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COMPARISON ANALYSES OF DIFFERENT MODELS USED TO DETERMINE SOIL THERMAL CONDUCTIVITY AND DIFFUSIVITY AT NIMEX SITE, IBADAN

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ABSTRACT: *Soil thermal properties regulate the separation of energy fluxes at the ground surface and they control the exchange of energy and mass between the soil and the atmosphere. The knowledge of these properties is needed in order to ascertain the heat flux distribution in the soil under steady and non-steady conditions. In this study, which lasted for 11 months starting from March 2006 to January 2007, we estimated soil thermal conductivity and thermal diffusivity at Nigeria Mesoscale Experiment (NIMEX) site, Ibadan using Johansen and Kersten models and Horton Numerical method. The aim of this work is to compare the results obtained from these models and to ascertain the level of agreement of the results. The result showed that for Johansen and Kersten models, the highest mean values of thermal conductivity and thermal diffusivity were obtained in the month of September 2006. For Johansen model the values are 4.18±0.08 $Wm^{-1}K^{-1}$ and 4.56±5.57*$10^{-8}m^2s^{-1}$ for thermal conductivity and thermal diffusivity respectively and for Kersten model the thermal conductivity and thermal diffusivity values are 1.00±0.05 $Wm^{-1}K^{-1}$ and 1.07±0.22*10^{-8} m^2s^{-1} respectively. This may be due to the observed increase in the soil moisture content within this month. The result obtained using Horton Numerical method showed that the highest mean thermal conductivity and thermal diffusivity values of 9.76 ±3.00 $Wm^{-1}K^{-1}$ and 10.70±3.30*$10^{-8}m^2s^{-1}$ respectively were obtained in the month of December 2006 while the lowest mean values of -0.44 ±14.68 $Wm^{-1}K^{-1}$ for thermal conductivity and 0.10±12.70*$10^{-8}m^2s^{-1}$ for thermal diffusivity were obtained in the month of September contrary to the results obtained with the first two models. The negative mean thermal conductivity value of -0.44 ±14.68 $Wm^{-1}K^{-1}$ obtained in the month of September 2006 using Horton Numerical method was probably due to the increase in soil moisture content which is as a result of increase in the amount of rainfall within this month that lowered the temperature at the near soil surfaces. Kersten model is in agreement with Johansen model but has low values making it unsuitable for very low soil moisture. Johansen model is likely the best model for estimating thermal conductivity and diffusivity.*

KEYWORDS: Soil moisture content, thermal conductivity, thermal diffusivity, volumetric heat capacity.

INTRODUCTION

Soil thermal conductivity, diffusivity and volumetric heat capacity are known as soil thermal properties. These properties regulate the separation of energy fluxes at the ground surface and they control the exchange of energy and mass between the soil and the atmosphere (Bristow et al. 2001; Ochsner et al. 2001). Therefore, the knowledge of these properties is needed in order to ascertain the heat flux distribution in the soil under steady and non-steady conditions (Usowicz 1995). Soil thermal diffusivity is the ratio of thermal conductivity to volumetric heat capacity; it has strong influence on soil temperature making it a very important property (Gao et. al., 2009; Adeniyi et al., 2012). Soil thermal conductivity describes the heat conduction ability of the soil (Lu et al., 2007 and the references therein) and can either be measured or estimated based on the knowledge of the values of the other properties (Anandakumar et al 2001). Volumetric heat capacity is a product of mass density and specific heat capacity and can be estimated from soil properties such as soil porosity, soil mineral, soil organic and water content (Arya, 2001; Gao et al. 2003; Anandakumar et al 2001). This property relates thermal conductivity and thermal diffusivity such that knowing any of the later properties can lead to the estimation of the other. There are different methods used in estimating soil thermal properties. Horton et al. (1983) fitted a Fourier series representation of soil temperature to evaluate six methods of estimating soil thermal diffusivity. Kersten (1949) and Johansen (1975) developed models for estimating soil thermal conductivity. Kersten (1949) model only needs bulk density but not reliable for estimating thermal conductivity of soils with very low water content. For a more accurate thermal conductivity values Johansen (1975) model is preferred. Other models for both thermal diffusivity and thermal conductivity include de Vries (1963), Massman (1992), Sikora and Kossowski (1993), Côté and Konrad (2005) and Lu et al (2007).Although different soil thermal property models give different results (Anandakumar et al 2001; Gao et al. 2009) but do these results agree? In this work we will be comparing results obtained from thermal conductivity and thermal diffusivity models based on the research carried out at the Nigeria Mesoscale Experiment Site (NIMEX), Ibadan. We estimated soil thermal conductivity and soil thermal diffusivity based on Johansen (1975) and Kersten (1949) models and Horton et al. (1983) Numerical method.

THEORETICAL BACKGROUND

Horton Numerical Method

For Horton Numerical method, the temperature difference between two time steps (Δt=1 min) is determined from temperature sensors installed at three depths:

$$\frac{T_{10cm}^{t+1} - T_{10cm}^{t}}{\alpha * \Delta t} = \frac{T_{30cm}^{t} - 2T_{10cm}^{t} + T_{5cm}^{t}}{(\Delta z)^2} \qquad (1)$$

where T is the soil temperature, α is the thermal diffusivity, t is time in seconds and Δz is the depth of the soil subsurface where the temperature sensors are installed (Foken, 2006); Δz used for this study is 25cm (the difference between 30cm and 5cm depths).This model was derived from Fourier's equation of heat conduction in one dimension given as:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial z^2} \qquad (2)$$

The left hand side of the equation (1) is the rate of change of internal energy within the soil and the right hand side is the net heat flow in the vertical direction within the soil.

Johansen Model

Johansen (1976) developed a model with the concept of normalized thermal conductivity, the

Kersten number (K_e) and established a relationship between thermal conductivity and the Kersten number for unsaturated soils, based on conductivity values at dry and saturated states:

$$\lambda = (\lambda_{sat} - \lambda_{dry})K_e + \lambda_{dry} \quad (3)$$

where λ_{dry} and λ_{sat} are the thermal conductivity of dry and saturated soils (W m^{-1} K^{-1}), respectively, K_e is the Kersten number given as:

$$K_e \approx \log S_r + 1.0 (S_r > 0.1) \quad (4)$$

S_r is the normalized soil water content estimated by:

$$S_r = \frac{\theta \rho_b}{n \rho_w} \quad (5)$$

where θ is the soil moisture, ρ_b is the bulk density of soil, n is the porosity and ρ_w is the density of water, which is 1000kg/m^3. A geometric mean equation based on the thermal conductivity of water (λ_w= 0.594 Wm^{-1} K^{-1} at 20°C) and effective thermal conductivity of soil solids (λ_s), is used to estimate λ_{sat} as:

$$\lambda_{sat} = \lambda_s^{1-n} \lambda_w^n \quad (6)$$

where n is soil porosity and is estimated using the expression

$$n = 1 - \frac{\rho_b}{\rho_s} \quad (7)$$

where ρ_s is the density of soil solids (2700 kg m^{-3}), (Côté and Konrad, 2005)

The value of λ_s was determined using another geometric mean equation from the quartz content of the total solids content(q) and thermal conductivities of quartz (λ_q= 7.7 W m^{-1} K^{-1}) and
other minerals (λ_o) as:

$$\lambda_s = \lambda_q^q \lambda_o^{1-q} \quad (8)$$

where λ_o is taken as 2.0 W m^{-1} K^{-1}.

The semi empirical relationship used to obtain λ_{dry} is:

$$\lambda_{dry} = \frac{0.135\rho_b + 64.7}{2700 - 0.947\rho_b} \tag{9}$$

where 2700 kg m^{-3} is the density of soil solids.

Kersten Model

Kersten (1949) worked on the thermal conductivity of soils in which over 1000 measurements were made on 19 different soil types, including gravels, crushed rocks, sands, silts, clays and peat. However, the results from only nine of the 19 soil types were used to develop the empirical relationships between thermal conductivity, water content and dry density for both unfrozen and frozen states. The relationships proposed by Kersten (1949) for the prediction of thermal conductivity of sandy soils are given as:

$$\lambda = 0.14442[0.9log(\theta) - 0.2] \times 10^{0.6243\rho_b} \tag{10}$$

where λ is the thermal conductivity, θ is the soil moisture and ρ_b is the dry bulk density, (g/cm^3, Côté

and Konrad, 2005).

MATERIALS AND METHODS

NIMEX_3 Ibadan site is located within the campus of the University of Ibadan, the site coordinates are latitude 7º 26′ and longitude 3º 54′ E. The two major seasons in Nigeria are rainy season from April to October and the dry season from November to March. The climate is influenced by two air masses—the moist southerly monsoon and the dry northerly winds blowing from the subtropical high pressure system across the Sahara Desert. In August or late July is a period of little or no rainfall popularly called August break (Adeniyi et al. 2012).

NIMEX is a research project between the following institutions: Obafemi Awolowo University, Ile-Ife, University of Ibadan and Federal University of Technology, Akure. One of the primary objectives of NIMEX is to determine the surface energy balance of the humid tropical area of south-western Nigeria (Nymphas et al, 2009).The instrumentation provided data for the following micro-meteorological parameters: wind speed and wind direction, wet and dry bulb temperature, net radiation, global radiation, soil temperature, surface temperature, air pressure and soil water content. The data is sampled every 1 second and stored as a 1 minute averaged values (Oladosun et al, 2007). Soil sample from the NIMEX site, Ibadan was collected, dried and weighed in a cylinder of radius 4.5cm and height 7.3cm in order to estimate the soil bulk density, which was found to be 1364.6 Kg m^{-3}. Volumetric heat capacity, C_v , is estimated from the volumetric water content, Θ_m , and the soil bulk density, ρ_b (Kg m^{-3}) of the study site, using the equation below:

$$C_v = \rho_b\left(c_{pav} + \Theta_m c_{pw}\right) \tag{11}$$

where c_{pav} and c_{pw} are the average specific heat capacity of mineral soils and the specific heat capacity of soil water, which are 840 $Jkg^{-1}K^{-1}$ and 4180 $Jkg^{-1}K^{-1}$ respectively (Mayocchi and Bristow, 1994).

For the Horton Numerical method used in this study, thermal conductivity, λ, is estimated from

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the volumetric heat capacity and thermal diffusivity using the relations below:

$$\lambda = \alpha * C_v \quad (12)$$

Similarly, thermal diffusivity for Johansen and Kersten models was estimated using equation (12). Other quantities estimated for Johansen model include λ_{dry} using equation (9), having the value 0.177Wm^{-1}K^{-1}, porosity, n, using equation (7) as 0.5, λ_s, from equation (8) estimated as 4.5 W m^{-1} K^{-1} and λ_{sat} estimated from equation (6) as 1.63W m^{-1} K^{-1}.

RESULTS AND DISCUSSION

The results of the estimated values of soil thermal conductivity, thermal diffusivity and volumetric heat capacity for each month as shown in table 1-3 below. These tables showed the maximum (Max) and minimum (Min) estimated values of the soil thermal properties. Also shown are the mean and standard deviation for the three models used. The quantities, λ_1; λ_2; λ_3, represents estimated thermal conductivity values (Wm^{-1}K^{-1}), and α_1; α_2; α_3 represents estimated thermal diffusivity values (m^{2}s^{-1}). The subscript 1, 2, and 3 represents the 3 different models used for this work namely: Horton Numerical Method, Johansen Model, and Kersten Model respectively.

Figures 1 to 5 are the results for soil thermal conductivity, thermal diffusivity and volumetric heat capacity.

Table 1 showed that the highest maximum thermal conductivity values for the three models was obtained in September, 2006 with the values of 54.45±14.48 Wm^{-1}K^{-1} for Horton Numerical method, 4.25±0.08 Wm^{-1}K^{-1} for Johansen Model and 1.04±0.05 Wm^{-1}K^{-1} for Kensten model. Similar values were obtained in June, 2006 for Kensten model. The lowest minimum thermal conductivity values for Horton Numerical method and Kensten model were obtained in September, 2006 having values of -34.59±14.68 Wm^{-1}K^{-1} and 0.79±0.05 Wm^{-1}K^{-1} respectively. For Johansen model the lowest minimum value of 3.72±5.65 Wm^{-1}K^{-1} was obtained in June, 2006. Thermal diffusivity, for Horton Numerical method, has its maximum values ranging from 9.36±2.93x10^{-8} m^{2}s^{-1} in July, 2006 to 49.40±12.70x10^{-8}m^{2}s^{-1} in September, 2006 and its minimum values ranges from -30.00±14.68x10^{-8}m^{2}s^{-1} in September, 2006 to 5.34±1.91x10^{-8}m^{2}s^{-1} in January, 2007. The mean thermal conductivity values for Horton Numerical method ranges from -0.44±14.68 Wm^{-1}K^{-1} in September, 2006 to 9.76±3.00 Wm^{-1}K^{-1} in December, 2006 and for thermal diffusivity the mean values ranges from 0.10±12.70x10^{-8}m^{2}s^{-1} in September, 2006 to 10.70±3.30x10^{-8}m^{2}s^{-1} in December, 2006. The zero values obtained in April, 2006 are due to errors in the temperature data for that month. The negative values obtained in Horton Numerical method is due to the fact that the model takes temperature difference between two time steps with Δt being equal to 1 minute. If the temperature at 10cm depth of the next minute is greater than the one before, then there is a negative value for thermal diffusivity which also affects thermal conductivity. This is the reason why September which has the highest maximum thermal conductivity and thermal diffusivity values has the lowest minimum thermal conductivity and thermal diffusivity values. This in turn gave rise to the negative mean value of thermal conductivity and very low thermal diffusivity value. The reason for the above negative values is due to the increase in soil moisture caused by increased rainfall in this month (as shown in figure 6) the temperature at the near soil surfaces were low given rise to negative thermal diffusivity and thermal conductivity values.

For Johansen model, it is seen that the maximum thermal conductivity values from March to November are almost constant with values between 4.20±0.04$Wm^{-1}K^{-1}$ in March to 4.25±0.08$Wm^{-1}K^{-1}$ in September, 2006 (which is the highest maximum value), except for June, 2006 whose value is 3.87±0.04$Wm^{-1}K^{-1}$ being the lowest maximum value. The minimum values of thermal conductivity for this model ranged from 3.72±0.04$Wm^{-1}K^{-1}$ in June to 4.11±0.04$Wm^{-1}K^{-1}$ in July. The mean thermal conductivity value was highest in September with the value of 4.18±0.08$Wm^{-1}K^{-1}$ and lowest in the month of June, 2006 with value of 3.81±0.04$Wm^{-1}K^{-1}$. The mean thermal diffusivity for this model ranged from 3.29±0.21x$10^{-8}m^2s^{-1}$ in June, 2006 to 4.56±5.59x$10^{-8}m^2s^{-1}$ in September, 2006. The highest maximum thermal diffusivity value of 39.40±5.59x$10^{-8}m^2s^{-1}$ was also obtained in September, 2006 and the lowest minimum value of 3.02±0.21x$10^{-8}m^2s^{-1}$was obtained in June, 2006.

Kersten model showed the similar trend with Johansen model. The maximum values of its thermal conductivity are almost constant from March to November with values ranging from 1.02±0.02$Wm^{-1}K^{-1}$ to 1.04±0.03$Wm^{-1}K^{-1}$. January had the least maximum thermal conductivity value of 0.90±0.00$Wm^{-1}K^{-1}$ and highest maximum value of 1.04±0.03$Wm^{-1}K^{-1}$ was obtained in June, 2006 and 1.04±0.05$Wm^{-1}K^{-1}$ in September, 2006. The minimum values of thermal conductivity for this model ranged from 0.90±0.00$Wm^{-1}K^{-1}$ in November and December, 2006 to 0.95±0.04$Wm^{-1}K^{-1}$ in July. The mean value of thermal conductivity was highest in June and September, 2006 with values of 1.00±0.03$Wm^{-1}K^{-1}$ and 1.00±0.05$Wm^{-1}K^{-1}$ respectively, the lowest mean value of 0.90±0.00$Wm^{-1}K^{-1}$ was obtained in November and December, 2006. The mean thermal diffusivity for this model ranged from 0.86±0.04x$10^{-8}m^2s^{-1}$ in both June and July, 2006 to 1.07±0.22x$10^{-8}m^2s^{-1}$ in September, 2006. The highest maximum thermal diffusivity value of 7.46±0.22x$10^{-8}m^2s^{-1}$ was also obtained in September, 2006 and the lowest minimum value of 0.80±0.22x$10^{-8}m^2s^{-1}$was also obtained in September, 2006. For the Johansen and Kensten models, the month of September gave the highest mean and maximum values of both thermal conductivity and thermal diffusivity.

The maximum values of volumetric heat capacity obtained ranged from 0.91±0.00**x**10^8 J m^{-3} K^{-1} in January, 2007 to 1.30±0.22x10^8 $Jm^{-3}K^{-1}$ in September, 2006 and its minimum values ranged from 0.91±0.00x10^8 $Jm^{-3}K^{-1}$ in December and January to 1.17±0.00x10^8 $Jm^{-3}K^{-1}$ in September. The mean values were highest in both July and September, 2006 with values of 1.16±0.08x10^8 $Jm^{-3}K^{-1}$ and 1.16±0.22x10^8 $Jm^{-3}K^{-1}$, the lowest mean value of 0.91±0.00x10^8 $Jm^{-3}K^{-1}$ was obtained in January, 2007.

Figures 1-5 below showed the mean values of thermal conductivity, thermal diffusivity for the three models and volumetric heat capacity plotted against the months. In figure 1 due to negative values obtained from Horton Numerical method, as explained earlier, thermal conductivity in September, 2006 had the least mean value though it had the highest maximum value. The other two models had the highest thermal conductivity values in that month. Figure 6 is the variation of soil moisture in the period of investigation. From the figure the month of September, 2006 has the highest soil moisture content. Thermal diffusivity values, by Johansen model and Kersten model, and volumetric heat capacity were also highest in that month, as seen in figure 4 and 5. This shows that the increase in soil moisture has effect on the values of these soil thermal properties.

From figure 6, there was increase in soil moisture between March and September, 2006 because of the increase in rainfall during these months. This gave rise to increased evaporation from the soil surface and a substantial part of net radiation goes into evaporation resulting to the reduction of the energy available for heating the soil (Arya, 2001; Anandakumar et al, 2001). Also due to the increased heating of the soil from October to January there is increased evaporation and decrease in soil moisture. Under this evaporation conditions there is a net upward flux of water (liquid and vapor) that responds to the progressively drying surface condition result to associated net convective heat flux (Gao et al, 2009).

Increase in soil moisture resulted to increase in soil thermal conductivity, thermal diffusivity and volumetric heat capacity. The increase in the value of the soil thermal properties can slow the warming of the upper layer of the soil in response to the radiative heating of the surface thereby lowering soil temperature. Due to the negative values of thermal conductivity and thermal diffusivity obtained from Horton Numerical method and the low values for Kersten model, Johansen model is likely the best model for estimating thermal conductivity and diffusivity. Although Kersten has low values but it is in agreement with Johansen models.

CONCLUSION

In this study, we compared soil thermal conductivity and thermal diffusivity estimated using Johansen and Kersten models and Horton Numerical method. The result showed that for Johansen and Kersten models, the month of September, 2006 gave the highest thermal conductivity and thermal diffusivity values, and volumetric heat capacity was highest in this month. This may be due to the observed increase in the soil moisture in this month. Horton Numerical method had its highest thermal conductivity and thermal diffusivity values in December, 2006 and the lowest in September, 2006. Horton Numerical method had negative values for the month of September probably due to the increase in soil moisture caused by increased rainfall in this month that lowered the temperature at the near soil surfaces. Kersten is in agreement with Johansen models but has low values making it unsuitable for very low soil moisture. Johansen model is likely the best model for estimating thermal conductivity and diffusivity.

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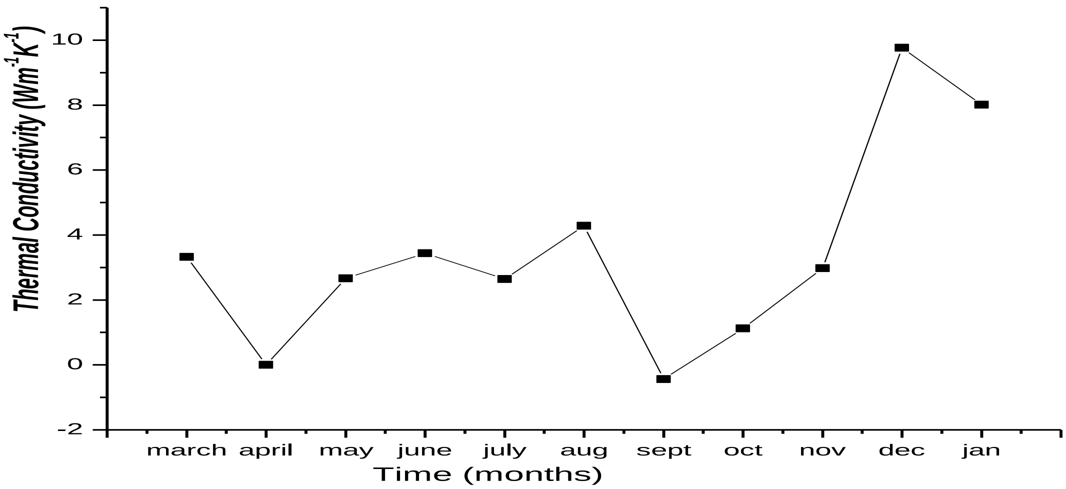

Fig 1: Variation of thermal conductivity for Horton Numerical method from March, 2006 to January, 2007.

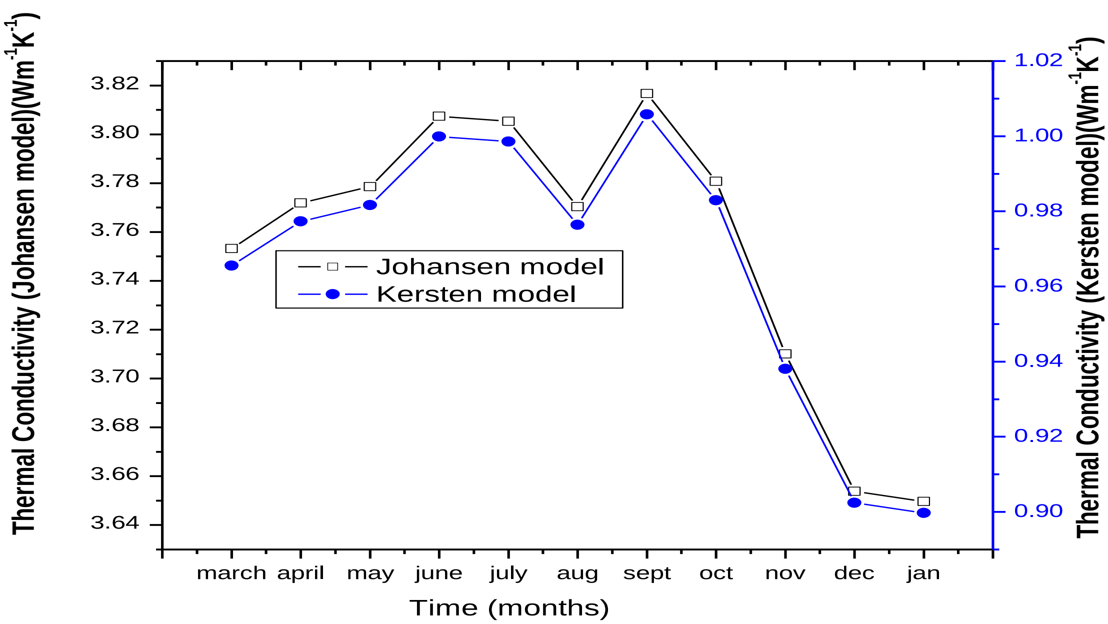

Fig 2: Variation of thermal conductivity for Johansen and Kersten models from March, 2006 to January, 2007

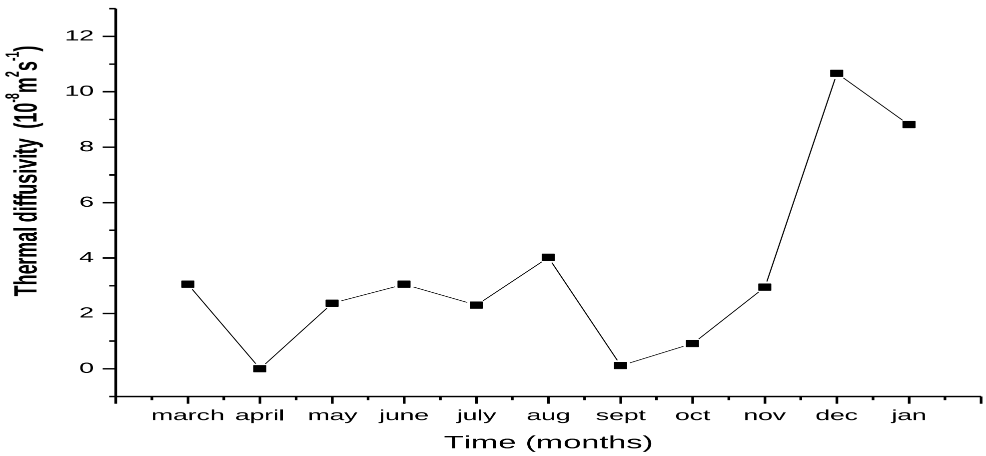

Fig 3: Variation of thermal diffusivity for Horton Numerical method from March, 2006 to January, 2007.

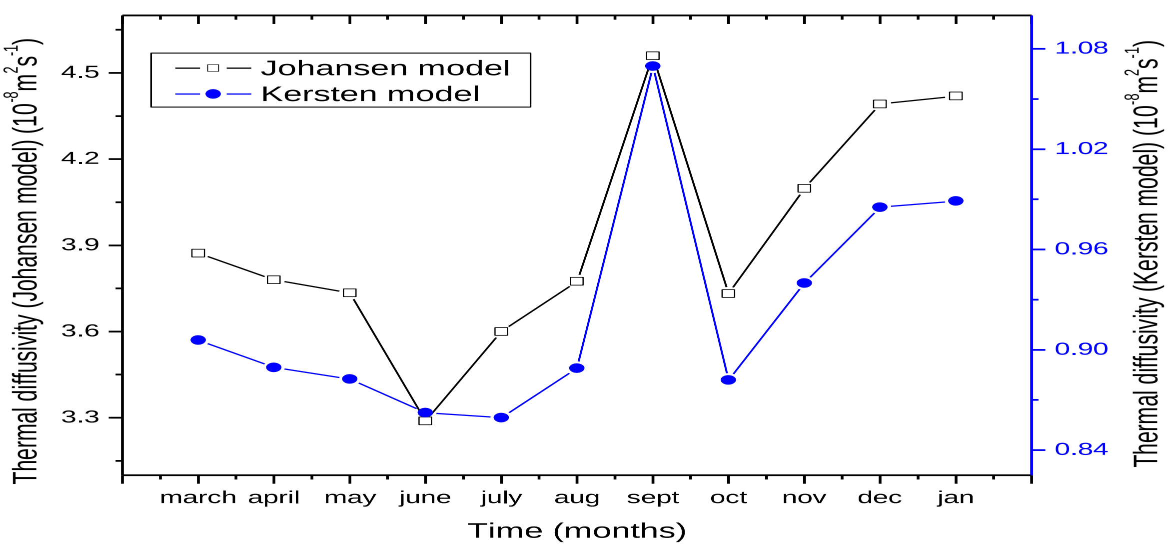

Fig 4: Variation of thermal diffusivity for Johansen and Kersten models from March, 2006 to January, 2007

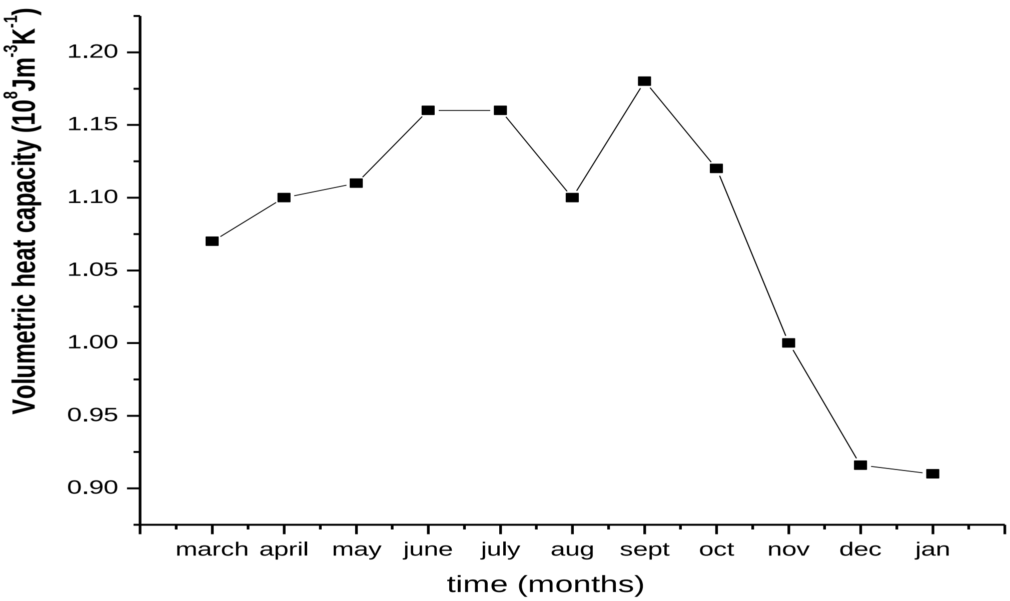

Fig 5: Variation of volumetric heat capacity from March, 2006 to January, 2007

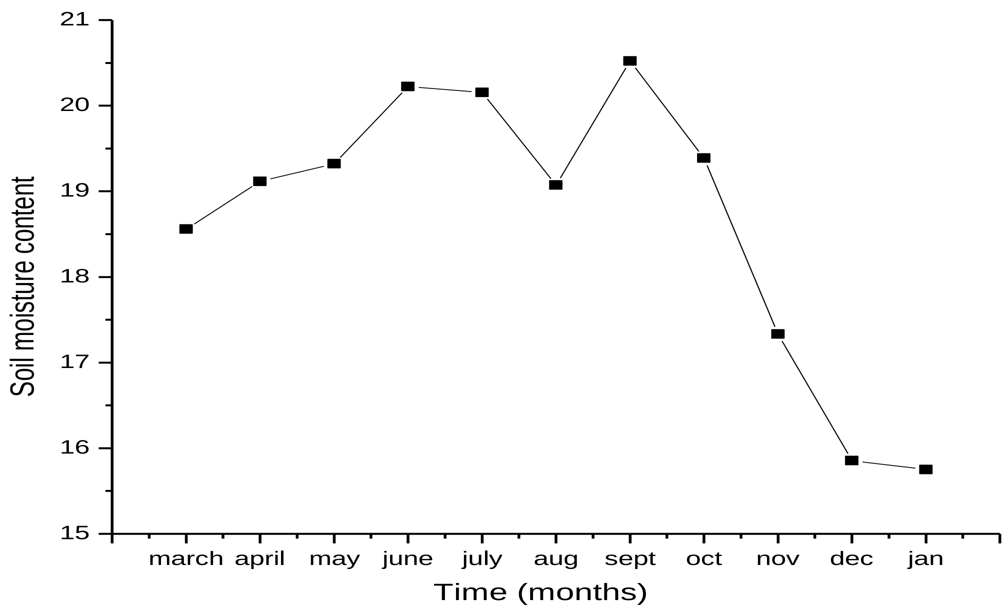

Fig 6: Variations of soil moisture content (m^3/m^3) from March, 2006 to January, 2007

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Table 1: Estimates of Soil Thermal Conductivity ($Wm^{-1}K^{-1}$) from March, 2006 to January, 2007

		Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan
Max	λ_1	19.65±6.41	0.00±0.00	23.88±9.79	14.20±5.65	11.66±3.45	16.94±5.23	54.45±14.68	24.87±7.16	47.97±10.67	14.09±3.00	15.50±1.91
	λ_2	4.20±0.04	4.23±0.06	4.23±0.04	3.87±0.04	4.23±0.04	4.21±0.04	4.25±0.08	4.20±0.05	4.21±0.05	4.03±0.00	4.02±0.00
	λ_3	1.02±0.02	1.03±0.04	1.03±0.02	1.04±0.03	1.03±0.03	1.02±0.02	1.04±0.05	1.02±0.03	1.02±0.03	0.91±0.00	0.90±0.00
Min	λ_1	-10.23±6.41	0.00±0.00	-24.36±9.79	-9.50±5.65	-3.64±3.45	-2.64±5.23	-34.59±14.68	-15.55±7.16	-18.54±10.67	1.55±3.00	4.86±1.91
	λ_2	4.07±0.04	4.06±0.06	4.10±0.04	3.72±0.04	4.11±0.04	4.08±0.04	3.85±0.08	3.93±0.05	4.03±0.05	4.02±0.00	4.02±0.00
	λ_3	0.93±0.02	0.93±0.04	0.95±0.02	0.95±0.03	0.95±0.03	0.94±0.02	0.79±0.05	0.84±0.03	0.90±0.03	0.90±0.00	0.90±0.00
Mean	λ_1	3.33±6.41	0.00±0.00	2.66±9.79	3.44±5.65	2.64±3.45	4.28±5.23	-0.44±14.68	1.12±7.16	2.98±10.67	9.76±3.00	8.01±1.91
	λ_2	4.12±0.04	4.14±0.06	4.15±0.04	3.81±0.04	4.17±0.04	4.11±0.04	4.18±0.08	4.14±0.05	4.08±0.05	4.02±0.00	4.02±0.00
	λ_3	0.96±0.02	0.98±0.04	0.98±0.02	1.00±0.03	0.98±0.03	0.98±0.02	1.00±0.05	0.98±0.03	0.94±0.03	0.90±0.00	0.90±0.00

Table 2: Estimates of Thermal Diffusivity ($x10^{-8}m^2s^{-1}$) from March, 2006 to January,2007

		Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan
Max	α_1	16.40±6.04	0.00±0.00	23.10±9.04	11.30±4.98	9.36±2.93	16.40±4.98	49.40±12.70	21.10±6.40	39.60±9.20	15.40±3.30	17.10±2.11
	α_2	4.15±0.18	4.16±0.28	3.98±0.17	3.69±0.21	3.98±0.21	4.10±2.03	39.40±5.57	4.98±0.27	4.37±0.27	4.41±0.01	4.43±0.01
	α_3	0.96±0.03	0.95±0.05	0.92±0.03	0.95±0.04	0.92±0.04	0.94±0.03	7.46±0.22	1.07±0.04	0.98±0.00	0.99±0.00	0.99±0.00
Min	α_1	-9.15±6.04	0.00±0.00	- 23.20±9.04	-8.15±4.98	- 3.40±2.93	-1.73±4.98	- 30.00±12.70	- 15.10±6.40	- 16.00±9.20	1.70±3.30	5.34±2.11
	α_2	3.47±0.18	3.38±0.28	3.33±0.17	3.02±0.21	3.33±0.21	3.42±2.03	3.27±5.57	3.47±0.27	3.45±0.27	4.37±0.01	5.34±0.01
	α_3	0.84±0.03	0.82±0.05	0.81±0.03	0.81±0.04	0.81±0.04	0.83±0.03	0.80±0.22	0.84±0.04	0.83±0.00	0.98±0.00	0.99±0.00
Mean	α_1	3.05±6.04	0.00±0.00	2.37±9.04	3.05±4.98	2.29±2.93	4.02±4.98	0.10±12.70	0.90±6.40	2.90±9.20	10.70±3.30	8.81±2.11
	α_2	3.87±0.18	3.78±0.28	3.73±0.17	3.29±0.21	3.60±0.21	3.77±2.03	4.56±5.57	3.73±0.27	4.10±0.27	4.39±0.01	4.42±0.01
	α_3	0.91±0.03	0.89±0.05	0.88±0.03	0.86±0.04	0.86±0.04	0.89±0.03	1.07±0.22	0.88±0.04	0.94±0.00	0.99±0.00	9.89±0.00

Table 3: Estimates of Volumetric Heat Capacity ($x10^8Jm^{-3}K^{-1}$) from March, 2006 to January, 2007

	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan
Max	1.21±6.05	1.27±0.10	1.27±0.06	1.28±0.08	1.27±0.08	1.23±0.07	1.30±0.22	1.21±0.08	1.22±0.09	0.92±0.00	0.91±0.00
Min	0.98±6.05	0.98±0.10	1.03±0.06	1.02±0.08	1.03±0.08	0.99±0.07	1.17±0.22	0.79±0.08	0.92±0.09	0.91±0.00	0.91±0.00
Mean	1.07±6.05	1.10±0.10	1.11±0.06	1.11±0.08	1.16±0.08	1.10±0.07	1.16±0.22	1.12±0.08	1.00±0.09	0.92±0.00	0.91±0.00

Reference

Adeniyi, M. O., Oshunsanya, S. O. and Nymphas, E. F.: Validation of Analytical Algorithms for the Estimation of Soil Thermal Properties Using de Vries Model, American Journal of Scientific and Industrial Research, 3 (2), 103-114, 2012.

Anandakumar, K.,Venkatesan, R. and Prabha, T. V.: Soil Thermal Properties at Kalpakkam in Coastal South India, Proc. Indian Acad. Sci, 110, 239-245, 2001.

Arya, S. P.: Introduction to Micrometeorology (2nd ed), California USA: Academic Press, 2001.

Bristow, K. L., Kluitenberg, G. J., Goding, C. J., Fitzgerald, T. S.: A Small Multi- needle Probe for Measuring Soil Thermal Properties, Water Content and Electrical Conductivity, Computer and Electronics in Agriculture, 31, 265-280, 2001.

Cote, J. and Konrad, J. M.: Thermal Conductivity of Base-Course Materials, Canada Geotechnical Journals, 42, 61-78, 2005.

de Vries, D. A.: Thermal Properties of Soils. In van Wijk WR (eds.)Physics of Plant Environment, North Holland Publishing Company, Amsterdam, 210-235, 1963.

Gao, Z., Wang, L., and Horton, R.: Comparison of Six Algorithms to Determine the Soil Thermal Diffusivity at a Site in the Loess Plateau of China, Hydrol. Earth Syst. Sci. Discuss, 6, 2247-2274, 2009.

Gao, Z., Fan, X., and Bian, L.: An Analytical Solution to One-Dimensional Thermal Conduction-Convection in Soil, Soil Sci., 168, 99-107, 2003.

Horton, R., Wierenga, P. J. and Nielsen, D. R.: Evaluation of Methods for Determining the Apparent Thermal Diffusivity of Soil Near the Surface, Soil Science Society of America Journal, 47, 23-32, 1983.

Johansen, O.: Thermal Conductivity of Soils, Ph.D Thesis Norwegian University Of Science and Technology, Trondheim (CRREL Draft Translation 637), 1975.

Kersten, M. S.: Laboratory Research for the Determination of Thermal Properties of Soils, ACFEL Technical Report 23, University of Minnesota, Minneapolis, 1949.

Lu, S., Ren, T., Gong, Y. and Horton, R.: An Improved Model of Predicting Soil Thermal Conductivity from Water Content at Room Temperature, Soil Physics, 71(1), 8-14, 2007.

Massman, W. J.: 1992 Correcting Errors Associated with Soil Heat Flux Measurements and Estimating Soil Thermal Properties from Soil Temperature and Heat Flux Plate Data, Agric. For. Meteorol. 59, 249-266, 1992.

Mayocchi, C. L. and Bristow, K. L.: Soil Surface Heat Flux: Some General Questions and Comments on Measurements, Agriculture and Forest Meteorology, 75, 43-50, 1995.

Nymphas, E. F., Adeniyi, M. O., Ayoola, M. A. and Oladiran, E. O.: Micrometeorology Measurements in Nigeria During the Total Solar Eclipse of 29 March, 2009, Journal of Atmospheric and Solar Terrestrial Physics, 71, 1245-1253, 2009.

Oladosu, O. R., Jegede, O. O., Sunmonu, L. A. and Adediji, A. T.: Bowen Ratio Estimation of Energy Fluxes in a Humid Tropical Agricultural Site Ile-Ife, Nigeria, Indian Journal of Radio and Space Physics, 36, 213-218, 2007.

Ochsner, T. E., Horton, R. and Ren, T.: A New Pespective on Soil Thermal Properties, Soil Science Journal. 65. 1641-1647, 2001.

Sikora E., Kossowski J.: Thermal Conductivity and Diffusivity Estimations of Uncompacted and Compacted Soils Using Computing Methods, Polish J. Soil Sci., 26(1), 19-26, 1993.

Usowicz, B.: Evaluation of Methods for Soil Thermal Conductivity Calculations, Int. Agrophysics, 9, 109-113, 1995.