Journal of Applied Sciences 4 (3): 418-423, 2004
ISSN 1607-8926

A Comparison of Estimated and Measured Diurnal Soil Temperature Through a Clay Soil Depth

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Abstract: In this study, diurnal soil temperature fluctuation through a clay soil depth was estimated with respect to time using a measured data set in a cosinusoidal harmonic equation. Some soil thermal properties, such as amplitude, heat diffusivity, damping depth and retardation time were also determined at 0, 10, 20, 30, 40 and 50 cm soil depth. The highest amplitude value 12.31°C was obtained at the soil surface. However, heat diffusivity, damping depth and retardation time increased at the deeper soil layers compared with the soil surface values. Estimated temperature values by the cosinusoidal harmonic equation fitted very well with the measured values. Estimated temperatures at 10 cm soil depth gave the significant correlations with measured data set by the Agricultural Faculty, Meteorological Station in Ondokuz Mayıs University (0.903**) and measured temperatures at six times in a day by the researchers (0.861**). It showed validity of the equation under the given soil properties and boundary conditions. The most fluctuation in soil temperature with respect to time and depth was observed at the soil surface. Changes in soil temperature at the deeper layers (>30 cm) remained almost constant during a day.

Key words: Soil temperature, amplitude, diffusivity, damping depth, retardation time

INTRODUCTION

Soil temperature is one of the most important physical property in determining the rates and directions of soil physical processes including energy and mass exchange, evaporation and aeration. Soil temperature varies in time and space and influences types and rates of chemical reactions and biological processes such as, seed germination, seedling emergence and growth, root development and microbial activities[1-3]. Optimum soil temperature and vertical temperature gradients for the net photosynthesis and plant growth change in a wide range depending on plant species and cultivars[4]. It is known that there is an interrelation between water and heat flow within the soil. This can influence the soil temperature regime and is important for soil freezing, thawing and water vapor movement during surface evaporation[3]. Sung *et al.*[5] studied heat and mass transfer in the vadose zone with plant roots. They found that vapor flux in the subsurface, root distribution and surface boundary conditions such as evaporation were affected by the soil temperature. They suggested that temperature effects should be taken into account for temperature dependent biological reactions as well as chemical reactions. It is also known that soil temperature affects pesticide degradation rates and elemental release from metal contaminated soils[6,7]. Tenge *et al.*[8] studied diurnal soil temperature fluctuations for different erosion classes of an oxisol and found that the maximum soil temperature was about 1°C lower at 5 cm depth and 0.5°C at 30 cm depth for least compared with severely eroded phase.

There are several numerical and empirical models to predict soil temperature using boundary conditions and thermal properties of the soils[3,9-12]. Most of these methods require complex variables and several inputs which are not easily available. The transfer of heat from soil surface to various depths is expressed with the one dimensional heat conduction differential equation as follow[1,9,12]:

$$\frac{\partial T_{(x,t)}}{\partial t} = D\frac{\partial^2 T_{(x,t)}}{\partial x^2} \qquad (0 \le x < \infty; t \ge 0) \qquad (1)$$

where, T(x,t) is the soil temperature when x = 0, x is the vertical coordinate, t is the time computed from a given initial moment, D is the diffusivity. Nerpin and Chudnovskii[12] reported that this equation involves comparing the experimental data of the distribution of temperature with time and depth in the natural soils to the temperature regimes obtained by the analytical solution. Equation (1) can be solved according to the boundary condition of $T_{(0,t)}$. Then, the temperature at the soil surface (x = 0) as a function of time is expressed as:

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$$T_{(0,t)} = T_m + A\cos(wt) \qquad (2)$$

where, T_m is the average temperature of the soil surface, A is the amplitude of the surface temperature fluctuation, which is the range from maximum or minimum to average temperature and w is the daily frequency which is $2\pi/86400$ sn and equals to $7.27\text{x}10^{-5}$ sn^{-1}.

This Eq. (2) is also a boundary condition for the soil surface (x = 0). The solution of Eq. (1) using the boundary condition Eq. (2) gives the following cosinusoidal harmonic equation[1,12-14]:

$$T_{(x,t)} = T_{m(x)} + Ae^{-(x/d)}\cos\left(-x\sqrt{\frac{w}{2D}} + wt\right) \qquad (3)$$

where, d is the damping depth and related to the thermal properties of the soil and the frequency of the temperature fluctuation. According to the Eq. (3), soil temperature at any depth x and time t during a day can be estimated with using mean temperature, surface amplitude, damping depth and diffusivity constant. The objectives of this study were i) to determine some soil thermal properties with depth, ii) to estimate diurnal soil temperature fluctuations through soil profile with respect to time and iii) to compare the estimated results to measured soil temperatures for the same depths.

MATERIALS AND METHODS

The study was carried out at the Agricultural Faculty Experimental Field in Ondokuz Mayıs University, Samsun (41.3° N, 36.3° E), Turkey in May 2002. Some physical and chemical properties of the soil profile were determined as follows: particle size distribution by hydrometer method[15] soil reaction, pH, 1:1 (w:v) soil water suspension by pH meter, electrical conductivity ($EC_{25°C}$) in the same soil suspension by EC meter, cation exchange capacity (CEC) by sodium acetate method and organic matter (OM) contents by modified Walkley-Black method[16].

Meteorological and soil temperature data at 10 cm depth were obtained from the measurement records of the Meteorological Station of Agricultural Faculty, Ondokuz Mayıs University, between 2 and 16 of May, 2002. The average air temperature and soil temperature at 10 cm depth were 13.9 and 18.7°C, respectively and no precipitation was observed during the study. The soil used in this study is Vertic Hapludolls and has a mesic soil temperature regime. Measurements of soil temperature between 2 and 16 of May, 2002 were also done at 0, 10, 20, 30, 40 and 50 cm depths by using mercury-in-glass thermometer[17]. Temperature readings were taken six times in a day at 6, 9, 13, 16, 19 and 22 h for 15 days. Some soil thermal properties such as amplitude (A), heat diffusivity (D), damping depth (d) and retardation time (t_r) were also determined at the different soil depths[1,12,13]. Amplitude values at each soil layer were calculated as subtracting mean soil temperature from the maximum soil temperature measured at that depth. If amplitude values, A at the soil surface and $A_{(x)}$ at any given depth, are known, heat diffusivity (D) at that depth (x) can be estimated using a daily frequency (w) by the following equations:

$$A_{(x)} = Ae^{-x\sqrt{\frac{w}{2D}}}, \quad D = wx^2\left[2\ln^2\frac{A_{(x)}}{A}\right]^{-1} \qquad (4)$$

Damping depth (d) is a characteristic depth at which the temperature amplitude decrease to the fraction 1/e = 0.37 of the soil surface amplitude A[1]. Damping depth was calculated for each soil layer by the following equation:

$$d = (2D/w)^{1/2} \qquad (5)$$

Retardation time (t_r) of the temperature waves is a time delay between the maximum temperature peaks at soil surface and at any given depth x. If soil surface temperature has a maximum or minimum value, cos term in Eq. (3) will be equal to ±1. Therefore, statement of $[-x(w/2D)^{-1/2}+wt]$ in Eq. (3) will be zero. In this condition, solution of this statement for t gives the t_r as follow:

$$t_r = x\,[1/(2Dw)]^{1/2} \qquad (6)$$

The diurnal soil temperature fluctuation with respect to time and any given soil depth was computed putting the measured thermal properties in Eq. (3). To compare the measured soil temperatures to predict data set, simple correlation analyses were carried out according to Steel and Torrie[18].

RESULTS AND DISCUSSION

The results can be showed that the textural class of soil is clay, low in organic matter (OM), neutral in pH, non saline according to EC value[19] (Table 1).

The most fluctuation in the measured soil temperatures during a day was observed at the soil surface compared with fluctuations in the temperatures at deeper soil layers (Table 2). The highest and the lowest mean soil temperatures were obtained 31.5 and 13.5°C at the soil surface, respectively. General mean temperature values at each soil depth decreased from 22.4°C at soil surface to 16.5°C at 50 cm soil depth.

Amplitude values decreased with increasing soil depth. The highest amplitude value was found as 12.31°C

Table 1: Some properties of the soil

Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	pH (1:1)	EC (mmh cm^{-1})	OM (%)	CEC (me 100 g^{-1})
0-25	18.7	27.5	53.8	6.73	0.30	2.00	78.52
25-50	19.5	24.3	56.2	6.75	0.27	1.78	74.50

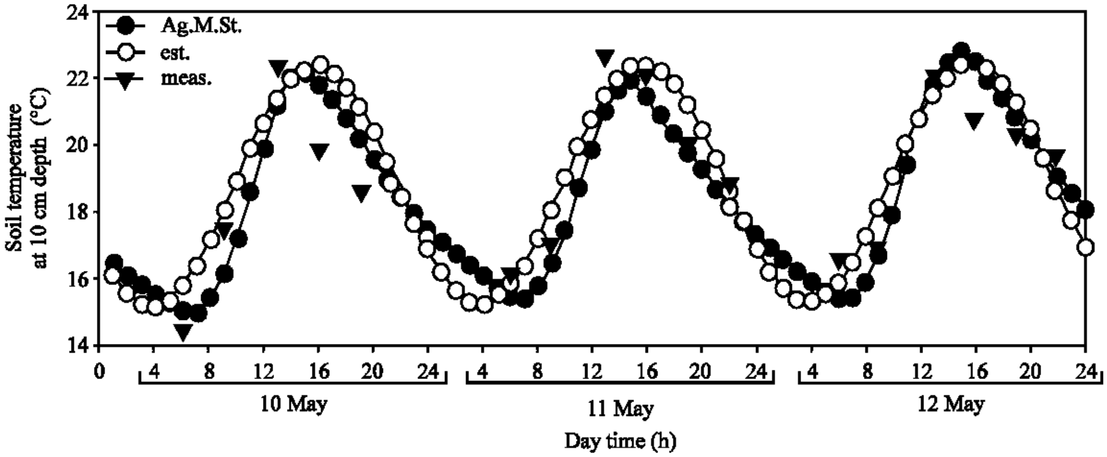

Fig. 1: Comparison of estimated soil temperature with measured data set by Agricultural Metorological Station (Ag.M.St.) and by the researchers at 10 cm soil depth in May 10-12, 2002

Table 2: Measured average soil temperatures (°C) at different soil depths

Soil depth (cm)	Day time (hours)						General mean
	6:00	9:00	13:00	16:00	19:00	22:00	
0	13.6	23.1	32.1	30.1	21.6	14.4	22.4
10	14.0	16.1	18.4	21.6	22.4	20.4	18.8
20	17.1	17.2	17.4	18.3	18.7	18.8	17.9
30	16.8	16.9	17.0	17.4	17.5	17.6	17.2
40	16.6	16.7	16.8	17.0	17.1	17.3	16.9
50	16.5	16.3	16.4	16.5	16.6	16.7	16.5

Table 3: Some thermal properties at the different soil depths

Soil depth (cm)	A (°C)	D (cm^2 sn^{-1})	d (cm)	t_r, h
0	12.31	0.00	0.00	0.00
10	3.53	2.33x10^{-3}	8.00	4.77
20	1.47	3.22x10^{-3}	9.41	8.12
30	0.90	4.78x10^{-3}	11.47	9.99
40	0.64	6.65x10^{-3}	13.52	11.30
50	0.40	7.74x10^{-3}	14.60	13.09

at the soil surface while the lowest one was 0.40°C at 50 cm soil depth (Table 3). Heat diffusivity, damping depth and retardation time values in the deeper soil depths increased compared with that near the soil surface. Diffusivity values varied between 2.33x10^{-3} and 7.74x10^{-3} cm^2 sn^{-1} and decreased in deeper soil depths due to decreasing amplitude values.

Damping depth is a constant characterizing the decrease in amplitude with an increase in distance from the soil surface[1]. Damping depth values varied between 0 and 14.60 cm and also increased in proportion to soil depth. If x equals to d at depth x, the amplitude value at x depth will decrease to 0.37 ($e^{-x/d} = e^{-1}$) of its surface amplitude in Eq. (3). In this study the amplitude values at 10, 20, 30, 40 and 50 cm depths reduced to 0.296, 0.120, 0.073, 0.052 and 0.033 of the surface amplitude value, respectively. It indicates that at deeper depths, soil temperatures remain constant with time and do not show much fluctuations compared with surface or near the surface soil temperatures. Andrade and Abreu[20] reported that at 2 cm depth in the Vertisol, the amplitudes reached 29°C in summer and spring and 5°C in winter. They obtained that damping with depth of the daily temperature wave was visible in the reduction of amplitude as in the delay of occurrence of thermal extremes. In their study, damping depths at 2, 4, 6, 8, 16 and 32 cm of Vertisol ranged from 12.2 cm in summer to 19.6 cm in winter.

Estimated soil temperatures using the Eq. (3) as a function of time fitted very well with the measured data set by Agricultural Faculty Metorological Station (Ag.M.St.) and by the researchers at 10 cm soil depth. A comparison of estimated soil temperature to measured soil temperature data set by Ag.M.St. and the researchers between May 10 and 12 is given as an example (Fig. 1). There was a significant positive correlation (r = 0.903**) between estimated and measured data set by Ag.M.St during the study period (Fig. 2). This high correlation indicates that estimated soil temperatures using Eq. (3) represented the diurnal soil temperature fluctuations very well when compared to the measured data set by Ag.M.St. at 10 cm soil depth. Therefore, it is expected that diurnal soil temperature at different soil depths can be estimated as a function of time by putting the thermal properties of each soil depth in Eq. (3). Mihalakakou[10] reported that estimated surface soil temperatures gave the significant

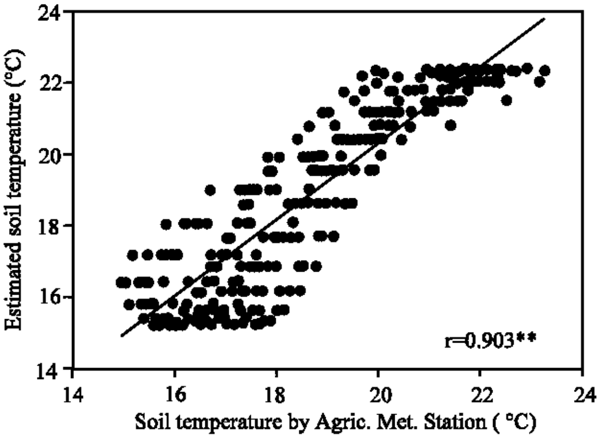

Fig. 2: Correlation between estimated and measured soil temperature by Agric. Met. St. at 10 cm soil depth

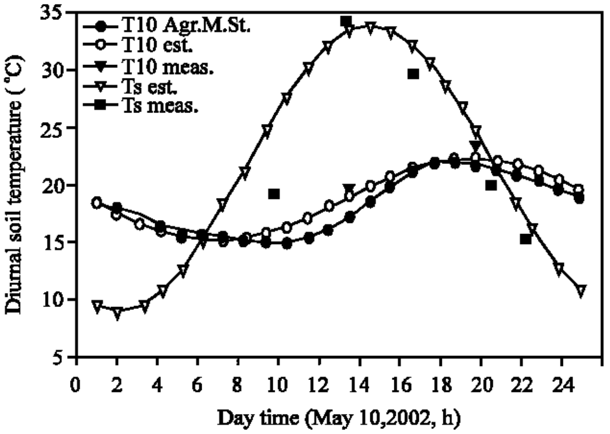

Fig. 3: Diurnal soil temperature fluctuation at soil surface (Ts) and 10 cm soil depth (T10) in May 10, 2002

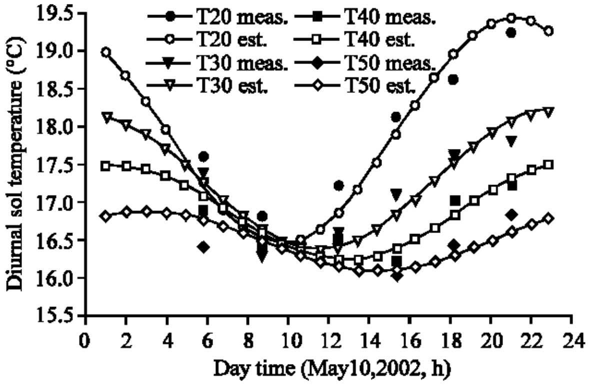

Fig. 4: Diurnal soil temperature fluctuation at 20 (T20), 30 (T30), 40 (T40) and 50 (T50)cm soil depth in May 10, 2002

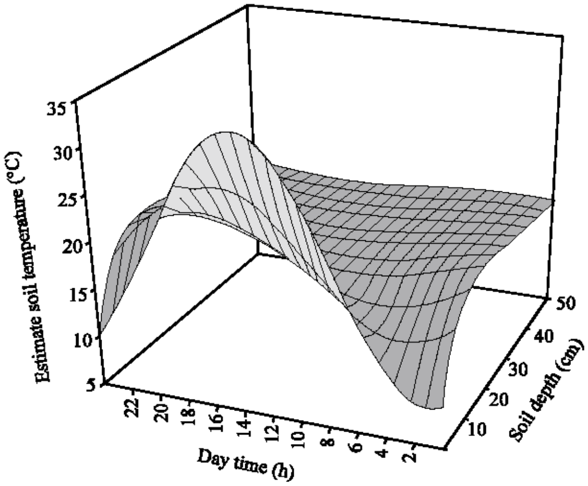

Fig. 5: Estimated diurnal soil temperature fluctuation with respect to time and soil depth

correlation with measured values in January (0.93) and in July (0.95). Estimated diurnal soil temperature values at 0, 10, 20, 30, 40 and 50 cm depth gave the significant correlations with measured soil temperature values as follow: 0.871**, 0.861**, 0.842**, 0.766**, 0.713** and 0.744**, respectively. Correlation coefficients decreased with increasing soil depth. It shows that estimation of soil temperature for deeper soil layers was not good as well as estimation for upper soil layers. Changes in soil temperature at deeper soil layers with respect to time become almost constant during a day compared with the upper soil layer temperatures. Also soil heterogeneity through soil profile should be regarded. Andrade and Abreu[20] used the sinusoidal harmonic functions to estimate daily soil temperature. They reported that this function should be applied in a homogeneous layer of soil only.

Estimated and measured diurnal soil temperatures for soil surface and 10 cm soil depth for May 10 is given in Fig. 3. While the highest measured and estimated soil temperature peaks were 33.8 and 34.2°C at soil surface around 1:30 pm, they were 22.9 and 22.3°C at 10 cm depth around 6:00 pm, respectively in May 10, 2002. It indicates that there was 4.77 h time delay for surface soil temperature waves to show the highest peak at 10 cm depth (Table 3). The similar results were obtained for the other soil depths (Fig. 4). After the temperature waves reached the soil surface, effect of surface soil temperature waves on temperature peak at 50 cm depth was obtained 13.09 h later. Diurnal soil temperature fluctuation was also estimated using Eq. (3) with respect to time and soil depth (Fig. 5). The most fluctuation in soil temperature during a day was observed at the soil surface when compared with the other soil depths. Thus, it was apparent that changes in the soil temperatures at deeper depths remained nearly constant with time.

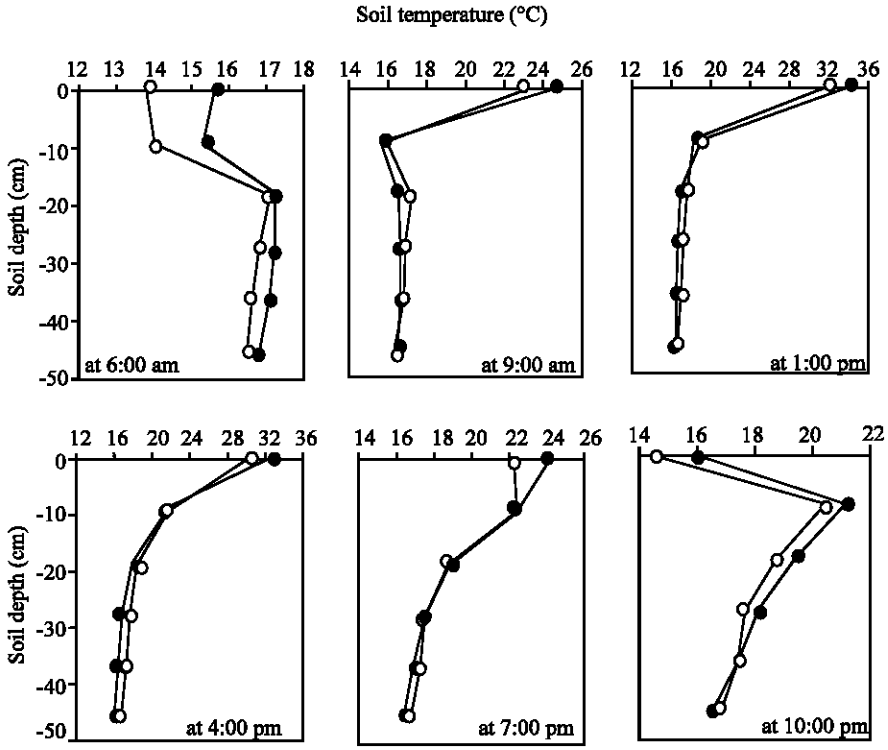

Fig. 6: Measured (○) and estimated (●) soil temperatures at different day time with respect to soil depth

Near the early morning at 6 am, deeper soil layers (≥20 cm) were warmer than upper soil layers. Soil surface warmed up and reached the highest temperature value around 1 pm while deeper soil layers became cooler. At the night around 10 pm, while the surface temperature decreased, temperatures at deeper layers (≥10 cm) were still warmer than soil surface temperature (Fig. 6). Tenge *et al.*[8] used the same equation to predict diurnal soil temperature fluctuations. They reported that the equations do not simulate the rapid temperature changes which may occur during rainfall or irrigation. Although precipitation was not recorded during the study period, there was a variation in estimated and measured surface soil temperatures at 6 am and 7 pm compared with the other day times. It can be explained that the most rapid temperature changes in soil surface temperature occurred at the early morning and late afternoon within a day.

According to the results, soil thermal properties such as amplitude, heat diffusivity, damping depth and retardation time varied among the soil depths. While the highest amplitude value was obtained at the soil surface, the values of D, d and t_r increased from soil surface to 50 cm soil depth. The experimental soil temperature values conform well with their fitted curves and thus support the validity of the Eq. (3) under the given soil properties and boundary conditions. The most fluctuation in soil temperature with respect to time was observed at the soil surface. Soil temperature at the deeper layers (>30 cm) stayed almost constant during a day. Diurnal soil temperature fluctuations can be estimated for the similar soil and boundary conditions to asses the ideal planting time for different crops. Kaspar[21] reported that soil temperatures below the 30 cm depth are usually less than optimum for root growth of summer annual crops like cotton, maize or soybean at the start of the growing season. It seems that estimation of soil temperatures is important for different soil management practices and agronomic productivity. The results of this study can be used only similar soil type and boundary conditions. Therefore, further studies should be carried out with more detail for different soil types including different physical and chemical properties and boundary conditions.

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