EXPERIMENTAL AND THEORETICAL INVESTIGATION OF SOIL TEMPERATURE PROFILES DURING SOLARIZATION OF MULCHED AND BARE SOIL

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الملخص

الهدف الرئيسي من هذا البحث هو التحقق تجريبيا ونظريا في السلوك الحراري وفعالية التسخين بالطاقة الشمسية في التربة وذلك في حالة تغطيتها بغطاء شفاف لحبس الطاقة ومقارنتها مع حالة تركها معراة بدون غطاء. من خلال التجارب العملية والحسابات النظرية تم دراسة توزيع درجات الحرارة خلال التربة المعراة والمغطاة الى عمق 50 سم وفي بعض التجارب حتى عمق 60 سم وذلك اثناء وبعد تشميس التربة. أجريت هذه التجربة في مزرعة في تاجوراء –ليبيا (خط العرض N32° 40′ وخط الطول E13 09′) حيث تم قياس درجات حرارة التربة على أعماق مختلفة في ثلاث حالات. الحالة الاولى هي عند تغطية التربة بغطاء بلاستيكي شفاف سمكه 100 μm والحالة الثانية عند تغطية التربة بغطاء بلاستيكي اسود ليساعد على امتصاص الاشعاع الحراري وفوقه غطاء بلاستيكي شفاف والحالة الثالثة هي التي تكون فيها التربة معراة بدون غطاء حيث استخدمت كمرجعية. بينت النتائج ان التشميس بتغطية التربة بالغطاء الشفاف في فصل الصيف قد يرفع درجة حرارة التربة الى حوالي 62 م° عند السطح وحوالي 51 م° عند عمق 30 سم وتصل الى حوالي 36 م° عند عمق 60 سم، أي أن التشميس بتغطية التربة يرفع درجة حرارة الارض بمتوسط 15 م° عنه في حالة ابقاء التربة معراة. ودرجات الحرارة هذه كافية لتعقيم التربة من الأمراض. كما تم استخدام نموذج رياضي في هذه الورقة للتنبؤ بقيم درجات الحرارة لليوم الكامل وعند أعماق مختلفة في التربة. يستند النموذج على معادلة التوصيل الحراري أحادي البعد والشبه اللانهائي في المواد الصلبة المتجانسة في الخصائص الفيزيائية مثل تربة الارض. وقد تم تقييم النموذج الرياضي بمقارنته بالبيانات التجريبية ووجدت القيم المتوقعة وقياس درجات الحرارة في اتفاق مقبول أثناء النهار عند سطح التربة وتحيد القيم النظرية عن التوافق مع القيم التجريبية أثناء الليل وكلما زاد العمق في التربة. التحليل الشامل والتنبؤ بالأداء الحراري وفعالية التسخين بالطاقة الشمسية في التربة مفيد في تقييم تعقيم التربة وكذلك مفيد في عدة تطبيقات أخرى التي يتم الاحتياج فيها الى تقدير درجات حرارة التربة في الاعماق الصغيرة.

ABSTRACT

The main objective of this study is to investigate experimentally and theoretically the thermal behavior and solar heating effectiveness on bare and mulched soil. Temperature profiles of bare and mulched soil during soil solarization are investigated experimentally and theoretically. The experiment was carried out in a farm in Tajoura–Libya (N32° 40′ latitude, E13 09′ longitude). A set of soil's temperatures were measured at different depths up to 60 cm. Two $4m^2$ plots were mulched with 100μm thickness PE sheets and one plot (same size) without the cover was used as control (bare soil). Results indicated that in the summer time, the mulched soil temperatures reached values of about 62 °C at ground surface and reached about 51 °C and 36 ^{o}C at 30 cm and 60 cm depths respectively. Temperatures exceeding 45 ^{o}C in solarized soil at depths up to 50 cm have also occurred in several days during summer time; June, July and August; the temperatures of mulched soil get higher by an average of 15 ^{o}C than that of bare soil, these temperatures of the soil are high enough for controlling soil borne diseases. A mathematical model has been used in this paper to predict the temperature values for the whole day and at different depths in the soil. The mathematical model has been evaluated by comparison with experimental data. The expected values and measured temperatures have been found to be in acceptable agreement during the day at the soil surface; however, a deviation were recorded during the night and at higher depth in the soil. Comprehensive analysis and prediction of thermal performance and efficient solar heating in soil is helpful in evaluating soil solarization as well as useful in several other applications that need to estimate ground temperatures in small depths.

KEYWORDS: Soil Solarization; Mulched Soil; Temperature in Soil; Soil Borne Diseases.

INTRODUCTION

Knowledge of the ground temperature Profile at the surface and at various depths is required for agricultural greenhouses and building. One of the important uses of this knowledge is that for soil solarization. The potential for using soil solarization is to control disease and pests. It is typically accomplished by placing the clear plastic sheets on moist soil over the area that you wish to sterilize, the plastic sheet, allow the sun's radiant energy to be trapped in the soil heating the upper layers of soil. Solarization during the hot months can increase soil temperature to levels that kill many disease organisms (pathogens), nematodes, weed seeds and seedlings. It leaves nontoxic residence and be easily used on small and large scale. The heating process also induces other environmental and biological changes in the soil that indirectly affect soil-borne pests as well as survival of beneficial organisms. The duration of soil mulching that is required for successful effect is usually four to six weeks [1,2], depending on the pest, soil characteristics, climatic conditions and the PE properties. Several works have been done on soil solarization includes theoretical and experimental investigation on soil solarization to estimate the daily average soil temperature values at different depths in the soil. Most of the models developed try to predict the average daily temperature of the soil during the solarization and few of them concerned with the hourly soil temperature at different depth of the soil. Mihalakakou, G. et al. [3], introduced a model based on the transient heat conduction differential equation. The model use the energy balance equation at the ground surface which involves the convective energy exchange between air and soil; the solar radiation absorbed by the ground surface, the latent heat flux due to evaporation at the ground surface as well the long-wave radiation emitted from the ground. The model is validated by the measured temperatures for bare and short-grass covered soil in Athens and Dublin. Cenis J**.** L. [4] developed a model to describe temperature variations in a solarized soil. The Cenis model uses Fourier methodology to simulate the daily sinusoidal change of temperature in a homogeneous soil. Because its input requirements are daily maximum and minimum soil temperatures at two depths, its application is site specific. Wu, J. and Nofziger D. [5] introduced a model for estimation of annual variation of daily average soil temperature at different depths using a sinusoidal function. The study estimates average daily soil temperatures and displays these values as functions of time or depth for defined input parameters. The annual variation of daily average soil temperature at different depths was described with sinusoidal function. Yihua Wu a et al. [6] developed a numerical model to estimate the temperature profile of both mulched and bare soils. Atmospheric and soil conditions, are considered in the model. The required dynamic inputs are hourly measurements of global radiation, air temperature. The model was validated using hourly observations from 12 contiguous days of July 6-18, 1990 at the North Carolina State University. Yihua Wu a et al claimed that their model worked very well on both clear and rainy days except July 17 when large, rapid changes of the air temperature and solar radiation occurred.

The main objective of this study is to investigate the soil thermal behavior experimentally and theoretically when solar heating is applied to the bare and mulched soil.

MATERIAL AND METHODOLOGY

The experimental study was undertaken in farm at Tajoura–Libya (N32^o 40′ latitude, E13 09′ longitude) at altitude of 20 meter above sea level. The measurement was carried out from May 5, to September 30. A small area of about 12m^2 is chosen for solarization. This area before it had been solarized it was freed of weed, debris and large clods, which could raise the plastic off the ground. The soil was disked, turned over by hand and raked smooth to provide an even surface. After the soil dried a set of thermocouples were inserted at different depths in the soil up to 60 cm as listed in Table (1), the other ends of thermocouples were connected to the digital-meter used for temperature reading.

Table 1: Thermocouples locations

Type of soil solariazation	Bare soil						Soil is covered with transparent PE						Soil attached with black PE& covered with transparent PE					
Point	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Depth from surface, cm	1	10	20	30	40	50	1	10	20	30	40	50	1	10	20	30	40	50

The 12 m^2 area as shown in Figure (1) was divided into three smaller areas as following:

- Area about 4m^2 is left uncovered (bare), and 7 thermocouples were inserted at different depths up to 60 cm deep starting from the soil surface.
- Area about 4m^2 is mulched (covered) with 100µm thickness low-density transparent polyethylene (PE) sheet. This plastic cover was anchored to the soil by burying the edges in a trench around the treated area.
- Area about 4m^2 was attached by black plastic sheet and then covered with transparent PE sheet of 100µm thickness. The black sheet works as an absorber for solar radiation and the transparent sheet works as radiation trap and to reduce the heat loss due to convection; the two sheets were anchored to the soil by burying the edges in a trench around the treated area.

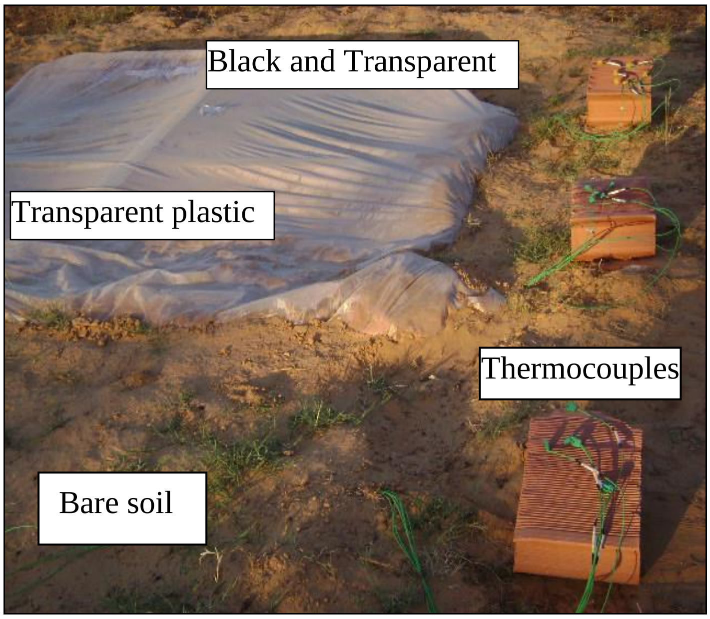


Figure 1: Bare and mulched soil covered with plastic sheet

EXPERIMENTAL MEASURMENTS

Temperatures of air, temperature of soil surface, and temperatures at different soil depths (up to 60 cm) are measured. Other parameters, such as wind velocity, solar radiation, and pressure, are measured; using Anemometers type (AR836) for wind and a pyranometer with data-logger of range of 0 to 4000 W/m^2 for solar radiation; (sometimes data of solar and wind were obtained from the metrological data of Tripoli at the internet). All the thermocouples used to measure the soil temperature were a Ni-cv/Ni-Al, type K, the thermocouples connected to digital thermometer; (the thermocouples together with the digital thermometers were calibrated over range of temperature between 0-100^{o}C. Because the temperature measurements are taken directly from the digital thermometer, the uncertainty of the temperatures measurements is assumed to be defined by the calibration accuracy, which is equal ± 0.2^{o}C. To determine the thermal conductivity of the soil, five sample of the soil were taken from different depths; the thermal conductivity was measured in a laboratory in University of Tripoli. The average value of thermal conductivity of the five samples of the soil was found 1.8 W/m. K.

THEORETICAL MODEL

The theoretical study was represented based on the transient heat conduction in one dimension in semi infinite solid case, since the solid (ground) extend to infinity in one direction (depth) it is characterized by single identifiable surface ($T(\infty,t)=T_i$). If a change of condition is imposed at the solid surface, transient one dimensional condition will occur within the solid. The semi infinite solid may provide a useful approximation for our problem.

The undisturbed ground temperature can be modeled by the general equation, which describes temperature (T) in homogenous, inert and isotropic soil at a given time (t) and depth (x) which is given by Fourier's law;

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{\partial T(x,t)}{\alpha \ \partial t} \tag{1}$$

Where α is the ground thermal diffusivity and x is the depth below the surface. An analytical solution of equation (1) for a semi-infinite homogenous solid with constant physical properties is reported in many textbooks like Incropera and Dewitt [7].

The transient Temperature distribution T(x,t) near the surface of a semi-infinite solid (like ground) as derived in text books for the case of constant heat flux q_o at surface is;

$$T(x,t) = Ti + \frac{2q_0(\alpha t/\pi)^{1/2}}{k} \exp(-\frac{x^2}{4\alpha t}) - \frac{q_0 x}{k} \ erfc\ (\frac{x}{2(\alpha t)^{1/2}}) \tag{2}$$

Where T_i is the initial temperature of the ground, q_0 is the constant heat flux flow to the ground, erfc is the complementary error function, k is the thermal conductivity of the soil, and x is the depth of the ground.

The heat flux q_0 in Equation (2) is considered as the average heat flux exposed to the surface of the ground and is evaluated as an average flux started from the morning when the sunrise at ST time up to time of the day at which the calculation of T(x,t) is looked-for, then q_0 is calculated as,

$$q_0\ (\text{at time j}) = \frac{\sum_{i=ST}^{j-1} \bar{q}_i}{\text{j - ST}} \quad , \bar{q}_i = \frac{q_i + q_{i+1}}{2} \tag{3}$$

Where, j is day-time (j = ST+1, ST+2, ST+3,… ST+23), q_i is the heat flux at the time of day started from sunrise ST (ST, ST+1 , ST+2 , ….,and when i = 25 to ST+23 stand for 1AM, 2 AM, ……, (ST-1) AM). For example, if sunrise at ST=7 O’clock, then the q_0 at j=11 O' clock is calculated as;

$$\frac{\sum_{i=7}^{11-1} \bar{q}_i}{11-7} = \frac{\bar{q}_7 + \bar{q}_8 + \bar{q}_9 + \bar{q}_{10}}{11-7} \quad , \bar{q}_7 = \frac{q_7 + q_8}{2}, \cdots ,$$

In order to solve equation (2) the net heat flux (q_i) at the certain time is calculated using the energy balance equation at the ground surface as follows:

$$q_i)_t = (SR - LR - CE - LE)_t \tag{4}$$

Where: SR is the solar radiation (short wave) at the ground surface (measured), LR is the long- wave radiation, CE is the convective energy exchange between air and ground surface, and LE is the latent heat flux due to evaporation.

The emission of long-wave radiation (LR) by the ground depends on the surface temperature and also affected by emissivity, according to the Stefan–Boltzmann law [7], the rate of energy emitted per square meter is computed as follows,

$$LR = \varepsilon\sigma(\mathrm{T_{sur}})^4 \tag{5}$$

Where: σ is Stefan Boltzmann constant (σ=5.669 *10^{-8} $Wm^{-2}K^{-4}$), ε is emissivity of the ground and T_{sur} is the surface temperature. The availability of energy and moisture at the earth-atmosphere interface is the critical condition for evaporation. The energy required for evaporation (heat used in the phase change from liquid to gas) is generally termed as the latent heat flux LE, which can be computed by the following formula [3];

$$LE = 0.0168 \ f \ h_{sur} \left[(aT_{sur} + b) - r_a (aT_a + b)\right] \tag{6}$$

where $\mathrm{h_{sur}} = 0.5 + 1.2(\mathrm{u})^{0.5}$

Where f, is fraction which depends on the humidity level of the ground and estimated [3] as; (f =1 for saturated soil and f = 0.6 - 0.8 for moist soil and f = 0.4 - 0.5 for dry soil and f = 0.1 to 0.2 for arid soil), h_{sur} convective heat transfer coefficient between air and soil, u is air velocity near the ground surface, T_{sur} is ground surface temperature, T_a is the air temperature and r_a is the relative humidity of the air and (a =103, b =609).
The energy exchange between the air and ground CE calculated as:

$$CE = h_{sur}(T_s - T_a) \quad and \quad \mathrm{h_{sur}} = 0.5 + 1.2(u)^{0.5} \tag{7}$$

T_s is the temperature at the ground surface, t_a is the air temperature near the ground surface, h_{sur} is the heat transfer coefficient, and u is the air velocity near the ground surface.

RESULTS AND DISCUSSION

EXPEREMENTAL RESULTS

The temperatures distribution are obtained experimentally at the ground surface and at different depths of the soil (1 cm to 60 cm) during the day time for period between (5/5/2008) to (30/9/2008) at farm in Tajoura - Libya (N32° 40′ latitude, and 20 m above the see level) [8]. The following cases of solarization are considered;

1) Bare soil,
2) Soil covered with transparent PE,
3) Soil attached with black PE and covered with transparent sheet (PE).

Figures (2 and 3) show samples of the experimental results, which represent the temperatures variations verses the daytime at different depths. The figures show that the soil temperature reaches its maximum value about 6 PM, and drops to its minimum value at night forming sinusoidal wave shape. The maximum temperatures values achieved during solarization at different depths are presented in Table (2).

From Figure (2 and 3), the surface temperature during the solarization of the bare soil (case A) reaches its maximum value of 41°Ċ at about 6 PM and it decreases to 33°Ċ at 8 PM, while the surface temperature for the soil covered with transparent PE cover reaches its maximum value of 59°Ċ at 6 PM then it decreases to 43°Ċ at about 8 PM. The surface temperature for the soil attached with black and covered with transparent PE cover (case B) reaches its maximum value of 61Ċ at 5 PM then decreases to 45Ċ at about 8 PM. The results show that the case (C) of soil attached with a black plastic and covered with transparent cover recorded the highest temperature values; regardless of economic point of view case (C) is the best way of soil solarization to kill most of disease organisms.

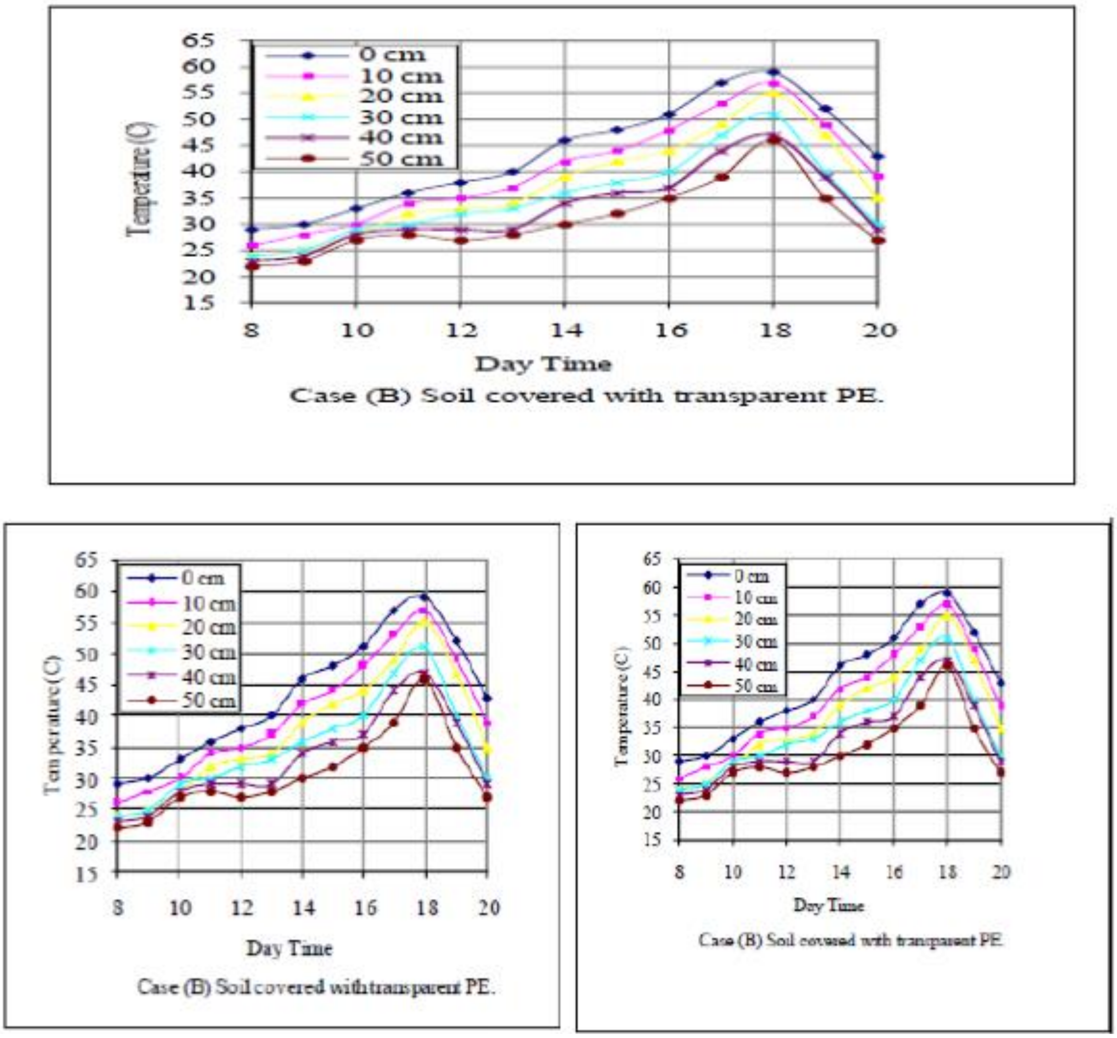


Figure 2: measured temperatures for the three types of soil solarization (Experimental data 18/6/2008)

Daily values of maximum temperature of both sollarized and bare soil throughout the solarization period are presented in Table (2) and Figure (3). The maximum temperature was always higher in solarized soil than bare soil, regardless of depth.

Table (2): Maximum temperatures values for the three cases of solarization

Soil Depth (cm) / Solarization Type	Max. temperature (ºĊ)						
	0	10	20	30	40	50	60
Bare soil	54	47	40	36	34	32	31
Soil mulched with Transparent plastic sheet	62	60	55	51	48	42	36
Soil attached with black PE and covered by Transparent PE	68	64	59	55	51	45	39

Figure (3) illustrates the influence of mulching type on soil temperature at different depths. The Figures show that the mulch has high contribution on the elevating of soil temperature; during the summer time, the temperature of mulched soil has an average values about 15Ċ higher than that for bare soil.

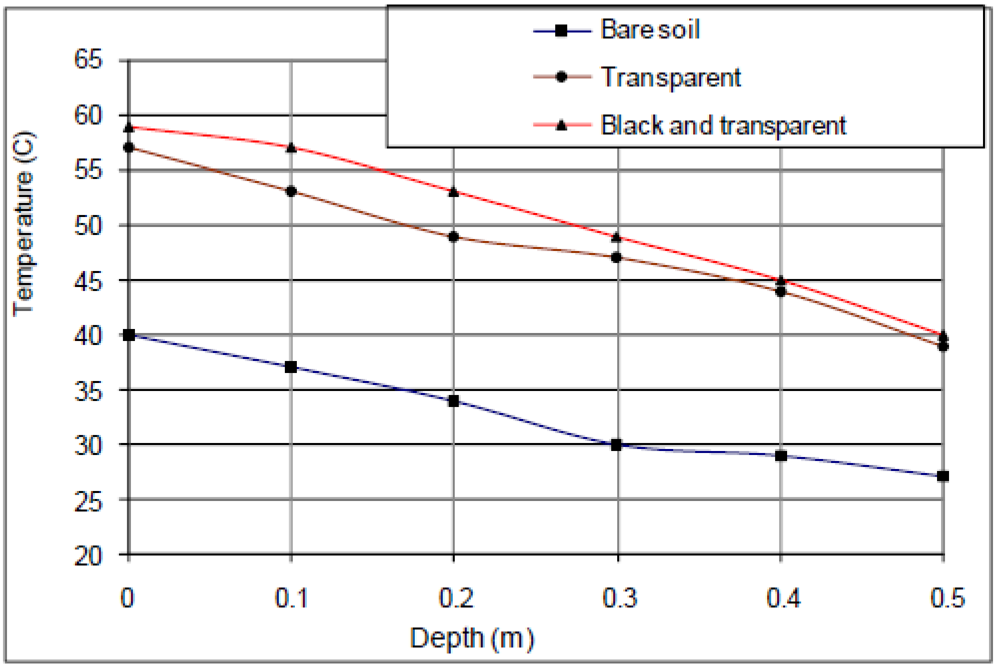


Figure 3: measured soil temperature vs. depth for the three cases of soil solarization (Experimental data 18/6/2008)

RESULTS COMPARSION AND VALIDATION OF THE MATHEMATICAL MODEL

FORTRAN program has been written to implement the model equations (2 to 7) to calculate the temperatures at different depths during the day for the three cases of soil solarization (i.e. Bare soil, Soil covered by transparent PE and Soil attached with black PE and covered by transparent PE.).

The input data are; soil specific heat is 1500 J/kg. K [9], soil thermal conductivity (measured) (1.8 Watt/m .K), soil density (measured) 1553 kg/m^3, soil temperature at infinity depth measured (T_∞ = 20 °C at depth 1 m), soil albedo 0.25, Latitude N32° 40′ and initial temperature of the ground T_i = 25°C. Other parameters, such as wind velocity, solar radiation, and pressure, are measured or sometimes obtained from the metrological data for Tripoli in the internet.

To validate the mathematical model, the calculated temperature values at different depths of the soil were compared with those from experiments. Figure (4) shows the predicted and the measured values of the soil surface temperature for bare and mulched soil. The figure shows that theoretical and measuring values are in good agreement. However, at the depths of 20 cm and over, the agreement between the experimental and that of the model deteriorated (see Figures 5 and 6).

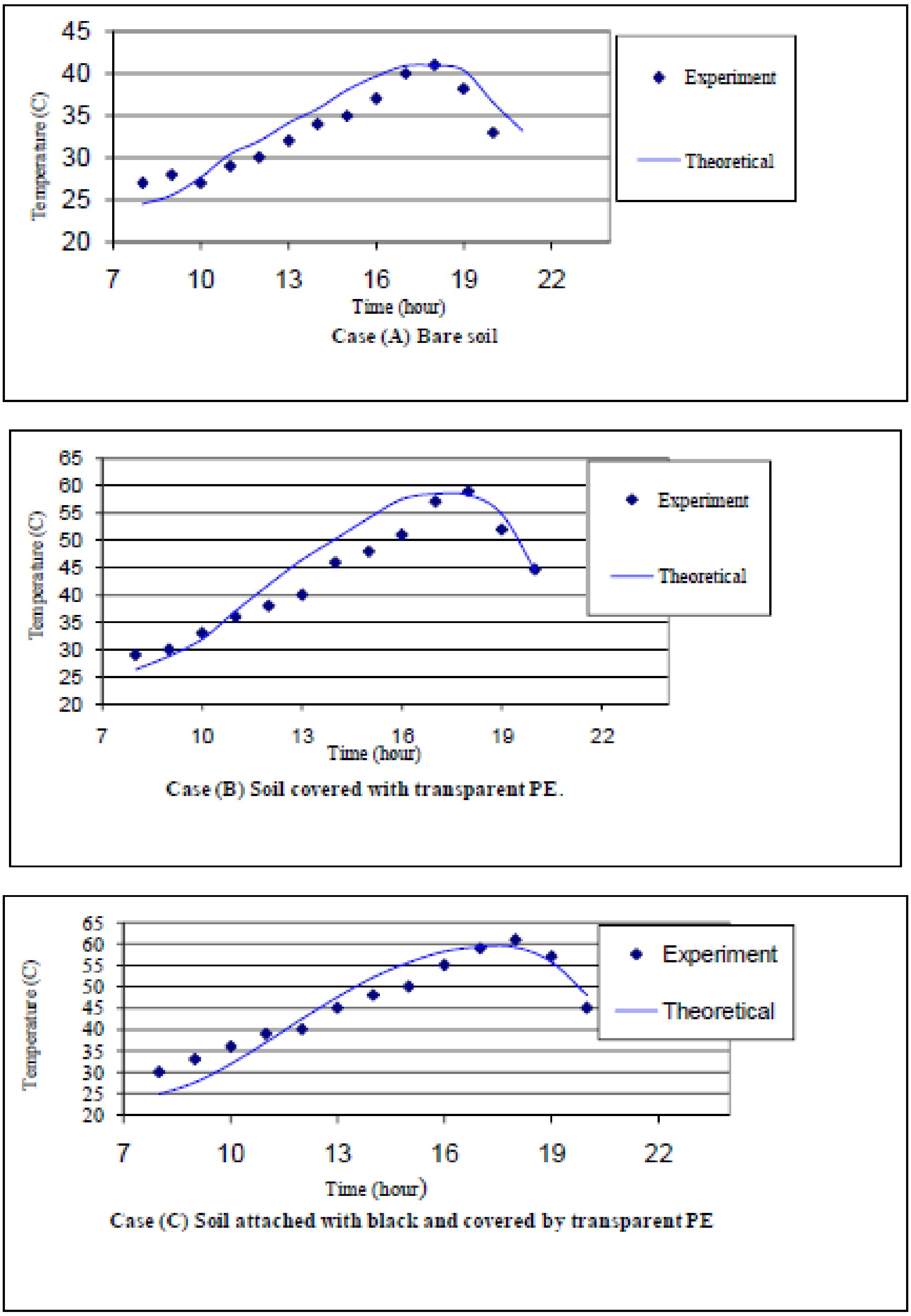


Figure 4: Comparison of measured and calculated temperatures at soil surface before model modification (day 18/6/2008)

The calculated temperatures at depths 20 cm, 40 cm, 50 cm or 60 cm, gave much lower values than those from experimental observations; therefore a development of the model is needed in particularly equation (2) which is responsible for evaluation of temperatures at various depths in the soil.

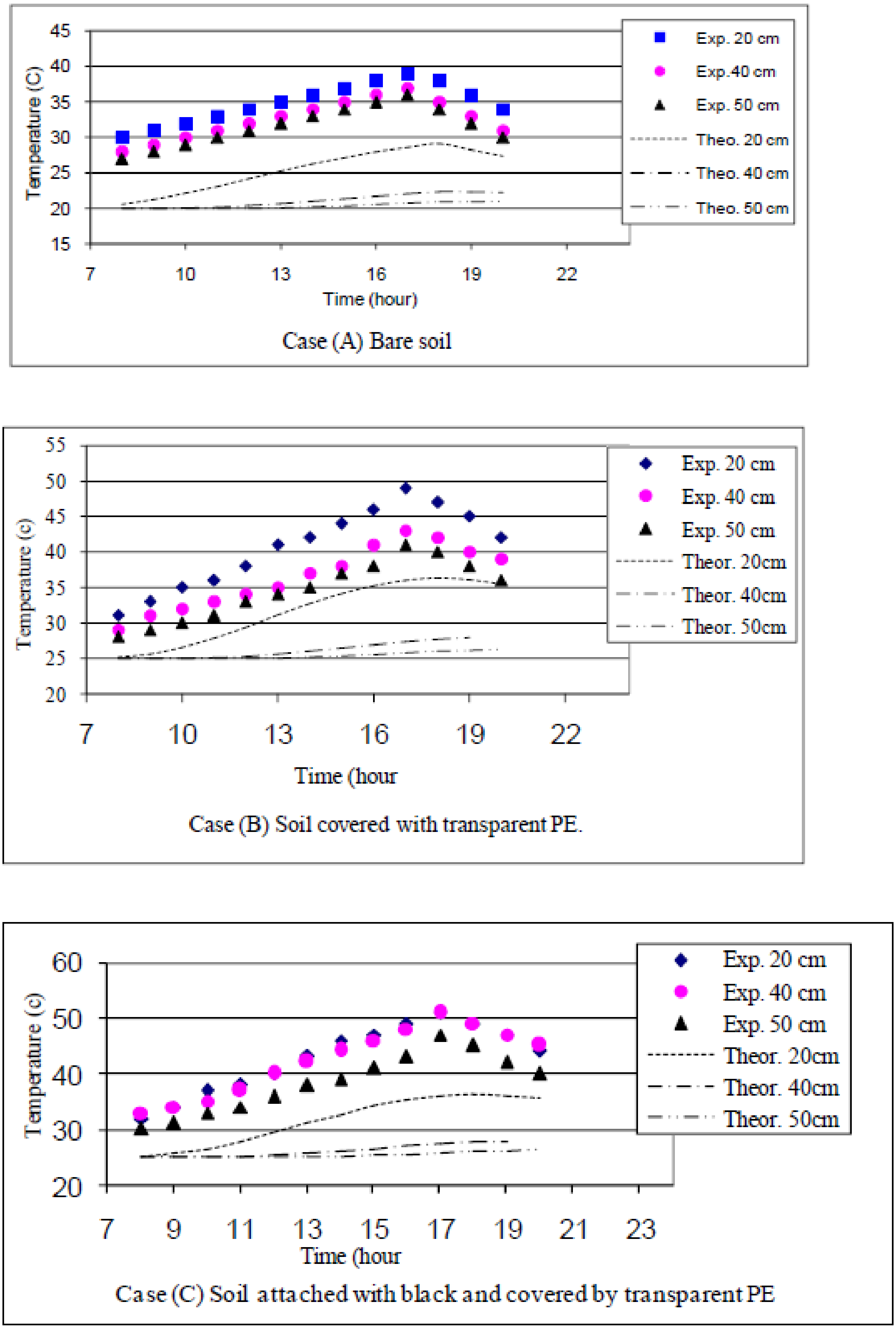
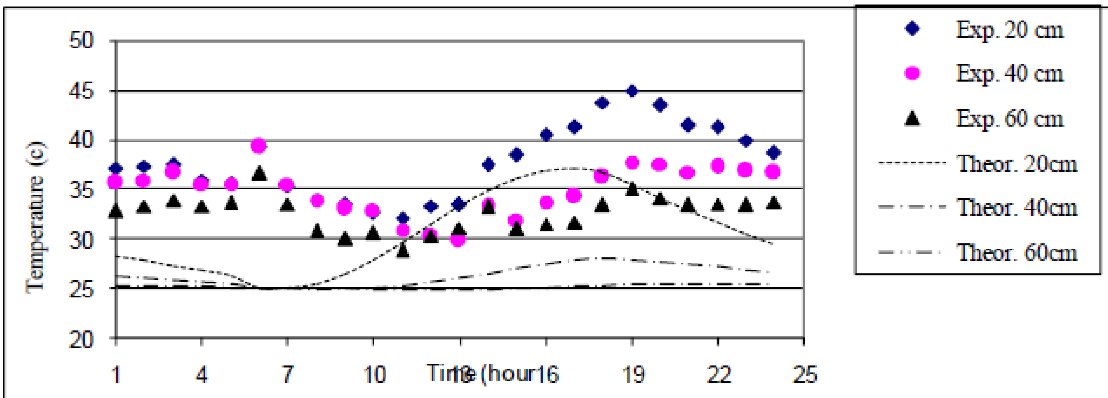
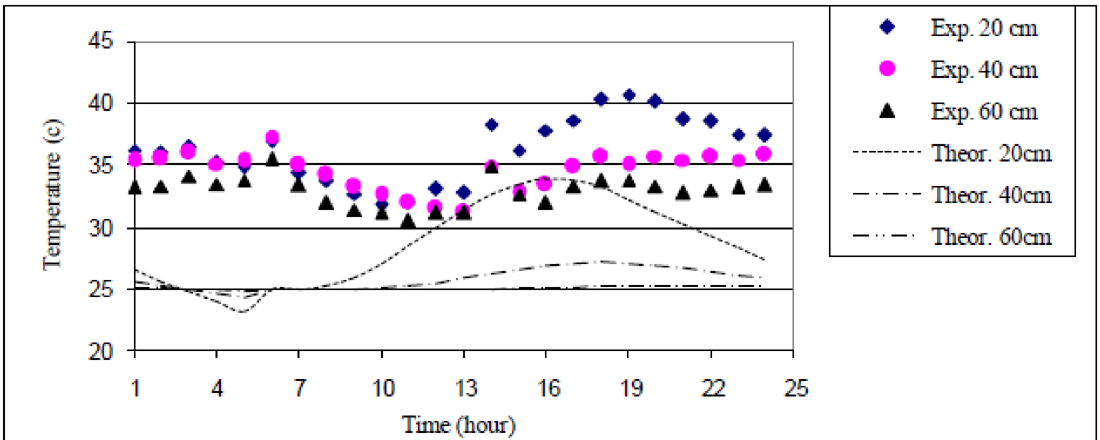


Figure 5: Comparison of measured and calculated temperatures at different soil depths before model modification (day 14/7/2008)



Case (C) Soil attached with black and covered by transparent PE



Case (B) Soil covered with transparent PE.

Figure 6: Comparison of measured and calculated temperatures at different soil depths before model modification (day 13/8/2008)

MODEL MODIFICATION

Maximum temperature in both solarized and bare soil decreased when soil depth increased. This behavior follows the classical theory of soil heat flux, which states that there is a harmonic function of time and that the temperature wave is dampened when depth is increased [4]. The behavior represented by equation (2) and the experimental data were used to develop a correlation to predict better temperatures distribution at different soil depths. By applying equation (2) to the experimental data, the statistical calculation gave the developed correlation, which somehow fit the experimental data as;

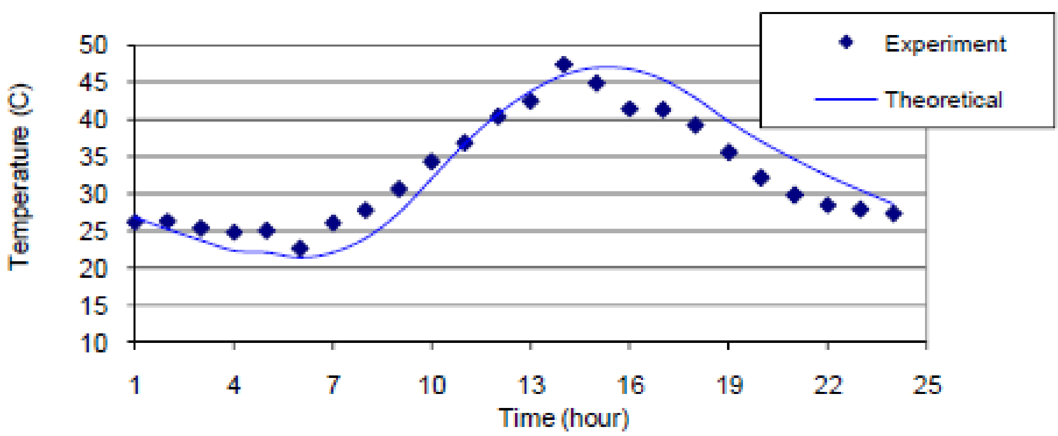
$$T(x,t) = Ti + \frac{2q_0(\alpha\, t/\pi)^{1/2}}{k}\exp\left(-\frac{x^2}{4\alpha\, t}\right) - \frac{q_0 x}{k}\, erfc\left(\frac{12x}{2(\alpha\, t)^{1/2}}\right) \qquad (8)$$

The percent standard deviation (PSD) and the standard deviation (SD) are calculated according to the following formula.

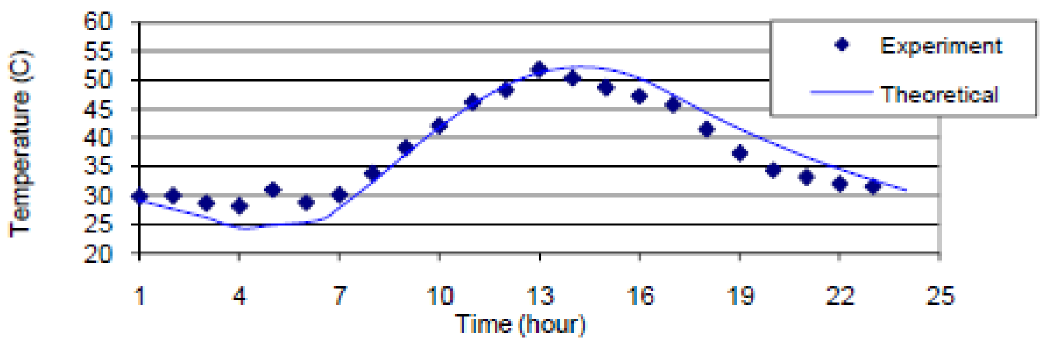
$$PSD = \sqrt{\frac{\sum_{i=1}^{N} \frac{(x - x_i)^2}{x^2}}{N}} * 100 \quad \text{and} \quad SD = \sqrt{\frac{\sum_{i=1}^{N} (x - x_i)^2}{N}}$$

Where N is the number of the values of temperature taken, x is the values from the experimental data; x_i is the corresponding value of temperature from equation (8). The PSD of equation (8) from that of the experimental data is found 14.6 and SD is found 2.4.

The results from the correlation (8) are compared again with the experimental data and are represented in Figures (7 to 9). From the figures, it can be seen that the developed correlation reasonably simulated the soil temperatures for both bare and mulched soils at different depths during daylight. However, the model did not work well during the nighttime. Further investigation and validation should be carried out to produce better correlations to simulate soil temperatures during both daytime and nighttime.

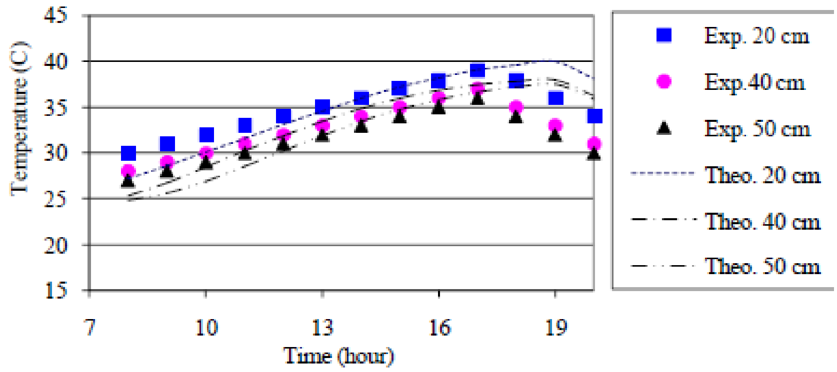


Case (A) Bare soil

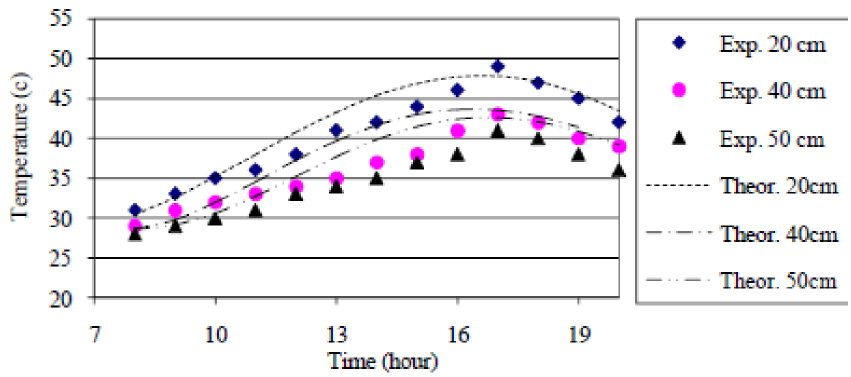


Case (B) Soil covered with transparent PE.

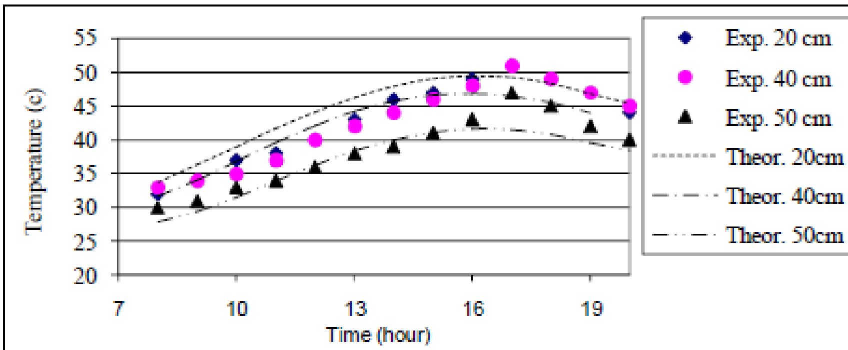
Figure 7: Comparison of measured and calculated temperatures at soil surface after model modification (day-13/8/2008)



Case (A) Bare soil Case



Case (B) Soil covered with transparent PE.



Case (C) Soil attached with black and covered by transparent PE

Figure 8: Comparison of measured and calculated temperatures at different soil depths after model modification (Exp. day 18/6/2008)

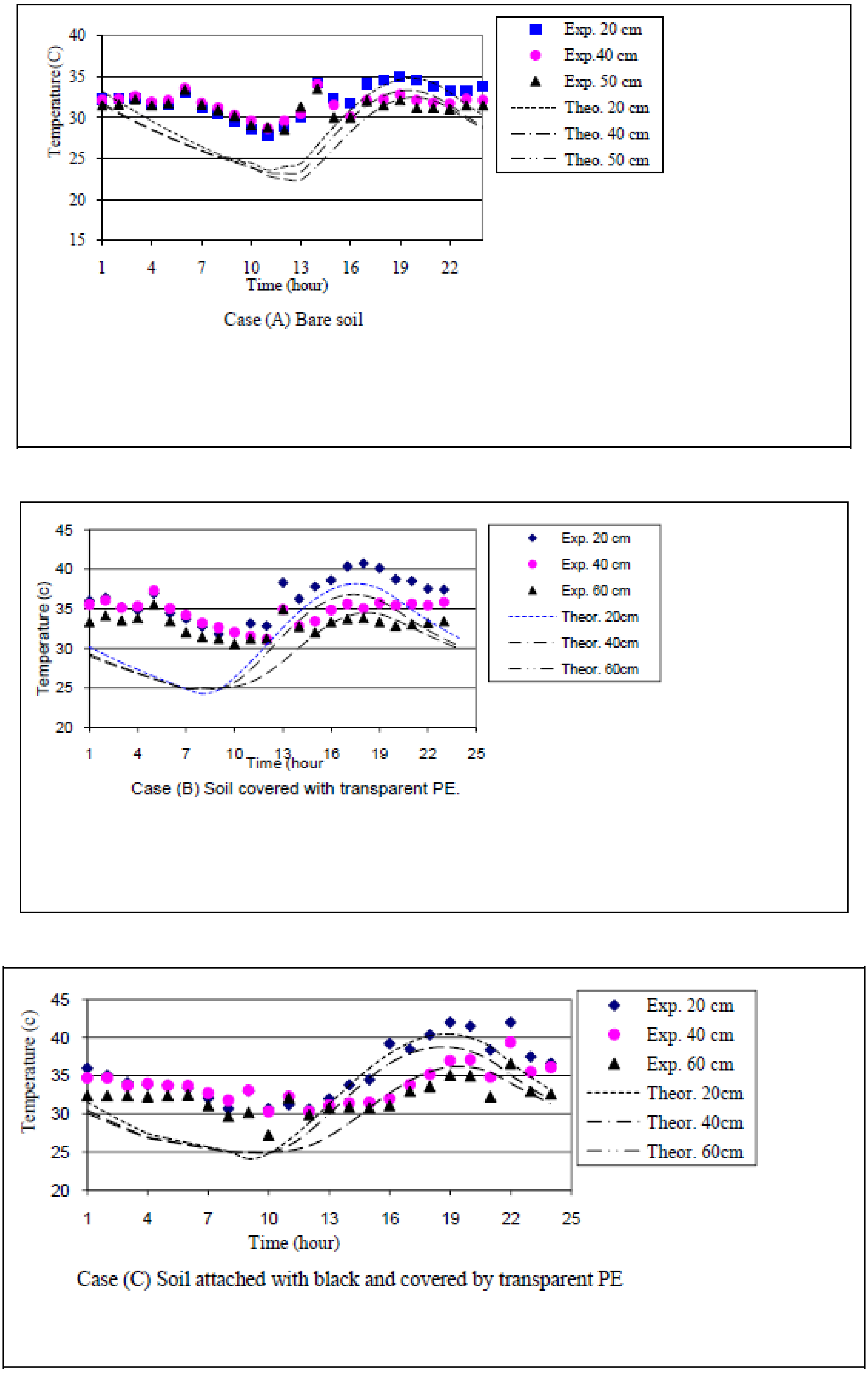


Figure 9: Comparison of measured and calculated temperatures at different soil depths after model modification (Exp. day 13/8/2008)

CONCLUSIONS

From the tests and experimental results considered in this study, it may be concluded the following;

- Soil solarization using soil mulching technique may rise temperatures of the soil during summer time about 15Ċ above that of bare soil therefore, the temperatures of the soil reach values that are high enough for controlling soil borne disease at 30 cm depth or less,
- Temperature in mulched soil was much higher than that in bare soil,
- The differences between mulched and bare soil temperatures changed during the day, and changed with soil depth; they were larger during daylight than at night, larger at shallow depth than at deep depth,
- The highest temperatures among the three cases are recorded when the solarization takes place using attached black PE to the ground and covered with transparent PE sheet; in summer time, the mulched soil temperatures reached values of about 62 ºC at ground surface and reached about 51ºC, 42ºC and 36ºC at 30 cm, 50 cm and 60 cm depths respectively. A model was developed and evaluated by comparison with experimental data and it was found that the expected values and measuring temperatures are in acceptable agreement during daylight. However, the agreement between the experimental and that of the model is terminated during nighttime.

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