\frac{\partial^2 T}{\partial z^2} = \frac{\partial T}{\partial t} \qquad (2)$$

where k is the soil thermal diffusivity coefficient, m^2.s^{-1};

z – the soil depth, m.

In most cases, the investigated soil layer is inhomogeneous and anisotropic. If it is divided into two bordering homogenous layers with heights δ_{12}=z2-z1 and δ_{32}=z3-z2 (Figure 1), the heat transfer processes could be expressed as (ASHRAE 2001):

$$T_{Z2}^{t+\Delta t} = T_{Z2}^{t} + \Delta t.\left(\frac{Q_{12}}{\rho_{12}.C_{12}.\delta_{12}} + \frac{Q_{32}}{\rho_{32}.C_{32}.\delta_{32}}\right), °C, \qquad (3)$$

where Q_{12} and Q_{32} are the heat flows, directed from z1 and z3 towards z2, W.m^{-2};

ρ_{12} and ρ_{32} – the densities of the two soil layers, kg.m^{-3};

δ_{12} and δ_{32} – the heights of the two soil layers, m;

C_{12} and C_{32} – the specific heat capacities of the two soil layers, J.kg^{-1}.K^{-1};

Δt - the time interval, s;

T_{z2}^{t} and $T_{z2}^{t+\Delta t}$ - the soil temperatures at depth z2, in the moments of time t and t+Δt respectively, ^{0}C.

The suggested method requires soil temperature measurements at three depths: z1, z2 and z3 (fig. 1). This method relies on the approximation that the thermal diffusivity of soil between the depths z1 and z2 is equal to k1, and between the depths z2 and z3 – to k2. In order to determine the mean daily values of the two coefficients, it is assumed that k1 and k2 are constants during the investigated day.

The instantaneous values of the heat flows Q_{12} and Q_{32} are given with:

$$Q_{12(32)} = \lambda_{12(32)} \frac{T_{Z1(Z3)} - T_{Z2}}{\delta_{12(32)}}, \text{ W.m}^{-2}, \qquad (4)$$

where λ_{12} and λ_{32} are the heat conductivities of the two soil layers, W.m^{-1}.K^{-1}.

Based on equations (3) and (4), the temperature variation of the soil at depth z2 can be evaluated with:

$$T_{Z2}^{t+\Delta t} = T_{Z2}^{t} + \Delta t.\left(\frac{k1(T_{Z1}^{t} - T_{Z2}^{t})}{\delta_{12}^2} + \frac{k2.(T_{Z3}^{t} - T_{Z2}^{t})}{\delta_{32}^2}\right), °C. \qquad (5)$$

The thermal diffusivities k1 and k2 of the two layers can be evaluated using the least square algorithm, by comparing the experimental and modeled values of the soil temperature at depth z2:

$$\sum_{t=0}^{t_{MAX}} \left(T_{Z2.Exp}^{t+\Delta t} - T_{Z2.Mod}^{t+\Delta t}\right) = \min \quad , \qquad (6)$$

where $T_{z2.Exp}^{t+\Delta t}$ is the experimental value of the temperature at depth z2, and $T_{z2.Mod}^{t+\Delta t}$ – the modeled one.

If the thermal conductivity coefficients λ_{12} and λ_{32} of the two layers are known, the heat flows Q_{12} and Q_{32} could be determined with:

$$Q_{12} = \left(\frac{T_{Z2}^{t+\Delta t} - T_{Z2}^{t}}{\Delta t} - \frac{k2(T_{Z3}^{t} - T_{Z2}^{t})}{\delta_{32}^2}\right)\frac{\lambda_{12}.\delta_{12}}{k1}, \text{ W.m}^{-2} \qquad (7)$$

and

$$Q_{32} = \left(\frac{T_{Z2}^{t+\Delta t} - T_{Z2}^{t}}{\Delta t} - \frac{k1(T_{Z1}^{t} - T_{Z2}^{t})}{\delta_{12}^2}\right)\frac{\lambda_{32}.\delta_{32}}{k2}, \text{ W.m}^{-2}. \qquad (8)$$

In case the topmost sensor measures the surface temperature and the thermal conductivity λ_{12} of the top layer is known, the instantaneous value of the heat flow between the environment and the soil surface can be determined with:

$$Q_{Env} = \left(\frac{T_{Z1}^{t+\Delta t} - T_{Z1}^{t}}{\Delta t} - \frac{k1(T_{Z2}^{t} - T_{Z1}^{t})}{\delta_{12}^2}\right)\frac{\lambda_{12}.z1}{k1}, \text{ W.m}^{-2}. \qquad (9)$$

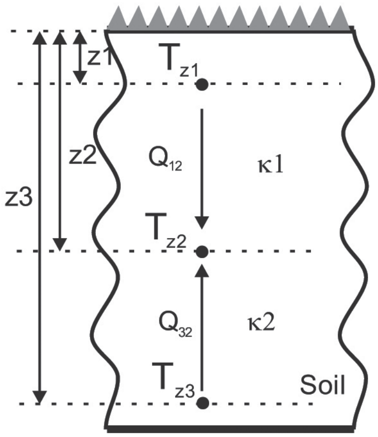

Fig. 1. Heat transfer processes in a soil with two bordering isotropic layers

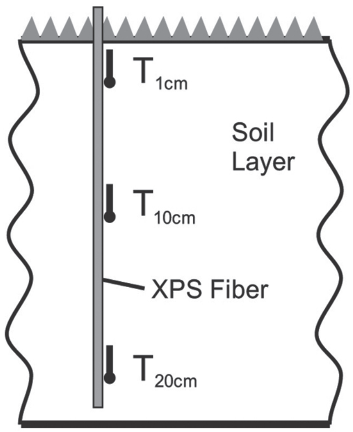

Fig. 2. Sensors placement during the experimental data acquisition

Performance conditions

The method requires a couple of conditions to be met in order to function properly. The first condition is to have positive soil temperatures during the investigated period:

$$T_{soil}(t) > 0 \ ; \ 0 < t < t_{Max} \,. \qquad (10)$$

This requirement is forced by the non-zero soil water content, whose phase changes (melting and freezing) lead to a great energy consumption or discharge. Since these processes are not taken into account in the presented method, they would lead to inaccurate estimates of k1 and k2.

The second performance condition follows from equation (2) - the thermal diffusivity can be obtained only for soil whose temperature varies in both time and depth:

$$\begin{cases} Crit1 = Grad_{Max}(T_{Z1} - T_{Z2}) - Grad_{Min}(T_{Z1} - T_{Z2}) > Crit \\ Crit2 = Grad_{Max}(T_{Z3} - T_{Z2}) - Grad_{Min}(T_{Z3} - T_{Z2}) > Crit \end{cases}, ^\circ C, \quad (11)$$

where $Grad_{Max}$ and $Grad_{Min}$ are the maximal and minimal instantaneous temperature gradients of the soil layers (z1÷z2) and (z3÷z2), ^0C;

Crit - the critical value of the criteria, for which the thermal diffusivity can be determined accurately, ^0C.

The value Crit depends on the accuracy of the temperature sensors and should be determined experimentally.

Results and Discussion

The experimental data used in this study were acquired at the territory of the University of Ruse. The soil temperatures were measured at three depths (1 cm, 10 cm and 20 cm), using temperature sensors DS18B20 with accuracy 0.1^0C. The spacing between the sensors was fixed on a XPS fiber with heat conductivity 0.03 $W.m^{-1}.K^{-1}$. The sensors were connected through a 1-Wire network to the USB port of a personal computer, where the measurements were read and stored in a database at a 10 minutes interval.

In this study have been presented and analyzed experimental data for the period from 19.11.2011 to 30.04.2012. In accordance with the first performance condition of the method, only days with positive soil temperatures have been analyzed.

For each of the periods (Figures 3, 4, 5 and 6) have been presented the soil temperature variation at the three controlled depths, the values of the criteria Crit1 and Crit2, as well as the thermal diffusivities of the two layers, evaluated using the developed method (k1, k2) and the harmonics one ($k1_{Har}$, $k2_{Har}$). The colors of the criteria columns are as follows: blue for rain, grey for snow cover and red for the rest of the days. Their values are evaluated in accordance with equation (15).

On Figure 3 are presented the results for the period 21.11.2011 – 17.12.2011. Crit1 varies in the range ($1.4÷17.3^0C$), and Crit2 – in the range ($0.4÷3.8^0C$). During this period the thermal diffusivities estimated using the harmonics method vary in wide range for values of Crit1 and Crit2 lower than 3^0C, i.e. for days with low daily soil temperature amplitudes.

The results for the period 05.01.2012 – 31.01.2012 are presented on Figure 4. The values of Crit1 are in the range ($0.1÷12.2^0C$) and of Crit2 – in the range ($0.1÷1.2^0C$). During this period the thermal diffusivities k1 and k2 returned by the harmonics method are random, while those evaluated by the developed method are realistic for values of Crit1 and Crit2 higher than 1^0C.

No results are presented for February 2012, because during this period, there was a thick snow cover, and the values

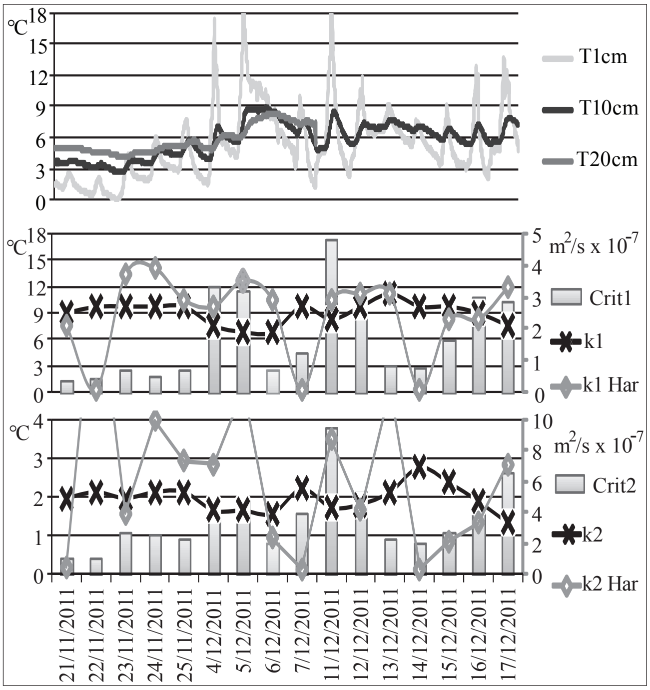

Fig. 3. Soil temperature variation and mean daily thermal diffusivities evaluated using the harmonics method and the developed method in the period 21.11.2011 – 17.12.2011

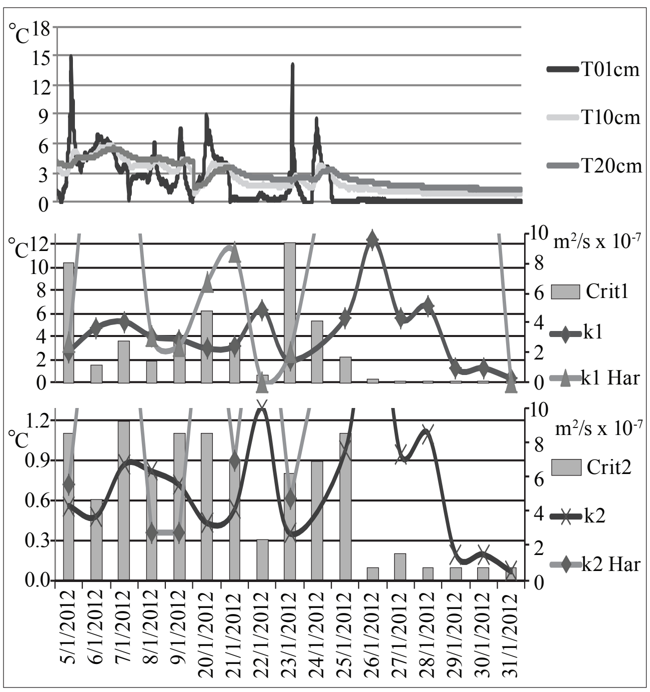

Fig. 4. Soil temperature variation and mean daily thermal diffusivities evaluated using the harmonics method and the developed method in the period 05.01.2012 – 31.01.2012

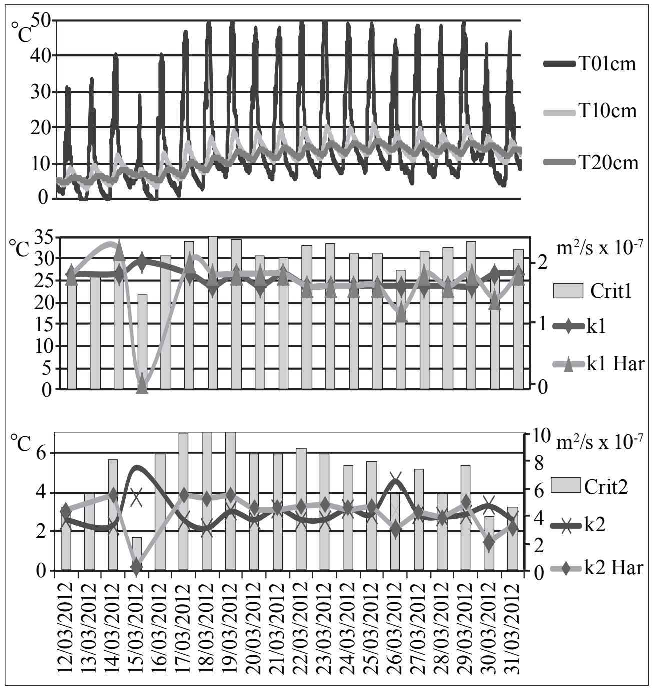

Fig. 5. Soil temperature variation and mean daily thermal diffusivities evaluated using the harmonics method and the developed method in the period 12.03.2012 – 31.03.2012

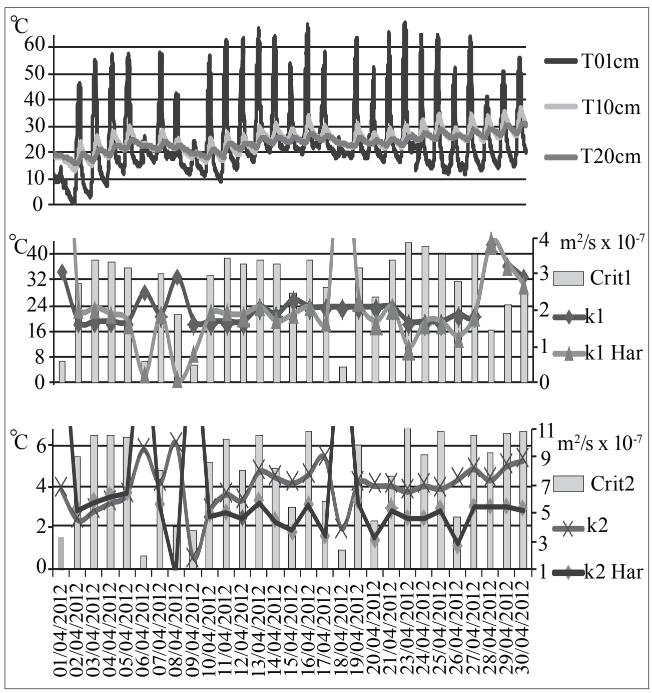

Fig. 6. Soil temperature variation and mean daily thermal diffusivities evaluated using the harmonics method and the developed method in the period 01.04.2012 – 30.04.2012

of Crit1 and Crit2 were less than 0.1^{0}C, thus making it impossible to estimate the thermal diffusivities of the two soil layers with the required accuracy.

The next period (12.03.2012 – 31.03.2012) is characterized with large daily soil surface temperature amplitudes and is presented on Figure 5. Crit1 varies in the range (21.4÷34.2^{0}C) and Crit2 – in the range (1.6÷7.0^{0}C). The two methods return very similar values for k1 and k2 with the exception of a couple of days when the weather conditions were changing (15.03, 26.03 and 30.03). It is important to note that for days with steady state condition of the soil temperature variation (for example 22.03, 23.03, 24.03, etc.) the two models returned equal values for the thermal diffusivity.

On Figure 6 are presented the results for April 2012. This period is characterized with many showers, but most of them were either light or short rains. The criteria Crit1 and Crit2 vary in the ranges (4.7÷43.1^{0}C) and (0.6÷6.8^{0}C) respectively. The harmonics method determined unrealistic values of k1 and k2 for the days with low soil temperature amplitudes (1.04, 6.04, 8.04, 9.04 and 18.04).

The presented results can also be used to determine the critical values of Crit1 and Crit2 for temperature sensors with accuracy 0.1^{0}C. The developed model returns reliable estimates of the thermal diffusivities for Crit>1^{0}C, while for Crit>5^{0}C the thermal diffusivities are evaluated with a very high accuracy.

Conclusion

In the present study has been developed a method for evaluation of the mean daily thermal diffusivity. It assumes the soil is vertically inhomogeneous and is divided into two homogenous layers, whose thermal diffusivities are evaluated simultaneously. Unlike other known methods, which require soil temperature measurements at two depths, this method requires measurements at three depths. The instantaneous soil surface heat flow has also been defined as a function of the thermal diffusivity and the thermal conductivity of soil.

An experimental study has been carried out, measuring the soil temperature at depths 1 cm, 10 cm and 20 cm. The results have been processed and the mean daily soil diffusivities have been evaluated using the developed and the harmonic methods. The second returned inaccurate values for days with low soil temperature amplitudes and for days with changing weather conditions, while the developed method returned more accurate and less fluctuating values. For the days the soil temperature variation was in a steady state condition, the two methods evaluated identical values of the mean daily thermal diffusivity.

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