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ON THE GROUND TEMPERATURE PROFILE FOR PASSIVE COOLING APPLICATIONS IN BUILDINGS

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Abstract—Several statistical characteristics of the soil temperature in Athens/Greece are determined through Fourier analysis of a 74 year record (1917–1990) of soil temperatures at the surface and at various depths and for both bare and short-grass-covered areas. Specifically the soil temperature patterns are presented along with the Fourier amplitudes and phases of the most important harmonics. It was found that the first three harmonics can reproduce most of the observed patterns in soil temperatures at the surface and at various depths. Finally, the results of the present analysis are compared with some existing data from other known sets of measurements. Copyright © 1996 Elsevier Science Ltd.

1. INTRODUCTION

The use of the soil for the heating and/or cooling of buildings has received an increasing interest during the last two decades. Two main strategies are defined: (i) the direct earth contact, which involves partial or total placing of the building envelope in direct contact with the soil, and (ii) the indirect contact which involves the use of a buried pipe through which air from indoors or outdoors of a building is circulated and then is brought into the building (Hazer, 1975).

Earth-contact buildings offer various advantages, e.g. limited infiltration and heat losses, solar and heat protection, reduction of noise and vibration, fire and storm protection, and improved security. In addition they present important environmental benefits while their maintenance and operational costs are low. In contrast, frequent problems are included, for example, inside condensation, slow response to changing conditions, poor indoor air quality and so on (Labs, 1990). The direct earth-coup ling techniques have been used at different timesin history and in different parts of the world. Important underground dwellings, villages and communities have been developed in the Mediterranean region (Hazer, 1975; Mihalakakou *et al.*, 1992). The concept of underground pipes can be traced back several centuries. Applications to this technique are described by Saini (1973) and Fanciotti and Scudo (1981). The use of earth-to-air heat exchangers in modern architecture for space heating/cooling has been reported frequently during the last decade (Koronakis *et al.*, 1989; Tombazis *et al.*, 1990; Mihalakakou *et al.*, 1995). High thermal efficiencies associated with the use of buried pipes in which the system's cooling capacity covers 100% of the building's cooling needs are reported by Santamouris (1990), Agas *et al.* (1991), Santamouris *et al.* (1995), and Jacovides and Mihalakakou (1995).

In general, the use of direct or indirect earth-coupling techniques for building engineering purposes requires knowledge of the soil temperature profile. Knowledge of the diurnal and annual variation of the soil temperature at various depths is necessary in predicting the performance of the direct or indirect earth-integrated systems. A full discussion on the soil temperature can be found in Fluker (1958). Measurements of the soil temperature at various depths are spatially and temporally limited. The existing data depend strongly on the local meteo-climatic conditions and soil properties, and can be used only locally. Using the existing data, mathematical models for the prediction of the earth's temperature as a function of depth, season and soil properties have already been developed (Labs, 1990). Development and application of such models facilitate the estimation procedure as they provide a continuous spectrum of values while at the same time they can provide information on parameters which are not measured directly, like the soil temperature at higher depths or the diurnal variation of the ground surface temperature. Development

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of models requires knowledge of local parameters like the average annual ground temperature, the temperature amplitude, rms (root mean square), etc., and therefore should be based on analysis of multiyear measurements.

This article aims at presenting an analysis of a 74 year record (1917–1990) of ground temperature measurements obtained in Athens through the Fourier technique (Bloomfield, 1976).

2. DATA BASE

For the study of the soil temperature characteristics in Athens, soil temperature data for the period 1917–1990 were used. The observations were performed at 08.00, 14.00, and 20.00 Local Standard Time (LST is 2 h ahead of GMT) at the surface of both short-grass-covered and bare soil as well as at various depths below the short-grass-covered soil. The observations at 08.00 and 14.00 roughly correspond to the minimum and maximum temperature epochs of air, respectively. The standard soil thermometers installed at the various depths, 0.30, 0.60, 0.90, and 1.20 m below short-grass soil, are situated at the National Observatory of Athens (NOA) on a small hill 107 m above mean sea level (about 30 m above the street level of Athens) in the center of Athens city. The lawn is irrigated every day at about 09.00 LST during the dry period of the year. The temperature values at the surface of the bare soil were taken using a couple of thermometers (normal and extreme) while the surface temperature for the lawn was measured using thermometers of minimum and maximum indication. For the ground temperature at various depths below the earth's surface more specific thermometers were used named "soil thermometers". Since January 1993, temperatures have been recorded on a continuous basis using a data logger system. For this reason temperature sensors with thermistors and thermocouples are used for the soil temperature measurements. As regards bare soil the thermometers are placed horizontally on the soil surface at a depth of 1–2 mm. These thermometers are able to provide the temperature of the "inner ground surface". The thermometers of short-grass soil surface are placed horizontally in the middle of a little area (1–2 m^2) of the ground, which is covered by dense lawn. The thermometers are covered perfectly by the lawn, whose height is almost 0.10 m. The soil thermal conductivity and diffusivity were measured from a single experiment at the Observatory. The value 0.051 m^2/day was an average for all depths and for both bare and short-grass soil. Both types were considered to be relatively dry. The soil moisture migration phenomenon under a temperature or humidity gradient when an earth-to-air heat exchangers system is used was presented in Mihalakakou *et al.* (1994).

3. RESULTS AND DISCUSSION

3.1. Multiyear measurements of soil surface temperature

Daily values of soil temperature recorded at 08.00, 14.00, and 20.00 LST were averaged to obtain daily mean values. Monthly mean values were then formed for each standard month from 1917 to 1990. These means were then averaged to obtain the annual pattern of the surface temperature. The annual surface temperature for the bare soil as well as for the soil covered with short-grass follows a sine wave (Carson, 1963). Monthly mean maximum and minimum temperatures for bare soil are about 38°C (July) and 9°C (January). For the soil surface covered with short-grass the monthly mean maximum and minimum values are close to 31°C and 8°C, respectively. The multiyear monthly mean surface temperatures are given in Fig. 1, for both bare and short-grass-covered soil. It is observed that during the winter months short-grass-covered and bare soil exhibit almost the same temperatures. Contrary to this, during summer period the observed temperature difference is more effective and the order of 8°C.

Further, the multiyear variation of the annual mean ground surface temperatures for the bare and the short-grass-covered soil is shown in Fig. 2. For bare soil the multiyear annual mean temperature is close to 21°C, while for the short-grass-covered soil the corresponding value is of the order of 18.5°C. Regarding the air temperature values, during the summer period the maximum air temperature at 13.00 LST is about 12°C lower than the grass covered surface temperature and about 25°C lower than the bare soil surface temperature. Accordingly, for the night the air temperature at 24.00 LST is almost the same as the bare surface temperature while the air temperature is 1–2°C lower than the short-grass-covered temperature. For winter, the differences between air and bare soil temperature are not significant, whereas the short-grass-covered surface temperatures are 1–1.5°C lower than the air temperature values. The air

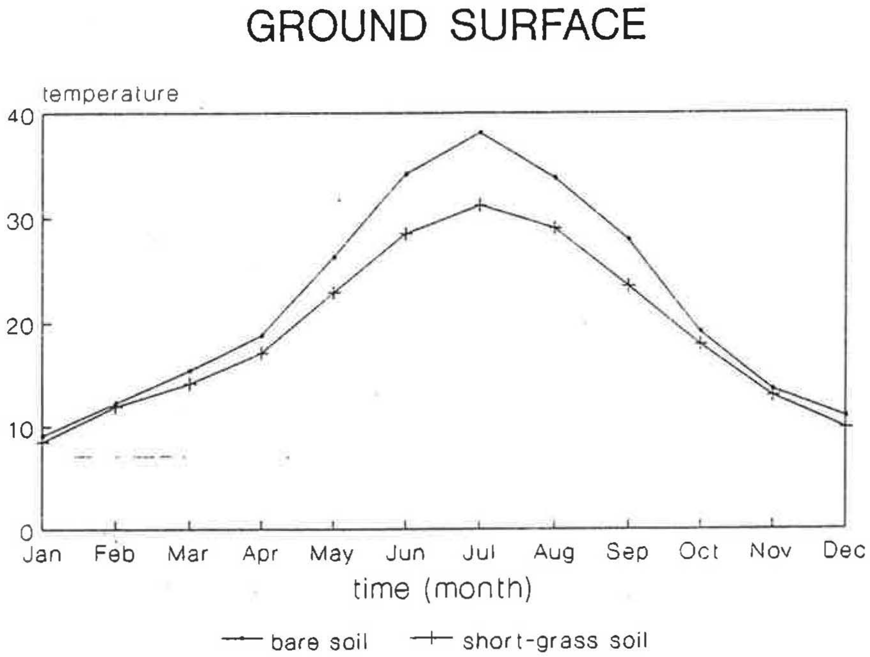

Fig. 1. Mean monthly surface temperature of the bare and short-grass-covered soil (1917–1990).

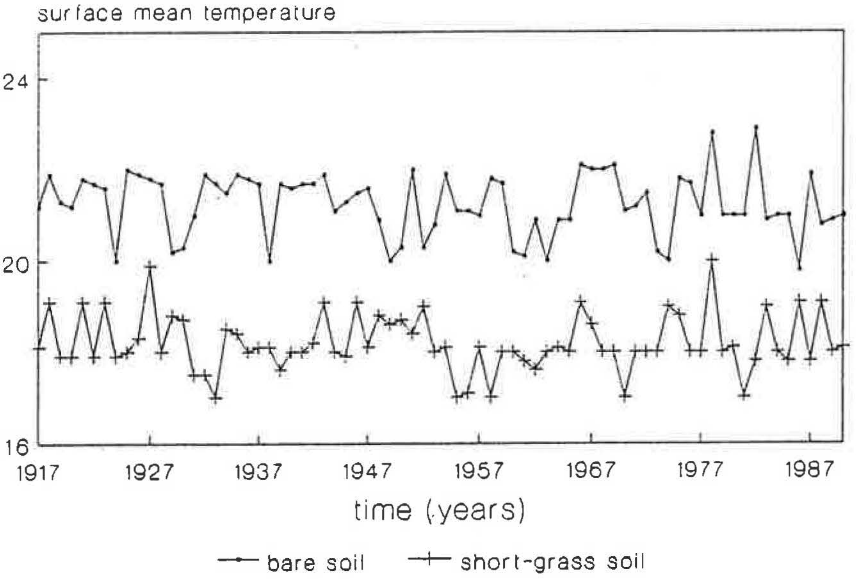

Fig. 2. Mean annual temperature for the bare and the short-grass-covered soil.

temperature was measured at a height of 1.5 m. Figures 3 and 4 show the mean monthly variation of the ambient air temperature and of the global solar radiation measured at the National Observatory of Athens.

3.2. Soil temperature patterns.

The resolution of the heat conduction equation for a semi-infinite homogeneous solid with constant physical properties gives, at order k, (Carslaw and Jaeger, 1980)

$$T(z, t) = T_m + \sum_{n=1}^{k} A_n \exp\{-z(n\omega/2\alpha)^{1/2}\} \times \cos\{n\omega t - z(n\omega/2\alpha)^{1/2}\}. \qquad (1)$$

Such an expansion can be applied to the surface as well as to the various depth temperature. The ground physical properties are assumed homogeneous and constant. Then, T_m and A_n are the Fourier coefficients for the wave temperature;

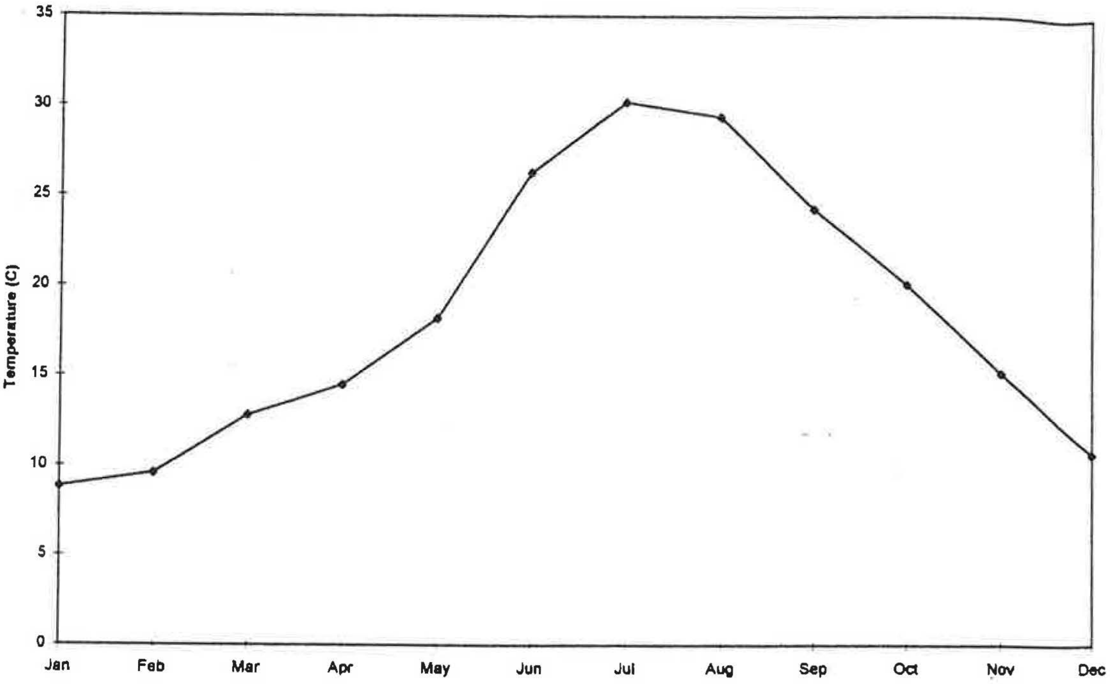

Fig. 3. Mean monthly air temperature variation.

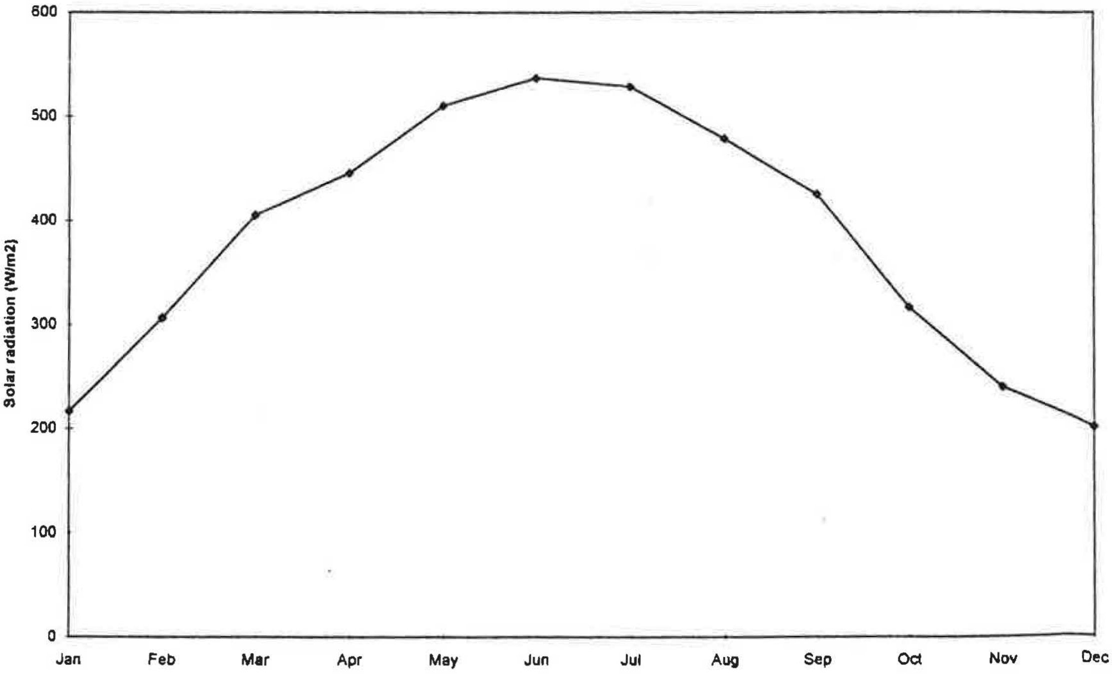

Fig. 4. Mean monthly variation of the global solar radiation.

$\omega = 2\pi/365$ (rad day^{-1}); α is the ground thermal diffusivity (Carslaw and Jaeger, 1980), and z is depth (m) and t is time (day). It is noted that the experimental values of temperature for each year were fitted with the predicted values using eqn (1). From this fitting and for each year T_m and A_n values were calculated.

This approach has been adopted and discussed in Labs (1990) and Lamba and Khambete (1991). Comparison between the predicted and observed values has shown that eqn (1) provides quite accurately the ground temperature. In Figs 5 and 6 we show mean daily observed values of ground surface temperature and the predicted ones via Fourier technique, for the whole set of 74 years (1917–1990),

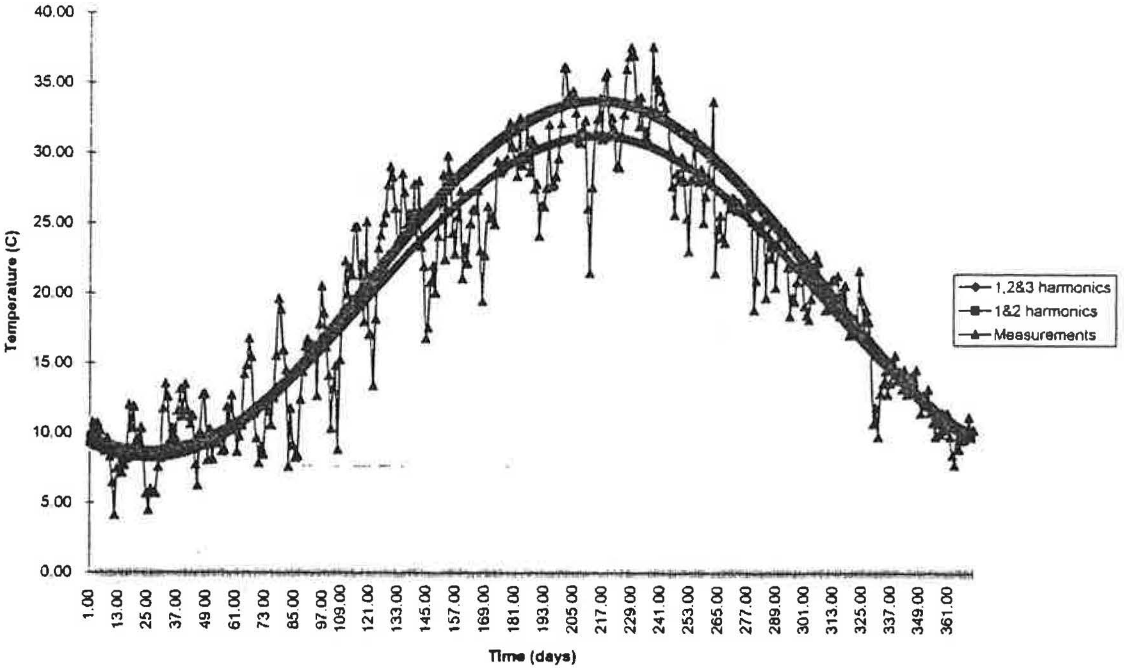

Fig. 5. Mean daily surface temperatures observed and predicted by first two and first three harmonics of the bare soil, for the 74 years (1917–1990).

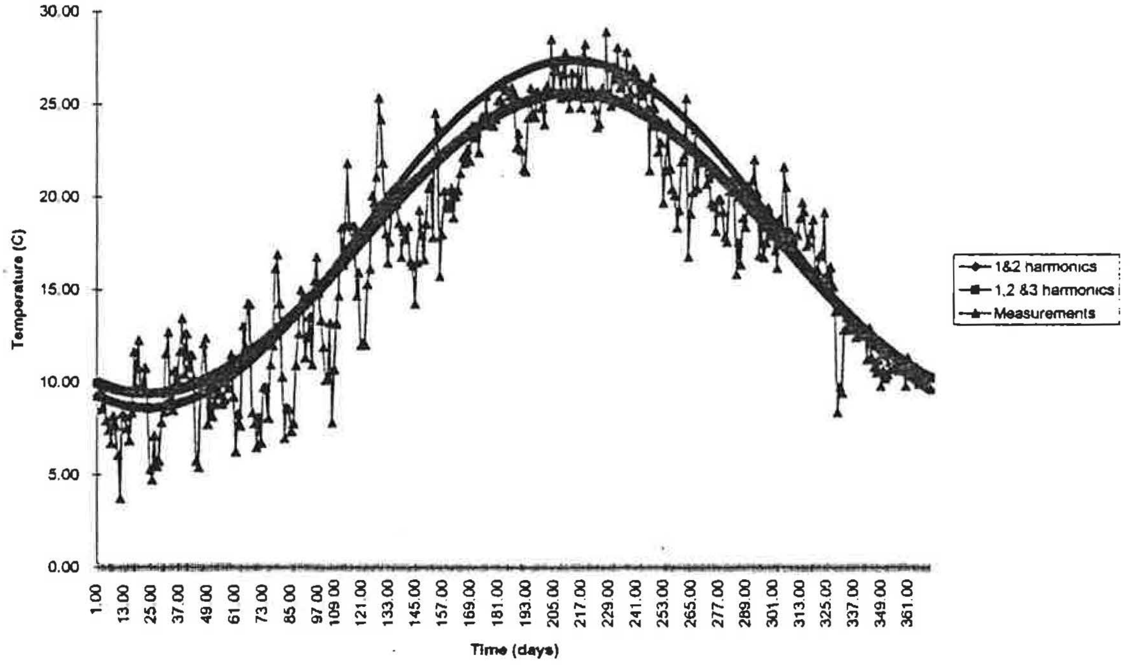

Fig. 6. Short-grass-covered soil, surface temperature, for the 74 years.

for bare and short-grass-covered soil. It is clear that the combination of the first and second harmonics represents almost 90% of the total variation in surface temperature for both soil covers. In contrast, the sum of the three harmonics provides an additional 9% of the total variation. Nevertheless, the agreement between the sum of the two harmonics and the observed values is very obvious. However, including the third harmonic the agreement between the Fourier-predicted values and the observations is improved.

Further, the mean daily predicted values via Fourier technique as well as the mean daily observed values of the ground temperature for the depths 0.30, 0.60 and 1.20 m are given in

Figs 7–9, and for the whole set of 74 years. From the overall analysis it is interesting to note that although many workers have reported that annual temperature cycle is well represented by the first harmonic alone (Krishnam and Kushwaha, 1972; Mihalakakou *et al.*, 1992), it has not been found true in this analysis. Thus the first harmonic explains only 70–90% of the total variation at different depths, while the second and third harmonics represent 5–18% and 0.5–7% of the total variation, respectively. Finally, the total variation explained by the sum of the first three harmonics taken together varies from 94 to 99% for all depths.

The Fourier analysis for the prediction of undisturbed ground temperature can be

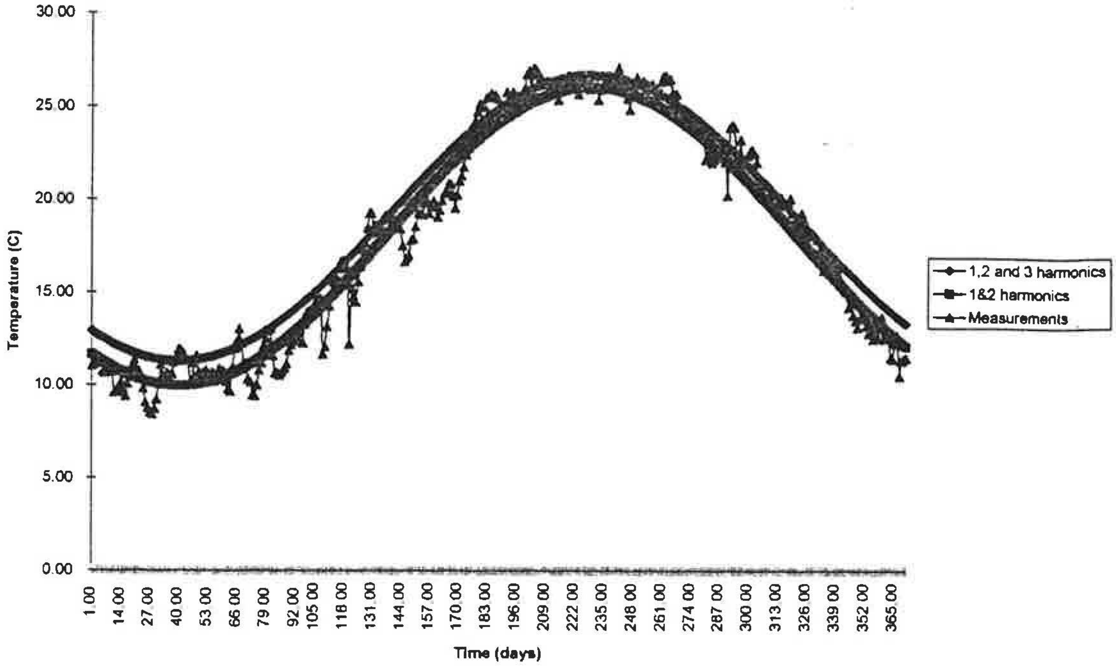

Fig. 7. Ground temperature at 0.30 m depth, for the 74 years.

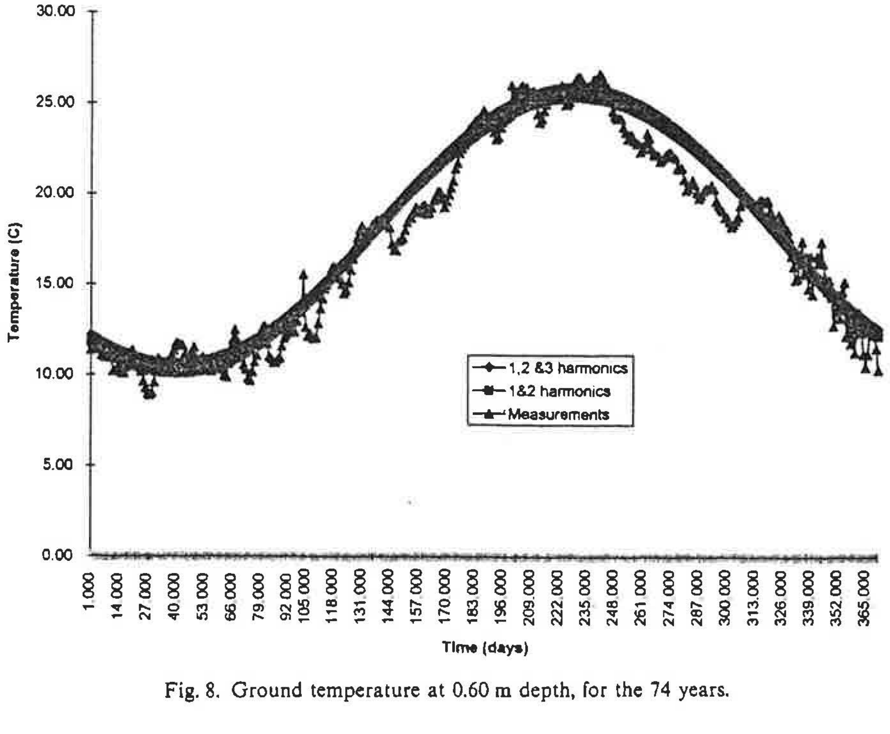

Fig. 8. Ground temperature at 0.60 m depth, for the 74 years.

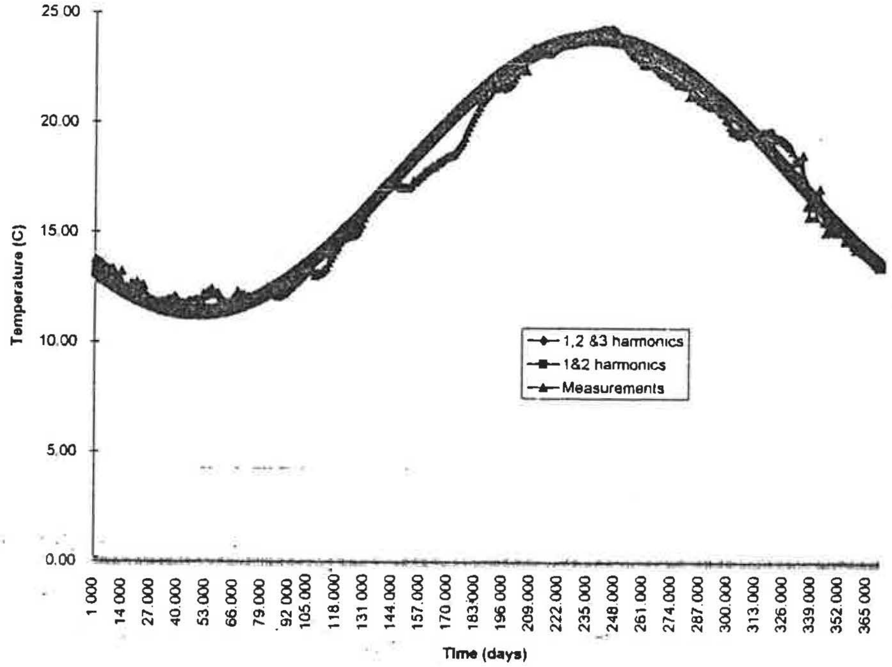

Fig. 9. Ground temperature at 1.20 m depth, for the 74 years.

extended for depths more than 1.2 m. These predictions can be extensively used for the assessment of the cooling and heating potential of an earth-to-air heat exchangers system (Santamouris *et al.*, 1995; Mihalakakou *et al.*, 1994; 1995).

3.3. Amplitude and time lag variation

The Fourier coefficients T_m, A_n and phase lag t_n, for the first three harmonics that are used in plotting mean 74 year, 3-harmonic curves shown in Figs 5–9, are summarized in Table 1 for both bare and short-grass-covered soil. Interestingly, Table 1 indicates that: (1) the amplitude A_n decreases sharply with increasing the order of the *n*th harmonic; (2) for the bare soil surface, A_n values are of the order of 14.4, 7.2 and 1.72°C for the corresponding first, second and third harmonics. However, the amplitudes A_n for short-grass-covered soil surface are of the order of 11.1°C for the first harmonic, 3.71°C for the second and 1.22°C for the third harmonic.

Table 1. Fourier coefficients T_m and A_n, and phase lag t_n, that are used in plotting mean 74 year, 3 harmonic curves shown in Figs 3–7

Site	Z[m]	T_m[°C]	A_1	A_2	A_3	t_1	t_2	t_3
Bare	0.0	22.1	14.4	7.2	1.74	—	—	—
Grass	0.0	18.9	11.2	3.7	1.22	—	—	—
Grass	−0.3	19.2	—	—	—	11.7	7.3	3.2
Grass	−0.6	19.6	—	—	—	17.6	12.6	6.9
Grass	−1.2	19.9	—	—	—	30.8	21.4	11.2

Further, the temperature phase lag is a parameter characterizing the lead/lag relationship of the particular temperature sinusoidal/cosinusoidal components. It has dimensions of time and is given for the *n*th harmonic (t_n) by the following expression:

$$t_n = z/2(365n/\pi\alpha)^{1/2}. \tag{2}$$

The first three harmonics have been considered in order to model the observed phase lag. Thus the average values of phase lag predicted from (2) and the multiyear average of phase lag provided directly from the data base are shown in Fig. 10 and summarized in Table 1, as a function of depth. This line has a slope of about 24 days per meter if the origin is included. It is interesting to note that the predicted phase lag from the first three harmonics and the observed one is in good agreement; 99% of the total observed phase lag variation can be accounted for by the first three harmonics. Further, the mean values of multiyear variation of the phase lag obtained through Fourier harmonic analysis for each harmonic and for the depths 0.30, 0.60, and 1.20 m below short-grass-covered soil surface are shown in Table 1. It is clear that the phase lag decreases with increasing the order of the harmonic, especially for lower depths; whereas the phase lag increases with increasing depth.

Measurements of the ground temperature at various depths are reported in several studies

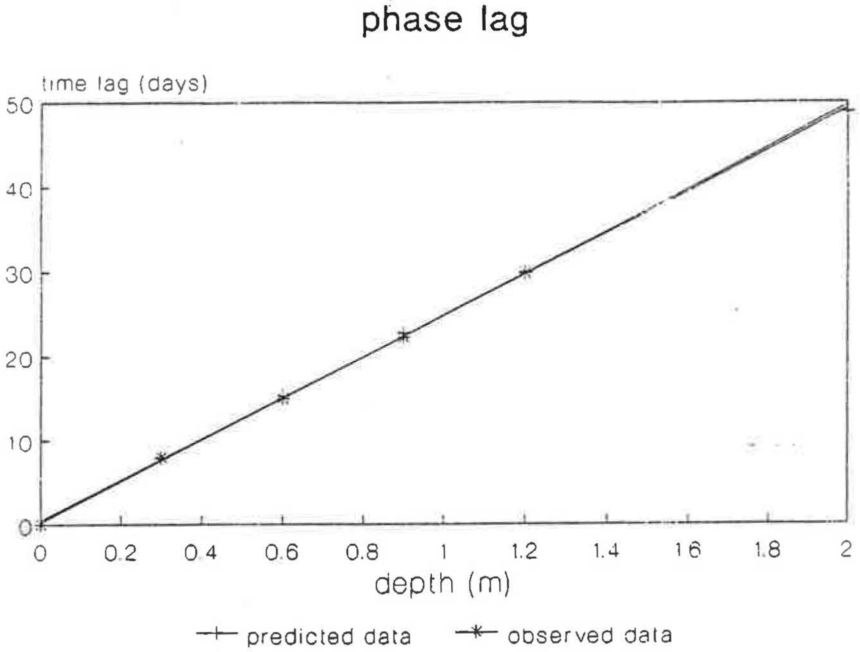

Fig. 10. Observed and predicted values of the phase lag as a function of depth.

(Carson, 1963; Kusuda, 1975; Bligh, 1975). A summary and a comparative analysis of the available data is given by Givoni and Katz (1985). These authors suggested that all the experimental data can be compared when brought to a common base. More clearly, comparison is made using the phase lag variation with the depth. According to Givoni and Katz (1985) all the data are spread about a common line having a slope of about 22 days per meter. As reported previously the present experimental data give a slope of about 24 days per meter.

4. CONCLUDING REMARKS

The main conclusions of the present analysis are as follows. (1) Soil temperatures and their minima/maxima at different depths and at any time can be estimated for a location and the nearby area on the basis of their annual periodicity with the help of harmonics computed by Fourier technique. (2) The first three harmonics taken together provide good agreement between the estimated and the observed soil temperatures at the surface as well as at various depths.

It is believed that the results presented here can serve as a useful reference of soil temperatures for future alternative sources of energy applications.

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