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Observations of daytime surface energy balance in cloudy tropical conditions at Ile-Ife, Nigeria

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सार – इस शोध-पत्र में वर्ष 1998 के अक्टूबर/नवंबर माह में तापमान की ली गई श्रृंखलाबद्ध सूक्ष्म मौसम वैज्ञानिक मापों के आधार पर आई.एल.ई.-आई.एफ.ई,. नाइजीरिया (7^{O} 33 उ., 4^{O} 34 पू.) मेघाच्छादित आकाश की उष्णकटिबंधीय स्थितियों में धरातल पर दिन के समय की ऊर्जा के संतुलन की जाँच की गई है। आर्द्र वातावरण अर्थात मिश्रित अनुपात 17-25 ग्राम / कि.ग्रा. में संवेदी ऊष्मा के मानों की अपेक्षा गुप्त उष्मा फलक्स के परिमाणों की मात्रा अधिक थी। प्रातःकाल के समय प्राप्त किया गया बोवेन अनुपात का औसतन मान 0.36 था जबकि अपराह्न में यह 0.74 था। अपराह्न में मिट्टी की सतह जब शुष्क हो जाती है तब संवेदी ऊष्मा तथा भूमि ऊष्मा फलक्सों दोनों के परिमाण परस्पर तुलनीय पाए गए हैं।

धरातल के ऊर्जा संतुलन के संबंध में परिमाणों में पाए जाने वाले उतार-चढ़ावों की आकाश में मेघों की संख्या, मृदा आर्द्रता की डिग्री, वायु तापमान तथा आर्द्रता के साथ परस्पर सुसंम्बद्धता पाई गई है। किन्तु इन सभी कारकों में से आकाश में मेघों की संख्या में पाई गई भिन्नता अधिक प्रभावी पाई गई है।

ABSTRACT. Daytime energy balance at the surface in cloudy tropical conditions for Ile-Ife; Nigeria (7°33'N, 4°34'E) is investigated based on a series of micrometeorological measurements performed in October/November of 1998. For the humid environment that it is (mixing ratio, 17 -25 g / kg), magnitudes of the latent heat flux were much larger than the values for the sensible heat. Of the morning hours the average value for the Bowen ratio obtained was 0.36, while for the afternoons it was 0.74. As the soil surface became dried up in the afternoons, magnitudes of both sensible heat and ground heat fluxes were found to be comparable.

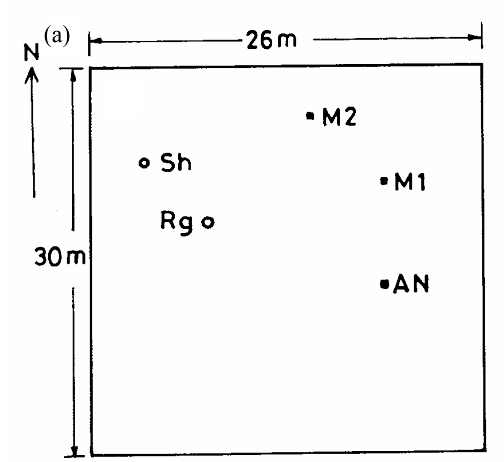
Fluctuations in the magnitudes of the terms of the surface energy balance correlated well to the cloud amount, degree of soil wetness, air temperature and humidity. But of all these factors, the variation in the amount of cloudiness appeared most dominant.

Key words – Surface energy balance, Daytime conditions, Bowen ratio, Cloudy tropical area, Ile-Ife; Nigeria.

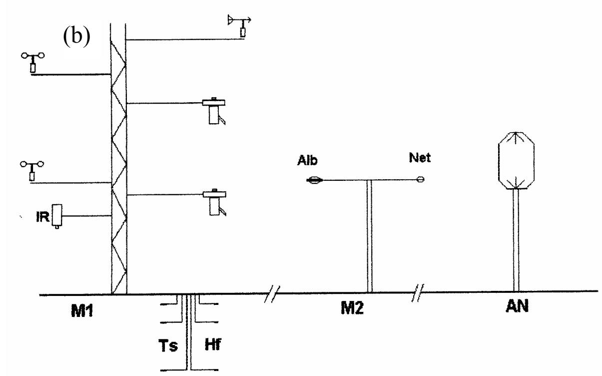
1. Introduction

The atmospheric environment over the West African (equatorial) sub-region is characterized by a moist southwesterly flow (of maritime origin) at the lowest layers forming a wedge beneath the very dry northeasterly winds (blowing from the Azores sub-tropical high pressure systems). This is like a tongue of humid air pushing inland with its northernmost position varying in the course of the year between latitude 70° N (January) and 22° N (July/ August). By a climatological classification, the present study location, Ile- Ife; Nigeria (7°33' N, 4°34' E), is within the tropical wet and dry (*Aw*) zone of tropical West Africa (Hastenrath, 1991) and all-year-round, it is enveloped by moist air.

For the location, the prevailing humid condition (typically, the relative humidity in the mornings is about 80%) is coupled with a high solar radiation input with maximum global radiation of about 1000 Wm^{-2}. Such a combination is indicative of prevalence of convective clouds (cumulus and stratocumulus). At Ile-Ife, the mean monthly cloud amounts for October and November at about 0900 hrs are 7 and 6 oktas respectively. Generally in the tropical areas, 50% or more cloud cover is frequent (Garstang and Fitzjarrald, 1999). When drifting or broken



(M1 = mast #, M2 = Mast#2, AN = sonic anemometer, Sh = sunshine hour recorder, Rg = rain guage)



Figs. 1(a&b). The experimental site at Ile-Ife, Nigeria (7° 33' N, 4° 34' E) (a) schematic layout and (b) measurement configurations (the dimensions are given in Table 1) Ts = soil thermometer Hf = heat flux plate, IR = infrared thermometer, Alb = albedometer, Net = net radiometer

tropical clouds are present, even for a few minutes, the net radiation becomes highly variable (hence the surface energy budget) and to some extent the surface temperature and albedo.

In the tropics, particularly for the West African sub-region, there is a lack of consistent observational studies of the surface energetics. In this paper, we present for the daytime, estimates of the energy budget over a bare soil surface at Ile-Ife Nigeria (7°33' N, 4°34' E), a humid tropical location. These micro meteorological measurements were conducted during a special observation period : 29 October to 12 November 1998.

2. Methodology

The surface energy balance (over bare soil) can simply be expressed as,

$$R_n = H + LE + G^* \qquad (1)$$

where R_n is the net radiation flux, H is the sensible heat flux, LE is the latent heat flux and, G^* is the total ground heat flux. Thus G^* includes the change of heat storage in the interfacial layer above which the soil heat flux plate is buried. Inclusion of this storage term can be very significant in the surface energy budget since it could be as much as 100 Wm^{-2} (Foken *et al.*, 1999). Both the net radiation and ground heat flux can be observed using standard instrumentation, but for the convective heat fluxes, the field measurements techniques are rather cumbersome (especially latent heat).

The Eddy Covariance (EC) technique is the most direct method of measuring these fluxes (Kaimal and Finnigan, 1994). But the complete instrumentation which include an ultrasonic anemometer and a fast response hygrometer are expensive and could be difficult to maintain in view of long-time field investigations. Other indirect methods such as the Bowen Ratio Energy Balance (BREB) provide a robust technique for the determination of the surface fluxes. But weak gradients or poorly developed turbulence conditions present serious problems for validation of the BREB method. Foken *et al.* (1997) have shown that for psychrometric measurements with a typical accuracy of ±0.05° C, temperature differences, ΔT less than 0.1° C are prone to substantially large errors (up to ±50% of the estimated sensible and latent heat fluxes), especially in a very humid condition.

In this study to determine the magnitudes of the convective heat fluxes, we have adapted an approach by Schotanus *et al.* (1983) with an assumption of the surface energy balance (Eqn. 1). This is realistic for a bare soil surface. In their method, they combined ultra-sonic anemometer measurements of the wind speed components (u', v', w') with standard micrometeorological instrumentation (net radiometer, soil heat flux plate, psychrometer, etc) to estimate the fluxes. But as a stand-alone equipment, the sonic anemometer only measures the buoyancy heat flux which is derivable from acoustic temperature. As such, a transformation relationship is employed to calculate the sensible heat flux.

According to Schotanus *et al.* (1983), the buoyancy flux, $\overline{w'T'_s}$ is related to the sensible heat flux, $\overline{w'T'}$, with corrections for the moisture and velocity fluctuations to be (in kinematic units) as,

$$\overline{w'T_s'} = \overline{w'T'} + 0.51\overline{Tw'q'} - 2\frac{\overline{T}}{c^2}(\overline{u.u'w'}.A + \overline{v.v'w'}.B) \qquad (2)$$

where, T is the actual air temperature, T_s is the virtual (acoustic) temperature, q is specific humidity and u, v, w are the wind speed components. For the 3-axis sonic

TABLE 1

List of the instrument deployed for the field measurements

Parameter	Device	Height (m)	Accuracy	Source
Wind speed	Cup anemometer (A101ML)	1.47	Distance const. 2.3m	Vector Instr., U.K.
Wind direction	Wind vane (W200P)	3.39	±2 deg.	Vector Instr., U.K.
Wet-and dry-bulb temperature	Psychrometer	1.47,3.43	±0.05°C	T. Friedrichs, Germany
Surface temperature	Infrared Pyrometer (KT15.82D)	1.13	±0.5°C	Heitronics, Germany
Soil temperature	PT-100Ω	-.02,(-05), -.1,-2,-5	±0.05°C	Thermometer-werk, Germany
Air pressure	Capacitive barometer	1.4	1hPa	Ammonit, Germany
Soil heat flux	Heat flux plate	-.02,(-.05), -.1,-2,-5	13.5μV/Wm^{-2}	Mc Vans Instr., Australia
Surface albedo	Albedometer (CM7B)	1.3	0.3-3μm	Kipp and Zonen, Netherlands
Net radiation	Net radiometer (Q7-REBS)	1.22	+9.6(-11.9) mV/Wm^{-2}	Campbell Sci., U.S.A.
Turbulent fluxes	Ultrasonic anemometer (USA-1)	1.3	10Hz	METEK Germany

anemometer that we have used (manufactured by METEK, model USA-1), the values for the parameters, $A = B = 0.75$ (Liu *et al*., 2001). It should be mentioned that the buoyancy flux could be as much as 20-30% higher than the sensible heat flux in humid conditions, especially for the tropics.

In terms of the turbulent heat fluxes Eqn. (1) can be re-expressed as,

$$R_n = \rho C_p \overline{w'T'} + \rho\lambda \overline{w'q'} + G^* \qquad (3)$$

Now using Eqn. (3) in (2) to replace the moisture flux term, and rearranging we obtain equation for the sensible heat flux as,

$$\overline{w'T'} = \left[\frac{\overline{w'T'_s} - 0.51\frac{\overline{T}}{\rho\lambda}(R_n - G^*) + 2\frac{\overline{T}}{C^2}(\overline{u}.\overline{v'w'}.A)(\overline{u}.\overline{v'w'}.B)}{\left(1 - 0.51\frac{\overline{T}}{\lambda}C_p\right)} \right] \qquad (4)$$

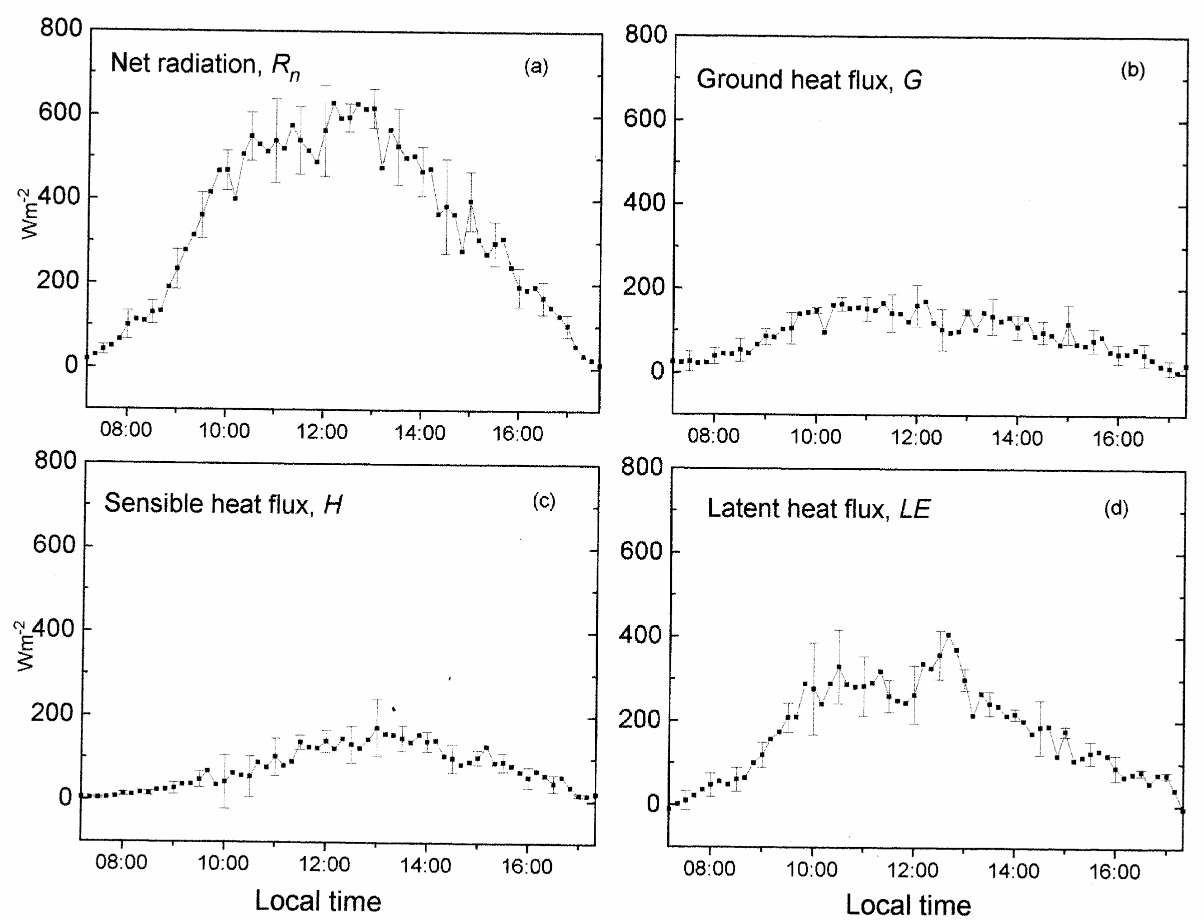
By multiplying Eqn. (4) with the dimensional constants (ρC_p), converts the sensible heat flux to the dynamical units (in Wm^{-2}). The latent heat flux we can obtain from Eqn. (3) as the residuum (assuming that there is energy balance at the surface), since both R_n and G^* are measured separately.

3. Site, instrumentation and data

An integrated micrometeorological system was set up comprising of the classical Bowen ratio energy balance (BREB) instrumentation and an ultrasonic anemometer at a site (224 m a.m.s.l.) inside the campus of Obafemi Awolowo University, Ile-Ife, Nigeria (7°33' N, 4°34' E) (Fig. 1). The measurements reported here were made during a special observation period : 29 October to 12 November 1998.

The net radiation and soil heat flux were measured by a REBS net radiometer (model Q7, manufactured by Campbell Scientific) and heat flux plate respectively. The experimental area, approximately 30 by 25 square metres, was maintained as a bare soil surface. The top soil was sandy-clay-loam soil and both the heat capacity, C_s and the surface albedo have been previously estimated to be $1.49 \pm 0.11 \times 10^6$ Jm^{-3} K^{-1} (Abimbola, 2000) and 0.14 ± 0.05 (Balogun, 2000), respectively. Away from the measurement surface were wild grasses and shrubs.

The ultrasonic anemometer was sampled 10 Hz and the raw data processed to obtain the 5-min turbulence



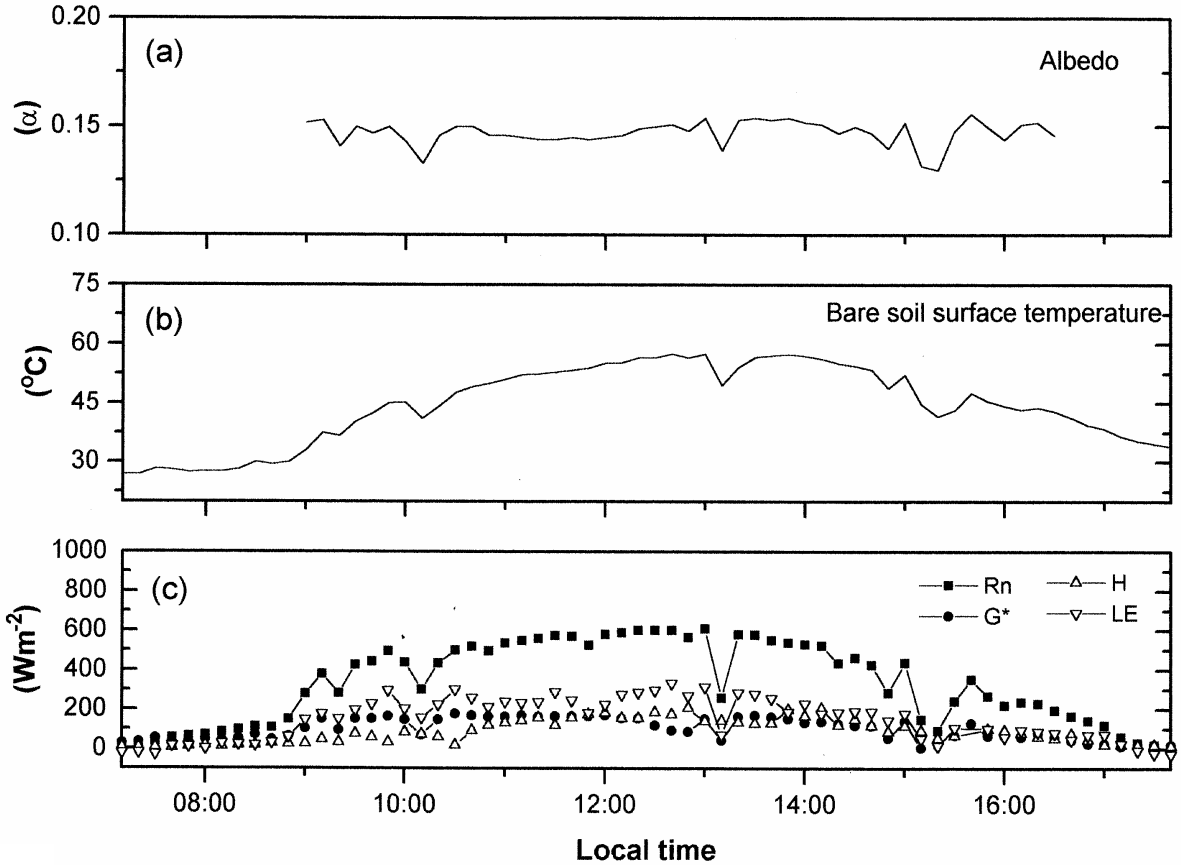
Figs. 2(a-d). The mean surface energy balance (day-time, *Rn* > 0) at Ile-Ife, Nigeria: 29 October -12 November, 1998

statistics. Since the positioning of the sonic was close to the surface (1.3 m), it is recognized that the larger-sized eddies may not be as well resolved and may lead to an underestimation of the surface fluxes. Consequently, a procedure for the spectral corrections by Moore (1986) and adapted by Foken (1992) was employed. The percentage of underestimation obtained ranged between 1.52 and 1.74. Also, the effective source area was estimated using the source area model, SAM-2 (Schmid and Oke, 1990). The model results indicated that the flux measurement was influenced largely by the surface conditions from within the measurement domain (that is, the bare soil). The instrumentation used are listed in Table 1.

4. Results and discussion

During the period under the investigation, the surface wind was weak (less than 1.5 ms^{-1}). Typically, in the early mornings it was cloudy (stratus, 6-8 oktas) but soon after the sunrise the low-level cloud deck often broke up. The environmental condition was very humid and the estimated values of the mixing ratio ranged between 17 and 25 g.kg^{-1}. Depending on the amount of cloudiness during the daytime, the observed net radiation was up to 650 Wm^{-2}, while the corresponding soil heat flux at 2 cm depth amounted to about 100 Wm^{-2}.

In Fig. 2 is shown the surface energy balance terms: net radiation, ground heat flux, sensible heat and latent heat fluxes estimated for the period under observation. Shortly after the sunrise net radiation increased steadily to attain maximum value of 627.8±24.4 Wm^{-2} at around 1240 hrs. The ground heat flux in Fig. 2(b) is observed to reach the daytime maximum value of 170.1±25.2 Wm^{-2} at about 1210 hrs. Both the sensible heat and latent heat fluxes showed a similar trend with maximum values of 173.0± 67.7 Wm^{-2} and 407.2± 0.9 Wm^{-2} respectively



Figs. 3(a-c). Case study 1 : 3 November, 1998. (a) albedo, (b) surface temperature and (c) surface energy balance

[Figs. 2(c&d)]. The latent heat flux was the larger term from the available energy. From the Fig. 2 it is very evident that between 0900 and 1500 hrs there were considerable fluctuations in the recorded magnitudes of the fluxes which is primarily due variability of the cloud amount during the convective conditions.

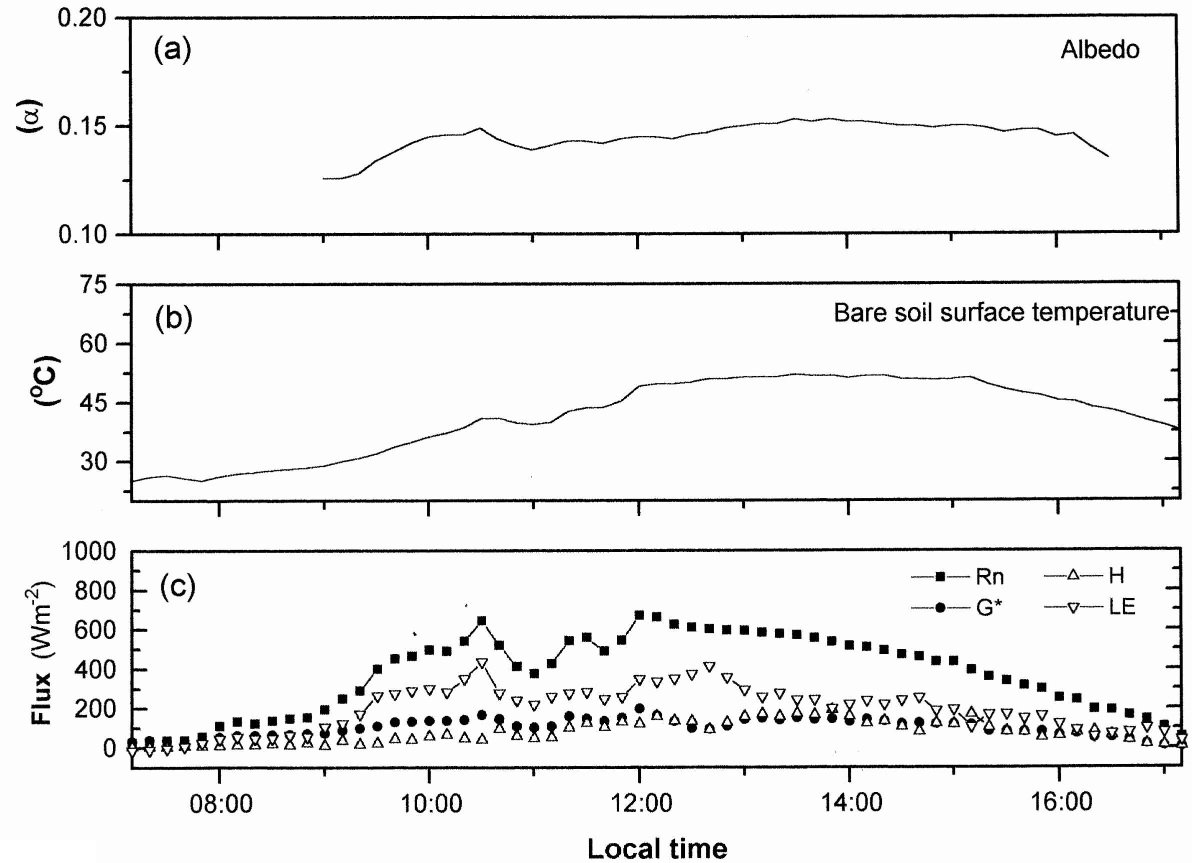
To emphasize this opinion, two contrasting case studies for the 4 (dry soil surface condition) and 8 of November (wet soil surface condition) are presented below.

(a) *Case 1: 3 November 1998*

The early morning condition was cloudy (stratus fractus/cumulus fractus, 6-7 oktas), humid (mixing ratio was 19 $g.kg^{-1}$), but the soil surface was dry (no rain after 31 October). From the plots shown in Fig. 3(a), it can be seen that the soil surface (skin) temperature rose rapidly during the morning hours from about 28° C (at 0800 hrs) to reach a maxima of 58° C by 1300 hrs local time. Between 0850 and 1030 hrs, the surface albedo values fluctuated very widely because of the clouds that were gradually clearing. The average value of albedo obtained was 0.15 which is comparable for the dry soil (sandy) surface condition (Oke, 1987).

Due to the low clouds (cumulus type), between 1020 and 1520 hrs, the surface temperature and albedo dropped in values by about 7 to 15% in Fig. 3(a). At about the same time both the net radiation and ground heat values decreased substantially by 40 to 80% [Fig. 3(c)]. The trend for latent heat flux was similar but to a lesser extent then sensible heat flux (which is comparable to that for the surface temperature).

In the morning hours, it can be observed in Fig. 3(c) that the latent heat flux was larger than the sensible heat flux. During the period (before the local noon), *H* and *LE* values were about 18% and 42% of the magnitude; of net radiation respectively. The average value of the Bowen ratio obtained was 0.61, thus indicating that there was a



Figs. 4(a-c). Same as for Fig. 3, but for the case study 2 on 8 November, 1998

considerable evaporation from surface. Despite a dry soil surface, the latent heat flux was high (about 300 Wm^{-2}). This is because of the high surface temperature and less relative humidity ~80 %. In the afternoons, as evaporation from the surface is reduced as surface temperature drops and relative humidity rises. The magnitudes of *H* and *LE* were about 34% and 41% of net radiation respectively (the Bowen ratio was 0.87). The available energy at the surface was of the ratio, 0.32 : 0.68 between latent and sensible heat. For the daytime on the 3rd November, the ground heat flux, $G^* = 0.32\ R_n$.

(b) *Case 2: 8 November 1998*

The early morning surface condition was very wet following the rainfall of previous evening. As such near the surface the air was very humid (18 g.kg-1). The cloudiness was of the type stratus (7-8 oktas). By 0800 hrs the low-level clouds had cleared off considerably to allow for the penetration of solar radiation for the surface warming. In Fig. 4(b), the ground surface temperature rose to attain maxima value of 53° C at about 1300 hrs. Due to the dark and wet soil surface condition, the surface albedo was considerably lower (mean was about 0.13) than it was recorded for the same time on the 3rd of November (0.15). But as the surface dried up it steadily increased in values.

In the morning hours the latent heat flux was dominant and almost a factor of 5 times the magnitudes of the sensible heat flux (the estimated Bowen ratio was 0.28). This is suggestive of the considerable evaporation that occurred at the surface. Also throughout the morning hours, values of the ground heat flux, G^* was about 3 times those for the sensible heat flux. In fact up to 1000 hrs, the measured sensible heat was less than 45 Wm^{-2}.

Between 1030 and 1300 hrs, there were large reductions up to 50 % [Fig. 4(b)] for the fluxes. This is due to the total cloud cover (8 oktas) in the sky during the period thereby effectively masking the solar disc. And it was to a lesser extent at other times during the daytime. It can also be seen that in the Figs. 4(a&b) for the same times as mentioned above, that a similar fall in magnitudes was observed for albedo and the surface

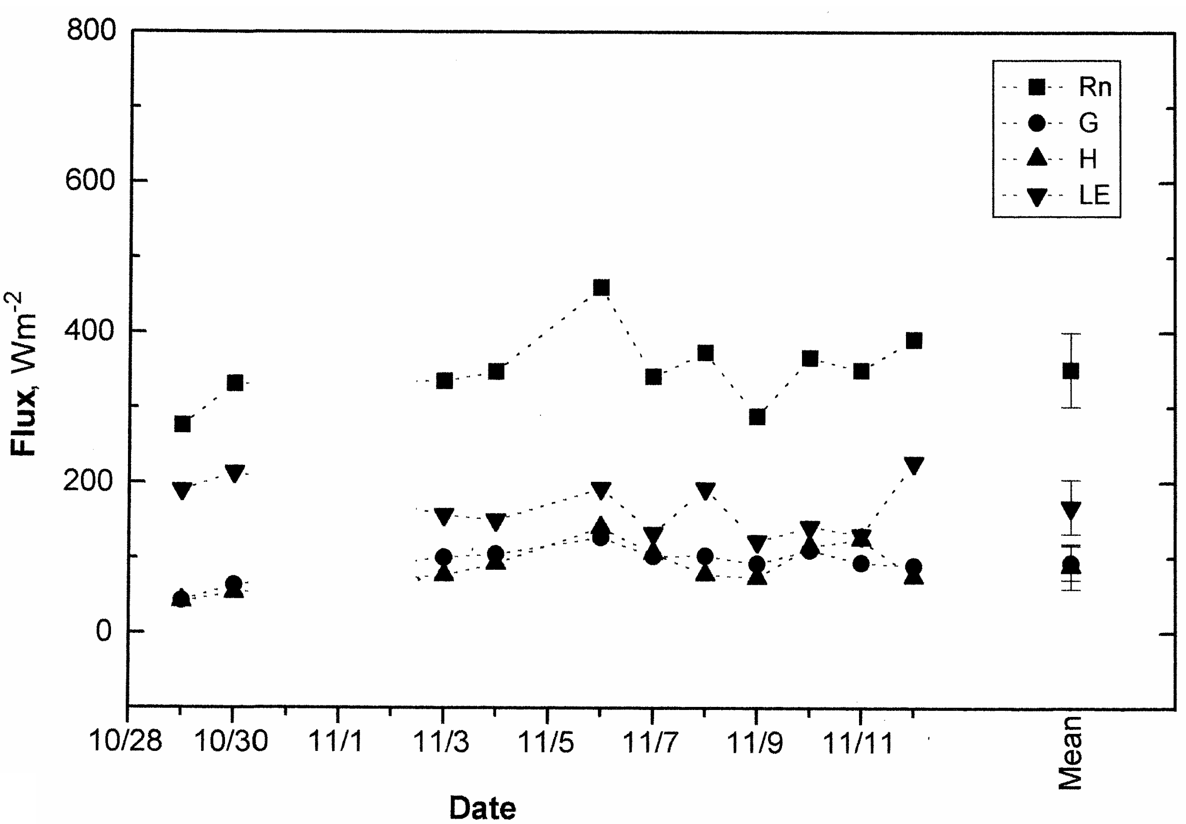


Fig. 5. Daily means of the surface energy balance (day-time, R_n>> 0) at Ile-Ife, Nigeria : 29 October – 12 November, 1998

temperature. Despite prominence of convective clouds on this day, intensity of incoming radiation was very high. Values of about 680 Wm^{-2} and 970 Wm^{-2} were recorded for both the net all-wave and global radiation respectively. This then explains why the surface temperature could rise up to 53° C for that day. For the daytime, we have established from the measurements that $G^* = 0.33\ R_n$. The average Bowen ratio for the afternoon period also increased to 0.62. Thus for the day, which had begun with very wet surface conditions, partitioning of the available energy was such that the sensible to latent heat flux averaged approximately 0.3 : 0.7.

(c) *The daily means of the sutface energy balance (R_n>> 0)*

Generally for the daytime, it can be seen that the latent heat flux, which is the dominant term, was about 40-50% of the net radiation values. The ground heat flux and latent heat flux were of comparable magnitudes, that is, 20-35% of the net radiation. For daytime period Bowen ratio was obtained to be 0.56±.0.25. The large standard deviation recorded of the Bowen ratio is indicative of the marked difference between morning (usually cool and moist) and afternoon (dry) surface conditions, thereby increasing the magnitude of the ratio to close to unity. Generally the values of the Bowen ratio obtained fell within the range that is typical of the humid tropical areas (Oke, 1987).

In Fig. 5 is shown the day-to-day variations of the mean surface energy balance for the daytime (R_n >>0) for the period of our investigations. It can be observed that from the surface energy balance, both the net radiation and the latent heat flux showed large daily fluctuations. This is ascribed to the large influences of the tropical clouds had on radiative fluxes. Both the sensible and ground heat fluxes were similarly affected but to lesser magnitudes. The period means obtained for the surface fluxes : net radiation, ground heat flux, sensible heat flux, and the latent heat flux were: 351.11 ± .49.47 Wm^{-2}, 93.88 ± 22.66 Wm^{-2}, 88.86 ± .30.14 Wm^{-2} and 168.35 ± .36.20 Wm^{-2}, respectively.

5. Conclusions

At Ile-lfe, Nigeria, which is a humid tropical location, the early morning sky in October/November is often misty or cloudy (stratus, 6-8 oktas). It has been observed that in the early mornings, the latent heat is the dominant convective heat flux (about 300- 400 Wm^{-2}) and can be 5 times the magnitude of the sensible heat (the Bowen ratio was 0.2-0.4). The large latent heat flux is a good reason for development of clouds (cumulus) which may develop fully into local thunderstorms by the late afternoons.

The radiative fluxes and hence, the surface energy balance are severely influenced by the varying convective cloud cover. The fluctuation in the magnitudes of surface energy balance (daytime) at the location is also linked to the soil wetness, air temperature and humidity. Of all these factors, the cloudiness appeared as the most dominant factor (Beringer and Tapper, 1998).

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