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TEMPERATURE VARIATIONS AND SOIL THERMAL PROPERTIES AT THE NIGERIA MESOSCALE EXPERIMENT SITE, IBADAN, NIGERIA

E. Nwaokoro*+, E. F. Nymphas**
*Abia State University, Uturu, Abia State.
**University of Ibadan, Ibadan Oyo State
+nwaokoro.emenike@abiastateuniversity.edu.ng

ABSTRACT: *Soil temperature has been observed to depend on a number of factors, which also determine the surface temperature. In this study, soil temperature at the Nigeria Mesoscale Experiment (NIMEX) site, Ibadan (7.4398° N, 3.8930° E) was investigated and the soil thermal properties were estimated for the period of March, 2006 to January, 2007 using Kersten model. The rainy seasons had increased the soil moisture content and soil thermal properties while the dry seasons had low soil moisture content and soil thermal properties. The maximum temperature of 32.10° C at the 30cm depth was measured in November 2006 during the dry season and the minimum temperature 26.80° C was measured at 5cm depth in September 2016 during the wet/rainy season. Soil moisture, thermal conductivity, thermal diffusivity and volumetric heat capacity had their maximum value of 20.52m^3m^{-3}, 1.006 $Wm^{-1}K^{-1}$, 1.07*$10^{-8}m^2s^{-1}$ and 0.91*$10^8Jm^{-3}K^{-1}$ in September 2006 respectively. The minimum values for soil moisture, thermal conductivity and volumetric heat capacity occurred in January, 2007 with values of 15.75 m^3m^{-3}, 0.90 $Wm^{-1}K^{-1}$ and 0.91*$10^8Jm^{-3}K^{-1}$ respectively, and the minimum value of 0.85*$10^{-8}m^2s^{-1}$ for thermal diffusivity occurred in July 2006.*

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

INTRODUCTION

The most important factors controlling the exchange of energy and mass between the soil and the atmosphere are soil temperatures and soil thermal properties (Ochsner et al., 2001). The influence of temperature on soil is noticeable already at the level of their formation, through their direct influence on the weathering of bedrock to produce mineral particles (Dec et al, 2009).Temperature variations are extreme at the soil surface and these variations are transferred to sub-surface layers at reduced rate as soil depth increases. Also there is a time delay (sometimes referred to as thermal lag) when maximum and minimum temperatures are achieved as soil depth increases (Lin et al, 2007).Soil temperatures depend on a number of factors such as the location (latitude), the time of the year (month or year), net radiation of the surface, soil texture and moisture content, ground cover, and surface weather conditions. Soil temperature may increase, or decrease or vary monotonically with depth, depending on the season and the time of the day (Arya, 2001). The aim of this work is to determine the influence of soil moisture on soil temperature and soil thermal properties at the Nigeria Mesoscale Experiment (NIMEX) site, Ibadan, Nigeria. The variation of soil temperature and the thermal properties during the wet and dry seasons was investigated.

THEORETICAL BACKGROUND

For an isotropic medium in one dimension the conductive heat transfer is given by:

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

Where T is the soil temperature, t the time, z the depth and α is the thermal diffusivity. α is

related to thermal conductivity, λ and volumetric heat capacity, C_v through the relation:

$$\alpha = \frac{\lambda}{C_v} \quad (2)$$

Thermal conductivity is either measured directly using thermal heat probes or estimated from known values of thermal diffusivity and volumetric heat capacity. Similarly, volumetric heat capacity is estimated from the knowledge of soil porosity, soil mineral, organic and water content. However, when the measurement probes and detailed soil data are not available indirect estimation methods are employed (Anandakumar et al, 2001).Horton et al. (1983) developed a method for estimating thermal diffusivity based on harmonic analysis. The method requires fitting a Fourier series to the diurnal soil temperature measured at 1meter intervals at 0.01meter depth followed by the prediction of temperatures at a depth, z (0.1 meter), based on the Fourier series solution to the one dimensional heat flux problem using an assumed value of thermal diffusivity

Kersten (1949) developed an empirical model to estimate thermal conductivity. This model only requires bulk density, ρb, as an input parameter, but it is not suitable for predicting thermal conductivity at lower water contents.Johansen (1975) developed an empirical model for estimating thermal conductivity, which he called normalized thermal conductivity. This model is based on the degree of saturation (S_r) and soil mineral composition. For many soils, the Johansen (1975) model gives accurate predictions of thermal conductivity.Steven (1994) used data from time domain reflectometry measurement system for water content to calculate soil thermal conductivity, and to determine a relationship between thermal conductivity and water content for soil.

Lu et al (2007) developed an improved model that describes the relationship between thermal conductivity and volumetric water content of soils. This new model estimates soil thermal conductivity using soil bulk density, sand (or quartz) fraction, and water content.
For this study we used Kersten (1949) model to estimate thermal conductivity at the NIMEX site, Ibadan Nigeria with the aim of studying the effect of soil moisture and temperature variations on soil thermal properties.

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METHODS AND MEASUREMENTS

This study is conducted at Nigeria Mesoscale Experiment (NIMEX) site located within the campusof the University of Ibadan in Ibadan, Nigeria about 145 km from the Gulf of Guinea.
The instrumentation, which provided the data, comprised of a 15-m mast to measure the profiles of the mean wind speed and air temperature (wet and dry bulb) at various heights. The same mast also supported radiation sensors for global and net radiation. Both the heat flux plates and the soil thermometers were buried in the ground carefully, so that the surrounding soil was left undisturbed. Other measurements made include the surface temperature, air pressure, and rainfall amount. The instrumentation provided data (time series) for the whole period of experimentation 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. Thermal conductivity was estimated using Kersten (1949) model (eq. 3), volumetric heat capacity was estimated from volumetric water content and soil bulk density (eq. 4) and thermal diffusivity was computed using eq.2. 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.

$$\lambda = 0.14442[0.9log(\theta) - 0.2] \times 10^{0.6243\rho_b} \qquad (3)$$

where λ is the thermal conductivity, θ is the soil moisture and ρ_b is the dry bulk density,

$$C_v = \rho_b\left(c_{pav} + \Theta_m c_{pw}\right) \qquad (4)$$

where C_v is the volumetric heat capacity, Θ_m is the volumetric water content, ρ_b is the soil bulk density, c_{pav} and c_{pw} are the average specific heat capacity of mineral soils and the specific heat capacity of soil water from Mayocchi and Bristow (1994), which are 840 $Jkg^{-1}K^{-1}$ and 4180 $Jkg^{-1}K^{-1}$ respectively.

RESULTS AND DISCUSSIONS

The soil temperature studied is from March 2006 to January 2007. These months are the two seasons in Nigeria, the wet or rainy seasons (April - October) and the dry seasons (November – March). Relative humidity is usually greater than 87% in the study site during the wet season due to the south-westerlies that are prevalent during this period. The warm and moist flow is associated with convective-type clouds and water vapor, which are the most important attenuators of solar radiation. The dry season is determined by the cold, dry and dusty northeasterly winds blowing from the Sahara Desert into West Africa (Nymphas et al, 2009).Figures 1-5 show the diurnal variation of measured soil temperature, soil moisture content, thermal conductivity, thermal diffusivity and volumetric heat capacity for the whole period.

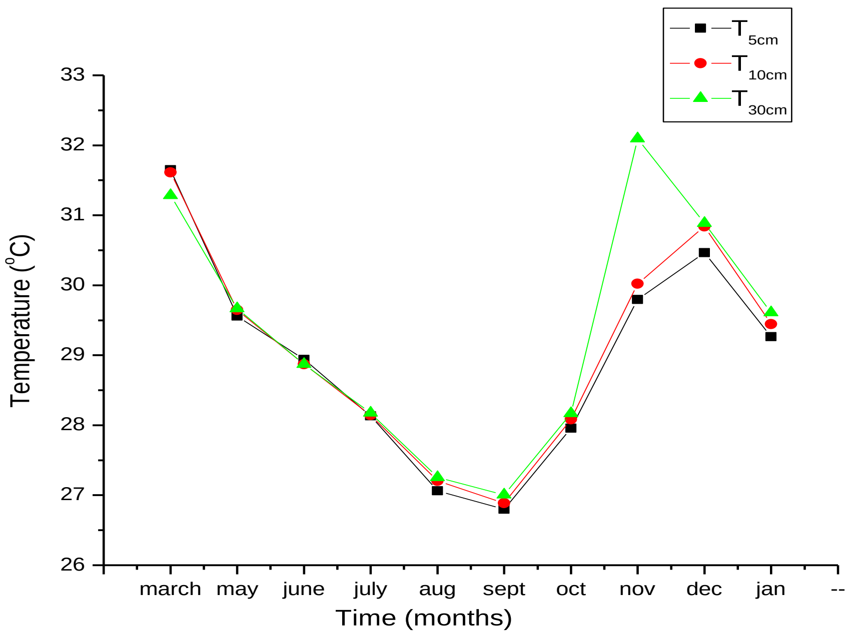


Fig.1: Variations of temperature (March, 2006 - Jan, 2007)

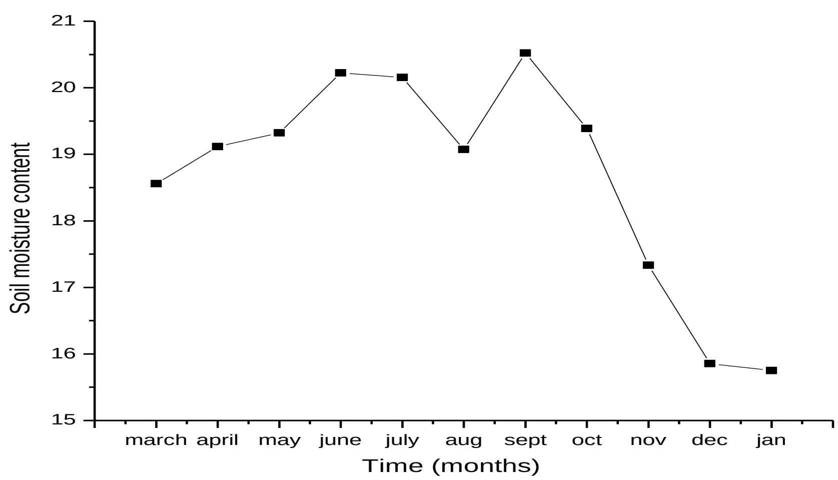
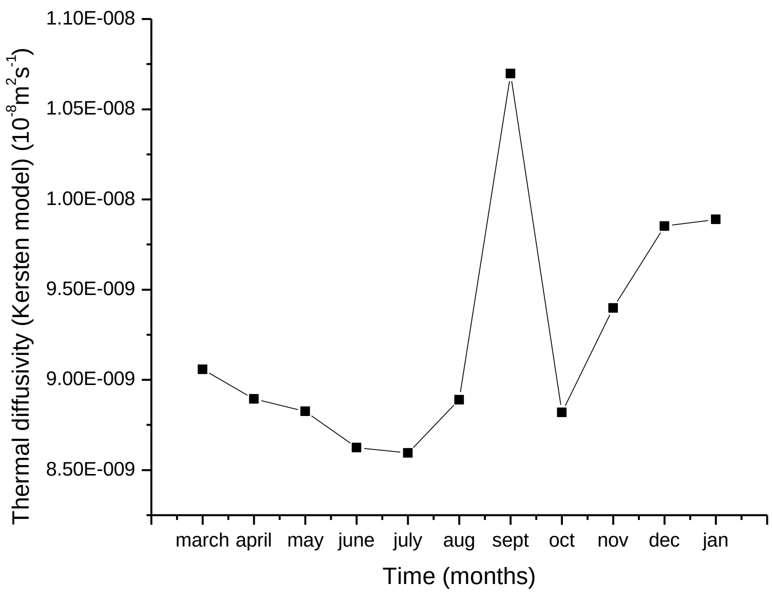


Fig.2: Variations of soil moisture content (m^3/m^3) (March, 2006 - Jan, 2007)

Fig 3: Variation of thermal conductivity (March, 2006-January, 2007)



The maximum temperature of 32.10° C at the 30cm depth (fig. 1) was measured in November 2006 during the dry season. The heat from the Sun (shortwave radiation) is usually high at this period this heats up the soil surface, the heat is then transmitted into deeper soil layers. Soil water content decreases at all depths during this period due to evaporation from the bare soil surface. Under this evaporation condition, there is a net upward heat flux (liquid and vapor) that responds to the progressively drying surface. The net flux of water causes an associated net convective heat flux (Gao et al, 2009).

The minimum soil temperature of 26.80°C was measured at 5cm depth in September 2006 during the wet season when precipitation was high, which causes increase in soil moisture. The presence of soil moisture at the soil surface and in the soil subsurface greatly moderates the diurnal range of soil temperatures. This is due to increased evaporation at the soil surface, and increase in thermal conductivity and volumetric heat capacity in the soil. At a wet, bare soil surfaces a substantial part of radiation goes into evaporation in the beginning, but reduces as soil surface dries up. Increase in volumetric heat capacity of the soil further slows down the warming of the upper layer of the soil in response to the radiative heating of the soil surface (Arya, 2001).

In December 2006, there was a decrease in temperature which extended to January 2007, although, soil moisture was low. This could be as a result of either slight precipitation that might have occurred and cooled the soil surface, or the harmattan which carry loose sand dust particles,

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atmospheric and other anthropogenic aerosols which may remain in the air thereby reducing visibility to less than 1km (Nymphas et al, 2009). These dust particles and aerosols absorb the incoming solar radiation before it reaches the earth surface. Another reason could be the presence of cloud, which may allow only a small part of solar radiation to reach the ground surface due its ability to reflect a good part of the solar radiation (Arya, 2001). The observed inversion in temperature, which started in July 2006, is due to increases in soil moisture caused by rainfall within that period till September. Figure 2 shows the variation of soil moisture for the period of investigation. Soil moisture has its maximum value of $20.52m^3\ m^{-3}$ in the month of September and minimum in the month of January with the value $15.75\ m^3m^{-3}$. The inversion in August is due to the dryness noticed in some of the days thereby reducing the soil moisture. The same inversion also occurred in figure 3 and 5 for thermal conductivity and volumetric heat capacity.

Figure 3 is the plot for estimated thermal conductivity. The figure shows that the month of September has the maximum thermal conductivity value of $1.006\ Wm^{-1}K^{-1}$ and the minimum value occurred in January 2007 with a value of $0.90\ Wm^{-1}K^{-1}$.

The thermal diffusivity plot for the period of investigation is shown in figure 4. It, also, has its highest value in September 2006 with a value of $1.07*10^{-8}m^2s^{-1}$ and its minimum value of $0.85*10^{-8}m^2s^{-1}$ occurred in July 2006.

Figure 5 shows the volumetric heat capacity, which has its maximum value of $1.18*10^8Jm^{-3}K^{-1}$ and a minimum value of $0.91*10^8Jm^{-3}K^{-1}$ in September 2006 and January 2007 respectively.

From the figures thermal conductivity and volumetric heat capacity increased linearly with increase in soil moisture in agreement literature (Arya, 2001, Peters-Lidard et al, 1998, Anandakumar et al, 2001, Lu et al, 2007, Ochsner et al, 2001, Cote and Konrad, 2005), but thermal diffusivity estimated decreased as the soil moisture increases.

Increase in soil moisture from March 2006 – September 2006 (the wet periods) gave rise to increased evaporation from the soil surface and a substantial part of net radiation went into evaporation, which also gave rise to the observed low temperature. As a result of this latent heat loss, caused by the evaporation from the soil surface, the energy available for heating the soil is reduced (Arya, 2001; Anandakumar et al, 2001). Evaporation from October 2006 – January 2007 (the dry periods) caused the soil moisture to decrease, and increase in soil temperature. Under this evaporation conditions there is a net upward flux of water (liquid and vapor) that responds to the progressively drying surface condition. The net flux of water causes an associated net convective heat flux (Gao et al, 2009). Increase in soil moisture, also caused increase in soil thermal conductivity, and volumetric heat capacity and decrease in thermal diffusivity except in the month of September, as seen in figure 2 to 5. The increase in volumetric heat capacity and thermal conductivity slowed the warming of the upper layer of the soil in response to the radiative heating of the surface, which also contributes to the low observed temperature.

CONCLUSION

Temperature variations and soil thermal properties at the Nigeria Mesoscale Experiment site, Ibadan, Nigeria was carried out in this work. Thermal conductivity, volumetric heat capacity and thermal diffusivity for Nigerian Mesoscale Experiment (NIMEX) site, Ibadan was found to have a good correlation with moisture content. Thermal diffusivity reduced as the moisture content increased while thermal conductivity and volumetric heat capacity increased with moisture content. This increase in thermal conductivity and volumetric heat capacity corresponds to the rainfall periods in Nigeria. This confirms that changes in soil moisture content cause significant changes in volumetric heat capacity, thermal conductivity and thermal diffusivity of soils. Increase in soil moisture gives rise to increased evaporation from the soil surface and a substantial part of net radiation goes into evaporation, which also gives raise to the observed low temperature. Increase in soil moisture also causes increase in thermal conductivity and volumetric heat capacity, slowing down the warming of the upper layer of the soil in response to radiative heating of the soil surface leading to low soil temperature.

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