DIURNAL CHARACTERISTICS OF THE SURFACE ENERGY FLUXES AT A TROPICAL SITE IN ILE-IFE, NIGERIA

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ABSTRACT

This study was carried out at Obafemi Awolowo University (O.A.U.) Meteorological station, Ile-Ife (7^0 $32^/ N$; 4^0 $31^/ E$) using a very direct and accurate eddy covariance (EC) method to measure and calculate turbulent fluxes within the atmospheric boundary layer. However, the study aimed at critically analyzing the partitioning of the net radiative fluxes and the surface energy fluxes characteristics from the EC dataset collated for the short observational period (SOP) from 1st to 9th of June, 2011. The result showed that the peak of the net radiation ranged between $317\ Wm^{-2}$ and $586\ Wm^{-2}$ between $12:30$ hrs and $14:30$ hrs depending on the cloud cover and type. Also, the ground heat flux was found to be relatively low in midnights and early morning hours for the days with the peak values ranging from $41\ Wm^{-2}$ to $134\ Wm^{-2}$ between 10.30 hrs and 14.00 hrs. However, the percentage estimated mean values for the latent heat fluxes for the days were found to be 61-88% of the net radiation. This also depended on the degree of the soil wetness and the prevailing atmospheric condition. The period was characterized by rainstorm events.

Keywords: Eddy Covariance Method, Surface Energy Balance, Net Radiation, Turbulent Fluxes, Ground Heat Flux.

INTRODUCTION

The earth's surface depends mostly on the solar radiation from the sun because all the heating experienced by the earth's surface comes directly from the sun. This released energy incidence on the earth's surface is responsible for the driving of both the atmospheric, oceanic circulations and also the biospheric processes. This energy exchange between the surface and atmosphere generally determine to a great extent the state and characteristics of the Planetary Boundary Layer (PBL). Thus, the net radiation, R_N , at the earth's surface (over bare surface) is either absorbed into the ground in the form of ground heat flux, H_G , or extracted from the surface by turbulent air motion and dry convection (H_S). Also, it can be transferred by evaporation of water from the surface (H_{LE}), (that is, $R_N = H_S + H_{LE} + H_G$). However, the accurate measurements of the fluxes are very useful in the study of weather and climate (Guo and Schuepp, 1994). Thus, by varying the surface heat and moisture flux spatially, cloud formation, precipitation as well as temperature distribution within the earth's atmospheric system will be affected.

The current understanding of the surface/atmosphere interaction is severely limited by lack of observation in West Africa (Nigeria inclusive) being one of the less instrumented regions of the world. The majority of the earlier attempt such as Jegede (2001), Balogun et al. (2002) and Ohumura (1982) estimated the surface energy fluxes using indirect flux-gradient and Bowen ratio methods. Therefore, this study is aimed at investigating the partitioning of the net radiative fluxes and surface energy fluxes at a tropical site using the eddy covariance method. The eddy covariance (EC) method has been described as the most accurate method for measurement of surface fluxes (Oladosu et al., 2007) and as a standard tool in the study of the surface-atmosphere boundary interactions (Sanchez et al., 2010).

THEORETICAL BACKGROUND

The net radiation available is responsible for most physical processes done within the earth-atmospheric system. This is the combination of the net longwave and shortwave radiation. Therefore, it is often convenient to split the net radiation term into four components; thus

$$R_N = (R_{S\downarrow} - R_{S\uparrow}) + (R_{L\downarrow} - R_{L\uparrow}) \quad (1)$$

where $(R_{S\downarrow} - R_{S\uparrow})$ is the net shortwave radiation and $(R_{L\downarrow} - R_{L\uparrow})$ is the net longwave radiation. The net shortwave is the combination of direct and diffuse beam of solar radiation (down welling shortwave radiation) as well as the reflected insolation which is incidence on the earth's surface (upwelling). More so, the net longwave comprises of the emitted infra red radiation by the cloud, aerosol, gases and the energy which is re-radiated by the earth's surface. Hence, the upwelling shortwave radiation can be expressed as:

$$R_{S\uparrow} = -aR_{S\downarrow} \quad (2)$$

Where a is the surface albedo which determines the amount of shortwave that is being reflected. Equally, the downward longwave radiation $R_{L\downarrow}$ is much more difficult to calculate because one must vertically integrate the radiative flux divergence equations. Thus, upwelling longwave radiation is given by

$$R_{L\uparrow} = \varepsilon_{IR}\sigma T^4 \quad (3)$$

Where σ is the Stefan-Boltzman constant and has a constant value of $5.67x10^{-8} Wm^{-2}k^{-4}$, ε_{IR} is the infra red emissivity. Hence, the combination of the net short and longwave radiation yields the approximated value for net radiation flux at the surface as shown in the equation:

$$R_N = (1-a)ST_K Sin\psi + R_L^* \text{ (during daytime)} \quad (4)$$

Where S is the solar irradiance and it is negative.

$$R_N = +R_L^* \text{ (during nighttime)} \quad (5)$$

Thus, soil heat flux is generally referred to as the amount of thermal energy that moves through an area of soil in a unit of time. This ground heat flux, H_G, is computed as the addition of the soil heat flux measurement H_g (usually buried at a depth in the soil) together with the estimate of the heat storage in the layer above the plate. The storage,, is estimated using the relationship:

$$\Delta G = \frac{c_S d\Delta \overline{T}}{\Delta t} \quad \text{(Oke, 1996)} \quad (6)$$

Where c_S is the estimated heat capacity of the soil ($Jm^{-3}K^{-1}$), d, the layer depth (m), ΔT, the change of average temperature in the soil layer above heat flux plate and Δt, the time interval. Thus,

$$H_G = H_g + \Delta G \quad (7)$$

The sensible and latent heat fluxes using the eddy covariance can be estimated using the combination of fast response ultra-sonic anemometer, infra red gas analyzer as well as temperature and relative humidity probes. Thus, the turbulent heat fluxes can be calculated in energetic (dynamic) units: Wm^{-2} for sensible heat H_S, defined as:

$$H_S = \rho C_P \overline{w'T'} \quad (8)$$

and the latent heat flux, H_{LE} as

$$H_{LE} = \lambda \overline{w'q'}, \quad (9)$$

Where ρ is the density of the air, is specific heat capacity of air at constant pressure,

λ is latent heat of evaporation (JKg^{-1}), and q is the specific humidity of water in air

SITE DESCRIPTION AND INSTRUMENTATION

The study area is located at O.A.U. Meteorological Station in Ile-Ife with geographic coordinate $7^0 32' N$; $4^0 31' E$ (Fig. 1) and an uncultivated flat bare soil. By climatological classification, Ile-Ife is situated within the tropical wet and dry belt of West Africa (Griffiths, 1974). The seasonal pattern is monsoonal, with alternating periods of wet (March/April-October) and dry (November-February) months. The weather change is as a result of the meridional movement of the International Tropical Discontinuity (ITD) lines, which demarcates at the surface the warm and the moist (maritime) south-westerly flow from the hot and dry (continental) north-easterly winds (Oladosu et al., 2007).

The annual average rainfall amount is between 1000 and 1500 mm with the weak surface wind flow of less than $1.5ms^{-1}$ which is generally a prominent feature of the tropical area. However, the instrumentation deployed to the measurement site for the purpose of this study were the Eddy Covariance (EC) System (Fig. 2) which is made up of a three-axial Sonic anemometer (CSAT3); an Infra red gas analyzer (IRGA) LI-COR 7500 used for the measurement of turbulent fluxes; a soil heat flux plate (Hukseflux model HFP01) buried at 0.5 m in the soil and net radiometer (NR-Lite), also mounted on another 6 m mast and positioned at a height of 1.70 m at the site. This arrangement of the instrumentation was to measure the soil heat flux and net all-wave radiation respectively. The EC system was controlled using the data logger with modules for data storage, and software deliberately designed for data acquisition, analysis and control. The necessary averages and calculation of the surface fluxes of momentum, sensible and latent heat were carried out. Also the PC200W software for the Window Operating System as well as USB cables enhanced effective communication between the computer and the data logger. All the measurements were controlled by the use of two Campbell CR 1000 data loggers which sampled the data every 1second and stored as 30 min average values for the whole observational period. The reduced data were used for the graphical presentation of the diurnal variations of the surface energy fluxes. A list of the available instruments for the field measurements is shown in Table 1

Table 1: Devices Deployed and Heights Installed at the Meteorological Station, OAU, Ile-Ife.

Parameter	**Device(Model)**	**Height(m)**	**Manufacturer**	**Accuracy**
Net Radiation	Net radiometer NR-LITE	1.70	Kipp & Zonen	$13.9\mu V / Wm^{-2}$
Soil heat flux	Heat Flux Plate (HFP01)	-0.05	Hukseflux Inc USA	$-50\mu V / Wm^{-2}$
Sensible heat flux	CSAT3	1.40	Campbell Scientific	$10Hz$
Latent heat flux	LI-COR 7500 (IRGA)	1.20	Campbell Scientific	$10Hz$
Data acquisition	Data logger CR1000X	Not applicable	Campbell Scientific	Not applicable
Temperature and Relative humidity	Temperature and relative humidity probe	1.40	Campbell Scientific	-

Figure 1: Map of a Section of the Obafemi Awolowo University, Ile-Ife, Showing the Measurement Site.

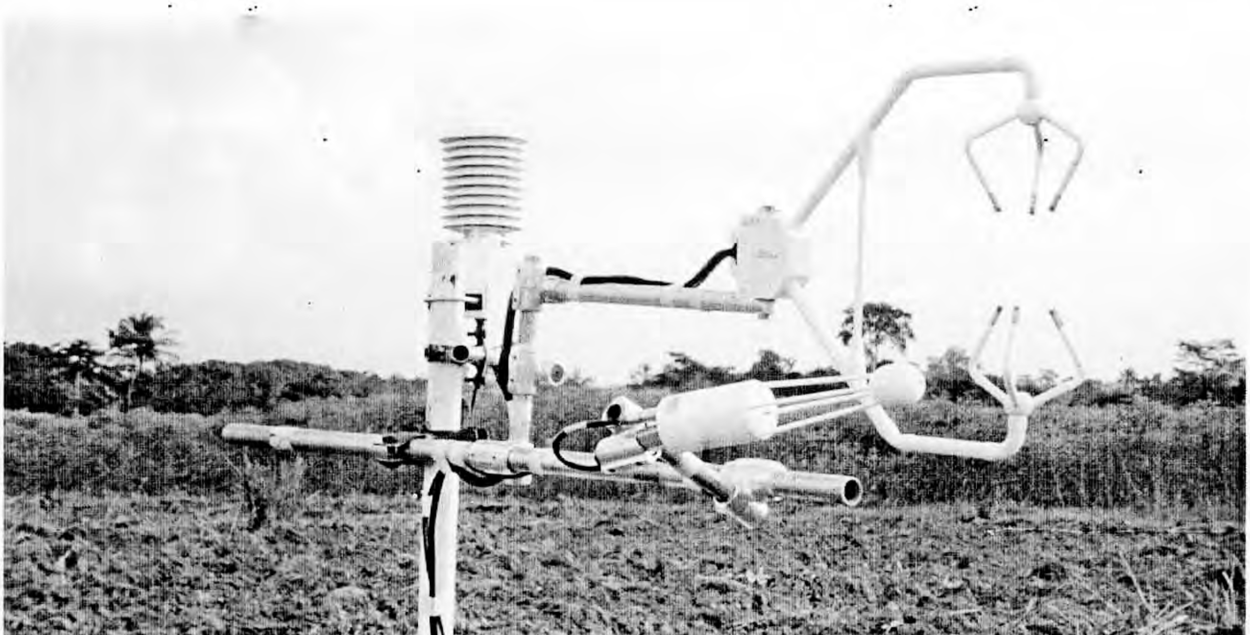


Figure 2: Photograph Showing Eddy Covariance System.

RESULTS AND DISCUSSION

This study was carried out from 1st to 9th of June, 2011 using consulted measured EC data for the analysis of the surface fluxes. Figures 3a-h show the diurnal variation of the energy budget terms: net radiation, ground heat flux, sensible heat flux and latent heat flux.

In the early morning hour of June 1st, 2011, the net radiation increased in value from $-0.68\ Wm^{-2}$ at 07:30 hrs to $405.12\ Wm^{-2}$ at local noon and attained a peak value of $448.38\ Wm^{-2}$ at 12:30 hrs (Fig. 3a). The negative values of the net radiation before 7:30 hrs were indicative of a substantial heat loss from the surface as a result of the surface cooling. On the same day, the ground heat flux was negative up to about 10:00 hrs with $-2.84\ Wm^{-2}$ because the surface was cooler than the soil beneath but rose around 10:30 hrs to reach a peak value $41.32\ Wm^{-2}$. The sensible heat flux was negative (about $-0.67\ Wm^{-2}$) at 1:00 hrs (Fig. 3a). It increased however around 8:30 hrs and attained the peak value ($143.08\ Wm^{-2}$) at 13:00 hrs and around 20:00 hrs its value was negative ($-0.44\ Wm^{-2}$). Also, the latent heat flux had a minimum value of $4.02\ Wm^{-2}$ at 5:00 hrs due to the cooling of the surface and rose to attain a peak value of $212.69\ Wm^{-2}$ at 13:00 hrs as a result of response to the solar heating (Fig. 3a). The mean value of net radiation was found to be $75.87\ Wm^{-2}$ and it was also noticed that the mean value of ground heat flux was found to be negative ($-7.28\ Wm^{-2}$). Equally, the mean latent heat flux was found to be $46.74\ Wm^{-2}$, which was about 61.6% of the mean net radiation recorded for the same day. Also, the mean value of sensible heat flux for the day was found to be $25.32 Wm^{-2}$ about 33.4% of the mean net radiation. The latent heat flux was found to be dominant and it was discovered that the surface heating had been reduced due to the soil wetness and the available energy was used for evaporation (Fig. 3a).

The peak value of the net radiation for June 2nd, 2011 was $585.63\ Wm^{-2}$ at 13:30 hrs (Fig. 3b). The net radiation dropped in values and by dusk (around 18:30 hrs) it became negative and changed the sign (with $-13.73\ Wm^{-2}$) which was an indicative of less surface heating as a result of the nocturnal cooling .

Similarly, the ground heat flux rose steadily from $-20.54\ Wm^{-2}$ (at 0:30 hrs) to reach a peak value of $133.71\ Wm^{-2}$ at 11:30 hrs. The sensible heat flux around midnight was relatively low in values due to surface cooling and increased to a maximum value of $170.71\ Wm^{-2}$ at 14:00 hrs as a result of response to solar heating (Fig. 3b). Though, from 19:30 hrs to 21:30 hrs, negative values were recorded which implied that there were less convective activities though cumulus cloud covered the whole atmosphere around that period. The latent heat flux was observed to have lower values of $8.91\ Wm^{-2}$ at 7:30 hrs and attained a peak value of $228.78\ Wm^{-2}$ at 13:30 hrs. It was observed that the values of the net radiation, ground, sensible and latent heat fluxes were greater than the values obtained on 1st of June, 2011 and this was an indication that there was an increase in the insolation rate due to the clear sky. However, the mean value of the net radiation recorded was found to be $130.69\ Wm^{-2}$ and minimum value (with $-50.17\ Wm^{-2}$) obtained at 19:30 hrs and this was due to the fact that in the late afternoon or early evening, the earth's surface and the air above it had begun to lose more energy than they received which resulted in the cooling of the surface (Fig. 3b). More so, the mean value of the latent heat flux was found to be greater than the mean value of the sensible heat flux and this was due to the soil wetness since the observation was done during the wet period.

On June 4th, 2011 (Fig. 3c), the net radiation value increased from dawn to reach the peak value of $546.98\ Wm^{-2}$ at 13:30 hrs as a result of solar heating. In the late afternoon, the value dropped steadily until it became negative again by the dusk because of the nocturnal cooling. The ground heat flux was also found to change from a value of $-3.11\ Wm^{-2}$ at 8:30 hrs due to strong surface heating to reach a peak value of $71.98\ Wm^{-2}$ at 14:00 hrs as a result of convective activities (Fig. 3c). The sensible heat flux was found to be maximum at 17:30 hrs with $186.35\ Wm^{-2}$ and the minimum value recorded at 18:00 hrs with $-13.75\ Wm^{-2}$ when the nocturnal cooling had started. The latent heat flux was also found to be maximum at 17:30 hrs with $280.53\ Wm^{-2}$ and minimum at 18:00 hrs with $-50.77\ Wm^{-2}$ because there were less convective activities as a result of the evolution of the surface cooling. The high peak value of the latent heat flux was primarily because of the early morning rain experienced before the evolution of the sunrise during this period. However, the mean value of the net radiation was found to be $70.23\ Wm^{-2}$ and it was also noticed that the mean value of ground heat flux was negative ($-8.90\ Wm^{-2}$). The mean value of the latent heat flux ($61.48\ Wm^{-2}$) was found to be higher than the mean value of sensible heat flux ($35.75\ Wm^{-2}$) and this was due to the soil wetness.

On June 5th, 2011 (Fig. 3d), the net radiation value increased from 7:30 hrs with $-10.57\ Wm^{-2}$ and attained a peak of $486.47\ Wm^{-2}$ as a result of solar heating. The plot of the diurnal variation of the net radiation confirmed the intermittent attenuation/absorption by clouds as can be observed from the variation trend. At 17:00 hrs, the net radiation values dropped steadily to $-5.41\ Wm^{-2}$ at 18:30 hrs until it reached the minimum value of $-44.79\ Wm^{-2}$ at 22:30 hrs and this was an indication that there was surface cooling in the late afternoon or evening due to less convective activities (Fig. 3d). The ground heat flux was found to be negative till 8:30hrs and it was due to precipitation which occurred usually in the early morning hour and late evening time. The peak value recorded on the same day was $60.99\ Wm^{-2}$ but it was found to be lesser than the value obtained in the previous day and this condition thus suggests that atmospheric cloudy conditions (stratocumulus) was responsible for the low value obtained this day. As usual, the sensible heat flux was relatively low in the early morning hour but increased at 9:30hrs from $26.08\ Wm^{-2}$ to attained peak value of $119.82\ Wm^{-2}$ at 14:00 hrs but this was due to strong convective activities around that period. The latent heat flux was found to be maximum at 12:30 hrs with $221.07\ Wm^{-2}$ and was minimum at 21:30 hrs with $-9.54\ Wm^{-2}$ because the surface was colder due to the radiative cooling (Fig. 3d). It was also observed that the values of the latent heat obtained for the daytime on this day showed that the latent heat flux was larger than the sensible heat flux thus indicating that most of the available energy was used for evaporation rather than sensible heating as a result of the soil wetness. However, the cloud effect was detectable in particular between $10:30$ hrs $-15:00$ hrs because there was sharp drop and rise in the net radiation and the effect was noticeable on all other energy fluxes. The daily mean value of the latent heat flux recorded on the same day was $67.39\ Wm^{-2}$ which was about 67.4% of the mean value of net radiation recorded on the same day. Moreover, on 6th of June, 2011 (Fig. 3e), the net radiation rose due to impulse received from the sun at 8:00 hrs and attained maximum value of $601.1\ Wm^{-2}$ at 13:30 hrs. However, it was found that the peak value was greater than the value obtained in the previous day. The higher value was as a result of the higher insolation received on that day compared to $486.47\ Wm^{-2}$ of the previous day. The ground heat flux was found to have a peak value of $73.31\ Wm^{-2}$ at 12:30 hrs but the value was noticed to be greater than the values obtained in the previous day and this suggests that much heat was conducted to the ground (Fig. 3e). The sensible heat flux was found to have lower values in the early morning hour but increased tremendously at 8:00hrs (with $4.49\ Wm^{-2}$) to a peak value of $150.93\ Wm^{-2}$ at 18:30 hrs. This observation was due to solar heating.

Also, latent heat flux was found to pick up at 8:30 hrs to reach a peak of $269.68\ Wm^{-2}$ at 12:00 hrs as a result of convective activities. The higher values recorded on that day was an indication that there was high insolation from the sun and most of the energy was used up for evaporation because of soil wetness. Despite the clear sky in the after noon, sharp drop in the net radiation was noticed at 12:00 hrs and this was as a result of cumulus cloud which appeared and shortly disappeared at 12:30 hrs though the effect was observed on other energy fluxes. Similarly, on June 7th, 2011 (Fig. 3f), the net radiation was maximum (with 413.17 Wm^{-2}) at 13:00 hrs and the ground heat flux was also at its peak (with 48.35 Wm^{-2}) at 13:00 hrs. There was stratus cloud covering the atmosphere as can be observed from the trace and this accounted for the low values of net radiation and ground heat fluxes as observed in the Figure 3f compared with values obtained on 6th of June, 2011. Between 9:30 hrs and 15:00 hrs, the latent heat flux was about a factor of two times higher than that of the magnitude of the sensible heat flux. This suggests that despite the evolving cloudiness, there was considerable heat exchange at the surface and this was manifested as sensible and latent output into the environment but because of the soil wetness, most of the heat was used up for evaporation. The sensible heat flux had its peak value of 119.92 Wm^{-2} while the latent heat flux reached a peak value of 206.73 Wm^{-2} at 12:30 hrs respectively when there was strong solar heating as a result of radiative driven. The mean values of sensible heat and latent heat fluxes were found to be 23.79 Wm^{-2} and 55.51 Wm^{-2} respectively. Noticeably, the cloudy effect between 13.00 hrs-16.30 hrs was responsible for the fluctuations in the net radiation and other energy fluxes as observed in Figure 3f. However, the diurnal distribution of net radiation, ground heat, sensible and latent heat fluxes for June 8th, 2011 is displayed in Figure 3g. As the sun began to rise at 8:30 hrs the fluxes also rose till 10:00 hrs. However, a gradual reduction of these fluxes was observed between 10:00 hrs and 11:00 hrs and this is attributed to the increased cloudiness experienced during this period. However, the peak of the net radiation was at 12:30 hrs with 401.83 Wm^{-2} though lesser than the values obtained in previous day (7th of June, 2011). Also, the ground heat flux was found to have a peak value of 59.00 Wm^{-2} at 12:30 hrs but more heat was conducted into the ground than the previous day (7th of June, 2011). The sensible heat flux was also found to have a peak value of 101.23 Wm^{-2} and the latent heat flux reached a peak value of 177.53 Wm^{-2} at 15:30 hrs and the values of all the fluxes after it had reached their peak slightly decreased due to the decrease in convective activities till the evening time when the sun began to break up (Fig. 3g).

Although, the values of these fluxes were found to be lesser than the one obtained on 7th of June, 2011 and this condition suggests that there was an increased cloudiness on that day. The mean values of net radiation, ground heat, sensible and latent heat fluxes were found to be 74.06 Wm^{-2}, -2.22 Wm^{-2}, 24.75 Wm^{-2}, and 53.52 Wm^{-2} respectively. The latent heat flux accounted for about 72.3% of the net radiation for that day which was an indication that larger percentage of the available energy was used up for evaporation due to soil wetness. This also suggests that the environmental condition was humid and there was seasonal effect on the surface energy balance. As usual, early morning cumulus cloud at 6:30 hrs-7:30 hrs was observed but it rained between 10:00 hrs-11:00 hrs which resulted to the decrease in the values of the net radiation and other energy fluxes. Furthermore, on 9th of June, 2011, the net radiation and ground heat fluxes reached their peak values of 317.43 Wm^{-2} and 45.49 Wm^{-2} around 13:00 hrs and 13:30 hrs respectively.

Although, the net radiation was found to have lesser value than what was obtained on 8th of June, 2011 and this was adduced to the occurrence of heavy rainfall in the midnight and around 11:00 hrs-12:00 hrs which manifested into cool and calm weather with few patches of cloud in the afternoon time (Fig. 3h). The sensible heat flux slightly increased around 8:30 hrs to attain a peak value of 97.78 Wm^{-2} at 13:30 hrs.

However, latent heat flux shot up around 8:30 hrs due to the evolution of strong solar heating to attain its peak value (with 147.36 Wm^{-2}) at 16:30 hrs. The mean values of these fluxes were found to be 58.11 Wm^{-2}, -6.17 Wm^{-2}, 21.80 Wm^{-2} and 40.84 Wm^{-2} for net radiation, ground, sensible and latent heat fluxes but the latent heat was dominant over the sensible heat flux and this was due to the wet season (Fig. 3h).

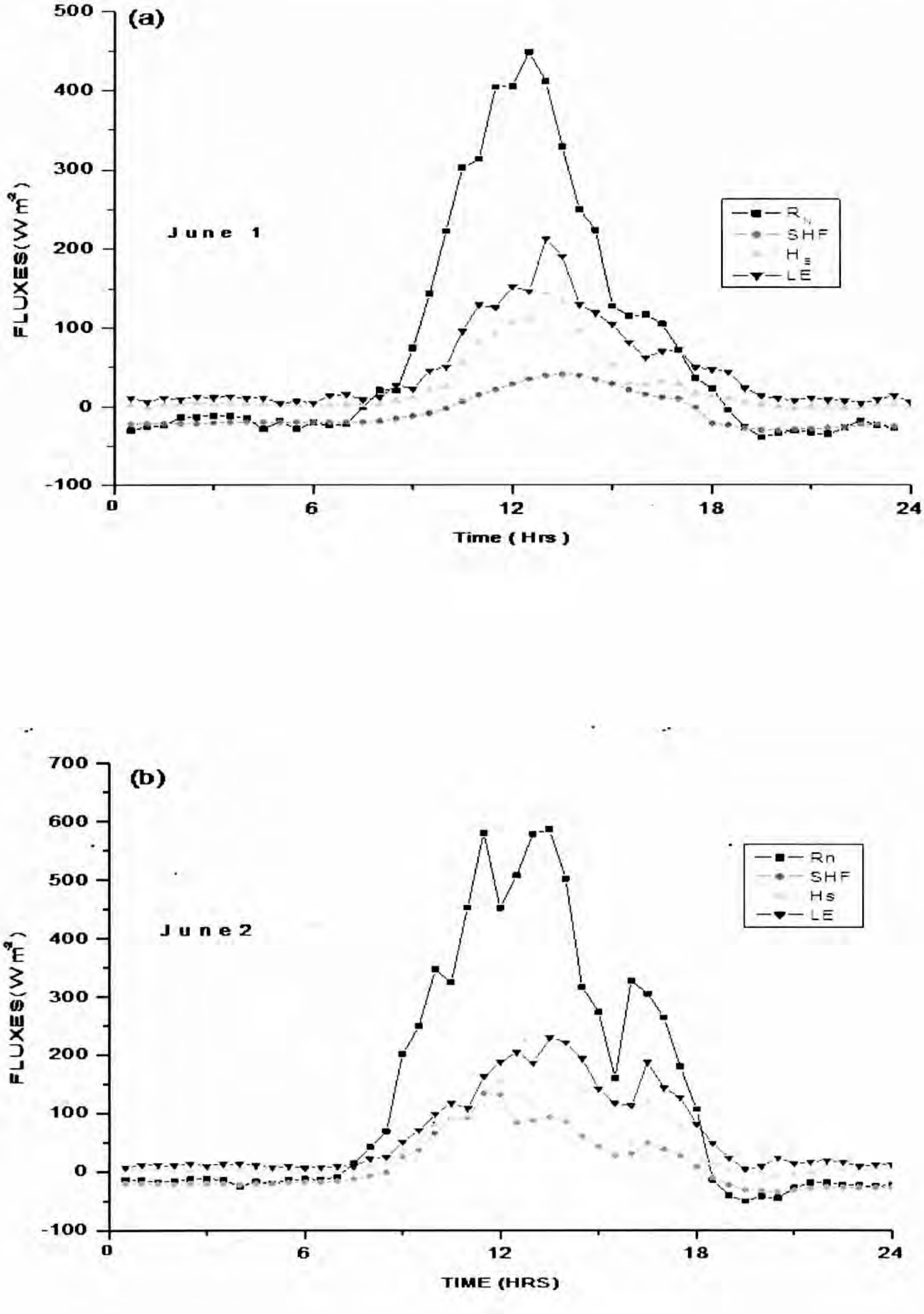


Fig. 3(a and b): Diurnal Variation of Surface Energy Balance Terms for 1st and 2nd of June, 2011 as Measured at the Measurement Site.

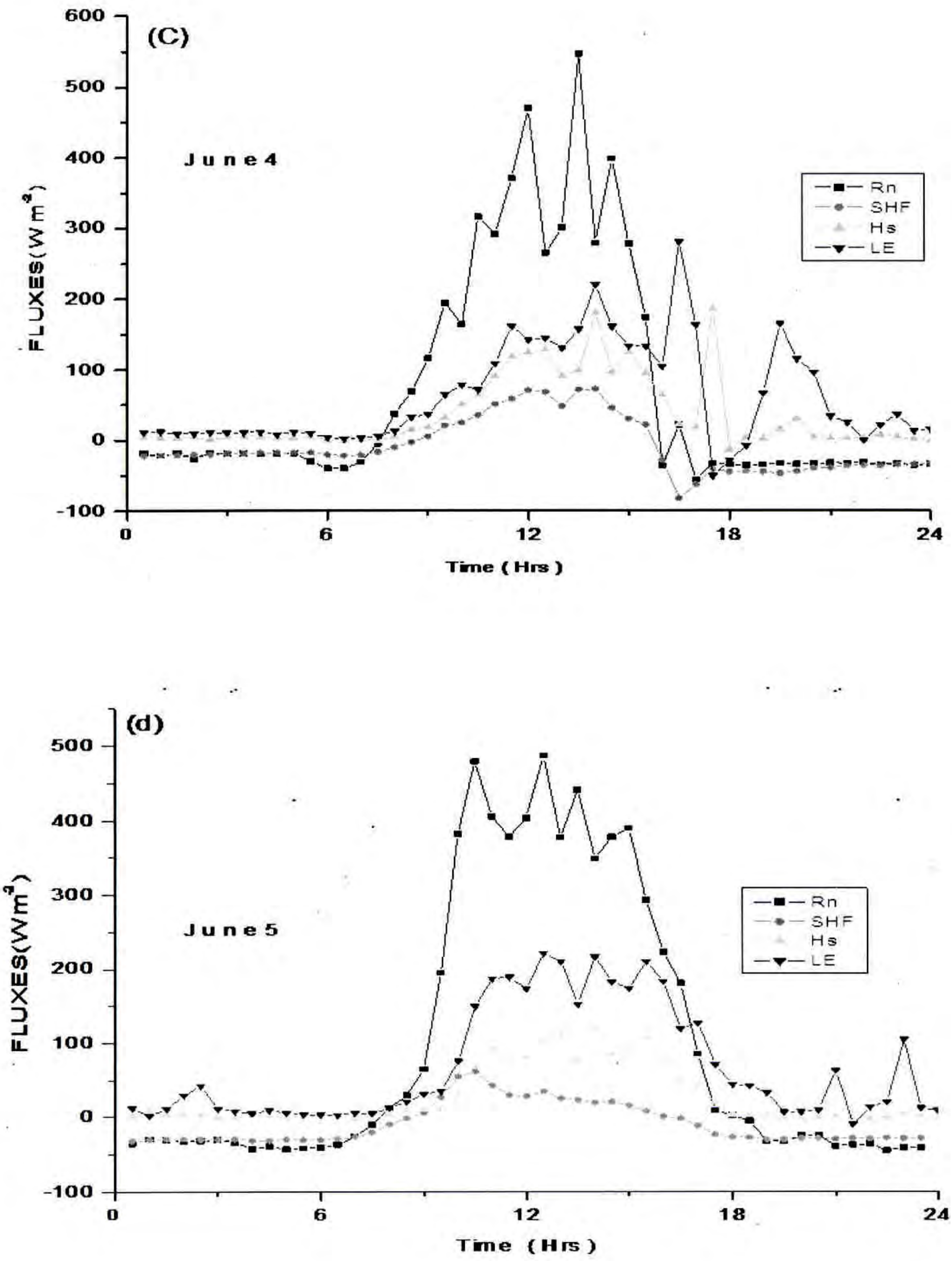
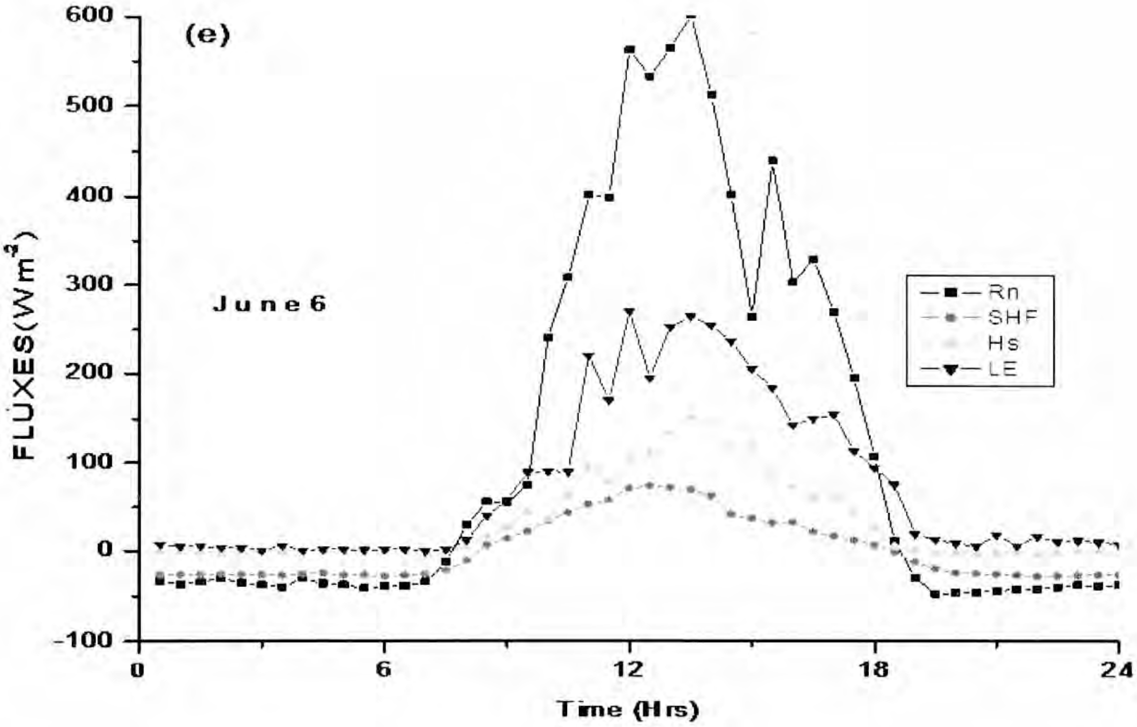


Fig. 3(c and d): Diurnal Variation of Surface Energy Balance Terms for 4th and 5th of June, 2011 as Measured at the Measurement Site.



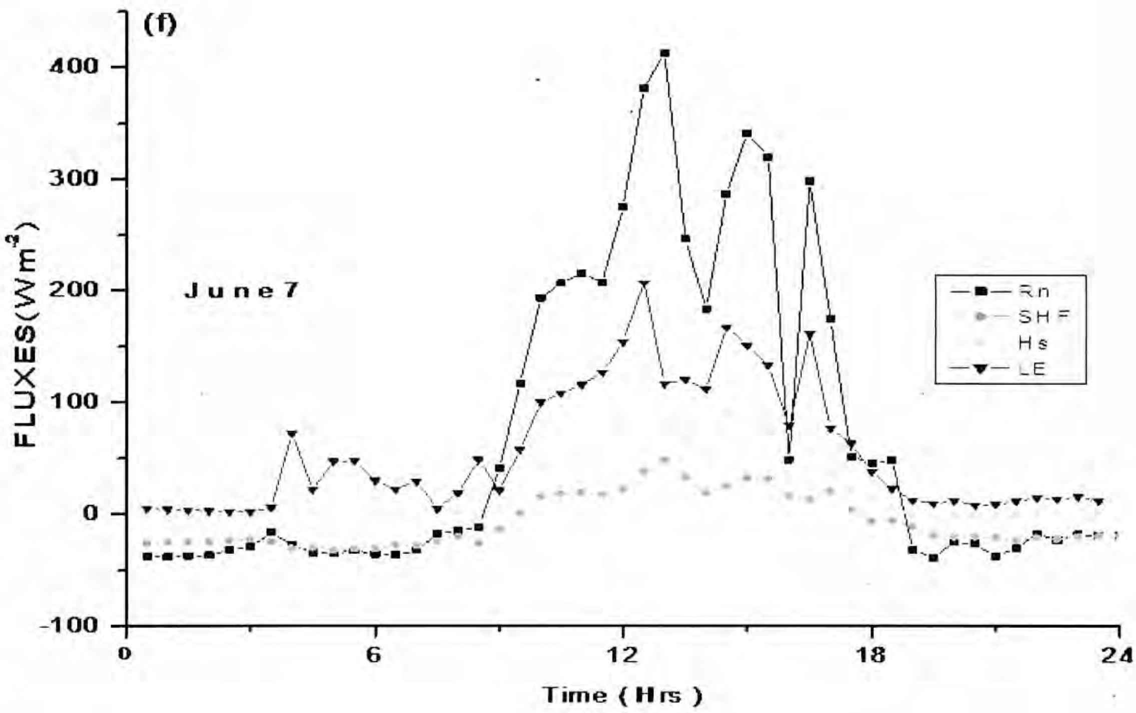
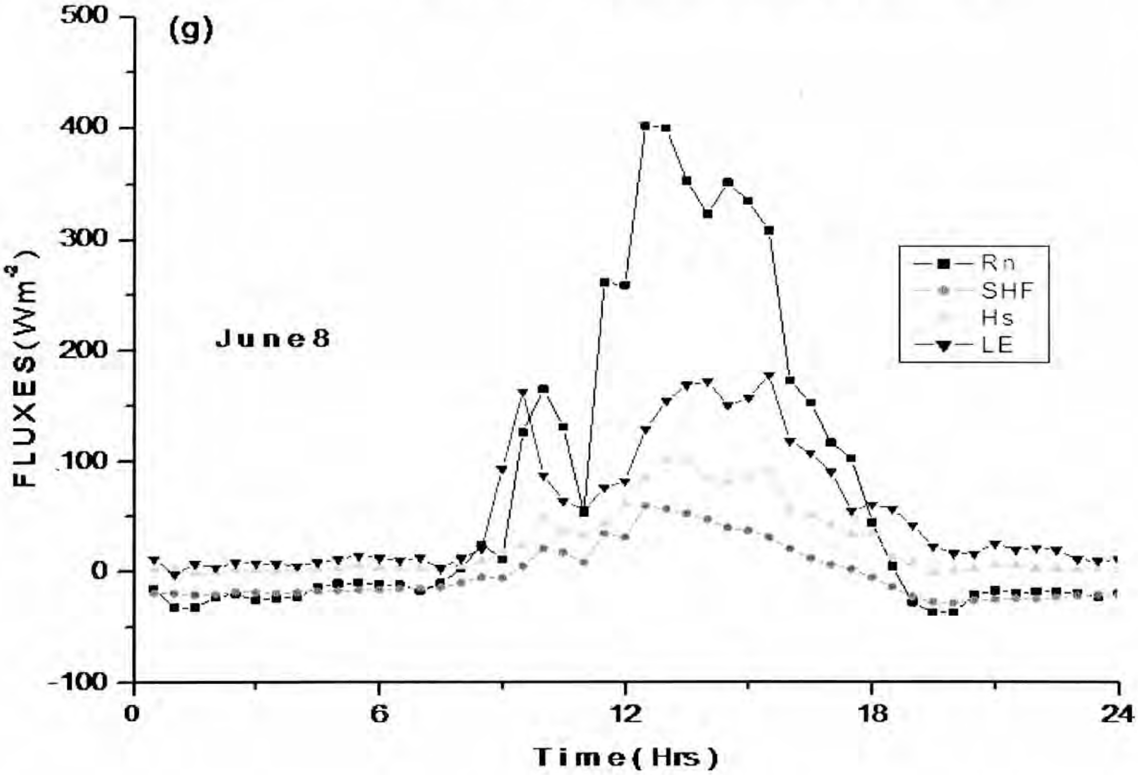


Fig. 3(e and f): Diurnal Variation of Surface Energy Balance Terms for 6th and 7th of June, 2011 as Measured at the Measurement Site.



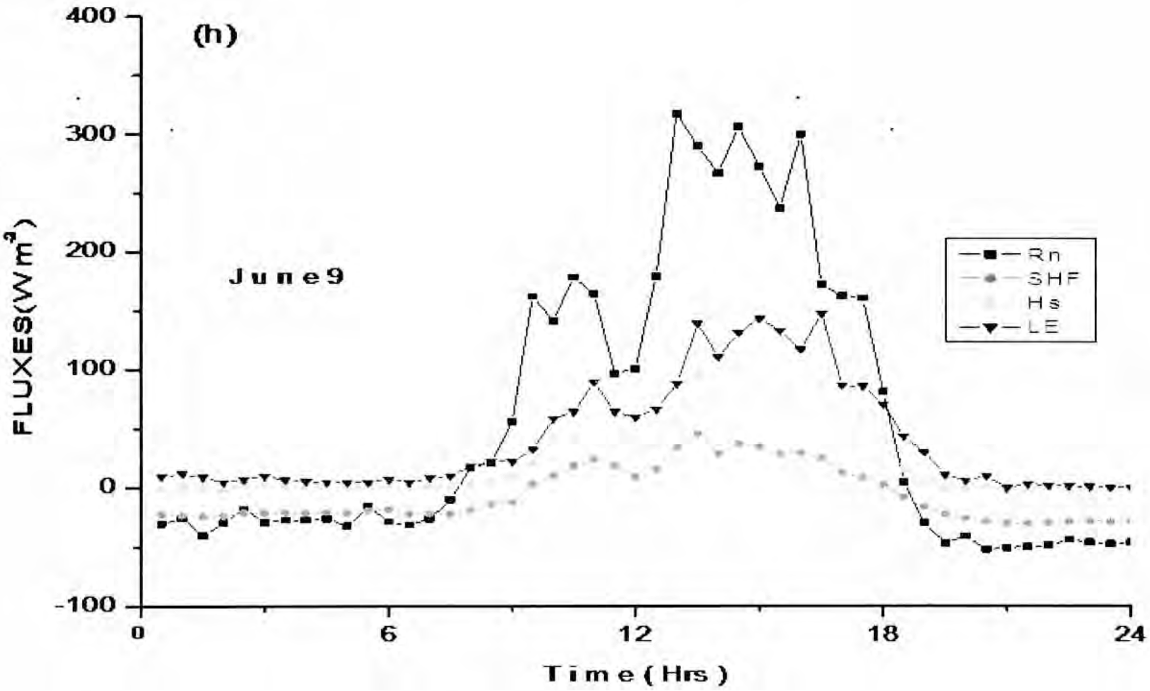


Figure 3(g and h): Diurnal Variation of Surface Energy Balance Terms for 8th and 9th of June, 2011 as Measured at the Measurement Site.

CONCLUSIONS

The partitioning of the net radiative fluxes and surface energy fluxes had been investigated in this work. The result showed that the midnight and early morning hours of the days recorded negative values for the net radiation but increased at $7:30$ hrs to peak values ranging from $317\ Wm^{-2}$ to $586\ Wm^{-2}$ between 12.30 hrs and 14.30 hrs as a result of the cloud cover, cloud drift and type of clouds as observed within the measurement location.

The ground heat flux was also found to have peak values ranging from $41\ Wm^{-2}$ to $134\ Wm^{-2}$ between 10:30 hrs and 14:00 hrs. The occurrence of precipitations during this wet period (which was a key factor to soil wetness) however led to the observed changes in the surface condition. This in turn led to the variation in magnitudes of the sensible and latent heat fluxes. Thus, the maximum average values for the sensible heat fluxes was within the range of $98\ Wm^{-2}$ to $187\ Wm^{-2}$ between 13:00 hrs and 17:30 hrs. Equally, the latent heat fluxes showed a diurnal variation with a reduced value at 7:30 hrs and attained its maximum values between $147\ Wm^{-2}$ and $287\ Wm^{-2}$ at about 12:30 hrs to 17:30 hrs. The estimated percentage mean values of latent heat fluxes for the days were 61-88%. When compared with that of the net radiation, the dominance of latent heat fluxes could be adduced to the fact that the period was characterized by rainstorm events which resulted in soil wetness for evaporation processes.

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