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Modelling the earth temperature using multiyear measurements

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Abstract

Seventy-four years of ground temperature measurements at various depths performed at the National Observatory of Athens are analysed. Simple accurate models for the prediction of the annual variation of the ground temperature at the earth's surface and at various depths have been developed. Algorithms to predict the daily variation at the ground surface are also proposed. Finally the results of the overall analysis are compared with the corresponding data from other known sets of measurements. The overall analysis is useful for the prediction of the performance of buildings in direct contact with the soil as well as for the prediction of the efficiency of the earth-to-air heat exchangers.

1. Introduction

The use of the ground for heating and cooling of buildings has gained an increasing acceptance during recent years. Two main strategies are defined. The direct earth contact, which involves partial or total placing of the building envelope in direct contact with the soil, and the indirect contact which involves the use of a buried pipe through which air from the building or from the outside is circulated and then is brought into the building.

Direct earth coupling techniques have been used at different times in history and in different parts of the world. Important underground dwellings, villages and communities have been developed in the Mediterranean region [1–4]. Today, estimates of the number of earth-sheltered houses in the USA range from 4000 to 8000 [5]. In Europe there is a large number of one or two-storey buildings which are set into hillsides, placed partially or completely below ground level.

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. Also they present important environmental and land-use benefits while their maintenance and operational costs are low. However they are not free of disadvantages. Inside condensation, slow response to changing conditions, poor daylighting and poor indoor air quality are frequent problems.

The concept of underground pipes can be traced back several centuries. Applications of this technique at different times and in different parts of the world are described elsewhere [6–8]. Use of earth-to-air heat exchangers, in modern architecture, for space heating and cooling has been frequently reported during recent years [9–11]. High thermal efficiencies associated with the use of buried pipes are reported in refs. 12 and 13.

Use of direct or indirect earth-coupling techniques for buildings requires knowledge of the ground temperature distribution. Knowledge of the annual variation of the soil temperature at various depths as well as its diurnal variation are necessary data to predict the performance of the direct and indirect earth-integrated systems.

Measurements of the earth's temperature at different depths are, however, spatially and temporally limited. The existing data depend strongly on the local conditions of climate and soil properties, and can be used only locally. Using the existing data, general mathematical models for the prediction of the earth's temperature as a function of depth, season and soil properties have been already developed [14]. Development and application of such a model facilitates the calculation procedure as it provides a continuous spectrum of values while at the same time it can provide information on parameters which are not directly measured, like the

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soil temperature at higher depths or the diurnal variation of the ground surface temperature. Development of a model requires knowledge of local validity parameters like the average annual earth temperature, the temperature amplitude, etc., and therefore should be based on an analysis of multiyear measurements.

In the present paper an analysis of 74 years' measurements of the ground temperature in Athens, Greece, is presented. Using this data, mathematical prediction models for the annual and diurnal variation of ground temperature at various depths have been developed. Finally, these results are compared with previously published ones.

2. The measured data

Ground temperature has been measured at the Athens National Observatory since 1917. The Observatory is situated on a hill in the centre of Athens (latitude = 37.58 °N, longitude = 23.43 °E and altitude = 107 m). Measurements are performed on the surface over bare soil and short-grass-covered soil as well as at depths of 0.3, 0.6, 0.9 and 1.2 m under the short-grass-covered soil. The temperature measurements were taken at 08:00, 14:00 and 20:00 LST. Recently, temperatures are recorded on a continuous basis using a data logger system. The soil diffusivity was measured to be equal to 0.051 m^2/day. All data used, from 1917 to 1990, are available on floppy disks.

3. The annual pattern of the surface temperature

Annual surface temperature, for the bare soil, almost follows a sine wave. Mean maximum and minimum monthly temperatures are about 38 °C and 9 °C and are observed during July and January respectively. Monthly absolute maximum temperatures are close to 43 °C, while the monthly absolute minimum is close to 5 °C. The multiyear mean monthly surface temperatures are given in Fig. 1 for bare soil.

A similar sinusoidal behaviour is also obtained for the soil surface covered with short grass. The mean monthly minimum temperature is close to 8 °C, while the mean monthly maximum temperature is close to 31 °C. Therefore, while during the winter period, short grass and bare soil present almost the same temperatures, during the summer period the observed temperature difference is significant and close to 8 °C. Monthly absolute maximum temperatures are close to 35 °C, while the monthly absolute minimum is close to 5 °C. The multiyear mean monthly surface temperatures are also given in Fig. 1 for soil covered with short grass.

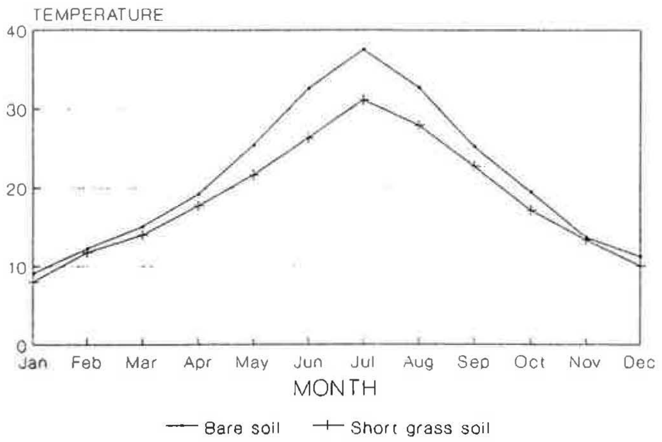

Fig. 1. Variation of the multiyear mean monthly surface temperature of the bare and short-grass-covered soil.

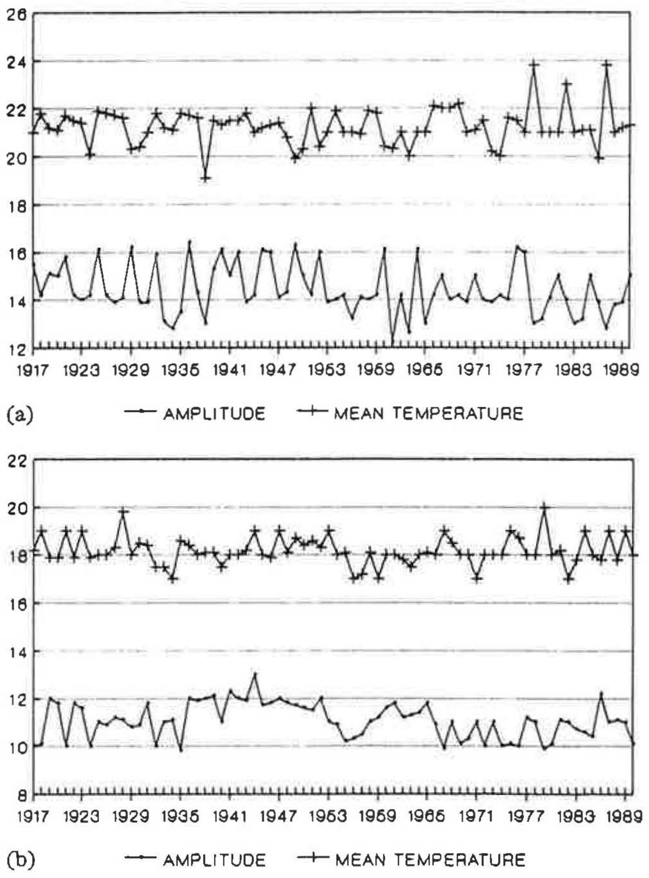

Fig. 2. Variation of the mean annual temperature as well as of the annual amplitude for (a) the bare and (b) the short-grass-covered soil.

Using regression techniques, it is found that the surface temperature can be estimated from the expression:

$$T_{\text{sur}} = T_{\text{m}} - A_{\text{s}} \cos(2\pi/365(t - t_0)) \tag{1}$$

where T_{m} is the average annual earth temperature and A_{s} is the temperature amplitude.

The multiyear variation of the average annual earth temperature and the temperature amplitude for the bare and the short-grass-covered soil are given in Fig. 2. For the bare soil the multiyear average annual temperature is close to 21 °C, while the multiyear amplitude is close to 14.7 °C. For the short-grass-covered soil the multiyear average annual temperature is close to 18.5 °C while the multiyear amplitude is close to 11.5 °C.

Comparison of measured with predicted values, using eqn. (1) data of the ground surface temperature, has shown an excellent agreement. The measured annual variation of the ground surface as well as the predicted one for a randomly selected year, 1954, is given for the bare and short-grass-covered soil in Figs. 3 and 4 respectively. As shown, the measured and predicted values are in close agreement.

4. Variation of the subsurface ground temperature

Using the available measurements of the ground temperature at various depths and assuming that the soil is homogeneous and of constant thermal diffusivity, the temperature at any depth z and time t can be found by the expression:

$$T_{z,\,t} = T_{\text{m}} - A_{\text{s}} \exp(-z(n/365a)^{0.5}) \cos[2\pi/365(t - t_0) - z/2(365/\pi a)^{0.5})] \tag{2}$$

where the values of T_{m} and A_{s} have been previously defined for the bare and the short-grass-covered soil and a is a lag coefficient. Comparison of the estimated and of the measured values has shown that eqn. (2) predicts quite accurately the ground temperature at various depths. A typical example, year 1954, of the predicted as well as the measured values of the ground temperature for depths equal to 30 cm and 120 cm are given in Figs. 5–6.

The ratio of the temperature range at a certain depth to the temperature range at the earth's surface $DT(z)/DT(0)$ can be predicted using eqns. (1) and (2). It is taken that:

$$DT(z)/DT(0) = \exp(-zk) \tag{3}$$

The obtained values from eqn. (3) as well as the experimental values are found in close agreement and are plotted in Fig. 7. When the experimental values are used, the mean multiyear variation of $DT(z)/DT(0)$ with depth can be calculated from the expression:

$$DT(z)/DT(0) = \exp(-0.425z) \tag{4}$$

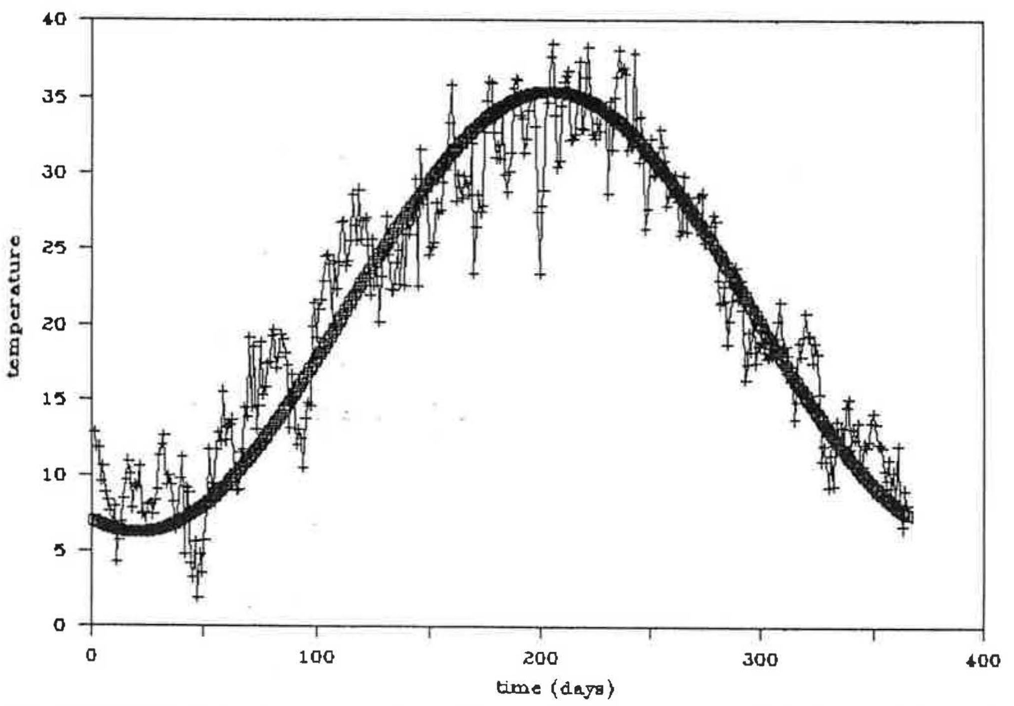

Fig. 3. Variation of the measured and predicted surface temperatures of the bare soil for 1954.

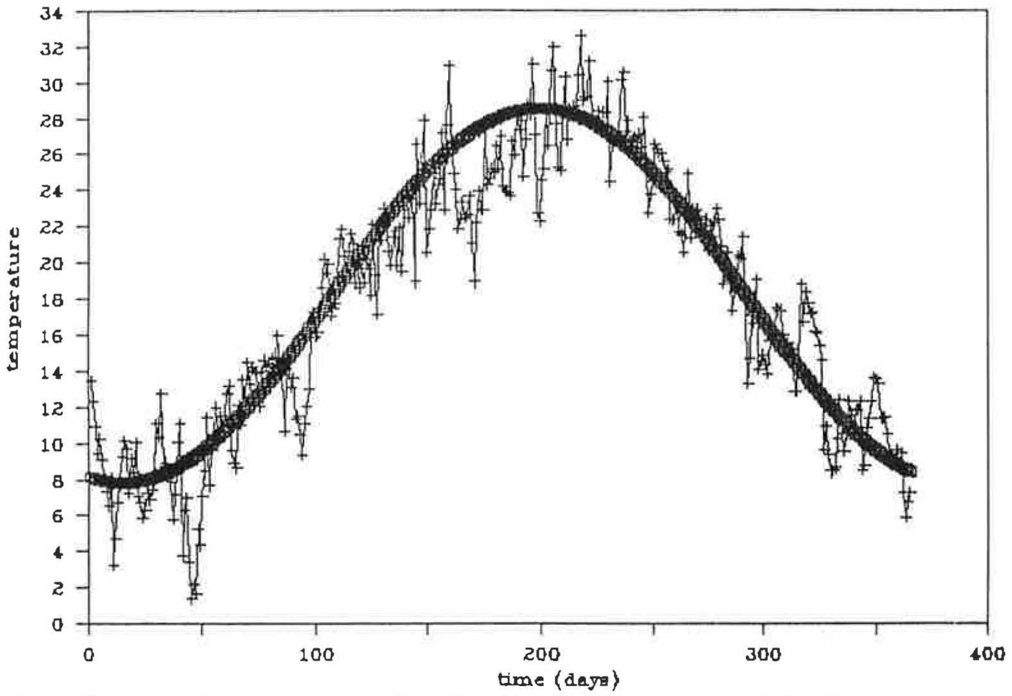

Fig. 4. Variation of the measured and predicted surface temperatures of the short-grass-covered soil for 1954.

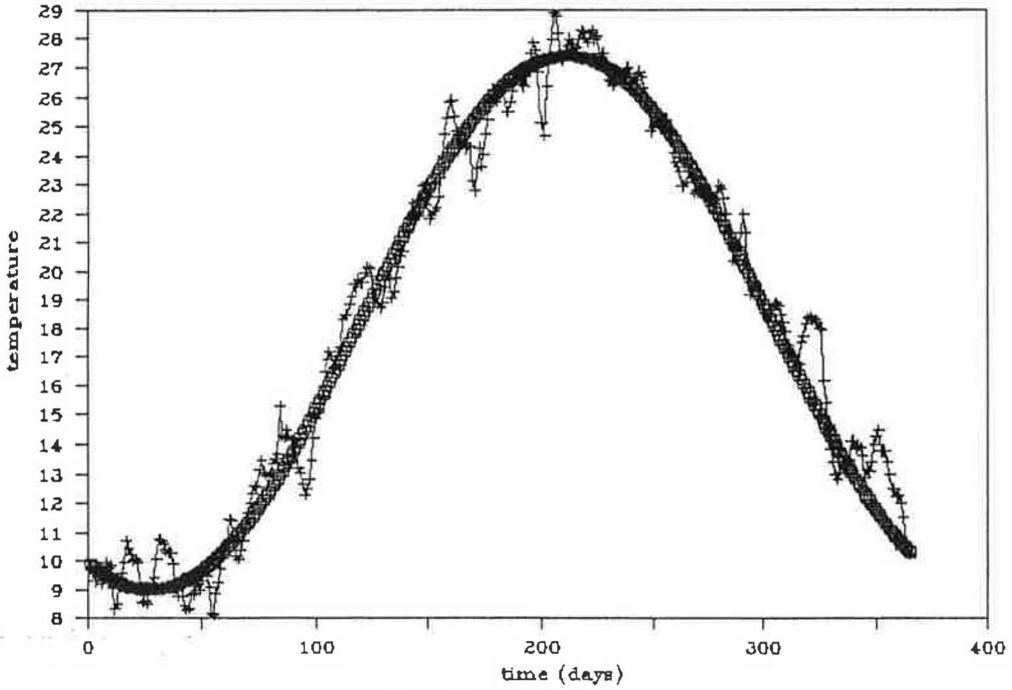

Fig. 5. Variation of the measured and predicted short-grass-covered ground temperatures at 0.3 m depth for 1954.

From the theoretical values and eqn. (3), $k = 0.414$.

The temperature time lag is a parameter which characterizes the retardation in time of the temperature wave. It has dimensions of time and is given by the following expression:

$$b = z/2(365/\pi a)^{0.5} \qquad (5)$$

The estimates of eqn. (5) as well as the time lag values provided directly from the measurements are given as a function of depth in Fig. 8. This line has a slope of about 23.5 days per metre if the origin is contained.

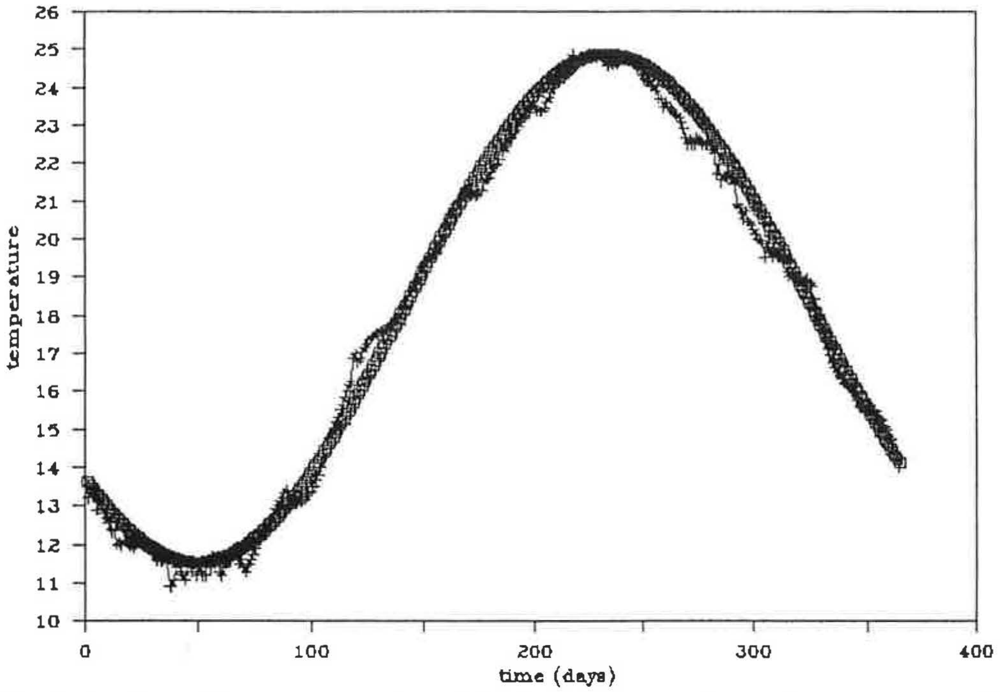

Fig. 6. Variation of the measured and predicted short-grass-covered ground temperatures at 1.2 m for 1954.

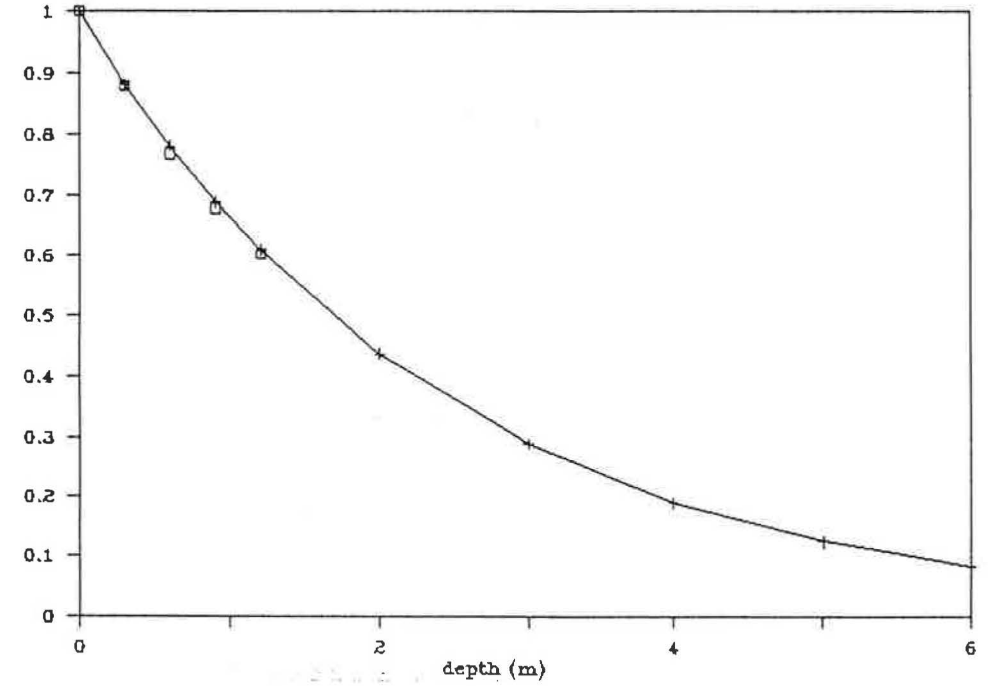

Fig. 7. Measured and experimental values of the ratio of the temperature range at a certain depth to the surface temperature range, $DT(z)/DT(0)$.

5. Comparison with other experimental studies

Measurements of the ground temperature at various depths are reported in various studies [15–21]. A summary as well as a comparative analysis of the available data is given in ref. 22. As suggested in ref. 22, all the experimental data can be compared when brought to a common base. More specifically, comparison is made using the ratio of the relative temperature range, at a given depth, related to the range of the surface temperature, $DT(z)/DT(0)$.

Values of the relative temperature range, $DT(z)/DT(0)$, as a function of depth given in refs. 15–21,

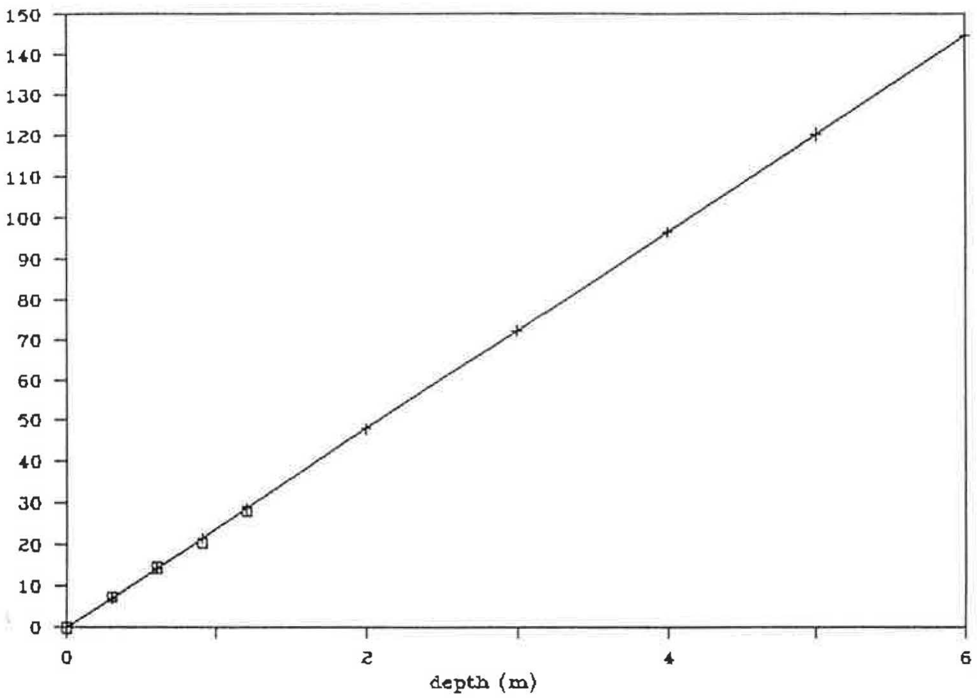

Fig. 8. Estimated and predicted values of the time lag.

TABLE 1. Monthly values of the parameters T_x, T_n and T_s for the bare soil

Month	T_x	T_n	T_s
January	17.6	3.8	4.5
February	19.3	5.5	7.3
March	26.2	8.9	10.8
April	33.7	11.5	13.2
May	42.2	15.0	16.4
June	48.3	18.0	19.8
July	54.2	22.9	24.7
August	51.6	20.4	22.2
September	45.8	17.7	19.8
October	37.4	14.4	16.9
November	28.3	10.9	13.2
December	18.7	8.3	10.2

TABLE 2. Monthly values of the parameters T_x, T_n, and T_s for the short-grass-covered soil

Month	T_x	T_n	T_s
January	14.0	2.8	3.9
February	16.3	4.8	6.1
March	19.2	7.9	9.4
April	23.7	10.8	12.3
May	30.1	13.1	15.0
June	35.4	15.9	17.3
July	39.8	18.1	19.8
August	37.1	16.1	17.7
September	31.8	14.4	15.6
October	26.4	11.3	13.1
November	19.9	9.6	11.2
December	15.7	6.7	8.5

are bounded by two curves similar to those described by eqn. (3) [22]. The upper boundary curve corresponds to humid places and is characterized by a k value, (eqn. (3)), equal to 0.3. The lower boundary curve of the relative range corresponds to arid regions and is characterized by a k value equal to 0.5. As previously reported, our experimental data correspond to $k = 0.425$.

Experimental studies on the time lag variation with the depth reported in ref. 22, show that all the data are spread about a common line having a slope of 22 days per metre. As already reported a linear variation of the time lag with the depth, having a slope of 23.5 days per metre, is also found in the present analysis.

6. The diurnal variation in soil surface temperature

The diurnal variation of the ground surface can be predicted using empirical or energy budget models. Empirical linear, non-linear, Fourier series or sinusoidal models have been proposed in refs. 23–27. Energy budget models are proposed in refs. 28–30. However, these models require an important number of data like solar radiation, wind speed, dew point temperature, air temperature, etc., and are difficult to use.

In order to predict the diurnal variation of the ground surface, the model proposed in ref. 31 has been used. The ground surface temperature during daytime is described by the following equation:

$$T_i = (T_x - T_n)\sin(\pi m/(Y + 2a)) + T_n \qquad (6)$$

where T_x is the maximum daily temperature, T_n is the minimum daily temperature, a is a lag coefficient, Y is the length of the day in hours, and m is the number of hours after the time of the maximum temperature and before the sunset hour.

The ground surface temperature during the night period is described by the following equation:

$$T_i = T_n + (T_s - T_n)\exp(-bn/Z) \qquad (7)$$

where T_s is the ground surface temperature during sunset, b is a nighttime coefficient, n is the number of hours after sunset and before the time that the

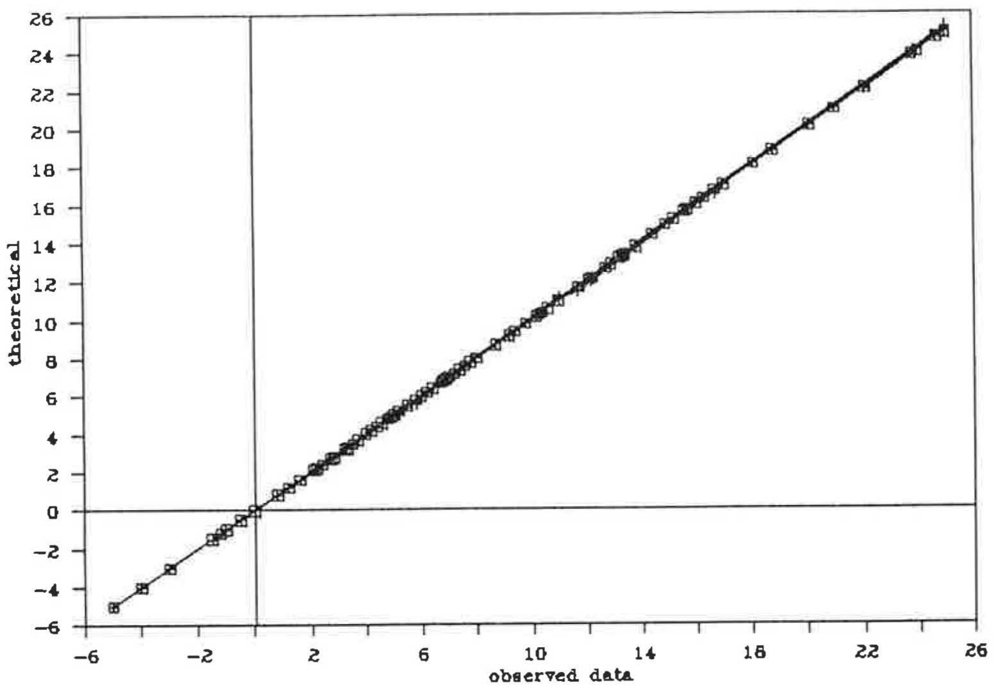

Fig. 9. Experimental vs. predicted values of the bare-soil ground temperature taken at 08:00, 14:00 and 21:00, during January.

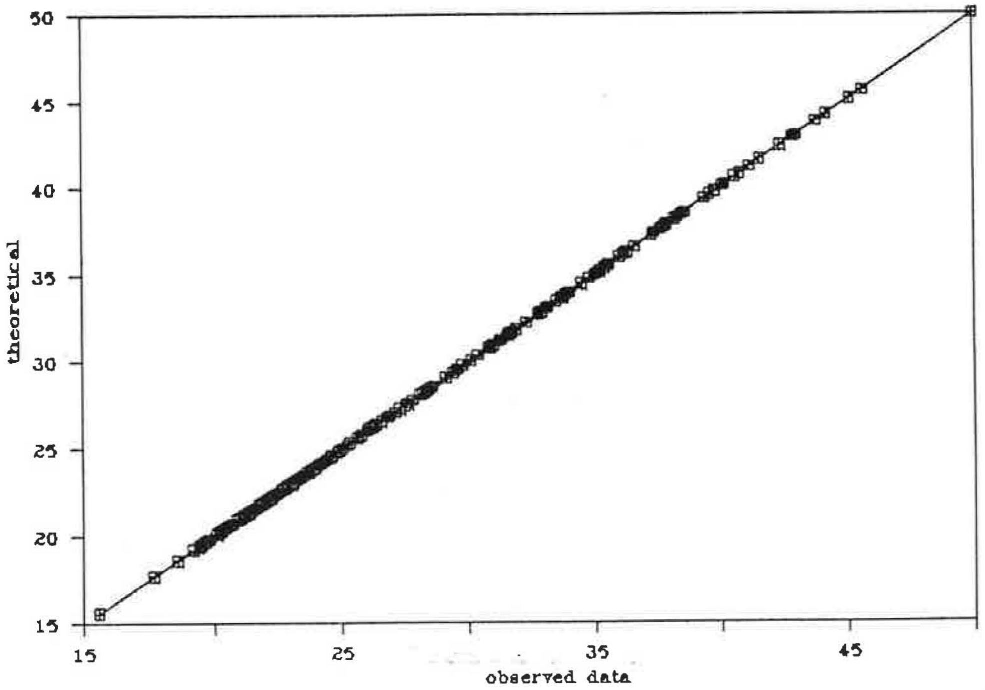

Fig. 10. Experimental vs. predicted values of the short-grass-covered soil temperature taken at 08:00, 14:00 and 21:00 for July.

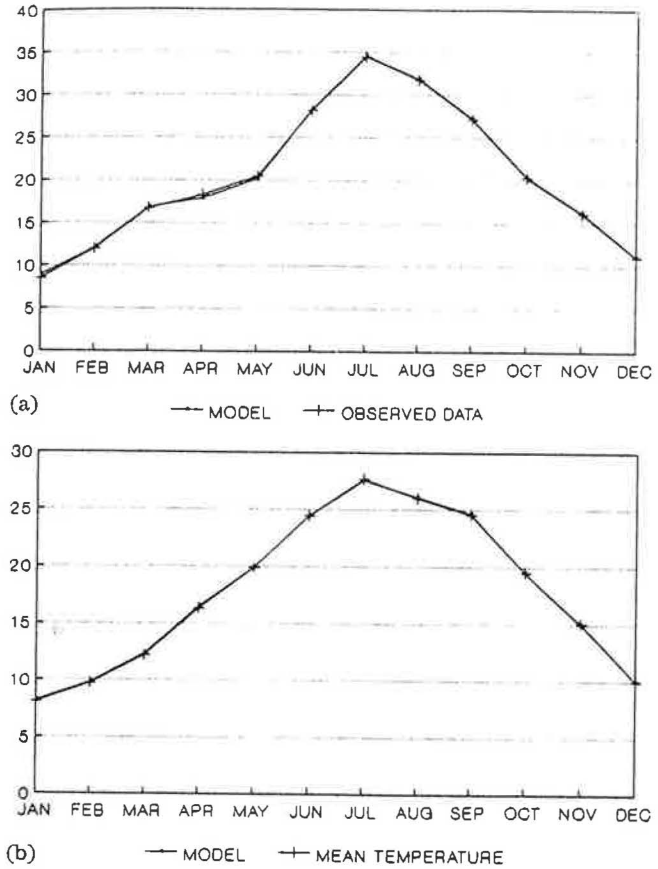

Fig. 11. Comparison of the predicted values from eqns. (6) and (7) of the mean monthly surface temperature of the (a) bare and (b) short-grass-covered soil with the corresponding value obtained from the measurements.

minimum daily temperature occurs, and Z is the length of the night in hours.

Using the available measurements we have found that for the bare and the short-grass-covered soil, the following values can be used:

$a = 0.5$ and $b = 1.81$.

Also the mean monthly values of T_x, T_n and T_s for the bare and the short-grass-covered soil are given in Tables 1 and 2 respectively.

The values predicted for 08:00, 14:00 and 20:00 LST by eqns. (6) and (7) have been compared with the corresponding measured values. The experimental vs. the calculated values for January and July for the bare and short-grass-covered soil respectively, are given as an example in Figs. 9 and 10. As shown, a very good agreement between the experimental and the estimated data is found. An excellent agreement is also observed for the remaining months.

Using eqns. (6) and (7) as well as the values given in Tables 1 and 2, the mean multiyear daily variation of the surface temperature for each month has been calculated. Then the mean daily temperature was estimated and compared with the corresponding value taken from the measured data. The results of this comparison for the bare and the short-grass-covered soil are given in Fig. 11. As seen from this Figure a very good agreement between the two sets of data exists. Thus, using the above given equations, the daily variation of the bare and short-grass-covered soil temperatures can be predicted accurately.

7. Conclusions and summary

Knowledge of the annual as well as of the daily variation of the ground temperature is necessary for the prediction of the performance of buildings or of systems in direct or indirect contact with the soil. Using 74 years of ground temperature measurements carried out at the National Observatory of Athens, simple models for the prediction of the annual and diurnal variation of the surface temperature of bare and short-grass-covered soils are proposed. The variation of the ground temperature with depth as well as the corresponding time lag and the ratio of the temperature range at a certain depth to the temperature range at the ground surface are analyzed and appropriate algorithms are proposed. In all cases the predicted values are in close agreement with the corresponding measurements.

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