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Bowen ratio determination of sensible and latent heat fluxes in a humid tropical environment at Ile-Ife, Nigeria

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सार - धरातल के समीप की संवेद्यी उष्मा और गुप्त उष्मा के फलस्कों का व्यापक रूप से आकलन करने के लिए, संकल्पनात्मक रूप से उपयुक्त और उपस्करों की वांछित सुगमता से युक्त बोएन अनुपात ऊर्जा संतुलन (बी.आर.ई.बी.) पद्धति का सर्वाधिक उपयोग किया जाता है। हमने यहाँ इसी तकनीक को Ile-Ife, नाईजीरिया (7° 33' उ., 4° 34'पू.) में 7 और 10 मार्च 1999 के बीच आर्द्र उष्णकटिबंधीय क्षेत्रों में सामान्य मृदा में उपलब्ध मापी गई ऊर्जा (नेट विकिरण और मृदा उष्मा फलस्क) के विखडंन का अध्ययन करने के लिए अपनाया है। धरातल की परिवर्तनशील स्थितियों (अध्ययन) के संदर्भ में दोनों फलस्कों के दैनिक परिवर्तनों से प्राप्त परिणाम काफी संतोषजनक रहे हैं। शुष्क दिनों में संवेद्यी उष्मा फलस्क तुलनात्मक रूप से गुप्त उष्मा फलस्क के परिमाण के समान ही पाए गए हैं किन्तु आर्द्र धरातल की स्थितियों में यह लगभग 10 से 60 प्रतिशत तक की कमी पाई गई है। इस अध्ययन से यह स्पष्ट है कि उष्णकटिबंधीय वन क्षेत्रों में सामान्य रूप से पाई जाने वाली आर्द्र स्थितियों में ऊर्जा संतुलन के संबंध में विकिरण के बाद वाष्पीकरण दूसरा महत्वपूर्ण कारक है। संक्रमणकालीन (सूर्योदय अथवा सूर्यास्त के समय) कुछ घटनाओं को छोडकर जब ग्रेडिएंट, विशेषकर आर्द्रता के, अत्यंत कमज़ोर होते हैं तब विद्यमान मौसमी स्थितियों के बावजूद यह तकनीक दिन और रात में संतोषजनक रूप से कार्य करती है।

ABSTRACT. The Bowen ratio energy balance (BREB) method is the most widely used for estimating the fluxes of sensible heat and latent heat near the surface largely because of its conceptual simplicity and the robustness of instrumentation required. We have adopted the same technique here to study partitioning of measured available energy (difference of net radiation and soil heat flux) over bare soil at a humid tropical location in Ile-Ife, Nigeria (7° 33′ N, 4° 34′ E) between 7 and 10 March, 1999. Results obtained of the diurnal variations of the both fluxes in relation to the changing surface conditions (case studies) are quite satisfactory. For dry days, the sensible heat flux is comparatively of the same magnitude as the latent heat flux but it is less, about 10-60% for the wet surface conditions. It is clear from the present study that for the tropical forest zone, evaporation is the next important factor after radiation in the energy balance due to the humid conditions that usually prevail. Except for the few instances when very weak gradients exist, particularly of moisture, during transition periods (at sunrise or sunset), the technique has worked satisfactorily for day as well as night time periods regardless of prevailing weather conditions.

Key words – Bowen ratio, Surface energy budgets, Humid tropics, Ile-Ife, Nigeria.

1. Introduction

Accurate measurements (short and long-term) of surface sensible and latent heat fluxes are often required for research and applications in weather and climate modelling, agriculture and hydrology. The eddy correlation (EC) method is the most accurate and straightforward (direct) technique available to measure these surface fluxes (Kaimal and Finnigan, 1994). But for routine applications the EC technique is not so feasible because of the nature of the instrumentation required, which are quite expensive and delicate to maintain in view of the long-term applications. And as such, other robust methods like the Bowen ratio energy balance (BREB) technique do exist which can easily be employed to estimate these fluxes (indirectly) from measurements of net radiation, soil heat flux, and temperature and moisture gradients observed near the surface.

Commonly, the surface energy budget is investigated based on the law of conservation of energy. This may be expressed simply as:

$$R_n = H + LE + G + \Delta S \qquad (1)$$

In Eqn. (1), R_n is the net (all-wave) radiation flux, H is the sensible heat flux; LE is the latent heat flux; G is the soil heat flux, and ΔS is the change of heat storage within the interfacial layer where energy exchange is taking place (*i.e.* from the level which the soil heat flux plate is buried to the ground surface). This quantity can be estimated from the relationship (Oke, 1987):

$$\Delta S = \frac{C_s \, . \, d.\Delta \overline{T}_s}{\Delta t} \qquad (2)$$

where C_s is the estimated heat capacity of the soil (in $Jm^{-3}K^{-1}$), d is the layer depth (in m), and ΔT_s is the change of average temperature in the soil layer above the heat flux plate and Δt is the time interval (in this case, the time period selected here is 10 mins. or 600 secs.). Inclusion of the storage term in the surface energy balance equation [given in equation (1) above] is significant since typically ΔS is about 5% of R_n (Snyder *et al.*, 2000). Foken *et al.* (1999) have obtained maximum values of about 100 – 140 Wm^{-2} for the storage. Combining the soil heat flux, G (measured at a depth d, which in this case was 2 cm) with the change in storage, ΔS, we can write the ground heat flux G^* as :

$$G^* = G + \Delta S \qquad (3)$$

and hence, the energy balance Eqn. (1) now takes the familiar form as:

$$R_n = H + LE + G^* \qquad (4)$$

The BREB method works simply by first determining a ratio of sensible heat to moisture flux in the surface layer (defined as the Bowen ratio, β) which in the bottom 20m or so of the atmosphere, is proportional to the ratio of the vertical gradients of temperature and moisture respectively.

That is,

$$\beta = \frac{H}{LE} \cong \gamma \frac{\Delta T}{\Delta q} \qquad (5)$$

where γ is the psychrometric constant (0.4 $g/kg.K^{-1}$). ΔT and Δq are the differences of air temperature and specific humidity respectively (must be measured between the same pair of heights). The estimated Bowen ratio in Eqn. (5) is then taken with the simultaneous measurements of net radiation and ground heat flux (the difference $R_n - G^*$, which is the available energy) in Eqn. (4) to calculate the sensible heat flux, H as

$$H = \frac{\beta(R_n - G^*)}{1+\beta} \qquad (6)$$

and the moisture flux, LE as

$$LE = \frac{(R_n - G^*)}{1+\beta} \qquad (7)$$

For an extended review of the BREB method and its comparison with other techniques, see the papers by Fritschen and Simpson (1989), Malek (1993) and Barr *et al.* (1994). The BREB method has become quite popular for studying the partitioning of available surface energy over various types of underlying surfaces (Lindroth and Halldin, 1990; Malek *et al.*, 1992). Its main advantages lie in its use of robust sensors allowing for continuous long time gradient measurements (requiring only two levels of observations) of only the air temperature and humidity and in low-fetch situations (Heilman *et al.*, 1989). However, flux estimates obtained by the BREB technique can be quite erroneous when the temperature and humidity gradients are very small (*e.g.* at dusk or dawn). Foken *et al.* (1997) have shown that for psychrometric measurements with typical accuracy of ±0.05°C, the temperature differences, $\Delta T < 0.1°$ C are prone to give substantially large errors (up to ±50%) of the estimated sensible and latent heat fluxes, especially when $LE >> H$. Hence we have imposed the condition that if $\Delta T < 0.1°$ C, then such data is not accepted. The BREB method fails generally when the β value is close to –1 and to eliminate such data, the criteria given by Ohmura (1982) is adopted whereby all values in the range, $-1.25 < \beta < -0.75$ (Tanner, 1988) are rejected. Furthermore, errors in the estimations of the surface fluxes by the BREB method can be reduced substantially if the upper and lower levels of measurements are so chosen such that the ratio $z_2/z_1 \sim 4\text{-}8$ (Foken *et al.*, 1997). A condition of strong advection is

TABLE 1

Instrumentation deployed during the conduct of the field study

Parameters	Device	Heights (m)	Manufacturer
Wind speed	Cup anemometer (A101ML)	1.47	Vector Instr., U.K.
Wind direction	Wind vane (W200P)	3.39	Vector Instr., U.K.
Wet and dry-bulb temperature	Psychrometer	0.37, 1.56	Theodor Friedrichs, Germany
Surface temperature	Infrared pyrometer (KT2D15.82)	1.13	Heitronics, Germany
Soil temperature	PT-100Ω	(-.02), -0.05, -.10, -.20	Thermometerwerk, Germany
Air pressure	Barometer (P6520)	1.40	Ammonit, Germany
Soil heat flux	Heat flux plates (HP3/CN3)	(-.02), -0.05, -.10, -.20	McVans Instruments, Australia
Net-radiation	Net radiometer (Q-7, REBS)	1.22	Campbell Scientific, USA

also a major limitation with the use of this technique (Dugas *et al.*, 1991).

A methodical problem with adoption of the BREB technique is that a priori, it is based on the assumption that the balance of the energy terms (in Eqn. 4) always holds irrespective of the surface conditions. However, recent results have indicated that an imbalance (non-closure) of the energy budget at the surface can exist due to measurement errors and influence of different footprints on the individual fluxes (Foken *et al.*, 1993; Foken and Oncley, 1995).

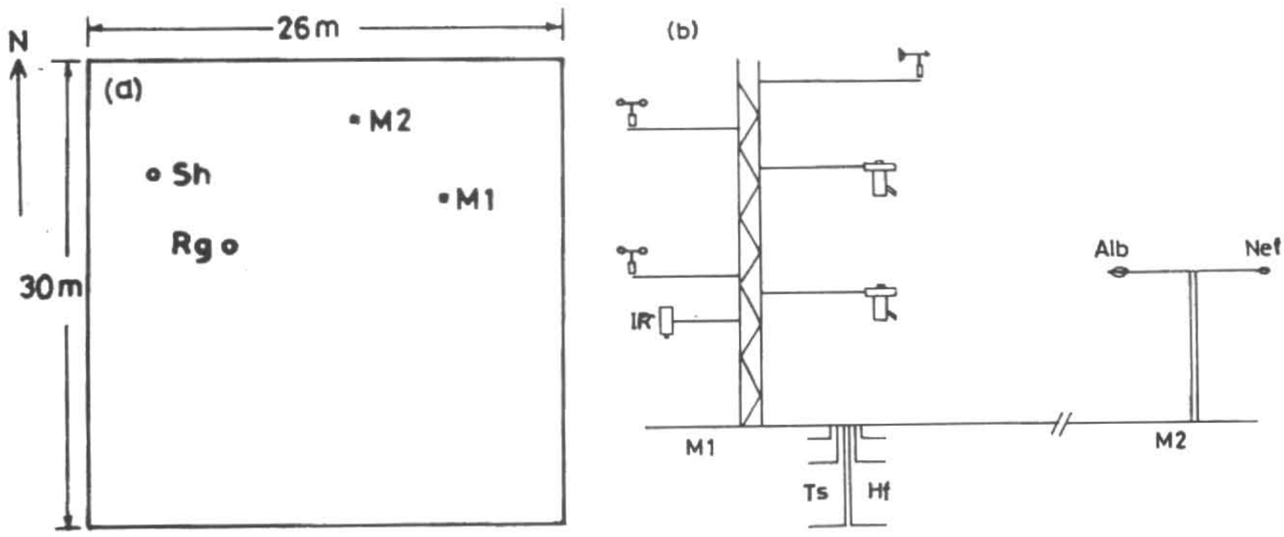
This paper presents some preliminary results obtained of the surface energy budgets: R_n, H, LE, and G^*, as measured by the Bowen ratio energy balance (BREB) method between 7-10 March, 1999. The field measurements were carried out at an experimental area located in Ile-Ife, Nigeria. The environmental conditions during the observation period were typified by generally weak surface winds (mean wind speed less than 1.5ms^{-1}), humid and strong insolation. Our main objective was to observe partitioning of the available energy at the surface in a humid tropical environment into sensible and latent heat fluxes and to ascertain whether it is in conformity with the prevailing weather situation and the ground surface conditions.

2. Site and instrumentation

An enhanced Bowen ratio system was set up at a site within the campus of Obafemi Awolowo University at Ile-Ife, Nigeria (7°33′ N, 4°34′ E). This location is in the tropical forest zone of West Africa. Thereby it experiences a climatic pattern of alternating rainy (April – October) and dry (November – March) seasons. The change of season occurs in association with the meridional movement of the Inter-Tropical Discontinuity (ITD) line which demarcates at the surface the warm and moist (maritime) southwesterly flow from the hot and dry (continental) northeasterly winds (Hastenrath, 1991).

The Bowen ratio energy balance (BREB) field measurements were conducted in phases beginning as from October 1998. The data presented here was for the month of March 1999 which was about the beginning of the monsoonal rains in the area. The measurement surface was a clearing (bare soil) of about 30 × 25 square meters in area which was maintained so throughout the observation period. The topsoil at the site was sandy soil, the estimated heat capacity, $C = 1.49 \pm 0.11 \times 10^6$ Jm^{-3}K^{-1} (Abimbola, 2000) and beneath was the loamy clay (lateritic) soil. The soil surface albedo at the site was previously estimated and the values obtained ranged between 0.12 and 0.16, depending largely upon the soil moisture content (that is, wetness of the surface).

The Bowen ratio system used comprised of high-sensitivity transducers (for such variables as air temperature, wind speed, soil heat flux, etc) all with response times of less than 30 sec. These devices included psychrometers (electrically aspirating air), photoelectronic light weight cup anemometers, a potentiometric wind vane, an infrared radiometer, a net radiometer, soil heat flux plates, steel encapsulated (platinum resistance wire) soil thermometers and a capacitive barometer. The



Figs. 1(a&b). (a) Schematic layout at the measurement site (M1 = mast #1, M2 = mast #2, Sh = sunshine hour recorder, Rg = rainguage) and (b) Measurement configuration (for positioning see fig.), Ts = soil thermometer, Hf = heat flux plate, IR = infrared thermometer, Alb = albedometer, Net = net radiometer

manufacturers specifications, model identification numbers for the devices and their assigned levels (or depths) of measurement are listed in Table 1. The temperature and moisture gradients were measured by a pair of psychrometers (PT- 100Ω) wired in a bridge circuit (accuracy, $\Delta T = \pm 0.05$°C). Both the heat flux plates and the temperature probes were carefully buried in the ground without disturbing much of the surrounding soil. The ground heat flux at the interface was taken to be the soil heat flux measured at a depth 2cm and added to it was the energy storage estimated in the layer between the surface and 2cm. A Campbell Scientific datalogger (measurement and control unit, model CR10X) was then used to facilitate data reduction and storage. A schematic diagram for the measurement array for the enhanced Bowen ratio system is shown in Fig. 1.

3. Data

The above mentioned instrumentation provided continuous data (as time series) for the whole period under investigation at specified measurement heights (Table 1) of the following micro-meteorological parameters: wind speed and direction, wet and dry bulb temperature, surface temperature, soil temperature, net radiation, soil heat flux, air pressure, and vapour pressure. All measurements were sampled every 30 sec (10 sec for wind speed) and subsequently stored as 10-min averages in the data logger.

During the period of observation (7 – 10 March, 1999), the surface wind flow in the area was weak (the mean wind speed, $\overline{u}$ < 1.5 ms^{-1}) which generally is typical of the tropical areas. That is, no strong advective conditions persisted except during the singular incidence of a passage of a squall in the evening (about 20:00 hrs) of 8 March. The daily air temperature maximum was about 35° C and very humid (RH > 80%) for most times. The solar heating at about the local midday were usually intense and as such, the afternoons were frequently convectively unstable (lapse rate < -1.9°C/100m, P-G-T class A). Convective-type clouds (*e.g.*, cumulus, stratocumulus) were observed in the sky during the late mornings and afternoons as well. The local weather summary as recorded for the study period is presented in the Table 2.

For the four days considered in this study, the data for the partitioning of the available energy at the surface is presented. Whereas the net radiation and the ground heat flux were directly measured using the appropriate instrumentation, both the sensible and latent heat fluxes have been estimated from values of the Bowen ratio, β. Since we are looking at energy budgets over a bare soil surface mostly in weak advective conditions, it is assumed here that the imbalance (non-closure) of the terms given in Eqn. 4 is negligible.

TABLE 2

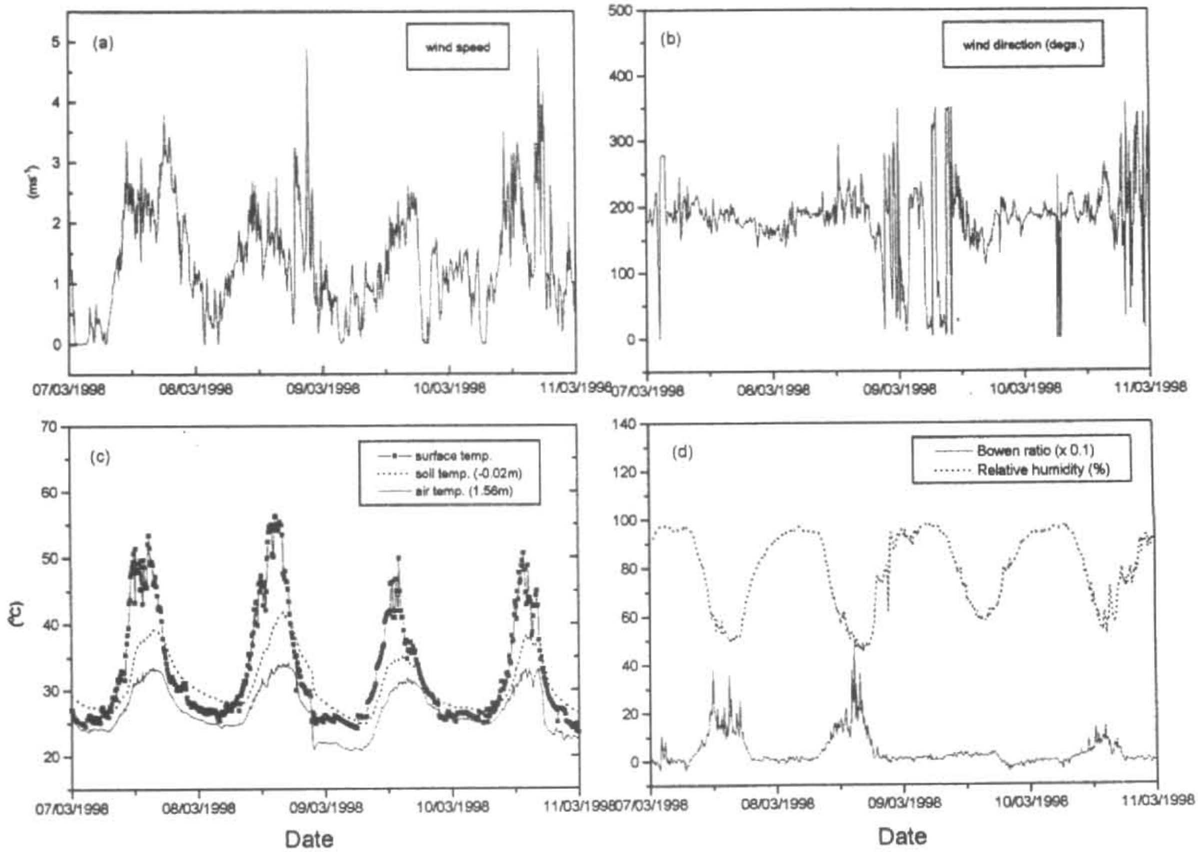
Observed weather conditions at the measurement site : 07-10 March, 1999

Date	0700 hrs	0900 hrs	1200 hrs	1500 hrs	1800 hrs	Overnight
07 March	Stratus (8/8 oktas)	Stratus (4/8 oktas), Cumulus/Strato-cumulus (5/8 oktas)	Cumulus/Strato-cumulus (5/8 oktas)	Cumulus/Strato-cumulus (5/8 oktas) Altostratus (6/8 oktas)	Cumulus/Stratocumulus (3/8 oktas) Altostratus (6/8 oktas)	Dry
	Cool and dry calms	Warm and dry Weak surface wind	Warm and dry Moderate surface wind	Warm and dry Moderate surface wind	Cool and dry Moderate surface wind	
08 March	Stratus (8/8 oktas)	Stratus (7/8 oktas), Stratocumulus (5/8 oktas)	Cumulus/Strato-cumulus (6/8 oktas)	Cumulus/Strato-cumulus (5/8 oktas) Cirrus (3/8 oktas)	Cumulonimbus-9 (3/8 oktas), Cirrus (3/8 oktas)	Squally weather accompanied by heavy pptn. 2125-2215 hrs (IST)
	Cool and dry Weak surface wind	Warm and dry Moderate surface wind	Warm and dry Moderate surface wind	Hot and dry Moderate surface wind	Cool and dry Gusty surface wind	
09 March	Stratocumulus (3/8 oktas), Altostratus (8/8 oktas)	Stratocumulus (5/8 oktas), Altostratus (7/8 oktas)	Cumulus/Strato-cumulus (5/8 oktas) Altostratus (6/8 oktas)	Cumulostratus (5/8 oktas), Altostratus (7/8 oktas)	Altostratus (7/8 oktas), Cirrus (5/8 oktas)	Dry
	Weak surface wind Wet surface (12mm pptn.)	Weak surface wind Wet surface	Weak surface wind Cool and dry	Warm and dry Moderate surface wind	Weak surface wind Cool and dry	
10 March	Stratus (8/8 oktas)	Stratus (3/8 oktas), Cumulus/Strato-cumulus (6/8 oktas)	Cumulus/Strato-cumulus (5/8 oktas)	Cumulus/Strato-cumulus (7/8 oktas) Cumulonimbus-9 (3/8 oktas)	Cumulus/Stratocumulus (7/8 oktas) Cumulonimbus-9 (3/8 oktas)	Dry
	Weak surface wind Cool and dry	Weak surface wind Cool and dry	Moderate surface wind Cool and dry	Weak surface wind Light drizzle (Trace)	Gusty Wet surface	

4. Results and discussions

In the early morning of 7 of March when this case study began, the surface (bare soil) was cool (about 21°C) and dry, while the sky was completely covered by low level stratus clouds. Later on at about 0900 hrs (IST), the cloud cover changed to cumulus/stratocumulus (5/8 oktas). Initially the wind was nearly calm at the surface but by the late morning it increased to about 2.5 ms^{-1} but it was unsteady [Fig. 2(a)]. From the wind direction trace, it can be observed that the surface wind was predominantly southerly [Fig. 2(b)], which is expected for the time of the year due to the southwesterly monsoon. On that day, in association with the intense solar radiation received at the surface, the ground quickly heated up (as can be observed in Fig. 2(c) so that by afternoon the surface temperature rose up to 55° C whilst the maximum soil temperature recorded at the 5 cm soil depth was 39° C at about 1540 hrs (IST). The air temperature (measured at 1.56m) also increased accordingly reaching about 33° C by the midday. The relative humidity trace in [Fig. 2(d)] showed that the environment was very humid especially early in the morning and at nighttime (RH ~ 100%).

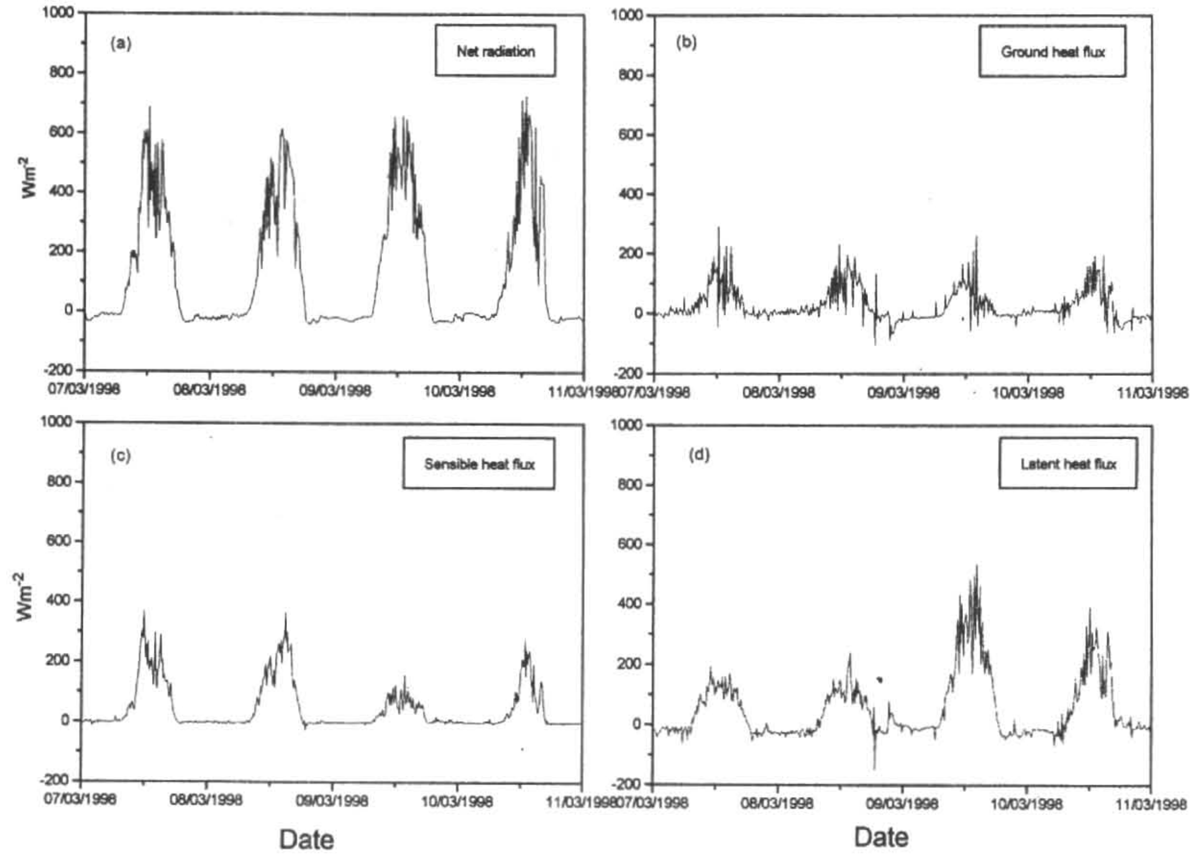
From the 10-min. averages of air temperature and humidity gradients, the Bowen ratio (β) values were determined for the 7 March. The Bowen ratio trace in Fig. 2(d) showed that the early morning [roughly between 0200 and 0700 hrs (IST)] and nighttime of that day, the values of the ratio obtained were negligibly small (β~0). This observation is supported by the time series in Figs. 2(c&d) that air temperature and humidity were nearly constant (very small gradients) about that period. The estimated values of the sensible heat obtained for the same period shown in Fig. 3(c) were negative and almost insignificant (in fact, the magnitude of H was less than



Figs. 2(a-d). Time series of meteorological parameters (a) wind speed, (b) wind direction, (c) soil, surface and air temperatures and (d) Bowen ratio (β) for the period : 7–10 March, 1999

5 Wm^{-2}) whereas the latent heat flux was up to about 40 Wm^{-2} (and also negative). Thereabout, negative net radiation values (about -20 Wm^{-2}) were recorded Fig. 3(a) and which was responsible for the radiative heat loss from the surface. Within the same period, the ground heat flux in Fig. 3(b) was observed to be positive and with the magnitude of less than 10 Wm^{-2}. Thus from the energy balance equation (4), it suggests that the energy loss from the surface (as the net outgoing radiation) was compensated for mainly by the latent heat released during the process of dew formation. It should be noted here that relative humidity at about early morning/evening was almost 100% and as such the atmospheric stability (negative lapse rate) which plays a significant role in partitioning of the surface energy budget. This effectively caps the moist air close to the surface thereby enhancing condensation.

During the daytime on 7 March, values of the Bowen ratio obtained were such that $\beta > 1$ [Fig. 2(d)] thus indicating that the sensible heat was larger than the latent heat ($H > LE$). Figs. 3 (c&d) shows the diurnal course of surface energy budget terms: net radiation, latent heat flux, and ground heat flux for 7 March. Between 1200 and 1600 hrs (IST), the sensible heat was about a factor of two that of the magnitude of the latent heat flux. In Fig. 3(a) it can be observed that the net radiation reached up to 700 Wm^{-2} by the local midday despite prominence of cumulus/stratocumulus clouds (5/8 oktas) which caused intermittence in the total penetration of solar radiation to the surface and the ground heat flux was also considerable (peaked to about 100 Wm^{-2}). The daytime condition does suggest that despite the cloudiness (which was evolving) there was considerable heat exchanges at the surface (occurring both by conduction and convection) which



Figs. 3(a-d). Time series for the surface energy balance components: (a) net radiation, (b) ground heat flux, (c) sensible heat flux and (d) latent heat flux measured at the location for the study period: 7–10 March, 1999

were well manifested as sensible and latent heat output into the environment. The implication of the strong lapse rate near the surface is that the atmosphere became very unstable in the afternoon and as such vertical movement of the eddies (buoyancy) was enhanced.

The weather situation that was observed for the early morning of 8 March is similar to that of the previous day, that is, with predominance of cumulus/stratocumulus clouds (5/8 oktas). The Bowen ratio estimates obtained for 8 March is shown also in Fig. 2(d). Due to the warm and dry daytime conditions, it was observed that mostly $\beta > 1$ (which implies that $H > LE$). The partitioning of the surface energy terms for the 8 of March shows that in Fig. 3 the daytime values of latent heat flux was 10-50% that of the sensible heat flux. Thus indicating that the available energy at the surface was mostly converted into sensible heating. By the evening [at about 1800 hrs(IST)], the surface winds became moderate (wind speed ~ 3.0 ms^{-1}) with the occasional breaking of gusts. A sharp drop in air temperature and corresponding increase in relative humidity accompanied it at the same time. This condition was followed by development of cumulonimbus clouds (3/8 oktas) which appeared together with cirrus clouds (3/8 oktas). This later developed into a squall as can be noticed by a rapid increase of wind speed (gusty conditions) in Fig. 2(a) which passed over the area at about 2125 hrs (IST). Correspondingly the wind direction was also observed as very unsteady at this time [Fig. 2(b)]. This stormy weather was accompanied by a heavy precipitation (but of short duration, lasting about 40 min.). By the time when the precipitation event occurred (in the late evening of 8 March), estimated Bowen ratio values fell almost to zero [as in Fig. 2(d)]. It can be observed in Fig. 3(b) that the precipitation brought about a sharp drop in the magnitude of the ground heat flux and in fact it turned to negative values at about 2100 hrs (IST). The downpour at the surface somewhat quenched the heat build up within the topsoil thereby making the surface colder than the layer beneath [Fig. 2(c)].

By the early morning of the 9 March, due to the heavy precipitation that occurred overnight, the ground surface (bare soil) was in a very wet condition. The sky conditions were such that clusters of low-level clouds (stratocumulus, 3/8 oktas) together with a complete cover of the altostratus were seen. In Fig. 3(a) though the net radiation did peak up to a value of 650 Wm^{-2} at about the midday of 9 March, the ground heat flux in the early morning did not rise to any significant values till about 0800 hrs (IST). So that the ground warmed slowly through the morning hours with the positive flux reaching a maximum of about 70 Wm^{-2} around 1100 hrs (IST). The weak heating of the ground is because of the initially wet surface so that only a small amount of the solar radiation input goes into heating the air (sensible heat) and the ground, while most of it is used to evaporate moisture (resulting in cooling of the surface). As the air temperature rises, relative humidity decreases and so evaporation increases. Most of the available energy at this period is used for evaporation, hence, larger values of latent heat flux observed.

For the daytime of 9 March, partitioning of the available energy at the surface was rather dramatic in the sense that it has changed from the typical pattern recorded on the preceding days (7 and 8 March). It can be observed in Figs. 3(c&d) that throughout the day, latent heat was more dominant than sensible heat ($LE > H$). Though the net radiation was considerable (maximum value about 700 Wm^{-2}) for that day, but relatively it was a cooler day with the maximum air temperature and ground surface temperature about 32° C and 40° C respectively. This situation is attributed to the very wet nature of the surface at that time which suggests that the available energy ($R_n - G^*$) mostly was utilized to evaporate moisture from the surface. It is noteworthy that at about 1600 hrs (IST) on the 9 March, the Bowen ratio values became negative, which coincided with a temperature drop.

Also during the transition periods (Fig. 3) it can be observed that H is less than LE at the site. The magnitudes of the sensible and ground heat flux were found to be nearly the same and both were far less than values of the latent heat flux. For the 9 March, by 1730 hrs (IST), the values of Bowen ratio in Fig. 2(d) showed to be small and negative. In the evening, as from 2000 hrs (IST), due to the very humid conditions (RH ~ 90%), the radiative heat loss (about 45 Wm^{-2}) is compensated mainly for by latent heat flux (about 70 Wm^{-2}) through condensation.

By the early morning of 10 March, the ground surface was relatively dry compared to the same period of the previous day. The sky cover was mainly of stratus clouds together with low level cumulus clouds (6/8 oktas). For this same period, estimated sensible heat flux was insignificant in magnitude while the available energy recorded was about -25 Wm^{-2}. This magnitude of the radiative heat loss at the ground surface was compensated for by the latent heat flux.

By the midday and into the afternoons, due to the dry conditions of the surface and intense solar heating, both the sensible heat and latent heat flux were observed to have risen significantly to about 200 Wm^{-2} and 300 Wm^{-2} respectively (Fig. 3). For the same period, the ground heat flux increased considerably to about 100 Wm^{-2}. The value of the Bowen ratio is positive and ranges between 0 and 1.

5. Conclusions

A day-by-day study of partitioning of the surface energy fluxes for our chosen site (humid tropical area) has supported the assertion that the surface energy budget is governed by the surface conditions. It was found that with changing surface conditions (as in this case wetness due to precipitation) the energy budget can vary considerably from day to day (even, from hour to hour) between the relative magnitudes of the sensible and latent heat fluxes (β value is highly variable). For example, for a sunny day that follows an overnight precipitation, the latent heat flux during the daytime was found to be about a factor of two more than sensible heat flux. It is then clear from the present study that in the tropical forest zone, that after radiation, evaporation was the most important factor in the energy balance due to humid conditions. For dry days, the sensible heat flux is comparatively of the same magnitude and the latent heat flux. Due to intense solar heating of the surface the ground heat flux was considerable (reaching about 100 Wm^{-2} on dry days) at this site. Generally for the tropical climates, during the dry season H is larger than LE, but during the wet season the opposite is the case (Kraus and Alkhalaf, 1995; Verhoef, 1995).

It has been demonstrated here (and also elsewhere) that the Bowen ratio energy balance method offers a simple and practical technique to determine the surface fluxes. The wetness of the surface is also important in the sense that it influences considerably the partitioning of the available energy, $(R_n - G^*)$. The net radiation is observed to strongly affected by cloudiness and to a lesser extent, the surface albedo; the ground heat flux by the soil moisture, while the available energy directly determines H and LE. The atmospheric stability also plays a role in determining whether the fluxes are enhanced or suppressed. Due to the rapidly evolving nature of the convective clouds which are prominent especially in the daytime, there are marked short-term fluctuations observed in time series of all the surface fluxes (though less for the ground heat flux).

The knowledge of energy budget is of primary importance in understanding the exchange processes and mechanisms at the surface. For example, to model land surface-atmosphere interactions in global circulation models, we need to include truly representative measurements of these surface fluxes as input in order to obtain more realistic predictions from such models. Therefore it is envisaged that the data from our present study area (humid tropical climate) will contribute towards meeting such demands.

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