Thermal diffusivity variations at Ministry of Agriculture Akure South, Ondo State,

South–West Nigeria

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Thermal diffusivity variations of different soil types in a tropical location, Akure, Nigeria at three different depths and 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 depths of 30, 40 and 50 cm. Results obtained show a larger variation of thermal diffusivity in the wet season as compared to 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.

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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 as a function of the incident solar radiation over the study locations (Chacko and Renuka, 2005). Other factors that might influence soil temperature include seasonal swings in overlaying air temperature, local vegetation cover, types of soil and depth in the earth (Uno et al., 2012). The annual variation of daily average soil temperature at different depths is described with the following sinusoidal function (Hillel, 1982 Marshall and Holmes, 1988; Norfziger, 1999):

$$T_{(z,t)} = T_a + A_o\, e^{-z/d} \sin \frac{2\pi\,(t - t0)}{365} - \frac{2}{d} - \frac{\pi}{2} \quad (1)$$

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

Due to much higher heat capacity of soil relative to that of air and the thermal insulation provided by vegetation and surface soil 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 wave Consequently, the temperature in the near sub-surface has a progressive phase shift; such that at minimum air temperature, ground temperatures are generally slightly higher, and at times of maximum air temperatures ground temperatures are lower (NERC, 2011). Temperature variation in different soil types is also due to the response precedent by changes in radiant, thermal and latent heat exchanges.

Knowledge of heat flux from the soil temperature variations can provide information of the loss or gain of heat by the soil.

Determination of heat transfer under the non-steady state heat flow requires the knowledge of basic thermal properties of the soil. Also, modeling of soil temperature in time and depth requires knowledge of the soil surface energy balance and of soil thermal properties such as conductivity and specific heat capacity, represented together by the soil thermal diffusivity. Thermal diffusivity can be estimated under field conditions from soil temperature data (Carslaw and Jaeger, 1959; Kirkham and Powers, 1972)

The present research is based on the determination of the soil thermal diffusivity and temperature variations at different depths in a tropical location, Akure, South-west, Nigeria. Consequently, the soil thermal diffusivity and temperature of the soil at different depths are also predicted.

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 meters 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 millimeters. The study utilizes data of daily soil temperatures values at depths of 30, 40, and 50 centimeters and air temperature for 1 m above the soil surface during the dry and rainy months, using a Davis Vantage Pro data logger and tiny sensors obtained from the Federal University of Technology, Akure, Ondo State Nigeria, installed at the experimental site. The depths were selected because major root density at reproductive stage of most of the cereal crops is at these depths (Ahmand and Rasul, 2008). The set-up is composed of different sensors like soil moisture content, soil and air temperature and humidity with a transmitter and receiver unit placed at about 250 m apart. 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. This is also the case of the soil temperature at different depth for the period of observation.

The air temperature and soil temperature at different sites were measured every three hours from 20th to 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 of the soil depth, estimation of other parameter as associated with the soil thermal properties such as soil moisture, soil bulk density, soil specific heat capacity, soil porosity, was done using laboratory measurement and average values obtained from the measurement for both dry and wet seasons are as shown in Table 1.

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, Akure south L.G.A	30	20.68	1.598	33.053	light reddish brown	Sandy clay	1.12
	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

3. THERMAL DIFFUSIVITY (*D*)

A material's thermal diffusivity (D) is a measure of its ability to conduct thermal energy relative to its ability to store thermal energy (Incorpera and Dewitt, 2002), 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.

Estimation of the thermal diffusivity was obtained through the phase lag method, where the phase lag between the waves at two depths was used (Oke, 1978)

$$D = \frac{\tau}{4\pi}\left[\frac{Z_2 - Z_1}{t_2 - t_1}\right]^2 \qquad (2)$$

where τ is the period of fundamental cycle,

z_2 and z_1 are different depths and t_2 and t_1 are time taken to reach maximum or minimum temperatures in depth Z_2 and Z_1.

This was achieved by determining the times at which the temperature waves reaches its maximum or minimum value at the two depths, $t_1(s)$ and $t_1(s)$, the period of oscillation was 24 hrs or 86400s (Oke, 1978). In obtaining the thermal diffusivity, a three hourly temperature variation was observed, as estimation of D using smaller time variations could yield little changes.

The phase lag method was used because it give 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.

Table 2: Thermal Diffusivity Chart for Ministry of Agriculture, Akure South, for the dry season for 20th to 22nd of December, 2011.

. Research site	Date	Time (Hours)	Soil depths in (cm)		
			30-40	40-50	30-50
Ministry of Agriculture, Akure South L.G.A	20/12/11	3am	6.63	238.7	1.95
		6am	26.52	0.00	106.1
		9am	238.7	238.7	955.8
		12pm	14.92	9.45	19.49
		3pm	0.00	0.00	0.00
		6pm	1.22	0.00	4.87
		9pm	1.41	0.00	5.65
		12am	0.00	0.00	0.00
	21/12/11	3am	0.00	0.00	0.00
		6am	0.00	0.00	0.00
		9am	0.00	0.00	0.00
		12pm	0.00	0.00	0.00
		3pm	0.00	0.00	0.00
		6pm	0.00	0.00	0.00
		9pm	0.00	0.00	0.00
		12am	0.00	0.00	0.00
	22/12/11	3am	0.00	0.00	0.00
		6am	2.95	0.00	11.76
		9am	0.00	0.00	0.00
		12pm	1.41	0.00	0.00
		3pm	0.00	0.00	0.00
		6pm	0.00	0.00	0.00
		9pm	0.00	0.00	0.00
		12am	0.00	0.00	0.00

Table 3: Thermal Diffusivity Chart for Ministry of Agriculture, Akure South, for the dry season for 23th to 25nd of December, 2011.

Research site	Date	Time (Hours)	Soil depths in (cm)		
			30-40	40-50	30-50
Ministry of Agriculture, Akure South L.G.A	23/12/11	3am	0.74	0.00	2.95
		6am	0.00	0.00	0.00
		9am	14.92	0.00	59.68
		12pm	2.95	0.00	11.79
		3pm	0.00	0.00	0.00
		6pm	0.00	0.00	0.00
		9pm	2.95	0.00	11.79
		12am	1.06	1.06	0.00
	24/12/11	3am	0.00	9.55	38.19
		6am	0.00	0.00	0.00
		9am	0.00	0.00	0.00
		12pm	1.41	14.92	3.30
		3pm	0.00	0.00	0.00
		6pm	4.87	0.00	19.49
		9pm	2.95	2.95	0.00
		12am	0.00	0.00	0.00
	25/12/11	3am	0.00	0.00	0.00
		6am	0.00	0.00	0.00
		9am	0.00	0.00	0.00
		12pm	6.63	1.97	3.30
		3pm	0.00	0.00	0.00
		6pm	1.41	0.00	5.64
		9pm	1.41	1.41	0.00
		12am	0.00	0.00	0.00

Table 4: Thermal Diffusivity Chart for Ministry of Agriculture, Akure South, for the wet season for the 10th, 11th and 12th of May, 2012.

Research site	Date	Time (Hours)	Soil depths in (cm)		
			30-40	40-50	30-50
	10/5/12	3am	9.55	26.52	14.92
Ministry of Agriculture					
Akure South, L.G.A		6am	59.68	26.52	38.19
		9am	26.52	3.73	38.19
		12pm	59.68	59.68	59.68
		3pm	26.52	59.68	38.19
		6pm	0.00	238.7	9.548
		9pm	238.7	238.7	238.7
		12am	3.73	6.63	238.7
	11/5/12	3am	9.55	2.95	59.68
		6am	26.52	0.00	106.1
		9am	238.7	0.00	238.7
		12pm	26.52	238.7	238.7
		3pm	59.68	26.52	954.8
		6pm	238.7	238.7	0.00
		9pm	59.68	26.52	954.8
		12am	59.68	14.92	954.8
		3am	26.52	4.87	59.68
	12/5/12	6am	3.73	59.68	26.52
		9am	238.7	9.55	0.00
		12pm	26.52	6.63	238.7
		3pm	26.52	6.63	238.7
		6pm	1.66	238.7	5.65
		9pm	238.7	59.56	106.1
		12am	0.00	238.7	238.7

Table 5: Thermal Diffusivity Chart for Ministry of Agriculture, Akure South, for the wet season for the 13th, 14th and 15th of May, 2012.

Research site	Date	Time (Hours)	Soil depths in (cm)		
			30-40	40-50	30-50
	13/5/12	3am	3.73	26.52	19.49
		6am	2.95	26.52	26.52
		9am	0.00	0.00	0.00
		12pm	26.52	9.55	954.8
		3pm	9.55	14.92	954.8
		6pm	0.00	0.00	0.00
		9pm	59.68	59.68	954.8
		12am	0.00	9.55	38.19
	14/5/12	3am	0.00	3.73	14.92
		6am	238.7	3.73	14.92
		9am	26.52	9.55	238.7
		12pm	14.92	0.00	59.68
		3pm	26.52	9.55	14.92
		6pm	238.7	2.39	7.89
		9pm	9.55	9.55	59.68
		12am	26.52	238.7	238.7
		3am	59.68	238.7	1.22
	15/5/12	6am	0.00	1.41	5.65
		9am	238.7	59.68	106.1
		12pm	59.68	238.7	954.8
		3pm	26.52	6.63	238.7
		6pm	59.68	238.7	238.7
		9pm	59.68	59.68	0.00
		12am	59.68	238.7	238.7

4. Results

Figure 1 and 2 show the diurnal variation of surface temperature for a dry (23rd and 24th December, 2011) day and for a wet (10th to 11th May, 2012) day respectively. During the dry season, the morning hours observed temperature depression due the Harmattan that is peculiar to this period of the year, while the afternoon evening hours experiences 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 value of about 30°C. Figure 3 and 4 also present the diurnal variation of soil temperature at depths 30, 40 and 50 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 for 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 predominate constant for the three depths (Fig 3) but as moisture content increased the temperature variation was observed to be much more frequent (Fig 4).

Figure 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 954.8 x 10^{-7} m^2/s for the wet season. It is also evident that thermal diffusivity for the wet season is much higher as compared to the dry season.

From the data obtained, it is obvious that there was more solar activity in the daytime and the intensity of 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 value of thermal diffusivity during the wet season. In the wetter range of water contents, thermal conductivity increases with water content at about the same rate (or a little slower)

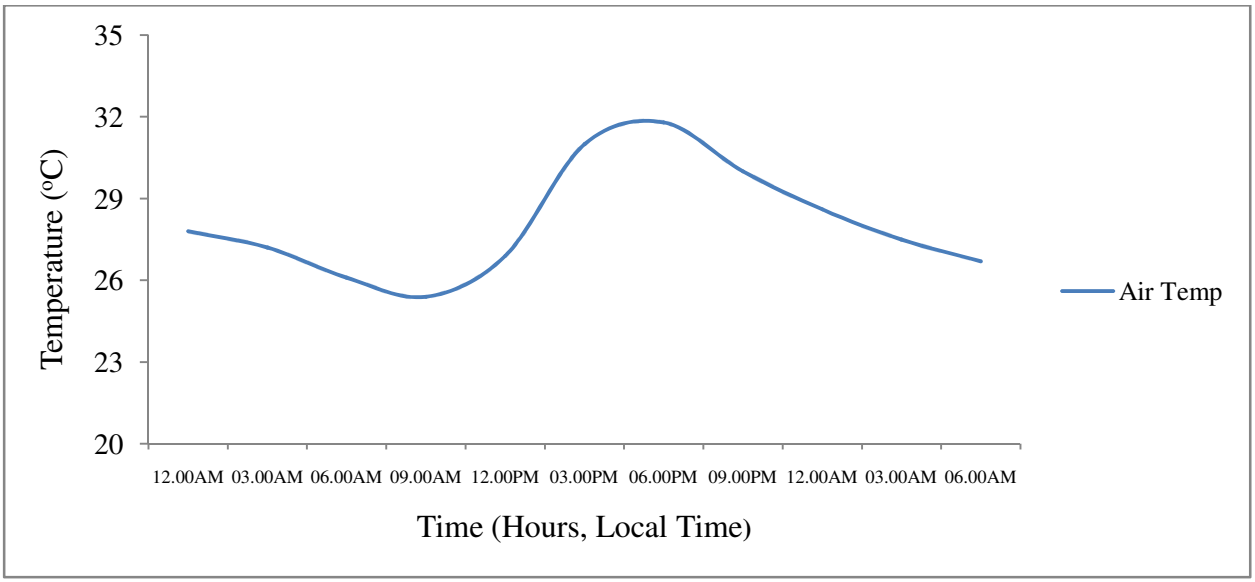

Figure 1: Variation of air temperature from 23rd and 24th December, 2011, for Ministry of Agriculture, Akure during the dry season.

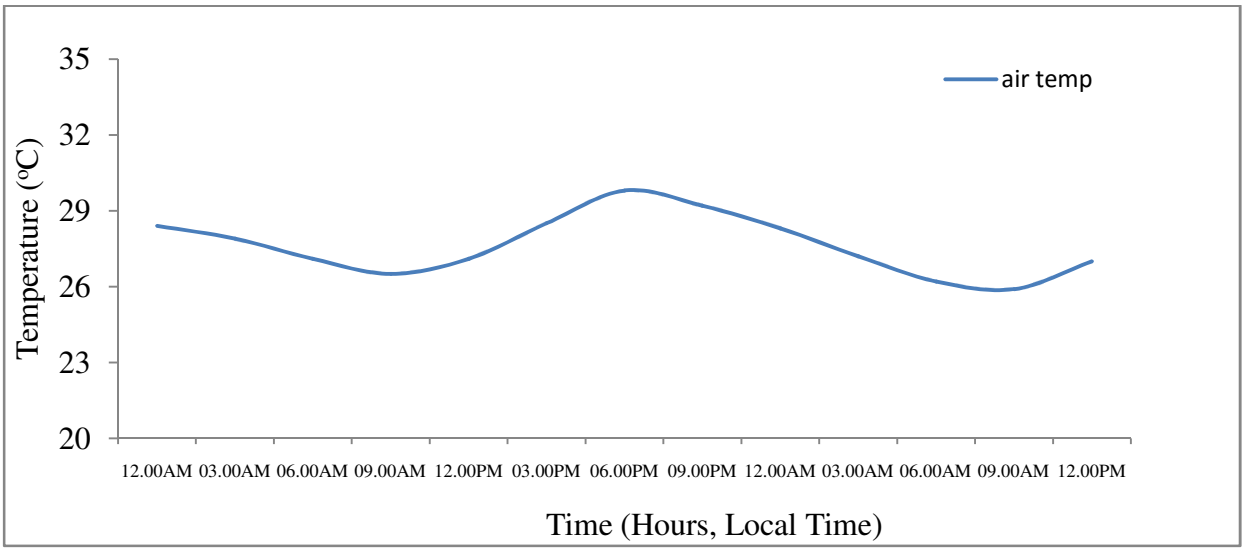

Figure 2: Variation of air temperature from 10th to 11th May, 2012, at Ministry of Agriculture, Akure during the wet season.

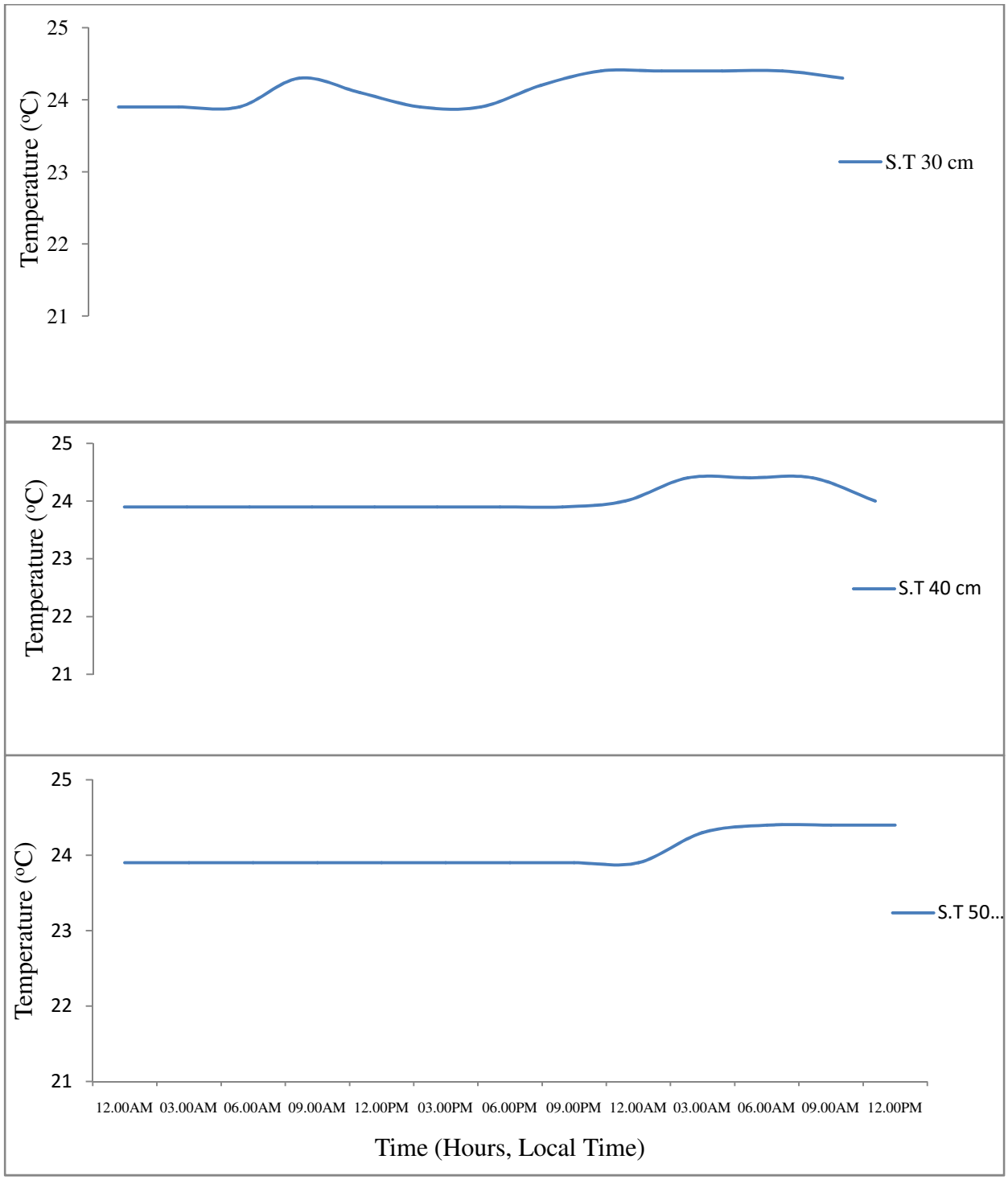

Figure 3: Variation of soil temperature from 23th to 24th, December, 2011 for Ministry of Agriculture, Akure during the dry season.

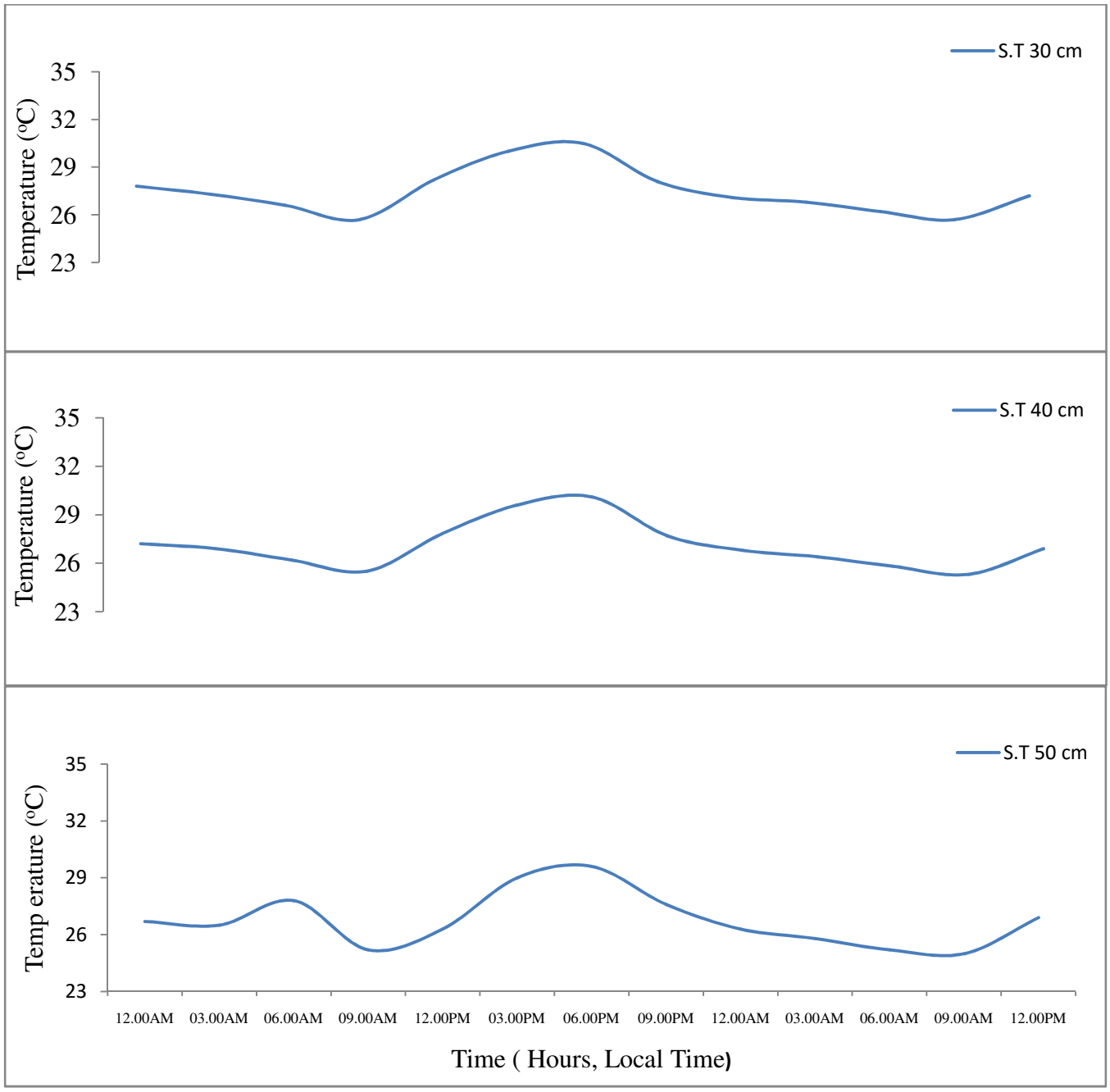

Figure 4: Variation of soil temperature from 10th to 11th May, 2012, at Ministry of Agriculture, Akure during the wet season.

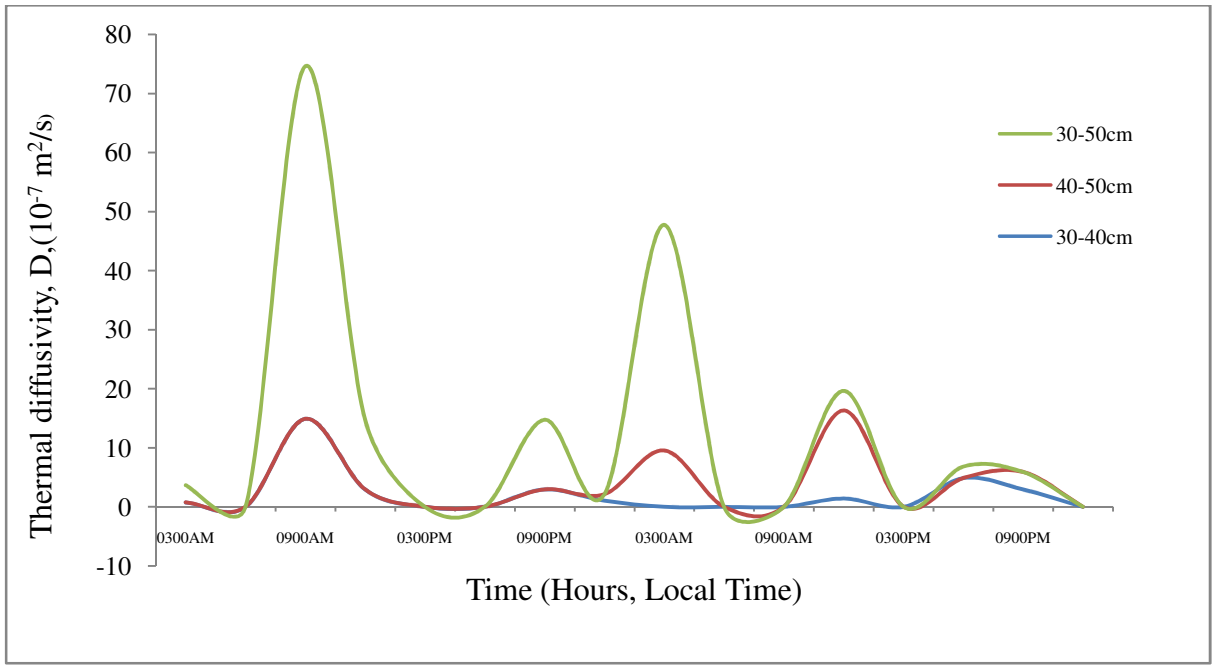

Figure 5: Thermal Diffusivity Chart for Ministry of Agriculture, Akure South, for the dry season for 23rd and 24th of December.

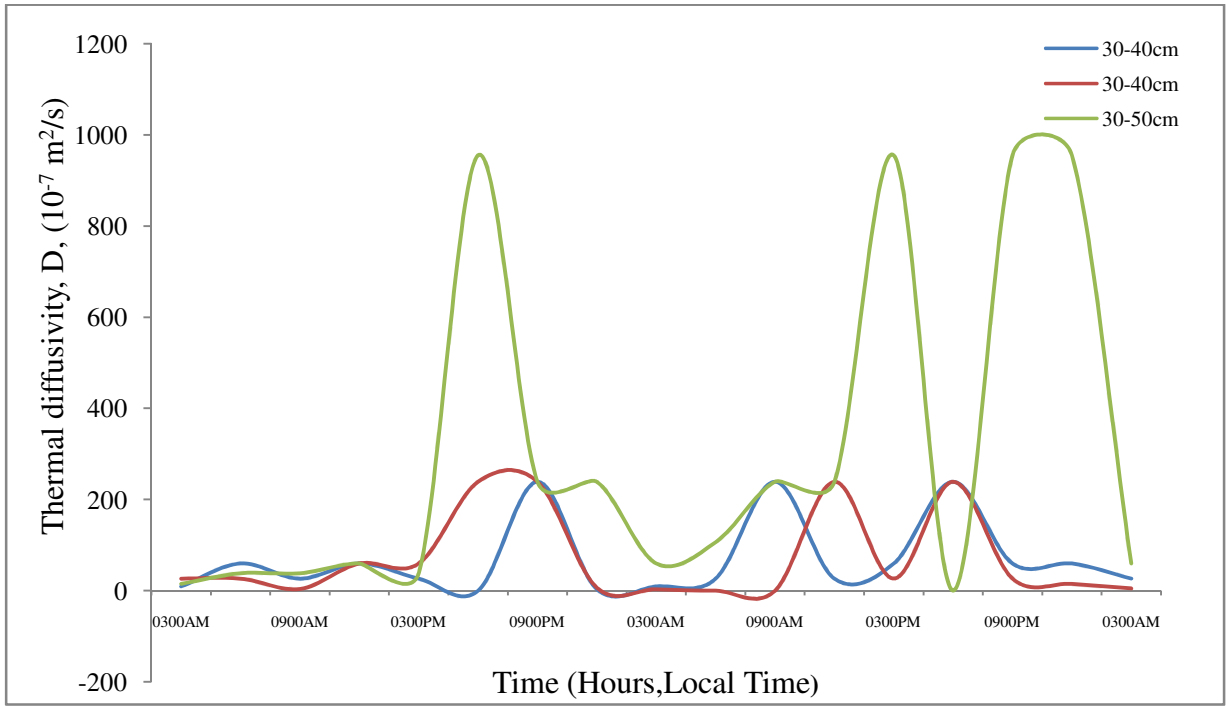

Figure 6: Thermal Diffusivity Chart for Ministry of Agriculture, Akure South, for the wet season for the 10th and 11th of May, 2012

than specific heat capacity, therefore diffusivity is to be expected to remain about constant or decrease slightly with increasing water content (De Vries, 1975; Nobel and Geller, 1987).

Soil moisture content was about 20%, and increase 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 (Chacko and Renuka, 2002). But as depth increased the soil moisture was found to decrease. A possible cause of this is the type of soil type present in the 40 and 50 cm depths. The 40 cm depth had a soil type of sandy clay loam as well as the 50 cm depth. Both soil types have lesser moisture retaining capacity as compared to the 30 cm depth that had a soil type of sandy clay.

5. CONCLUSION.

Thermal diffusivity and subsoil temperature 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. (Chacko and Renuka, 2002). 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°C for the 30 cm depth, 3°C for the 40 cm depth and 4°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.

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