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# SOIL TEMPERATURE REGIME OF AN ENTISOL IN THESSALONIKI, GREECE

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A b s t r a c t. The 10-day period mean soil temperature at the depths of 2, 5, 10, 25, 50 and 120 cm and at 08.00, 14.00 and 20.00 hours, the direction of heat flux at these depths as well as the conditions favouring temperature induced water vapour flux within the soil profile were studied in a loamy Entisol. It was found, for any depth and at any hour studied, that the soil temperature fluctuated in accordance to theory and it can be presented by a simple two-term harmonic. It was also found that the direction of heat flux was dependent on the soil depth, the season of the year as well as the hour of the day. The temperature induced water vapour flux was found to depend on both the hour of the day and the season of the year.

## INTRODUCTION

Soil temperature, its value at any moment and the manner with which it varies in time and space, is one of the most important soil characteristics because of its effect on soil chemical, physical, and biological processes and on plant growth and development [5]. Soil temperature is also used for soil classification purposes [7] and it is a component in assessing the energy balance at the soil surface and at any depth [6].

Soil properties and processes which are influenced by temperature include: chemical wheathering reactions (hydrolysis, hydration, oxidation [4]), biochemical reactions (organic matter decomposition, composition of organic compounds by microorganisms etc. [1]), soil-water interactions and hydraulic properties [10], diffusion coefficients of $O_2$, $CO_2$ and water vapour [8]. Since vapour pressure is temperature-dependent, temperature gradients result in movement of water in the vapour phase [8].

Soil temperature affects seed germination and plant emergence, root growth rate, nutrient uptake and plant development [12]. Often, soil temperature is the determining factor in plant production. Many crops cannot be grown unless the soil temperature is above a minimum level. In many areas planting dates for crops are completely dependent on soil temperature. In such areas planting is delayed until the temperature at a given depth in the soil profile has reached a predetermined level for several consecutive days [16]. Many of the plant growth models and nutrient cycling models require soil temperature with depth as a driving variable for the model [11]. Therefore, the knowledge and prediction of soil temperature at certain depths with time is of great importance for a better understanding of soil properties and processes, for soil temperature management, for planting at the proper time, as well as for predicting plant growth.

This work aims to study: 1) the variation of ten-day mean soil temperature at several depths for a period of ten years, 2) the direction of heat flux at different depths during a year and the direction of thermally induced water vapour flux.

## THEORY

In nature, soil temperature varies continuously in response to the everchanging meteorological regime which was characterized by a regular periodic succession of days and nights and of summers and winters. So, it is frequently assumed that the temperature ($T$), at the soil surface ($z=0$) fluctuates sinusoidally [15]:

$$T(0,t) = \overline{T} + A \sin \omega t \tag{1}$$

where $\overline{T}$ is the average soil temperature, $A$ is the amplitude of the surface temperature wave, $\omega$ is the radial frequency ( $\omega = 2\pi/P$ where $P$ is the period) and $t$ is the time. At any depth $z$ ($z>0$), the temperature variation is also assumed to be a sin function [15]:

$$T(z,t) = \overline{T} + A_z \sin [\omega t + \varphi(z)] \tag{2}$$

in which $A_z$ is the amplitude at depth $z$ and $\varphi(z)$ is the phase angle. Both $A_z$ and $\varphi(z)$ are functions of $z$ but not of $t$. However, the simplification that soil temperature varies sinusoidally is not correct and the soil temperature fluctuation has a more complex form. Therefore, a better description of temperature fluctuations in soil with time may be obtained with a Fourier expression [15]:

$$T(t) = \overline{T} + \sum_{k=1}^{N} (A_n \cos k\omega t + B_n \sin k\omega t) \tag{3}$$

where $A_n$ and $B_n$ are the Fourier coefficients, N is the number of harmonics, and $\overline{T}$ is the average soil temperature. Equation (3) may be written as:

$$T(t) = \overline{T} + \sum_{k=1}^{N} C_n \sin (k\omega t + \Phi_n) \tag{4}$$

where $C_n$ is the amplitude of the $n^{th}$ harmonic and $\Phi_n$ the phase angle.

The manner in which heat flows through the soil and the amplitude and phase of the temperature waves below the surface are of considerable importance in plant cultural practices. The first law of heat conduction, known as Fourier's law, states that the flux of heat in a homogeneous body is in the direction of and proportional to the temperature gradient:

$$qh = -\kappa \nabla T \tag{5}$$

where $qh$ is the thermal flux (i.e., the amount of heat conducted across a unit cross-sectional area in unit time), $\kappa$ is the thermal conductivity and $\nabla T$ is the spatial gradient of temperature $T$. In one-dimensional form, this law is written:

$$qh = -\kappa \, dT/dz \tag{6}$$

Equations (5) and (6) hold instantaneously and describe steady state heat conduction.

Temperature gradients can cause water to move in the vapour phase, in the direction of decreasing temperature, in response to the vapour pressure gradient. Vapour pressure of soil water is strongly affected by temperature and large vapour pressure gradients are quite commonly caused in this way. The vapour flux ($q_v$) is given by Fick's law [8]:

$$q_v = -D \nabla \rho_v \tag{7}$$

or one-dimensionally and as a function of saturation vapour pressure:

$$q_v = -DM/RT \, (de_s/dz) \tag{8}$$

where $D$ is the molecular diffusivity of the water vapour in the soil, $\rho_v$ is the vapour density of the soil atmosphere, $M$ is the molar mass of water, $R$ is the gas constant, $T$ is temperature and $e_s$ is the saturation vapour pressure at temperature $T$. The diffusivity depends upon the tortuosity of the path length for diffusion through the air-filled pores and the air porosity, $n_a$. It can be approximated as [10]:

$$D = 0.66 n_a D_o \quad (9)$$

where $D_o$ is the molecular diffusivity of water vapour in free air.

## MATERIALS AND METHODS

The experiment was conducted at the Meteorological Station of the Aristotelian University, which is situated almost in the centre of the city of Thessaloniki. The soil in this area is nearly homogeneous down to 120 cm, has a loamy texture and is classified as Entisol.

The soil temperature values used in the present study were obtained by geothermometers and thermometers of the Lamont-Negretti type, which were permanently installed at depths of 2, 5, 10, 25, 50 and 120 cm. The soil temperature measurements were taken every day at 08.00, 14.00 and 20.00 h, local time, and cover the period 1961-1970. Each year was divided into thirty six 10-day periods. It should be noted that the third 10-day period in months with 31 days includes 11 days, while that of February includes 9 days for leap years and 8 days otherwise. From the soil temperature values, the means per 10-day period were calculated for each depth and hour of measurement studied. Thus, for each depth and hour of measurement there were 36 values which were the mean soil temperatures of the thirty six 10-day periods of the decade 1961-1970.

## RESULTS AND DISCUSSION

### The mean annual temperature variation

The mean soil temperatures of the thirty six 10-day periods of the decade 1961-1970 and for the three hours of the day studied are presented in Figs 1, 2 and 3. As expected, the variation of the mean soil temperatures with time, at any depth and at any hour, follows a simple fluctuation. At 08.00 h (Fig. 1) the temperature minima appear in the 3rd 10-day period (January) for the depths of 2, 10, 25 and 50 cm and in the 4th 10-day period (February) for the depths of 5 and 120 cm. The temperature maxima exist in the 21st 10-day period (July) for the depth of 2 cm, in the 22nd 10-day period (August) for the depths of 5, 10 and 25 cm and in the 23rd 10-day period (August) for the depths of 50 and 120 cm. At 14.00 h (Fig. 2) the temperature minima appear during the 2nd 10-day period (January) for the depths of 2, 5 and 10 cm, during the 3rd 10-day period (January) for the depths of 25 and 50 cm and during the 4th 10-day period (February) for the depth of 120 cm. The temperature maxima exist in the 22nd 10-day period (August) for the depths of 2, 5, 10 and 25 cm and in the 23rd 10-day period (August) for the depths of 50 and 120 cm. At 20.00 h (Fig. 3) the temperature minima appear in the 3rd 10-day period (January) for the depths of 2, 5, 10, 25 and 50 cm and in the 4th 10-day period (February) for the depth of 120 cm. The temperature maxima occur in the 21st 10-day period (July) for the depths of 2, 5, 10 and 25 cm and in the 23rd 10-day period (August) for the depths of 50 and 120 cm. From the above results it is clear that for the area of Thessaloniki the temperature minima for the period 1961-1970, appeared between the 2nd and 4th 10-day periods (January-February) for any depth and at any hour studied. Similarly, the temperature maxima occurred between the 21st and 23rd 10-day period (July-August).

### Fourier harmonic analysis

Values of $C_n$ and $\Phi_n$ of Eq. (4), for any depth and hour studied, were obtained by fitting Eq. (4) (harmonic analysis) to the mean soil temperature measured values of the thirty six 10-day periods. The expressions found by this procedure are given in Table 1. As it may be noted from this table, only the first two harmonic terms of Eq. (4) were taken into account. This was done because, on applying the Brunt's criterion [3],

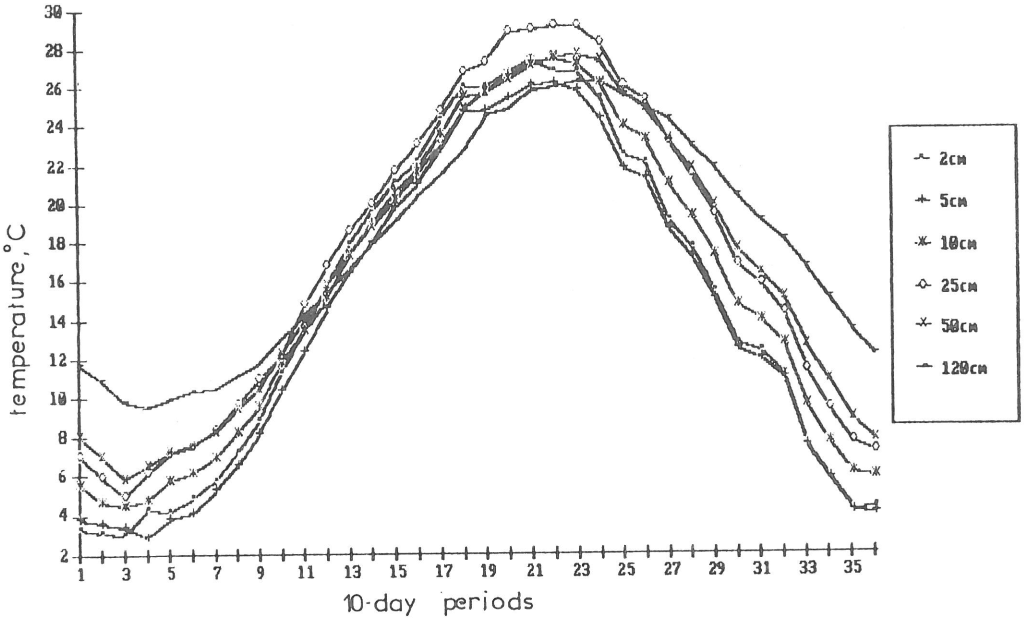


**Fig. 1.** The mean annual course of soil temperature at 08.00 h in Thessaloniki.

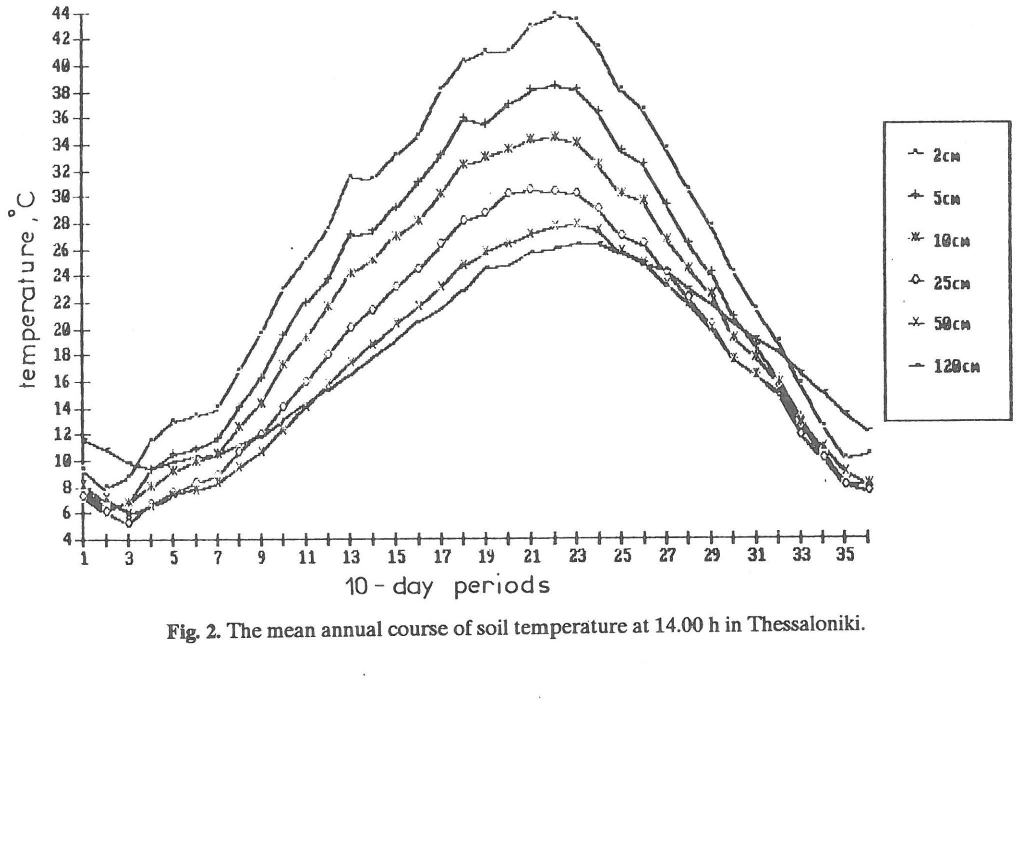


**Fig. 2.** The mean annual course of soil temperature at 14.00 h in Thessaloniki.

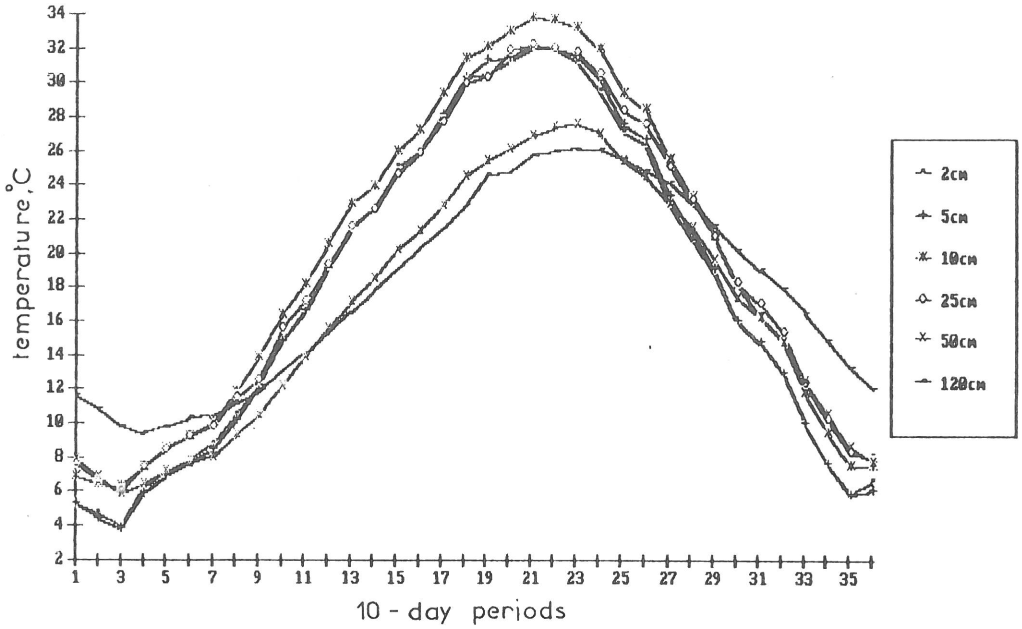


Fig. 3. The mean annual course of soil temperature at 20.00 h in Thessaloniki.

**Table 1.** The mathematical expressions of mean annual variation of the soil temperature according to Equation (4)

| Depth (cm) | 08.00 h |
|---|---|
| 2 | $T = 14.7 + 11.95 \sin(10t + 255) + 0.36 \sin(20t + 45)$ |
| 5 | $T = 13.9 + 11.53 \sin(10t + 242) + 0.38 \sin(20t + 44)$ |
| 10 | $T = 15.5 + 11.21 \sin(10t + 250) + 0.46 \sin(20t + 8)$ |
| 25 | $T = 17.0 + 11.47 \sin(10t + 248) + 0.57 \sin(20t + 353)$ |
| 50 | $T = 16.7 + 10.35 \sin(10t + 243) + 0.48 \sin(20t + 327)$ |
| 120 | $T = 17.8 + 8.07 \sin(10t + 231) + 0.24 \sin(20t + 320)$ |
| | **14.00 h** |
| 2 | $T = 25.8 + 16.58 \sin(10t + 255) + 1.45 \sin(20t + 328)$ |
| 5 | $T = 22.3 + 15.11 \sin(10t + 255) + 1.16 \sin(20t + 333)$ |
| 10 | $T = 20.4 + 13.46 \sin(10t + 253) + 0.69 \sin(20t + 325)$ |
| 25 | $T = 17.9 + 11.87 \sin(10t + 250) + 0.46 \sin(20t + 339)$ |
| 50 | $T = 16.7 + 10.29 \sin(10t + 243) + 0.45 \sin(20t + 328)$ |
| 120 | $T = 17.8 + 8.09 \sin(10t + 231) + 0.23 \sin(20t + 321)$ |
| | **20.00 h** |
| 2 | $T = 17.9 + 13.25 \sin(10t + 256) + 0.63 \sin(20t + 3)$ |
| 5 | $T = 18.0 + 13.53 \sin(10t + 255) + 0.67 \sin(20t + 358)$ |
| 10 | $T = 19.6 + 13.37 \sin(10t + 253) + 0.80 \sin(20t + 347)$ |
| 25 | $T = 19.0 + 12.44 \sin(10t + 251) + 0.59 \sin(20t + 344)$ |
| 50 | $T = 16.6 + 10.29 \sin(10t + 243) + 0.48 \sin(20t + 328)$ |
| 120 | $T = 17.8 + 8.09 \sin(10t + 231) + 0.24 \sin(20t + 321)$ |

t = 10 day period

it was found out that these two terms cover a percentage greater than 95% of the total variance in all cases. By solving the expressions in Table 1 for time, it was found that the differences between the measured and the predicted values were not significant. The importance of these equations arises from the fact that by using them it is possible to obtain the mean value of soil temperature of any particular 10-day period of a year, for any depth and at any hour of the day studied. Such assessments of soil temperature may be very useful for planning of sowing and planting at the proper time as well as for predicting plant growth and yield in the same area and in soils similar to that used in this study.

### The heat flux

In Figs 4, 5 and 6 the variation of the mean soil temperature of each 10-day period is presented, for the whole soil profile studied, at 08.00, 14.00 and 20.00 h, respectively. The variations of the mean soil temperature with depth of the thirty six 10-day periods at 08.00 h (Fig. 4) can be separated in three different types. The first one occurs only in January (from 1st to 3rd 10-day period) and is characterized by a continuous increase of temperature with depth. The second type of variation appears from February 1st to April 10th (from 4th to 7th 10-day period) and from September 21st to December 31st (from 27th to 36th 10-day period). During these time periods the variation is generally characterized by a decrease of temperature from the surface down to the depth of 5 cm, while from this level on and down to the depth of 120 cm a continuous increase of temperature is observed. The third kind of temperature variation occurs during the remaining part of the year and is characterized by a decrease of temperature down to the depth of 5 cm. Beyond this depth an increase down to the depth of 25 cm is observed, after which and down to the depth of 120 cm a decrease of temperature is again observed.

According to Eq. (6) when $dT>0$, then $qh<0$ that is, heat is transferred from a given soil depth upwards while the opposite

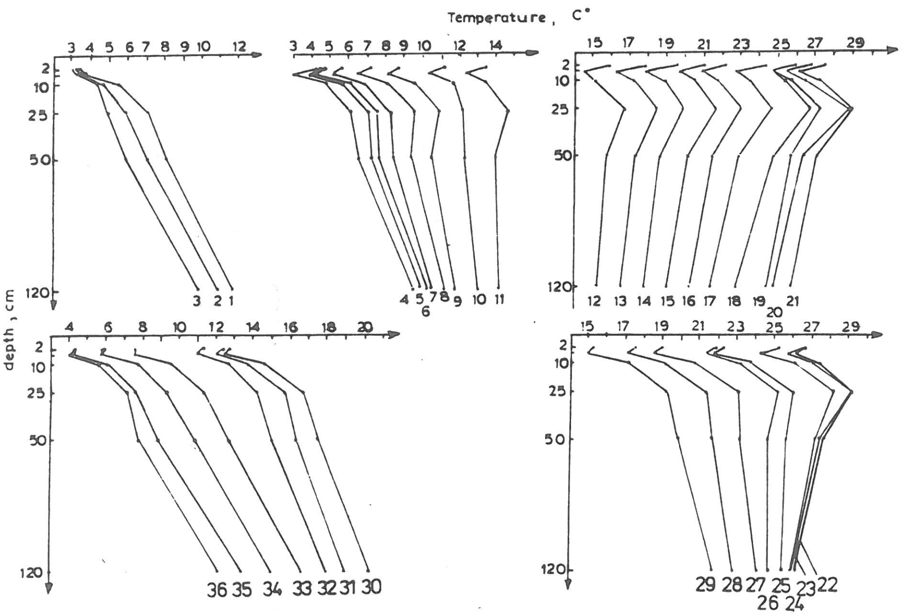


Fig. 4. Variation of soil temperature with depth at 08.00 h for thirty six 10-day periods.

happens when $dT<0$. Thus, if a soil is assumed to be homogeneous in respect of thermal conductivity and the temperature variation with depth is known, then it is possible to assess qualitatively those zones in the soil where cold prevails and those where heat does. In other words, it is possible to locate within the soil 'zones of heating' and 'zones of cooling' [13]. Thus, the whole soil profile is cooling at 08.00 h during January. From the (1st-11th and 26th-36th 10-day periods). During these periods a downward heat flux is observed from the surface down to 25 or 50 cm (zone of heating) while below these depths a zone of cooling is observed. The second type of soil temperature variation occurs during the rest of the year and is characterized by continuous decrease of temperature with depth. This results in a continuous downward heat flow and the

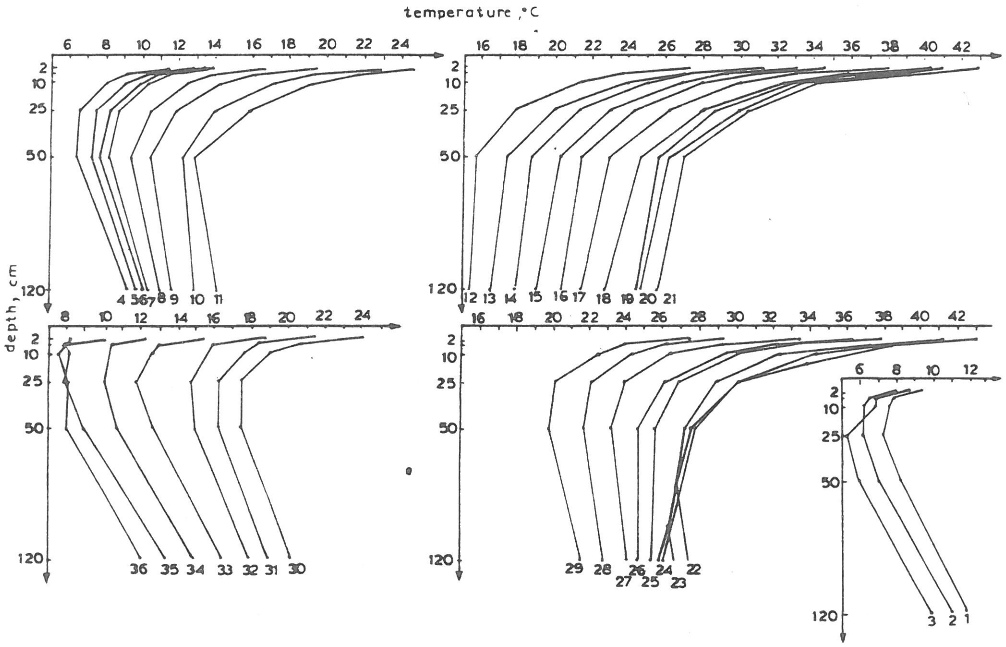


**Fig. 5.** Variation of soil temperature with depth at 14.00 h for thirty six 10-day periods.

4th to 7th and from the 27th to 36th 10-day periods, a zone of heating occurs from the surface down to 5 cm depth while from 5 to 120 cm a zone of cooling exists. For the rest of the year a zone of cooling (5-25 cm) occurs between two zones (0-5 and 25-120 cm) of heating.

At 14.00 h, two types of temperature variation are distinguished (Fig. 5). The first type generally refers to a decrease of temperature down to the depth of 25 or 50 cm and after that level to an increase of temperature down to the depth of 120 cm. This type is observed from January 1st to April 20th and from September 11th to December 31st whole soil profile constitutes a zone of heating.

Finally, at 20.00 h (Fig. 6) a double fluctuation occurs with depths of temperature inversion at 5, 10 and 50 cm, for the period January 1st to April 20th (1st-11th 10-day periods). Thus, two zones of heating are formed during this period with levels of symmetry at the depths of 5 and 50 cm and a zone of cooling between them with an axis of symmetry at the depths of 10 or 25 cm. During the period April 21st to August 31st (12th-24th 10-day periods) a simple fluctuation with slight deviations is observed having its level of temperature inversion at the depth

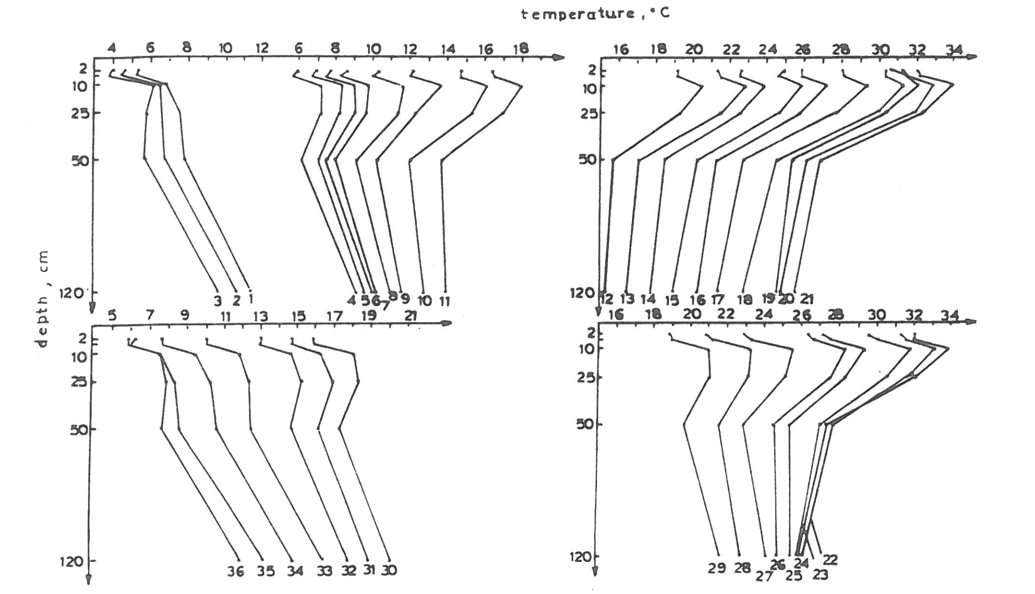


Fig. 6. Variation of soil temperature with depth at 20.00 h for thirty six 10-day periods.

of 10 cm. This means that a zone of cooling is generally formed at the depth of about 10 cm because of a flow of heat upwards as regards the soil profile above 10 cm and a reverse heat flow as regards the layer below 10 cm. During the period from September 1st to November 20th (25th-33rd 10-day periods) an increase of temperature is initially observed down to 10 or 25 cm and then a decrease of temperature down to 50 cm whereupon an increase is observed once again down to 120 cm. In this case a zone of cooling exists with level of symmetry at 10 cm as well as a zone of heating with level of symmetry at 50 cm. During the rest of the year a zone of heating is observed at about 5 cm just because temperature decreases down to 5 cm and from that depth on it increases down to 120 cm.

### Thermally induced water vapour flux in soil

According to Eq. (8) positive values of $de_s/dz$ indicate conditions favourable to upward water vapour movement while negative ones indicate conditions favourable to downward movement [9]. The calculation of $e_s$, in mbar, for the depths and hours studied, from the mean, per 10-day period, soil temperatures obtained over the 10-year period (1961-1970) by means of the empirical formula [14]:

$$e_s = 6.11 \cdot 10^{\{7.5T/(237.3 + T)\}} \qquad (10)$$

where $T$ is temperature in °C. $\Delta e_s/\Delta z$ values were computed for three soil layers, viz: 2 to 25 cm, 25 to 50 cm and 50 to 120 cm and these values are presented in Table 2. Regarding the top layer (2-25 cm), conditions are favourable to upward water vapour movement at 08.00 and 20.00 h to downward movement at 14.00 h (Table 2). An exception to the above trend is observed during the period May 21st to June 30th (15th-18th 10-day period) at 14.00 h. The $\Delta e_s/\Delta z$ values for this layer are generally quite greater at 14.00 as compared to the values of the other two values studied, and therefore the vapour flux is more intensive at 14.00 h. Concerning the second

**Table 2.** 10-day mean values of $\Delta e_s / \Delta z$ (mbar $cm^{-1}$) in three soil layers, Thessaloniki 1961-1970

| Number of 10-day period | Commencement date | (25 - 2 cm) | | | (50 - 25 cm) | | | (120 - 50 cm) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $\Delta e_s / \Delta z$ | $\Delta e_s / \Delta z$ | $\Delta e_s / \Delta z$ | $\Delta e_s / \Delta z$ | $\Delta e_s / \Delta z$ | $\Delta e_s / \Delta z$ | $\Delta e_s / \Delta z$ | $\Delta e_s / \Delta z$ | $\Delta e_s / \Delta z$ |
| | | Hours | | | | | | | | |
| | | 08.00 | 14.00 | 20.00 | 08.00 | 14.00 | 20.00 | 08.00 | 14.00 | 20.00 |
| 1 | 1 Jan. | +0.10 | -0.05 | +0.06 | +0.03 | +0.03 | +0.01 | +0.04 | +0.04 | +0.04 |
| 2 | 11 | +0.07 | -0.05 | +0.05 | +0.03 | +0.03 | +0.01 | +0.04 | +0.04 | +0.04 |
| 3 | 21 | +0.05 | -0.10 | +0.05 | +0.02 | +0.02 | 0.00 | +0.04 | +0.04 | +0.04 |
| 4 | 1 Feb. | +0.05 | -0.17 | +0.04 | +0.01 | 0.00 | -0.03 | +0.03 | +0.03 | +0.03 |
| 5 | 11 | +0.08 | -0.19 | +0.04 | 0.00 | -0.01 | -0.03 | +0.03 | +0.03 | +0.03 |
| 6 | 21 | +0.08 | -0.19 | +0.04 | 0.00 | -0.02 | -0.05 | +0.03 | +0.03 | +0.03 |
| 7 | 1 March | +0.07 | -0.20 | +0.03 | 0.00 | -0.02 | -0.06 | +0.02 | +0.02 | +0.02 |
| 8 | 11 | +0.08 | -0.27 | +0.04 | -0.01 | -0.04 | -0.08 | +0.02 | +0.02 | +0.03 |
| 9 | 21 | +0.07 | -0.38 | +0.01 | -0.02 | -0.05 | -0.08 | +0.01 | +0.01 | +0.02 |
| 10 | 1 April | +0.03 | -0.52 | +0.03 | +0.01 | -0.07 | -0.14 | +0.01 | +0.01 | +0.01 |
| 11 | 11 | +0.06 | -0.60 | +0.03 | -0.03 | -0.09 | -0.15 | +0.01 | +0.01 | +0.01 |
| 12 | 21 | +0.05 | -0.69 | +0.01 | -0.05 | -0.11 | -0.18 | -0.01 | -0.01 | -0.01 |
| 13 | 1 May | +0.04 | -0.98 | +0.01 | -0.06 | -0.14 | -0.24 | -0.01 | -0.01 | -0.01 |
| 14 | 11 | +0.02 | -0.87 | 0.00 | -0.07 | -0.15 | -0.24 | -0.02 | -0.02 | -0.02 |
| 15 | 21 | +0.04 | -0.96 | -0.03 | -0.09 | -0.18 | -0.23 | -0.02 | -0.02 | -0.03 |
| 16 | 1 June | +0.06 | -1.04 | -0.01 | -0.10 | -0.20 | -0.32 | -0.03 | -0.02 | -0.02 |
| 17 | 11 | +0.03 | -1.40 | -0.03 | -0.12 | -0.24 | -0.38 | -0.03 | -0.04 | -0.03 |
| 18 | 21 | +0.07 | -1.59 | -0.04 | -0.16 | -0.28 | -0.46 | -0.05 | -0.05 | -0.04 |
| 19 | 1 July | +0.11 | -1.66 | -0.02 | -0.13 | -0.31 | -0.43 | -0.03 | -0.03 | -0.02 |
| 20 | 11 | +0.20 | -1.52 | +0.07 | -0.11 | -0.36 | -0.53 | -0.04 | -0.04 | -0.04 |
| 21 | 21 | +0.14 | -1.84 | +0.03 | -0.16 | -0.30 | -0.51 | -0.04 | -0.04 | -0.03 |
| 22 | 1 Aug. | +0.23 | -2.01 | 0.00 | -0.14 | -0.24 | -0.44 | -0.05 | -0.05 | -0.04 |
| 23 | 11 | +0.23 | -1.97 | +0.06 | -0.14 | -0.21 | -0.40 | -0.04 | -0.04 | -0.04 |
| 24 | 21 | +0.26 | -1.69 | +0.11 | -0.08 | -0.14 | -0.32 | -0.03 | -0.03 | -0.03 |
| 25 | 1 Sept. | +0.28 | -1.33 | +0.11 | -0.03 | -0.10 | -0.24 | -0.01 | -0.01 | -0.01 |
| 26 | 11 | +0.25 | -1.15 | +0.11 | -0.04 | -0.11 | -0.24 | +0.01 | 0.00 | +0.01 |
| 27 | 21 | +0.26 | -0.94 | +0.18 | 0.00 | -0.06 | -0.16 | +0.02 | +0.02 | +0.03 |
| 28 | 1 Oct. | +0.23 | -0.72 | +0.16 | +0.02 | -0.02 | -0.11 | +0.03 | +0.03 | +0.03 |
| 29 | 11 | +0.22 | -0.57 | +0.14 | +0.03 | -0.02 | -0.08 | +0.04 | +0.04 | +0.05 |
| 30 | 21 | +0.19 | -0.41 | +0.13 | +0.04 | 0.00 | -0.05 | +0.05 | +0.05 | +0.06 |
| 31 | 1 Nov. | +0.15 | -0.29 | +0.11 | +0.03 | 0.00 | -0.04 | +0.05 | +0.05 | +0.05 |
| 32 | 11 | +0.13 | -0.21 | +0.10 | +0.03 | +0.01 | -0.02 | +0.05 | +0.05 | +0.05 |
| 33 | 21 | +0.13 | -0.16 | +0.09 | +0.05 | +0.03 | 0.00 | +0.06 | +0.06 | +0.06 |
| 34 | 1 Dec. | +0.11 | -0.08 | +0.09 | +0.05 | +0.05 | +0.02 | +0.06 | +0.06 | +0.06 |
| 35 | 11 | +0.10 | -0.07 | +0.07 | +0.04 | +0.03 | +0.01 | +0.06 | +0.06 | +0.06 |
| 36 | 21 | +0.08 | -0.09 | +0.04 | +0.02 | +0.02 | -0.01 | +0.05 | +0.05 | +0.05 |

layer (25-50 cm), conditions favourable to upward water vapour movement are observed during the periods: September 21th to April 30th at 08.00 h, November 1st to June 30th at 14.00 h and November 21st to January 10th at 20.00 h. During the rest of the year, conditions are favourable to downward movement. Regarding the third layer (50-120 cm) upward water vapour movement, at the three hours studied, takes place during almost the same period (September 11th to April 10th) while during the rest of the year downward water vapour movement prevails.

The experimental results that can be found in literature concerning the relative importance of water vapour flux to the overall water movement in soils are very limited. However, it has been found by theoretical consideration that the contribution of the water vapour flux to overall water movement is negligible in the main part of the root zone [2,8]. The absolute values of $\Delta e_s/\Delta z$ for the 2-25 cm layer at 14.00 h and for the period May to August are much greater than those of other depths, hours and periods of the year. Since these values are negative, it is possible that during this period (which coincides with the dry period at the Thessaloniki area) the downward thermally induced water vapour flux play some role in supplying plant roots with water in the 2-25 cm layer where the main part of the roots of the annual crops exists. Consequently, further and more detailed work is required to understand the water vapour flux in relation to other soil physical properties like soil water retention characteristics, hydraulic conductivity, soil water balance, porosity and air porosity.

## CONCLUSIONS

From the results of this work, the following conclusions can be drawn:

1. The mean annual (10-day period means) course of the soil temperature at the depths of 2, 5, 10, 25, 50 and 120 cm and for the hours 08.00, 14.00 and 20.00, presents a simple fluctuation with a maximum in July or August and a minimum in January or February. This temperature fluctuation can be presented by a two-term Fourier expression.

2. The direction of heat flux at different depths varies from season to season. This difference results in the formation of zones of heating and zones of cooling within the soil.

3. Conditions favourable for upward and downward water vapour fluxes were observed within the layers 2-25, 25-50 and 50-120 cm. The direction of vapour movement for any depth depend on both the hour of the day and the period of the year.

4. The work which can be found in literature so far on both heat and water vapour flux in soils is very limited. Thus, further work is required to study the heat and water (in both the liquid and vapour phase) fluxes in connection with other soil properties such as water retention, water content, hydraulic conductivity, porosity and air porosity.

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