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Assessment of Soil Thermal Properties in a Tropical Environment: Ile Ife and Ibadan

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Abstract Soil thermal properties are crucial parameters that affect soil heat flux. Time series of soil temperature, soil moisture content, and rainfall and soil heat flux were measured at two tropical locations in West Africa during the transition from dry to wet season, and at the peak of rainy season in July. The data were analyzed to estimate soil thermal diffusivity, thermal inertia and volumetric heat capacity.
The thermal properties were clearly related to soil moisture (and thus rainfall) throughout the measurement period. The modeled soil heat flux using the soil thermal properties compared favorably with the measured soil heat flux.

Keywords: Soil heat flux; Thermal diffusivity; Volumetric heat capacity; Thermal inertia; Moisture content.

Introduction

Soil heat flux, G is an important component of the earth's surface energy balance especially for measurements taken over bare or thinly vegetated surfaces. Accurate determination of soil heat flux requires *in situ* knowledge of soil thermal properties (thermal diffusivity, K_h and volumetric heat capacity, H). The volumetric heat capacity, H is defined as the change of heat content per soil volume per change in temperature. Thermal diffusivity, K_h is the heating and cooling rate accompany a given temperature profile. Thermal inertia, Γ, is a parameter that can be used to characterize the property of a particular soil since it combines H and K_h. It is a measure of impedance to heat transfer. All these properties are in turn dependent on soil moisture content,Θ, soil composition and vegetation cover [1].

Apart from the application of soil thermal properties in the calculation of soil heat flux, they are also used as atmospheric variable input in numerical models (i.e Surface Vegetation Atmosphere Transport models, SVATs). These models are used to study land surface processes. Realistic understanding of the soil thermal properties will therefore improve the performance of these models in accurate weather and circulation predictions. Measurements of soil thermal properties are however not easily available. Two micrometeorological experiments were carried out at two tropical sites in West Africa to investigate land surface processes and the data sets obtained provided an excellent opportunity to estimate the soil thermal properties in the region of study. This paper describes the thermal properties of the soil and their dependence on changing moisture conditions.

Materials and methods

Experimental Sites and Measurements

Nigerian Micrometeorology Experiment (NIMEX) [2] was conducted at Ile-Ife, Nigeria (latitude $7°33'N$ and longitude $4°33'E$) during the transition from dry to wet season. The period of intensive observation is from February 19 through to March 9 (this corresponds to Day Of the Year, DOY 55 through 68 using Julian days' notation) in 2004. This site is located in humid equatorial region of West Africa and the climate of the region can be classified as tropical with a dry winter season and wet summer season [3]. The site is at the altitude of 288 m above the sea level and its vegetation can be characterized as fallow bush-land of 0.30 m canopy height. The ground surface of the site is flat and homogenous. The soil is loamy sand and it is at its

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permanent wilting condition at the beginning of the experiment [2, 4]. However two types of heterogeneity of surface properties could be identified at the site. One is spatial and the other is temporal. The soil type changes with depth. At the depth of about 0.20 m, the soil type changes from loamy sand to clayey type. The rainfall of DOY 56 and 57 also caused transient temporal heterogeneity in the soil moisture content. The soil bulk density at 0.05 m depth is 1421.2 kg/m^3 and damping depth is 0.12 m on the average. The maximum and the minimum air temperature during the period of the experiment were 29.54 ^{0}C and 25.04 ^{0}C, respectively and the annual rainfall amount is 1225 mm (calculated over 50 years).

Another phase of NIMEX-experiment was carried out at Ibadan in the experimental field of Lower Atmospheric Physics unit, University of Ibadan, Ibadan, Nigeria ($7^\circ 26'N, 3^\circ 53'E$). Thirteen days of continuous measurement (June 3, 2006 to June 15, 2006) at the site were used in the study. The site is located at about 78 km from Ile Ife. The site comprises of an area of 850 m^2 of flat terrain at elevation of 220 m above the sea level. The soil type is loamy sand with a bulk density of 1600 kg/m^3 at 0.05 m depth. The ground surface of the target area was bare during the measurement period. The topography of the terrain surrounding the site can be classified as undulating low land with few high places which are easily sighted from the site. The maximum and the minimum air temperature during the period of the experiment were 38.7^{0}C and 24.2 ^{0}C respectively and the annual rainfall amount is 1250 mm (calculated over 50 years).

The soil temperatures were measured with two soil thermocouple probes (Campbell Scientific Inc., USA) at 0.05 m and 0.10 m depth. The volumetric moisture contents of the soils were measured at 0-0.05 m depth by soil moisture reflectometer (CS615 and CS616 Campbell Scientific Inc., USA). The soil heat flux was measured using Hukseflux Hfp01sc self-calibrating heat flux plate. The rainfall amounts were measured using Rainguage ARG100 (Campbell Scientific Inc.,USA). These sensors were controlled by using Campbell CR10X dataloggers which sampled the data every 1second and subsequently stored them as 1minute averaged values.

Thermal Diffusivity, K_h (m^2s^{-1})

This parameter is determined by solving the equation describing the heat transfer by conduction in a one-dimensional isotropic medium:

$$\frac{\partial G}{\partial z} = \frac{\partial T}{\partial t} = K_h \frac{\partial^2 T}{\partial z^2} \tag{1}$$

In this case K_h is independent of depth and time. Where t is time and z is the depth

Using the Fourier series representation, the soil temperature near the surface (depth of 0.05m in this case) can be represented as

$$T(t) = \overline{T} + \sum_{k=1}^{N} C_k \, Cos \left(\omega kt - \phi_k\right) \tag{2}$$

where $C_k = \left[A_k^2 + B_k^2\right]^{\frac{1}{2}}$ and

$$\phi_k = \begin{bmatrix} \tan^{-1}\left(B_k / A_k\right) A_k > 0 \\ \tan^{-1}\left(B_k / A_k\right) \pm \pi \quad A_k < 0 \\ \pi/2, \quad A_k = 0 \end{bmatrix}$$

$\overline{T}$ is the mean soil temperature, C_k is the amplitude. ϕ_k is the phase angle, ω is the angular velocity of the Earth's rotation and $\omega = \frac{2\pi}{P}$ with P representing the period of the diurnal cycle. N is the number of harmonics.

The following analytical solution to equation (1) (hereafter refers to as harmonic algorithm) was obtained by using the boundary condition of equation (2)

$$T(z,t) = \overline{T} + \sum_{k=1}^{N} \left\{ C_{ok} e^{-z\sqrt{k\omega/2K_h}} Cos \left(k\omega t + \phi_{ok} - z\sqrt{k\omega/2K_h}\right) \right\} \tag{3}$$

where C_{ok} *and* ϕ_{ok} are the amplitude and phase angle of the kth harmonic for the upper boundary, respectively. Though equation (3) is similar to that obtained by [5] both equation (2) and (3) are slightly different in that while [5] proposed a sine function, an equivalent cosine function with appropriate transformation of phase angle as define in equation (2) can be used. Thermal diffusivity K_h can be found by selecting K_h (through iteration) which gives the least of the sum of the squared differences between the measured and estimated temperature at the depth of 0.10 m [6]. Only the top 0.10 m depth of the soil was used in the determination of K_h since the calculation of soil heat flux, G as a parameter in characterizing a particular surface requires values of K_h at the homogeneous upper few centimeters of the soil.

Soil heat flux, G (W/m^2)

By combining Fourier equation with equation (2) and (3), an analytical equation that can be used to express soil heat flux, G was obtained as

$$G = \Gamma \sum_{k=1}^{N} \left\{ \sqrt{k\omega}\, C_{ok}\, e^{-z\sqrt{k\omega / 2K_h}}\, Cos \left(k\omega t - \phi_{ok} - z\sqrt{k\omega / 2K_h} \right) \right\} \tag{4}$$

Equation (4) was then used to model G. Modeled values of G were compared with the measured values at the depth of 0.10m to test the soil thermal response to transient fluctuation in moisture content.

Volumetric Heat Capacity and Thermal inertia

The volumetric heat capacity, H (Jm^{-3}K^{-1}) can be calculated if the values for bulk density and moisture content for the soil layer under consideration are available using

$$H = C_s f_s + C_\theta \theta \tag{5}$$

and

$$f_s = \frac{\rho_d^b}{\rho_s} \tag{6}$$

where ρ_d^b is bulk density of the soil sample (kgm^{-3}) and ρ_s is density of the soil sample which is taken as 2650 kgm^{-3} (Ten Berge, 1990).

The volumetric specific heat capacity for the mineral soil components C_s and water, C_o are 2.0 and 4.2 Jm^{-3}K^{-1}, respectively [7].

Thermal inertia, Γ (MJm^{-2}K^{-1}s$^{-1/2}$) is a parameter that combines two soil thermal properties, H and K_h, and it is calculated as: $\Gamma = H\sqrt{K_h}$. (7)

The dependence of soil thermal properties on soil composition and vegetation type was eliminated in this work by using two sites that were of either of bare surface or fading vegetation at the time of measurements, and with the same soil type. The measurement periods were chosen such that the influence of soil moisture content could easily be investigated.

Results and discussion

The temporal variation in soil moisture content, θ, between surface and 0.05 m depth at Ile Ife site is shown Figure 1. Precipitation occurred on DOYS 56 and 57 with amount of 0.91 mm. Since then, due to evaporation from the soil surface, the soil moisture content decreased gradually from DOY 57 through DOY 68 except for slight upsurge on DOY 60. Figure 2 showed the temporal variation soil moisture content, θ, at Ibadan site during the transitiȯn period at 0-0.05 m depth. The rainfall amount at this site from DOY 52 to 53 was 0.71 mm while the rainfall amount between DOY 60 and 61 was 0.16 mm. Due to evaporation from the soil surface, the soil moisture content decreased gradually from DOY 52 through DOY 59 and from DOY 60 through DOY68. The temporal variation soil moisture content,θ, at the same site during the rainy season is shown Figure 3. The rainfall amount at this site from DOY 150 to 153 is 0.9 mm while the rainfall amount on DOY 161 and DOY 165 were 24.6 mm and 20.4 mm, respectively. The soil moisture content decreased gradually from DOY 153 through DOY 159 and from DOY 161 through DOY164 due to evaporation from the soil surface. Figures 1-3 also showed that diurnal variations of the soil moisture content were superimposed on the temporal variations (points marked A to B on the charts are examples of such diurnal variations).

Thermal diffusivity, K_h showed an increasing trend with soil moisture content (Figure 4). This trend showed that K_h increased from the peak of dry season at Ile Ife site with θ=5% (see Figure 1) to the peak of wet season at Ibadan site with θ=22.3% (see Figure 3).

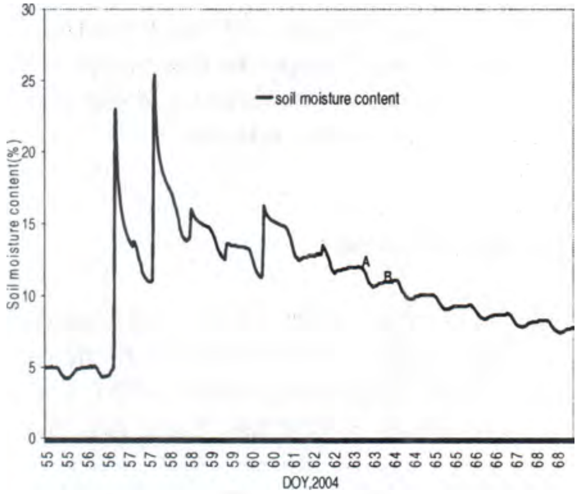

Figure 1 Temporal variations of soil moisture content (%) measured at depth of 0-0.05m at Ile Ife site from DOY 55 to DOY 68, 2004.

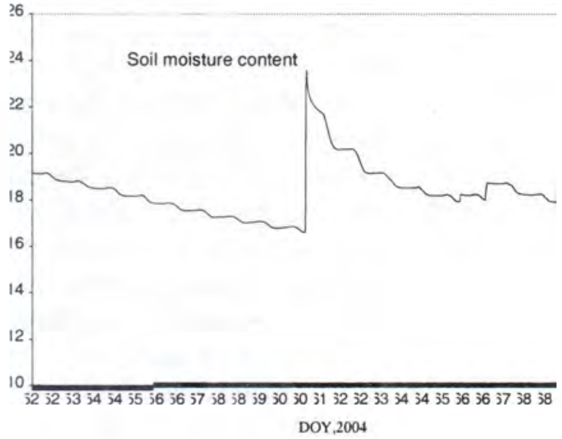

Figure 2 Temporal variations of soil moisture content (%) measured at depth of 0-0.05m at Ibadan site from DOY 52 to 68, 2006 (transition period).

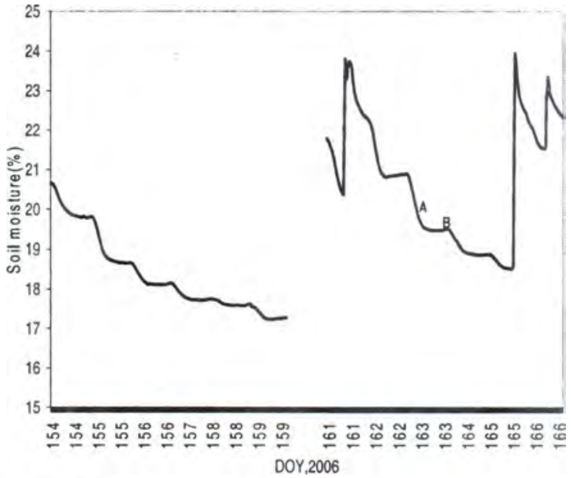

Figure 3 Temporal variations of soil moisture content (%) measured at depth of 0-0.05m at Ibadan site from DOY 154 to 166, 2006 (rainy season).

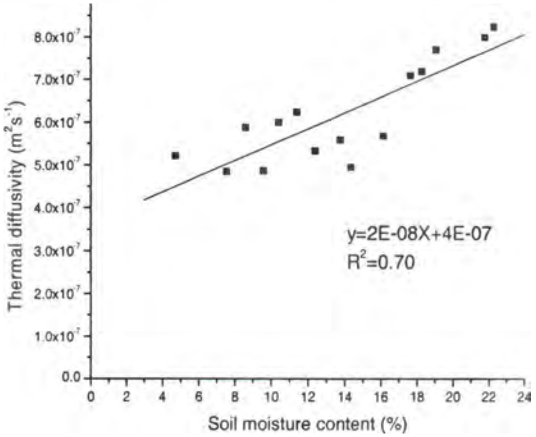

Figure 4 Variation of soil thermal diffusivity K$_h$($m^{2}s^{-1}$) with volumetric soil moisture content, θ(%).

The temporal variation of the volumetric heat capacity and the thermal inertia at Ile Ife site are shown Figures 5 and 6, respectively. Both of them showed decreasing trend with soil moisture content, θ (see Figure 1). Their scatter plots however showed that while volumetric heat capacity (Figure 7) perfectly varied linearly with θ ($R^2 \cong 1$), the thermal inertia (Figure 8) showed less dependence on θ ($R^2 = 0.83$). Table 1 gives the values of thermal diffusivity, heat capacity and thermal inertia at the depth of 0.05 m at Ile Ife site.

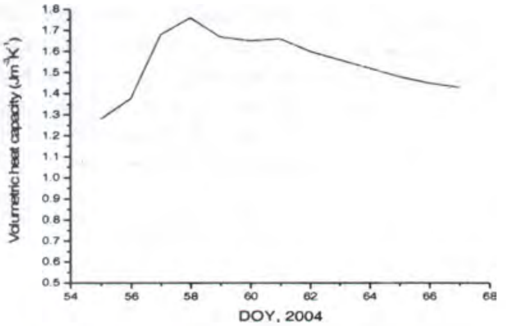

Figure 5 Temporal variation of volumetric heat capacity at depth of 0-0.05m at Ile Ife site from DOY 55 to DOY 68, 2004.

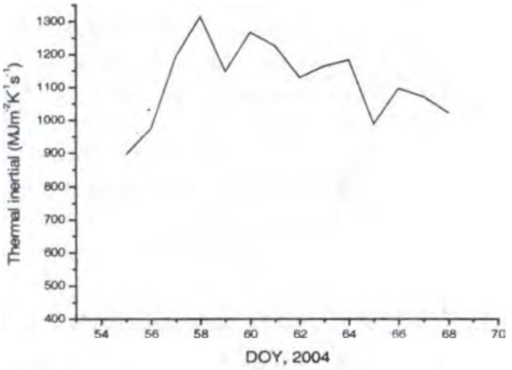

Figure 6 Temporal variations of thermal inertia at depth of 0-0.05m at Ile Ife site from DOY 55 to DOY 68, 2004.

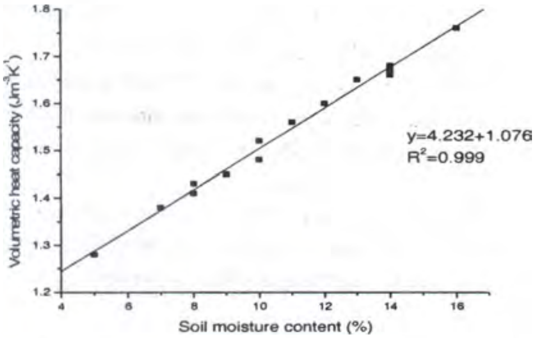

Figure7 Scatter plot of soil volumetric heat capacity against soil moisture content measured at depth of 0-0.05m at Ile Ife site from DOY 55 TO 68, 2004

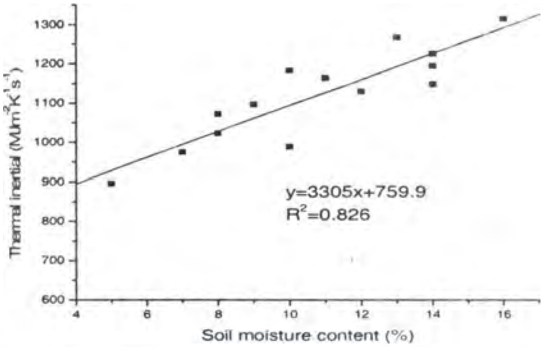

Figure 8 Scatter plot of soil thermal inertia against soil moisture content at Ile Ife site

Table1 Estimated values of volumetric heat capacity, *H*, thermal diffusivity, K_h, (from harmonic algorithm) and thermal inertia, Γ.

DOY	$H\times10^{-6}$(Jm^{-3}K^{-1})	$K_h\times 10^{7}$ (m^{2}s)	Γ (MJm^{-2}K^{-1}s$^{-1/2}$)
55	1.28	4.90	896
56	1.38	4.99	975
57	1.68	5.06	1195
58	1.76	5.58	1315
59	1.67	4.73	1149
60	1.65	5.90	1267
61	1.66	5.45	1225
62	1.60	4.99	1130
63	1.56	5.57	1164
64	1.52	6.06	1183
65	1.48	4.46	988
66	1.45	5.72	1097
67	1.43	5.62	1072
68	1.41	5.26	1023

The influence of thermal properties vis-à-vis soil moisture content, θ, on the estimation of soil heat flux, G was investigated through modeling using equation (4). Equation (4) incorporated the soil thermal properties. The plots of modeled and measured soil heat fluxes on diurnal time scale for dry and wet days, DOY57 and 67, respectively are given in Figure 9. The model for the dry day showed better fit than the one for wet day. This implied that soil heat flux was better approximated by the model's equation (equation 4) on a dry day than a wet day. This showed the impact of transient heterogeneity of rainfall (vis-à-vis the transient fluctuation in soil moisture) on the models that estimate soil heat flux.

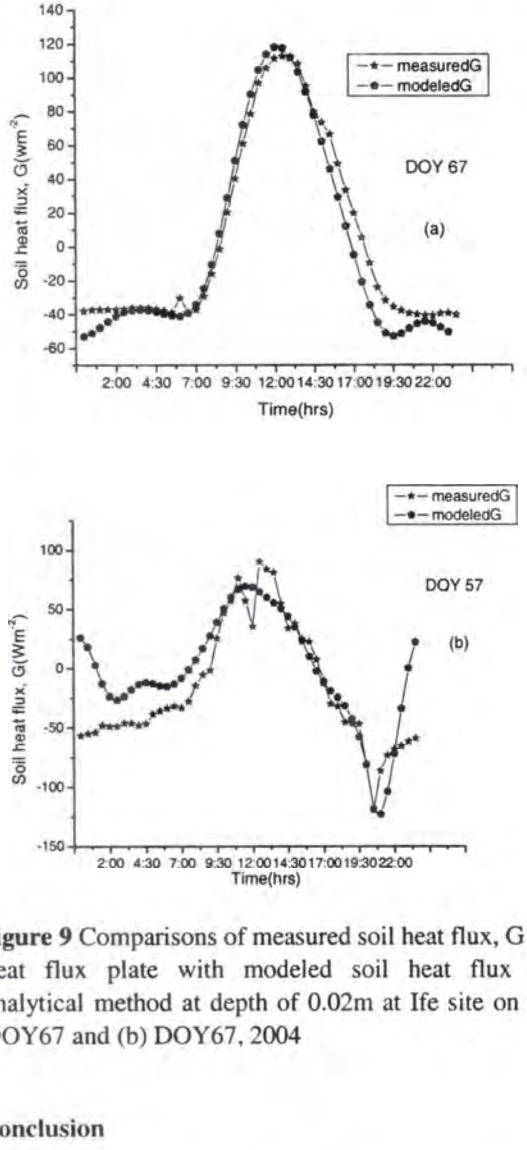

Figure 9 Comparisons of measured soil heat flux, G by heat flux plate with modeled soil heat flux by analytical method at depth of 0.02m at Ife site on (a) DOY67 and (b) DOY67, 2004

Conclusion

Temporal variation of soil moisture content, θ, at two micrometeorological sites was presented for transition period and the peak of rainy season. Soil thermal properties showed clear dependence on soil moisture content and thus rainfall. Soil heat flux modeled using soil thermal properties compared favorably with the measured soil heat flux. A dry day was however better modeled than a wet day. This revealed the impact of transient fluctuation of soil moisture content on modeling of soil heat flux.

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