INVESTIGATION OF THE SURFACE ENERGY BUDGET AT NIMEX_3 SITE, IBADAN USING BOWEN RATIO ENERGY BALANCE METHOD

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ABSTRACT

The surface energy budget measures the atmospheric turbulent fluxes and the interaction of heat exchange between land surface and atmosphere. The sensible (Q_H) and latent heat flux (Q_E) densities were computed using Bowen Ratio Energy Balance (BREB) for Nigeria Meteorological Experiment (NIMEX_3) site situated in University of Ibadan. The study examined 50days of data sets consisting of net radiation, wind speed, pressure, soil heat flux and air temperature measured at levels 6m and 12m. The daily calculated Q_H and Q_E range between 7.30 Wm^{-2} to 47.01 Wm^{-2}, and 20.98 Wm^{-2} to 184.57 Wm^{-2} respectively. The BREB estimation of the sum of Q_H and Q_E with day-time surface available energy revealed that the energy budget closure varied closely to 100%, and the ratio of the residuum to available energy indicates that there was no imbalance in surface energy budget for the site. The Bowen ratio latent heat fluxes are higher than sensible heat fluxes during the daytime. Furthermore, BREB method partitioned energy fluxes differently favouring latent heat flux. Consequently, the diurnal variations of the surface energy fluxes for the periods under considerations correspond to the periods of higher closure ratio. The analyses revealed irregular variations of Bowen Ratio for the Julian Days 51-100 which are consistent with the daily variation of the weather conditions of air masses and moisture transfer. The result of this study could be used to determine surface energy budget closure over Tropical stations.
Keywords: *Sensible Heat Fluxes, Latent Heat Fluxes, Bowen Ratio,*

INTRODUCTION

A continuous exchange of energy takes place between the Earth's surface and the atmosphere. These land surface-atmosphere interactions can be described by the surface energy balance (SEB):

$$Q_s = Q_H + Q_E + Q_G \qquad (1)$$

Assuming that horizontal flux divergence and heat storage are insignificant, the equation 1 above states that the net radiation (Q_S) is dissipated as sensible heat (Q_H), latent heat (Q_E) and soil heat (Q_G) fluxes (Garratt, 1992). For many decades, meteorologists have tried to quantify the SEB by making direct ground measurements, their efforts were often confined to the temperate parts of the world and to economically important vegetations such as agricultural crops, pasture or forest. Recently, experimental interest has shifted more to the semi-arid and arid areas which cover nearly 40% of the world (Seller, Mintz, Sud and Dalcher, 1986; Foken and Wichura, 1996). The estimation of surface latent and sensible heat fluxes can be accomplished by many different methods. Most of these usually require key input parameters such as surface air temperature, specific humidity and wind speeds (Stull, 1988). This type of data is not always easily accessible therefore some researchers have turned towards land surface models forced by observation to help derive these fields. These numerical simulations have shown that mesoscale differences in the land surfaces can have significant impacts on mesoscale variabilities of surface fluxes and thus affect mesoscale weather and climate in many important ways (Mc Cumber and Pielke, 1981).

The surface fluxes determine to an important extent the steady state of the atmosphere. They also determine the mean profiles of the surface layer and the atmospheric boundary layer. The precise representation of these surface parameters is highly desired but often difficult to implement due to a lack of surface observations (Stull, 1988). The recent related research works includes that of Seller, Mintz, Sud and Dalcher (1986), Sun, Esbensen and Mahrt (1995), Wyngaard, Cote and Izumi (1971) and Barr et al (1994). The objective of this study is to calculate sensible and latent heat fluxes using Bowen ratio energy balance method. The daily trends of Bowen ratio over the Julian days will also be considered. The diurnal trends of the surface heat fluxes will be critically examined. Problems with the measurement of the available energy components Qs and QG are examined in comparison with BREB.

MATERIALS AND METHODS

The University of Ibadan has the NIMEX _3 site available for use. The NIMEX _3 site is a dense network of meteorological station situated within 7.38°N and 3.93°N. The data used in this investigation were collected from the Nigeria Micrometeorological Experiment (NIMEX_3) site situated in University of Ibadan in Ibadan, Oyo State, Nigeria. The elevation of the site above the sea level is 234.2 m. The experiment covered 20th of February to 11th of April 2007, this falls within the Julian day 51 to 100. The site is on extensive flat non-vegetated land that provides a general overview of energy fluxes, wind speed and the cloud situations (Ayoola, Olatona and Oladiran, 2006). The station measures up to 14 meteorological parameters (for example, air temperatures at 6m and 12m, soil temperature and wind speed) over an observation period of 5minutes. The Bowen ratio was computed from the equation 2 (Stannard, 1992; Bowen, 1926).

$$\beta = \frac{Q_H}{Q_E} = \gamma \frac{dT}{dz} \Big/ \frac{de}{dz} = \gamma \frac{\Delta T}{\Delta e} = \gamma \frac{T_2 - T_1}{e_2 - e_1} \qquad (2)$$

T_2 and T_1 are air temperature at different levels where γ is the Psychometric constant. The γ is computed from this expression below

$$\gamma = \left(\frac{K_H}{K_V} \right) \frac{C_p P}{\varepsilon \lambda_V} \qquad (3)$$

Where K_H and K_V are the eddy diffusivities for vapour and heat respectively .The ratio$\left(\frac{K_H}{K_V} \right)$ is assumed unity. ε is the ratio of molecular weight of water vapour to that of dry air (ε =0.622).

C_p is the specific heat capacity of dry air at constant pressure, which is given as

$$C_p = 1 + \left[\left(\frac{e_2 + e_1}{2} \right) \times 0.522 \right] \times 1004.67 \quad (4)$$

λ_V is the latent heat of vaporization($\lambda_V = 2.44 \times 10^6 JKg^{-1}$)

P is the atmospheric pressure, which can be computed by the expression below (Wallace and Hobbes, 1977; Foken and Wichura, 1996)

$$P = 101.3 \left(\frac{293 - 0.0065z}{293} \right)^{5.26} \quad (5)$$

Where z is the elevation of the site above the sea level and value of z for Nimex_3 site, Ibadan is about 235.2 m.
The vapour pressure e_1 and e_2 was computed from Penman equation (Buck, 2001) as

$$e_a = e^o(T) = 0.6108 \exp \left[\frac{17.27T}{T + 237.3} \right] \quad (6)$$

The latent heat flux can be obtained by

$$Q_E = \frac{Q_S - Q_G}{1 + \beta} \quad (7)$$

Where Q_S is the net radiation, Q_G is the soil heat flux and β is the Bowen ratio.

Also, the sensible heat flux can be obtained by

$$Q_H = \frac{\beta (Q_S - Q_G)}{1 + \beta} \quad (8)$$

Energy Budget Closure (EBC) (Baldocchi, 2003) was computed as

$$\text{EBC} = \left(\frac{Q_H + Q_E}{Q_S - Q_G} \right) \times 100 \quad (9)$$

Where available energy $E_a = Q_S - Q_G$

The residuum surface energy fluxes δ is given by

$$\delta = Q_S - Q_G - Q_H - Q_E \quad (10)$$

RESULTS AND DISCUSSION

For the period under consideration, the daily mean Bowen ratio, latent heat and sensible heat were calculated from the daily records obtained from the instruments. Also, the mean energy budget closures were determined. From table 1, the highest Bowen ratio was obtained in day 81 and day 66 has least value. These results showed that there was a pronounced dry season in February and March with little or no rainfall in early April. The standard deviation of Bowen ratio is 0.026 which shows that the values have minimum scatter. The observation is due to the fact that the parameters like temperature, wind speed, net radiation and soil heat flux are fairly stable on daily basis. They are quantities that vary with time and are much more reliable on daily and hourly basis (Gash, 1986; Aubinet et al, 2000). The daily mean sensible heat and latent heat fluxes computed by Bowen ratio energy balance method range between 7.30 Wm^{-2} to 47.01 Wm^{-2} and 20.98 Wm^{-2} to 154.37Wm^{-2} respectively. The results from the table show that Bowen ratio latent heat fluxes are about (30 ± 0.10) Wm^{-2} higher than sensible heat fluxes during the daytime. It was observed in Figure 1 that the temporal fluctuations observed in the graphs over the period under consideration tend to suggest, in part, the influence of the atmospheric stability and wind speed, as well as surface roughness over the bare soil (Tyler, et al, 1997; Famighetti and Wood, 1994). Figure 2 shows that the daily trend of the Bowen ratio sensible and latent heat fluxes during days 51-100. The fluctuations observed can be attributed to dryness and wetness of the different Julian days under consideration (Oke, 1978). The relatively low value of Bowen ratio sensible heat fluxes may be due to the dryness of the periods under consideration (Garratt, 1992; Wieringa, 1986).

Figure 3 shows that there is a linear correlation between $Q_H \pm Q_E$ and available energy. The correlation coefficient is 0.52 and slope of the straight line regression plot is 1.32 which represents the surface energy budget closure for the Nimex_3 site, Ibadan. In fig 4, the mean closure at NIMEX_site 3 varied closely to 100% for the period under consideration. The coefficient of determination for the flux comparison between the sum of latent heat and sensible heat fluxes and available energy for regression with free intercept was 0.52. The BREB estimation of the sum of Q_H and Q_E with day-time surface available energy revealed that the energy budget closure varied closely to 100%, and the ratio of the residuum to available energy indicates that there was no imbalance in surface energy budget for the site (Garratt, 1992; Finnigan, 2004).

Figures 5-10 show the diurnal variations of surface energy fluxes for the period, corresponding to the period of complete closure rate. These periods were associated with weak synoptic forcing and no rainfall, and the net radiation is seen to be substantially larger than the sum of other terms in equation 1. In day 54, a short heavy rainfall event occurred between 0900 and 0930hrs, and the net radiation flux varied over the day due to cloud cover. For day 55, the cloud was heavy for rainfall at about 0935hrs and the net radiation varied smoothly. Day 56 was very clear in the morning, but became cloudy in the afternoon with a corresponding change in the net radiation flux. However, no precipitation was observed. The sensible heat flux was about 90 Wm^{-2} in the afternoon of day 55. The latent heat flux exceeded 53 Wm^{-2} in the afternoon of 56 and 59, and the Bowen ratio was between 0.2 and 0.4 during the day. The ground diffusive flux at the surface was about 27 Wm^{-2}, interestingly, on day 55; the latent heat flux was close to 0.

Table 1: The daily mean values of Bowen ratio , and sensible heat and Latent hear fluxes computed by Bowen Ratio energy Balance For Julian Days 51-100 (20th of February to 11th of April 2007).

Julian day(s)	Bowen Ratio	Q_HBREB (Wm^{-2})	Q_EBREB (Wm^{-2})	Q_S- G (Wm^{-2})	Q_H+Q_E (Wm^{-2})
51	0.317	35.68	112.56	60.04	148.240
52	0.325	23.37	72.00	167.65	95.380
53	0,323	46.81	144.98	165.70	191.800
54	0,324	47.01	144.90	47.69	191.911
55	0.322	17.01	52.88	37.30	69.890
56	0.316	17.26	54.65	66.23	71.910
57	0.374	27.91	74.59	24.96	102.500
58	0.346	20.28	58.69	93.01	78.970
59	0.314	32.50	103.38	16.47	135.880
60	0.337	21.95	65.17	43.98	87.120
61	0.342	33.74	98.79	58.23	132.530
62	0.329	28.09	85.34	29.53	113.430
63	0.320	20.45	63.95	0.62	84.400
64	0.324	17.09	52.69	10.08	69.780
65	0.334	18.95	56.76	21.01	75.709
66	0.371	24.64	66.49	16.99	91.130
67	0.373	22.47	60.29	12.95	82.760
68	0.356	21.44	60.26	41.92	81.700
69	0.350	23.02	65.68	61.47	88.690
70	0.328	23.90	72.81	12.52	96.700
71	0.326	20.37	62.46	3.75	82.830
72	0.330	10.17	30.83	-36.18	41.010
73	0.344	8.07	23.46	-34.21	31.530
74	0.348	7.30	20.98	40.65	28.279
75	0.322	22.70	70.49	45.77	93.190
76	0.314	21.73	69.29	77.08	91.020
77	0.322	34.17	106.14	73.34	140.310
78	0.347	36.72	105.73	5.81	142.450
79	0.363	21.32	58.74	37.20	80.060
80	0.306	20.34	66.48	-22.37	86.820
81	0.374	13.27	35.52	68.38	48.789
82	0.331	35.14	106.21	71.52	141.350
83	0.306	21.38	69.78	70.19	91.160
84	0.307	21.90	71.24	44.60	93.140
85	0.305	17.51	57.47	45.72	74.980
86	0.299	17.52	58.67	71.78	76.190
87	0.300	46.24	154.37	67.52	200.610
88	0.349	27.14	77.84	38.09	104.980
89	0.302	26.81	88.83	49.00	115.640
90	0.302	17.98	59.55	73.74	77.531
91	0.291	23.76	81.54	61.71	105.300
92	0.288	18.51	64.26	41.23	82.770
93	0.297	17.56	59.21	105.39	76.770
94	0.298	33.82	113.44	70.35	147.260
95	0.308	22.87	74.20	86.03	97.070
96	0.304	28.68	94.26	70.47	122.940
97	0.283	23.71	83.71	69.36	107.430
98	0.273	19.53	71,68	81.22	91.220
99	0.272	21.07	77.55	117.47	98.620
100	0.273	26.21	96.05	86.82	122.260

Wm^{-2} for about 3 hrs immediately after sunrise, and then increased suddenly at 1030 LT. The residuum, δ increased rapidly to an extreme peak of about 200 Wm^{-2} subsequently fluctuating between 220 and100 Wm^{-2} throughout the afternoon under fine conditions. In fig 11 and 12 show the diurnal fluctuations of day and nighttime sensible and latent heat fluxes which was due to oasis effect of warm dry air advection over the site (Garratt, 1992).

Studies have shown (Twine et al, 2000) that lack of closure indicates that either available energy was overestimated or the turbulent fluxes were underestimated. The complete budget closures are believed to be in a large part due the overestimation of available energy with heat exchange not being accounted for in surface waters during substantial period of surface vapour pressure.

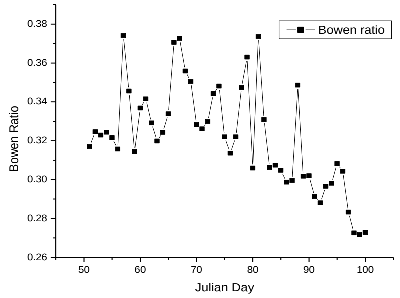


Figure1;Graph of Bowen Ratio versus Julian Day-Julian Day 51-100 in 2007

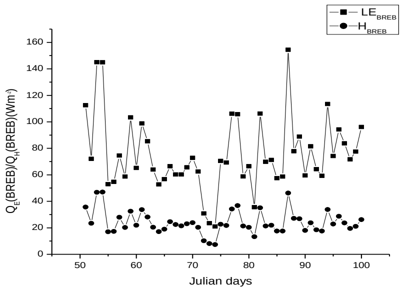


Fig 2;Graph of Q_E(BREB)/Q_H(BREB) against Julian Days 51-100 for 2007

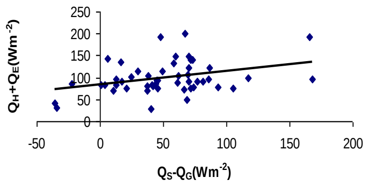


Figure 3; Daily surface energy budget closure using Bowen ratio for the Julian days ,51-100,2007

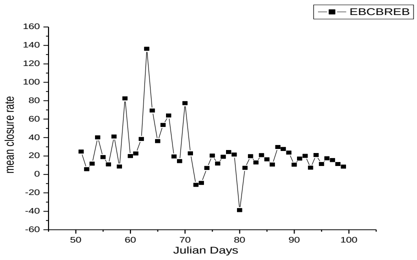


Figure 4; Graph of energy budget closure computed fof BREB over the Julian Days 51-100.

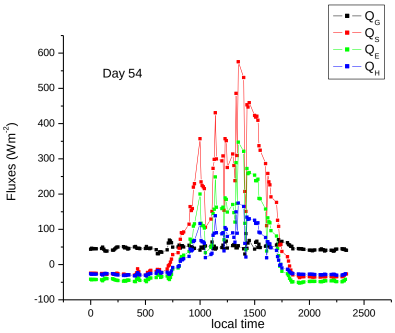


Fig 5 Diurnal variation of surface heat fluxes for Day 54

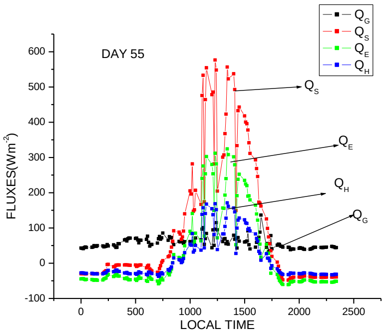


Fig 6; Diurnal variation of surface heat fluxes for Day 55

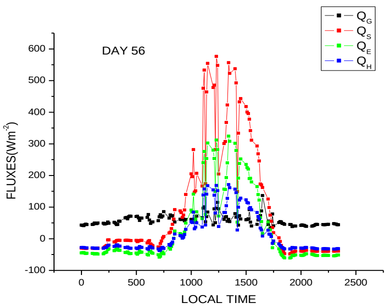


Fig 7; Diurnal variation of surface heat fluxes for Day 55

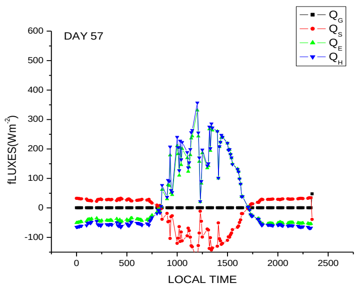


Fig 8; Diurnal variation of surface heat fluxes for Day 57

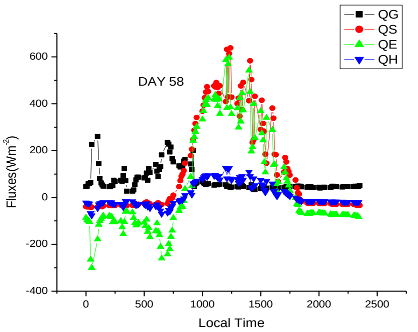


Fig 9; Diurnal variation of surface heat fluxes for Day 58

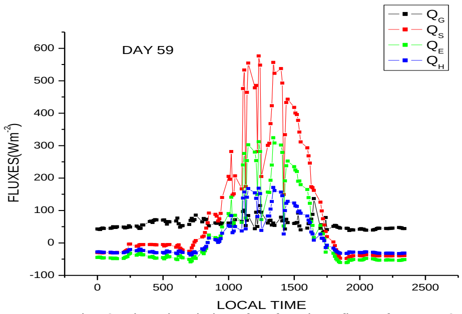


Fig 10; Diurnal variation of surface heat fluxes for Day 59

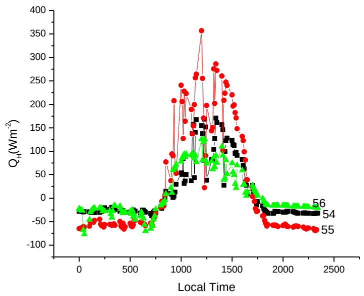
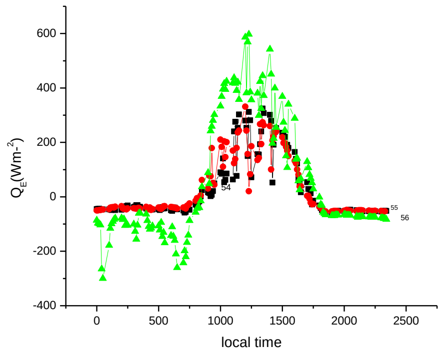


Fig 11;Diurnal variation of sensible heat fluxes for day 54 to 55



ffig 12;Diurnal variation of latent heat fluxes for Day 54 to 55

CONCLUSION

The work investigates surface energy budget at NIMEX_3 site, Ibadan using Bowen ratio energy balance method. These findings correlate with those of Tyler, et al (1997), Oke, 1978, Gash, (1986) and Garratt, (1992). The detailed diurnal variation of the surface energy fluxes for the six days (54-59 Julian days), corresponding to the periods of complete closure was associated with no rainfall. The Bowen ratio latent heat fluxes are about (30 $\pm$ 0.10) Wm^{-2} higher than sensible heat fluxes during the daytime. The relatively low value of Bowen ratio sensible heat fluxes may be due to the dryness of some the periods under consideration. Also, the reliability of the Bowen ratio energy balance was assessed by the Energy budget closure equation and mean EBC for Bowen ratio energy balance varied closely to 100% for periods under consideration. The result of this study could be used to determine surface energy budget closure over Tropical station.

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