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## Effect of Near-Earth Surface Temperature on Soil Temperature at 5 cm Depth

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### Authors' contributions

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

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### ABSTRACT

The research investigates the effects of ground surface temperature (air temperature) on soil temperature at a depth of 5 cm. The study covers a period of fourteen (14) months from May 2010 to June 2011 in Akure, Southwestern Nigeria. With the aid of an automatic weather station, temperature readings were taken at a depth of 5 cm below the soil surface at five (5) minute intervals daily. It was also observed that many analyses of soil temperature are based on the theories of heat flow and energy balance. The study reveals that surface temperature has a weak effect on soil temperature. The best correlation coefficient obtained for the study period is about 0.56 with a quadratic equation of order 2 at 5% significance level. This implies that air temperature cannot be solely used to predict soil temperature at a depth of 5 cm. A study of diurnal variation reveals that air temperature is usually higher than soil temperature during the day, and vice versa. The study also revealed that surface and soil temperatures are generally lower during the wet months when compared with the dry months. The wet season average daily temperatures are 23.42°C and 27.69°C for air and soil while the corresponding dry season values are 33.92°C and 30.91°C respectively. The results are recommended for agricultural purposes such as determination of soil and environmental conditions for crop production.

*Keywords: Heat flow; energy balance; surface temperature.*

## 1. INTRODUCTION

The concept of temperature is rooted in the quantitative ideas of hot and cold based on our sense of touch. A body or system that feels hot usually has a higher temperature than a similar system that feels cold. Most properties of matter that can be measured depend on temperature. This is because temperature reveals microscopic information about matter at any given time [1]. For instance, temperature is directly related to the average translational kinetic energies of the molecules of a material. Hence, the temperature of a system contributes to the magnitude of thermal and mechanical vibrations of a system.

Ground surface temperature is the measure of the average kinetic energy of the air molecules above the ground surface, while soil temperature is the measure of the average kinetic energy of the air molecules below the surface. Soil temperature varies in response to the change in radiant thermal and latent energy exchange processes that proceed through the soil surface. Soil temperature is an important agrometeorological parameter. In general, the flow of heat through the soil is critical to plant growth. Extreme levels of soil temperature as well as air affect plant life. The availability of water content causes variation in soil temperatures. The microclimate of soil is well understood through the study of heat flux. The ground surface gets heated more during the day by intense solar radiation than the layers beneath, resulting in a temperature gradient between the surface and subsoil. Within the soil, this causes heat to flow downward as a thermal wave, the amplitude of which changes with depth. Estimation of heat flux from the soil temperature data can provide an understanding of the gain or loss of heat by the soil from the atmosphere. Many previous studies have been conducted on similar issues such as soil temperature prediction, heat storage variations, thermal diffusivity of the soil, and so on [2-6]. Climatic conditions on the earth's surface are in part a function of varying physical position (elevation, latitude, and aspect) and the influence of large-scale meteorological forces such as air and ocean currents. The density and architecture of plant canopies in natural systems are directly influenced by climatic factors.

By contrast, for agricultural systems, it is the crop canopies that often influence the local microclimate. In both instances, the soil plays an important role in affecting the climate near the surface. The properties of the surface soil layer,

including colour, water content, texture, and density, affect the partitioning of incident radiation and the amount of energy used to evaporate water, warm the air above the ground, or warm the soil. The amount of thermal energy that moves through an area of soil in a unit of time is the soil heat flux or heat flux density [2]. The ability of soil to conduct heat determines how fast its temperature changes during a day or between seasons. Soil temperature is a key factor affecting the rate of chemical and biological processes in the soil essential to plant growth. However, the importance of soil heat flux in predicting the energy transfer process in the soil cannot be overemphasized. Soil heat flux is important in micrometeorology because it effectively couples energy transfer processes at the surface with energy transfer processes in the soil [7].

Several models have been introduced to predict soil temp at different depths. These models are location dependent [8-11]. Hence, there is need to consistently measure directly and compare result with some available models for climatic regions. It is important to note that formulation of these models was based on empirical measurement taken in specific climatic zones. Researches have revealed that soil temp is influenced by several factors such as depth, weather, climate, soil type etc [12]. For instance, [13] reported a close correlation between air temperature and soil temperature at depth of about 20 cm in spring at Nanchang.

### 1.1 Surface Energy Balance and Soil Heat Flux

In micrometeorology, measurement of soil heat flux is often considered within the context of the surface energy balance

$$R_n - G = LE + H \quad (1)$$

where  $R_n$  is the net radiation,  $G$  is the soil heat flux density at the soil surface, and  $LE$  and  $H$  are the latent and sensible heat flux densities, respectively. All terms in the equation above have units of  $J m^{-2} s^{-1}$  or  $W m^{-2}$ . Note that in the equation stated above, all fluxes away from the soil surface are defined as positive except for  $R$ . The left side of the equation ( $R - G$ ), represents the available energy, while the terms on the right side ( $LE$  and  $H$ ) are often referred to as the turbulent fluxes. Much of the energy that enters the soil during the day returns to the atmosphere

at night through terrestrial long-wave radiation. As a result, G is frequently the smallest component of the daily surface energy balance and has been overlooked in some cases; however, there are often significant transfers of energy into and out of a soil during both day and night hours, and failure to include G in short-time (i.e., hourly) energy balance determinations can lead to significant errors [14].

## 2. METHODOLOGY

### 2.1 Research Location and Instrumentation

The experimental site used in this study is the Meteorological Observatory Garden of the Department of Physics, Federal University of Technology Akure (FUTA), shown in Figs. 1 and 2. Surface and soil temperatures were retrieved from the archive of the automatic weather station. The weather station is a Davis Vantage Pro Instrument with multiple sensors for

measuring such as temperature, humidity, pressure, wind speed, wind direction. It has a resolution of 5 minutes and it is integrated with a data logger for the data measured at every time interval.

The data acquired from the automatic weather station covers the two major seasons in Nigeria, which are the rainy and dry seasons. The atmospheric and soil temperatures (in degrees Celsius) cover a period of one year from May 2010 to June 2011. Surface temperatures utilized in this research refer to the air temperature at a height of 200 cm above the surface of the ground. The soil temperature is the temperature of the soil as measured by a temperature sensor buried at a depth of 5 cm below the soil surface. This depth was chosen because most soil ecosystem processes such as decomposition of soil organic matter and mineralization of soil nutrients occur between 0 – 20 cm below the top layers of soil [15-16].



**Fig. 1.** The automatic weather station at FUTA within the premises of physics department



**Fig. 2. The data logger showing the process of data retrieval**

**2.2 Computation of Mean Temperatures**

The 5-minute interval temperature data was downloaded to a computer and processed as follows. The data was sorted and arranged orderly by removing the null and obviously arbitrary values. The raw data was sorted into days and months to study the diurnal and seasonal variation of both temperatures. The average hourly values *x* for surface and soil temperatures were computed separately using equation (2).

$$x = \frac{1}{n} \sum (P_1 + P_2 + P_3 + \dots + P_n) \quad (2)$$

where *n* is the number of datapoints and *P<sub>n</sub>* is the temperature values at a 5 minute interval.

The corresponding daily values *y* for the entire study period were deduced by averaging the daily values as illustrated by equation (3)

$$y = \frac{1}{m} \sum x_1 + x_2 + x_3 + \dots + x_m \quad (3)$$

where *m* is the number of hours in a day (24) and *x* is the hourly mean values of the surface and soil temperature as indicated in equation (2).

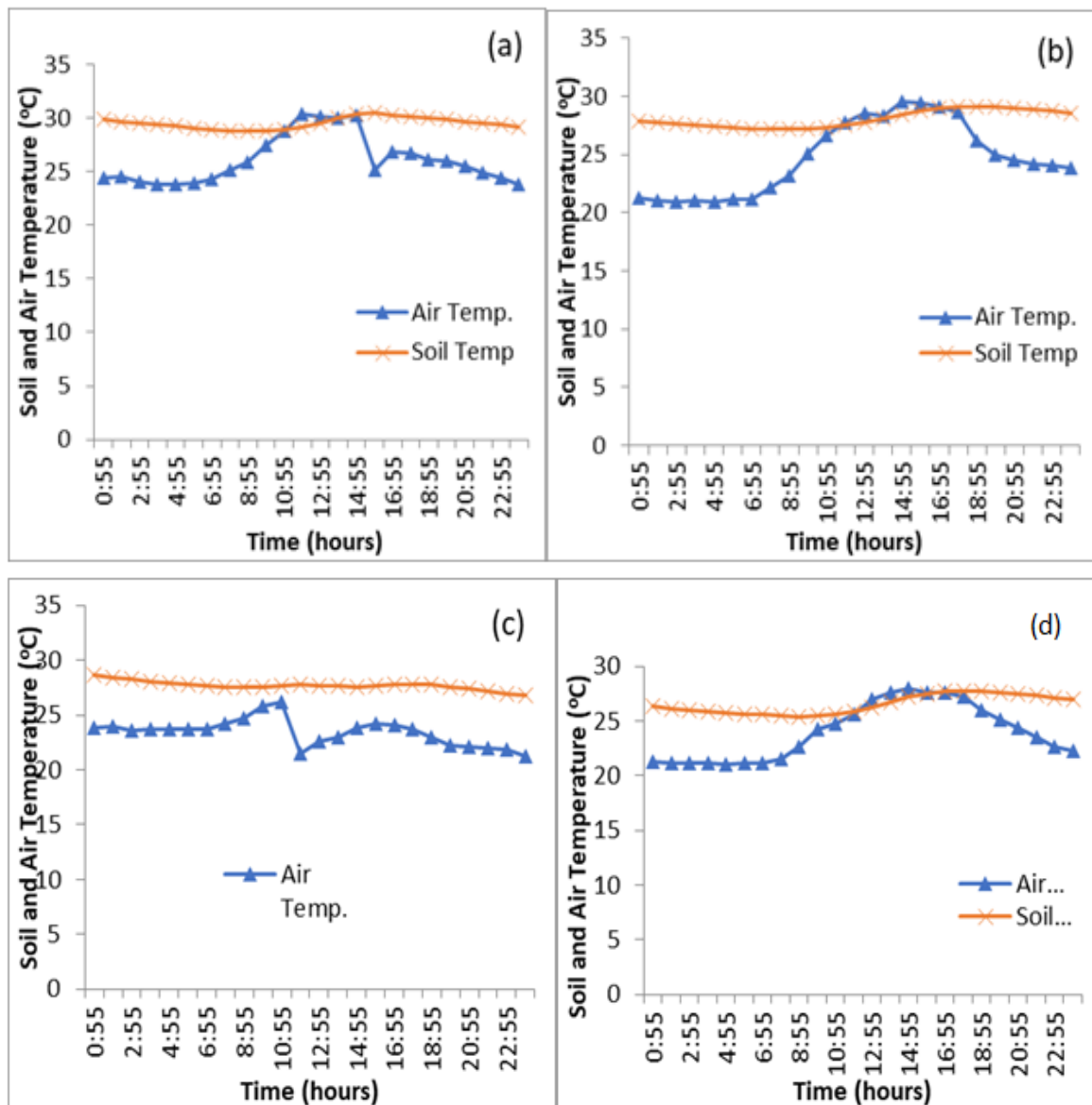
The maximum and minimum surface temperatures corresponding to the soil temperature were also determined from the data. The diurnal, seasonal variation, and relationship between surface temperature and soil temperature were investigated and discussed in the subsequent sections.

### 3. RESULTS AND DISCUSSION

#### 3.1 Diurnal Variation

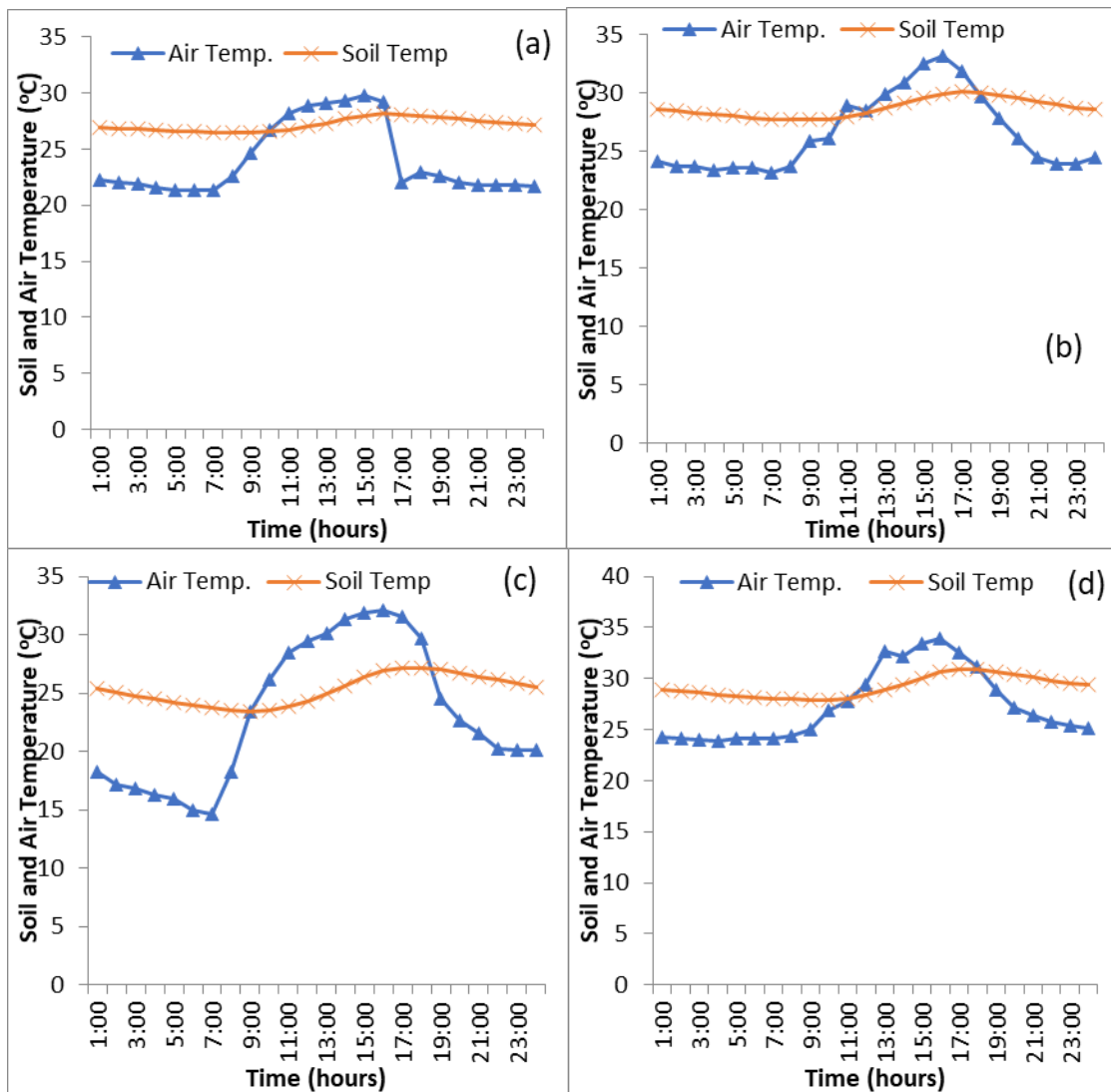
The diurnal variation of air and soil temperatures was also studied based on the available data. Figs. 3a-d and 4a-d show the diurnal variation for the wet and dry months. It was observed that both air and soil temperatures are usually low during the early hours of the day, i.e., between 00:00 and 10:00 hours. This could be attributed to the absence of solar radiation from the sun.

The gradual increase in atmospheric temperature during the day is mostly due to the convective heating of matter by solar radiation [17]. The quantity of heat energy absorbed by the soil depends on the mass of soil exposed to the sun and other factors, such as the specific heat capacity of the soil. The consequence is an increase in temperature with depth, which is a unique feature of the troposphere [18]. This explains why the measured soil temperature is always higher than the corresponding air temperature.



**Figs. 3(a-d). Diurnal variation of soil and air temperature during the wet months; (a) May, (b) June, (c) July, (d) August**





**Figs. 4(a-d). Diurnal variation of soil and air temperature during the dry months; (a) November, (b) December, (c) January, (d) February**

As the sun rises, both the air and soil temperatures rise gradually with respect to the radiant energy emitted by the sun per unit time.

Both temperatures increase gradually until they attain peak values. Figs. 3 and 4 indicate that the average daily temperatures for both air and surface attain peak values between 14:00 and 16:00, which implies that maximum solar radiation is received by the soil during this period. The maximum daily air and soil temperatures throughout the study period are 33.92°C and 30.91°C which were recorded at about 16:00 in February, respectively. It is worthy to note that the air temperature gradually surpasses the soil temperature during that period of the days. This is due to the direct and ground-

reflected heat fluxes received by the air molecules near the soil surface. This is the period when the air temperature reaches its daily maximum, as shown in Figs. 3 and 4. Similar results were obtained by [19] for soil temperatures between 0 – 20 cm. The temperature begins to fall due to the gradual disappearance of solar radiation. The air molecules near the surface lose heat at a higher rate than the soil; hence, its temperature becomes lower than that of the soil.

### 3.2 Seasonal Variation of Air and Soil Temperature

The seasonal variation of air and surface temperature was studied by considering the months where the seasonal effects on

temperature were intense. The selected wet season months are May, June, July, and August, while the dry months are November, December, January, and February. In the wet months, the air temperature varies between 21.5°C in July and 30.4°C in May, while the soil temperature is fairly constant between 29.8°C and 26.0°C. This shows that the temperature is uniform throughout the rainy season. This could be attributed to frequent rainfall, which keeps the soil moisture content at a minimal during this period. Figs. 3a-d show that air temperature rises slightly between 11:00 a.m. and 15:00 a.m. due to sporadic solar activity during the rainy season. The influence of solar radiation during the rainy season is quite minimal when compared with the dry season. The 'bumpy' shape of the hourly trend of the air temperature is more pronounced in the dry season, as depicted in Figs. 4a-d. This is because the air temperature rises sharply as a result of intense solar radiation between 9:00 hrs and 15:00 hrs daily. This causes the air temperature to surpass the soil temperature during the active solar hours. The maximum and minimum daily air temperatures were observed to be about 33.92°C in the month of February and 14.60°C in January during the dry season, respectively. The extremely low air temperature in January could be likened to the peak of harmattan when cool winds from the Sahara Desert move into the Gulf of Guinea [20]. Hence, the super-cooled wind suppresses the air temperature. This is usually accompanied by hot weather between February and March signifying the end of dry season.

### 3.3 Correlation between Soil and Air Temperature

The two temperatures were compared to investigate the relationship between them. A scatter plot of soil temperature against air temperature for all the periods of the days shown in Fig. 5 reveals that there is a very poor correlation between these temperatures. Among all the regression models, a polynomial of order 2 produces the best correlation coefficient of 0.33.

$$S_r = -0.0209A_r^2 + 1.272A_r + 9.3337 \quad (4)$$

This implies that equation (4) cannot satisfactorily predict the soil temperature for a known air temperature. In order to obtain a better result, the active solar hours of 10:00–17:00 hours were filtered, since Figs. 3a-d and 4a-d had earlier depicted a poor relationship during the sunshine hours. The new scatter plot and the corresponding equation obtained are presented in Fig. 6 and equation (5) respectively. Although the correlation coefficient improved to about 0.56, this is not sufficient to recommend the modelled equation for prediction of soil temperature based on air temperature. The improved relationship is due to the absence of solar radiation which creates tendency for the ground surface air molecules and the soil to approach thermal equilibrium.

$$S_r = -0.0017A_r^2 + 0.1015A_r + 29.345 \quad (5)$$

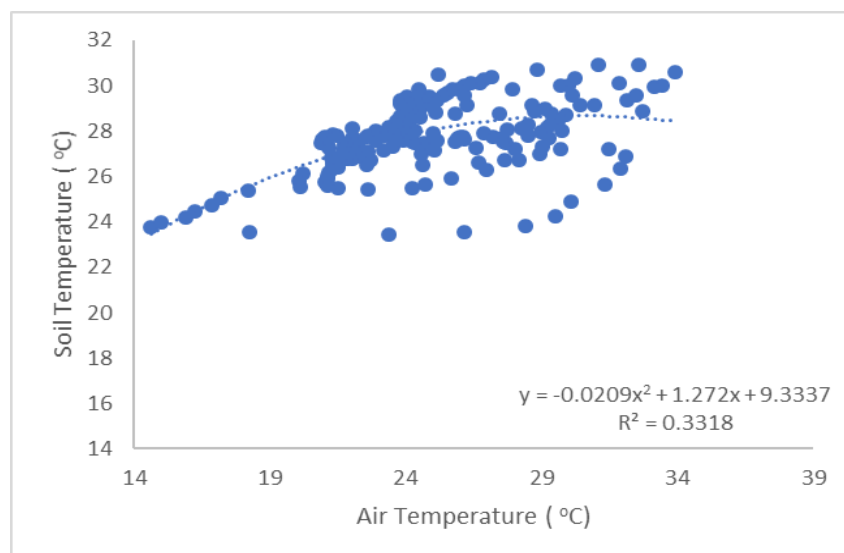
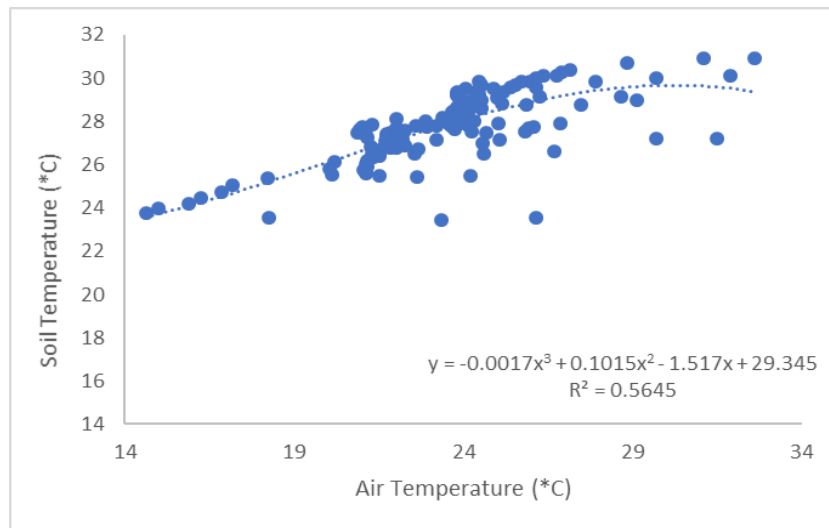


Fig. 5. Correlation between air and surface temperature for inactive and active solar periods



**Fig. 6. Correlation between air and surface temperature for inactive solar period**

**Table 1. Comparison of correlation coefficient from previous and present studies**

Literature	Soil Depth (cm)	Location	Climate	Correlation coefficient (R <sup>2</sup> )
Zheng et al. [8]	10	United States	Temperate	0.86
Ana et al., [21]	0	South Africa	Subtropical	0.996
Ahmad and Rasul [9]	10-20	Faisalamad, Pakistan	Temperate	0.32 – 0.86
Zhan [13]	20	Nanchang, China	Temperate	0.85
Present study (Lawal et. al., 2022)	5	Akure, Nigeria	Tropical	0.33 - 0.56

The correlation results obtained in this study were compared with previous works as presented in Table 1. Although the results from most of the previous work depicts good correlation, factors such as climate, soil type could have influenced the results. Nigeria (Akure) is a tropical climatic region whereas the stations used in the available previous are temperate except South Africa which is subtropical. Moreover, the type of soil used most previous studies were not indicated. In order to obtain consistent, effective and reliable comparative analysis, factors that influence soil temperature such as soil depth, soil type and climate should be made uniform.

#### 4. CONCLUSION

The effects of surface temperature on soil temperature have been investigated, using Akure as the study location. The diurnal variation reveals that soil temperature is typically lower than air temperature, but this trend is reversed during peak solar hours due to direct and ground-reflected heat flux absorbed by air

molecules. It was observed that the values of surface or air temperatures are high in the dry season and apparently low in the rainy season. This is in conjunction with the associated temperatures in the tropical region. It was also observed that many analyses of soil temperature are based on the theories of heat flow and energy balance. Although some similar research works conducted in other climatic regions suggest good correlation between air and soil temperature, the present study reveals the existence of a very weak coefficient of correlation between these temperatures. This is attributed to the impact of other determinants of soil temperature such as soil depth, soil type, climate etc. The results suggest that the variation of air temperature is not absolutely governed by soil temperature.

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### COMPETING INTERESTS

Authors have declared that no competing interests exist.

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