THE MICROMETEOROLOGICAL INVESTIGATION OF HEAT FLUX AND MOISTURE CONTENT OF THE SOIL AS MEASURED AT A TROPICAL STATION IN IBADAN, NIGERIA.

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(Received: 5th June, 2014; Accepted: 30th July, 2014)

ABSTRACT

The diurnal and seasonal variations of heat flux and the moisture content in the soil at a site for the Nigeria Mesoscale Experiment (NIMEX) in the University of Ibadan, Nigeria (7.38^0 N and 3.93^{0}E), had been investigated. The study also investigated effects of the atmospheric phenomena on magnitudes of the surface layer parameters. The month of May to August (wet months) had the least soil moisture of about 19% which was beyond the maximum obtained in the dry months. The frequency of this was above 10, and there was a record of soil moisture content above 22% in the month of June when the mean rainfall amount approached 22 mm. The frequency of soil moisture, which was less than 17%, was as high as 16, particularly in the month of November (the peak of the dry month). The month of October was peculiar with the frequency as high as 14 and soil moisture content well above 20%. This was because of the unusual heavy rainfall in the month of October, 2006. The substantial difference recorded for time lag in the same soil layer was attributable to increased wetness. Both soil heat flux and soil moisture content exhibited a similar variation, attained maximum at noon and gradually decreased as it approached the night time. Thus there was a positive association between the soil moisture and soil heat flux. Equally, the disturbed weather phenomena that prevailed clearly established the reason for the large difference in the fluxes.

Keywords: Heat Flux, Micrometeorology, Moisture Content, Soil Disturbance

INTRODUCTION

Soil moisture content is a measure of the actual water content in the soil and is defined as the percentage volume of a moist soil occupied by water. Soil moisture is an important regulator of soil temperature and source of water for evaporation (Hillel, 1980). This necessitated the need to examine the relationship between the soil heat flux and soil moisture content. Changes of soil moisture with depth and time, according to Munn and Richards (1963), must be related in one way to surface water losses. Dry soil has much lower specific heat than the wet soil (Arya, 2001). Hence, more heat is required to raise the temperature of wet ground than of dry ground of equivalent amount.

The water table is the upper surface of unconfined groundwater. Above this water table, there is a capillary fringe, where moisture is held against the pull of gravity by the forces of adhesion, cohesion, and surface tension (Chandler, 1978). Essentially, the soil moisture availability governs the partitioning of surface latent heat and the thermal response of the soil. The soil moisture content is a short-term variable which may cause significant changes in heat capacity, conductivity and diffusivity of soils, (Oke, 1996). These conditions which affect soil moisture content equally affect soil heat flux variability.

Significantly, different climates exist in relation to different soils. One of the most important variables governing the differences is the soil moisture availability, (Blanc, 1958). Rainfall is capable of increasing or decreasing moisture content of the soil as well as transporting heat as it percolates down through the soil. (Money, 1980). This equally depends upon the temperature of the rain in comparison with the soil. According to Adedokun, (1978), the quantity of precipitation, its seasonal distribution, the changes in soil and the air temperature, have considerable bearing on the upward or downward movements of water through the soil.

High moisture content of the soil, with a ready supply of oxygen according to Beringer and Tapper (1998), favours bacterial activity and speed up many chemical processes. On the other hand, excess water and reduction in the amount of oxygen available, tend to hinder bacterial activities

(Oladosu, 2002).

The high moisture content observed during the wet period usually affects radiation fog, subjecting the ground heat flux and soil temperature to the same condition (Ahren, 1991; Foken and Wichura 1996). During the sunrise hour, sunlight penetrates the fog and warms the ground, causing the temperature of the air in contact with the ground and the immediate soil depth (layer) to increase. Equally, in the slightly warmer air, more sunlight reaches the ground, thus producing more heating and a direct reflection in the values of soil heat flux (Wang and Bras, 1999). The ability of a soil to conduct heat is determined mainly by the soil moisture since water has about 20 times the thermal conductivity of air. It has been observed that water and air are the only soil constituents which vary considerably on a daily basis (Baver *et al*,.1972). The presence of water films at points of contacts between particles not only improves the thermal contact but also replaces air in the soil pore space (Hanhs and Ashcroft, 1986).

Description of the Experimental Site

The experimental site is located uphill of the University of Ibadan campus, (7.38°N; 3.93°E;). The University of Ibadan is located at about 5 km from the centre of the city of Ibadan, the capital of Oyo State. Oyo State is bounded in the south by Ogun, in the north by Kwara State, in the west partly by the Republic of Benin and in the east by Osun State. This experimental site (Fig.1) is about 1 km away from the Department of Physics building. The site was formally known as the Ionospheric station. The site's dimension is approximating 1000m by 300m. this is the standard fetch approved by the World Meteorological Organization for this type of point measurement. (WMO, 1992) It is an open and level terrain surrounded with low wild grasses and shrubs. But the station (actual site) was maintained as bare soil surface throughout the period of the research activity in order to ensure the homogeneity of the surface.

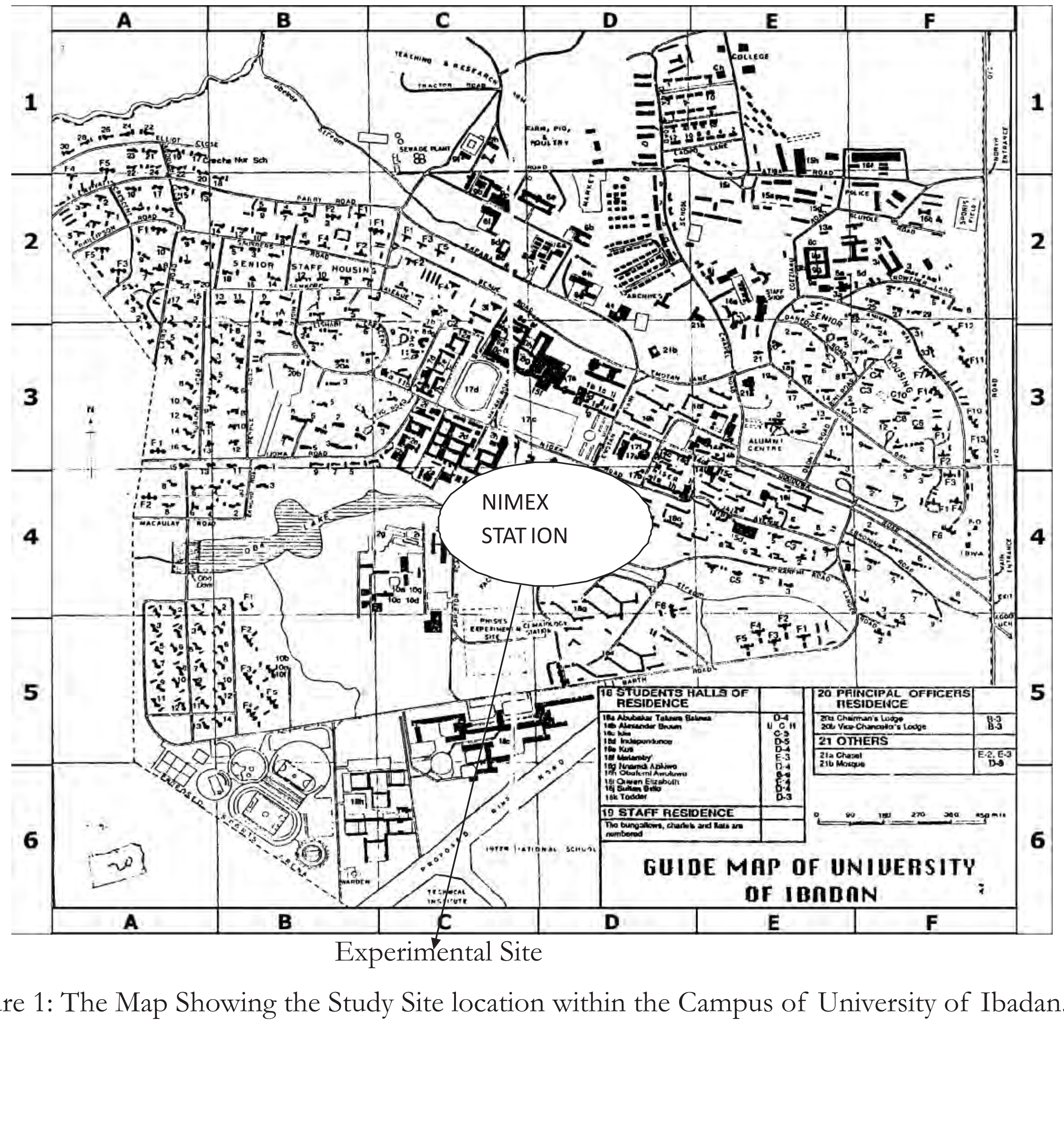

Figure 1: The Map Showing the Study Site location within the Campus of University of Ibadan.

METHODOLOGY

In this project, the acquisition of data was achieved by using Campbell Scientific datalogger systems (measurement and control module) model CR10-X. The datalogger consists of add-ons like relay multiplexers, pulse counters, etc. USB OR SERIAL cables were used for communication purposes. The dataloggers were connected directly to all the sensing elements thereby accepting their respective signals. The data which was collated in ASCII format were then reduced using a data reduction program, SPLIT (Campbell Scientific, 2010). All the sensors used were sampled every 10 s and averaged to produce 10 min and 30 min statistics. A list of the available equipment for the field measurements is shown in Table 1. The arrangement of the sensors on the mast is shown in Plate 1.

Table .1: Summary of Characteristic of Instrumentation Deployed to the Site During the Conduct of the Field Studies

Parameter	Device	Height (m)	Accuracy	Manufacturer
Wind speed	Cup anemometer	0.7, 3.3, 6.2, 14.8	Dist. Cons. 2.3 m	Vector Instr., U.K.
Wind direction	Wind vane	14.8	Dist. Cons. 2.3 m	Vector Instr., U.K.
Air Temperature (wet and dry bulb)	Psychrometer	0.9,4.8,12.4	±.05°C	Theodor Friedrichs
Surface temperature(unused)	Infrared Thermometer	Nil	±1°C	Heitronics
Soil heat flux	Heat flux plate	-0.05.	~ 50μV/W.m $^{-2}$	Hukseflux
Soil moisture	Water content reflectometer	- 0.05	2% of water content	Campbell Scientific
Global radiation	Pyranometer	1.2	23.94 μV/W.m $^{-2}$	Kipp & Zonen
Net Radiation	Net radiometer	1.2	13.9 μV/W.m $^{-2}$	Kipp & Zonen
Rainfall	Raingauge	0.7	±0.07mm	Ammonit
Data acquisition	Datalogger CR10-X	Not applicable	Not applicable	Campbell Scientific

Plate 1: Photograph of the 15 m Mast and the Mounted Sensors at the Experimental Site.

RESULTS AND DISCUSSION

The data obtained for the heat flux revealed a diurnal pattern from the soil probe buried in the soil upper layer (less than 0.020 m). The soil heat flux as shown in Figure 2 and Figures 3(a,b) is maximum at mid-day. The maximum values of 130.4 Wm^{-2}, 181.6 Wm^{-2} and 200.7 Wm^{-2} were obtained at 1.00pm and 2.30 pm for (Julian) days 53, 73 and 75 respectively. But for the early rainfall between 8.00pm to 9.30pm on the month of March (Julian day 73 and 75), 2006, the soil heat flux dropped drastically to -102.4 Wm^{-2} at about 8.35 pm local time. There seems to be a positive association found between the soil moisture and soil heat flux, just as revealed in Figure 2 and Figures 3(a,b) below. This result is similar to the one reported by Munn, 1966 and Oke 1996. Both soil heat flux and soil moisture content established a consistent and uniform response to surface weather system during the early hours of the day and the night time. But the remarkable differences observed at noon were due to the insolation at the period of the day and the cloud (type and amount) blocking out the solar radiation (see the summary Table 3 on the synoptic weather condition)

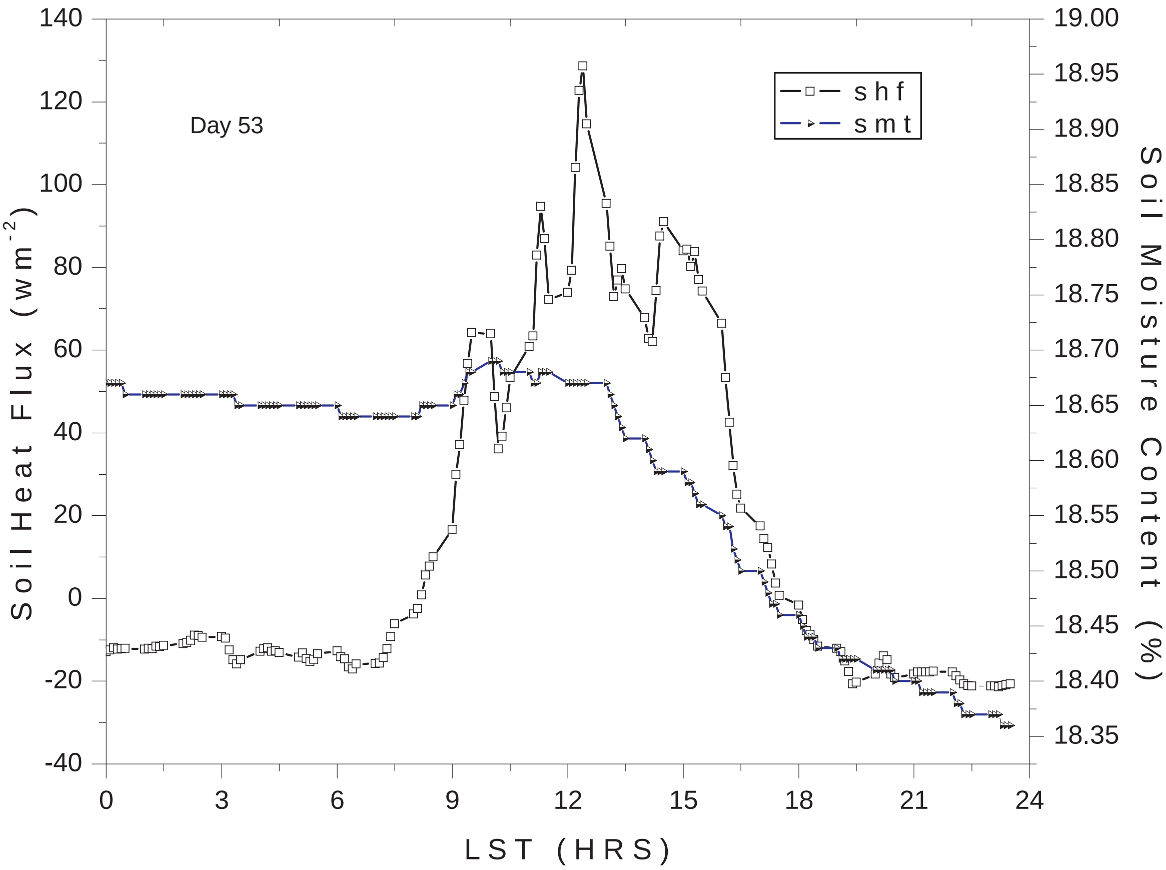

Fig. 2: Diurnal variation of Soil Heat Flux (s.h.f.) and Soil moisture Content (smt) of day 53, 2006 as Measured at the Nimex Site, Ibadan

Thus, as shown in Figure 2, the time of occurrence for the maximum value of soil heat flux obtained in the mid-day corresponded to the period of maximum percentage (18.65%) of soil moisture content measured in the same (Julian) day 53 which was 22nd of February, 2006. It can also be observed that the values of the two parameters (heat flux and moisture content of the soil) gradually reduced as they approached the night time. That is, the soil heat flux reduced to -21.34 Wm^{-2} and the soil moisture to 18.26%.

Unlike the wet periods, Julian days 73 and 75 (in Figures 3a and 3b) which was 13th and 15th of March, 2006 the percentage of water in the soil was almost constant or the same throughout the days considered. The soil heat flux was as low as -125 Wm^{-2}. The sudden increase in the soil heat flux also led to the proportional increase in the soil moisture content just as indicated in Figures 3(a,b) between 7.00 pm to 12.00 midnight and this was observed to be quite rapid. This does not totally agree with a case reported by Oke (1996) on the measurement over Chicago where the study showed that the soil heat flux and moisture content response was very slow. Differences in weather, location and soil type of the site could be responsible for the observed differences.

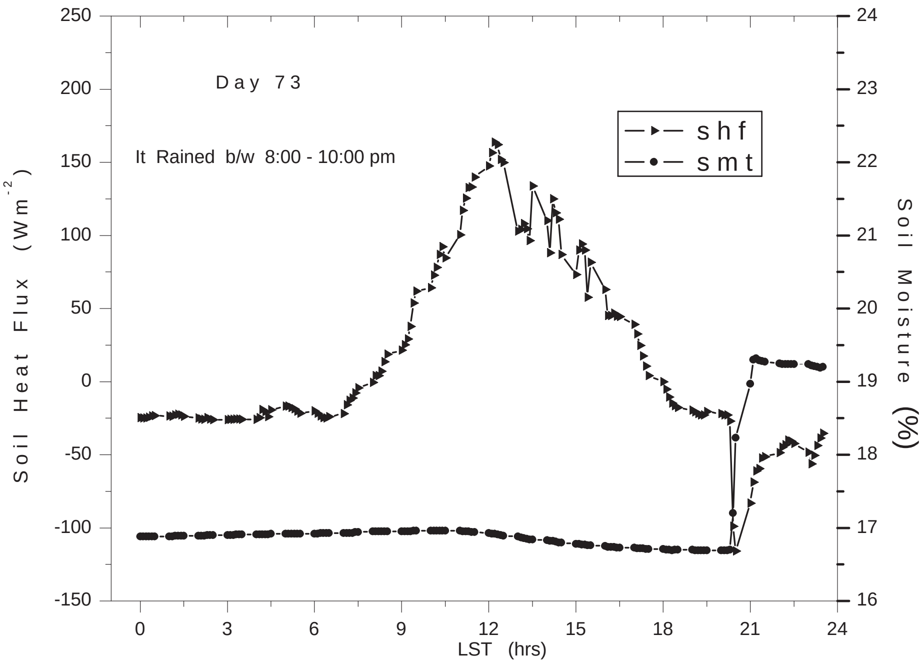

Fig.3(a): The Diurnal variation of s.h.f. and smt of the Julian day 73, March 2006 as Measured at the Nimex Site, Ibadan

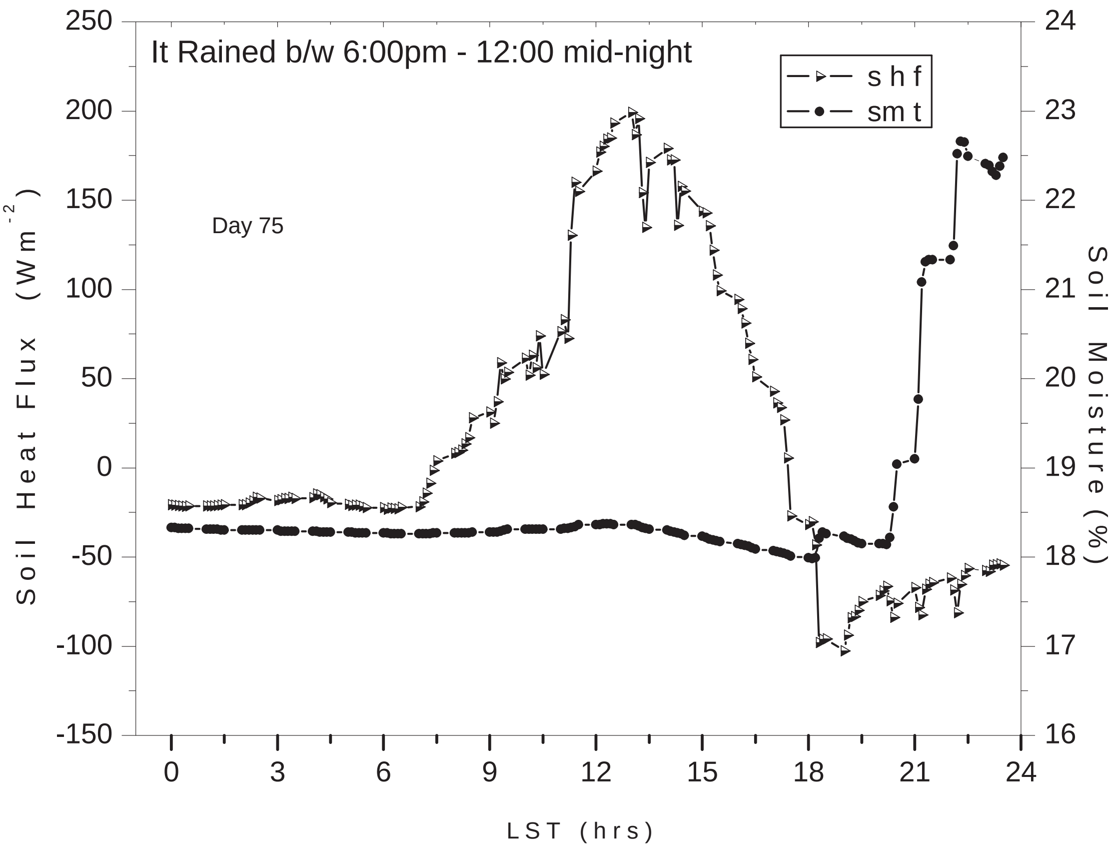

Fig.3(b): As in fig 2(a) but for Julian day 75, Between 0.00 hr to7.50 hrs of the Julian days 73 and 75, Figure 3(a and b) showed that the fluctuation in the soil heat flux was more pronounced during the wet period than that of the soil moisture content. This agrees fully with the result of Ahren (1991) as well as Monteith and Unsworth (1999). That is, the energy fluxes in the soil respond faster to the seasonal changes than the moisture content of the same soil.

Figure 4 revealed the daily averages of soil heat flux for both wet and dry months. There are specific days of weather disturbance due to prolonged periods of fogs, clouds and occurrence of solar eclipse. For examples, March 22nd and 28-29th are days of cloud drift and period of the passage of a solar eclipse respectively. Despite the dry period, which was Julian day 88 (29, March) the soil heat flux values dropped to -20 Wm^{-2} and -80 Wm^{-2} when the solar eclipse passage was recorded over the measurement station.

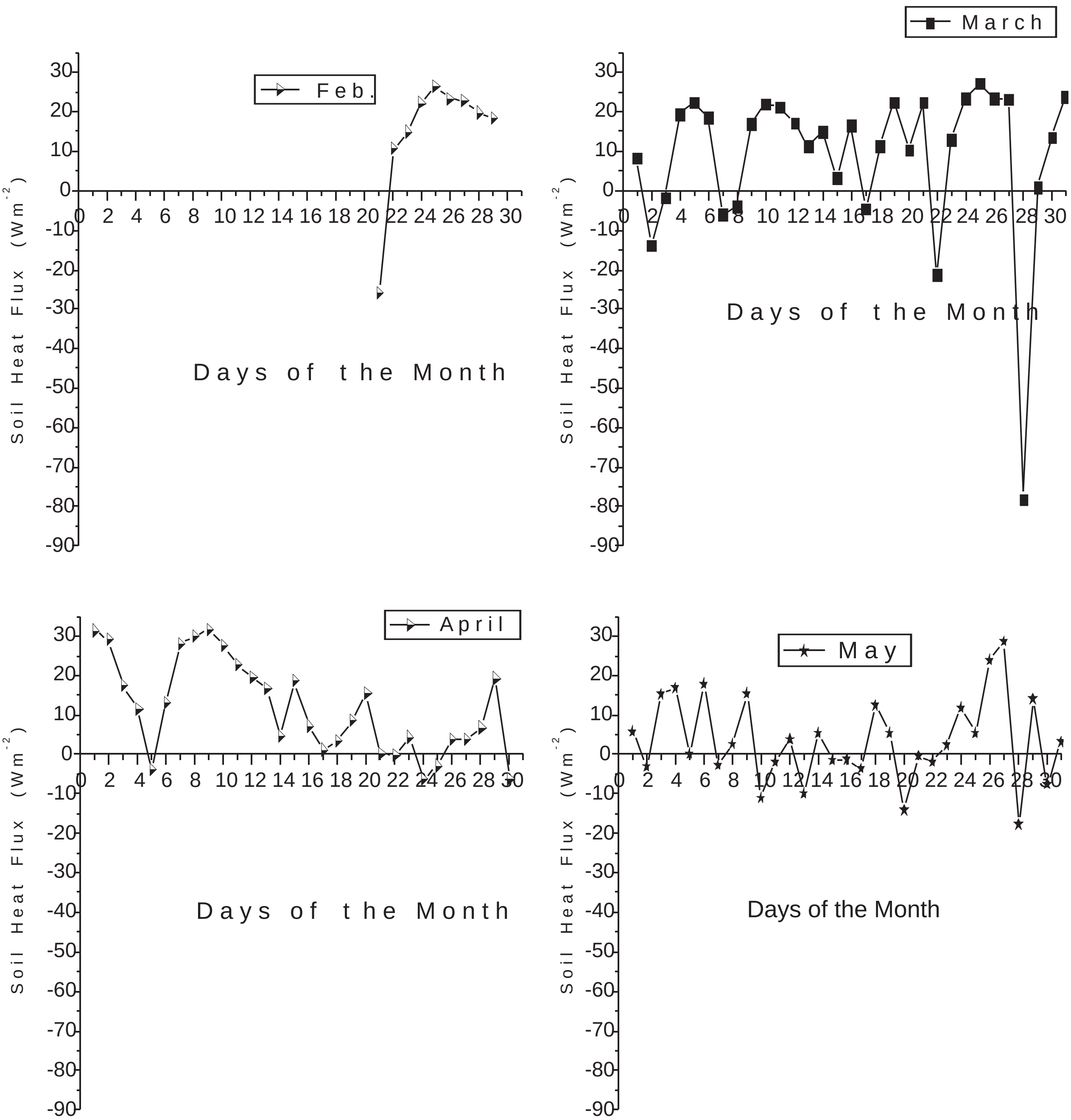

Figure 4(a): Daily Averages of the Soil Heat Fluxes for February to May, 2006 as Measured at the NIMEX Site, Ibadan.

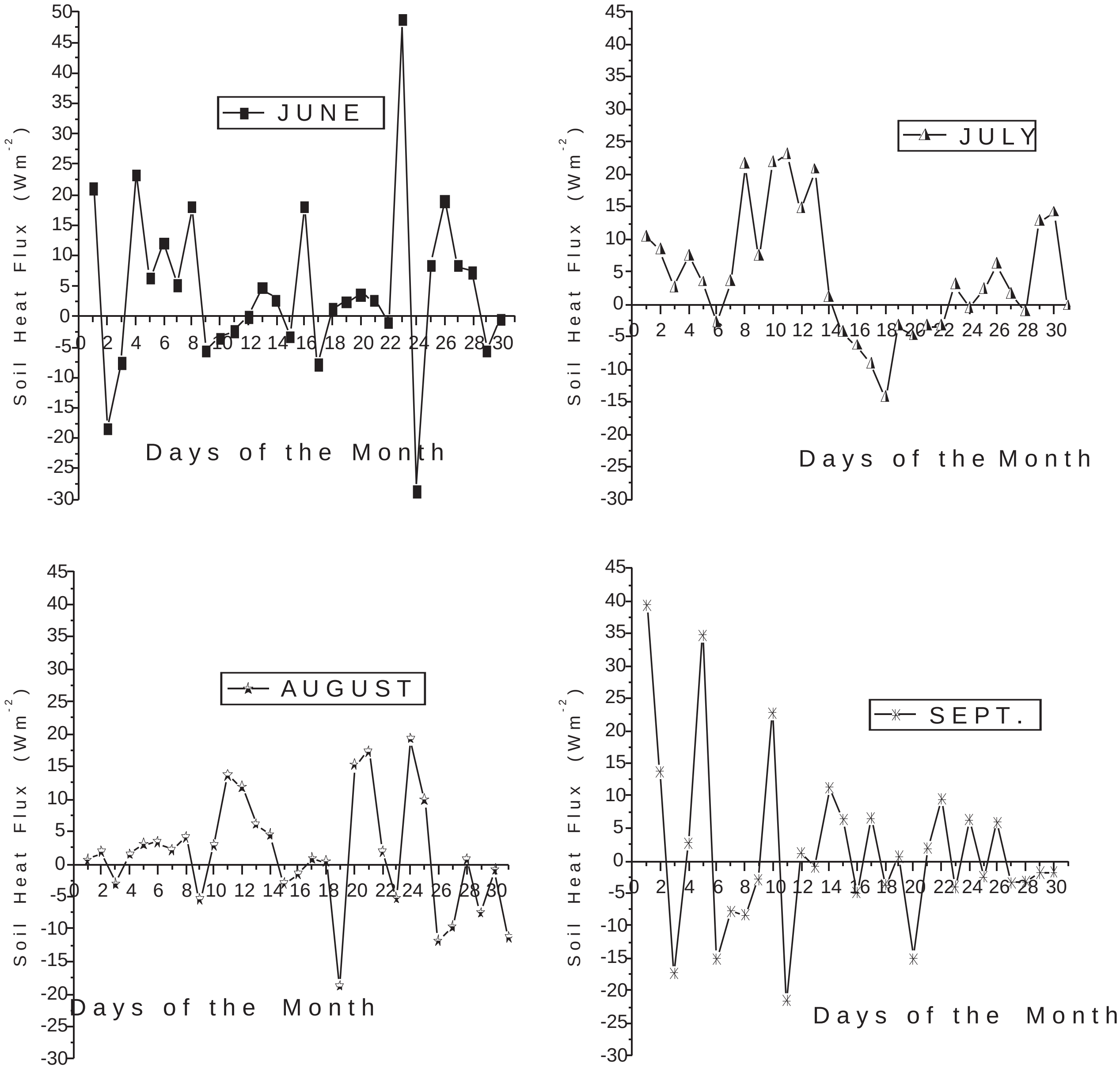

Fig.4(b): As in Fig. 4(a) but for June to September, 2006

Between June 2nd and 3rd (as in Fig.4b), the soil heat flux dropped to -20 Wm^{-2} and -30 Wm^{-2} on the 24th of the same month. This sudden drop in the values of heat flux in the soil cut across the months of August and September. This was due to the interception of the rain clouds (such as cumulus and cumulonimbus), rain and deep fogs in contact with the immediate surface of the soil. This result equally etablished the fact that dry period has greater effect on the heat fluxes than it has on the soil moisture at the same condition (Munn and Richards, 1988). This was possible because the time taken to retain water or moisture in the soil is longer than the time for the heat transfer into the soil depth.

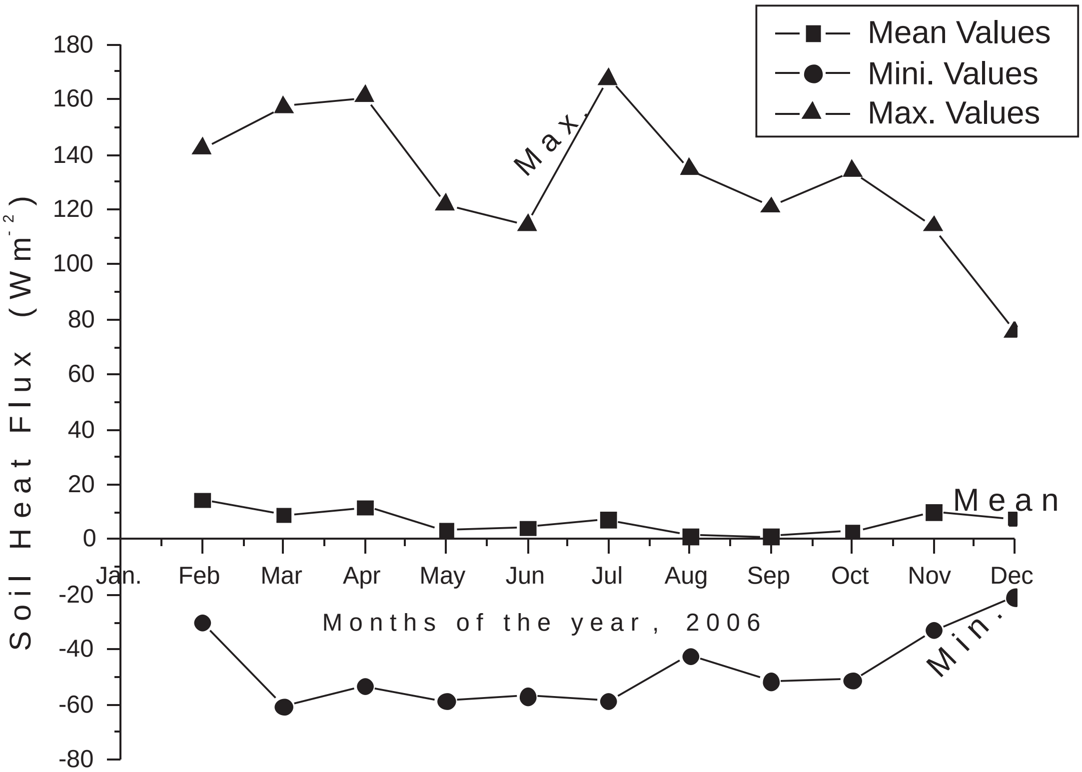

Fig.5: Monthly Variations for the Mean, Minimum and Maximum Values in Soil Heat Flux as Measured in 2006, at Ibadan.

The summary of the monthly mean, minimum and maximum values of the soil heat flux over the station for 2006 is presented in Figure 5. There was an unusual dry spell for about two weeks in July, 2006. This accounted for sudden rise in the value of soil heat flux. This agreed with the findings and reports in literature (Synder etal. 2000 and Stull, 1988), that precipitation is directly connected with the response of heat fluxes on the ground particularly over a tropical region.

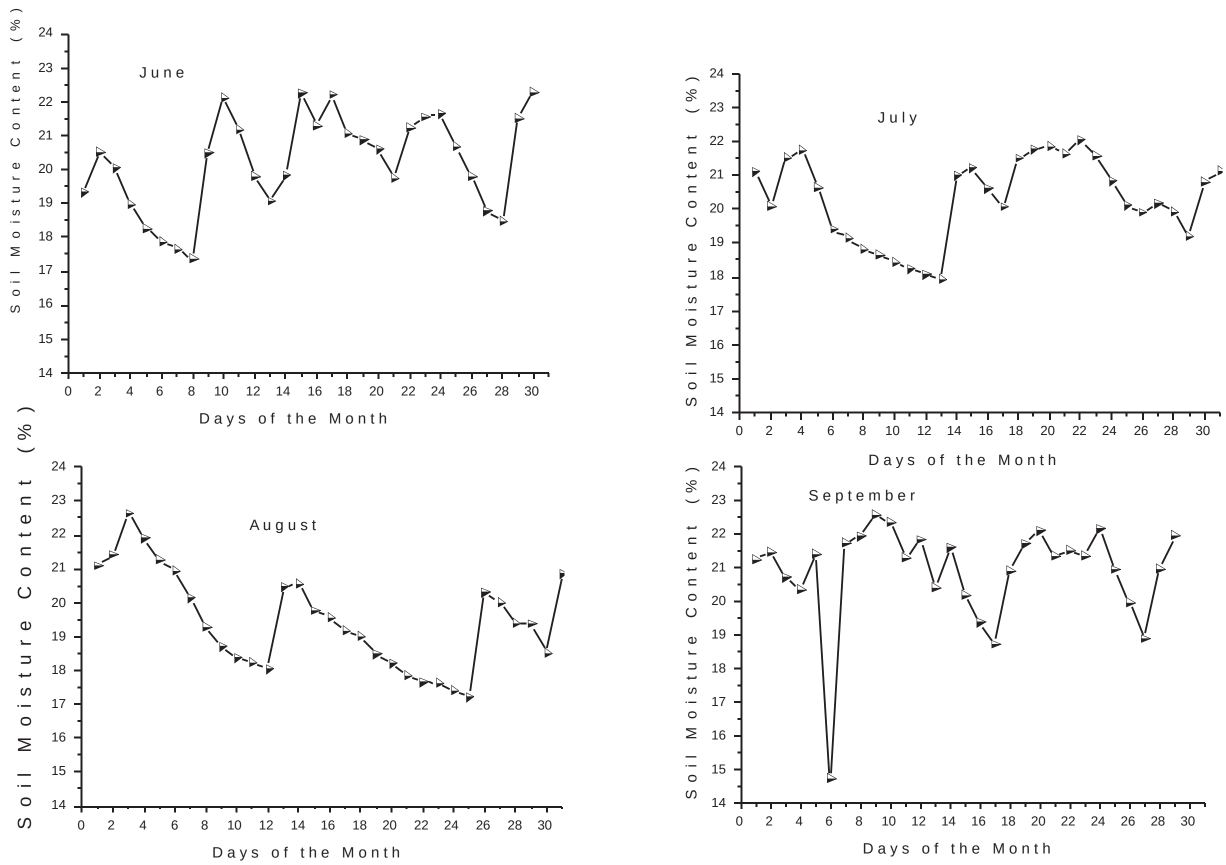

Figure 6: Daily Averages of Soil Moisture Content for the Typical wet season (June-Sept.) as Measured Over a NIMEX Station, Ibadan in 2006.

Figure 6 revealed the daily variations of the soil moisture content for the typical wet period at the measurement site. The fluctuation in the profile confirmed the general pattern of soil moisture in the wet season in Western part of Nigeria. The moisture contents were between 17% and 25%, which were quite high when compared with that of the dry period of the same year. The active soil moisture from this micrometeorological study was obtained by direct measurement of soil moisture content in the field. A time series of moisture values revealed the actual changes in water content. The difference between the wettest and driest months as indicated in the profiles was a pointer to an estimate of the extractable soil moisture storage (Nieuswolt, 1982). From the soil moisture values (in Figure 6) particularly on days 8, 12, and 29 in the month of June and days 13th and 25th of August, 2006, it could be seen that there was a sharp fall in the value of soil moisture in the afternoon period due to the heat exchange in the sub-soil layer as wetness of the surface commenced, (see table 2 on rainfall period) The irregular pattern was as a result of the predominant cloud drift, fogs and rainfall within these periods. The gravity of the effect of rainfall was pronounced by virtue of bare soil surface (Cannoffs and Bernardi, 1982).

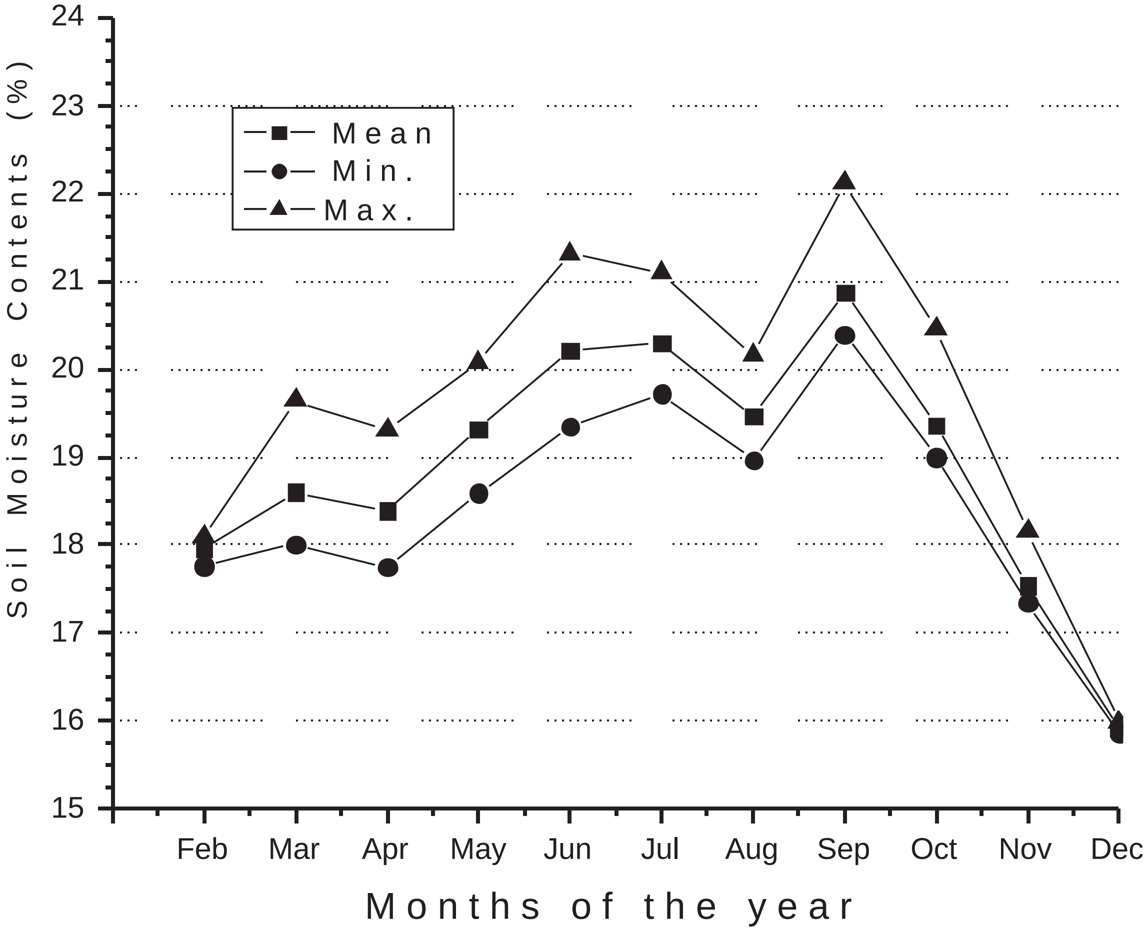

Figure 7: Monthly Variations for the Mean , Minimum and Maximum Values of Soil Moisture as Measured in 2006, in Ibadan

Figure 7 revealed the seasonal pattern for the early and later part of the year under consideration. The month of August and September were heavy rainfall months for the year 2006. Due to frequent rainfall occurrence, there was a large day to day variation for the soil moisture content (14% - 25%). However the relatively dry surface condition observed throughout days like Julian days 274-304 and 305-343 which were for the months of October and November, 2006, revealed the gradual change or decrease in soil moisture content. This conformed with the result obtained by Ewanlen, (1997) on moisture content characteristics. It can be inferred from this result that soil moisture is an important regulator of soil temperature and for an equivalent amount of soil, more heat is required to raise the temperature of wet than of dry ground.

Hence it can be concluded that changes of soil moisture with time is related to surface water losses. The frequency of occurrence of the soil moisture content for 2006 was presented in Figure 8 (a,b,c). In the month of February, the highest value of soil moisture content was between17-18% and that was the highest frequency for that month. Unlike the months of March and April, the soil moisture content was as high as 24% and with the frequency of occurrence as high as 13.

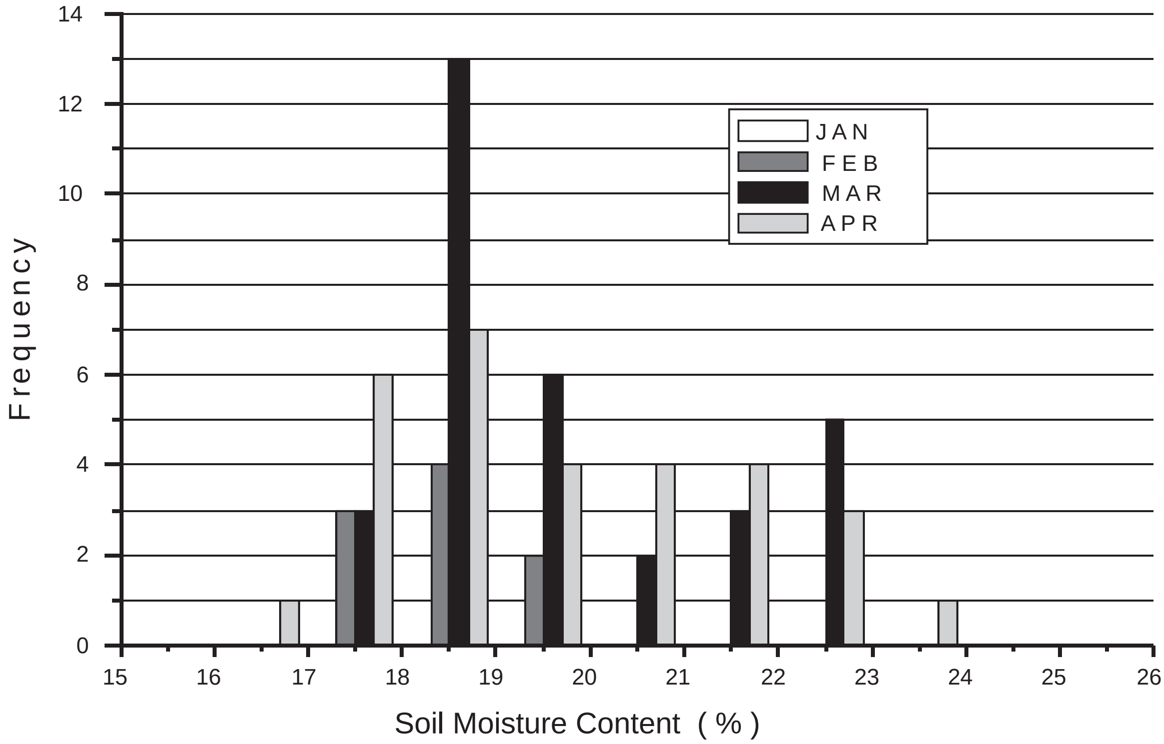

Figure 8.(a): The Percentage by Month of Soil Moisture Content with Frequency of the Occurrence as Measured Between January-April 2006 at the NIMEX Site, Ibadan.

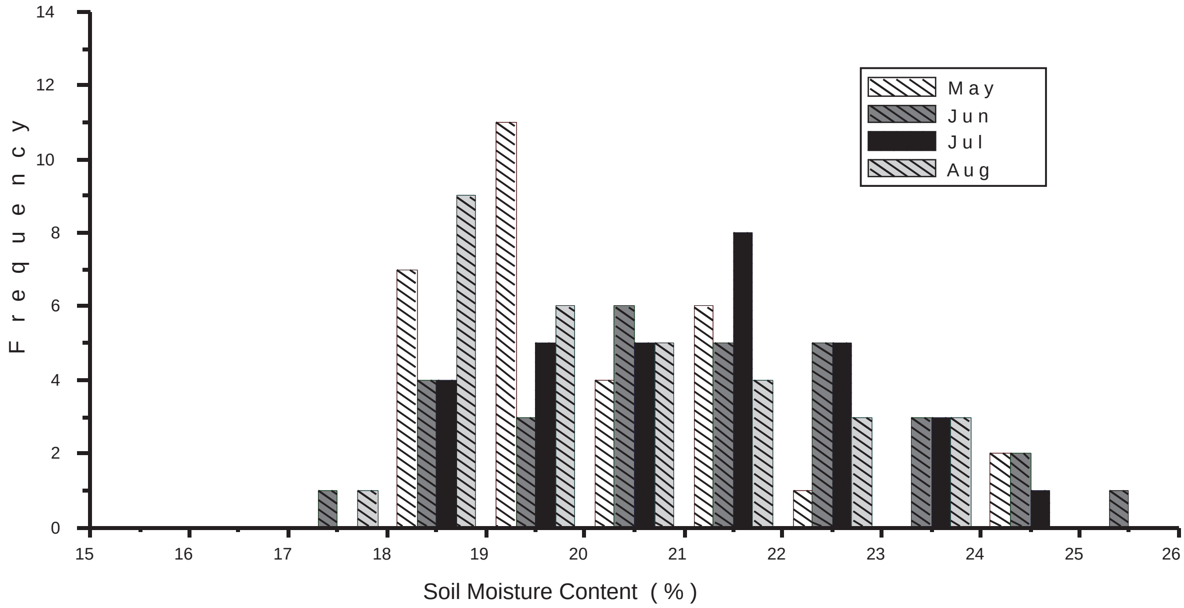

Fig.8(b): As in Fig.8(a) but for May – August, 2006 at the NIMEX Site , Ibadan

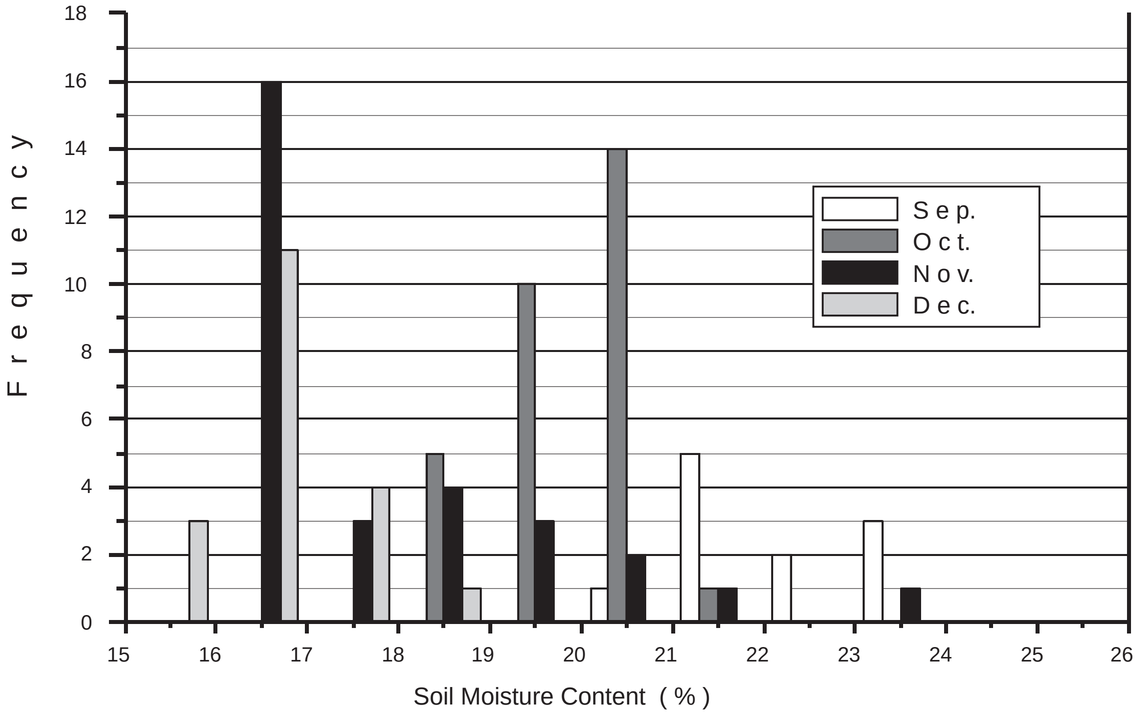

Fig.8©: As in Fig.8(a) but for September – December, 2006 at the NIMEX Site, Ibadan

The months of May to August (wet months), had the least soil moisture to be above 19% which was beyond the maximum obtained in the dry month in Figure 8 (c). The frequency of occurrence for this was above 10, and there was a record of soil moisture content above 25% in the month of June when we recorded average heavy rainfall (see Figure 8b). The frequency of soil moisture which was less than 17% was as high as 16, particularly in the month of November (the peak of the dry month). The month of October was peculiar with the frequency as high as 14 and soil moisture content well above 20%. This was because of the unusual heavy rainfall in the month of October, 2006. (see Table 2 on rainfall).

CONCLUSION

In conclusion, It can be established from this work that rainfall is capable of transporting heat as it percolates down through the soil. Thus, quantity of precipitation (rainfall) and its seasonal distribution, have considerable bearing on the upward or downward movements of water through the soil.

There was a positive association established between heat flux and moisture content of the soil during midnight and early morning hours of the day. That is, both soil heat flux and soil moisture content observed uniform variation during the early period of the day, attained maximum at noon and gradually decreases as we approach the night time. The marked difference in value at noon was as a result of the differences in the insolation hour, and the cloudiness (type and amount) blocking out the solar radiation. The fluctuation in the soil heat flux is more pronounced during the wet season than that of the soil moisture content. Thus, the heat fluxes in the soil respond faster to the seasonal changes than the moisture content of the same soil and at the same time. Hence it can be established that changes of soil moisture with time is related to surface water losses. In other word, the amount of water that can be stored in soil and evaporated or actively used by plants is a key parameter in hydrologic models Therefore, this information is important for crops and pasture production.

ACKNOWLEDGEMENT

The author is grateful to Professor O.O. Jegede and the entire members of NIMEX, Atmospheric Research Group and the technical staff of Department of Physics, University of Ibadan, Nigeria for their assistance in the pre-field measurement phase. The financial and equipment support for this research study by International Programmes in the Physical Sciences (IPPS) of Uppsala University, Sweden and Bayreuth University, Germany are highly appreciated.

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Table2: Showing the Days of Major Rainfall Periods for the Year 2006, as Measured at Ibadan.

DATE	JULIAN Day	PERIOD OF THE DAY (A.M) LST	PERIOD OF THE DAY P.M. (LST)
03/04/06	93		6.40-7.20,8.30-8.40
23/04/06	113	3.10-3.20	2.20-2.40
25/04/06	115	4.00-8.30	
26/04/06	116		2.00-2.10, 10.30-1040
29/04/06	119		8.40-10.00
30/04/06	120	4.00-8.40	2.00-2.20, 5.20-10.00
1/5/2006	121		8.40-9.10
05/05/06	125	3.10-3.30	12.40-12.50,
07/05/06	127		3.10-3.40
10/05/06	130	7.50-8.30,9.10-10.30	
13/05/06	133	10.50-11.30	12.20-1.20
16/05/06	136		7.20-7.30
17/05/06	137	5.00-5.10	
19/05/06	139	8.10-8.30	
20/05/06	140	1.30-820, 9.50-10.10	1.50-2.00
22/05/06	142	11.20-12.00	12.01-12.30,1.00-2.30,3.40
25/05/06	145	7.3	
27/05/06	147		10.30-10.50, 11.20
30/05/06	150	4.20-6.00	
2/6/2006	153		7.10-7.30
09/06/06	160	5.20-730	
10/06/06	161	11.5	3.3
14/06/06	165		5.20-7.50
15/06/06	166		1.30-1.50
17/06/06	168	1.50-3.10	
19/06/06	170	8.00-8.10, 11.10-1200	1.30-140
20/06/06	171	11.30-11.40	12.01-1.00

Table2: Contd.

DATE	JULIAN Day	PERIOD OF THE DAY (A.M) LST	PERIOD OF THE DAY P.M. (LST)
22/07/06	203	3.40-5.10, 10.10-10.30	10.05-10.20, 11.50-12.00
23/07/06	204	10.20-10.30	
24/07/06	205	11.40- 12.00	
25/07/06	206	7.10-7.20	
26/07/06	207		12.30- 1.11
27/07/06	208		1.00- 1.10, 1.20-1.50
5/9/2006	248	6.50am- 7.20 am	
07/09/06	250		9.30pm – 9.50pm, 11 .50pm-12.00pm
08/09/06	251	12. 00..-12-21am,1.40am	
09/09/06	252	3.40-4.50, 7.50	6.00-7.50, 11.30-11.40
14/09/06	257	2.30 – 2.40	
18/09/06	261	7.30-7.40	10.30-1040
20/09/06	263	11.10-12.00	12.01-12.30,2-2.10,6.50-7.0, 10.50-11.0, 11.20-11.30
21/09/06	264	10.30-10.50	12.10-12.20
22/09/06	265	4.20-430, 5.00-5.20	7.45-8.00, 10.30-10.40
23/09/06	266	1.20-1.30, 9.40-10.00,11.50-12.00	12.20-1.00, 1.20-3.00, 3.40-4.00, 7.50-8.00
24/09/06	267		5.20-9.40, 10.0-10.50, 11.20-12.00
25/09/06	268	12.05-3.50	3.15-3.40, 4.00-4.50
29/09/06	272	5.40-8.10, 9.10-10.40, 11.40-11.50	8.50-9.00
30/09/06	273	00.50-1.10, 3.20-3.40, 6.40-7.10, 10.30-12.00,	12.00-12.50, 7.10-7.30,

Table 3: The Synoptic Weather Observations During the Measurement Period in 2006 at the Study Site

Months of the Year (MOY)	**Mean Wind Speed (ms^{-1})**	**Wind Direction (degs.)**	**Daily Average Temp.(^{o}C)**	**Relative Humidity (%)**	**Daily Ave. Global Rn (Wm^{-2})**	**Synoptic Condition**
Jan	1.2	210	29.5	49.1	306.4	High Insolation with Alto. Cumulus
Feb	1.5	198.5	28.3	52.7	176.8	Heavy rainstorm but short-lived (30mins) started at about 7.30pm
Mar	1.2	138.7	26.6	74.4	187.7	Eclipse Passage and low wind. Stratified Cloud prevalence.
Apr	1.1	108.5	27.3	56.7	189.7	No rain
May	1.0	80.4	26.2	65.1	166.8	No Rain
Jun	1.2	118.6	26.6	95.0	196.8	Cb. Cloud and Continuous rain
Jul	1.4	118.7	27.5	93.5	184.7	Light Shower
Aug	1.6	110.8	26.6	94.6	150.9	Slight drizzle at about 7.30 pm
Sep	1.1	40.6	26.6	90.5	163.9	Heavy and violent rainstorm with Cumulus Cloud
Oct	2.3	25.0	27.9	88.7	235.6	No rain
Nov	1.9	352.1	25.2	52.5	166.7	Low level fog with turbid condition in the morning
Dec.	1.9	13.6	25.0	48.1	256.4	No rain poor visibility persisted