Bowen ratio estimation of surface energy fluxes in a humid tropical agricultural site, Ile-Ife, Nigeria

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The Bowen ratio energy balance (BREB) is a micrometeorological technique often used for estimating the surface energy fluxes (i.e. latent heat, sensible heat fluxes) because of its simplicity, robustness, and affordability. The same method has been applied in this study to partition the available energy \( (R_n - G) \) at a humid tropical agricultural site in Ile-Ife, Nigeria \( (7°33'N, 4°33'E) \) during the transition period (wet and dry) between 25 and 29 Feb. 2004. Results obtained for the diurnal variations of the energy fluxes in relation to changing surface condition are satisfactory. For the relatively dry days, the sensible heat flux is comparatively of the same magnitude as the latent heat flux except on a day when it was a little higher, but it is less during the wet days. It is therefore obvious from this study that for a tropical weather, evaporation is the next essential factor after radiation in the energy balance due to the prevailing humid conditions in the zone.

Keywords: Bowen-ratio, Surface energy balance, Humid tropics, Ile-Ife, Nigeria

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1 Introduction

Many field studies in topics such as micrometeorology, micrometeorology, and hydrology require reliable and continuous measurement of the surface fluxes of sensible and latent heat. The eddy-correlation technique is generally considered the most accurate method¹,² for these measurements, but considerations of cost and ruggedness of sensors often restrict its use to basic research studies. In applied studies therefore, it is often common to use other robust and indirect methods like the Bowen ratio energy balance (BREB) method that uses time-averaged measurements of temperature and humidity profiles in the surface boundary layer for the estimation of these fluxes.

The Bowen ratio, \( \beta \), is expressed in the form

\[
\beta = \frac{H_s}{H_L} \approx \frac{\gamma \Delta T}{\Delta q}
\]

(1)

by approximating the fluxes by the temperature and humidity gradients. In Eq. (1), \( \gamma \) is the psychrometric constant (0.4 g/kg K\(^{-1}\)); \( \Delta T \) and \( \Delta q \) are the differences of air temperature and specific humidity respectively (measured at same heights).

Commonly, Eq. (1) is used to calculate the sensible and the latent heat by combining with the surface energy balance simply as

\[
R_n = H_s + H_l + G + \Delta s
\]

(2)

where \( R_n \) is the net radiation, \( H_s \) the sensible heat flux; \( H_l \) the latent heat flux; \( G \) the soil heat flux and \( \Delta s \) the change of heat storage within the interfacial layer where energy exchange is taking place.

The quantity, \( \Delta s \), can be determined from the relationship³

\[
\Delta s = \frac{C_s d \Delta \overline{T}}{\Delta t}
\]

(3)

\( C_s \) being the estimated heat capacity of the soil (Jm\(^{-3}\)K\(^{-1}\)), \( d \) the layer depth (in m); \( \Delta \overline{T} \) the change of average temperature in the soil layer above heat flux plate and \( \Delta t \) the time interval (in this case, the time is 1800s). Addition of the storage term in the surface energy balance is significant⁴ because typically, \( \Delta s \) is about 5% of \( R_n \). Foken⁵ have obtained maximum values in the range of 100-140 Wm\(^{-2}\) for this term. Combining the soil heat flux, \( G \) (measured at a depth
The ground heat flux, $G_s$, can be written as

$$G_s = G + \Delta s$$ \hspace{1cm} (4)

and subsequently the energy balance term Eq. (2) can be rewritten as

$$R_n = H_S + H_L + G_s$$ \hspace{1cm} (5)

The calculated Bowen ratio in Eq. (1) is combined with the measurements of net radiation and ground heat flux to calculate the sensible heat flux, $H_S$ as

$$H_S = \frac{\beta (R_n - G_s)}{1 + \beta}$$ \hspace{1cm} (6)

and the evaporative flux, $H_L$, as

$$H_L = \frac{(R_n - G_s)}{1 + \beta}$$ \hspace{1cm} (7)

For more details about the use of BREB method and comparison with other techniques, see papers by Atsumu [Ref 6]; McCaughhey [Ref. 7] and Todd [Ref. 8], etc.

The Bowen ratio method has been used to quantify water use\(^8\), calculate crop coefficients\(^9\)\(^10\) and investigate the plant-water relation\(^11\)\(^12\). Its advantages include straight-forward simple measurements, with no information required on the aerodynamic characteristics of the surface. It can integrate heat fluxes over a large area (hundreds to thousands of square meters), estimate fluxes on fine time scales (less than 1 h) and provide continuous, unattended measurement. The disadvantages include sensitivity to the biases of instrument which measure gradients and energy balance terms\(^8\) and the possibility of discontinuous data when the ratio approaches $-1$. To eliminate such data, the criteria given by Atsumu\(^6\) was adopted, and the requirement common to micrometeorological methods of adequate fetch was adopted to ensure adherence to the assumption of the method.

This paper presents some preliminary results obtained of the surface energy budgets: the net radiation, $R_n$, the sensible heat, $H_S$, the latent heat, $H_L$, and the ground heat flux $G_s$, as measured by the Bowen ratio energy balance (BREB) method between 25 and 29 Feb. 2004. The field measurements were carried out at an agricultural teaching and research farm located in Ile-Ife, Nigeria ($7^\circ33'$N, $4^\circ33'$E). The mean wind speed during the period was approximately 1.5 m/s. It was a transition period between dry and wet season, and thus humid with strong insolation. The main objective was to quantitatively determine the magnitude of the terms of the energy balance equation for conditions peculiar to a tropical (wet and dry) area, as is typical for the south-western part of Nigeria.

2 Site and instrumentation

This study was conducted at the agricultural teaching and research farm situated within the campus of Obafemi Awolowo University, Ile-Ife, Nigeria ($7^\circ33'$N, $4^\circ33'$E), between 15 Feb. and 10 Mar. 2004. The main project was the first Nigerian Micrometeorological Experiment, dubbed the acronym, NIMEX-1, a partnership research project between five institutions, namely the Department of Physics at Obafemi Awolowo University in Ile-Ife; the Department of Physics at the University of Ibadan in Ibadan; the Department of Meteorology at the Federal University of Technology in Akure and the African Regional Center for Space and Science and Technology Education in English also at the Obafemi Awolowo University, Ile-Ife and the Department of Micrometeorology of the University of Bayreuth in Germany.

The primary objective of the study was to determine the surface energy balance for conditions of a tropical (wet and dry) area. The summary of the achievements of the NIMEX-1 experiment can be found in Jegede\(^13\). A Bowen ratio system was set up at a farm site which spans about 1400 ha, and the area that was investigated for the experiment has the dimensions approximating 1000m×300m. The surface roughness length varied during the period of observation, from about 0.5 cm to 3 cm. The estimated heat capacity at the site was $1.56\pm0.19$ Jm\(^{-3}\)K\(^{-1}\) [Ref. 14]. The soil surface albedo at the site ranged between 0.16 and 0.20, depending on the soil surface wetness\(^13\).

By climatological classification, Ile-Ife is situated within the tropical wet and dry belt of West Africa\(^5\)\(^16\). The seasonal pattern is monsoonal, such that there are alternating periods of wet (March/April-October) and dry (November-February) months. This change of weather is in association with the meridional movement of the International Tropical Discontinuity (ITD) lines, which demarcates at the surface, the warm and the moist (maritime) south-westerly flow from the hot and dry (continental)
north-easterly winds. The relative humidity for the area is about 80% in the mornings except in the dry season, when the figure drops to about 70%.

The system (BREB) comprised of a 15-m mast to measure the profiles of the mean wind speed and air temperature (wet and dry bulb) at various heights (see Table 1). The same mast also supported radiation sensors for the global and net radiation. Both the heat flux plates and the soil thermometers were buried in the ground carefully, so that the surrounding soil was left undisturbed. Other measurements made include the surface temperature, air pressure, and rainfall amount.

The instrumentation provided data (time series) for the whole period of experimentation for the following micro-meteorological parameters: wind speed and direction, wet and dry bulb temperature, net radiation, global radiation, soil temperature, surface temperature, air pressure and the soil water content. All the measurements were controlled by the use of two Campbell CR-10X dataloggers, which sampled the data every 1 second and stored as 1 min average values, for the whole period the observation lasted. A list of all the devices, measurement heights and the manufacturer are contained in Table 1. For more details about the experimental set-up and data processing see Ref. 13.

3 Results and discussion

The results presented here was from 25 to 29 Feb. 2004 (Julian day 56-60). For the five days considered, the data for the partitioning of the available energy at the surface are presented. The net radiation and the ground heat flux were measured while both the sensible and the latent heat fluxes have been estimated using the Bowen ratio technique. It is assumed that the imbalance (non-closure) of the terms given in the energy balance equation is insignificant.

In the early morning of 25 Feb. 2004 (day 56) when this case study started, the soil surface was warm and dry (about 32°C), and it was a cloudy morning with low level stratus cloud cover. There were slight showers of rain at about 0915 hrs LT. Initially the wind was calm but by late morning and afternoon it increased to about 2.2 ms⁻¹, by late evening the wind speed increased to about 3.5 ms⁻¹ [see Fig. 1(a)]. This was followed by a heavy rainfall but short-lived (30 min) at about 1930 hrs LT. As observed from the wind direction trace [Fig. 1(b)] the surface wind was southerly, and this is expected during this time of the year because of the south-westerly monsoon associated with the beginning of the wet season in the area. In response to the solar heating received at the surface that day, the surface temperature rose to about 48°C at about 1500 hrs LT whilst the maximum soil temperature recorded at 5 cm depth was about 40°C at about 1800 hrs LT [Fig. 1(c)]. The air temperature (at 0.9 m) reached about 37°C at about 1400 hrs LT. The relative humidity trace [Fig. 1(d)] showed that the environment was very humid, particularly in the morning and nighttimes (more than 90% for early morning and night times that day).

Figure 2 [(a)-(e)] shows the diurnal variation of the energy budget terms: net radiation, latent heat flux, the ground heat flux and the sensible heat flux. On day 56 the net radiation was about 420 Wm⁻² and the ground heat flux was peaked at about 100 Wm⁻².

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Device</th>
<th>Height, m</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed</td>
<td>Cup anemometer</td>
<td>0.7-14.8</td>
<td>Vector Instr., UK</td>
</tr>
<tr>
<td>Wind direction</td>
<td>Wind vane</td>
<td>14.8</td>
<td>Vector Instr., UK</td>
</tr>
<tr>
<td>Air temperature</td>
<td>Psychrometer</td>
<td>0.9, 4.9, 10</td>
<td>Theodor Friedrichs</td>
</tr>
<tr>
<td>Surface temperature</td>
<td>Infrared Thermometer</td>
<td>1.8</td>
<td>Heitronics</td>
</tr>
<tr>
<td>Soil temperature</td>
<td>PT-100 Ω</td>
<td>– 0.05, – 0.1, – 0.3</td>
<td>Campbell Scientific</td>
</tr>
<tr>
<td>Soil heat flux</td>
<td>Heat flux plate</td>
<td>– 0.02, – 0.05, – 0.1, – 0.3</td>
<td>Hukseflux</td>
</tr>
<tr>
<td>Soil moisture</td>
<td>Water content reflectometer</td>
<td>0-0.05</td>
<td>Campbell Scientific</td>
</tr>
<tr>
<td>Global radiation</td>
<td>Pyranometer</td>
<td>1.5</td>
<td>Kipp &amp; Zonen</td>
</tr>
<tr>
<td>Net radiation</td>
<td>Net radiometer</td>
<td>1.7</td>
<td>Kipp &amp; Zonen</td>
</tr>
<tr>
<td>Air pressure</td>
<td>Capacitive barometer</td>
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<td>Ammonit</td>
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<td>Turbulent flux</td>
<td>Ultrasonic anemometer</td>
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<td>Datalogger CR10-X</td>
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<td>Campbell Scientific</td>
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</table>
Fig. 1—Time series of meteorological parameters (a) wind speed (b) wind direction (c) surface, air, and soil temperature and (d) relative humidity/Bowen ratio for the period 25-29 Feb., 2004

Fig. 2—Diurnal variation of surface energy balance terms for (a) day 56 (b) day 57 (c) day 58 (d) day 59 and (e) day 60
There was a lot of intermittent blockage by clouds as can be observed from the trace [Fig. 2(a)]. Between 1200 and 1500 hrs LT the sensible heat was about a factor of three times higher than that of the magnitude of the latent heat. This condition thus suggests that despite the evolving cloudiness, there was considerable heat exchange at the surface (occurring both by conduction and convection) and this was manifested as sensible and latent heat output into the environment. The estimated values of the sensible heat obtained for the daytime on this day showed that the sensible heat flux was larger than the latent heat flux thus indicating that most of the available energy was converted to sensible heating [Fig. 2(a)]. The surface and weather condition observed for the early morning on 26 Feb. 2004 (day 57) was slightly different from that of the previous day, because of the late evening rain that occurred on 25 Feb. 2004 (day 56). The surface was colder (about 30°C) due to the soil wetness. The maximum surface temperature recorded for the day was about 46°C, despite the higher insolation received that day (about 600 Wm\(^{-2}\)) when compared to 420 Wm\(^{-2}\) of the previous day. The partitioning of the surface energy terms for 26 Feb. 2004 [day 57, Fig. 2(b)] show that the daytime values of latent heat was greater than that of the sensible heat, about 300 Wm\(^{-2}\) and 200 Wm\(^{-2}\), respectively. This indicates that the available energy at the surface was used for evaporation, rather than for sensible heating. The ground heat flux showed negative values [see Fig. 2 (b)] during morning and nighttime periods (about 50-80 Wm\(^{-2}\)).

By the evening at about 1930 hrs LT, there was a drop in air temperature and an increase in relative humidity. This weather condition was followed by cloud formation and increased surface winds, which subsequently was accompanied by a heavy violent and short-lived rainstorm at about 2025 hrs LT. This precipitation brought about a noticeable drop in the magnitude of the ground heat flux (≈120 Wm\(^{-2}\)). The surface was thus made colder (wetness) than the layer beneath, because of the heat build up within the topsoil that was quenched [Fig. 1(c)].

By the morning of 27 Feb. 2004 (day 58), the ground surface (bare soil) condition was wet due to heavy rainfall that occurred the previous night. The skies were covered with stratus clouds. Although the net radiation rose to about 450 Wm\(^{-2}\) [Fig. 2(c)] at about 1000 hrs LT on 27 Feb. 2004, the ground heat flux in the early morning did not rise to a significant value until about 1300 hrs LT. This indicates that only a small part of the solar heating goes into heating the air (sensible heat) and the ground, most of it is used up in evaporating the water in the soil surface (latent heat). Most of the available energy was used for evaporation as manifested in the trace of these fluxes this particular day [Fig. 2(c)]. Despite the value of about 650 Wm\(^{-2}\) recorded for the net radiation, the latent heat and sensible heat flux observed were approximately 400 Wm\(^{-2}\) and 180 Wm\(^{-2}\), respectively.

By the midday and into afternoons of 28 Feb. 2004 (day 59), due to the intense solar heating and the dry condition of the soil surface, the value of the latent heat flux were observed to have reduced from the large value recorded the previous day (about 400-250 Wm\(^{-2}\)). The magnitude of the sensible heat rose to about 150 Wm\(^{-2}\) while that of the latent heat dropped to about 250 Wm\(^{-2}\) [Fig. 2(d)].

By the morning, on 29 Feb. 2004 (day 60), the ground surface was relatively dry compared to other days. The sky cover was mainly stratus with moderate wind and surface temperature of about 35°C. By midday the magnitude of the sensible heat was fairly close to that of latent heat flux [Fig. 2(e)] although not with a very large difference – about 220 Wm\(^{-2}\) and 280 Wm\(^{-2}\), respectively.

4 Conclusion

The study of a day-to-day partitioning of the surface energy fluxes at the site agreed with the assertion that the surface energy budget is governed by the surface conditions. It was observed that as the surface condition changes due to wetness caused by precipitation, the energy budget varied significantly between the relative values of the sensible and the latent heat fluxes. As observed from the study, for any day that follows a previous night precipitation, the latent heat flux during the daytime was found to be greater by a factor of two or more than the sensible heat flux. It is thus clear from the present study that in the tropical zone that evaporation was the next key factor after radiation. For the relatively dry days however, the sensible heat flux is of the same magnitude or slightly higher when compared with the latent heat flux. Due to intense solar heating of the surface the ground heat flux reached about 110 Wm\(^{-2}\) at the site. Generally, for the tropical zones, during the dry seasons the sensible heat flux is larger than latent heat, but during wet seasons the reverse is the case.\(^{17}\)
It has been demonstrated from this study that the Bowen ratio energy balance method offers a simple technique to determining the surface energy fluxes. The soil surface condition (wet or dry) is also important, because it influences the partitioning of the available energy. The net radiation is affected by clouds, and to a small extent by the surface albedo. The ground heat flux is driven by the soil wetness and the available energy determines the sensible and the latent heat fluxes. It is envisaged that the data from this study (humid tropical zone) will contribute to meeting the demands required to model land surface-atmosphere interaction in global circulation models.

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References