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Thermal Diffusivity Variations at Ministry of Agriculture Akure South, Ondo State, South–West Nigeria

K. D. Adedayo[1], J. S. Ojo[1] and I. E. Okoroafor[1*]

[1]Department of Physics, Federal University of Technology, Akure, Ondo State, Nigeria.

Authors' contributions

This work was carried out in collaboration between all authors. Author KDA was fully involved in the experimental and data acquisition. Authors JSO and IEO managed the analyses of the study and wrote the first draft of the manuscript. Author IEO also managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Thermal diffusivity variations of different soil types in a tropical location, Akure, Nigeria at three different depths over dry and wet seasons are presented. The time lag method was used to estimate the thermal diffusivity (*D*) of the experimental site using the hourly and mean weekly temperature distribution alongside soil properties such as moisture content, bulk density, porosity and soil heat capacity, at the depths of 30, 40, and 50 cm. Soil type include sandy clay for the 30 cm depth and sandy loamy clay for the 40 and 50 cm depths. Results obtained show a larger variation of thermal diffusivity, having an average value of 59.68×10^{-7} m^2/s in the wet season as compared to 1.41×10^{-7} m^2/s for the dry season. Strong correlation exists between the diurnal variation of soil temperature modeled based on different depths and the measured values.

Keywords: Thermal diffusivity; temperature; soil moisture content.

**Corresponding author: E-mail: iernest72@yahoo.com;*
Communication id: josnno@yahoo.com;

1. INTRODUCTION

Soil temperature is a fundamental factor of great importance as it affects many physical, chemical and biological processes in the soil. Its occurrence may vary diurnally, weekly, monthly as the case may be and this is primarily a function of the incident solar radiation over the study locations [1]. Other factors that might influence soil temperature include seasonal swings in the overlaying air temperature, local vegetative cover, types of soil and depth in the earth [2]. The annual variation of daily average soil temperature at different depths is described with the following the following sinusoidal function [3]:

$$T_{(z,t)} = T_a + A_0\, e^{z/d} \sin \frac{2\pi(t - t_o)}{365} - \frac{2}{d} - \frac{\pi}{2} \quad (1)$$

where $T_{(z.t)}$ is the soil temperature at time t(s) and depth z(m), T_a is the average soil temperature (°C), A_o is the annual amplitude of the surface soil temperature (°C), d is the damping depth (m) of the annual fluctuation and t_o is the time lag i.e (days) from the arbitrary starting date to the occurrence of the minimum temperature in the year.

Due to much higher heat capacity of the soil relative to that of air and the thermal insulation provided by vegetation and surface layers, seasonal changes in soil temperature deep in the ground are much less than and lag significantly behind seasonal changes in the overlying air temperature.

During the day, the earth's surface gets heated up as a result of the impact of solar radiation and this thermal radiation penetrates through the soil in the form of a thermal wave. Consequently, the temperature in the near sub-surface has a progressive phase shift, such that at minimum air temperature is generally slightly higher, and at times of maximum air temperatures, ground temperatures are lower [4]. Temperature variation in different soil types is also due to the response precedent by changes in the radiant, thermal and latent heat exchanges.

Thermal diffusivity is the change in temperature occurring in a unit volume as result of the quantity of heat flowing through the volume in unit time under a unit temperature gradient.

As defined by Incorpera and Dewitt [5], a materials thermal diffusivity (D) is a measure of its ability to conduct thermal energy relative to its ability to store thermal energy. Its S.I. unit is m^2/s. Materials with high thermal diffusivity will respond faster and will reach thermal equilibrium in a shorter time as its thermal environment changes as compared to a material with a smaller thermal diffusivity. Ultimately, soils with high thermal diffusivity undergo large and rapid subsurface responses to surface temperature change.

Modeling of soil temperature in time and depth requires knowledge of the soil surface energy balance as well as the soil thermal properties such as thermal conductivity and volumetric heat capacity, represented together by the thermal diffusivity. Thermal diffusivity can be estimated under field conditions from soil temperature data [6,7]. The temporal variability of the parameters that govern heat transfer in soils is determined mainly by the soil moisture. This is due to the fact that water and air are the only soil constituent which can vary considerably on a daily basis. The specific objective of the research is to determine the rate of temperature variations at different depths in a tropical location, Akure, South-West, Nigeria and consequently, obtain the soil thermal diffusivity of the soil at the location.

2. SITE AND DATA

The experimental site is the Ministry of Agriculture at Akure (7.15°N, 5.17°E), South-west Nigeria. The site has a height above sea level of about 350 m and belongs to soils of clayey-sandy type under a dense rain forest vegetation of the tropical climate. The region experiences alternate dry and wet seasons. The temperature ranges between 21°C to 30°C with high relative humidity and annual rainfall of about 1750 mm. The study utilizes data of daily soil temperature values at depths of 30, 40 and 50 cm and air temperature for 1 m above the soil surface during the dry and rainy months, obtained through in-situ method using a Davis Vantage Pro data logger and tiny sensors gotten from the Federal University of Technology, Akure, Ondo State, Nigeria, installed at the experimental site. The depths were selected because major root density at the reproductive stage of most of the cereal crops is at these depths [8]. The set-up is composed of different sensors units that measure soil moisture content, as well as soil and air temperature humidity, also a transmitter and receiver unit placed at about250 cm apart is part of the set-up. Depths of 30, 40 and 50 cm were dug and the sensors placed into them being spaced about 50 cm from each other.

Table 1. Characteristics of the soil obtained for Ministry of Agriculture, Akure South, at different depths for both dry and wet seasons

Location	Depth (cm)	Soil moisture (θ) %	Bulk density (ρ_b),g/cm^3	Porosity (ϕ) %	Soil color	Soil texture	Specific Heat (C_p), J/Kg k
Ministry of Agriculture,	30	20.68	1.598	33.053	light reddish brown	Sandy clay	1.12
Akure south L.G.A.	40	19.824	1.703	33.771	light reddish brown	sandy clay loam	1.12
	50	15.009	1.410	21.167	light reddish brown	Sandy clay loam	1.08

Although the equipment measures the parameters at different hours of the day, a 10 minutes interval of temperature readings were obtained and averaged to obtain the daily mean. the air temperature and soil temperature at the site was also measured every three hours from the 20th to the 25th of December 2011 and 10th to 15th May, 2012. The above six days in December and May were chosen to represent the dry and rainy days respectively. For each soil depth, estimation of other parameters associated with the soil thermal properties such as soil moisture, soil bulk density, soil specific heat and porosity was done using laboratory measurements obtained from the site using a soil measuring can and the average values obtained from the measurements for dry and wet seasons are shown in Table 1 above.

3. THERMAL DIFFUSIVITY

A materials thermal diffusivity (D) is a measure of its ability to conduct thermal energy relative to its ability to store thermal energy.

Estimation of the thermal diffusivity was obtained through the phase lag method, where the phase-lag between thermal waves at two depths was used [9], the relation is given as:

$$D = \frac{\tau}{4\pi}\left[\frac{z_2 - z_1}{t_2 - t_1}\right]^2 \tag{2}$$

where τ is the period of fundamental cycle which is a day measured in seconds, z_2 and z_1 are the different depths and t_2 and t_1 are the time taken to reach maximum or minimum temperature at depths z_2 and z_1.

In obtaining the thermal diffusivity, a three hourly temperature variation was observed from the data logger, as estimation of D using smaller time variations would yield little changes. The temperature variation between the two depths was then determined by applying the phase-lag equation.

The phase-lag method was used because it gives a better determination under uncontrolled conditions and where there is a temporal temperature gradient such as observed in deeper layers where the temperature amplitude is slightly appreciable.

Figs. 1 and 2 show the diurnal variation of surface temperature for dry (23rd and 24th December) days and for wet (10th to 11th May, 2012) days respectively. During the dry season, the morning hours observed temperature depression due to the Harmattan that is peculiar to this period of the year, while the afternoon–evening hours experienced rise in temperature. Air temperature variation of up to 1 m above soil surface shows a distinct variation between the dry and rainy season. A range of about 3°C is observed for both seasons but the temperature distribution for the dry season was as high as 32°C while the wet had a value of about 30°C. Figs. 3 and 4 also present the diurnal variation of soil temperature at depths 30, 40 and 50 cm during the dry and wet season respectively. The diurnal soil temperature wave penetrates to 30 cm and 50 cm with ranges of 0.85 and 0.12°C. Temperature variations for the diurnal soil temperature had a range of 2°C for the 30 cm depth, 3°C for the 40 cm depth and 4°C for the 50 cm depth both dry and wet seasons respectively. The increase in range is due to the drop in temperature as wave penetrates the soil medium especially during the rainy season. During the dry season, the temperature distribution was predominately constant for the three depths (Fig. 3) but as moisture content increased, the temperature variation was found to be more frequent (Fig. 4). Figs. 5 and 6 also present the plots of the diurnal variation of thermal diffusivity during the dry and wet season respectively. The average thermal diffusivity range obtained using the phase-lag method were observed to be from 0.74 x 10^{-7} m^2/s to 238.7 x 10^{-7} m^2/s for the dry season and 1.06 x 10^{-7} m^2/s to 958 x 10^{-7} m^2/s for the wet season. It is also evident that the thermal diffusivity for the wet season is much higher as compared to the dry season.

Table 2. Variation of Soil Thermal Diffusivity D (10^{-7} m^2/s), For Ministry of Agriculture, Akure South L.G.A, for the dry season 20th to 22nd of December, 2011

Research site	Date	Time of day (Hours)	Thermal diffusivity, D (10^{-7} m^2/s),		
			30- 40 cm	40- 50 cm	30 – 50 cm
Ministry of Agriculture, Akure South Local Government Area	20/12/2011	3 am	6.63	238.7	1.95
		6 am	26.52	0.00	106.10
		9 am	238.70	238.70	955.80
		12 pm	14.92	9.45	19.49
		3 pm	0.00	0.00	0.00
		6 pm	1.22	0.00	4.87
		9 pm	1.41	0.00	5.65
		12 am	0.00	0.00	0.00
	21/12/2011	3 am	0.00	0.00	0.00
		6 am	0.00	0.00	0.00
		9 am	0.00	0.00	0.00
		12 pm	0.00	0.00	0.00
		3 pm	0.00	0.00	0.00
		6 pm	0.00	0.00	0.00
		9 pm	0.00	0.00	0.00
		12 am	0.00	0.00	0.00
	22/12/2011	3 am	0.00	0.00	0.00
		6 am	2.95	0.00	11.76
		9 am	0.00	0.00	0.00
		12 pm	1.41	0.00	0.00
		3 pm	0.00	0.00	0.00
		6 pm	0.00	0.00	0.00
		9 pm	0.00	0.00	0.00
		12 am	0.00	0.00	0.00

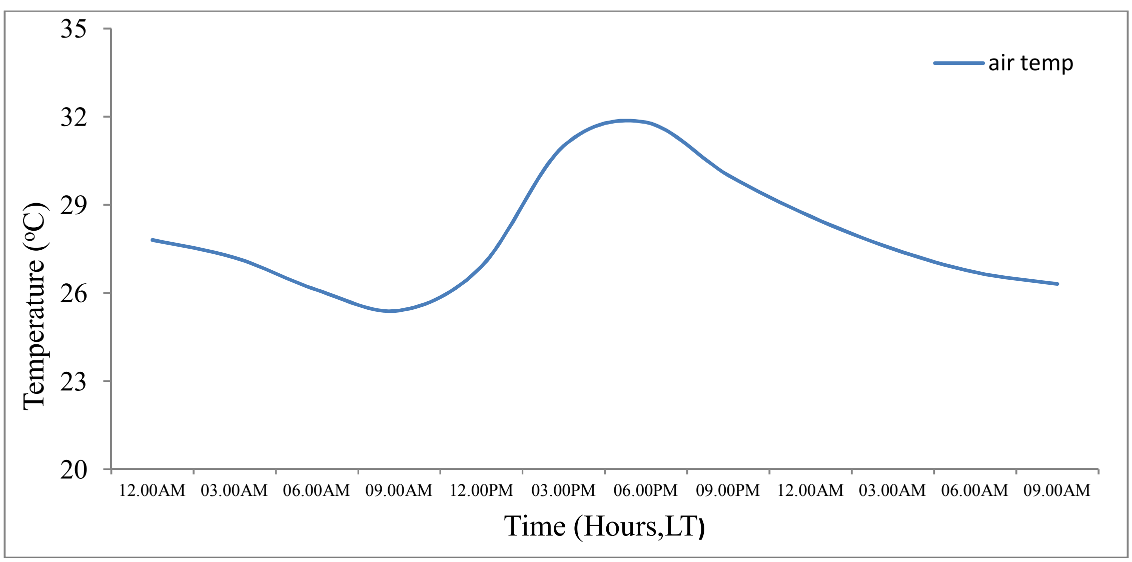

Fig. 1. Diurnal variation of air temperature between the 23rd and 24th December,2011, for Ministry of Agriculture, Akure during the dry season

Table 3. Variation of Soil Thermal Diffusivity D (10^{-7} m^2/s), For Ministry of Agriculture, Akure South L.G.A, for the dry season 23th to 25nd of December, 2011

Research site	Date	Time of day (Hours)	Thermal diffusivity, D (10^{-7} m^2/s),		
			30- 40 cm	40- 50 cm	30 – 50 cm
Ministry of Agriculture, Akure South Local Government Area	23/12/2011	3 am	0.74	0.00	2.95
		6 am	0.00	0.00	0.00
		9 am	14.92	0.00	59.68
		12 pm	2.95	0.00	11.79
		3 pm	0.00	0.00	0.00
		6 pm	0.00	0.00	0.00
		9 pm	2.95	0.00	11.79
		12 am	1.06	1.06	0.00
	24/12/2011	3 am	0.00	9.55	38.19
		6 am	0.00	0.00	0.00
		9 am	0.00	0.00	0.00
		12 pm	1.41	14.92	3.30
		3 pm	0.00	0.00	0.00
		6 pm	4.87	0.00	19.49
		9 pm	2.95	2.95	0.00
		12 am	0.00	0.00	0.00
	25/12/2011	3 am	0.00	0.00	0.00
		6 am	0.00	0.00	0.00
		9 am	0.00	0.00	0.00
		12 pm	6.63	1.97	3.30
		3 pm	0.00	0.00	0.00
		6 pm	1.41	0.00	5.64
		9 pm	1.41	1.41	0.00
		12 am	0.00	0.00	0.00

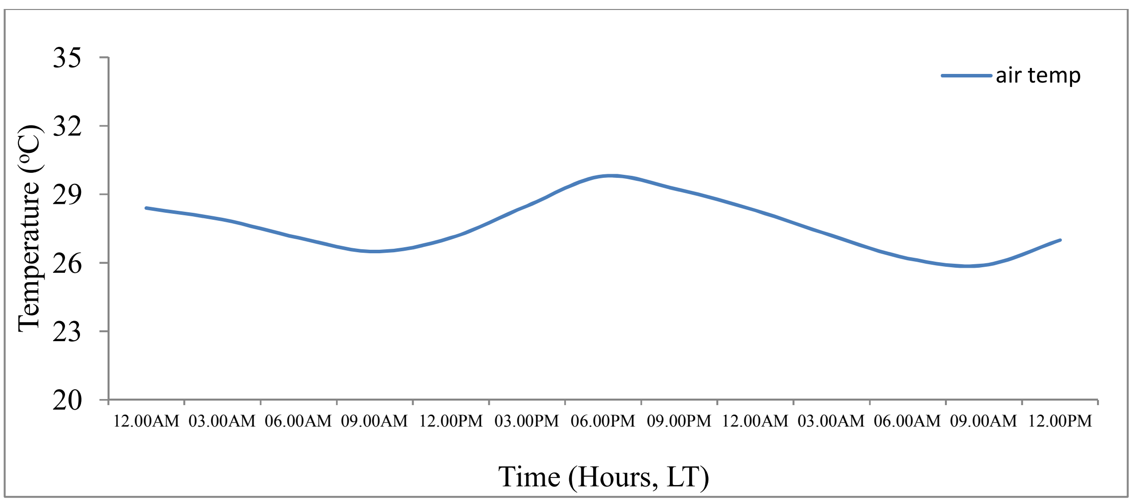

Fig. 2. Diurnal variation of air temperature between the 10th and 11th May, 2012, at Ministry of Agriculture, Akure during the wet season

From the data obtained, it is obvious that there was more solar activity in the daytime and the intensity of the solar radiation through the soil medium reduced as the day proceeded. The upper layers had more temperature fluctuations as however; the diurnal surface temperature decreased as soil depth increased. This in turn led to the continuous variation of the thermal diffusivity during the wet season. During the wet season, thermal conductivity increases with water content at about the same rate (or a little slower) than the specific heat capacity, therefore diffusivity is to be expected to remain constant or decrease slightly with increasing water content

[10,11]. Soil moisture content was about 20%, an increased in this would lead to a possible decline in the value of thermal diffusivity, but an increase was recorded indicating constancy in the soil moisture content [12]. However, as depth increased the soil moisture was found to

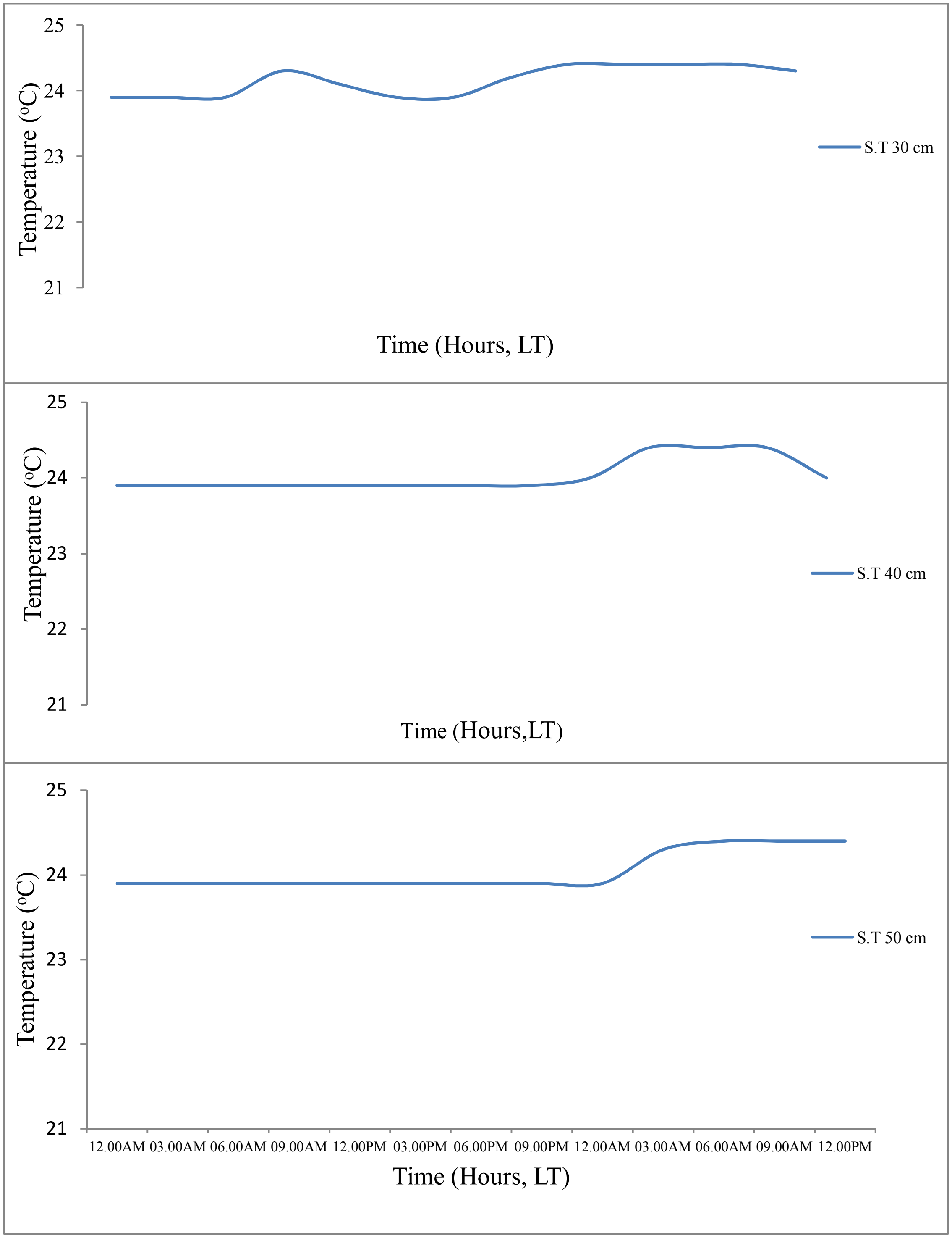

Fig. 3. Diurnal variation of soil temperature between the 23rd to 24th, December, 2011 at Ministry of Agriculture, Akure during the dry season

decrease. A possible cause of this is the soil type present at the 40 and 50 cm depths. The 40 cm depth had a sandy clay loam soil type as well as the 50 cm depth. This soil type has lesser moisture retaining capacity as compared to the 30 cm depth that had a soil type of sandy clay.

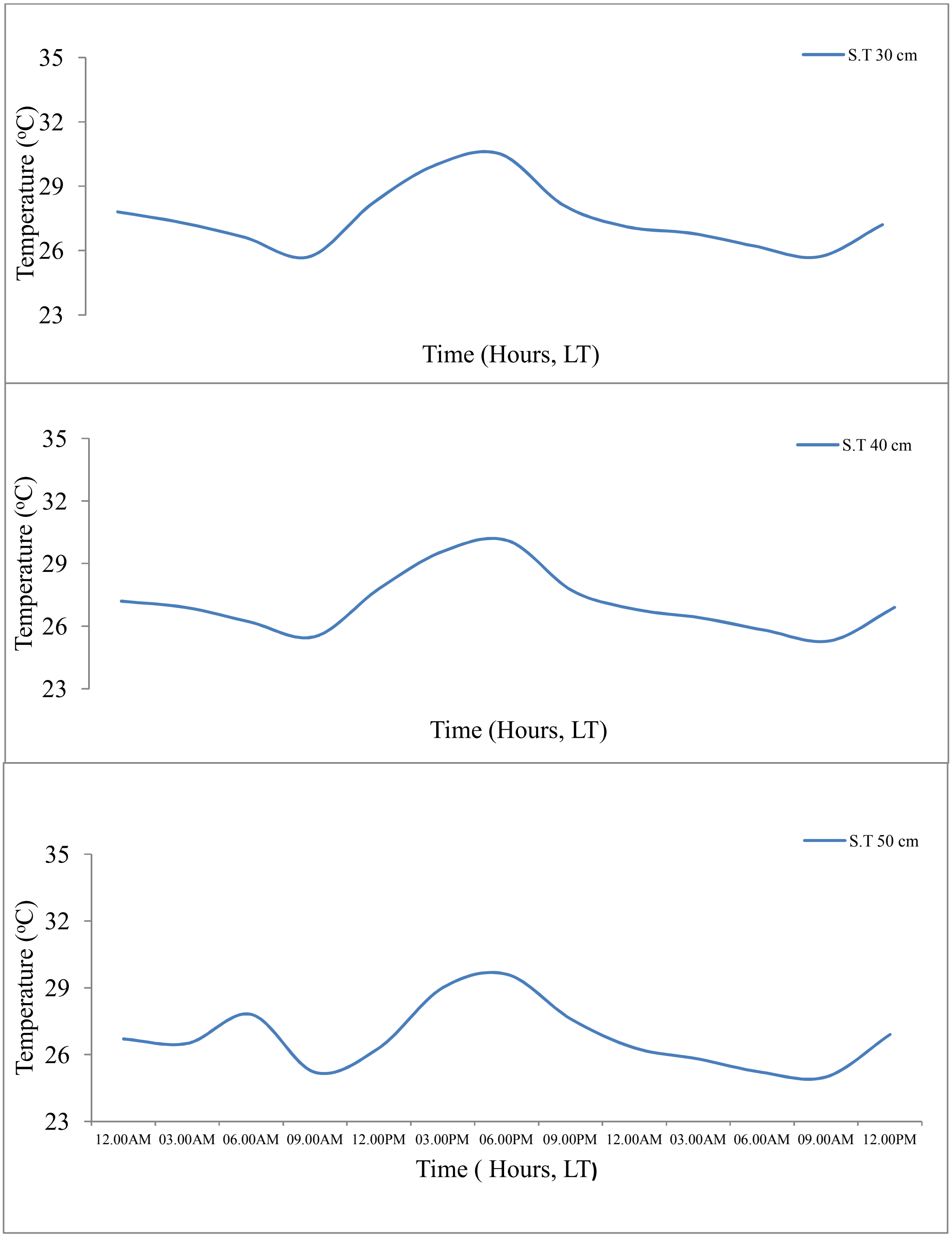

Fig. 4. Diurnal variation of soil temperature between the 10th and 11th May, 2012, at Ministry of Agriculture, Akure during the wet season

Table 4. Variation of Thermal Diffusivity D (10^{-7} m^2/s), for Ministry of Agriculture, Akure South L.G.A, for the wet season 9th, 10th and 11th of May, 2012

Research site	Date	Time of day (Hours)	Thermal diffusivity, D (10^{-7} m^2/s), 30- 40 cm	40- 50 cm	30 – 50 cm
Ministry of Agriculture, Akure South Local Government Area	9/5/2012	3 am	59.68	238.7	954.8
		6 am	59.68	1.66	7.89
		9 am	9.55	26.52	14.92
		12 pm	238.70	238.70	954.8
		3 pm	238.70	6.63	38.19
		6 pm	14.92	59.68	238.70
		9 pm	9.55	238.70	26.52
		12 am	26.52	1.41	3.43
	10/5/2012	3 am	9.55	26.52	14.92
		6 am	59.68	26.52	38.19
		9 am	26.52	3.73	38.19
		12 pm	59.68	59.68	59.68
		3 pm	26.52	59.68	38.19
		6 pm	0.00	238.70	9.55
		9 pm	238.70	238.70	238.70
		12 am	3.73	6.63	238.70
	11/5/2012	3 am	9.55	2.95	59.68
		6 am	26.52	0.00	106.10
		9 am	238.70	0.00	238.70
		12 pm	26.52	238.70	238.70
		3 pm	59.68	26.52	954.80
		6 pm	238.70	238.70	0.00
		9 pm	59.68	26.52	954.80
		12 am	59.68	14.92	954.80

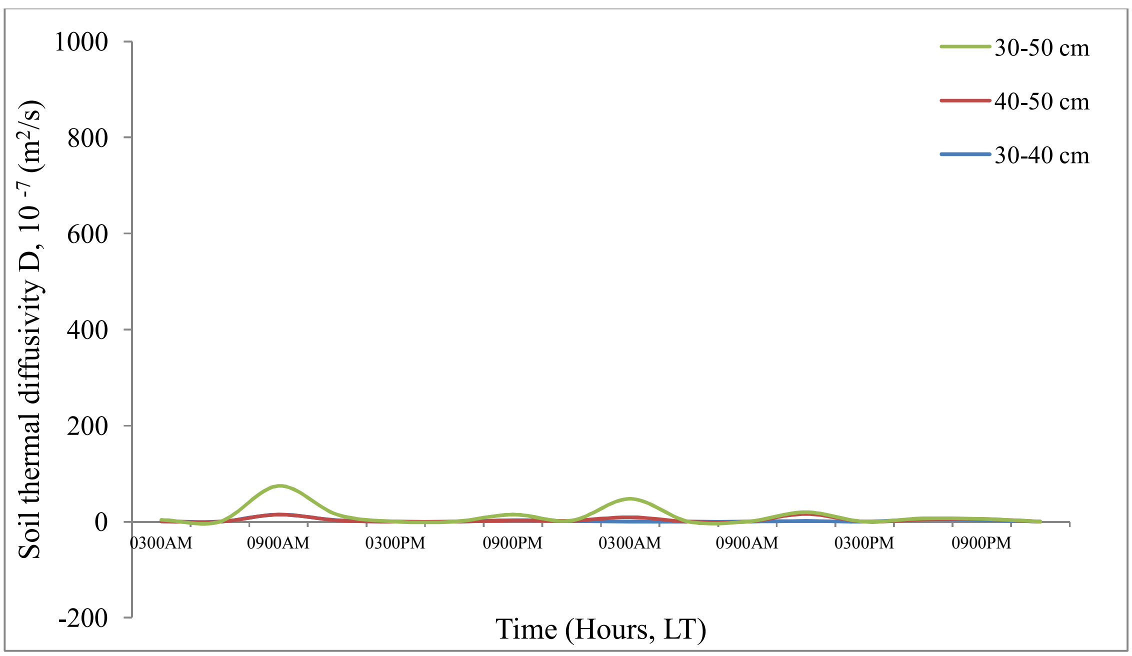

Fig. 5. A typical plot of diurnal variation of thermal diffusivity for Ministry of Agriculture, Akure South, during the dry season (23rd and 24th of December, 2011)

Table 5. Variation of Thermal Diffusivity D (10^{-7} m^2/s), for Ministry of Agriculture, Akure South L.G.A, for the wet season 12th, 13th and 14th of May, 2012

Research site	Date	Time of day (Hours)	Thermal diffusivity, D (10^{-7} m^2/s), 30- 40 cm	40- 50 cm	30 – 50 cm
Ministry of Agriculture, Akure South Local Government Area.	12/5/2012	3 am	26.52	4.87	59.68
		6 am	3.73	59.68	26.52
		9 am	238.7	9.55	0.00
		12 pm	26.52	6.63	238.70
		3 pm	26.52	6.63	238.70
		6 pm	1.66	238.70	5.65
		9 pm	238.70	59.56	106.10
		12 am	0.00	238.70	238.70
	13/5/2012	3 am	3.73	26.52	19.49
		6 am	2.95	26.52	26.52
		9 am	0.00	0.00	0.00
		12 pm	26.52	9.55	954.80
		3 pm	9.55	14.92	954.80
		6 pm	0.00	0.00	0.00
		9 pm	59.68	59.68	954.80
		12 am	0.00	9.55	38.19
	14/5/2012	3 am	0.00	3.73	14.92
		6 am	238.70	3.73	14.92
		9 am	26.52	9.55	238.7
		12 pm	14.92	0.00	59.68
		3 pm	26.52	9.55	14.92
		6 pm	238.70	2.39	7.89
		9 pm	9.55	9.55	59.68
		12 am	26.52	238.70	238.70

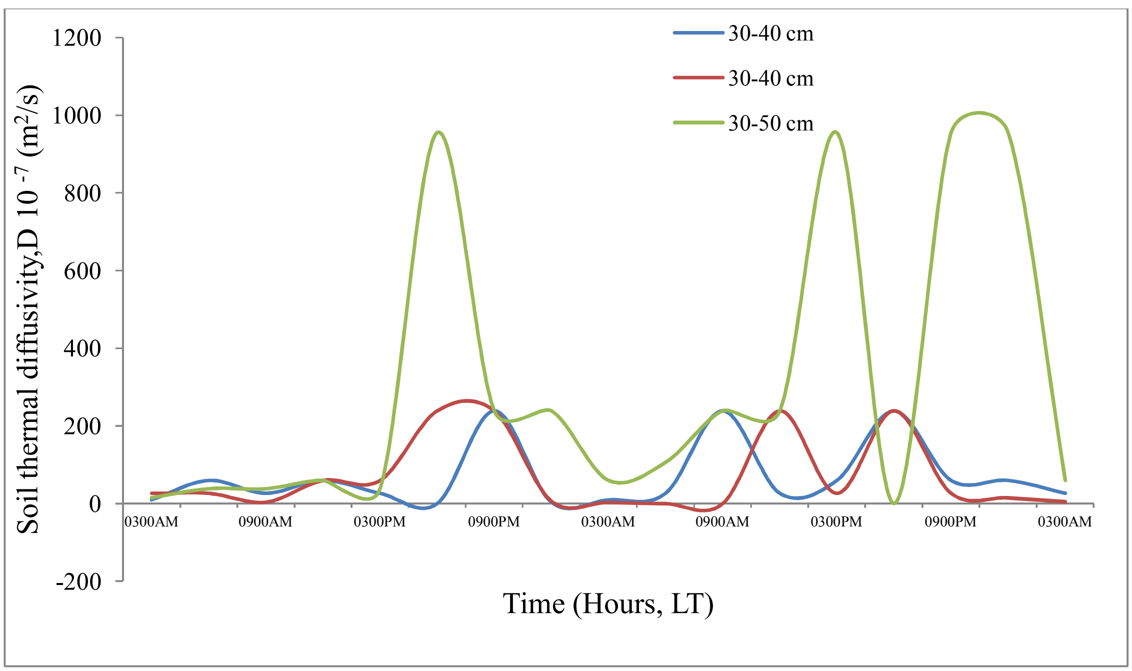

Fig. 6. A typical plot of diurnal variation of the thermal diffusivity for Ministry of Agric, Akure South, during the wet season (10th and 11th of May, 2012)

4. CONCLUSION

Soil temperature and thermal diffusivity over a tropical site in Nigeria has been presented. The results obtained shows that the value of thermal diffusivity obtained varied across different depths. Thermal diffusivity values for the wet season were higher as compared to that of the dry season. The diurnal pattern on a wet day show regular trend than on a dry day. Air temperature variation of up to 1 m above soil surface shows a distinct variation between the dry and rainy season. Temperature variations for the diurnal soil temperature had a range of about 2^{o}C for the 30 cm depth, 3^{o}C for the 40 cm depth and 4^{o}C for the 50 cm depth for both dry and wet seasons respectively. Also, soil moisture content increased due to increase in rainfall, leading to frequent temperature value variations across the three depths.

The values of thermal diffusivity obtained indicate that the soil type would be favorable for planting as if offers proper drainage of moisture through the soil.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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